International Indian Ocean Expedition

Collected reprints III

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Preface

The third volume of Collected Reprints of the International *Indian Ocean Expedition* comprises reprints received by Unesco during the second half of 1964 and throughout 1965. The papers presented in the volume are roughly grouped into four major parts:

I. Marine biology;
II. Marine chemistry;
III. Physical oceanography;
IV. Marine geology and geophysics

As was indicated previously, this classification is only a very approximate one which is accepted here simply for convenience of presentation. Some papers of biological importance are included in Part III, "Physical oceanography" since they treat environmental processes, although with application to biological ones. Everyone knows also how difficult it is to separate a chemical description of the environment from a physical one.

It is planned, therefore, to complete eventually the series of volumes of collected reprints with an index volume which will contain both the name and the subject indexes.

The fourth volume of the series will be compiled by the end of 1966.

Collected reprints of the IIOE

List of reprints

Marine biology

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Part I Marine biology

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SHARKS OF THE WESTERN INDIAN OCEAN—II

Triaenodon obesus (Rüppell)

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(Received for publication on 13th August, 1959)

Triaenodon obesus was first described by Rüppell in 1835 (as *Carcharias obesus*) from specimens up to 3½ ft. in length (1,070 mm.) that he collected at Djetta on the Red Sea. It has since been recorded at a number of localities in the tropical Indian and Pacific Oceans, those of former including the Seychelles (Playfair, 1867), Madagascar (Sauvage, 1891), India (Day, 1889) and the Chagos Archipelago (Wheeler and Ommanney, 1953), but, curiously enough, it has not been observed until recently in Zanzibar or among the fishes of East Africa (Playfair and Gunther, 1866, Copley, 1952), nor does it range to the south far enough to be included among the fishes of southern Africa (Barnard, 1927, Smith, 1949).

Day (1878) described a second species, *obtusus*, from a young male 19 inches long (483 mm.) collected at Kurrachee (Karachi). In this specimen the first dorsal was much further forward than in *obesus*, so far indeed that the pectoral overlapped it as far as its midpoint; also the second dorsal was considerably smaller than that shown in Rüppell's figure or in the actual fins of preserved specimens in the British Museum. This species has not been found again as far as I know, but from the evidence of my specimens it does not appear to be a growth stage of *T. obesus*.

Material

The description that follows is based on a full series of measurements and notes taken from three immature females with a profile outline of one of them and a drawing of the underside of its head which was preserved and has since yielded the jaws and teeth. I have some measurements and a painting of a mature male caught at Peros Banhos in the Chagos Archipelago: also another record with a few measurements of a pregnant female caught at the same time and place. All the measurements, calculated as percentages of the total lengths, are given in the table appended. Those of the male from the Chagos have been taken from the painting, the outline of which was reduced from the profile made from the shark itself. The method of outlining and reduction was described on page 43 in the Report on the Mauritius-Seychelles Fisheries Survey, 1948-49 (Wheeler and Ommanney, 1953).

Details of the material examined are as follows:—

(1) Female, 680 mm. long, 2¾ lb., caught on a handline from 5-8 fathoms, Vulture Bank, Mafia Channel (north) on 4th March, 1955.

(2) Female, 830 mm. long, 5 lb., caught in a trammel net on Tutia Reef, South Mafia, on 20th June, 1956.

(3) Female, 837 mm. long, 3 lb., caught on a handline at Jewe Reef, Kilwa Main Pass, on 30th October, 1958.

(4) Male, mature, 1,100 mm., 12 lb., caught on a handline off Yeye Island in the Lagoon of Peros Banhos, Chagos Archipelago on 17th October, 1948.

(5) Female, mature, 1,170 mm., 16 lb., caught on a handline at same place and time as No. 4 above. Pregnant with two foetuses, 47.5 mm. and 50 mm., sex undetermined.

Description

The Chagos specimens were black-grey on the back of the body, darker on the head and on all the fins, both paired and unpaired. Low on the flanks the colour faded to white beneath. The first dorsal and the upper lobe of the caudal were abruptly tipped with white. The Tanganyika females varied in colour from reddish-brown to mauve-brown on the body, darker again on the head and fins, and again white beneath. In one specimen (680 mm.) there were abrupt white tips to D I, D II and both dorsal and ventral lobes of the caudal. In another (837 mm.) D I was white at the tip but not D II, the dorsal lobe of the caudal was white-tipped but not the ventral. In all the underside of the pectorals was dark at the tip and trailing edge fading into white towards the insertion.

The form is very slim and the head is flat, thin and nearly hemi-spherical in outline from above. Nictitating membranes are present but there are no spiracles, no ridge between first and second dorsals, no evident lateral line, no ventral caudal pit, and when lifted the body seems very limp. This lack of rigidity is a noticeable feature, as is the unusual smoothness of the skin, and, of course, the size of the second dorsal and anal relative to the size of

the animal (Fig. 1A). The gill slits are large. In the 1,100 mm. male the second, third and fourth were about equal in length at 35 mm., i.e. 3.2 per cent of the total length (3.1 per cent average length in the immature females). In the pregnant female of 1,170 mm. the third gill slit measured 40 mm.—3.4 per cent total length. Labial furrows are confined to the angles of the mouth (Fig. 1B).

The dentition in the specimen I examined $\frac{23\text{-}1\text{-}25}{22\text{-}1\text{-}22}$ (680 mm.) was ——— (Fig. 1 C). The teeth are in the main tricuspid with the centre cusps considerably longer than the side ones and they are similar in both jaws. In a few teeth there is a second anterior cusp. In my specimen the 8th, 9th and 10th teeth in the upper jaw on the left and the 7th to the 10th on the right were quadricuspid and so were the 7th to the 12th on the left and the 7th to the 14th on the right in the lower jaw. Further back this cusp merges into a knob at the base of the central cusp.

The scales are loosely spaced, irregular in size, faintly keeled with as many as eight keels, and gently incurved (Fig. 1D). The surface of each scale appears glazed like porcelain and their free ends are without projections, hence the smoothness of the skin.

The percentage measurements indicate that the head as far as the gill slits tends to become shorter relative to the increasing length of the growing shark. That growth concerns the body rather than the head latterly is shown by the relative increases in the distance of D II from D I and from the snout to the origin of the anal. According to Klunzinger (1871) this species may attain 1½ m. I believe this to be the extreme limit of growth.

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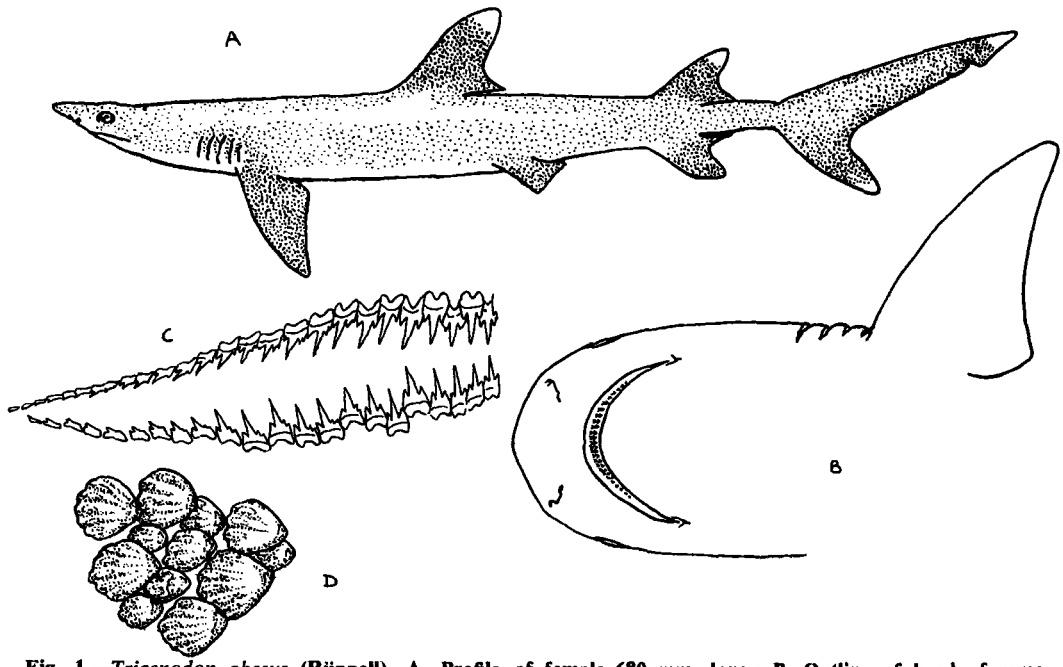


Fig. 1.—*Triaenodon obesus* (Rüppell). A. Profile of female 680 mm. long; B. Outline of head of same from below; C. Teeth of upper and lower jaws of same; D. Scales of same.

TRIAENODON OBESUS (Rüppell)

	F. 8–3–55	F. 23–6–56	F. 9–10–58	Av. per cent	F. 17–10–48	M. 17–10–48
Total length	680	830	837		1,170	1,100
Snout to line joining ant. end nostrils	2·1	1·3	1·8	1·7		1·1
Snout to line joining post. end nostrils	2·9	2·4	2·3	2·5		1·8
Snout to point of lower jaw	4·4	3·6	3·2	3·7		2·4
Snout to line joining angles of jaw	9·6	8·7	8·6	9·0		6·6
Snout to line joining 1st gill slits	15·4	14·5	14·9	14·9		13·7
Snout to line joining 5th gill slits	20·6	18·8	18·8	19·4		19·2
Snout to axilla of pectoral	24·1	21·7	23·3	23·0		
Snout to origin D I	34·6	35·0	34·6	34·7		35·8
Base of D I	7·4	7·2	8·6	7·7		} 13·2
End of D I	4·1	4·6	4·5	4·4		
Height of D I	8·1	8·4	9·0	8·5	8·5	6·6
Origin of D I to origin D II	24·3	27·7	28·1	26·7		28·9
Base of D II	5·9	5·4	6·2	5·8		} 9·2
End of D II	3·2	3·4	3·9	3·5		
Height of D II	5·1	5·4	5·7	5·4	5·1	4·5
Origin D II to base of caudal	14·7	15·0	13·6	14·4		13·7
Dorsal edge of caudal (straight)	25·7	25·3	25·1	25·4		22·4
Base caudal (dorsal) to notch	8·1	8·2	8·6	8·3		
Base ventral lobe to notch	8·5	7·8	7·8	8·0		
Ventral base to tip of ventral lobe	12·9	12·7	13·1	12·9		11·1
Snout to insertion of pelvics	45·6	47·0	47·2	46·6		46·8
Ant. edge pelvics	7·4	7·3	7·2	7·3		
Post. edge pelvics (median)	2·9	3·6	3·6	3·4		
Post. free edge pelvics	5·9	6·0	6·6	6·2		
Snout to origin A	58·8	62·7	60·9	60·8		64·2
Base of A	5·3	5·4	6·0	5·6		4·2
End of A	2·6	3·1	3·7	3·1		3·7
Height of A	4·4	4·8	5·4	4·9		4·2
Origin A to base of caudal (ventral)	13·9	13·6	14·3	13·9		
Ant. edge pectoral	13·7	13·9	14·3	14·0		12·9
Greatest width of pectoral	8·2	8·4	8·4	8·3		6·6
Depth body at D I	8·1	9·0	—	8·5		11·3
Length 3rd or longest gill slit	3·5	2·7	3·1	3·1	3·4	3·2
Largest diameter eye	2·2	1·9	1·0	1·7		
Distance between ant. ends of nostrils	8·5	6·6	6·9	7·3		
Width head at eyes	10·6	10·8	10·8	10·7		
Width head at 1st gill slit	11·4	13·0	13·1	12·5		
Snout to centre of eye	6·2	5·1	5·3	5·5		
Distance between post. ends of nostrils	4·5	4·7	5·0	4·7		
Distance between angles of jaw	9·4	8·4	8·7	8·8		
Width of head at gape	11·4	12·0	12·2	11·9		
Origin of pectoral to origin of A	26·5(?)	44·0	43·0			
Origin of pelvic to origin of A	14·7	15·1	14·7	14·8		
Length of claspers	—	—	—	—	—	9·2
Presence or absence of ridge		0	0			

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23. Supplementband, 1960, p. 175-182

19. WOLFGANG KLAUSEWITZ:

Systematisch-evolutive Untersuchungen über die Abstammung einiger Fische des Roten Meeres

(Mit 5 Abbildungen)

Der paläogeographisch-historische Wandel des Roten Meeres ist für die Zusammensetzung und Evolution der dort lebenden Ichthyofauna bedeutsam. Nach KRENKEL (1925, 1957) entstand dieses Meer an der Wende von Eozän und Oligozän, also im unteren Tertiär, durch Tafrogenese als Erythreischer Graben. Allerdings war diese Zone zu dieser Zeit noch nicht überflutet, sondern gekennzeichnet durch einen mediterranen Meeresarm im Norden, während sich im südlicheren Bereich mehrere Süßwasserseen befanden, wie sie heute auch für die Grabenbildungen des ostafrikanischen Festlandes charakteristisch sind. Die eigentliche tiefe Rinne des Roten Meeres entstand im oberen Miozän durch eine weitere starke Bruchphase. Zu dieser Zeit entstand hier ein riesiger Binnensee, der durch den abessinischen Landriegel, eine Querschwelle zwischen dem Jemen und Abessinien, vom Indischen Ozean getrennt war. Erst im oberen Pliozän, also der letzten Phase des Tertiärs, sank diese Schwelle so weit ab, daß das Wasser des Indik über die Perimstraße in den Rotmeer-Graben eindringen und bis ans Ende des Suez-Golfes vorstoßen konnten.

Im unteren Diluvium, also bereits im Quartär, entstand im Norden für relativ kurze Zeit ein Meeresarm zum Mittelmeer, so daß sich während eines begrenzten Zeitraumes im Rotmeer die indopazifischen und mediterranen Faunenreiche mischen konnten. Mit Ausnahme der erneuten Schließung dieser nördlichen Verbindung durch eine epirogenetische Bewegung im ägyptisch-syrischen Raum ist seitdem der Rotmeer-Graben geologisch zur Ruhe gekommen und scheint keine größere gestaltliche Veränderung mehr erfahren zu haben.

Vom zoogeographischen Standpunkt aus ist die durchgehende Nord-Süd-Verbindung zwischen Mittelmeer und Indischem Ozean über das Rote Meer zu Beginn des Pleistozän besonders bemerkenswert, da man infolgedessen auch heute noch eine Mischfauna aus beiden Anteilen vorfinden sollte.

Merkwürdigerweise unterscheidet sich aber die Ichthyofauna des Roten Meeres in vieler Hinsicht von beiden benachbarten Gewässern, und zwar ganz erheblich von derjenigen des Mittelmeeres, weniger erheblich, aber doch bemerkenswert vom Indischen Ozean. Wir hatten Gelegenheit, auf der jüngsten Xarifa-Reise durch vergleichende Untersuchungen im Roten Meer und im Indischen Ozean diese Fragen eingehender zu studieren.

Bereits KLUNZINGER (1870, 1871) wies darauf hin, daß es im Roten Meer mehrere Fischarten gibt, die im Indischen Ozean nicht vorkommen. CLARK & GOHAR (1953) gaben eine Reihe von Beispielen für unterschiedliche Formen an, ohne allerdings in den meisten Fällen systematisch-nomenklatorische Konsequenzen daraus gezogen zu haben. Nach GOHAR (1954) sind etwa 15% aller Rotmeer-Fische endemisch. Allerdings beschränkt sich nach unseren Feststellungen dieser Endemismus in den weitaus meisten Fällen auf subspezifische Kriterien, so daß die indopazifischen Ursprungsformen und die Deszendenten des Roten Meeres vielfach Rassenkreise im Sinne von RENSCH (1929) bilden. Aller-

dings berücksichtigt merkwürdigerweise FOWLER (1956) diese Differenzierungen überhaupt nicht.

Eindeutig subspezifische Differenzierungen weist z. B. der Kugelfisch *Arothron hispidus* auf. Diese Art hat auf Kopf, Rücken und Flanken zahlreiche weiße Flecken auf dunklem Untergrund, während der Bauch einfarbig hell erscheint. Bei den Exemplaren aus dem Roten Meer ist ventralwärts eine ± ausgeprägte Tendenz zur Streifenbildung festzustellen und sind die hellen Dorsaltupfen bedeutend kleiner und zahlreicher als bei der Stammform aus dem Indischen Ozean. Wir bezeichnen daher die Nominatrasse aus dem Indik *Arothron hispidus hispidus* (Linnaeus) und die geographische Rasse des Roten Meeres *A. h. perspicillaris* (Rüppell).

Bei *Anisochaetodon auriga* des Indopazifik (Abb. 1 a) befindet sich ein großer ovaler schwarzer Fleck auf dem weichen Teil der Dorsale unterhalb des Filaments. Den zur selben Art gehörenden Tieren aus dem Roten Meer fehlt hingegen normalerweise dieser Dorsalfleck beim adulten Farbkleid (Abb. 1 b). Die juvenilen und subadulten Exemplare weisen hingegen einen solchen, aller-

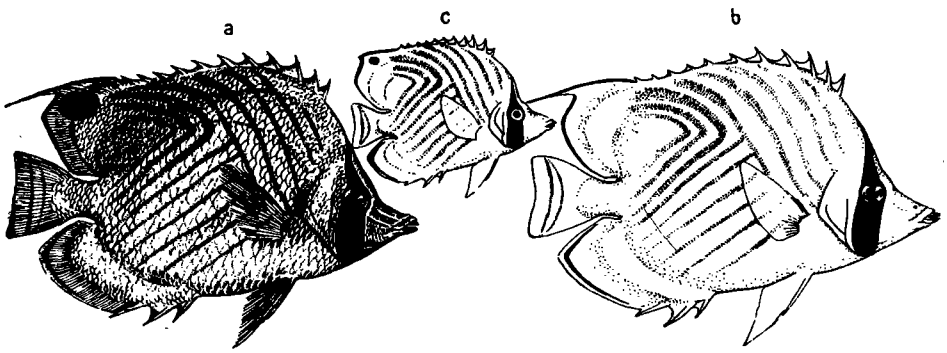


Abb. 1 a. *Anisochaetodon auriga setifer* (Bloch), Indopazifik;
b. *Anisochaetodon auriga auriga* (Forskål), adult; Rotes Meer; c. Jugendkleid von b.

dings relativ kleinen schwarzen Tupfen auf, der aber im Verlaufe des Wachstums allmählich verschwindet. In der Jugendzeichnung der Deszendenten (Abb. 1 c) sind also die Zeichnungskriterien der Vorfahren manifestiert. Auch diese Differenzierung sehen wir nur als subspezifisch an, wobei nach den Nomenklaturregeln aus Prioritätsgründen die Form des Roten Meeres als Nominatrasse *Anisochaetodon auriga auriga* (Forskål), die Ursprungsform aus dem Indischen Ozean *A. a. setifer* (Bloch) heißen muß.

Des weiteren sind eine Reihe spezifischer Differenzierungen festzustellen, von denen einige Beispiele genannt werden sollen. Aus dem allbekannten sogenannten Picassofisch, *Rhinecanthus aculeatus* (Linnaeus) des Indopazifik hat sich unter Rückbildung der Flankenzeichnung, leichter Veränderung der Grundfärbung von lichtgrau zu helloliv und unter einem gewissen Wandel der Lebensweise von einem Bewohner der reinen Sandzone zu einem solchen der Tangwälder im Roten Meer die Art *Rhinecanthus assasi* (Forskål) entwickelt. Auf diese Differenzierung wie die der folgenden Art sind CLARK & GOHAR (1953) näher eingegangen. Der schlanke, langschnäuzige Pinzettenfisch, *Oxymonacanthus longirostris* (Bloch & Schneider) (Abb. 2 a) des Indopazifik wurde im Roten Meer zu einer relativ kurzschnäuzigen, kompakter gebauten, farblich ab-

weichenden und auch in den Flossenformeln differierenden Spezies, *Oxymonacanthus halli* Marshall (Abb. 2 b).

Ferner hat sich der in den Korallenriffen des Indischen Ozeans häufige *Chaetodon trifasciatus* (Mungo Park) (Abb. 3 a) im Roten Meer zu einer deutlich abweichenden eigenen Art entwickelt, nämlich *Ch. austriacus* Rüppell (Abb. 3 b).

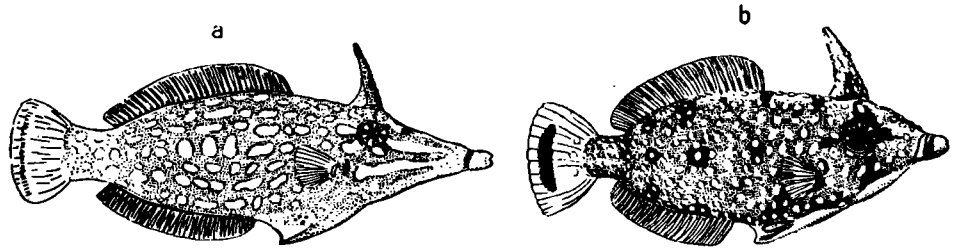


Abb. 2 a. *Oxymonacanthus longirostris* (Bloch & Schneider), Indopazifik;
b. *Oxymonacanthus halli* Marshall, Rotes Meer.

Beiden steht nach FRASER-BRUNNER (1951) die im Golf von Aden beheimatete Spezies *Ch. melapterus* (Guichenot) sehr nahe, so daß alle drei Arten einen Formenkreis bilden. Wir können aber nicht der Auffassung von AHL (1923) zustimmen, daß es sich bei *Ch. trifasciatus* und dessen Verwandten um einen Rassenkreis handelt.

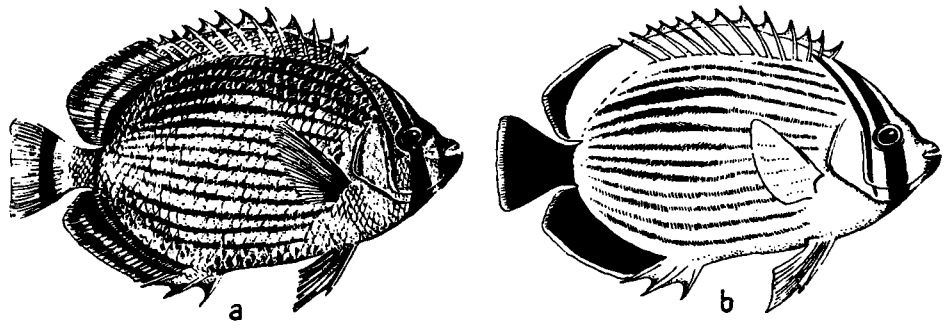


Abb. 3 a. *Chaetodon trifasciatus* (Mungo Park), Indopazifik;
b. *Chaetodon austriacus* Rüppell, Rotes Meer.

Neben solchen Arten, deren Deszendenz leicht rekonstruierbar ist, gibt es im Roten Meer auch eine Reihe von Spezies, die so stark abgewandelt sind, daß man deren Abstammung nicht mehr ohne weiteres nachzuweisen vermag. So ist *Acanthurus sohal* (Rüppell) (Abb. 4 a) ein im Roten Meer häufiger Fisch, der im Indik völlig fehlt. Morphologisch, ökologisch und ethologisch sehr ähnlich ist dort *A. lineatus* (Linnaeus) (Abb. 4 b). Obwohl beide Arten längsgestreift sind, unterscheiden sie sich doch im Farbkleid so erheblich, daß eine direkte Verwandtschaft nur vermutet werden kann.

Als genetische Ursache dieser schwächeren oder stärkeren Veränderungsprozesse liegt hier wohl in jedem Falle eine intraspezifische Evolution mit richtungslosen Mutationen vor. Als weiterer wesentlicher formbildender

Faktor kam die beim Eindringen des Indischen Ozeans in das Rote Meer bedingte erhebliche Verschiebung der Arealgrenze mit sehr kleinen Anfangspopulationen hinzu, was ohne Zweifel im Sinne einer Evolutionsbeschleunigung wirksam war. Während die Selektion für den evolutiven Ablauf in diesem Falle sicher nicht sehr bedeutungsvoll war, hatte hingegen die Isolation daran einen wesentlichen Anteil. Es handelt sich dabei um eine relative geographische Isolation durch die teilweise als Barriere wirkende Flachzone des Südens und um eine damit zusammenhängende hydrographisch wirksame ökologische Isolation, die, worauf bereits GOHAR (1954) hinwies, besonders in erhöhter Salinität und Wassertemperatur ihren Ausdruck findet. Ob diese Abtrennung allerdings so absolut wirksam ist, wie der genannte Autor annimmt, erscheint uns fraglich, denn immerhin gibt es eine Reihe von Arten, die nicht nur im Roten Meer,

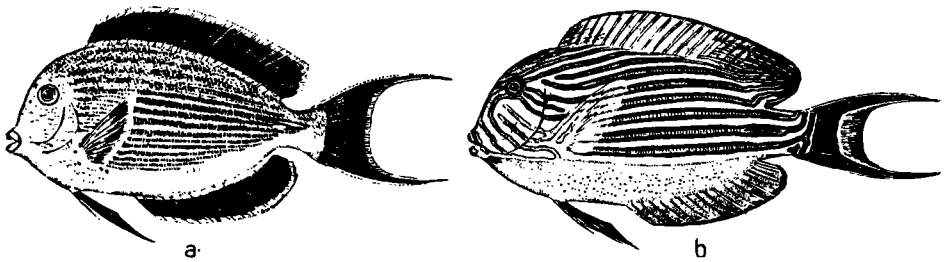


Abb. 4 a. *Acanthurus sohal* (Rüppell), Rotes Meer;
b. *Acanthurus lineatus* (Linnaeus), Indopazifik.
Zeichnungen: K. GROSSMANN.

sondern auch im Golf von Aden vorkommen, nicht aber in den übrigen Gebieten des Indischen Ozeans.

Eine andere, uns wesentlich erscheinende Frage ist die nach dem Alter der im Roten Meer abgewandelten Arten und Unterarten. Man sollte annehmen, daß diese Formen indopazifischen Ursprungs aus dem oberen Pliozän stammen. Da, wie anfangs ausgeführt wurde, aber im unteren Pleistozän durch eine Verbindung mit dem Mittelmeer im Roten Meer eine Mischfauna entstanden war, müßten heute zumindest noch Reste dieser Vergesellschaftung tropischer und gemäßigter Faunenelemente zu finden sein. Demgegenüber gibt aber GOHAR an, daß nicht nur die Fische, sondern auch zahlreiche andere Tiergruppen des Roten Meeres in der Heutzeit rein indopazifischen Ursprungs sind, während von dem mediterranen Anteil nichts mehr zu finden sei. Dieser Autor vertritt die Ansicht, daß die Verbindung über die Perimstraße seit dem Pliozän ununterbrochen bestehen geblieben ist; der Rückgang und das endliche Verschwinden der mediterranen Formen sei durch die geographische Unterbrechung des nördlichen Nachschubweges bedingt, was zu einer Entartung und zum Aussterben dieser Faunenelemente geführt haben soll.

Dem ist aber entgegenzuhalten, daß eine solche völlige Verdrängung eines ganzen Faunenreiches durch rein biologische Einflüsse, Nahrungskonkurrenten, Feinde usw. als völlig unwahrscheinlich erscheint. Es ist aber auch nicht anzunehmen, daß ungewöhnliche abiologische Umwelteinflüsse, wie hoher Salinitätsgrad und hohe Wassertemperaturen, selektiv nur die mediterrane Ichthyofauna vernichtet haben, während die indopazifischen Formen am Leben geblieben sind. Daß bestimmte Arten des Mittelmeeres im Roten Meer trotz erheblich verän-

derter Umweltbedingungen günstige Lebensmöglichkeiten und ökologische Nischen finden, zeigen jene Formen, die mit Eröffnung des Suezkanals von N nach S vorgedrungen sind und sich, wie wir selbst feststellen konnten, recht weiträumig ausgebreitet haben. Es müssen also andere Gründe für das Fehlen des ursprünglichen mediterranen Anteils der Ichthyofauna vorgelegen haben.

Es ist anzunehmen, daß im Pleistozän nochmals eine völlige Isolierung des Roten Meeres eingetreten war. Zwar ist die Ursache hierfür sicher nicht in Krustenbewegungen zu suchen, sondern in eustatischen Schwankungen des Meeresspiegels. Nach KOSSMAT (1936) fanden während der glazialen Inlandvereisungen im Eiszeitalter erhebliche allgemeine Senkungen des Ozeanspiegels statt. Diese durch Wasserentzug bedingte Niveau-Änderung soll im Indopazifik 50—70 m betragen haben. Nach ZEUNER (1945) hat dieser Niveaufall sogar 90—200 m ausgemacht, so daß an einem Trockenfallen der flachgründigen Südpforte von Bab-el-Mandeb des Roten Meeres und somit an einem völligen Abschluß gegen den Adengolf nicht mehr zu zweifeln ist.

Wir stehen zwar mit dieser Anschauung im Gegensatz zu GOHAR, finden aber keinerlei andere Erklärung für die rein indopazifische Fischfauna im Roten Meer. Daher sind wir der Ansicht, daß im Pleistozän während der beschriebenen, postulierten Isolierung des Roten Meeres die Umweltbedingungen so lebensfeindlich geworden waren, daß die gesamte Ichthyofauna, und nicht nur der mediterrane Anteil, ausgerottet wurde und daß die heutigen Formen erst nach dieser Isolierung mit Ansteigen des Wasserspiegels den Erythräischen Graben besiedelt haben. Die von STEINITZ (1929) angenommene pleistozäne Verbindung des Roten Meeres mit dem Mittelmeer muß vor der Isolationsphase gelegen haben.

Auch SEWELL (1948) vertritt auf Grund der Untersuchungen an der Verbreitung der Copepoden die Ansicht, daß während der letzten Glazialperiode das Rote Meer vom Mittelmeer und vom Indischen Ozean separiert und sogar zu zwei Binnenseen reduziert worden war. Hypersalinität hätte während dieser Zeit dort jegliches Leben ausgelöscht. Erst am Ende der Glazialperiode sei eine neue marine Fauna vom Indischen Ozean her in das Rote Meer vorgedrungen.

Wenn wir im Prinzip mit dieser Ansicht übereinstimmen, so können wir hingegen nicht glauben, daß diese geographische Situation einer Isolierung des Roten Meeres während des langen Ablaufes aller Glazial- und Interglazialperioden angehalten hat und sich erst postglazial verändert habe. Denn die relativ kurze Zeitspanne von höchstens 10000 Jahren seit dem Abklingen der letzten, also Würm-Eiszeit, genügt wohl nicht zur Entstehung jener deutlich differenzierten Formen des Roten Meeres. Vielmehr glauben wir, daß nur zu einem relativ kurzen Teil des Gesamtablaufes, höchstwahrscheinlich nur im Maximalstadium der Günz-Eiszeit allein oder auch zur Mindel-Eiszeit, also vor etwa 700000 und 400000 Jahren, eine Isolation des Roten Meeres stattgefunden habe. Diese Auffassung erhärtet sich auch durch die Angaben von WERTH (1952), der für die 1. (Günz-) Eiszeit die größte Pegeldepression der Weltmeere von etwa 200 m errechnet hat, für die 2. (Mindel-) Eiszeit eine solche von etwa 100 m; hingegen hätten die eustatischen Meeresschwankungen während der beiden letzten Eiszeiten (Riß, Würm) nur etwa maximal 60 bzw. 30 m Tiefe betragen. Da die Südzone des Roten Meeres relativ flach ist und die Tiefenwerte nicht unter 200 m liegen (meistens sogar erheblich darüber), war zweifelsohne

eine völlige Isolation zumindest während der 1. Eiszeit die Folge (Abb. 5). Hierbei entstanden lebensfeindliche Bedingungen, die das Aussterben der gesamten marinen Fauna bewirkten. Eine Neubesiedelung fand daraufhin vor etwa 600000 Jahren im Günz-Mindel-Interglazial statt, das gegenüber dem heutigen Pegel einen Meereshochstand bis zu 80 m aufgewiesen haben soll. Eine nochmalige, wohl aber nur relative Isolation trat während der folgenden 2. Eiszeit

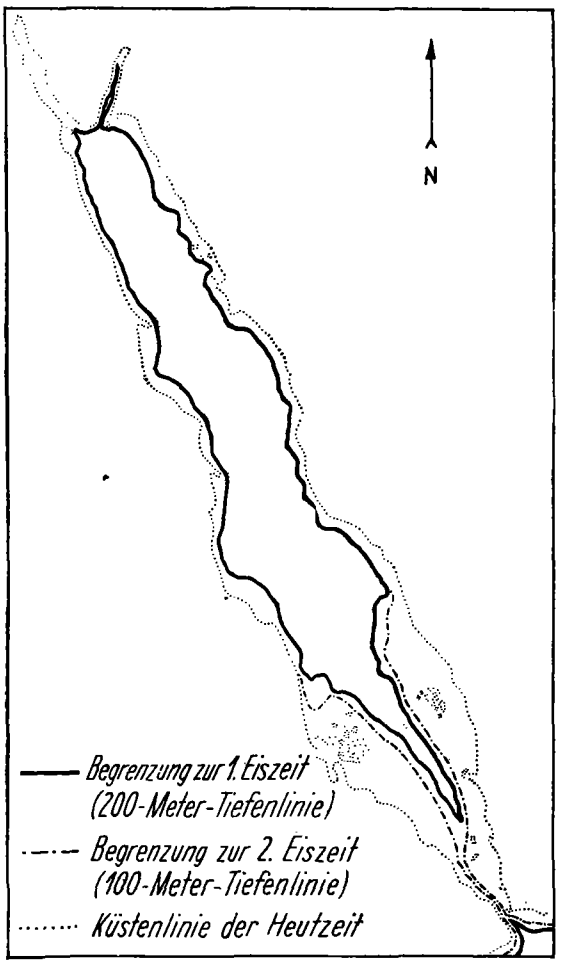


Abb. 5. Küstenverlauf des Roten Meeres im Pleistozän.

ein: durch eine schmale, unter 100 m Tiefe liegende, langgezogene kanalartige Rinne blieben Rotes Meer und Indik über die Perimstraße und den Golf von Aden miteinander in Verbindung. Es erscheint uns daher fraglich, ob während dieses Zeitraums die Lebensbedingungen wiederum so unnormal wurden, daß die marine Fauna verschwand. Vielleicht deutet eine Reihe von ganz erheblichen Differenzierungen bestimmter Rotmeer-Fische auf evolutive Vorgänge besonders während der geographischen Isolation der 2. Eiszeit hin. Hingegen würden die geringeren subspezifischen Differenzierungen so zu deuten sein, daß es

sich bei diesen Formen um Immigranten aus dem Mindel-Riß-Interglazial oder folgender Zeiten handelt.

Damit berühren wir die Frage nach der absoluten Geschwindigkeit dieser evolutiven Vorgänge. RENSCH (1954) gibt für die Differenzierung von Arten und Rassenkreisen u. a. eine Reihe eiszeitlich entstandener Fische an. Entsprechende Verhältnisse liegen in unserem Falle vor. Wir könnten für die stärker differenzierten Formen des Roten Meeres, wie z. B. *Acanthurus sohal, Haliophis guttatus, Anisochaetodon semilarvatus,* einen Zeitraum von etwa 400 bis 500000 Jahren, für die Unterarten oder weniger stark abgewandelten Arten hingegen höchstens einen solchen von 300—350000 Jahren annehmen. Wenn allerdings die von GERMAN (1959) dargestellten Ergebnisse der Radiokarbonmethode für die Eiszeitforschung, die eine erhebliche Reduzierung der bisherigen jüngeren Zeitangaben erbracht hat, entsprechende Resultate für die gesamte Glazialepoche ergeben sollten, müßten wir doch bedeutend kürzere Zeiträume, etwa 300000 bzw. 150000 Jahre, für die Herausbildung der Arten und Unterarten der differenzierten Rotmeer-Fische ansetzen.

Abschließend sei nur noch erwähnt, daß nach unseren Erfahrungen niemals pelagische Fische oder Arten mit großem Aktionsradius eine Tendenz zur Rassenbildung aufweisen, da bei ihnen eine relative Panmixie die isolierte Herausbildung besonderer Merkmale verhindert. Hingegen weisen die Biotop-Spezialisten oder Korallenfische mit ausgeprägter Standorttreue, Bindung an Areal- bzw. Reviergrenzen oder mit geringer Vagilität eine Tendenz zur Variabilität auf, die durch die bekannten Evolutionsgesetze zur subspezifischen und spezifischen Differenzierung geführt hat.

Diskussion:

KOSSWIG: Die folgenden Einwände sollten diskutiert werden:

1. Reicht die Zahl der Individuen, welche aus dem Roten Meer untersucht wurden, aus, um sicher zu sein, daß die Merkmale von systematischem Wert bei den Fischen aus dem Roten Meer außerhalb der Variabilitätsbreite ihrer Verwandten aus dem Indischen Ozean liegen?
2. Gibt es Unterschiede zwischen den Bewohnern der indischen Küste einerseits und der afrikanischen andererseits bei den als Nächstverwandte der Rotes-Meer-Fische betrachteten Formen?
3. Bereits mehrfach ist darauf hingewiesen worden, daß als Ergebnis der eustatischen Meeresspiegelschwankungen während des Pleistozäns in Glazialen das Becken des Roten Meeres in einen oder in eine Reihe von hypersalinen Binnenseen umgewandelt wurde. Gibt es Anhaltspunkte dafür, daß nicht nur in den Interglazialen, sondern auch in den Glazialen im Roten Meer Korallenriffe bestanden? Wenn man bedenkt, daß trotz des Vorhandenseins von interglazialen Verbindungen zwischen Rotem Meer und Mittelmeer keine erythräischen Formen die Würmeiszeit im Mittelmeer überstanden, liegt es nahe, für Glazialperioden auch ungünstige Temperaturverhältnisse im Roten Meer anzunehmen.
4. Eine Neubesiedlung des Roten Meers in postglazialer Zeit kann m. E. auch für die systematisch abzweigbaren und endemischen Formen des Roten Meers nicht ausgeschlossen werden, und zwar
   a) in Anbetracht der oben angeführten Gründe,

b) weil die phylogenetische Entwicklungsgeschwindigkeit bei Knochenfischen offenbar besonders groß ist und
c) damit gerechnet werden muß, daß die Eroberung des wiederbesiedelbaren Roten Meers nur durch eine relativ geringe Individuenzahl durchgeführt wurde. Es sei daran erinnert, daß Einwanderer durch den Suezkanal ins Mittelmeer sich teilweise in ihren äußeren Merkmalen außerordentlich schnell veränderten, woraus noch nicht auf genetische Veränderungen geschlossen werden muß.

Schlußwort KLAUSEWITZ: Das vorhandene und untersuchte Museumsmaterial an Rotmeer-Fischen ist groß genug, um eine eindeutige systematische Einordnung sicherzustellen.

Unterschiede zwischen den Bewohnern der indischen und der afrikanischen Küste gibt es normalerweise nicht, hingegen in einigen Fällen zwischen Formen des Indischen Ozeans und des Golfes von Aden.

Der Einfluß ungünstiger Temperaturverhältnisse während der Glazialperioden im Roten Meer ist durchaus möglich, kann aber nicht als alleiniger ausmerzender Faktor angesehen werden, da er für die mediterrane Fauna (die im Roten Meer unterdessen verschwunden ist) positiven Selektionswert hatte.

Gegen eine postglaziale Wiederbesiedelung des Roten Meeres spricht die starke Differenzierung zahlreicher endemischer Formen, wofür trotz großer phylogenetischer Entwicklungsgeschwindigkeit mancher Knochenfische der anzusetzende Zeitraum von maximal 10000 Jahren nicht ausreichen dürfte.

Schrifttum

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ON *URASPIS WAKIYAI* SP. NOV. (PISCES, CARANGIDAE), FROM THE WESTERN INDIAN OCEAN, WITH A REVIEW OF THE SPECIES OF *URASPIS* BLEEKER, 1855, S.S.

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[Plate IV]

AMONG the stomach contents of a yellow-fin tuna (*N. macropterus*) taken by surface trolling in British East African waters on 18th June, 1952, was a very small unusual Carangid fish. After examination and preservation the fish was put to one side and not discussed by the author in "Fishes of the Family Carangidae in British East African Waters" (Williams 1958). However, a similar fish was taken from the stomach of a sailfish (*Istiophorus* sp.) caught by longline on 19th January, 1959, which revived interest in the first specimen. Although the specimens had suffered damage by digestion to varying degrees, it proved possible to carry out detailed examinations for taxonomic evaluation. Both specimens obviously belonged to the genus *Uraspis*, but it has been found necessary to describe them as *species novum*. An apparently similar specimen taken in Japanese waters and described in Wakiyai 1924 was referred to *Caranx* (*Uraspis*) *uraspis* Gthr. Unfortunately this species cannot stand as Günther's *Caranx uraspis* is indeterminate and is itself based on an indeterminate species, *U. carangoides* Blkr. This matter is discussed more fully later in the paper. The literature on *Uraspis*-like Carangids is in a most confused state and many nominal species, referred to *Uraspis* or other genera, have been described. An attempt has been made, therefore, by the author to collate and discuss all available data on the subject, and reduce the number of nominal species on the grounds that geographical variation and growth changes have invariably been described as new or separate species.

Definition of terms used in the paper is as given in Williams (1958).

Family **Carangidae.**

Genus URASPIS Bleeker, 1855 s.s.

Uraspis Bleeker 1855.
Leucoglossa Jordan & Evermann in Jordan, Evermann & Tanaka 1927.
Type species—*Uraspis carangoides* Bleeker 1855 (Monotypic).

Body oblong, compressed. Adipose eyelids only feebly developed, forming a rim around eye. Lower jaw slightly prominent. Small teeth in both jaws in one or two series (in the latter may be in a single series posteriorly) ; no teeth on vomer, palatines or tongue. Palate and tongue covered with thick membranes. Colour of mouth distinctive, palate and tongue and immediately surrounding areas white, contrasting sharply with the rest of the mouth mainly blue black. Gill rakers of normal size.

Scales small ; breast naked ventrally, and laterally for about half distance to pectoral base. Lateral line with a long, low to moderate arch ; posterior straight part of lateral line with armed scutes throughout its length. Second dorsal and anal fins without falcate lobes anteriorly ; rays decreasing in size gradually from anterior to posterior of fin.

Uraspis, a genus of carangid fish, was first used by Bleeker in 1855 and was characterized by biseriate teeth on the inter- and infra-maxillaries and no teeth on the vomer, palatines or tongue. Bleeker goes on to describe *Uraspis carangoides*, the type species, a 129 mm. long fish from Amboina, East Indies, with biseriate teeth in the jaws except that posteriorly in the lower the teeth may be uniseriate. The other main feature of the genus as described in the type species, was the swollen tongue and the palate membranes which are white and contrast with the blackness of the rest of the mouth. Although Bleeker, and Günther, 1860 (*Caranx uraspis*= *U. carangoides* preoccupied in *Caranx*) did not mention the presence of scutes in the lateral line with reversed points, that is points directed anteriorly (and thus a unique feature in Carangidae), later workers (Wakiya 1924, Jordan, Evermann & Tanaka 1927, Fowler 1938 (ii), 1949 and Ginsberg 1952) have regarded this feature as the main generic character. It is not understood how so careful a worker as Bleeker would have missed such an unusual and important character as scutes with reversed points. The type species is not present in the Amsterdam or Leiden Museums and is presumed lost and, in the absence of anything to the contrary in the original description, the character of reversed scute points cannot be accepted as diagnostic of the genus *Uraspis* in the strict sense.

The genus *Leucoglossa* was erected by Jordan and Evermann to take two fishes which were similar to *Uraspis* in general characters except that the direction of the points of the lateral line scutes was normal, that is directed posteriorly. However as stated previously, *Uraspis* Blkr. *senso stricto* does not have reversed scute points as a diagnostic feature and thus *Leucoglossa* is here regarded as a synonym of *Uraspis s.s.*

It is interesting to note that Weber & de Beaufort 1931, though copying Wakiya's 1924 description of *C.* (*U*) *uraspis* (non Gthr.), omitted the character of reversed scute points as given by Wakiya for his 172 mm. specimen. The 60 mm. specimen referred to by Weber & de Beaufort from Nias I., Sumatra is also missing from the Amsterdam and Leiden Museums. Fowler 1928 believed *Leucoglossa* to be synonymous with *Uraspis*, the only real difference between the two being the reversed scute points and that this might be a factor of age (see *Discussion* later in this paper). In 1949, however, Fowler reverted to *Uraspis* and *Leucoglossa* as separate genera on the character of reversed and normal scute points respectively.

Uraspis wakiyai, sp. nov. (Plate IV, fig. 1.)

(?) *Uraspis carangoides* Bleeker 1855.
(?) *Caranx uraspis* Günther 1860. (*carangoides* preoccupied in *Caranx*).

Caranx (*Uraspis*) *uraspis* (non Gthr.) Wakiya 1924.
Uraspis carangoides (non Blkr.), Jordan, Evermann & Wakiya in Jordan, Evermann & Tanaka 1927 (in key to species of *Uraspis* only) ;
(?) *Uraspis reversa* Jordan, Evermann & Wakiya in Jordan Evermann & Tanaka 1927.
(?) *Uraspis carangoides* Blkr., Fowler 1928 (after Blkr. 1855).
(?) *Caranx* (*Uraspis*) *uraspis* Gthr., Weber & de Beaufort 1931.

The Holotype 66 mm. standard length from the stomach of a yellow-fin tuna (*N. macropterus*) taken trolling on 18th June, 1952, off the coast of Tanganyika Territory—position 4° 45′ S. 39° 30′ E. A single Paratype 51 mm. standard length from the stomach of a sailfish (*Istiophorus* sp.) taken on tuna longline on 19th January, 1959, off the coast of Tanganyika Territory—position 7° 30′ S. 40° E. Both specimens are damaged due to digestive action in the stomachs of the fishes in which they were found. Holotype and Paratype to be deposited in the British Museum (Nat. Hist.)

DESCRIPTION.

Holotype.

D I (P) + VIII + I 31.
A II + I 21.
Pect. I 23–25.

Scutes present along whole of lateral line straight as far as base of central caudal rays, 26–27 ; the posterior 75 per cent of the scutes strong and laterally produced into plate-like keels having a forward directed point, the remainder of the scutes decreasing in size anteriorly, the direction of the scute points changing through laterally to posteriorly directed. Highest scute 3 in eye.

Gill rakers on first gill arch (left) 7 + 1 + 14 = 22. Upper limb, first two rakers club-like, others of normal shape and increasing in size towards angle of arch ; single raker at angle ; lower limb, rakers larger near angle, 1·33 in eye, decreasing in size anteriorly. Inner edges of rakers of lower limb with a few minute bony setæ. On lower limb of arch about 14 tubercles detached from rakers and each with several small bony setæ. Longest gill filaments 1·7 in eye.

Depth 2·31 ; head 2·87 ; both in standard length. Eye 3·83 ; snout 3·28 ; interobital 3·83 ; suborbital 9·2 ; postorbital 2·19 ; upper jaw 1·93 ; pectoral fin 1·6 ; pelvic fin 0·88 ; 3rd dorsal spine 4·18 ; 1st dorsal ray 2·87 ; 1st anal ray 2·09 ; all in length of head. Eye in snout 1·16 ; in postorbital 1·75. Lateral line curve in lateral line straight 1·18. Angle of snout profile with longitudinal axis of body 60° to interorbital, then about 30°–35° to origin of dorsal fin.

Body oblong compressed. Dorsal profile strongly convex to interorbital then in an even curve to origin of 2nd dorsal fin ; ventral profile slightly convex to isthmus, then almost straight to origin of 2nd anal fin. Caudal peduncle wider than high. Head as high as long. Interorbital only slightly convex. Eye in front half of head. Cleft of mouth a little below level of eye, slightly oblique. Upper jaw moderately protrusible, lower jaw slightly prominent. Maxilla with large posterior expansion, reaches under a point between posterior edge of pupil and posterior edge

of eye. Adipose eyelids only feebly developed, and because of damage it is difficult to determine if they form a rim around the eye.

Teeth, small acute curved " conicals ". In two series in each jaw except posteriorly in lower jaw becoming uniserial. In addition there are, in each jaw, a small number of minute teeth immediately posterior to the inner row ; and on both sides of the upper jaw there are two odd " conicals " posteriorly which point inwards. The teeth are not dense or regular in either jaw, and the outer row of teeth flare outwards as a result of which the jaws do not close completely. No teeth on vomer, palatines or tongue. Tongue covered by a thick membrane partially damaged ; the membrane covering the palate has been almost completely destroyed. Operculum and pre-operculum entire, the latter expanded at lower posterior corner. Pectoral girdle not crossed by a furrow at the isthmus. Cheeks and part of upper operculum scaled, rest of head naked. Scales on body small but conspicuous, missing in places because of partial digestion. Breast naked ventrally, and laterally for a short distance towards pectoral base. Lateral line with a low regular arch which joins straight section under 10th–11th dorsal ray.

Procumbent dorsal spine almost completely covered. Third dorsal spine longest, 8th the smallest ; 1st and 7th about equal in length. The dorsal spines are basally strong and thick, whereas the tips are produced into very fine filaments. The membrane between the spines appears to be strong although it is severely damaged in this specimen. Spine of second dorsal fin about length of 1st dorsal spine. Second dorsal fin not falcate anteriorly, the rays decreasing in size posteriorly. As with the dorsal spines, the fin rays are produced into very fine filaments ; however, the fin membrane reaches to the tips of the filaments, the edge of the fin being straight. Anal spines almost embedded. Spine of second anal fin very small, rest of fin the same as the second dorsal. Pectorals short, rounded ; pelvics very long (middle ray longest), subfalcate, reach beyond origin of second anal fin. Pelvic origin in advance of pectoral origin. Caudal fin damaged but appears to be widely forked with upper and lower lobes about equal in length.

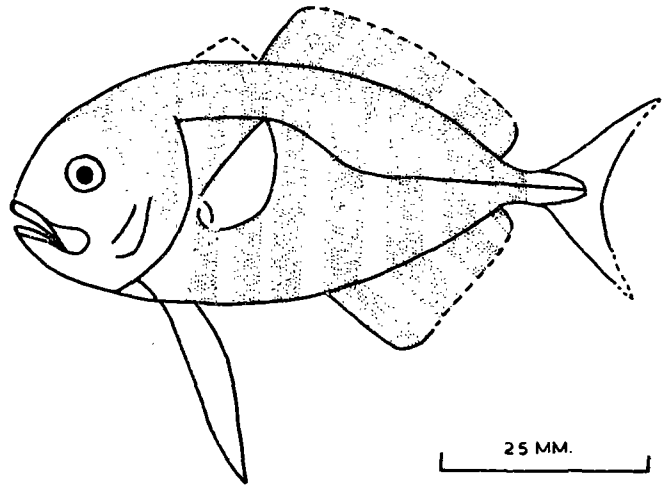
Colour.

Preserved in formalin. Head brownish, cheeks and interorbital generally a little darker. Remains of a vertical blue brown band on upper operculum and nape. Inside of mouth pale. Body brownish, with seven vertical blue-brown crossbands which are wider than the interspaces. First band from dorsal spines through origin of pectoral to just behind pelvic base : second from front of second dorsal fin to anus ; third from dorsal fin to anal spines : fourth from dorsal fin through join of arch and straight section of lateral line to front of anal fin ; fifth and sixth from second dorsal to anal fin across lateral line straight and seventh from last rays of second dorsal to anal across anterior end of caudal peduncle. There is possibly an eighth crossband posteriorly on the caudal peduncle. The crossbands of colour are carried across on to the dorsal and anal fins, but

posteriorly become very faint towards the edges of the fin. Pectorals pale except inside base of the fin and inner parts of some rays dark brown, as is the axil. Pelvics ; outside base and outer rays pale to dusky, mid rays black ; inside of fin black. Caudal pale. Eye dark, pupil lighter.

Immediately after capture the crossbands on the body appeared blue black. The tongue and palate pale whitish, rest of the mouth dusky.

Fig. 1.



Uraspis wakiyai sp. nov. Holotype. Standard length 66 mm.

Paratype (similar to Holotype unless otherwise stated).

D I (P) + VIII + I 29.

A I + I 21.

Pect. 21–23.

Scutes on lateral line straight, 26–27. Highest scute 5·5 in eye.

Gill rakers on first gill arch 4 + 1 + 15 = 20 (left) and 5 + 1 + 14=20 (right). All of normal shape. Longest gill raker 2·2 in eye ; longest gill filament 2·2 in eye.

Depth 2·31 ; head 2·83 ; both in standard length. Eye 3·27 ; snout 4·5 ; interorbital 6 ; suborbital 18 ; postorbital 2·25 ; upper jaw 1·89 ; pectoral fin 1·63 ; pelvic fin 1·00 ; 3rd dorsal spine 3 ; 1st dorsal ray 2·11 ; 1st anal ray 1·58 ; all in length of head. Eye in snout 0·72 ; in postorbital 1·45. Lateral line curve in lateral line straight 1·46. Angle of snout profile with longitudinal axis of body 50° to interorbital, then 30° to origin of dorsal fin.

Cleft of mouth oblique and a little above lower level of eye. Maxilla reaches to a point under centre of eye. Teeth similar to those in Holotype except that the two odd teeth posteriorly in the upper jaw are absent; however, there is a single acute tooth centrally just anterior to the vomer. Tongue and palate covered by thick membranes.

Adipose eyelids, operculæ, scales on head, breast and the lateral line arch are all damaged by partial digestion.

Third, 4th and 5th dorsal spines almost equal in length. Pelvics long, reach to origin of anal fin, tips of rays filamentous.

COLOUR.

Almost all colour lost since preservation in formalin. When freshly " caught ", grey with vertical blue black crossbands on the body as in the Holotype. Pectorals pale ; dark axillary patch. Pelvics ; base, edges and filaments of outer rays pale, rest black. Tongue and palate membranes pale whitish, rest of mouth dusky to black.

Data on the Holotype and Paratype are given in Table I as a percentage of the standard length.

TABLE I.—Data on the Holotype and Paratype of *Uraspis wakiyai* sp. nov. expressed as a percentage of the standard length.

Character	Holotype SL. 66 mm.	Paratype SL. 51 mm.
Head	34·84	35·29
Depth	43·18	43·13
Eye	9·09	10·78
Snout	10·66	7·84
Interorbital	9·09	5·88
Postorbital	15·99	15·68
Upper jaw	18·18	18·62
Pectoral fin	22·75	21·56
Pelvic fin	39·39	37·25
3rd dorsal spine	8·33	11·76
1st dorsal ray	12·12	16·66
1st anal ray	16·66	22·54

TAXONOMIC RELATIONSHIPS.

Uraspis wakiyai is most closely related to *U. heidi* Fwlr. of the Atlantic Ocean. In *U. heidi* the dark crossbands are restricted to the body, whereas in *U. wakiyai* they are carried onto the second dorsal and anal fins (see figs. 1 and 3). Certain proportions such as depth and head in standard length vary slightly between the two species but may be growth factors (see Tables I & III). The affinities of *U. wakiyai* and *U. heidi* with *U. helvola* are discussed fully in the review of the genus *Uraspis* which follows.

DISTRIBUTION.

Coast of East Africa (two specimens). Nagasaki, Japan (one specimen).

The Ryukyu Islands are also given as a locality by Wakiya (1924) but without reference to particular specimens. As Weber and de Beaufort (1931) pointed out, Wakiya rather exaggerated when he stated that the species is distributed throughout the Indo-Pacific Ocean. The dubious position of *U. carangoides* and *U. reversa*, as shown in the synonomy, further limits the known distribution [*U. carangoides* from Amboina

(one specimen) and Nias I. (one specimen) in the East Indies, and *U. reversa*, from Hawaii], said in Jordan, Evermann & Tanaka 1927 not to be rare.

Ecological note.

The stomach contents of the yellow-fin tuna and sailfish from which the Holotype and Paratype were taken are as follows :—

Holotype		*Paratype*	
Penæid prawn	1	Squid	1
" Shrimps "	40–50	Chiasmodontidæ	1
Oplophorid prawn ..	1	Balistid juvenile	1
Chiasmodontidæ	30–35	Unident. fish remains ..	1
Nemipterus sp. juv. ..	1		
Balistid juv.	1		
Unident. juv. fish ..	1		

All were in an extremely fresh state. The presence of the deep-water prawn and Chiasmodontidæ suggests that the fish may have been feeding at the rich food zone which is thought to be present just above the main thermocline in these waters. This seems to be borne out by the character of the stomach contents of the fishes caught on a tuna longline used by this Organization at subsurface levels, i.e. thermocline depths. However, the taking of *Uraspis wakiyai* in this zone does not mean that the species is defintely one of deep-water, as the juveniles and postlarval forms of many shallower water fishes are also found at this depth. Nothing is known of the origin of Wakiya's 1924 specimen.

Review of the species of *Uraspis* Bleeker 1855, *s.s.*

The exact status of Bleeker's type species *Uraspis carangoides* is uncertain because of the lack of information concerning the direction of the scute points in the original description. The details given by Bleeker are very close to those of *U. wakiyai*, but are also not unlike those of *Uraspis* spp. with normal direction scute points, that is *C. helvolus* (Forster) (see later in this discussion) provided the irregularly biserial teeth become uniserial with age. Bleeker pointed out in his discussion that *U. carangoides* was very similar to *C. helvolus* and *C. micropterus* Rüpp., especially the former, but that the distant points of capture suggested different species ; modern work on the Carangidae, however, shows that the differences between the three species could easily be growth factors. *U. carangoides* is, in the absence of the type specimen (presumed lost), best regarded as an indeterminate species. *Caranx uraspis* Günther 1860 was based on Bleeker's description and this also must be regarded as an indeterminate species. Wakiya (1924) described and gave a text figure, under *C. (U) uraspis*, of a 172 mm. specimen from Nagasaki, Japan, which is identical with the specimens from East Africa. Unfortunately, Günther's *C. uraspis* is indeterminate and cannot be used as a valid name for Wakiya's specimen. In Table II data on *U. wakiyai*

and Wakiya's fish are given, and in the case of the latter additional data have been derived from the text figure and one given in parentheses. Data for Bleeker's *U. carangoides* are also given in Table II ; it is noted that the pectoral fin in *U. carangoides* is falcate and much shorter than in specimens of *U. wakiyai*, although the former is intermediate in length

TABLE II.—Data on *U. wakiya* sp. nov. from East Africa, and Japan [under *C. (U) uraspis* (non Gthr.) Wakiya 1924], and on the indeterminate but possible synonym, *U. carangoides* Blkr.

Character	*Uraspis wakiya* sp. nov.		*C. (U) uraspis* (non Gthr.) Wakiya 1924 SL. 172 mm. Japan	*U. carangoides* Bleeker 1855 Type description. L. 129 mm. Amboina, East Indies
	Paratype SL. 51 mm. East Africa	Holotype SL. 66 mm. East Africa		
Source of data	specimen	specimen	text (text fig.)	text
H in TL.	3·22	3·39	3·84 (3·88)	4
D in TL.	2·63	2·73	2·74 (2·65)	2·75
H in SL.	2·83	2·87	3·30 (3·46)	—
D in SL.	2·31	2·31	2·35 (2·36)	—
E in H.	3·27	3·83	4·16 (4·33)	2·4
Snt. in H.	4·5	3·20	3·25 (3·25)	—
IO in H.	6	3·83	— —	—
SO in H.	18	9·2	— (8·66)	—
PO in H.	2·25	2·19	— (2·16)	—
Upper jaw in H.	1·89	1·93	— (2·36)	—
Pect. in H.	1·63 (rounded)	1·6 (rounded)	— (1·23) (rounded)	1·00 (falcate)
Pelv. in H.	1	0·88	1 (1·04)	—
Max. ht. D^1 in H.	3	4·18	— (3·71)	—
„ „ D^2 „ „	2·11	2·87	1·58 (1·36)	—
„ „ A^3 „ „	1·58	2·09	— (1·52)	—
E in Snt.	0·72	1·16	— (1·33)	—
E in PO.	1·45	1·75	— (2)	—
L1 C in L1 S.	1·46	1·18	0·87 (1·1)	—
Dorsal fin count	VIII+I 29	VIII+I 31	VIII+I 28	VIII+I 28
Anal fin count	I+I 21	II+I 21	0+I 21	II+I 21
Pect. fin count	I 21	I 21–23	—	II 19
Scutes on L1 S	26–27[1]	26–27[1]	33[1]	32[1]
Gill rakers (1st arch)	5+1+14 } =20 4+1+15 }	7+1+14=22	—	—
Teeth	Biserial	Biserial, posteriorly on lower jaw uniserial.	Biserial	Biserial, posteriorly on lower jaw uniserial.
Position of maxilla in relation to eye.	Reaches centre of eye.	Between post. edge of pupil and eye.	Almost to centre of eye.	Reaches centre of eye.
Vertical crossbands on body.	Yes	Yes	Yes	Yes
	[1] Majority of scute points reversed.		[1] Reversed scute points.	[1] Direction of scute points not mentioned.

between the specimens of the latter from East Africa and Japan. Increase in the number of scutes is a known growth change in juvenile Carangids (Blegvad 1944, Bapat & Prasad 1952, and Williams 1958). Details given in Jordan, Evermann & Tanaka 1927 under *U. carangoides* and those in Weber and de Beaufort 1931 under *C.* (*U*) *uraspis* are obviously based on Wakiya 1924 ; and those in Fowler 1928 under *U. carangoides* on Bleeker 1855.

TABLE III.—Data on *Uraspis reversa* Jordan, Evermann & Wakiya 1927 from the text, text figure and key to the species in Jordan, Evermann & Tanaka 1927.

Character	*Uraspis reversa* J.E.W. 1927. Type specimen SL. 133 mm. Honolulu		
Source of data	Text	Text figure	Key
H in SL.	3·4	3·59	—
D in SL.	2·5	2·50	2·2
E in H.	4·3	4·11	4·25
Snt. in H.	—	3·36	—
IO in H.	—	—	—
SO in H.	—	6·16	—
PO in H.	—	2·05	—
Upper jaw in H.	2·6	2·84	—
Pect. in H.	1[1]	0·90[1]	—[1]
Pelv. in H.	1·75[2]	1·60[2]	1·2[2]
Max. Ht. D^1 in H.	—	5·28	—
,, ,, D^2 ,,	2	2·05	—
,, ,, A^2 ,,	2	2·05	—
E in Snt.	—	1·22	—
E in PO.	—	2	—
L1 C in L1 S.	—	1·24	—
Dorsal fin count	—	VIII+I 28	—
Anal fin count	—	— I 21	—
Pect. fin count	—	—	—
Scutes on L1 S.	26[3]	—	26
Gill rakers (1st arch)	—	—	—
Teeth	Biserial	—	Biserial
Position of maxilla in relation to eye.	—	Reaches anterior edge of eye.	Reaches anterior edge of pupil.
Vertical crossbands on body.	Yes	None visible.	Yes, but faint or obsolete.
	[1] pectorals short, rounded. [2] pelvics long, reach to anal. [3] reversed scute points.		[1] pectorals long, falcate. [2] pelvics short, not reaching to anal.

Uraspis reversa Jordan, Evermann & Wakiya from Honolulu was described as a new species in Jordan, Evermann & Tanaka 1927 and was said not to be rare in that area. The position of the species is most uncertain because of considerable variations between details given in the key, text and text figure in the original description. These details are

given in Table III and it may be seen that the major differences concern the pectoral and pelvic fins. From the key the species would be close to *U. wakiyai*, but from the text and text figure close to the other section of the genus in which the direction of the scute points is normal (*C. helvolus*, etc.), and also to the original Bleeker description of *U. carangoides* (in which the direction of scute points was not given). If *U. reversa* were the young of *U. helvola* then this would postulate a change in scute point direction with age, and this was considered a likely event by Fowler 1928 (see also comments of Fowler 1938 (ii) on scute points of subgenus *Platyuraspis*). In the key to the species *Uraspis* in Jordan, Evermann & Tanaka 1927 differentiation between *U. reversa* and *U. carangoides* (the latter based on *C. (U) uraspis* (non Gthr.) Wak. 1924) is as follows :—

	U. reversa Type	*U. carangoides* (non Blkr.)
	133 mm.	172 mm.
(i) D in SL.	2·2 (text 2·5)	2·5
(ii) E in H.	2·25	4
(iii) Max. ht. D^1 in H.	2·2	1·5
(iv) Reversed scutes	26	32
(v) Maxilla reaches under	Anterior margin of pupil.	Centre of eye.
(vi) Crossbands on body	7–8, do not reach D^2 and A^2 fins. Tips of fins not white.	6, reach onto D^2 and A^2 fins. Tips of fins white.

The first five differences are very slight and can be accounted for by the variations in size of the specimens ; it is also probable that the extension of the bands onto the fins and the whiteness of fin tips varies with age. Fowler 1928 included *U. reversa* as a synonym of *C. uraspis* Gthr., but the same author in 1949 gives *U. reversa* as a separate species (*C. uraspis* not being mentioned). Although *U. reversa* was said to be common in the Hawaiian area there seems to be very few other references to the species in the literature. The exact position of *U. reversa* might be solved by examination of the type (Musm. Cal. Acad. Sci. 307) but this has not been done by the author.

There is thus *U. wakiyai* (three existing specimens), with *U. carangoides* (type lost) and *U. reversa* (type) as doubtful synonyms.

Yet another species of *Uraspis* with reversed scute points was described from New Jersey, U.S.A., by Fowler 1938 (ii) (Type fig. in Fowler 1952) as *Uraspis heidi* from a fish of SL. 273 mm. Since then other confirmed records in the literature are, a 207 mm. specimen from off the Mississippi Delta (Ginsberg 1952) and one 192 mm. from off North Carolina, U.S.N.M. 163884 (Berry 1959 and personal communication). The data for the three specimens are given in Table IV (in the case of the type additional data has been derived from the text figure). More recently two other specimens have been taken by the Marine Laboratory, University of

Miami, a 1½ in. specimen off Puerto Rica and an adult (length not known to the author) off Florida. Richards, University of Miami (personal communication) states that both accord with the type and that his findings on the adult in no way add to the information given in Ginsberg 1952. The latter thought that direct comparison of specimens of *U. carangoides* and *U. heidi* might show them to be the same species ; however, Richards believes that they are not similar. *U. heidi* differs

TABLE IV.—Data on *U. heidi* Fwlr. from the N.W. Atlantic Ocean.

Character	*Uraspis heidi* Fwlr.		
	U.S.N.M. 163884 Berry 1959 SL. 192 mm. North Carolina	Ginsberg 1952 SL. 207 mm. Off Mississippi Delta	Fowler 1938 and 1952 Type SL. 273 mm. New Jersey
Source of Data	Text	Text	Text (Text fig.)
H in SL.	—	3·12	3·25 (3·4)
D in SL.	—	2·12	1·9 (2)
E in H.	—	—	4 (4·33)
Snt. in H.	—	—	3·13 (3·25)
IO in H.	—	—	2·75 —
SO in H.	—	—	— (7·09)
PO in H.	—	—	— (2·29)
Upper jaw in H.	—	—	— (2·36)
Pect in H.	(slightly falcate)	1·00 (slightly falcate)	1·2 (rounded) (1·14)
Pelv. in H.	—	—	0·9 (0·95)
Max. Ht. D^1 in H.	—	—	3·5 (3·9)
,, ,, D^2 ,,	—	—	1·75 (1·62)
,, ,, A^2 ,,	—	—	1·5 (1·5)
E in Snt.	—	—	1·33 (1·33)
E in PO.	—	—	— (1·88)
L1 C in L1 S.	—	? 1·4	1·25 (1·22)
Dorsal fin count	VIII+I 29	VIII+I 29	VIII+I 28
Anal fin count	I+I 22	O+I 21	II+I 22
Pectoral fin count	I 22	23	ii 21
Scutes on L1 S.	10+25=36[1]	38[1]	34[1]
Gill rakers (1st arch)	6+14=20	6+14=20	6+15=21
Teeth	—	Biserial	Biserial
Position of maxilla in relation to eye.	At least to anterior margin of eye.	Anterior edge of eye.	Front edge of pupil.
Vertical crossbands on body.	? faint.	6 on body, faint.	8 on body and head.
	[1] first 10 normal, rest with reversed points.	[1] anterior 5 normal or lateral, rest reversed.	[1] majority of scutes with reversed points.

from *U. wakiyai* in only a few features ; depth and head in standard length, the crossbands on the body being very much wider than the interspaces in *U. heidi* and, as in *U. reversa*, not carried onto the second dorsal and anal fins. Although Fowler's text figure of the type (273 mm.) shows

TABLE V.—Data on *Uraspis helvola* (Forster), and its synonyms ;

Character	*U. pectoralis* Fwlr. Fowler 1938 SL. approx. 165 mm. Type (TL. 215) U.S.N.M. 98820 Philippine Islands	*L. herklotsi* Herre Herre 1932 SL .180 mm. Type Hong Kong	*C. micropterus* Rüpp. Rüppell 1835 SL. 190 mm. (TL. 226) Red Sea
Source of Data	Text (Text Fig.)	Text	Text (Text Fig.)
Head in Standard Length	2·88 (2·95)	3·15	(2·90)
Depth ,, ,, ,,	2·33 (2·61)	2·2	(2·46)
Eye in Head	3·2 (3·9)	3·35	(4·12)
Snout in Head	2·88 (3)	2·9	(4·12)
Interorbital in Head	3 —	—	—
Suborbital in Head	— —	—	(11)
Postorbital in Head	— (2·66)	—	(3)
Upper jaw in Head	2·33 (2·66)	2·3	(2·75)
Pectoral in Head	— (1·00)	0·91	(0·99)
Pelvic in Head	2·75 (2·4)	2·4	(2·75)
Maximum height D^1 in Head	6·25 (6·85)	—	(10·75)
,, ,, D^2 ,, ,,	2·10 (2·4)	1·6	(2·75)
,, ,, A^2 ,, ,,	2·50 (2·6)	1·8	(2·36)
Eye in Snout	1·2 —	—	(1)
Eye in postorbital	— —	—	(1·36)
Lateral line curve in lateral line straight.	0·8 (0·87)	L1 C. a little longer than L1 S.	(0·86)
Dorsal fin count	VIII+I 25 (VIII+I 28)[2]	VIII+I 27	VIII+I 17 (VIII+I 27)[2]
Anal fin count	II+I 20	II+I 20	? +I 21
Pectoral fin count	ii 21	—	22
Scutes on lateral line straight	36[1]	31[1]	25–30[1]
Gill rakers (1st arch)	4+13=17	i4+13i=17ii[2]	—
Teeth	Uniserial	Uniserial	Uniserial
Position of maxilla in relation to eye.	Just beyond front edge of pupil.	Not quite reaching front edge of eye.	Front edge of pupil.
Crossbands on body	None	Faint crossbands present.	None
	[1] Direction of scute points are not mentioned (requires checking on type specimen). [2] Text figure different to text.	[1] Direction of scute points are not mentioned, presumed normal. [2] ii=short stubs.	[1] Direction of scute points are not mentioned, but appear normal in text figure. [2] Text figure different to text.

and *L. albilinguis* J.E.W. 1927 a probable synonym.

L. candens J.E.W. Jordan, Everman and Tanaka 1927	*S. helvolus* Forst. Forster 1775	*C. helvolus* Forst. Jayakar del.	*C. helvolus* Forst. Jordan and Evermann 1905	*L. albilinguis* J.E.W. Jordan, Evermann and Tanaka 1927
SL. 268 mm.	SL. 274 mm. Type	SL. 281 mm.	SL. 380 mm.	SL. 267 mm. Type
Hawaiian Islands	B.M. (N.H.) Ascension Island, Atlantic Ocean	B.M. (N.H.) Muscat	Hawaiian Islands	Mus. Cal. Acad. Sci. 305 Hawaiian Islands
Text	Type Specimen	Specimen	Text (Text Fig.)	Text (Text Fig.)
3·37	3·22	3	3·3 (3·82)	3·52 (3)
2·45	2·81	2·39	2·5 (2·74)	2·33 (2·54)
4·2	3·5	4·00	4·3 (4·25)	— (4·35)
—	—	—	2·9 (2·83)	— (3·52)
—	3·5	3·03	2·9 —	— —
—	—	—	— (7·25)	— (7·4)
—	2·33	2·32	— (2·31)	— (2·17)
—	2·27	2·54	2·5 (2·43)	— (2·78)
>1	0·89	1·03	— (0·87)	greater than head (0·88)
2·34	2·8	2·47	— (2·21)	2·17 (2·31)
5·91	—	—	— (5·1)	6·29 (6·16)
2·54	—	—	— (2·55)	2·17 (2·31)
—	—	—	— (2·37)	— (2·24)
—	—	—	— (1·5)	— (1·23)
—	1·5	1·72	— (1·83)	— (2)
—	—	—	— (1·04)	— (1·27)
VIII+I 28	VIII+I 29	VI+I 28	V+I 28	VI+I 27
? +I 28[2]	III+I 21	III+I 19	I 22	(VIII+I 30)[2] (I 21 I 21)[2]
—	—	—	—	—
33[1]	32[1]	32[1]	36[1]	36[1]
4+15=19	5+1+13=19	5+1+12–13 = 18–19	—	Lower limb 15
Uniserial	Uniserial	Uniserial	Uniserial	Uniserial
Just beyond anterior edge of pupil.	—	—	Front edge of eye.	Just beyond anterior edge of pupil.
None	None	None	None	None
[1] Scute points weak normal : keels weak.	[1] Scute points normal.	[1] Scute points normal.	[1] Scute points normal, moderately well developed keels.	[1] Keels with plates well developed: a blunt spine posteriorly.
[2] In synonymous *C. helvolus* J.E. 1905 is I 22.				[2] Text figure different to text.

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distinct crossbands, they are already faint in the smaller specimens of 192 and 207 mm. standard length.

The genus *Uraspis*, as stated earlier, includes a number of fishes which have the characteristic white and black mouth but in which the teeth are uniserial and the scute points normal in direction (points directed posteriorly). Forster (1775) described the first of these " white mouth crevalles " under *Scomber helvolus* and according to his description the specimen was from Ascension I., Atlantic Ocean—" *Habitat in mari Atlantico albiente Insularim Ascensionis* ". The type specimen is present in the British Museum (Nat. Hist.) and the author is indebted to Mr. G. Palmer for his examination of the fish, full details of which are given in Table V. Rüppell (1835) described and gave a text figure of *C. micropterus* from the Red Sea; proportional data (see Table V) have been derived from the text figure to supplement the description of the 229 mm. (approx. 190 mm. SL.) type specimen, which is presumed lost. The second dorsal fin count is given in the text as 17 but from the text figure it is obviously 27. There is no mention of the direction of the scute points and it is presumed that they are normal, and certainly they appear so in the text figure. The teeth of Rüppell's type were not described but the species was placed under the kind of *Caranx* with one small row of fine teeth in the jaws. Günther 1860 synonymises *C. micropterus* Rüpp. with *C. helvolus* Forster, and although as Bleeker (1855) points out there are some differences between the two species, the author does not believe they are other than variations with growth and geographical location. Jordan and Evermann (1905) described *C. helvolus* Forster from Hawaii at 381 mm. and details (also given from text figure) are given in Table V. There is general agreement with the types of *C. helvolus* and *C. micropterus* except that the snout and postorbital are longer in this larger Hawaiian fish, the number of dorsal spines is reduced to five and also the scutes of the lateral line straight have a distinct keel with a blunt spine posteriorly. Jordan, Evermann & Wakiya in Jord., Ever., & Tanaka 1927 state that *C. helvolus* J. & E. (1905) can not be the same as *C. helvolus* Forster, as the scute points in the former specimen were normal in direction. To take these *Uraspis*-like fishes with normal direction scute points, Jordan & Evermann (in Jord., Ever., & Tanaka 1927) instituted the new genus *Leucoglossa* ; the type species was given as *L. candens* J.E.W. 1927 = *C. helvolus* J. & E. 1905 and the type specimen designated as Synder's *C. helvolus* Forster U.S.N.M. 55170. However, the 1927 statement of Jordan, Evermann & Wakiya is incorrect, as the type specimen of *C. helvolus* (Forster) definitely has normal direction scute points ; in addition, as *Leucoglossa* J. & E. = *Uraspis* Blkr. *s.s.*, the position is that *C. helvolus* Forster = *C. helvolus* J. & E. = *L. candens* J.E.W.

Leucoglossa herklotsi Herre (1932) was described from a single specimen 180 mm. in length collected in the Hong Kong fish market in 1931. Details are given in Table V and the fish is obviously very similar to *C. micropterus* Rüpp. and the following species *U. pectoralis* Fwlr. The direction of the

scute points is not stated, but as the species is described under *Leucoglossa*, it is presumed that it is normal, i.e. points directed posteriorly. *L. herklotsi* differs from other fish in this category in having vertical crossbands remaining on the body, but as they number only four, or perhaps five, it suggests that this juvenile feature is gradually fading. The disappearance of crossbands in the Carangidæ rarely takes place at a fixed length, even in specimens of the same species.

Uraspis pectoralis Fwlr. 1938 (ii) is described from the type only, a 215 mm. long (SL. approx. 165 mm.) specimen collected from Manilla, Philippine Is. in 1908. Details are given in Table V (from text and text figure) and it may be seen that *U. pectoralis* is also very similar to *C. micropterus* Rüpp. (Greatest differences are in the proportions E in H and E in Snout.) It is also noted that in Fowler's type description the second dorsal fin count is I 25 (24 i) whereas the text figure shows it to be I 28. The direction of the scute points is not mentioned and can not be discerned in the text figure ; although described under *Uraspis* Bleeker presumably in the wide sense (i.e. with reversed scutes) the fish is very much closer in other details to the *U. helvolus* group—especially in the length of the pelvic, shape of the pectoral and dentition. It is most probable that on examination the type specimen will prove to have normal direction scute points.

Data are given in Table V on a 281 mm. SL. specimen of *C. helvolus* (Forster) collected by Jayaker from Muscat and present in the collections of the British Museum (Nat. Hist.).

In the opinion of the author the very similar fishes, data on which is listed in Table V, should be combined under the name *Uraspis helvola* (Forster) 1775. Thus *U. helvola* becomes a species known from 165 to at least 380 mm. standard length, and within these limits characterized by uniserial teeth in the jaws and the scute points directed posteriorly (the 165 mm. type specimen of *U. pectoralis* needs checking on this latter point—see above).

Although it is clearly stated by Forster that his type specimen of *C. helvolus* was from Ascension Island, Atlantic Ocean, doubt as to the correctness of his statement has been made by all later authors on this subject. Günther (1860) states " ? Atlantic ", and Jordan & Evermann (1905) " ? Society Islands " as he visited that group on the second voyage of Captain Cook. Fowler (1936) states " *S. helvolus* Forster[1] is evidently only known from the Indo-Pacific. Lichtenstein's record from Ascension Island doubtless pertains to the Pacific Island of that name ". Fowler's footnote is as follows : " [1] Descr. An.", pp. 414, 415. Probably Society Is.—Lichtenstein's 1884, Descript. Animal Forster, p. 415, Ascension Is." There is little definite proof to show that Forster's type locality is incorrect except that *U. helvola* does not seem to have been identified from the Atlantic Ocean since that date.

Leucoglossa albilinguis Jordan, Evermann & Wakiya in Jordan, Evermann & Tanaka 1927 was described at the same time as *L. candens*

J.E.W. and it was supposed to be differentiated from it as under :—

L. candens	*L. albilinguis*
(i) Body oblong, its depth not 2/5 its length.	Body rather deep, its depth more than 2/5 its length.
(ii) Keel on scutes distinct but scarcely developed into a plate, ending in a blunt spine at posterior end.	Keel on scutes each developed into a plate with a blunt spine posteriorly.

Neither of these differences can be regarded as really significant, and the development of the scute keels in *L. albilinguis* is more like that in *C. helvolus* of Jordan & Evermann which is said to be synonymous with *L. candens*. Details on *L. albilinguis* (text and text figure) are given in Table V, and it is treated as a probable synonym of *U. helvola* Forster. Fowler 1928 combined *L. candens* and *L. albilinguis* under *C. helvolus* but in 1949 referred to them as separate species of *Leucoglossa*.

TABLE VI.—Data on *C. helvolus* and *C. micropterus* both of Wakiya 1924.

Character	*C. (U) micropterus* (non Rüpp.) Wakiya 1924 (=*U. riukiuensis* Wak. in J.E.T. 1927) SL. 210 mm.	*C. (U) helvolus* (non Forster) Wakiya 1924 SL. 250 mm.
Source of Data	Text (Text fig.)	Text (Text fig.)
Head in SL.	3·44 (3·4)	3·52 (3·65)
Depth in SL.	2·36 (2·33)	2·55 (2·47)
Eye in Head	4·7 (4·42)	4·58 (5·75)
Snout in Head	3 (3·44)	2·95 (3·28)
Interorbital in Head	— —	— —
Suborbital in Head	— (7·75)	— —
Postorbital in Head	— (2·06)	— (2·2)
Max. in Head	— (2·58)	— (2·3)
Pect. in Head	slightly less than head. (1·06)	slightly more than head. (0·88)
Pelv. in Head	1·45 (1·55)	1·65 (1·77)
Max. ht. D^1 in H.	— (3·44)	— (3·83)
,, ,, D^2 ,,	1·6 (1·63)	1·82 (1·91)
,, ,, A^2 ,,	— (1·72)	— (1·77)
Eye in Snout	— (1·28)	— ?(1·75)
,, ,, Postorbital	— (2·14)	— (2)
L1 C in L1 S.	0·86[2] (1·14)	1·2 (1·37)
Dorsal fin count	VIII+I 29	VI+I 27
Anal fin count	I+I 22	O+I 21
Pectoral fin count	—	—
Scutes on L1 S.	36[1]	37[1]
Gill rakers (1st arch)	13 on lower limb.	13 on lower limb.
Teeth	Uniserial	Uniserial
Position of maxilla in relation to eye	Front margin of pupil.	Front edge of eye.
Vertical crossbands on body	None	None
	[1] Reversed scute points. [2] Text and text figure vary.	[1] Reversed scute points.

The position of *C. helvolus* (non Forster) and *C. micropterus* (non Rüpp.) both of Wakiya 1924 is in doubt. Data (from text and text figures) for the two species are given in Table VI.

The author believes *C.* (*U*) *helvola* Wak. to be the same as *C.* (*U*) *micropterus* Wak., even though the two species are separated by Wakiya as under :—

C. (*U*) *micropterа* Wak. 210 mm.	*C.* (*U*) *helvola* Wak. 250 mm.
Body more than 2·5 in its length.	Body lower than 2·5 in its length.
Maxilla reaching pupil.	Maxilla not reaching pupil.
Gill rakers 2·17 in eye.	Gill rakers 1·72 in eye.
Lateral line moderately curved.	Lateral line a little curved.
Ventral 1·45 in head.	Ventral 1·65 in head.
Colour blackish brown.	Colour brown.

Wakiya in Jordan, Evermann & Tanaka 1927 describes *C. micropterus* (non Rüpp.) Wak. 1924 as a new species *U. riukiuensis* because " . . . it cannot be Rüppell's species as shown in the original description and figure given by Rüppell, it has the body no deeper than in *helvola*." This was a questionable decision, but in any case it has now been shown that *C. helvolus* (Forster) (= *C. micropterus* Rüpp.) has normal direction scute points and not reversed ones as in Wakiya's specimens given the same names. If the adult of *U. heidi* taken off Florida has the majority of scute points reversed (as is assumed from Richards' remark, see page 12) then it is possible that *C.* (*U*) *micropterus* (= *U. riukiuensis*) and *C.* (*U*) *helvolus*, all of Wakiya, are the adults of *U. wakiyai* sp. nov., the vertical crossbands disappearing and the biserial teeth becoming uniserial with growth. It was stated by Jordan, Evermann & Wakiya that *U. riukiuensis* was very close to *L. albilinguis* but differed in several features, the only one which appears to be significant being the different direction of the scute points.

Table VII summarizes the specimens and varying nominal species of fish which should be described under the genus *Uraspis* Blkr. *s.s.* There appears to be a maximum of three confirmed species.

(i) *Uraspis wakiyai* from the Indo-Pacific Ocean.
(ii) *Uraspis heidi* Fwlr. from the Atlantic Ocean.

These species are very similar and the direct comparison of all known specimens is required (as Ginsberg 1952 suggested) to ascertain if they might not be the same species.

(iii) *Uraspis helvola* (Forster) which has been recorded under many different names from the Indo-Pacific and Atlantic Oceans.

Of the five species of doubtful taxonomic position assignments may possibly be as follows for reasons given earlier :—

(i) *U. carangoides* and *U. reversa* to *Uraspis wakiyai* or *U. helvola.*
(ii) *C. micropterus* Wak. (= *U. riukiuensis* Wak.) and *C. helvolus* Wak. to *U. wakiyai.*
(iii) *L. albilinguis* to *U. helvola.*

TABLE VII.—The species of *Uraspis* Blkr. *s.s.*

Uraspis Bleeker 1855 *senso stricto*.
Uraspis Bleeker 1855 ; *Leucoglossa* Jordan & Evermann 1927. (No teeth on vomer, palatine or tongue ; large tongue and palate membranes with characteristic black and white mouth coloration.)

	Reference	Locality	Standard length in mm.	Characters
(1)**Uraspis heidi* Fwlr. 1938. N.W. Atlantic Ocean.				
U. heidi	Berry 1959	North Carolina	192	b/rs/x
U. heidi	Ginsberg 1952	Gulf of Mexico	207	b/rs/x
U. heidi	Fowler 1938 (i)	New Jersey	273 Holotype	b/rs/x
(2) *Uraspis wakiyai* Indo-Pacific Ocean.				
U. wakiyai	Williams	East Africa	51 Paratype	b/rs/x
U. wakiyai	Williams	East Africa	66 Holotype	b/rs/x
C. (U) uraspis (non Gthr.)	Wakiya 1924	Japan	172	b/rs/x
(3) *Uraspis helvola* (Forster) 1775. Indo-Pacific and Atlantic Oceans.				
U. pectoralis	Fowler 1938 (ii)	Philippine Is.	165 Holotype	u/?ns/nx
Leucoglossa herklotsi	Herre 1932	Hong Kong	180 Holotype	u/ns/x
C. micropterus	Rüppell 1835	Red Sea	190 Holotype	u/ns/nx
†*L. candens*	Jordan, Evermann & Wakiya in J.E.T. 1927.	Hawaiian Is.	268	u/ns/nx
Scomber helvolus	Forster 1775	Ascension I. Atlantic Ocean	274 Holotype	u/ns/nx
C. helvolus (Forster)	Jayakar del. (specimen in B.M. [N.H.])	Muscat	284	u/ns/nx
†*C. helvolus*	Jordan & Evermann 1905	Hawaiian Is.	380	u/ns/nx
(4) Species of doubtful position :				
(a) *U. carangoides*	Bleeker 1855	Amboina	129 Holotype	b/?/x
†(b) *U. reversa*	Jordan, Evermann & Wakiya in J.E.T. 1927.	Hawaiian Is.	133 Holotype	b/rs/x
(c) *C. micropterus* (non Rüpp.) (= *U. riukiuensis*)	Wakiya 1924 Wakiya in J.E.T. 1927.	Japan	210 Holotype	u/rs/nx
(d) *C. helvolus* (non Forster)	Wakiya 1924	Japan	250	u/rs/nx
(e) *L. albilinguis*	Jordan, Evermann & Wakiya in J.E.T. 1927.	Hawaiian Is.	280	u/ns/nx

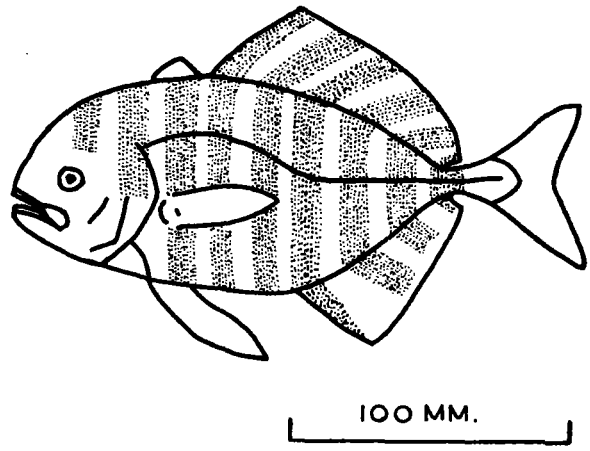
* A 1½ in. specimen from Puerto Rica and an adult from Florida said to be similar to above specimens.
† Other specimens known ; common in Hawaiian Islands.
Characters : b = biserial teeth in jaws. r = direction of scute points reversed. x = vertical crossbands on body.
u = uniserial teeth in jaws. ns = direction of scute points normal. nx = no vertical crossbands on body.

Tentative Key to the confirmed species of **Uraspis** *Blkr. s.s. as given in Table VII.*

1 (a) Teeth in jaws biserial except that posteriorly in lower jaw may be uniserial. Majority of points of lateral line scutes reversed, that is directed anteriorly.
  2 (a) Dark crossbands on body do not reach onto the second dorsal and anal fins..... *U. heidi* Fwlr. (Atlantic).
  2 (b) Dark crossbands on body reach onto the second dorsal and anal fins..... *U. wakiyai* sp. nov. (Indo-Pacific).

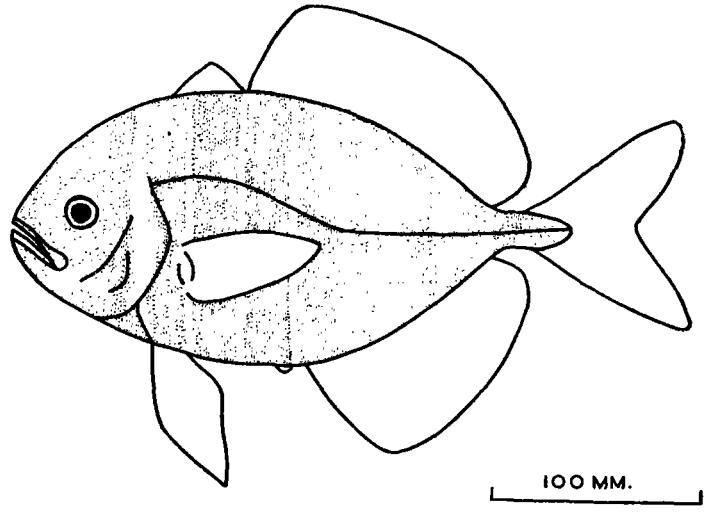
1 (b) Teeth in jaws uniserial. Points of lateral line scutes normal, that is directed posteriorly. No crossbands on body ..... *U. helvola* (Fstr.) (Indo-Pacific & Atlantic).

Fig. 2.



Caranx (*Uraspis*) *uraspis* (non Gnthr.), Wakiya 1924. 192 mm. (after Wakiya 1924.)

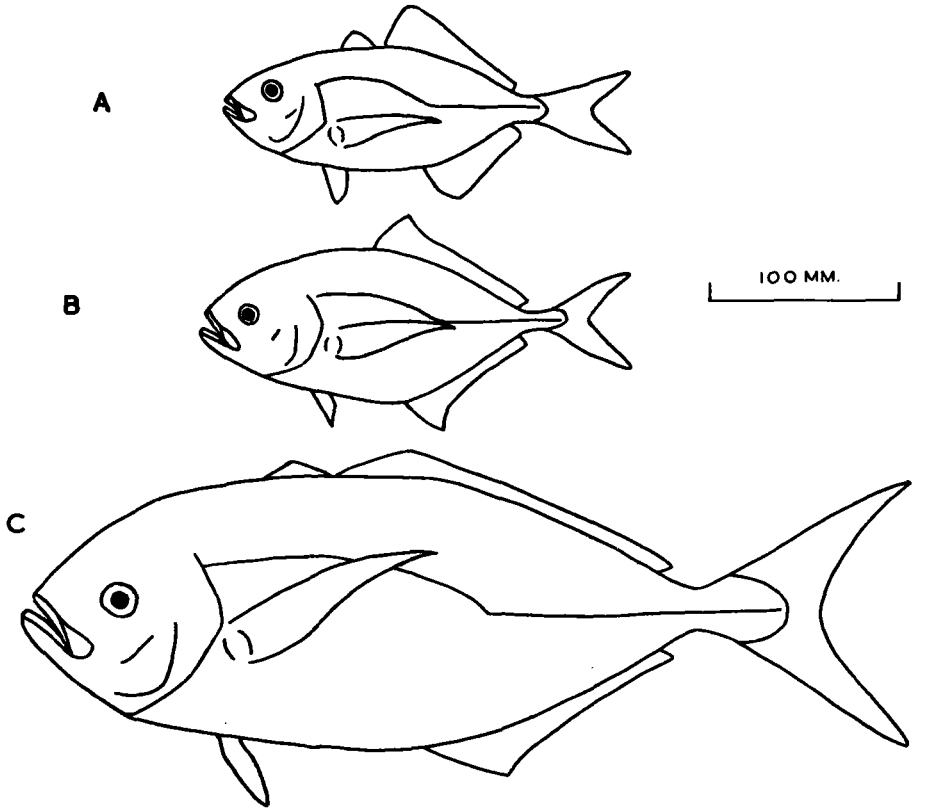
Fig. 3.



Uraspis heidi Fwlr. 1938. Holotype 273 mm. (after Fowler 1952).

Text figures 2–5 give outline drawings, with position of crossbands where present, of some of the species of *Uraspis* referred to in this discussion. Figure 6 shows the geographical distribution of the species of *Uraspis* Bleeker, 1855, *s.s.*

Fig. 4.



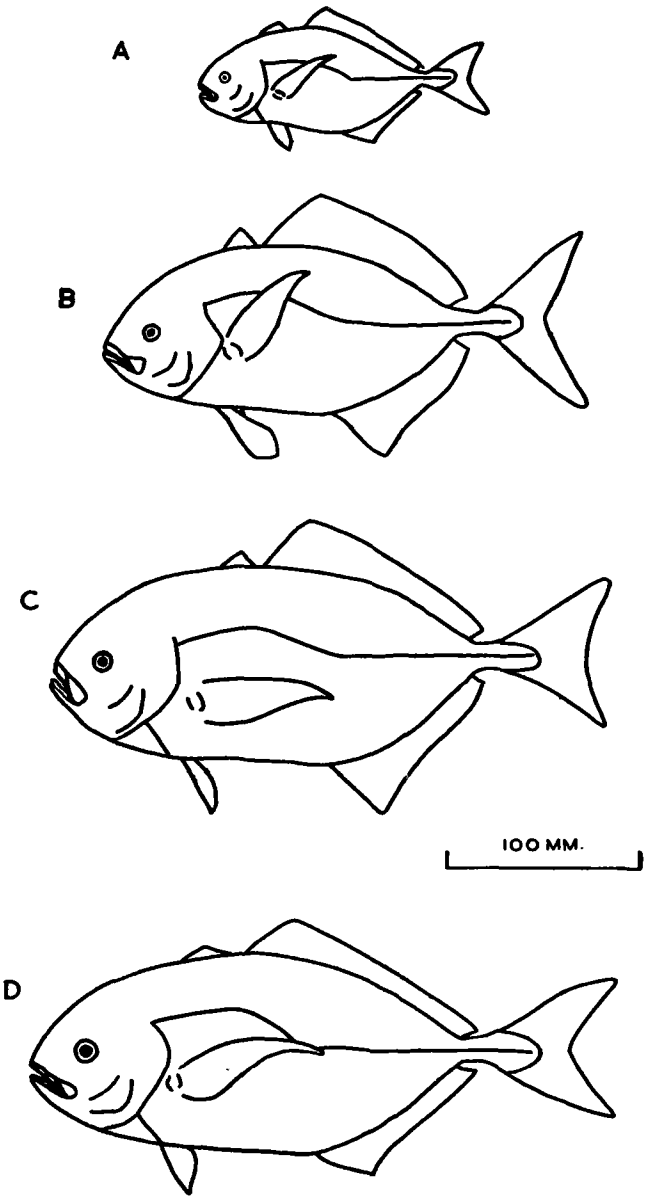
Uraspis helvolus (Forster) 1775 and its synonyms, A. *Uraspis pectoralis* Fwlr. 1938. Holotype 180 mm. (after Fowler 1938). B. *Caranx micropterus* Rüpp. 1835. Holotype 190 mm. (after Rüppell 1835). C. *Carangus helvolus* (Forster) 1775. 380 mm. (after Jordan & Evermann 1903).

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I wish to express my thanks for much help and advice to the Director and staff of the East African Marine Fisheries Research Organization, Zanzibar ; Mr. G. Palmer, Fish Section, British Museum (Nat. Hist.) ; Dr. J. J. Hoedmann, Zoologische Museum, Amsterdam ; Mr. Frederick H. Berry, Biological Laboratory (U.S. Fish & Wildlife Service), Brunswick, Georgia ; Mr. C. Richard Robins, Marine Laboratory, University of Miami, Florida ; and Mr. E. H. Bryan, Jnr., Bernice P. Bishop Museum, Honolulu, Hawaii.

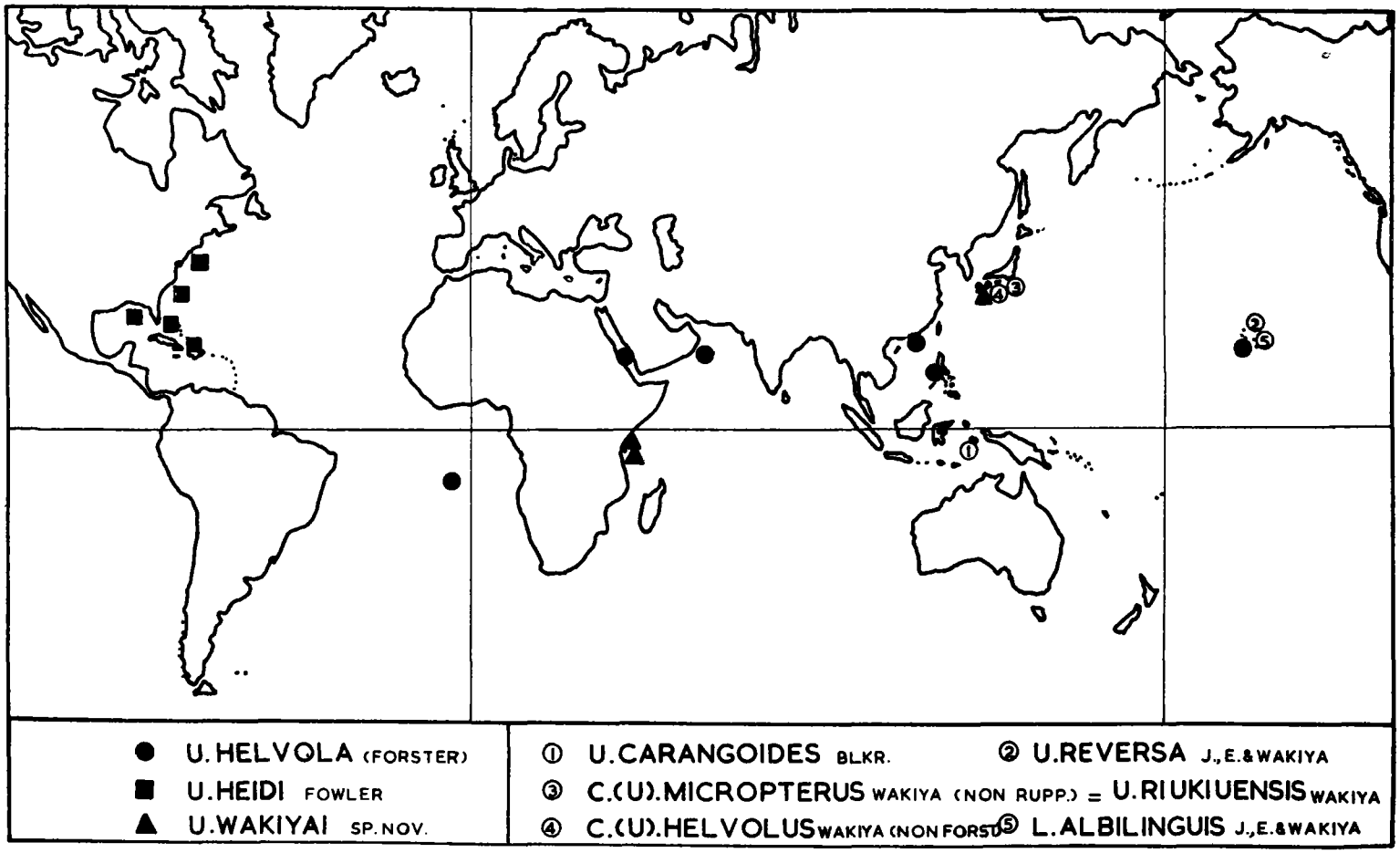
I am also indebted to Mr. N. B. Marshall, British Museum (Nat. Hist.) for critical reading of the manuscript and making suggestions for its improvement.

Fig. 5.



Species of the genus *Uraspis*, the taxonomic positions of which are still in doubt. A. *Uraspis reversa* J., E. & Wak. 1927. Holotype 133 mm. (after Jordan, Evermann & Tanaka 1927). B. *Caranx (Uraspis) micropterus* Wakiya 1924 = *Uraspis riukiuensis* Wak. 1937. Holotype 210 mm. (after Wakiya 1924). C. *Caranx (Uraspis) helvolus* Wakiya 1924. 250 mm. (after Wakiya 1924). D. *Leucoglossa albilinguis* J., E. & Wak. 1927. Holotype 267 mm. (after Jordan, Evermann & Tanaka 1927).

Fig. 6.



The world distribution of the species of Uraspis Blkr., 1855, s.s. (as given in Table VII).

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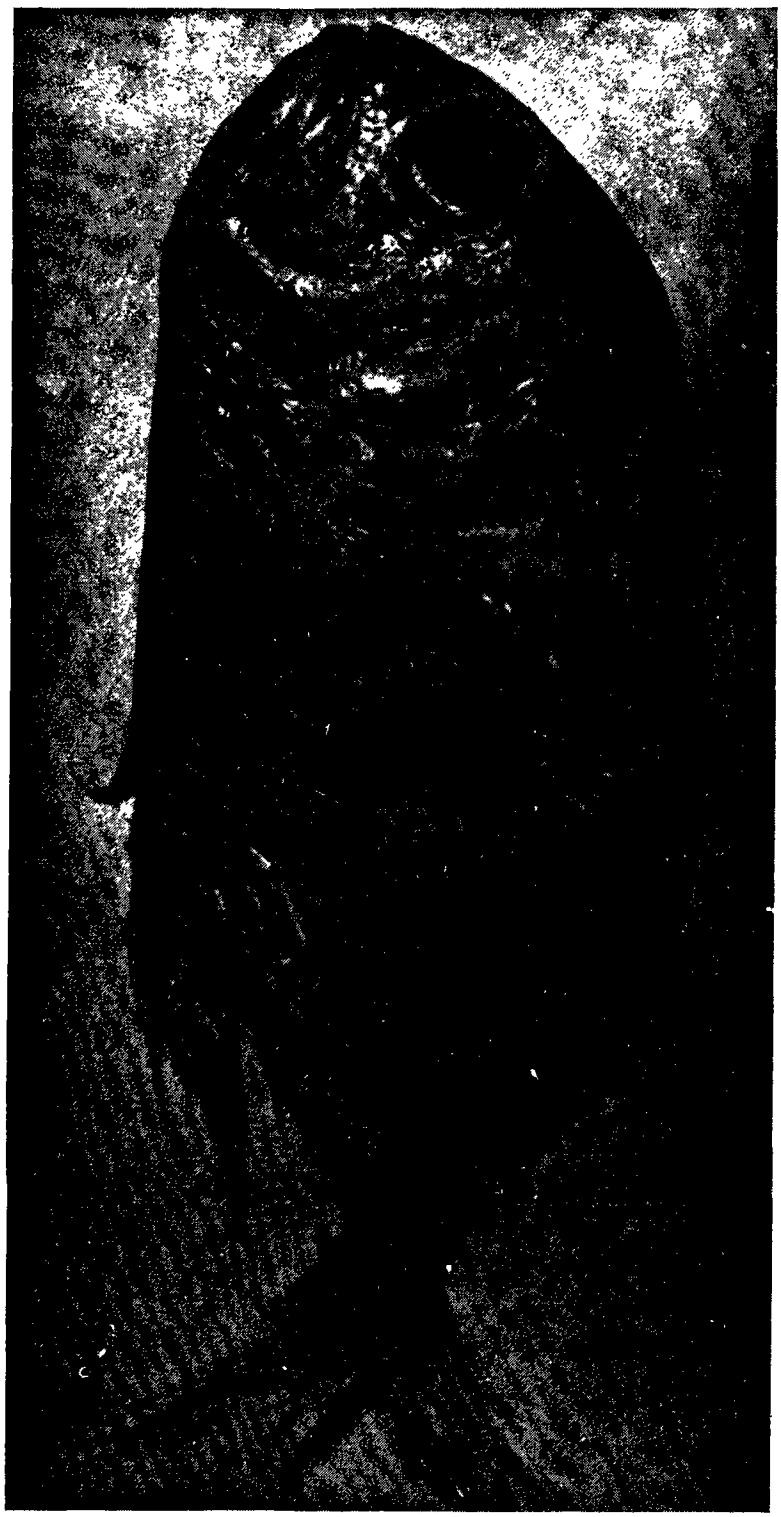
Addendum.

Since this paper was written a third specimen of *Uraspis wakiyai* has been taken from the stomach of a striped marlin (*Makaira audax*) caught by longline on 4th March, 1960, off the Kenya Coast—position 4° 10′ S. 39° 50′ E. The specimen was badly damaged, the upper head being almost torn from the rest of the body.

It has been possible to work out the following : depth 2·11 ; head 2·71 ; both in standard length. Pectoral 1·30 ; pelvic 0·87 ; 4th and 5th dorsal spines 4·2 ; anterior dorsal ray 1·75 ; anterior anal ray 1·31 ; all in length of head. Lateral line curve in lateral line straight 1·15.

D VIII + I 30–31.
A O + I 21.

Scutes on lateral line 26–28 ; anterior 5 or 6 scutes with lateral points, rest with points reversed, that is directed anteriorly. Gill rakers on 1st gill arch (left) 5 + 1 + 14 = 20. Gill rakers, teeth, mouth membranes, scalation of breast are as in the other two specimens. Second dorsal and anal fins are damaged but tips of rays appear filamentous. Anal spines embedded. Pectorals not falcate ; pelvics very long, tips filamentous. Pelvic origin in advance of pectoral origin. Other features not discernible because of damage.



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Plankton on the North Kenya Banks

DURING the investigations of the East African Marine Fisheries Research Organization into the resources of part of the coast of East Africa a hitherto uncharted shallow area was located off the north Kenya coast in the vicinity of Lamu[1]. Subsequent investigations have indicated that this area, designated the North Kenya Banks, has a good fish population and is of importance as a potential fishery[2,3].

Due to lack of specialists it has been difficult to make an extended and continuous investigation of the various facets of this marine environment which, together, result in the production of a good fishery. However, during plankton investigations along the East African coast, facts were discovered which substantiate the claim that the North Kenya Banks is a fertile area and potentially a good fishery.

Part of the plankton investigations constituted taking a series of lines of samples from the coast (*c.* 100 fm., or 50 fm. when the fringing reef permitted) outwards for some 40 or 50 miles. These lines of stations were worked from Cape Delgado, near the southern Tanganyika border, to Dick's Head, near the northern Kenya border; the outward lines from the coast were at approximately 30–50-mile intervals. The plankton net used was a Currie and Foxton 70-cm. net[4] without the meter. A filtration coefficient of 1 : 1 has been assumed (reasonable in the light of former experience), in view of the short duration of the haul, the speed of hauling (*c.* 1 m./sec.) and the evident lack of clogging. All were vertical samples from, usually, both 200 m. and 50 m. to the surface at each station. In shallower water the samples were from the bottom to the surface. All samples were duplicated, the first being for numerical and specific analysis, the second for dry weights. These latter samples were dried to a constant weight at 50° C. in a controlled oven. The resulting weights were applied to the height of the water column from which they were taken, the final result being expressed as mgm./m.^{3} of sea-water.

Full analysis of the results is not yet complete, but the preliminary results are of much interest. Towards Cape Delgado the plankton dry weight is about 8–12 mgm./m.^{3}, with no great variation in off-shore samples. Farther north in the Mafia area the coastal water is rather richer with *c.* 20–30 mgm./m.^{3}, decreasing to *c.* 8–12 mgm./m.^{3} in off-shore waters. This trend towards a relatively enriched coastal water increases to the north, and in the Dick's Head

area in-shore figures are *c.* 30–40 mgm./m.^{3}, the off-shore figures being *c.* 10–15 mgm./m.^{3}.

A preliminary Survey Report of the 1960 cruise of the Russian research vessel *Vitiaz*, for the International Indian Ocean Expedition, shows the contouring of the plankton dry weight in the top-most 100 m. of the Indian Ocean. It agrees in showing that water with a low plankton dry weight (7·5 mgm./m.^{3}) is much nearer the coast-line in the Cape Delgado area than farther north in the Dick's Head area.

The stations worked over the North Kenya Banks showed the highest figures. Thus, among others, plankton dry weights of 65·1, 55·0 and 62·8 mgm./m.^{3} were recorded at the bottom end of the range, with the largest reading being 161·6 mgm./m.^{3}. This sample was taken at a depth of 108 m., the position being 2° 25·5′ S. 40° 54′ E.

These readings show that the water over the North Kenya Banks is demonstrably richer than the remainder of the Tanganyika–Kenya coast. Further readings will have to be taken before it can be stated confidently that this applies throughout the year, although there is reason to believe that this is, in fact, the case.

It is worth noting that the colour of the sea over these Banks was the 'bottle-green' associated with such temperate water as the North Sea, and neither the clear blue of the off-shore East African waters nor the dirtier blue or pale greens of the in-shore waters was in evidence.

Of interest is the consideration of the plankton dry weight underneath one acre of water over the North Kenya Banks. Assuming a mean depth of 80 m. and a plankton dry weight of 100 mgm./m.^{3} the resulting figure is 32·27 kgm. plankton dry weight beneath 1 acre of water.

Analysis of the preserved samples has not yet been completed, but random examinations give every indication of a richer population of fish eggs and larvæ compared with the rest of the coast. This poses the problem, to be investigated later, of whether the North Kenya Banks are a breeding ground, with the fish converging from outlying waters to breed, or whether the North Kenya Banks are mainly a feeding ground, the breeding being resultant and dependent on this.

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Indian Species of Synchytrium.

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Species of *Synchytrium* are abundant and widely distributed in India, and up to the present time fifty-nine species have been reported from that country. Prior to 1945 only six species were known to occur there, according to Butler and Bisby (1931), but since that time interest in these fungi has increased greatly with the result that fifty-three species have been added within a decade and a half. Most students of these obligate parasites, however, have created new species without intensive study of the developmental stages at different season of the year and cross inoculation studies to determine the host range of the species. Consequently, many of these are poorly known, and it is not evident from the descriptions in the literature whether they are long — or short-cycled. That many species which were previously diagnosed as short-cycled are really long-cycled became evident when Lingappa (1952) reexamined such species in the living state. My study of herbarium specimens of the India species has confirmed these observations in several instances.

The present contribution is a result of this study and is presented as a supplement to the observations of numerous mycologists in India who have studied these obligate parasites. It is presented also to emphasize the need of more intensive study at different seasons of the year, and to summarize the available information on Indian species of *Synchytrium*. It is based on a study of types and other specimens in the Herbarium Cryptogamiae Indae Orientalis (HCIO), Division of Mycology and Plant Pathology, New Delhi, the Commonwealth mycolocigal Institute (CMI), the Herbarium of Agra College, Agra, and the Royal Botanic Gardens, Kew, (K). I am very gryteful to Directors J. C. F. Hopkins, G. Taylor, and R. S. Vasudeva, and Drs. Grace M. Waterhouse, S. Sinha, and B. G. Nikam for the loan of these and other specimens. Also, I wish to express my thanks to Dr. B. T. Lingappa for the generous gift of specimens which he collected and identified. Unfortunately, I have not been able to secure and study type specimens of all Indian species, and for this reason I do not regard this contribution as complete.

This study has been supported by a grant from the National Science Foundation.

Synchytrium rytzii.

This species was created by Sydow and Butler in 1907 for a parasite on *Anisomelis ovata* which they placed in the subgenus *Pycnochytrium* because only resting spores were found. In 1912, however, they reported it on three additional hosts, *Peristrope* sp., *Justicia* sp., and *Leucas aspera*, and created three forms of it on these hosts on the basis of distribution, size, appearance and structure of the galls, size and method of gemination of the resting spores, and the size of the sporangia. According to them, form *a* differs from *S. rytzii* on *Anisomelis ovata* by the aggregation of galls in crusts, its slightly to completely composite galls, the shape of the infected cell and its lack of residue, and the size of the resting spores, average 96 μ. Form *b* on *Justicia* has smaller resting spores, average 79 μ, which germinate in the living host without a dormant period and give rise to external sori of sporangia which are 18—30 μ in diameter. In form *c* on *Leucas aspera* the infected cell is quite small and bears 2 to 4 resting spores which average 78 μ in diameter. These germinate in the living host cells also and functio nas prosori. In this form, however, the sporangia are smaller, 12—24 μ, than in form *c*.

In studying these and other herbarium specimens, Mhatre and Mundkur (1945) reported only resting spores in *S. rytzii*, and limited it in host range to *Anisomelis ovata*, *Leucas* sp. and *L. aspera*. Sydow and Butler's forms *a* and *b* on *Peristrophe* and *Justicia* were segregated to constitute a new species *S. lepidagathidis*. Lingappa (1952) found *S. rytzii* on these hosts as well as on *Orthosiphon pallidus* and reported that it develops prosori, sori, sporangia and resting spores. I have examined HCIO specimens 653, 1379, 1382, 2035, 20476, Nikam and Kulkarni's collection on *Leucas aspera* at Gwalior (1959), as well as those collected by Lingappa, and in all of these prosori, sori, sporangia, resting-sporegalls and resting spores were present, which confirms Lingappa's discoveries. From these observations I interpret the germinating resting spores in the living host, which were reported by Sydow and Butler, as evanescent initial cells which functioned as prosori and gave rise to sori of sporangia. In the material studied their walls are amber colored and only 2 to 2.6 μ thick in contrast to those of the resting spores which are 3.8 to 5—2 μ thick and brown in color. Furthermore, the empty prosori in the base of the infected cell had collapsed. This does not occur generally when thick-walled resting spores germinate as Lingappa (1955, fig. 54, 57) showed for this species. According to these observations and interpretations, *S. rytzii* is a long-cycled species which belongs in the subgenus *Microsynchytrium*.

The differences in size and structure of the galls, size and shape of the infected cell, size of the resting spore and lack or presence of residue around it, which were noted by Sydow and Butler, fall within

the range of variation which a species might exhibit on different hosts, in my opinion. Nevertheless, these differences as well as the variations in the size of the sporangia should be studied more intensively in living as well as in fixed and stained sections of material. Host range studies may possibly reveal biological races within this species.

Synchytrium collapsum.

This is the second Indian species created by Sydow and Butler in 1907 for a fungus on *Clerodendron infortunation*, and they described it as a member of the subgenus *Pycnochytrium* which develops only resting spores. Mhatre and Mundkur studied the type (HCIO, 654) and other specimens and described only resting spores also. Lingappa (1952), however, found prosori, sori, sporangia and resting spores in living material collected in September, and demonstrated that *S. collapsum* is a long-cycled species. Later (1955) he germinated the resting spores and thus completed our knowledge of its life cycle. In a collection (HCIO, 2006) made by Butler, 8—10—1913, in Bengal I found numerous cupulate sporangial galls with collapsed, empty prosori in them in addition to resting-spore galls and resting spores, and my observations thus confirm those of Lingappa.

Synchytrium lepidagathidis

As noted above Mhatre and Mundkur segregated Sydow and Butler's forms *a* and *b* of *S. rytzii* on *Peristrophe* and *Justicia*, combined them with a species which had been collected on *Lepidagathis* sp., *L. cristata* and *Dicliptera* sp., and named it *S. lepidagathidis*. They reported only resting spores in this species, but in 1952 Lingappa found prosori, sori, sporangia and resting spores in living specimens on *Andrographis paniculata, Dicliptera roxburghiana, Justicia diffusa, J. quinqueangularis, Peristrophe bicalyculata*, and *Rungia parviflora* var. *pectinata*. He made a careful comparison of the resting spores on these host with those on the hosts listed by Mhatre and Mundkur and came to the conclusion that his fungus was *S. lepidagathidis*. In specimens 10355 (type), 10355A, 2020, 2023, 20472, 20473, 20477, 2048, HCIO, I found prosori, sori sporangia and resting spores and confirmed Lingappa's observations. Accordingly, *S. lepidagathidis* also is a long-cycled species which belongs in the subgenus *Microsynchytrium*.

Whether or not it is distinct from *S. rytzii* is open to question, however. Its resting-spore galls are reported to be simple, but in the material noted above simple to composite galls are present. Apparently, the host reaction may vary to a marked degree as I have found when *S. macrosporum* is grown on different hosts, and it is doubtful that *S. lepidagathidis* is always diheterogallic. Its hosts are acanthaceous

and overlap those of *S. rytzii*. The differences in the prosori, sori, sporangia and resting spores of both species are not very great, and on these grounds I believe *S. lepidagathidis* may prove to be identical with *S. rytzii*.

Synchytrium lagenariae

Mhatre and Mundkur created *S. lagenariae* for a species on the leaves of *Lagenaria vulgaris* which Mony collected at Pusa, August 31, 1918. Here also they described only resting spores, but in examining this type material as well as specimen. 25549 on *Luffa aegyptica*, 25450 on *L. acutangula*, 25451 on *Cucumic sativus*, 2452 on *Citrullus vulgaris* var. *fistulosus* and 25453 on *Curcurbita pepo*, HCIO, I found sporangial galls with empty prosori, sori and sporangia in addition to resting-spore galls with resting spores. Accordingly, this species is long-cycled and belongs in the subgenus *Microsynchytrium*. *Synchytrium luffae* Sinha (HCIO, 25449 and 25450), *S. cucumis — sativa* Sinha (HCIO, 25451), and *S. fistulosus* Sinha (HCIO, 25452) in herb. are identical to the fungus in type specimen 2019, and should be listed as synonyms of *S. lagenariae*.

Lingappa (1952, 1955a) regarded this species as well as *S. trichosanthidis* as identical with *S. wurthii* which Rytz (1907) described on another cucurbit, *Gymnopetalum cochinchinense*, from fixed material sent him by Wurth from Java. Rytz found only resting spores in this material but noted that these had germinated in the living host without a long dormant period and given rise to sori of sporangia. Lingappa believed that Rytz overlooked the thin-walled prosori, but, in my opinion, it is probable that the germinated spores found by Rytz were evanescent prosori. In that event *S. wurthii* and *S. lagenariae* are fairly similar, and Lingappa's view may prove to be correct. However, until *S. wurthii* is collected again in Java, studied intensively in living material and compared developmentally and morphologically with *S. lagenariae* on different hosts, it is prudent to maintain them as distinct species. In the event *S. lagenariae* is identical with *S. wurthii* its host range includes *Bryonopsis laciniosa*, *Coccinia indica*, *Cucurbita maxima*, *Momordica charantia* and *Trichosanthis dioica* in addition to the hosts listed above.

Synchytrium trichosanthidis

Mhatre and Mundkur created this species for a fungus they found on herbarium specimens of *Trichosanthes dioica*, *Citrullus vulgaris* and *Cephalandra* sp. Here again they reported only resting spores. However, in the type material (10365, HCIO), I found two types of galls: large cupulate empty ones which look like sporangial galls with collapsed empty prosori in their base, and smaller ones bearing resting spores. Sometimes resting spores occurred in the basal

sheath cells of the sporangial galls. No sori and sporangia were found in the larger galls, but because of the presence of empty prosori I believe these developmental stages will be found on this host when collections and observations are made on it at different seasons of the year.

In specimens labeled *S. trichosanthidis* on *Cucumis melo* var. *pubescens* (25548, HCIO) which Sinha collected in 1956 and 1957, sporangial galls with prosori, sori and sporangia are present in addition to resting-spore galls and resting spores. The sheath cells of the sporangial galls are commonly infected with resting spores and in such cases are unusually large. Similar developmental stages were found on *C. melo* var. *ultissimus* collected by Gupta and Sinha in September 1948 at Agra, which Sinha kindly sent to me. Also, similar developmental stages were found in cotypes 10363 and 10364, HCIO, on *Citrullus vulgaris* and *Cephalandra* sp., respectively. The fungi on these hosts are very similar to *S. lagenariae*, and I believe they are identical with it.

The appearance of the fungus on *Trichosanthes dioica* and the reaction of this host to infection, however, are different in the material I examined, and it may prove to be a different species from the ones collected on the other cucurbitaceous hosts. As noted previously, Lingappa (1952, 1955b) believed that *S. trichosanthidis* as well as *S. lagenariae* are identical with *S. wurthii*.

Synchytrium sesamicola

This species was created by Lacy (1950) for a parasite on *Sesamum indicum* which he described as developing only resting spores. However, in the type material I found large empty cupulate galls which are different in appearance from those which bear resting spores. In the base of some of these were amber colored, thin-walled collapsed vesicles which I interpret to be empty prosori. Accordingly, from these observations *S. sesamicola* appears to be a long-cycled species, as reported by Lingappa (1955).

Sinha and Gupta (1951) described a new species, *S. sesami*, on the same host from Agra which forms large single galls or scarlet crusts of coalescing galls on the young shoots, leaves and stems. These galls vary from 300—400 μ in diamter on the leaves to 600—700 μ on the stems and contain solitary, spherical, 172—201 μ, smooth, olive-btown resting spores with an epispore 10—13 μ thick. However, in a collection of this species by Gupta in 1954 (HCIO, 22115) I found sporangial galls with empty prosori, sori, and sporangia in addition to resting-spore galls and resting spores. The prosori are subspherical, 80—90 μ, or ovoid, 75—87 × 90—98 μ, with an amber-brown wall, 1.8—2 μ thick. The sori are subspherical 90—102 μ, ovoid, 72—96 × 102—116 μ, or flattened on the lower surface and contain

50—92 sporangia which are golden-yellow, polyhedral and 19—28 μ in greatest diameter. The resting spores are dark amberbrown, ovoid, spherical, 55—186 μ, with a smooth wall, 3.4—4.6 μ thick. Sinha and Gupta reported that the epispore is 10—13 μ thick, but they probably included the adhering layer of residue in their measurements.

In another collection on *Sesamum indicum* from Agra, August, 1955, which Sinha sent me similar sporangial galls, empty prosori and sori with sporangia in addition to resting-spore galls and resting spores were found. The resting spores varied markedly in size, depending on the degree of injection. In areas where most of the epidermal cells were infected the spores were as small as 40 μ in diameter. Also, the sheath cells of the sporangial galls were infected frequently, and in such instances the spores were heaped up in masses similar to what I (1957) described for *S. cinnamomeum.*

If Gupta's and the 1955 collections are representative, *S. sesami* is a long-cycled species like *S. sesamicola,* and seems to be identical with it. Accordingly, I am listing it as a synonym of *S. sesamicola.*

Synchytrium melongenae

This fungus was collected and described by Gupta and Sinha (1951) as a short-cycled species which develops relatively small, 56—76 μ, spherical, solitary resting spores in spherical to oval galls on leaves of *Solanum melongena* at Agra. I have studied their type material and can confirm in general their observations on the resting spores, although I found the spores to vary from 40 to 92 μ with a wall only 4.8 to 6.2 μ thick and yellow contents. In addition to the composite resting-spore galls I found several larger empty cupulate ones which looked like sporangial galls which had discharged their sporangia. These were thoroughly soaked and dissected apart, but no sori or sporangia were found. In the apex of some, however, occurred a collapsed, dark-amber vesicle or cell which looked very much like an empty prosorus. In light of these observations I suggest the possibility that *S. melongenae* may be a long-cycled species which forms prosori, sori and sporangia in addition to resting spores. At least, it should be studied more intensively at different seasons of the year. In the event it proves to be long-cycled as suggested it may turn out that Lingappa's, (1953) *S. akshaiberi* on the same host at Banaras may be identical with it.

Synchytrium micranthum

This species was created by Singh (1954) for a fungus on *Micranthus oppositifolius* which he collected in Bihar. He described sporangial sori, 68,5—145.8 μ in diameter, which bear 100 to 150 sporangia, 22.2—35.9 in diameter, in addition to ovate and spherical resting

spores, 55.5 to 142.2 μ in diameter. My study of the type material (HCIO, 2213) confirms his observations that this is a long-cycled species. Singh, however, did not report the presence of a prosorus, ans it is not certain from his description whether or not the initial cells is transformed directly into a sorus. In the type specimens which I examined empty prosori were present in the base of the host cell with sori of sporangia lying above them. These prosori were subspherical, 130—166 μ, with smooth, amber wall 2.5—4.2 μ thick. The sori were subspherical, 60—144 μ, or ovate, 102—114×132—180 μ. The resting spores were abundant in separate or confluent composite galls, and in some instances the sheath cells of sporangial galls were infected with resting spores.

Although germination of the resting spores has not been observed, I believe this species will prove to be a member of the subgenus *Microsynchytrium*. When its life cycle and host range are fully known, it may possibly prove to be identical with *S. lepidagathidis* which occurs on numerous acanthaceous hosts in India.

Synchytrium alysicarpi

Ramakrishnan and Sundaram (1954) created this species for a fungus on *Alysicarpus vaginalis* which had been collected at Walayar by Sundaram and Rao (September 19, 1953). They described it as follows: "Galls numerous, on stems and leaves, reddish-orange in color, galls on stem swollen, sometimes irregularly lobed; on leaf amphigenous, becoming cupulate and whitish with age; hypnospores numerous, embedded within hypertrophied cells and surrounded by proliferating tissue, subglobose or oval, orange brown, thick-walled, wall differentiated into a thickened endospore surrounded by a laminated thicker exospore, with granular contents, 53—130× 50—98 μ, sorus subglobose or elliptical, made up of several sporangia, orange-yellow contents, 25×22 μ (19—43×19—37), rounded or polygonal, due to pressure." They did not report the presence of a prosorus, but one of their figures suggestes its presence in the upper part of the infected cell.

The fleshy outgrowths induced by this species on the stem, as shown in their fig. 1, resembles very closely those caused by S. *cookii* on *Alysicarpus monilifer* as shown by Lingappa (1953). I examined a portion of Sundaram and Rao's material (HCIO, 22500), but it was a poor sample and yielded nothing significantly different. Nevertheless, I believe *S. alysicarpi* will prove to be identical with *S. cookii* when it has been studied intensively. Its resting spores and sporangia are similar in size to those of *S. cookii*.

Recently I received some leaves of *Alysicarpus* sp. from G. B. Nikam at Gwalior, India which are infected with a species of *Synchytrium*. This material was collected by Nikam and Kulkarni on

Aug. 10, 1959 at Gwalior. Only resting spores are present and these occur in abundance on the lower surface of the leaves and on stems in large, protruding, light-yellow to slightly reddish galls. The spores are spherical, 156—180 μ, subspherical, 180—206 μ, or ovoid, 160—190×175—200 μ, with a dark-amber wall, 4—5.2 μ thick, and hyaline granular content. They are enveloped by a fairly thick layer of residue which fills the remainder of the host cell. The galls are subspherical to ovoid in general outline, 200—276 μ high by 208—280 μ broad, with a sheath 2—4 cells thick. The sheath cells are greatly enlarged.

The resting spores of this fungus are considerably larger than those of *S. alysicarpi* and *S. cookii*, with hyaline instead of yellow contents, and on these grounds it appears to be a different species. No outgrowths or malformations were present on the stems *Alysicarpus* sp. like those induced by *S. cookii* on *A. monilifer*.

Another unidentified species of *Synchytrium* was collected by Nikam and Kulkarni, 8—10—1959, at Gwalior, India on *Corchorus* sp. and kindly sent to me. This is the first species to be collected on *Corchorus* or any other member of the *Tilliaceae* in nature, although I (1960) have succeeded in infecting species of this family with *S. macrosporum* under greenhouse conditions. Only resting spores are present in the Gwalior fungus, and these are subspherical, 140—168 μ, or ovoid, 152—165×170—178 μ, with a smooth, amber-brown wall, 4.6—5.3 μ thick, which is enveloped by a relatively thick layer of brownish-red residue and light-yellow contents. The galls occur on the leaves, petioles and stems and are dark-brown, large and protruding, flattened on top with a well-defined apical pore, 208—468 μ broad by 208—312 μ high with sheaths 3—5 cells thick. The sheath cells are greatly elongate and enlarged outward, and most of the galls appear to "sit" on the palisade layer. In other galls the base is embedded in the palisade, and occasionally the base of the gall causes a protrusion on the opposite side of the leaf. Apparently, this is a short-cycled species, but its identity is uncertain. In the material I studied there were no characteristics which distinguishes it sharply from other short-cycled species with similar spores.

Nikam and Kulkarni collected, 8—17—1959, a third species at Gwalior on *Ipomoea* sp., which is the first record of *Synchytrium* on a member of this genus in nature. Apparently, this is a short-cycled species also inasmuch as only resting spores were present. On the material sent me the galls were sparse on the under side of the leaf, relatively small, and did not protrude conspicuously. In fixed and stained sections, they were embedded largely in the leaf with their base protruding slightly or equally on the opposite side of the leaf. In size they were 98—274 μ high by 70—168 μ broad with a sheath 1—3 cells thick. In several cases the upper port of the infected cell was exposed with only a basal fringe of sheath cells, and these galls

often appeared to be simple. The spores were ovoid, 64—90 × 70—120 μ, spherical to subspherical, 144—168 μ, thick with a smooth, dark-amber wall, 4.8—6 μ and lemon-yellow content. They filled the host cell almost completely and had little or no enveloping residue.

Synchytrium vulgatum.

Mhatre and Mundkur identified as *S. vulgatum* Rytz a parasite which had been collected by Khan and others on leaves of *Launea asplenifolia* and *Conyza* sp. Inasmuch as they found only resting spores which resembled those of Rytz's fungus, they assumed that it was the same species. Later Ligappa (1952) examined Kahn's collection at New Delhi and found thin-walled prosori and sporangia in some of the galls. Their presence as well as sori and resting spores in this fungus was verified by a study of living material which he collected on *Launea asplenifolia*, and it became evident that Mhatre and Mundkur's identification was incomplete and incorrect. As a result, Lingappa (1955) created a new species for this fungus and named it *S. launeae*. I studied samples of the same specimens (HCIO, 10358, 10359) that Mhatre and Mundkur examined, and in both of these a few large empty cupulate galls were present in which empty prosori occured. In this respect then my observations confirm those of Lingappa that this is not *S. vulgatum*.

Synchytrium emiliae.

This species was created by Ramakrishnan and Sundaram (1953) for a fungus they found on the petioles and lamina of *Emilia sonchifolia* at Bantawal, South Kanara. They described it as follows: "Galls numerous, on petioles and lamina, minute, crowded, yellow brown, amphigenous; hypnospores spherical, solitary or sometimes two in each gall, dark brown, 47—124 μ, wall thick, 3-layered, epispore dark brown, up to 15 μ thick; sporangial sorus yellow; subglobose or oval, 98—140 × 65—93 μ, made up of numerous sporangia; sporangia rounded or angular by pressure, thin-walled, 19 × 15 μ (16—22 × 12—19), yellow." They reported further that "the sorus escapes out of the resting spore as a yellowish globular body with numerous sporangia," which suggest that they observed germinating resting spores.

I examined their material (HCIO, 20421) and found numerous sporangial galls in which were empty prosori, sori, and sporangia. The prosori were subspherical to spherical, 50—110 μ, with a dark brown encrusted wall, 2—2.6 μ thick. The sori were subspherical, 64—130 μ, or flattened on their lower surface and bore 60—140 sporangia which were polyhedral, 17 to 24 μ in diameter. The resting spores were predominently spherical to subspherical, 45—120 μ, with

a dark brown wall, 4.8—5.2 μ thick, and an enveloping encrusted layer of residue. These occurred usually in composite galls, but the sheath cells of the sporangial galls also were frequently infected with resting spores so that they appeared heaped up.

Although Ramakrishnan and Sundaram's description suggests that they observed germinating resting spores, my observations lead me to believe they saw evanescent prosori which were forming sori.

It may be noted here that Petch (1926) earlier described *S. fuscum* on *Emilia sonchifolia* in Ceylon, and the question has been raised whether or not *S. emiliae* is identical with it. He reported only resting spores and described their contents as dividing into hyaline globose zoospores. I studied a fragment of the type material in the herbarium of the Peradeniya Department of Agriculture, (PDA) but it yielded very little new information. A few large cupulate and empty galls were present, and in two of these a collapsed prosorus-like vesicle was present. However, in the extype material (Kew, spec. 3367) from Galboda, Ceylon, numerous sporangial galls, prosori, sori, sporangia, resting spore galls and resting spores are present, and these are similar to those found in Ramakrishnan's collection at Bantawal. On the basis of these observations and comparisons I believe that *S. emiliae* is identical with *S. fuscum* and belongs in the subgenus *Microsynchytrium* instead of *Pycnochytrium*.

Synchytrium vernoniae.

This species was created by Gupta and Sinha (1951) for a fungus on the stems of *Vernonia patula* which they collected at Agra in September, 1948. They described the galls as scattered, single, rarely compound, and spherical, 350—600 μ in diameter. Each gall contained a spherical, 106—149 μ, or ovoid, 88—99×132 μ, dark brown resting spore with an epospore, 8—10 μ thick. In a portion of their specimen (HCIO, 20026) I found the resting spores to be generally as they described them, except that the wall was only 4 to 5.6 μ thick. In addition to the resting-spore galls a few larger, cupulate empty ones were present and looked like sporangial galls. No prosori, sori, and sporangia were found in them, but the difference in appearance of these galls suggested that *S. vernoniae* might prove to be a long-cycled species. The sheath cells of the galls were frequently infected by resting spores and had a heaped;up appearance somewhat similar to that I (1957) described for *S. cinnamomeum*. Similar galls were observed in a species on *Vernonia cinera* which B. G. Nikam sent me from Gwalior in 1958. In additional infected material of *V. patula* received from Nikam in 1960 from Gwalior, sporangial galls with prosori, sori, and sporangia were present as wall as resting spores, and their presence show that *S. vernoniae* is long-cycled and probably belongs to the subgenus *Microsynchytrium*.

Synchytrium hibisci.

Gupta and Sinha (1951) established this species for a fungus which develops solitary, spherical, 182—210 μ, smooth, resting spores, with an epispore 20 μ thick, in scattered or confluent, spherical, 500—700 μ, galls on the leaves and stems of *Hibiscus esculentus* at Agra. In CMI specimen 53271 small galls are present and form an almost uniform brown scarf over the surface of the leaf. Fixed and stained sections of the leaf contain uniformly stained bodies in the galls which are quite unlike resting spores of *Synchytrium*. On the basis of these observations, I concluded that *S. hibisci* was a doubtful or invalid species. However, in specimens received from Singha at Agra College the lower part of the stem is covered with large separate or confluent galls with bear 1 to 3 resting spores These spores range in size from 115 to 230 μ in diameter with a dark-amber wall, 3.8 to 4.6 μ thick, and yellow content. Gupta and Sinha, as noted above reported the wall to be 20 μ thick, but is is probable that they included the enveloping reddish-brown residue in their measurements.

Synchytrium travancoricum.

Ramakrishna, 1956. Proc. Ind. Acad. Sci., Sect. B, 44: 114, fig. 1-8.

This name relates to a fungus which T. S. Ramakrishnan collected on *Impatiens chinensis* and deposited as type specimen 23860 in the Herbarium Cryptogamiae Indae Orientalis. A few sporangial galls with empty prosori, sori and sporangia were present in addition to resting-spore galls and resting spores. On the basis of the meager information at hand I am offering the following description, realizing fully that it will have to be emended considerably as more data are obtained.

Prosori usually solitary, subspherical, 60—114 μ, with amber walls, 2—2.8 μ thick, collapsing and lying in base of infected cell when empty. Sori spherical to subspherical, 72—130 μ, ovoid or flattened on lower surface. Sporangia, 110—160 per sorus, polyhedral, 20—30 μ. Planospores unknown. Resting spores solitary, subspherical, 54—72 μ, to ovoid, 60—80×72—96 μ, with a dark-amber wall 3.6—4.2 μ thick; residue sparse or usually lacking; germination unknown.

Compositely dihomeogallic, galls scattered on leaves or aggregated along midrib, frequently confluent and sometimes compound. Sporangial galls lowly mound-shaped, 220—260 μ broad by 80—150 μ high; sheath 1—3 cells thick. Resting spore galls small, low, 170—208 μ broad by 78—130 μ high; sheath 1—2 cells thick; sheath cellwalls usually thickened and lignified.

Type spec. 23860, HCIO, New Delhi.

On leaves petioles and stems of *Impatiens chinensis*, Kohayan, T. C. State, India.

Obviously this is a long-cycled species which probably belongs in the subgenus *Microsynchytrium*, but I hesitate to diagnose it as a new species on the grounds that only a small amount of material was available for study. The only other species known to occur on *Impatiens* in nature is *S. impatientis* Cook (1951), a parasite of *I. biflora* in Louisiana, U.S.A. which I (1955) found to be long-cycled. In general it is considerably larger than *S. travancorieum* so far as the latter is known, but further studies may possibly prove them to be identical or closely related.

The life cycles of other Indian species, *S. ajarekari*, *S. melongenae (S. akshaiberi)*, *S. biophytii*, *S. cassiae*, *S. cookii*, *S. crustaceum*, *S. maculans*, *S. meliloti*, *S. millingtonicolum*, *S. minutum*, *S. nyctanthidis*, *S. oroxyli*, *S. phyllanthi*, *S. rhynchosiae*, *S. thirumalachari*, *S. trichodesmatis*, and *S. zorniae*, are now fully known from Lingappa's (1952, 1953, 1955a, 1955b, 1955c) excellent supplementary studies and need not be discussed further. I have examined the types of his species (HCIO) as well as his prepared slides of them and can confirm his observations. Other species such as *S. ampelocissi*, *S. anemones*, *S. biophytum*, S. *celosiae*, *S. cessampelum*, *S. cymopsae*, *S. desmodicolum*, *S. gei*, *S. micranthum*, *S. phaseoli-radiati*, *S. physalidis*, *S. phyllanthicolum*, and *S. stereospermi* are incompletely known and will require additional intensive study before their relationships and classifications are fully understood.

Possibly *S. akshaiberi* is the sorus and sporangial stages of *S. melongenae*, and *S. biophytum* and *S. phyllanthicolum* may prove to be the resting spore stages of *S. biophyti* and *S. phyllanthi*, respectively.

The short-cycled species which form only resting spores and parasitize *Phaseolus* and other legumes have been subject to considerable disagreement among Indian mycologists. *Synchytrium indicum* (*S. phaseoli* Patel et al.) on *Phaseolus mungo* is a doubtful species, as will be indicated further on. In 1951 Gupta and Sinha created *S. phaseoli-radiati* for a fungus which they found on *Phaseolus radiatus*, *P. mungo*, *Cajanus cajan* and *Crotalaria junceae* because it appeared to be quite different from *S. indicum*. In the same year Pajak established *S. ajrekari* for a parasite on *P. mungo*. *Synchytrium phaseoli-radiati* is reported to have resting spores 165—200 μ in diameter with an epispore 13—16.5 μ thick, which are borne in single, rarely compound cupulate, sherical galls, 400 to 600 μ in diameter. *Synchytrium ajrekari*, on the other hand, is described as having resting spores 114— to 270 μ in diameter with a wall, 8—11.5 μ thick. Safeeula and Govindu (1952), apparently without studying Gupta and Sinha's material, maintained that *S. phaseoli-radiati* is identical with *S. ajrekari* and, therefore, a synonym of it. In studying

Gupta and Sinha's material (CMI, 253266) of *S. phaseoli-radiati* I found the galls to be unicellular or simple, and rarely composite. In *S. ajrekari*, on the other hand, Lingappa (1952) figured the galls as being composite on *P. mungo*, and I have confirmed his observations from a study of his material. Similar galls are present in specimens of *S. ajrekari* collected by Payak on *P. radiatus* at Poona (HCIO, 19810) and by Pargi (HCIO, 20114) at Banaras. However, the specimens (HCIO, 20017) collected by Sinha and Gupta (August 22, 1948) at Agra on *P. radiatus* and labeled *S. ajrekari* is not a *Synchytrium* species. The large, light-amber bodies in the galls are probably the eggs of an insect or microscopic animal. Similar galls and bodies were found in another collection of *P. radiatus* made by Sinha and Gupta on September 12, 1948 at Agra which Sinha kindly sent me. From examination of these specimens it appears that *S. ajrekari* will infect *P. radiatus* as well as *P. mungo*, and that it differs from *S. phaseoli-radiati* by the reaction it induces in the same host, *P. mungo*. Obviously, more intensive study of living as well as fixed and stained sections of these two species is essential before their exact identity and relationships are fully known.

So far only six representatives of the subgenus *Woroninella* have been reported from India — *S. atylosiae*, *S. dolichi*, *S. decipiens (S. aecidioides)*, *S. minutum (S. puerariae)*, and *S. umbilicytum*. *Synchytrium cajani* in herb (HCIO, 20089) is a questionable species and is probably identical with *S. umbilicatum*. The latter species was described as *Aecidium umbilicata* by Berkeley and Broome (1875) on *Phaseolus grahamianus*. Petch (1909) described it as *A. cajani* on *Cajanus cajan* and later (1918) on as *Woroninella umbilicata*. In 1950 Petch and Bisby stated that the same species apparently occurs on *Phaseolus calcarius*, *Cajanus cajan*, *Atylosia rugosa*, *A. condollei*, *Dunbaria heynei*, *Crotalaria walkeri*, and *Glycine javanica*. In 1954 *Ramakrishnan* and *Sundaram* reported it as *Woroninella umbilicata* on *Cajanus cajan* at Cinchona (Anamalais) in India. However, their herbarium specimen is labeled *S. cajani* (type 20889, HCIO). The fungi reported by Petch (1909) and Petch and Bisby on *Atylosia condollei* and *A. rugosa* apparently are *S. atylosiae*, as Gäumann (1927) has indicated. Whether or not the fungi on the other hosts are one species remains to be proven, in my opinion. Ramakrishnan and Sundaram noted that the sporangia of their species were bright orange in contrast to the hyaline sporangia previously reported for *S. umbilicatum*, and this is probably the reason why they labeled their specimens *S. cajani*. I have studied their type material and can confirm their observations on the size and shape of the sori and sporangia. However, the sporangia are hyaline, which shows that in the six years since the material was collected they have lost their bright orange color.

Synchytrium atylosiae, *S. decipiens*, *S. dolichi* and *S. minutum* are well known, and I have confirmed the identifications by a study of the specimens in the Herbarium Cryptogamiae Indae Orientalis and the Commonwealth Mycological Institute. I have some reservations, however, regarding the Ramakrishnan's identification (1950) of *S. crotalariae*. They described the sporangia as being slightly larger, $17-20\times34$ μ, than those of other Indian *Woroninella* species, but these differences are not great enough to justify the creation of a new species. *Synchytrium umbilicatum* parasitizes *Crotalaria* also, and Ramakrishnan's species may prove to be identical with it.
Woroninella species are quite common on legumes in tropical and subtropical countries, and are very similar in development and morphology. Therefore, to identify them more sharply, host range experiments must be made with each species to supplement studies on the morphological variations which they exhibit on the same and different hosts. My study (1954) of *S. decipiens, (S. aecidioides)* produced unexpected results when attempts were made to grow it on a large number of different legumes.

Doubtful Species

Additional species to those mentioned above have been reported from India, but a study of specimens of these in the Herbarium Cryptogamiae Indiae Orientalis and the Commonwealth Mycological Institute has shown that they are doubtful or invalid species. These are described below.

S. piperi Mhatre and Mundkur, 1945. Lloydia 8: 136.

This species was created for what Mhatre and Mundkur believed to be *Synchytrium* species in the leaves of *Piper betle* which had been collected by B. R. Topany (May 24, 1921) at Alibog, Bombay. They described the galls as minute white dots, somewhat deep-seated in the leaves, which bear a single, spherical, 30—38 μ, smooth, thin-walled, light brown resting spore. I observed these dots in a portion of the type (HCIO, 10366), and other material (HCIO, 22681), but found nothing that resembles the resting spores of *Synchytrium*. Deep-seated and fairly uniformly distributed, thin-walled, amber bodies are present throughout the leaves in fixed and stained sections of these specimens, but they do not relate to *Synchytrium*. Also, in fixed and stained sections of *S. piperi* collected by M. I. Thirumalachar at Bangalore (January 26, 1946) and sent to the herbarium of the University of Wisconsin, I found similar bodies throughout the leaves. If the specimens which I have studied are representative, I do not believe *S. piperi* is a species of *Synchytrium*.

S. indicum (Patel et al.) Karling, 1953. Mycologia 45: 282.

S. phaseoli Patel, Kulkarnia and Dhande, 1949. Current Sci. 18: 342.

This fungus was described as a short-cycled species, *S. phaseoli*, on *Phaseolus mungo* at Poona, but inasmuch as its specific name had been preempted by Weston's (1934) *S. phaseoli*, I renamed it *S. indicum*. Patel et al. described the resting spores as unusually small, spherical, 18—26.6 μ, to slightly ellipsoidal with a thick, smooth, brown wall. No galls *per se* were present on the host, but the leaves were covered on both sides with quadrilateral to polygonal crusts, 1×1—2 mm in diameter. Payak (1951) examined the material collected by Patel et al. and found that the so-called sporangia in the intercellular spaces of the mesophyll were similar to the oospores of downy mildews. Accordingly, he questioned the validity of this fungus as a member of *Synchytrium*. Lingappa (1952) also examined the herbarium specimens at the Agricultural College at Poona and found no trace of the fungus. In view of the small size of the resting spores reported by Patel et al. and the observations of Payak and Lingappa I do not think this is a species of *Synchytrium*. However, I have not been able to secure specimens for study.

S. borreriae Lacy, 1950. Indian Phytopath. 3: 159.

The resting spores of this species on *Borreria hispida* has been shown by Lingappa (1956) to be the cysts of an endophytic alga.

S. khandalensis Payak and Thirumalachar, 1956. Sydowia 10: 38.

This species was described as having globose, ovate to spherical resting spore, 110—175 μ in diameter, with a reticulate or areolate exospore, 7.1—15 μ thick. These are borne in glistening, lemon-yellow to brownish composite galls on both surfaces of the leaves of *Blepharis asperrima* and *Asystasia dalzelliona* at Khandula, Bombay. Previously, Payak (1953) listed two species, *S. asytdsiae* and *S. khandalensis* for this organism, but as indicated above he and Thirumalachar merged them.

In the type material (HCIO, 26540) on *B. asperrima* and the specimen (HCIO, 26541) on *A. dalzelliana* I found that the reticulate or areolate bodies described above are not resting spores of *Synchytrium*. They occur singly in small galls or in groups of large protruding galls, and each is surrounded by a hyaline envelope. They are predominantly pyriform with a blunt peg at one end, but may be ovoid to elongate also. The wall is unusaully thick and sculptured by regular or irregular polygons. The points of convergence of the polygons may protrude outward as blunt spines over the periphery. The content of these bodies is markedly different from that of *Synchytrium* resting spores, and I believe they may be the eggs or cysts of an insect or possibly cysts of an alga.

Key to Indian species

The known Indian species which I regard at present to be valid may be classified in various subgenera according to the following

key. In the list of species presented below in the subgenera, those in parentheses are regarded as possible synonyms of the immediately preceding ones.

A. Long-cycled; life cycle including summer sporangial sori and resting spores.

1. Mature initial cell or thallus functioning as a prosorus; contents emerging to form a thin-walled vesicle which cleaves into sporangia and becomes a sorus within the infected cell.

a. Resting spore functioning as a prosorus in germination; contents emerging to form a thin-walled superficial sorus which cleaves into sporangia.

Subgenus *Microsynchytrium*

Synchytrium melongenae (S. akshaiberi), S. biophyti, S. cassiae, S. collapsum, S. cookii (S. alysicarpi), S. crustaceum, S. lagenariae, S. launae, S. lepidagathidis, S. maculans, S. nyctanthidis, S. oldenlandiae, S. oroxyli, S. phyllanthi, S. rytzii, S. sesamicola (S. sesami), S. trichodesmatis, S. trichsanthidis, and *S. zorniae.* Resting spore germination has not been observed in *S. micranthum, S. stereospermi,* and *S. travancorieum,* but these species will probably prove to be species of this subgenus when they are fully known.

b. Resting spore functioning as a sporangium in germination and forming planospores directly.

Subgenus *Mesochytrium*
Synchytrium endobioticum

2. Mature initial cell or thallus developing directly into a sorus of sporangia; sporangia delimited by cleavage within the sorus and freed by the rupture of its wall.

a. Resting spores functioning as sporangium in germination and giving rise directly to planospores.

Subgenus *Synchytrium (Eusynchytrium)*

(Unless *S. desmodicolum* belongs here, this subgenus is not represented in India so far as our knowledge goes.)

b. Resting spore functioning as a prosorus in germination; contents emerging to form a superficial vesicle or incipient sorus which cleaves into sporangia.

Subgenus *Exosynchytrium*

(This subgenus is not represented in India so far as our knowledge goes.)

B. Short-cycled, life cycle including only sporangial sori, or resting spores.

1. Only resting spores known.
   a. Resting spore functioning as a prosorus in germination.

Subgenus *Pycnochytrium*

Synchytrium ajrekari, *S. meliloti*, *S. millingtonicolum*, *S. rhinchosiae*, *S. thirumalachari*, and *S. viticola*. Resting spore germination has not been observed in *S. ampelocissi*, *S. anemones*, *S. biophytum*, *S. celosiae*, *S. cessampelum*, *S. cymopsae*, *S. gei*, *S. phaseoli-radiati*, *S. physalidis*, and *S. phyllanthicolum*, but they will probably prove to be members of this subgenus when they are fully known.

2. Only sporangial sori and sporangia known.
   a. Mature initial cell or thallus developing directly into a sorus of sporangia. Sporangia delimited by cleavage within the incipient sorus; freed by rupture of sorus wall and appearing as powdery masses in open aecidium-like pustules.

Subgenus *Woroninella*

Synchytrium alytosiae, *S. crotalariae*, *S. decipiens (S. aecidioides)*, *S. dolichi*, *S. minutum (S. puerariae)*, and *S. umbilicatum (S. cajani)*.

Summary.

1. Species of *Synchytrium* are abundant in India, and up to the present time fifty-nine species have been reported from that country. However, a study of the types and other specimens has shown that several of these are identical, or not fully known, and require further intensive study. Several others have been found to be invalid.
2. *Synchytrium rytzii*, *S. collapsum*, *S. lepidagathidis*, *S. lagenariae*, *S. trichosanthidis*, *S. sesamicola*, *S. micrantum* and *S. fuscum* (*S. emiliae*) were found to be long-cycled, and belong, thus, in the subgenus *Microsynchytrium*.
3. *Synchytrium luffae*, *S. cucumis-sativa* and *S. fistulosa* in herb. (HCIO) appear to be identical with *S. lagenariae*. *Synchytrium sesami*, *S. alysicarpi*, *S. akshaiberi*, *S. biophytum*, and *S. phyllanthicolum* appear to be identical with *S. sesamicola*, *S. cookii*, *S. melongenae*, *S. biophytii*, and *S. phyllanthi*, respectively.
4. Species previously identified as *S. vulgatum* have been found to be long-cycled and identical with *S. launeae*.
5. *Synchytrium indicum* (*S. phseoli*), *S. khandalensis*, *S. borrariae* and *S. piperi* are invalid.
6. On the basis of their life cycles and development the known valid species may be classified provisionally in five subgenera: *Microsynchytrium*, *Mesochytrium*, *Synchytrium* (*Eusynchytrium*), *Pycnochytrium* and *Woroninella*.

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NOTES ON THE THREE COMMON SPECIES OF SHARKS IN THE MAURITIUS-SEYCHELLES AREA.

by

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During the Mauritius-Seychelles Fisheries Survey of 1948-49 all but 18 of the 1,138 sharks caught belonged to one or other of three species of the genus *Carcharinus*, and, in the absence of relevant literature they were known and recorded under vernacular names. Two of these names — REQUIN BAR (or BARRE) and REQUIN BLANC — were used by the Seychellois fishermen, who, not being interested in sharks as such, make no distinction between the species most frequently taken on the barrier reefs or «barres» of the Seychelles plateau, but recognise REQUIN BLANC as different because of its pallid appearance in the water as seen from above.

When fishing from the schooner «Sarcelle» on the Vigilant Bank (Seychelles plateau N.W.) in October, 1947, I noticed that four sharks, being noticeably different in colour and markings, could be set aside from the remainder of the catch of ten which were similar to the forty-seven caught during the previous day on another part of the Bank. These had been called REQUIN BAR by René Houareau, skipper of the «Sarcelle» at that time. I gave the name REQUIN HOUAREAU to the new kind of shark and it was retained thereafter throughout the Survey. REQUIN BAR was thus restricted to a single species of which six hundred and sixty-two were caught in the course of the Survey and seventy-six had been noted previously in the catches of the «Sarcelle» and the motor launch «Janette». Four hundred and twenty-nine REQUIN HOUAREAU plus eleven from earlier cruises were recorded but only forty REQUIN BLANC were seen altogether, eight of them before the arrival of the Survey vessel M.F.R.V.1 at the Seychelles.

The taxonomy of the Carcharinid sharks is very confused. Because most of the species grow to a large size and in consequence are difficult to preserve and transport there are few specimens in collections and the majority of these are dried and distorted. Information concerning the group is derived mainly from written accounts, usually of single specimens, more often than not juveniles, whose proportions, dentition and colour pattern may change with age, and which, even if adult, possess few distinctive characters.

Provisional identifications of the sharks of the Survey from my notes and paintings were made in 1950 by Mr. Fraser-Brunner at the British Museum (Natural History). Comparison with Ruppell's figure and text of *Carcharinus albimarginatus* from the Red Sea confirmed his identification of REQUIN HOUAREAU. The identification of REQUIN BAR as *C. amblyrhynchus* Bleeker and of REQUIN BLANC as *C. bleekeri* Duméril appeared more open to question although the latter was recorded from the Seychelles by Playfair (1867) and the descriptions could quite well apply to them. Our many records were not sufficiently critical to make confirmation certain as there were a larger number of similar species in the literature than had been anticipated.

Gunther (1870) suggested that Duméril's *bleekeri* was synonymous with *spallanzani* of Lesueur (1822) and that Bleeker's *henlei* and *brachyrhynchus* were actually Quoy and Gaimard's *melanopterus*. Fowler (1941) concurred. Müller and Henle (1841) had placed Lesueur's *spallanzani* with *melanopterus* Q. and G. but their description of this latter species included specimens with two shapes of snout, one moderately long and pointed, the other short and round, as well as $\frac{25}{25}$ teeth in some but $\frac{31}{31}$ in one small example. Klunzinger (1871) retained *melanopterus* for the short-snouted species, synonymous with Bleeker's *brachyrhynchus* and named the other form *ehrenbergi*. Bleeker's *henlei*, according to his own account in a note appended to his description of *amblyrhynchus*, was re-named *brachyrhynchus* when he found that *henlei* was preoccupied by another type from Cayenne (*C. henlei* Val. of Müller and Henle).

The characters on which these species are based do not differ greatly and individual variations or growth changes have not, of course, been taken into account. Nevertheless, there are differences. For instance, the upper teeth of *melanopterus* and *bleekeri* are said to be oblique with a re-entrant angle while those of *ehrenbergi* and *amblyrhynchus* are almost upright and almost equal sided. It would appear that the pectoral fins of *melanopterus* are broad, while those of all the other species, including *brachyrhynchus*, are narrow and falciform.

Since 1951, when the East African Marine Fisheries Research Organization came into being, many specimens of sharks from Zanzibar and the East African coast have been studied and it is now possible to confirm the identification of REQUIN BAR as *C. amblyrhynchus* and to correct that of REQUIN BLANC to *C. milberti* (M. and H.), a species named by Valenciennes to commemorate the donor, Milbert, of a specimen from New York preserved in spirit in the Paris Museum and recognised by Müller and Henle among specimens from the Mediterranean. Fowler (1936) as quoted by Bigelow and Schroeder, held that Nardo's (1827) meagre description of *plumbeus* from the Mediterranean (Adriatic) which 26 years later he referred to *milberti* gives his specific name precedence over *milberti* for the European form and also for the American form if it should turn out to be identical. I retain the known and well-authenticated *milberti*.

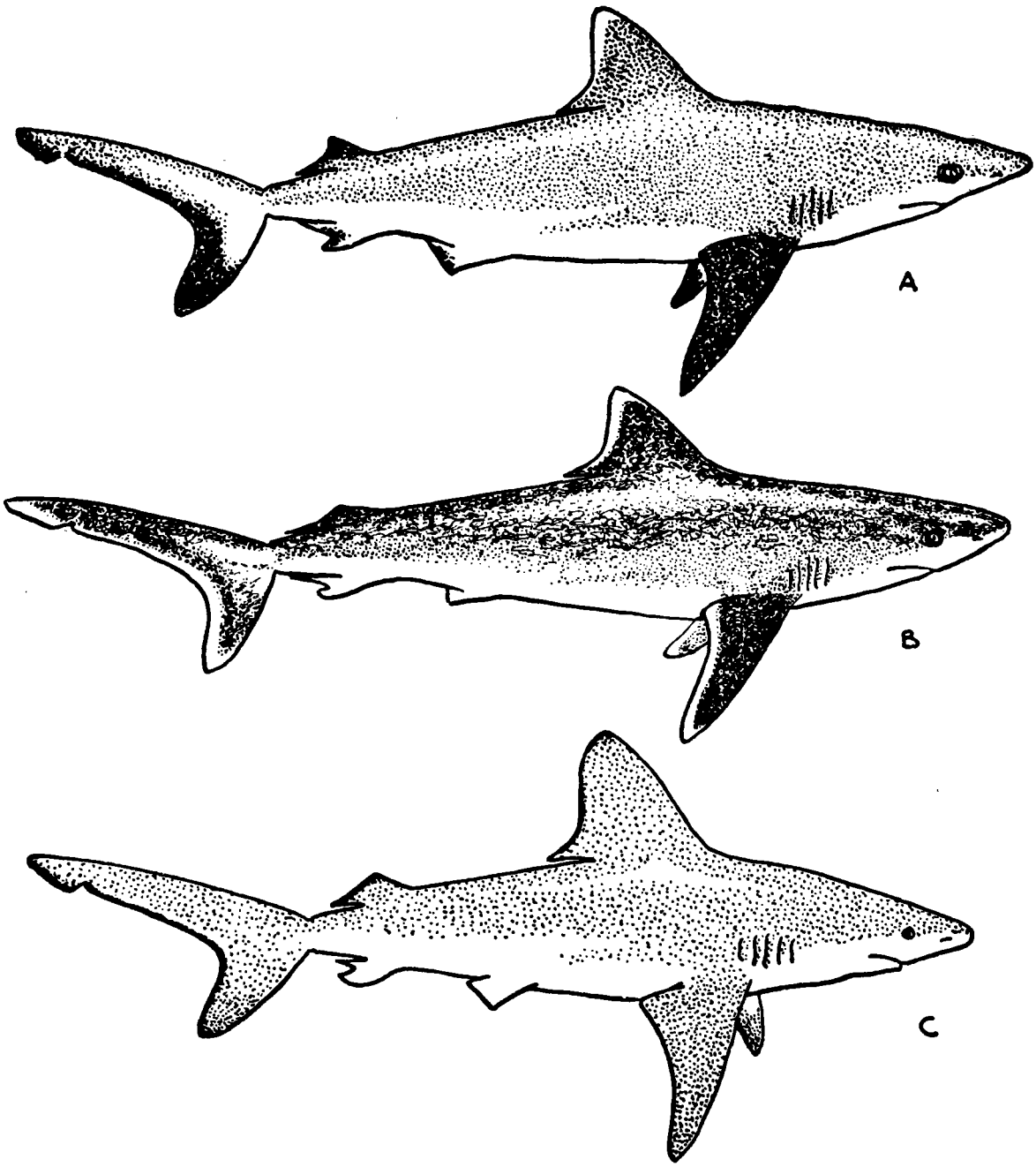


FIG. 1.—Three common sharks of the Mauritius-Seychelles area. A, *Carcharinus amblyrhynchus* Blkr.; B, *Carcharinus albimarginatus* Rupp.; C. *Carcharinus milberti* M. and H.

Carcharinus amblyrhynchus Bleeker
(Fig. 1, A.)

REQUIN BAR was caught in the shallow waters over and immediately around all the banks and islands of the Mauritius and Seychelles Dependencies area.

The largest one taken was a female, 1720 mm. long, weighing 85 lb. A male of 1680 mm. weighed 64 lb. From a length of about 1100 mm. females are heavier than males of the same length, this difference increasing to nearly 10 lb. among the largest specimens.

Study material

Descriptions of seven females and one male taken on the Mauritius-Seychelles Survey have been used, supplemented by full measurement series and colour notes of five females and four males from Zanzibar or the East African coast. On the Survey (with the above exceptions) only the total length, weight, sex, sexual condition and stomach contents were recorded and it is from these data that the conclusions on growth and breeding have been extracted. Proportional measurements expressed as percentages of the total lengths are given in the table appended.

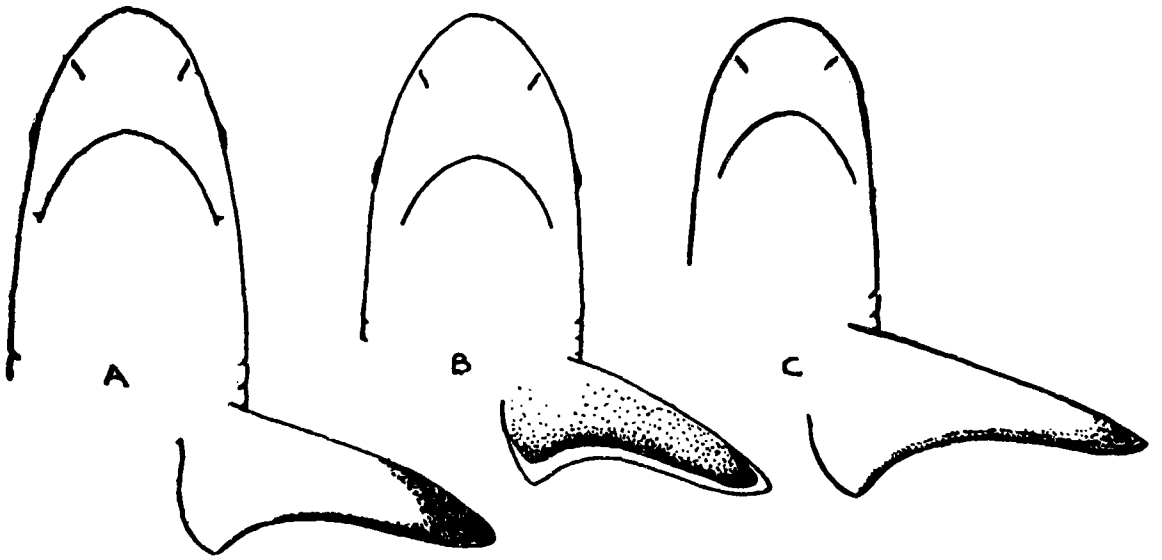


FIG. 2.—Under surface of heads of : (A), *C. amblyrhynchus*, female, 1300 mm. from the Swan Bank, Seychelles ; (B), *C. albimarginatus*, female, 1210 mm. from the Vigilant Bank, Seychelles; (C), *C. milberti*, male, 1850 mm. from the Chagos Archipelago.

Description

The form is typically Carcharinid with a broad head flattened in profile, a rounded pointed snout, nostrils nearer the snout tip than the point of the lower jaw and very short labial furrows extending at right angles on the upper jaws (fig. 2, A.). The first dorsal fin is higher than its base is long

and is about three times higher than the 2nd dorsal which is opposite the anal and about equal to it in size. There is no longitudinal ridge between DI and DII but occasionally a slightly raised seam can be felt rather than seen.

The pectorals are narrow, the distal margin being sharply incurved from the posterior point. I should here remark that considerable variation occurs in the proportional measurements. This is due in some degree to individual oddity but mainly to changes in growth. Thus the proportion of caudal fin decreases as the total length increases while measurements such as snout to origin of DI, DII or the anal tend to increase. The eye is invariably larger in the small individuals and it seems that the fins stop growing before the body has attained its maximum size.

The head of Bleeker's single specimen was 20% of its total length. My figures vary from 16.7 to 21.2% in eleven specimens. Similarly the caudal measurement of his specimen was 25% of the total length while mine range from 25.4 to 31.2% in eight specimens, all but one of which were far smaller than his specimen in length. His pectoral was 17.9% and mine vary between 16.5 and 21.5%; his body depth was 13% and mine vary from 11.7 to 16.0%.

Four or five teeth in the upper jaw on each side of the small symphysial tooth are almost symmetrical, the blade being equal-sided and springing sharply from the shoulders of the base. The fifth or sixth and the remaining lateral teeth of the upper set slope more and more obliquely, the median edge becoming straighter and the outer re-entrant angle more acute as they diminish in size. Both edges are serrated, the blade finely, the basal shoulders more coarsely (fig. 3).

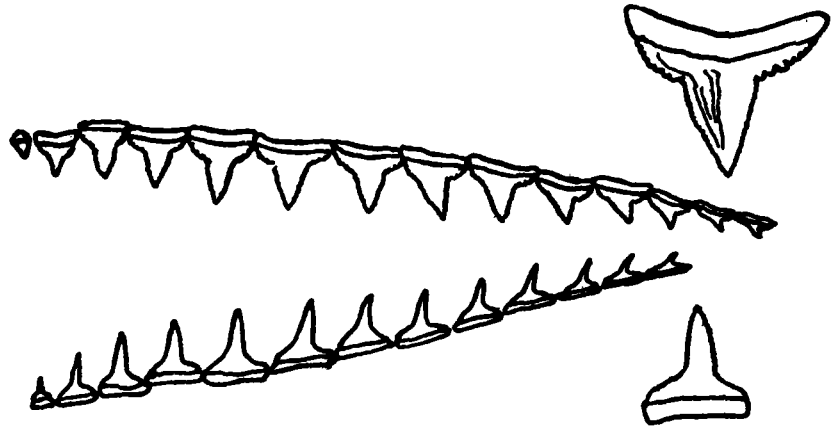


FIG. 3.—*C. amblyrhynchus*. Upper and lower teeth of left side and 4th upper and lower teeth enlarged.

The lower teeth are more awl-shaped, i.e. the points are less blade-like than the uppers, and the points arise from bases of about their own length and are only slightly canted backwards and outwards. The outer

shoulder of the base is lower than the median one and the edges of both shoulders and point are finely serrated — the serrations being more evident to the touch than to sight. In two specimens the dentition was $\frac{13-1-13}{12-1-12}$. In a third it was $\frac{13-1-13}{12-1-13}$.

When freshly caught the back is bronze with a glistening sheen. On the sides the colour fades into white. A broad strip of bronze passes obliquely down from the region of the pectoral and fades towards the region of the pelvics. The first dorsal fin is brown or bronze like the back but has a white or whitish tip fairly sharply marked and extending down the trailing edge. The second dorsal is brown like the back or somewhat darker and the upper surfaces of the pectorals are brown, darker than the back, and merging into blackish at the tips. The undersides of the pectoral tips are blackish fading gradually into white and the trailing edges of these fins are also edged with black. The lower part of the lower lobe of the caudal and the trailing edge to the tip of the dorsal lobe are blackish. The free edges of the anal and pelvics may be grey merging into white.

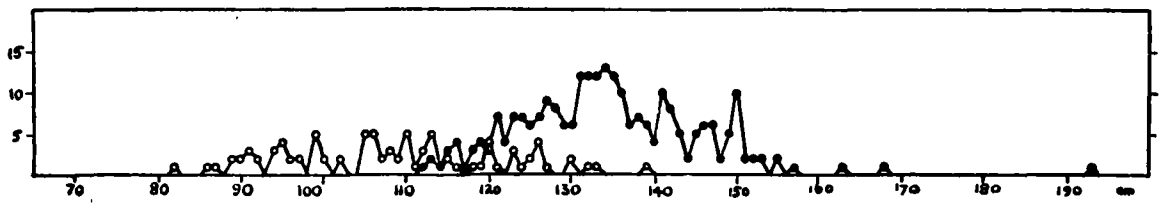


FIG. 4 —*C. amblyrhynchus*. Frequency of immature (°) and mature (•) males.

The rich bronze or copper colour of the fresh specimens from the banks of the Mauritius-Seychelles area becomes dull after death. I have records of pale blue grey, pale brown grey, greyish olive and grey with very faint darker cross-bars among specimens brought in from East African waters with all the fins except the white tipped DI darker than the back.

The average proportional measurements expressed as percentages of the total length with their maximum and minimum values are given in the comparative table on p.

C. amblyrhynchus males become sexually mature between 112 and 140 cms. and do not appear to exceed 170 cms. in length when fully grown (168 cm. & 64 lb.) (Fig. 4). (It is likely that the specimen 193 cm. long was erroneously recorded as REQUIN BAR).

The smallest female with eggs in the oviduct was 122 cm. long and the smallest pregnant female was 125 cm. long carrying a single male fœtus 16 cm. long. The largest female taken was 172 cm. long, weighing 85 lb. inclusive of her four fœtuses. The largest non-pregnant female was 168 cm. long and weighed 70 lb. The number of fœtuses carried ranged from one to four with a very distinct tendency for larger numbers in the larger sharks.

	No of Fœtuses			
Length of female	One	Two	Three	Four
From 120-130 cm.	5	3	—	—
From 131-140 cm.	2	16	7	—
From 141-150 cm.	2	17	18	—
From 151-160 cm.	—	2	8	4
From 161-170 cm.	—	1	3	—
From 171-180 cm.	—	—	—	1

When the lengths of the fœtuses are plotted month by month (Fig. 5) a broad path of growth is evident which indicates a season of sexual activity from June to January with the greatest intensity about September. Fœtal growth starting in this month culminates some twelve or thirteen months later in birth at about 70 cm. Continuation of the curve of growth suggests that the length is about 105 cm. at the end of the first year and that sharks of this species become sexually mature at the end of their second year of free life when they are about 125 cm. long.

The stomachs of half the sharks examined contained food. *C. amblyrhynchus* ate fish of a number of surface and bottom species along with squid and octopus.

Carcharinus albimarginatus Rüppell

(Fig. 1, B.)

The most conspicuous features of REQUIN HOUAREAU are the white borders of the pectorals, caudal and 1st dorsal fins. Small specimens were caught along with REQUIN BAR on all the banks, particularly of the Seychelles plateau but the larger ones inhabited the deeper surrounding waters.

C. albimarginatus grows to a very much larger size than *C. amblyrhynchus*. the largest male we caught being 235 cm. (160 lb.) and the largest female 261 cm. (245 lb.). This one carried two full term fœtuses, both males, 80 and 82 cm. long.

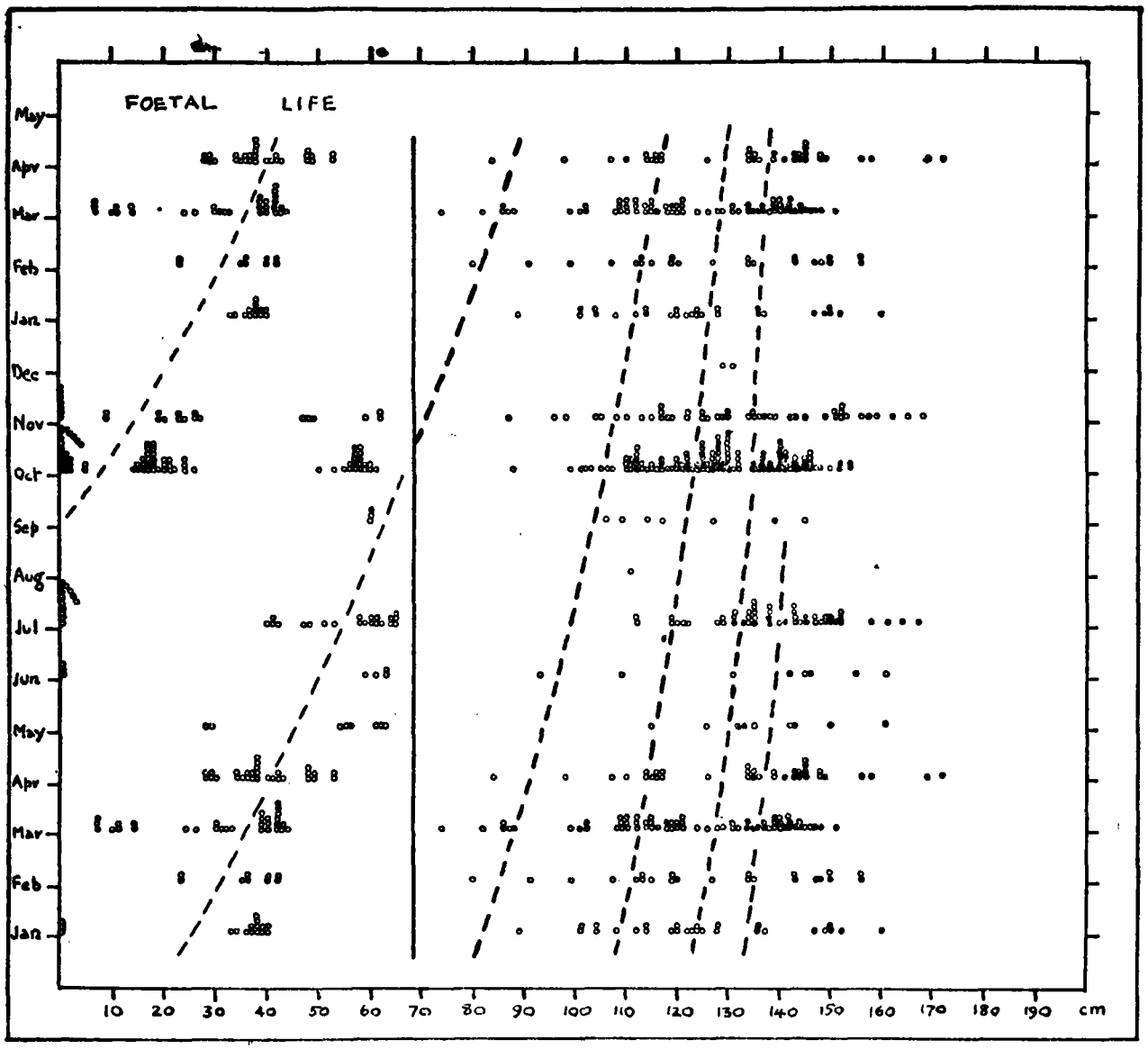


FIG. 5.—*C. amblyrhynchus*. Frequency of females and fœtuses (of both sexes) in each month of the year. (Figures of whole period combined and first four months duplicated). Immature and non-pregnant females — o. Pregnant females — • .

Material Studied

A partial series of measurements and descriptions of four females and one male taken at the Seychelles with the lower teeth of one specimen and outlines and a painting made at that time. The recorded lengths, weights, sex, sexual condition and stomach contents of the 429 specimens caught before and during the Mauritius-Seychelles Survey.

Description

Carcharinus albimarginatus is golden bronze or rich burnt sienna in colour on the back, darker than *amblyrhynchus*, and its white fin borders are sharply distinct at all stages of growth. It is white beneath. The white borders can be seen on the undersides of the pectorals where they appear densely white against the slightly translucent white of the fin. The iris of the eye is amber with a dark rim.

The body form is slimmer and more shapely than *amblyrhynchus* and there is a proportionally longer snout and a very distinctly lower and smaller 2nd dorsal fin (Fig. 1, B). There is a strong ridge between DI and DII.

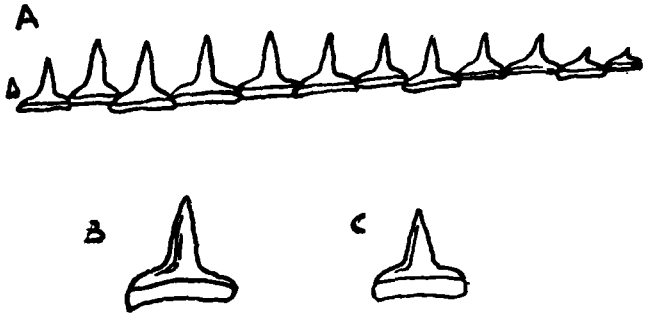


FIG. 6.—*C. albimarginatus*. A, Lower teeth of left side; B, 4th lower tooth of female, 1210 mm.; C, 4th lower tooth of *C. dussumieri*, male, 1260 mm.

The teeth in the upper and lower jaws are similar in shape to those of *amblyrhynchus*. Both sets are serrated but the serrations of the lower set are too fine to be seen. They are barely perceptible to the finger nail. The points of these teeth are fairly narrow where they join the basal shoulders and in this they differ from those of *C. dussumieri* (Fig. 6, A, B, & C.) which are wider. *C. dussumieri* is the only species likely to be confused with *C. albimarginatus*, particularly when young, because of the whitish edges to its fins; but (a) it has only a very slight ridge between DI and DII whereas in *C. albimarginatus* the ridge is very strong, (b) its white edgings are little more than an absence of fringing colour to the fins quite unlike the conspicuous and sharply marked borders of *albimarginatus*, (c) its 2nd dorsal fin is white-edged but in *albimarginatus* this fin is darker than the back, (d) its teeth are small compared with those of *albimarginatus* of approximately the same length, and (e) the points of its lower teeth are flatter and broader than those of *albimarginatus*.

Of the 247 females recorded during the Mauritius-Seychelles Survey twenty-two were pregnant. The smallest being 2150 mm. long. The number of fœtuses carried varied from 1 to 10 and there was no apparent increase in number with increase in length of the parent.

Length of mother	No of Fœtuses									
mm.	One	Two	Three	Four	Five	Six	Seven	Eight	Nine	Ten
2101-2200	—	—	—	1	—	—	1	—	—	—
2201-2300	—	—	—	—	—	1	—	—	—	—
2301-2400	—	—	1	2	3	2	2	—	—	—
2401-2500	1	—	1	—	1	2	1	1	—	1
2501-2600	—	—	—	—	—	—	—	—	—	—
2601-2700	—	1	—	—	—	—	—	—	—	—

Males were approaching maturity at 1650-1730 mm. long judging by the increased length of their claspers, and fully mature at 1800 mm.

When the length of the females and their fœtuses are plotted against the months in which they were caught (fig. 7) the approximate curve of fœtal growth carried onwards suggests that if conception occurs in January or February, birth will take place about a year later at 800 mm. and sexual maturity at about three years from birth. It is not supposed that the largest shark of this species caught (2610 mm.) represents the limit of growth. *C. albimarginatus* has not been recorded so far from Zanzibar or the East African coast.

Carcharinus milberti M. & H.

(Fig. 1, C.)

When freshly caught this species is easily recognised among specimens of *amblyrhynchus* or *albimarginatus* by reason of its yellowish grey-green or pale blue-grey colour on the back and by the height of its 1st dorsal fin.

The body appears heavily built an impression due partly to the thickness of the trunk and partly to the position of DI and the breadth of the pectorals (Fig. 1, C.). The snout is short and bluntly rounded as seen from above. The eyes are relatively small.

DI is inserted above or slightly before the axilla of the pectoral and its vertical height (13.8% total length) is greater than the distance from the eye to the 1st gill slit (10.7%) but less than that from the eye to the 5th gill (16.3%). DII is inserted anterior to the anal but it is neither so high nor so long. The free ends of both fins are short. There is a variably strong ridge between DI and DII. The pectoral is longer and broader than that of either of the other species.

The colour on the back is palely blue — or greenish-grey and the lateral stripes from the origin of the pectoral towards the anus are faintly marked. The belly is white. DI and DII are coloured as the back but the posterior margins and extreme tips are blackish. The pectorals are dark grey on their dorsal surfaces, white ventrally with black trailing edges and slight grey or blackish tips. The dorsal lobe of the caudal is grey, the ventral lobe sometimes whitish. Both lobes have thin black posterior margins.

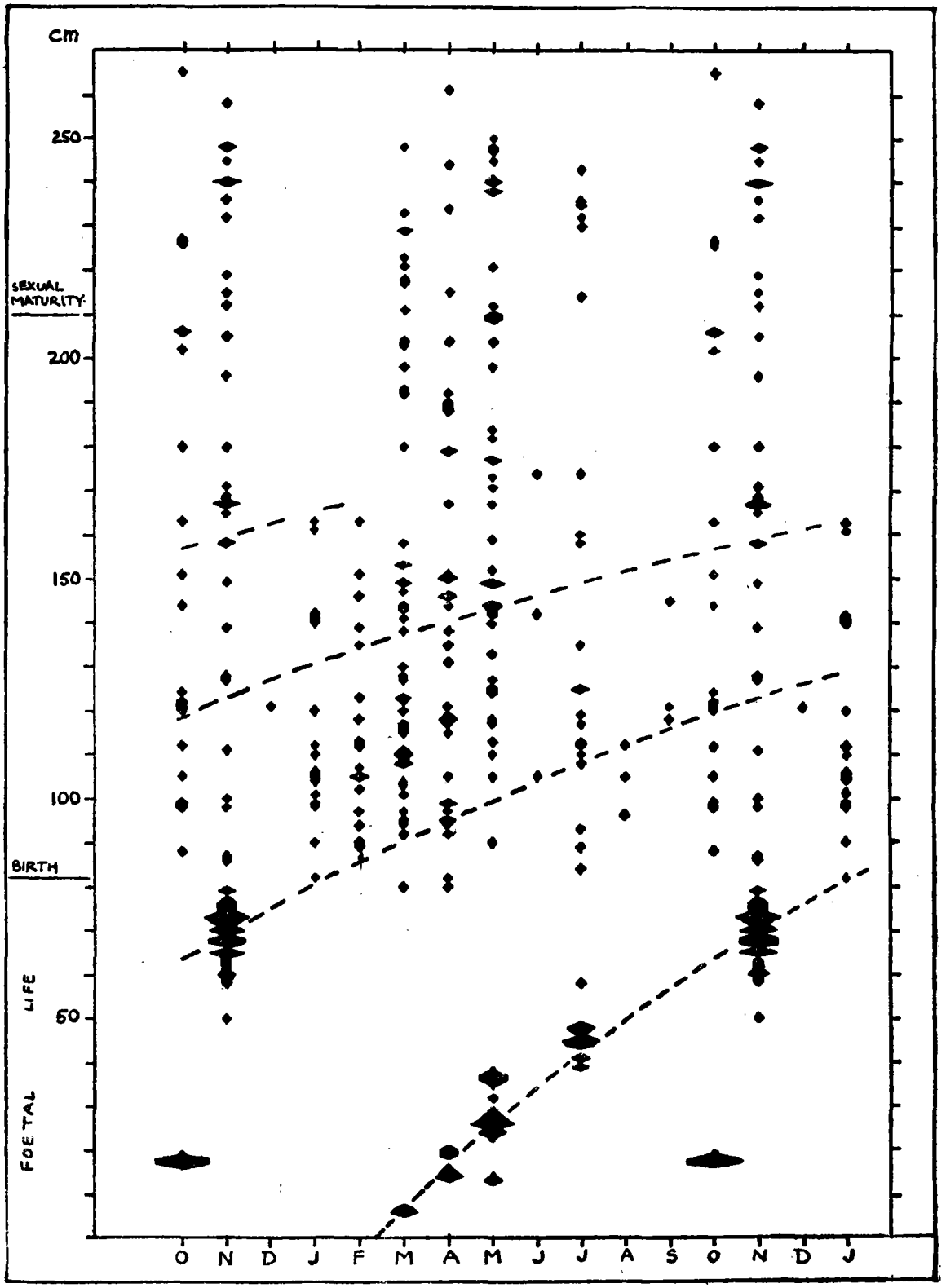


FIG. 7.—*C. albimarginatus* Frequency of females and fœtuses (of both sexes) in each month of the year. (Figures of whole period combined and three months duplicated). Fœtuses of October from Chagos Archipelago only.

The teeth ($\frac{14-1-15}{13-1-14}$ in a female 1910 mm.) are as usual dissimilar, the uppers being triangular and blade-like, the lowers narrow points on broad bases (Fig. 8). The serrations are very fine. Towards the tips of the

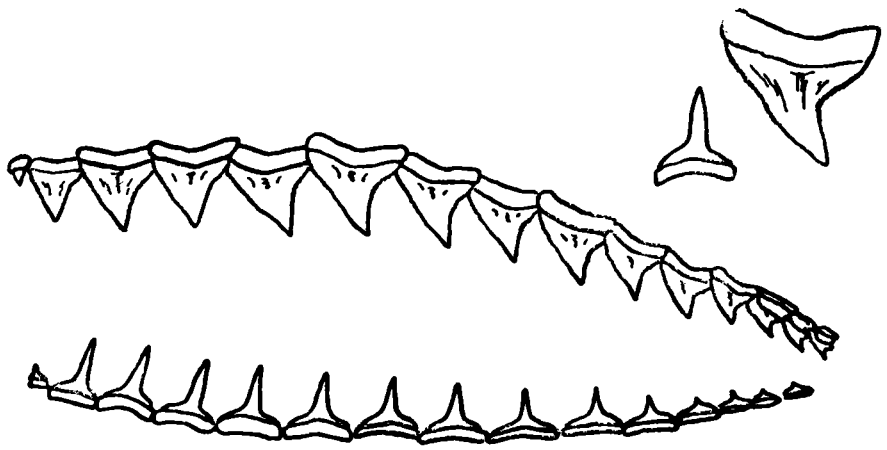


FIG. 8.—*C. milberti*. Upper and lower teeth of left side. 5th upper and lower teeth enlarged.

upper teeth they can be felt rather than seen, particularly on the inner edges; but among the lower teeth they are perceptible to the fingernail towards the tips of the points only. Under magnification the 'wavy' — rather than 'saw' — edging can be traced from point to base.

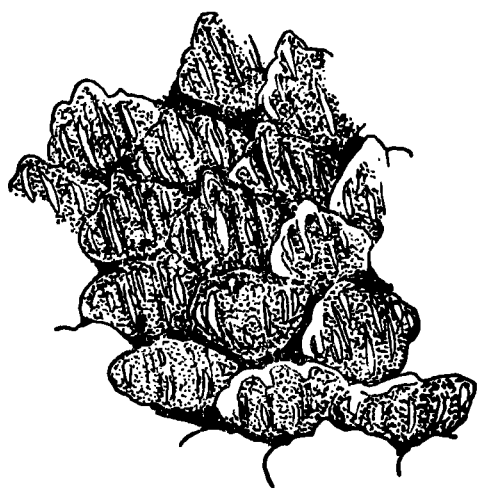


FIG. 9.—*C. milberti*. Scales from back magnified.

The skin of this species is much thicker than either of the preceding ones and the scales are convex and loosely spaced (Fig. 9).

Three of the 18 females caught were noted as immature (1110-1670 mm.), eight were mature, non-pregnant (1770-2200 mm.) and seven were pregnant (1850-2180 mm.). Two of the pregnant females carried seven fœtuses, the other five had six, eight, nine, ten and eleven respectively. The numbers are small but when the average size of the fœtuses of each litter is plotted against the time of year when it was taken and the curve of growth carried on to the following year (Fig. 10) it coincides approximately with the four smallest sharks (2 males, 2 females, all immature) caught in September which so should be approximately six months old.

There were 18 mature males (1800-2130 mm), 1 noted as immature-mature (1700 mm.) and three immatures (1220-1590).

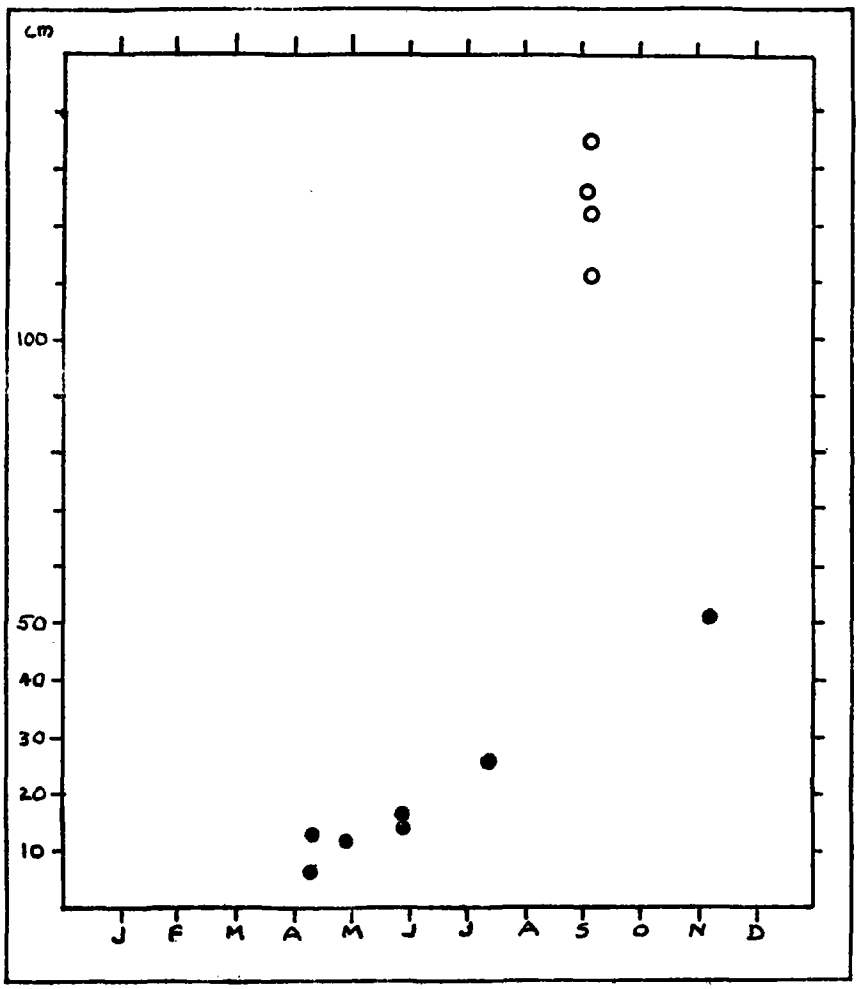


FIG. 10.—*C. milberti.* Average size or fœtuses of each litter (•) and size of smallest juveniles (○) at each month of the year.

TABLE of average proportional measurements of the three species *C. amblyrhynchus*, *C. albimarginatus*, and *C. milberti* expressed as percentages of the total lengths with the extreme values and the number of records from which they were derived

	Carcharinus amblyrhynchus	*Carcharinus albimarginatus*	*Carcharinus milberti*
Total lengths	730 — 1460mm	1050 — 1370mm	1110 — 1910mm
Snout—line of ant. ends of nostrils	2.7 (2.3 — 3.0) (17)	—	2.7 (1)
Snout—line of post. end of nostrils	4.0 (3.6 — 4.4) (18)	4.9 (4.5 — 5.1) (5)	3.7 (3.2 — 4.0) (3)
Snout—point lower jaw	7.2 (6.8 — 7.7) (17)	8.7 (8.3 — 9.1) (5)	6.6 (6.2 — 6.9) (6)
Snout—line of angles of jaw	12.5 (10.9 — 13.4) (18)	13.9 (13.6 — 14.3) (5)	12.0 (10.8 — 12.6) (3)
Snout—line of 1st gill slits	18.8 (16.7 — 21.2) (12)	—	19.1 (17.7 — 21.1) (5)
Snout—line of 5th gill slits	23.3 (21.3 — 24.6) (17)	24.1 (24.0 — 24.3) (5)	24.7 (22.6 — 26.8) (2)
Snout—insertion of pectoral	22.9 (1)	—	—
Snout—axilla of pectoral	25.7 (23.2 — 28.3) (11)	—	28.3 (1)
Snout—origin DI	30.3 (29.2 — 31.5) (13)	—	27.4 (26.2 — 28.9) (4)
Base of DI	9.5 (8.5 — 10.3) (14)	—	7.3 (7.0 — 7.6) (2)
End of DI	4.5 (3.7 — 5.4) (14)	—	5.9 (4.2 — 7.3) (5)
Height of DI	9.8 (9.1 — 10.5) (22)	9.7 (8.0 — 11.5) (5)	13.8 (12.6 — 15.2) (5)
Origin DI—origin DII	30.7 (28.3 — 32.6) (14)	—	35.1 (32.2 — 37.2) (4)
Base of DII	4.2 (3.2 — 5.0) (14)	7.0 (6.9 — 7.1) (2)	4.3 (3.7 — 4.7) (5)
End of DII	4.2 (4.2 — 4.7) (15)	5.0 (1)	3.4 (3.1 — 3.7) (5)
Height of DII	3.3 (2.9 — 3.7) (18)	1.8 (1.5 — 2.2) (3)	3.1 (2.6 — 3.5) (3)
Origin DII—base C.	11.5 (10.8 — 11.8) (12)	—	11.3 (1)
Dorsal edge C.	27.4 (25.4 — 31.2) (13)	—	27.3 (26.7 — 28.4) (3)
Dorsal base C to notch	8.7 (8.1 — 9.2) (10)	—	8.6 (1)
Ventral base C to notch	8.1 (7.1 — 8.9) (9)	—	8.3 (1)
Ventral base to tip ventral lobe	13.6 (12.2 — 15.0) (10)	—	12.3 (11.7 — 12.6) (3)
Snout—insertion of pelvics	48.8 (46.6 — 51.0) (14)	—	49.4 (1)
Anterior edge pelvic	5.1 (4.9 — 5.3) (9)	—	6.5 (5.1 — 7.9) (2)
Post edge pelv.	5.7 (5.1 — 6.3) (9)	—	7.2 (1)
Snout—origin of A.	61.2 (58.3 — 64.7) (13)	—	62.3 (1)
Base of A.	4.1 (3.6 — 4.7) (13)	—	5.3 (4.3 — 6.9) (3)
End of A.	3.9 (3.4 — 4.2) (13)	—	3.5 (1)
Height of A.	3.4 (2.7 — 4.1) (13)	—	3.7 (1)
Origin A—base C.	10.4 (9.2 — 10.6) (12)	—	6.3 (1)
Ant. edge pectoral	18.1 (16.5 — 21.5) (19)	16.5 (16.2 — 16.8) (5)	20.3 (19.3 — 21.4) (4)
Greatest width pect.	8.8 (8.2 — 9.9) (14)	8.8 (1)	11.3 (1)
Depth of body	13.7 (11.7 — 16.0) (10)	—	15.1 (1)
Length longest gill slit	3.9 (3.2 — 4.2) (15)	3.4 (3.2 — 3.6) (4)	4.0 (1)
Diameter of orbit	2.2 (1.8 — 2.5) (3)	—	—
Diameter of eye	1.8 (1.4 — 2.3) (12)	2.1 (1)	1.4 (1)
Distance between ant. ends nostrils	7.7 (6.3 — 8.6) (13)	—	8.1 (1)
Width head at eyes	11.3 (10.0 — 12.2) (14)	—	11.7 (1)
Width head at 1st gill slit	13.3 (11.6 — 15.4) (10)	—	14.3 (1)
Snout—centre of eye	7.7 (7.0 — 8.2) (13)	8.4 (7.9 — 8.8) (3)	8.4 (6.7 — 9 4) (3)
Distance between post. ends nostrils	6.3 (5.4 — 6.9) (11)	7.1 (6.6 — 7.6) (4)	6.3 (5 7 — 6.4) (4)
Distance between angles of jaw	9.6 (7.7 — 10.4) (15)	9.7 (9.1 — 11.2) (5)	8.9 (8.1 — 9 4) (5)
Width head at gape	12.8 (11.0 — 13.8) (13)	13.0 (12.4 — 13.7) (5)	12.4 (11.3 — 13.5) (2)
Origin pect.—origin pelv.	40.2 (38.0 — 41.3) (11)	—	27.0 (1)
Origin pelv.—origin anal	12.9 (11.2 — 13.7) (11)	—	14.7 (13.6 — 15.7) (2)
Teeth	$\frac{13-1-13}{12-1-12}$ (13)	$\frac{13-1-13}{12-1-12}$	$\frac{14-1-15}{13-1-14}$

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Ecological Aspects of Demersal Tropical Fishes off East Africa

COMPARATIVELY little is known of the ecology of warm-water tropical fisheries and there is, in particular, no body of general knowledge about the demersal fishes except, perhaps, for those in and about coral reefs. Now that a preliminary survey of the bottom fishes of the North Kenya Banks has been completed, a number of facts have come to light that are likely to be of general interest.

Since my former communication[1] there have been further cruises and a full report is ready for submission to the Colonial Office for its series of publications on fisheries. Fishes were obtained by handlining at the bottom, generally at 20–60 fathoms, in all seasons. Naturally this was selective.

More than sixty species were taken. Of these a dozen or so were especially important, but the quantity of trash fish was negligible. Catches consisted of the following groups: Lutianidae (8 spp.), Serranidae (14 spp.), Lethrinidae (11 spp.), sharks (more than 13 spp.) and miscellaneous (14 spp.), in the proportion by weight of 8 : 6 : 4 : 2 : 1 respectively. The fishes generally ranged in size from 3 to 20 lb. Incidentally, the sharks took the hook legitimately and there was no robbing of the lines by them.

It must be explained that the sorts of species taken (and consequently their proportions in cruise catches, as quoted here) depended on what body of water was fished. Certain species inhabit the surface layer, the East African Coastal Current, and others the Arabian Sea water beneath. The intervening thermocline lies at very variable depth, 30–70 fathoms, and is usually shallow during the north-east monsoon and deep during the south-east monsoon.

More than half the catch (by weight) taken from the East African Coastal Current was made up by three species of *Lutianus*, one of *Lethrinus* and one of *Epinephelus*. In the Arabian Sea water the most important species were *Cheimerius nufar* (Denticidae) and *Pristipomoides* spp. No flatfishes or rays took the hook.

Virtually all the species have been found to be general predators at the bottom. The chief foods were fishes, Crustacea and Cephalopoda, all of small size. Occasionally large plankton, for example,

planktonic tunicates, dominated the stomach contents of several species. Most of the predators obviously took moving prey and only the Lethrinidae appeared to favour the additional habit of plucking food that lay on the bottom (echinoderms of many types). There seemed to be no species that specialized in grubbing about under the bottom deposits. An important deduction is that these line fishes are unlikely to migrate in close pursuit of specially favoured foods.

The bottom topography of the North Kenya Banks is extremely varied, with smooth and rough grounds, hills and valleys in close proximity. Depths can change from 20 to 60 fathoms within a mile. This high relief is important to the distribution of the fishes when taken in conjunction with the depth of the thermocline, for the various regions between the 30 and 70 fathom contours are bathed in East African Coastal Current water on some occasions and in Arabian Sea water on others. This surely causes a concentration of the fishes of the East African Coastal Current in the north-east monsoon, when the thermocline is shallow, and a dispersal of the same fishes in the south-east monsoon when the thermocline is deep.

It seems that most of the bottoms are predominantly sandy despite the 'rough' or 'folded' profiles recorded by the echo-sounder. Rocks and mud seem to be rare, certainly in quantity. Consequently it is not surprising that the available species are taken almost anywhere on bottoms of appropriate depth, although they clearly favour the 'rough' or 'folded' localities. It does seem, though, that the very flat regions support a distinctive fish population dominated by *Lethrinus crocineus* Smith.

The North Kenya Banks are not only a feeding ground but also a breeding ground. Gonad inspections suggest that most species maintain a low level of breeding throughout the year with additional peaks of intense activity. There is strong evidence for two general breeding peaks, one about April and one about November–December (that is, at the start of each monsoon). There is the possibility of an additional peak about August, perhaps for some species only.

It was a striking feature of catches that they had peaks at the turn of the monsoons plus a high general level in the north-east monsoon and a low general level in the south-east monsoon. Undoubtedly, weather conditions influence the catches by being, typically, most benign when catches are best and most severe when catches are worst: but weather could not possibly account for all the great differential that was found.

It has been mentioned that there are no migrations for either feeding or breeding purposes. One notes that the months of peak catches coincide with (or slightly precede) the peaks of general sexual activity. Dissection showed that when a particular species was caught in unusually large numbers the specimens possessed an unduly large proportion of gonads in stages from nearly ripe to spent.

It is suggested that the demersal fishes of the East African Coastal Current behave, typically, as a diffuse mixture of species spread across the banks to the limit set by the depth of the thermocline, but favouring especially the regions of irregular bottom topography: there seems to be a low but definite tendency to form loose-knit shoals and in this it is likely that species show preference for shoaling with their own kind: most species tend to avoid the flat, level bottoms which are especially favoured by others. This basic pattern is affected by the onset of sexual ripeness, which appears to emphasize the tendency of each fish to shoal with other fishes in general and with its own species in particular. Thus dense shoals of fishes are congregated, usually of several species mixed together but sometimes almost entirely composed of one species: the fishes of each species are not all in the same stage of sexual activity and, indeed, include very many which are sexually inactive. The pattern of shoaling and dispersal is made sharper or more diffuse by the rising and falling of the thermocline, which greatly affects the area of the bottom over which the fishes may roam for food.

I do not have sufficient data to propose a corresponding hypothesis for the behaviour of fishes of the Arabian Sea water.

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[1] Morgans, J. F. C., *Nature*, **184**, 259 (1959).

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Plankton from the East African Area of the Indian Ocean

An earlier communication[1] has described how a series of plankton samples was taken from the coastal strips of Kenya and Tanganyika, extending outwards for some 50 miles. An analysis of some of the dry-weight data shows the following results.

For Figs. 1*a* and *b* all night samples, shallow water samples (that is, where the total depth was less than 200 fathoms), samples taken within 1 h after sunrise and within 1 h before sunset have been ignored. The remaining samples represent a scattering throughout an area of many thousand square miles.

In association with all these plankton samples Secchi disk readings were taken, using a 50-cm disk, to give a measure of the water transparency.

In Figs. 1*a* and *b* the Secchi disk readings, that is, the water transparency, has been plotted against the dry weight of plankton per m^3, this latter being on a logarithmic scale. The regression coefficient has been calculated for each graph and the calculated regression lines indicated. The independent equations are:

$$\text{Fig. 1}a \quad \log y_1 = 1{\cdot}6433 - 0{\cdot}01717x_1$$
$$\text{Fig. 1}b \quad \log y_2 = 1{\cdot}9441 - 0{\cdot}02535x_2$$

In both the regression is significant, $P = < 0{\cdot}001$; the difference between the regression lines is not significant.

Thus the data are consistent with equal rate of fall-off in the plankton dry weight/m^3 in the topmost 200 m with increase in transparency.

It might be argued that the relationship between the plankton and the water transparency is direct, the transparency depending on the plankton concentration. There is always a certain amount of suspended inorganic matter in the sea, plus varying concentrations of the microplankton; these might be the direct cause of variations in transparency. It is considered unlikely that the type and quantity of plankton taken in a 74 m.p.i. net, with apertures of 0·205 mm, will influence the transparency to a significant degree.

A further argument is that as the transparency increases so there is an increased rate of loss of

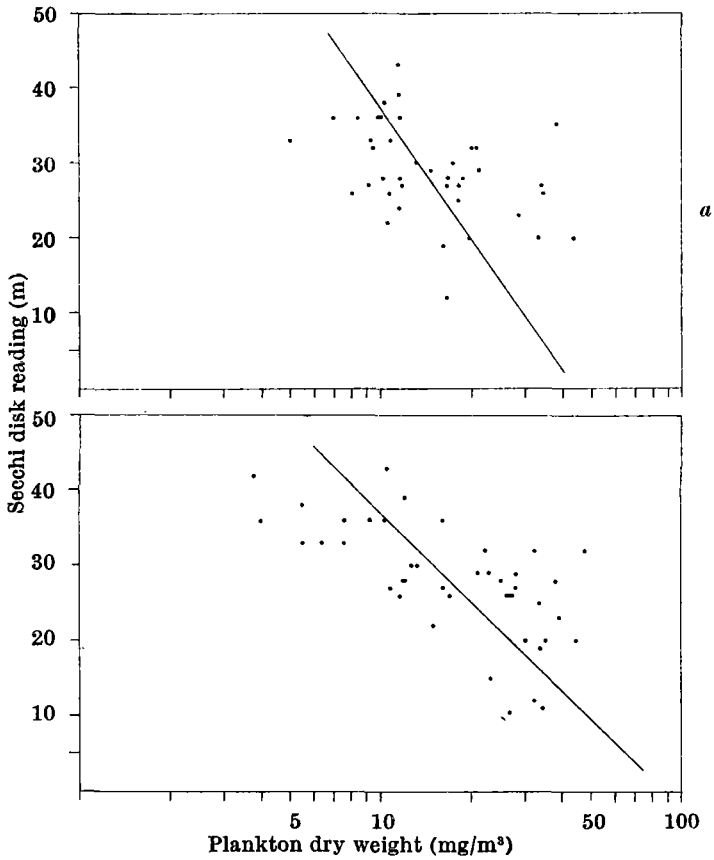


Fig. 1. Diagrams showing the relation of water transparency and plankton dry weight per m^3 (on logarithmic scale) from vertical samples taken from 200 m to the surface (*a*) and 50 m to the surface (*b*); the calculated regressions are indicated

plankton due to net avoidance. There was no evidence to support this.

My conclusions from the data available, applying therefore to the area within the limits of the survey, are as follows.

A small part of the plankton is a normal inhabitant of the topmost layers of the sea; therefore, theoretically, there would always be plankton at the surface even with water of infinite transparency.

The bulk of the plankton reacts according to the degree to which the transparency of the water permits penetration of light; this reaction modifies vertical movements due to negative geotropism, inherent vertical migration patterns, etc. Thus, throughout the area of the survey where the total depth exceeds 200 fathoms, there is, during daylight, no significant variation in the plankton dry weight per unit volume in the topmost 200 m. (The fact that all the points of the graphs do not lie on, or much closer to, the regression lines is no doubt due to the discrepancies

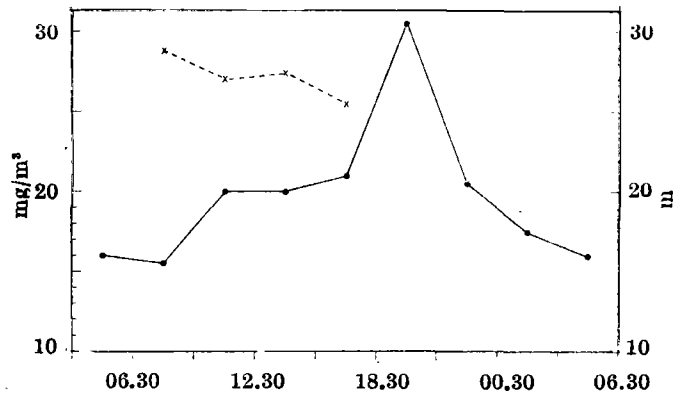


Fig. 2. Diagram showing the variation of the plankton dry weight (mg/m³), taken in vertical samples from both 200 m and 50 m to the surface, throughout 24 h; the former is shown as consecutive 3-hourly means of the latter. Secchi disk readings (m) are also indicated as four consecutive 3-hourly means of the 12-h daylight period

inherent with net sampling.) Variations of this plankton indicated previously[1] are not indicative of richer or poorer areas, but of the relative water transparency at the time of sampling.

Clearly this does not preclude the possibility that an assessment of the plankton of the complete water column, extending to beyond 200 m, would show wide variations in relative richness; but it does indicate that plankton estimations based on daylight samples from the topmost 200 m only can be misleading unless the samples are considered in relation to the water transparency.

The variations shown in the shallow water coastal areas do not necessarily conform to the deeper water plankton pattern and are true variations of plankton abundance indicating relatively rich or poor areas.

In Fig. 2 all shallow-water samples have been ignored; the remainder include samples taken at various times throughout the 24-h period. Time and Secchi disk readings are shown as 3-hourly means.

A vertical migration pattern is shown with the single peak occurring between 18.30 and 21.30 h (the annual range of sunset times here is between 18.15 and 18.45 h). Some indication is also given here of the relationship between water transparency and the plankton. As is to be expected the theoretical cross-over point values, about 23 mg/m³–23 m, are very close to the regression line in Fig. 1*b*, less so in Fig. 1*a*.

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COMPARISON OF ZOOPLANKTON BIOMASS DETERMINATIONS BY INDIAN OCEAN STANDARD NET, JUDAY NET AND CLARKEBUMPUS SAMPLER

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WITH the recent increase in the intensity of oceanographic research in the Indian Ocean there has come the need for comparing the various zooplankton sampling methods. The Juday net[1], the Clarke–Bumpus sampler[2] and the Indian Ocean standard net[3,4] are now in use. The essential characteristics of these nets are as follows: *Indian Ocean standard net*, large, non-truncate, medium-coarse mesh; *Juday net*, large, truncate, fine mesh; *Clarke–Bumpus sampler*, small, truncate, medium mesh. Their dimensions are shown in Fig. 1.

These nets were compared in August 1962 from the Soviet expedition vessel *Vitiaz* at *SCOR–UNESCO* Reference Station 1 in the south-east Indian Ocean (32° S. 111° 50′ E.). The experiment consisted of sampling with each net in quick succession the water column to 200 m. The work was carried out between 2100 h (August 6) and 0700 h (August 7), in which time nine successful hauls were made with each net.

Hauls with the Indian Ocean standard net and the Juday net were intended to be vertical, but in practice the drift of the ship led to considerable wire stray and at times the angle was as much as 50° from the vertical. The volume of water filtered was calculated by multiplying the mouth area of the net (Indian Ocean standard, 1 m²; Juday, 0·5 m²) by the length of wire out, this having been adjusted in accordance with the wire angle to place the net at approximately 200 m. Hauls with the Clarke–Bumpus were oblique, the volume filtered being measured by a flow-meter previously calibrated in a flume tank in which the flow pattern simulates that under operational conditions[2].

The Indian Ocean standard net was recovered from 200 m at 1 m/sec, the Juday net at 0·6–0·8 m/sec, these being the recommended speeds of hauling. The Clarke–

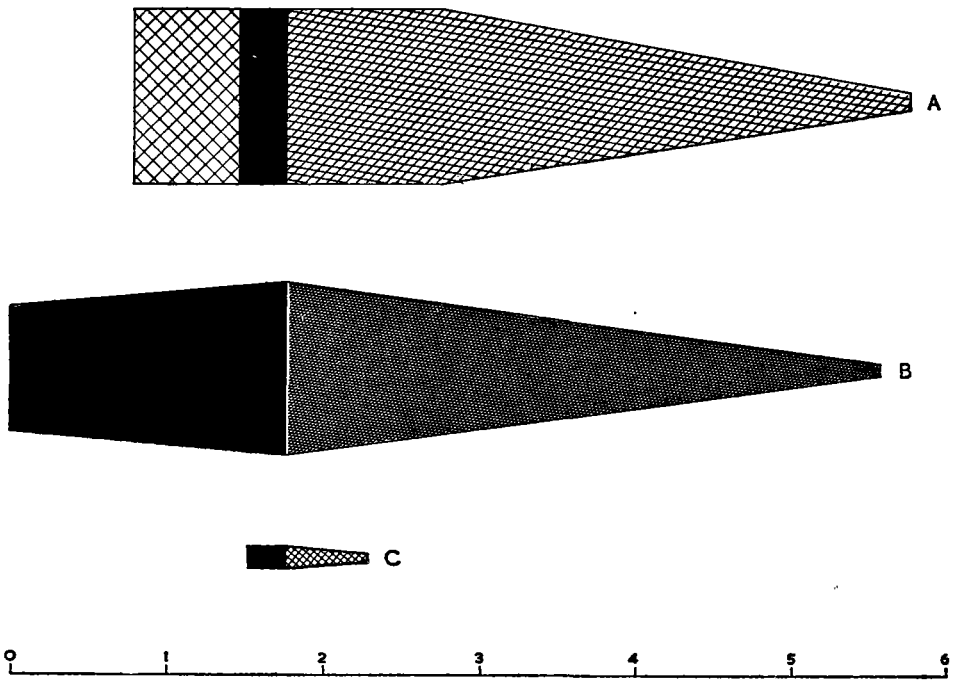


Fig. 1. The zooplankton samplers. *A*, Indian Ocean standard net (21·5 meshes/cm; mesh aperture 0·33 mm); *B*, Soviet 'Tropical' Juday net (38 meshes/cm; mesh aperture 0·17 mm); *C*, Australian Clarke–Bumpus sampler (24·4 meshes/cm; mesh aperture 0·27 mm). Hatching not to scale

Bumpus was paid out and hauled in at a constant speed of 0·4 m/sec with the ship under way at 2–3 knots. This yielded a wire angle of 45–50° which was maintained by stopping and starting the ship's engines as required. The larger nets were washed down after each haul by dipping in the sea and the washings were collected. The Clarke–Bumpus was washed down in a bucket.

Samples were later weighed in the laboratory by the method described in Tranter[2]. To facilitate removal of external interstitial water, weighing dishes with a large straining surface (25 cm^2) were used for large samples. On only two occasions were disproportionately massive organisms found in a catch. On the first occasion (Juday net, 2330 h) a single siphonophore increased the biomass of the sample by 86 per cent, and on the second (Clarke–Bumpus, 0241 h) the inclusion of an eel larva led to a similar artefact (Table 1). In the statistical analysis of the results the weight of these organisms is not included.

The results of the comparison are shown in Table 1. It is remarkable that three nets, so different in size and construction, should give such similar values. The mean of nine determinations with the Indian Ocean standard net was 40 mg/m^3, with the Juday net 56 mg/m^3, and

Table 1. RESULTS OF THE INTERCALIBRATION EXPERIMENT

(*a*) Biomass values for each net (mg/m³)

Indian Ocean standard		Juday		Clarke–Bumpus	
Time	Biomass	Time	Biomass	Time	Biomass
2100	36	2055	18	2130	45
2210	43	2207	42	2230	42
0001	38	2330	72 (134)	0120	42
0235	39	0035	60	0241	56 (97)
0305	36	0240	44	0330	66
0355	31	0310	60	0420	76
0453	52	0410	73	0510	44
0550	39	0550	95	0607	48
0645	45	0642	38	0705	54

Where values are exclusive of single massive organisms, the gross biomass of the sample is given in brackets

(*b*) Analysis of variation

Source of variation	*d.f.*	*S.S.*	*M.S.*	*F*	*d.f.*	*S.S.*	*M.S.*	*F*	*d.f.*	*S.S.*	*M.S.*	*F*
Between blocks	2	153·56	76·78	3·21	2	918·22	459·11	n.s.	2	861·56	430·78	10·07†
Within blocks	6	143·33	23·89		6	3287·33	547·89		6	256·67	42·78	
Total	8	296·89	37·11		8	4205·56	525·69		8	1118·22	139·78	

† Significant at 5 per cent level.

(*c*) Summary of results

Mean (mg/m³)	40	56	53
Ratio	1	1·4	1·3
S.D.	6·1 (4·9)*	22·9 (23·4)*	11·8 (6·5)*
S.D.: Percentage of mean	15 (12)*	41 (42)*	22 (12)*

( )* Excluding variation due to time of sampling

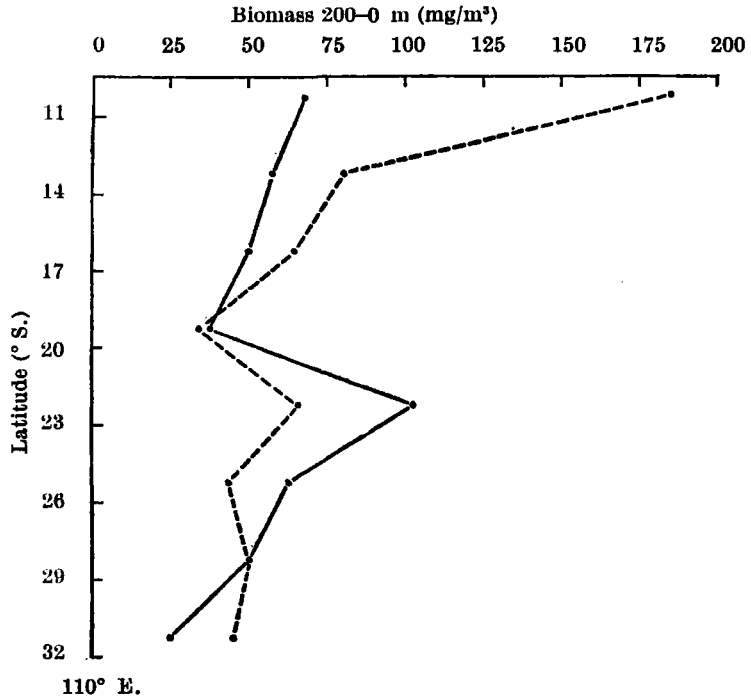


Fig. 2. Mean (200–0 m) zooplankton abundance along meridian 110° E. as determined by Indian Ocean standard net (——) (northward run, August 20–27) and Clarke–Bumpus sampler (– – –) (southward run, September 8–16). The values plotted (mg/m³) are the means of day (0800–1200) and night (2000–2400) observations at successive stations

with the Clarke–Bumpus 53 mg/m³. Further, both Indian Ocean standard net and Clarke–Bumpus sampler gave surprisingly consistent results. The standard deviations of single hauls were 6·1 and 11·8 mg/m³, respectively (4·9 and 6·5 mg/m³ respectively, when gross time effects due apparently to diurnal migration are excluded). Such variability is relatively small when one considers that biomass values in the eastern Indian Ocean vary from practically nil to more than 100 mg/m³ (ref. 2). Results with these two nets are therefore comparable.

More recent observations in the area support such a thesis. On cruise *G*4/62 of H.M.A.S. *Gascoyne* along meridian 110° E., sampling was carried out on the way north with the Indian Ocean standard net and on the way south (two weeks later) with the Clarke–Bumpus. The biomass distribution along the section is shown in Fig. 2. There is a significant difference between observations with the two nets at the northernmost station, otherwise the profiles are essentially the same.

The lack of consistency of the Juday net in the comparison is difficult to explain. Of the three nets it was by far the finest mesh (38/cm) and was made of silk. Perhaps there could have been some degree of clogging or uneven washing. It might be significant that on one occasion when the washings were not collected the catch was less than one-third that immediately before or after. Never-

theless, the variability (41 per cent of the mean) was not excessive and, given a sufficient number of observations, results with this net are probably comparable with the other two.

It needs to be emphasized that, in this investigation, the catches were all handled by a standard method. Where a variety of methods is used for measuring the weight or volume of samples the resultant variability might be greater than that due to the nets themselves. It is also necessary to direct attention to the limited nature of the experiment, which consists of only nine samples with each net. A more extensive series of observations by day and night at more than one station might lead to some modification of the conclusions outlined here.

The samples taken during the intercalibration on *Vitiaz* are being studied further in this laboratory. Counts are being made of major taxa and some selected species and genera. I wish to thank Dr. M. E. Vinogradov, of the Institute of Oceanology, U.S.S.R., for the incentive to carry out this investigation, and Dr. I. Sukhanova (U.S.S.R.), Dr. A. Daniel (India) and Dr. P. Canagaratnam (Ceylon) for their generous assistance with the field work.

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A new record of *Ellobiopsis chattoni* (Flagellata incertae sedis) and its incidence in a population of *Undinula vulgaris* var. *major* (Crustacea Copepoda)

By J. H. WICKSTEAD*

Department of Technical Co-operation

(*Received* 6 *July* 1962)

Ellobiopsis chattoni is an external parasite of pelagic copepods found, usually, on the cephalic appendages. First described by Caullery (1910), it was provisionally considered a peridinian, but no developmental stages were observed. Chatton (1920) found no developmental stages, but followed Caullery in referring it to the Peridiniidae, albeit with some misgivings. Jepps (1936) in her study of 'This enigmatical organism...' concluded by saying '...the information at present available seems to me to suggest a fungus relationship rather than any other...'. Boschma (1949) discusses the Ellobiopsidae, suggesting 'Principally *Amallocystis* is nothing but a compound *Ellobiopsis*...'. He also reviews the literature of the Ellobiopsidae.

This parasite has been recorded from widely separated points, Steuer (1932) considering that it appears to inhabit the upper levels in colder areas and between 200–400 m. depth in warmer areas. Sewell (1951) lists the following copepods from which this parasite has been recorded: *Calanus finmarchicus* (Gunn.), *C. helgolandicus* (Claus), *Pseudocalanus* sp. (*elongatus* Boeck), *Pleuromamma borealis* (Dahl), *P. gracilis* (Claus) and *Acartia clausi* Giesbrecht; to these he adds, although doubtfully, *Euchaeta marina* (Prest.) and *E. wolfendeni* A. Scott.

The present record is from two stations in the Zanzibar Channel; one in near-shore shallow water, position 6° 13′ 30″ S, 39° 11′ 30″ E., total depth *ca.* 10–12 m.; the other farther off-shore in deeper water, position 6° 17′ S., 39° 7′ E., total depth *ca.* 39–41 m. In every case where the parasite was observed it was attached to *Undinula vulgaris* var. *major* (Fig. 1). This species of copepod and the parasite proved to be particularly common in October, 1960, and a plankton sample from the deeper station was analysed completely for its incidence (Table 1).

These figures are to be regarded as minimal. Jepps (1936) has recorded the parasite as being as small as 3–4 μ; such small parasites might have been undetected on the copepods recorded as unparasitized. In this locality the host-parasite relationship was 100% specific, not one species of copepod from both of the stations other than *U. vulgaris* being parasitized. It was not possible to record any possible distinction between varieties since all the *Undinula* present were var. *major*.

All the specimens had been fixed in neutral formalin, a disadvantage when preparations for histological examination are made. However, serial sections were

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prepared and examined. The results, as far as they went, were in agreement with those of Jepps (1936), to which nothing could be added. After clearing and staining, the ovaries of numbers of parasitized and non-parasitized Stage VI females were examined, with the following results and conclusions.



Fig. 1. *Ellobiopsis chattoni* on *Undinula vulgaris* var. *major*. (A) ♀ with six parasites attached. (B) Young parasite on 1st. antenna. *Note*: In (A) total length of copepod is 2·78 mm. In (B) parasite measures 8·3 × 10·9 μ.

A small number of individuals, both parasitized and non-parasitized, had no apparent signs of eggs in the ovary or oviducts. Since they had attached spermatophores they were regarded as spent. The remaining non-parasitized females showed distended ovaries containing well-developed eggs, which extended anteriorly to the anterior end of the longitudinal muscle bands. Oviducts were completely or mostly filled, with the eggs looking healthy. A similar condition was observed in some of the parasitized females, this normal condition coinciding with only a slight degree of infestation. In other parasitized females the ovary was deflated, in varying degrees, the contained eggs being smaller, angular in outline, and not extending to the end of the longitudinal muscles. Oviducts were empty, or nearly so. These findings on a relatively large number of individuals agree with those of Jepps (1936) for *Calanus finmarchicus*.

Castration, partial or complete, of crustacea due to parasitization is well known, e.g. *Inachus* and *Sacculina*. Sewell (1951) discusses such castration in copepods. Here, there appears to be a hormonal and/or chemical upset, the ovary being

affected permanently. My observations suggest that the effect of *Ellobiopsis* on *Undinula* is dependent on the degree of infestation, and is reversible.

Table 1. *Analysis of a population of* Undinula vulgaris *var.* major *parasitized with* Ellobiopsis chattoni

		Immatures (mostly V, some IV)	♂	♀	Total
Total individuals (% of total)		291 (27·6 %)	337 (31·9 %)	428 (40·6 %)	1056 (100 %)
Parasitized individuals (% of total equivalents)		43 (14·8 %)	103 (30·6 %)	129 (30·1 %)	275 (26·0 %)
Individuals with more than one large cyst (% of parasitized equivalents)		12 (27·9 %)	39 (37·9 %)	21 (16·3 %)	72 (26.2 %)
*Total individuals with					
The % is of total females	1 spermatophore	—	—	109 (25·5 %)	183 (42·8 %)
	2 spermatophores	—	—	33 (7·7 %)	
	3 spermatophores	—	—	31 (7·2 %)	
	4 spermatophores	—	—	10 (2·3 %)	
*Parasitized individuals with					
The % is of parasitized females	1 spermatophore	—	—	41 (31·8 %)	63 (48·8 %)
	2 spermatophores	—	—	22 (17·1 %)	

* Some spermatophores had become detached and were loose in the sample, but not in sufficient numbers to affect the results significantly.

Total no. calanoid copepods in sample	9360
Total no. *Undinula* in sample	1056
Total no./m³ of calanoid copepods in sample	581
Total no./m³ of *Undinula* in sample	66
% of *Undinula* in calanoids	11·4 %

Marshall & Orr (1955) have shown that, in *Calanus*, the production of eggs depends on food. It is reasonable to assume that this would apply also to *Undinula*. Calculations indicate that the volume of a well-developed *Ellobiopsis* is *ca.* 0·04–0·05 mm³; the volume of an average female Stage VI *Undinula* is *ca.* 0·7–0·9 mm³. Therefore a female *Undinula* with one large *Ellobiopsis* would be nourishing a parasite the equivalent of *ca.* $\frac{1}{15}$—$\frac{1}{20}$ its own volume; with two, this would be the equivalent of *ca.* $\frac{1}{8}$—$\frac{1}{10}$ its own volume. This does not include the several smaller cysts which are usually to be found with the large cyst(s). The result would be a not inconsiderable drain upon the food resources of the copepod, and this could affect seriously such a specialized body function as egg production. In effect the animal would be starved (albeit the guts were almost invariably full), and starvation inhibits egg production. On this assumption if the parasite could, in some manner, be disposed of, recovery would be complete, and egg production would revert to normal.

SUMMARY

The presence of *Ellobiopsis chattoni* is recorded on *Undinula vulgaris* var. *major* for the first time.

The presence of this parasite in shallow tropical water, within a temperature range of 25·92–26·28° C. (salinity range 35·43–36·38‰) is recorded for the first time.

It is noted that the parasite was completely species specific to its host.

Table 1 analyses the incidence of the parasite in a population of *Undinula vulgaris*.

It was found that the parasite affected egg production in the ovaries. The suggestion is that it produces a starvation effect on the copepod, this effect being reversible.

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THE CLADOCERA OF THE ZANZIBAR AREA OF THE INDIAN OCEAN, WITH A NOTE ON THE COMPARATIVE CATCHES OF TWO PLANKTON NETS

By J. H. Wickstead*, Department of Technical Co-operation

(Received for publication on 4th February, 1963)

This paper forms part of the results from a plankton survey conducted along the Kenya/Tanganyika coast during 1960/61. The data shown apply to the three plankton stations in the Zanzibar area which were worked more or less continuously for 13 months. Two plankton nets were used, vertically, and were clamped side by side. The International Coarse Silk Net (I.C.S.N.) had an aperture of 50 cm., length of 2 m., mesh of 58 m.p.i. (23 per cm.), aperture size of 0.288 mm. and the open area of mesh is 47 per cent. The Currie and Foxton Measuring Net (CF 70) had an aperture of 70 cm., length of 2.5 m., mesh of 74 m.p.i. (29 per cm.), aperture size of 0.205 mm. and the open area of mesh is 34 per cent. Fuller details of the apparatus, methods of sampling and analysis, local conditions, descriptions of the stations, etc., can be found in a previous publication (Wickstead, 1963).

The plankton stations, called P.S.1, P.S.2 and P.S.3, are as follows:—

P.S.1.—Position 6°13′30″S. 39°11′30″E., total depth *ca.* 12 m., about 400-700 yards off-shore.

P.S.2.—Position 6°17′S. 39°7′E., total depth *ca.* 40 m., about 7 miles off-shore.

P.S.3.—Position 6°30′S. 39°48′E., total depth *ca.* 750 m., about 20 miles off-shore.

Vertical samples were taken from bottom to surface at P.S.1 and P.S.2 and from both 50 m. and 200 m. to the surface at P.S.3. All stations were worked by day and by night.

Results

Only three species were found, *Penilia avirostris* Dana, *Evadne tergestina* Claus and *Podon polyphemoides* Leuck. *Penilia* was the commonest while only six *Podon* were recorded from P.S.3 and two from P.S.2.

Penilia avirostris

This is a characteristic marine animal which is very readily identified, and is the only marine ctenopod cladoceran. Originally several species were included in the genus but it is now generally accepted that they all belong to the single species (Cattley and Harding, 1949). Distribution is in the warmer waters and is world wide (*see* Della Croce, 1958). Some subsequent records are Furnestin (1959), Negrea (1959) and Della Croce (1960).

As can be seen from Figs. 1 and 2 the appearance of this species in the plankton, and its subsequent disappearance, is very abrupt. This has been noted as a characteristic of this species wherever it has occurred. Much has been written about its biology; the papers of Lochhead (1954) and Pavlova (1961) have comprehensive literature lists.

The range of temperatures during its presence in the plankton was as follows.

At P.S.1 the species was first noted at 28.10° C., with the temperature rising. Maximum numbers occurred at 29.62° C., the temperature still generally rising. It was still present at the maximum of 30.02° C., but the numbers were falling rapidly. The last record was at 28.50° C., the temperature now falling. As seen in Fig. 3 there is a steady temperature curve at this station throughout the year. Without exception, at all periods when the temperature was 28.0° C. and above, *Penilia* was present; at all periods when below, it was absent.

At P.S.2 the presence and absence of *Penilia* was recorded at the same times here as at P.S.1. (The numbers at P.S.2 for the November/December period were in the range 0.5 to 1.5 per m^3; with the scale in Figs. 1 and 2 this appears to be plotted as "0".) It was first noted at a rising temperature of 28.05° C. 5 m. below the surface, with

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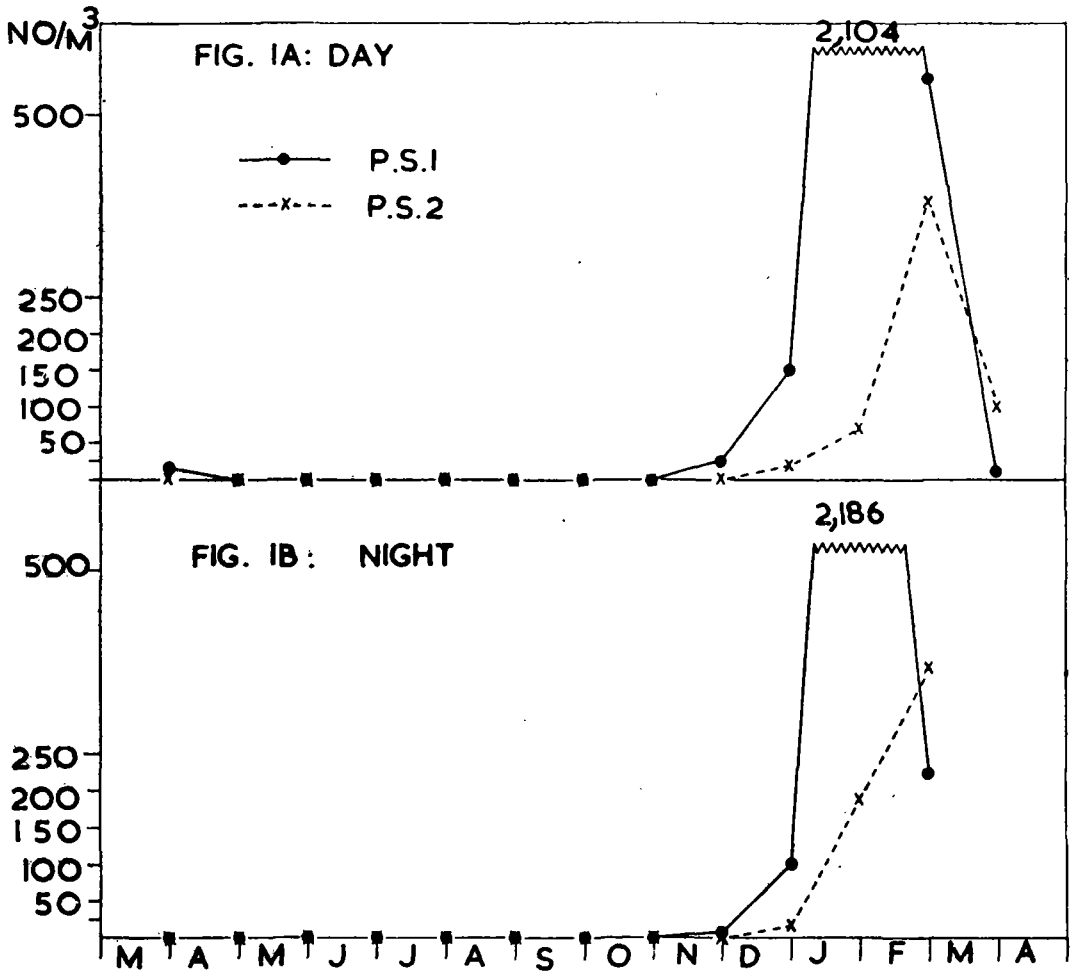


Fig. 1.—No/m³ of *Penilia avirostris* in the plankton, taken with the I.C.S. Net. 1A=Day samples. 1B=Night samples. Note: There were no samples for the last period in 1B

26.92° C. 5 m. above the bottom. Maximum numbers occurred at 29.25° C. 5 m. below the surface, with 28.65° C. 5 m. above the bottom; the temperature just below the surface had passed its maximum of 29.90° C. and was dropping. The last record was at 28.25° C., with the temperature still dropping.

The results of various workers show that *Penilia* lives in the topmost few metres of water. This being so it will be correct to say that at P.S.2, as was the case at P.S.1, at all periods when the temperature was 28.0° C. and above *Penilia* was present, and at all times when below, it was absent.

At P.S.3 only five or so specimens were recorded, all from the upper layers. The period corresponded with the highest temperatures at this station, that is *ca.* 27.0° C. at 30 m. depth. I have no doubt that in the upper few metres where the animals are to be found the temperature was 28.0° C. or more.

The forms of *Penilia* appeared in a logical succession. When first observed no males were found and the females had developing young in the brood sac; no resting eggs were noted. When numbers were at their maximum a small percentage of these were males. The majority of the females still had developing young in the brood sac, but about 10 per cent had one, more usually two, resting egg(s). In the last plankton sample taken which had *Penilia* present, no males were

found. Most of the females still had developing young in the brood sac, but about 30 per cent carried resting eggs. A number of brood sacs plus egg(s) were found in the plankton, sometimes with a disintegrating female attached.

Both the food and feeding mechanisms of *Penilia* have been studied (Pavlova, 1959B and Lochhead, 1936-7). All the Zanzibar specimens had a full gut; the food was clearly that of a filter feeder.

In Zanzibar, as is the case wherever it occurs, *Penilia* was far more common in-shore than over the deep water off-shore. It would seem that the *Penilia* were in a greater concentration at P.S.1 than at P.S.2. However, from the percentage depth distribution data (Wickstead, 1961), the writer has calculated that, at P.S.2, it would occur in about the upper quarter of the water column, having a concentration here of *ca.* 1,500/m³. Thus they would occur in concentrations only a little less than at P.S.1.

Penilia is noted for its appearance quite abruptly in the plankton, its enormous increase in numbers, followed by its equally rapid disappearance. In the author's experience this disappearance is quite complete, there being no residual active population to carry on the species. If, as in some areas, it is present in the plankton for a relatively extended period there appear to be always two peaks of abundance (Wickstead, 1961; Bainbridge, 1960). Since the conditions at the

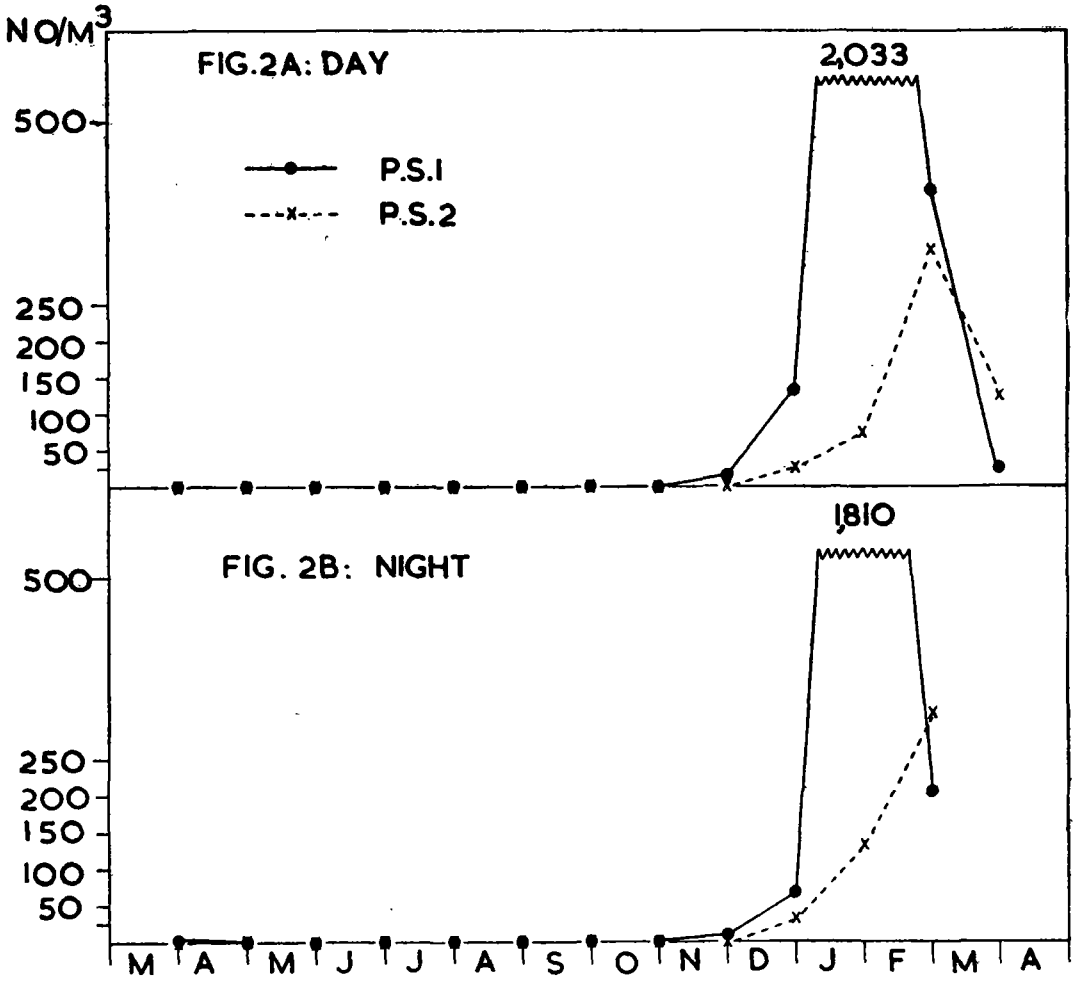


Fig. 2.—No/m³ of *Penilia avirostris* in the plankton, taken with the CF 70 Net. 2A=Day samples. 2B=Night samples. Note: There were no samples for the last period in 2B

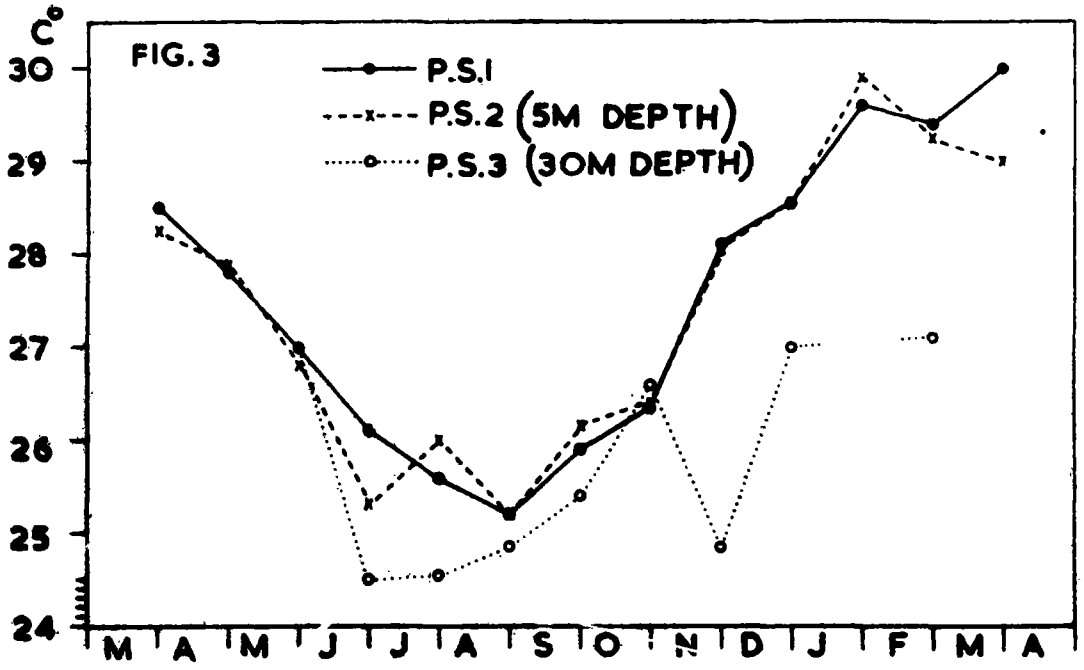


Fig. 3.—Surface, or near surface, temperatures at P.S.1, P.S.2 and P.S.3 during the period of the survey. Note: There were no records for the periods Mar./Apr., Jan./Feb. and Mar./Apr., at P.S.3

time of their disappearance are often, apparently, suitable for the continuation of the population, clearly something limits the duration of any population of this species. The following ideas are offered in explanation of this.

The author has little doubt that the resting eggs fall to the bottom with the parent disintegrating from around them; this differs from such forms as *Daphnia*, where the ephippium and the contained resting eggs is cast off. When conditions are favourable the eggs hatch and form the beginnings of the next population. It may be that conditions are favourable later on in the same year, in which case there will be two populations within the one year; otherwise there will probably be a lapse of time equivalent to about a year's interval between the populations. The resting eggs hatch as parthenogenetic females; each of these can have up to 13 young (Lochhead, 1954) with a mean figure of about six to eight (Pavlova, 1959A). These female *Penilia* have, normally, eight instars before becoming a fully grown adult, but start to have broods of young after the third instar (Pavlova, 1959A, p. 58). In the conditions prevailing in Zanzibar, using the findings of Pavlova (1959A) as a basis, the writer estimates that a brood of young can become developed and hatched with 3-4 days and the hatched young will themselves bear broods in 2-3 days. Since the original mother will continue to have broods, clearly there will be what can be aptly referred to as an explosive expansion in the population. The expansion reaches its climax and then diminishes with equal rapidity, coincident with the production of males and resting eggs. From the results of various workers it appears that a rapidly expanding population of *Penilia* cannot survive for longer than three months. The factors which end the population might be internal, as suggested by Weismann (1876-9), external (*see* Berg, 1934), or, in the author's opinion, a combination of the two. The following suggestion is made concerning the explosive population cycle, based on the plankton observations made in Singapore and Zanzibar and the experimental observations of Pavlova (1959).

The dormant eggs remain on the bottom until conditions are suitable for hatching; the dominant factor would appear to be temperature. They hatch as females, which, in a very few days, begin to hatch broods of

parthenogenetically produced young, all females. These in their turn soon begin to produce female young; thus the population increases at an ever increasing rate. Since every mother will go on to produce about five broods after the hatching of the first, the population will expand according to the expression $1—8—8^2—8^3—8^4—8^5—8^6$, where 7 is the mean number of young per brood. If we allow 6 as the number of generations, from a single mother there will be produced *ca.* 260,000 young within a period of about 36-40 days; that is to say approximately from the initiation to the climax of the population. This of course does not allow for any deaths; the author estimates that, of the theoretical 260,000, only 1/1,000, or 260, will survive.

This leads to such a rapid increase in the plankton population per unit volume that the respiration of the zooplankton uses more O_2 and produces more CO_2 than can be replaced by normal diffusion (there is normally very little turbulence in these waters). It has been observed that outbursts of *Penilia* coincide with a very great increase in the numbers of diatoms. It is suggested that these diatoms maintain the O_2 and CO_2 concentrations at acceptable levels. The diatoms then disappear quite rapidly, thus, in effect, destroying the balance between the zooplankton and the O_2 and CO_2. Lowering the O_2 concentration (or raising the CO_2 concentration) in the water will have its effect on the *Penilia.* This effect will be to cause the parthenogenetic females to produce both males and sexual eggs. It is a fact that the males and the resting eggs always seem to put in their first appearance at the climax of the population. Although it is possible that, under experimental conditions, a female *Penilia* which has produced resting eggs may revert to producing more parthenogenetic broods (Berg, 1934, p. 142), in nature it will die. This removal of mothers, plus the production of males, will cause a rapid decline in the population. To supplement this decrease, the females, plus their young, which are still reproducing parthenogenetically, will by now be getting degenerate, producing fewer and fewer young (Berg, 1934, p. 146). Thus, if there is no inception of a new population, the old population will die out. If conditions become favourable for hatching the resting eggs before the old population has disappeared, the remnants of the dying population will become mixed with the vigorous, parthenogenetic females of the new population. This stage will be the valley between two population peaks which sometimes occur within a few months in some areas.

It does seem that the factor most directly concerned with hatching the resting eggs is the temperature. Each population of *Penilia,* in its particular area, will have a temperature threshold related to local conditions; in the Zanzibar area it appears to be *ca.* 28° C. Figs. 1 and 2 show that peak numbers at P.S.2 occur approximately one month later than at P.S.1. As has been noted above when the population at P.S.1 was expanding the bottom temperature at P.S.2 was just below 27° C. The hatching of the resting eggs on the bottom would thus be delayed until a temperature of 28° C. is reached. This would explain the different peak periods.

From the idea of a temperature threshold it would follow that, generally speaking, in an area which has a regular annual temperature cycle with a single peak, *Penilia* will show a single population "explosion", and in an area which has a temperature cycle with two peaks, will show two populations. The Zanzibar area is an example of the single population; the Singapore area an example of the double population (Wickstead, 1961).

The suggested relationship between the *Penilia* and the increase in phytoplankton can explain the relationship found by Della Croce (1958) between *Penilia* and water transparency.

Evadne tergestina

In the writer's experience this species is almost invariably associated with *Penilia* in the tropics. It is typical of warm water coastal plankton, but does extend rather more off-shore than *Penilia*; however, it cannot be considered an oceanic species.

Figs. 4 and 5 show the occurrence of this species; sufficient numbers were taken at P.S.3 on occasion for this station to be included in the graph. It will be seen that its appearance, and disappearance, in the plankton corresponds with *Penilia.* Similar also is the sequence of parthenogenetic young and resting eggs; no males were found in the samples examined.

This species appears to have a slightly lower temperature threshold than *Penilia*; in these samples there were no records occurring at a temperature of less than 27.0° C. (The

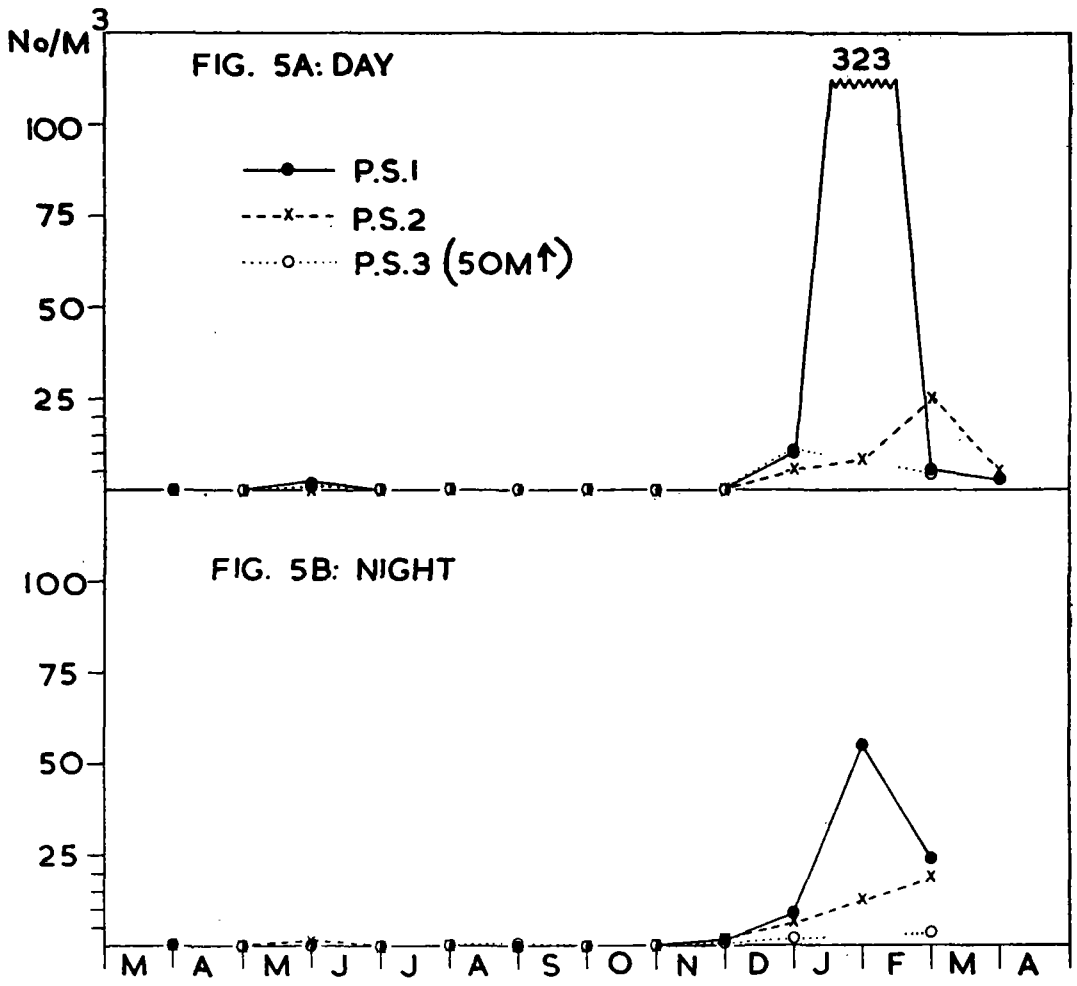


Fig. 5.—No/m³ of *Evadne tergestina* in the plankton, taken with the CF 70 Net. 5A=Day samples. 5B=Night samples. Note: There were no samples for the Jan./Feb. and Mar./Apr. periods at P.S.3 in 5A and 5B or for the last period in 5B

THE CLADOCERA IN THE PLANKTON

The group as a whole was absent, or virtually absent, throughout most of the year. In complete contrast, when at their maximum, they dominated the plankton numerically, forming 61½ per cent of the total numbers at one period according to the I.C.S.N., and 37 per cent of the total numbers according to the CF 70. Fig. 6 shows the percentages of *Penilia* and *E. tergestina* in the total plankton numbers during their periods of greatest abundance.

This group could well play a most important part in a fishery. They are, in the author's opinion, ideal food organisms for fish larvae in this area; the size range is just about right. A population of fish eggs which hatch at the beginning of the expansion phase of the Cladocera will have a great abundance of food, and a high proportion of them should reach the rather less vulnerable post-larval stage, say about 50 mm. With a minimum concentration of one cladoceran per 7 cm.³ an active fish larva should have little difficulty in catching them.

In a previous paper (Wickstead, 1961) it was stated that while one series of samples suggested that the Cladocera were fewer by night than by day, the other suggested that there was no difference; here the writer was

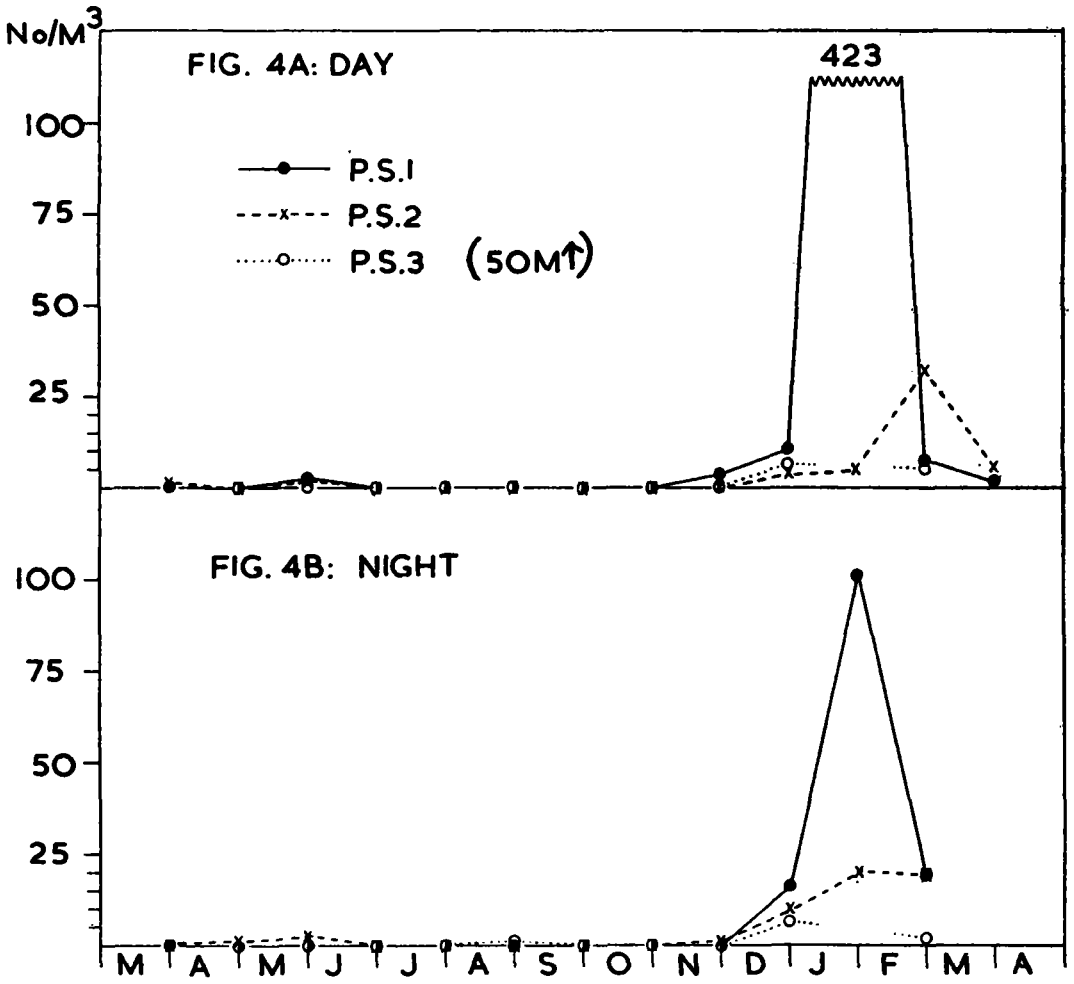


Fig. 4.—No/m³ of *Evadne tergestina* in the plankton, taken with the I.S.C. Net. 4A=Day samples. 4B=Night samples. Note: There were no samples for the Jan./Feb. and Mar./Apr. periods at P.S.3 in 4A and 4B or for the last period in 4B

remarks concerning the temperature at P.S.3 (p. 3) will apply here also.) Even so, the vitality of the population appeared to be at a low ebb when the temperature dropped below 28.0° C. *E. tergestina* was the only cladoceran recorded from the Great Barrier Reef plankton samples (Foxon, 1932). From the data of Russell and Colman (1934 and 1935, p. 270) it can be seen that, with one exception, it was recorded only when the temperature was above 28.0° C. The exception, when a small number was taken, was immediately after the end of the period during which the temperature was above 28.0° C.; the recorded temperature was 26.8° C. at 10 m. depth.

When comparing *Penilia* and *E. tergestina* the evidence suggests that these are two species which do inhabit the same ecological niche. Possibly there is a significant difference in the particle size of the food ingested, but a comparison of the setal configuration on the limbs makes this appear unlikely.

Podon polyphemoides

No fair comment can be made on this species in view of the very few individuals taken. The literature indicates that it is a widespread species, extending to rather higher latitudes than the other two, is not necessarily found near the coast and always appears to be found in relatively small numbers.

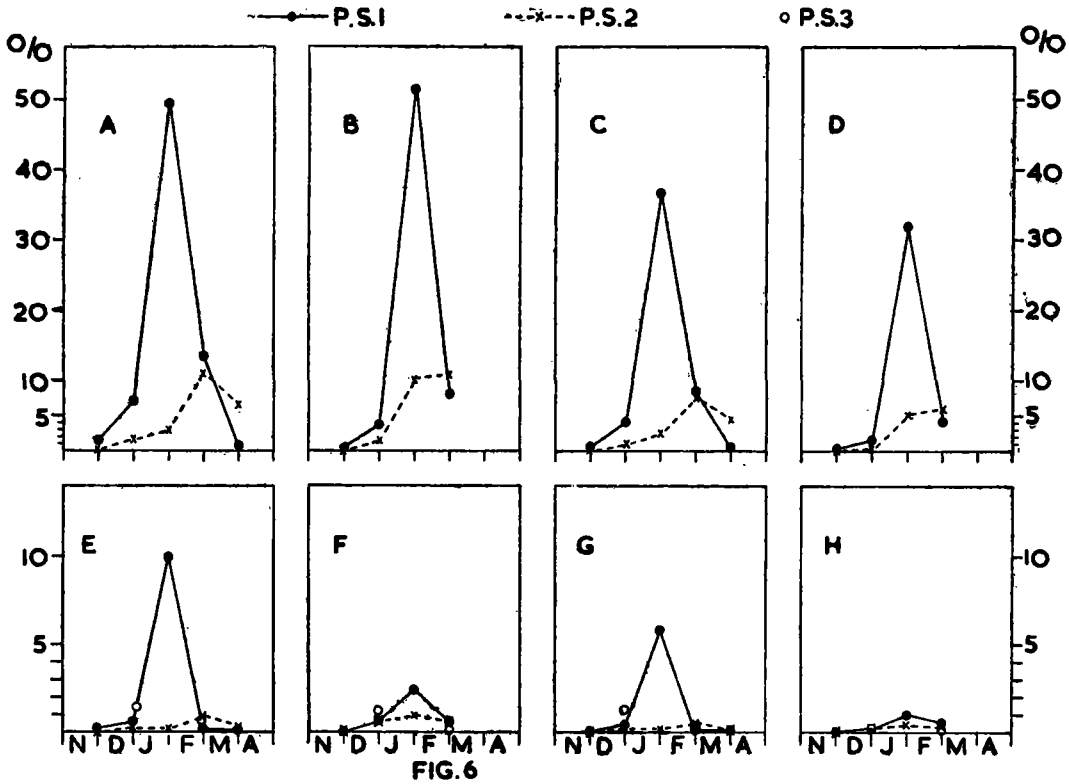


Fig. 6.—The numbers of *Penilia avirostris* and *Evadne tergestina* as a percentage of the total plankton numbers during their period of abundance. A=*Penilia*, I.C.S. Net day samples; B=*Penilia*, I.C.S. Net night samples; C=*Penilia*, CF 70 Net day samples; D=*Penilia*, CF 70 Net night samples; E=*Evadne*, I.C.S. Net day samples; F=*Evadne*, I.C.S. Net night samples; G=*Evadne*, CF 70 Net day samples; H=*Evadne*, CF 70 Net night samples

dealing with *Penilia* and *E. tergestina* together. The Zanzibar material, with its greater numbers, appears to resolve this point. There is no significant difference between the numbers of *Penilia* in day and night samples, but there is with *E. tergestina*. By night the I.C.S.N. samples showed a quarter of the daylight numbers, the CF 70 a sixth. (It must be remembered that each monthly period does not represent a single sample, but the mean of several samples taken within the monthly period.) No completely satisfactory explanation for this can be offered here. Possibly selective feeding by carnivores on this species occurs. It was suggested previously (Wickstead, 1961, p. 158), with some evidence, that predation occurs mainly at about sunset. Selective feeding on *E. tergestina* at this time could reduce the numbers in the night plankton compared with the numbers in the day plankton. If new broods are hatched at about dawn, this would replace the overnight losses.

The catches of the I.C.S.N. and CF 70 Nets compared

Each hauling of the clamped pair of nets gave a pair of samples, one from each of the nets. Only pairs of samples which contained significant numbers of the organisms are considered here. Thus there were 13 pairs of samples with significant numbers of *Penilia* and six pairs with *E. tergestina*.

The figures shown below are the numbers taken in the CF 70 expressed as a percentage above or below the numbers taken in the corresponding paired sample of the I.C.S.N. The figures are arranged in ascending order for convenience, there being no significance in the arrangement.

Penilia avirostris

1	2	3	4	5	6
−36%	−35%	−32%	−17%	−16%	−15%

7	8	9	10	11	12	13
−14%	−14%	−10%	−3%	+19%	+22%	+39%

Mean = −9%

Thus ten CF 70 samples took fewer per unit volume than the I.C.S.N.; only three took more. A general assessment then is that, for sampling *Penilia avirostris* quantitatively, the CF 70 is a little less efficient than the I.C.S.N., taking on average about 10 per cent fewer animals per unit volume of water filtered.

Evadne tergestina

1	2	3	4	5	6
−46%	−36%	−24%	−22%	−7%	−4%

Mean = −23%

In every example here the CF 70 net took fewer per unit volume than the I.C.S.N. Again the CF 70 appears to be less efficient than the I.C.S.N., taking about 20 per cent fewer animals per unit volume of water.

Since it is the coarser mesh net which catches the more animals, thus eliminating any differences which might be caused by mesh selection, it is clear that when the I.C.S.N. and CF 70 nets are used as they were in this survey (Wickstead, 1963), the I.C.S.N. is the more efficient for quantitative sampling of the Zanzibar cladocerans.

Summary

Three species of Cladocera are recorded from the Zanzibar area of the Indian Ocean, *Penilia avirostris, Evadne tergestina* and *Podon polyphemoides*; this last species was rarely taken. Two nets were worked at three stations for 13 months. Figs. 1 and 2 show the incidence of *Penilia* in the plankton, Figs. 4 and 5 the incidence of *E. tergestina*. Fig. 6 shows these two species as a percentage of the total plankton numbers during their periods of abundance. Fig. 3 shows the temperature conditions at the three stations. "Explosive" populations of *Penilia* are discussed, with the suggestion that a combination of the O_2 content of the water and inherent progressive degeneration of parthenogenetic females are the limiting factors of a population. The coincidence of heavy diatom and *Penilia* populations is noted, with the suggestion that the former supplies O_2 for the latter.

Catches of two nets are compared. The CF 70 catches about 10 per cent less *Penilia* and about 20 per cent less *E. tergestina* per unit volume of water than the I.C.S.N., this latter being therefore the more efficient net under the conditions in which they were used.

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ESTIMATES OF TOTAL ZOOPLANKTON IN THE ZANZIBAR AREA OF THE INDIAN OCEAN WITH A COMPARISON OF THE RESULTS WITH TWO DIFFERENT NETS

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[Accepted 11th December 1962]

(With 16 figures in the text)

Total plankton from vertical samples is estimated in terms of numbers, volume and dry weight per m^3. Three stations were sampled, by day and by night, over a period of thirteen months, using both a 58 m.p.i. and a 74 m.p.i. net clamped together. Three stations had total depths of 12, 40 and 750 m respectively. Some relevant and contemporary climatic and hydrographic factors are shown. The relative catches of the two nets are shown for all three measures and their relative catching ability is discussed.

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INTRODUCTION

Our knowledge of tropical plankton has been extended by various surveys over the past years. The Indian Ocean has been relatively unexplored, but the forthcoming international expedition should assist greatly in understanding the composition and distribution of the plankton of this area. There is always the disadvantage of such surveys, which have to cover such large areas, that cycles and variations in the plankton associated with any particular locality cannot be recorded owing to the wide intervals of time between sampling. It is hoped that the present work, which extended for over a year at three fixed localities, and indicates temporal variations, will provide a basis for comparison with the results from future extended cruise samples.

To make comparisons valid the choice of nets used was important. At the time of the survey, the problem of the standard " Indian Ocean Net " had

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not been settled. However, after consideration of the surveys from other tropical, sub-tropical and temperate areas, it was decided to use the International Coarse Silk Net and the Currie & Foxton Net, this latter slightly modified. By using both of these nets together, at the same time (Fig. 1), a direct comparison could be made between the two nets and the results from each would be available for comparison with samples taken with the same net from elsewhere.

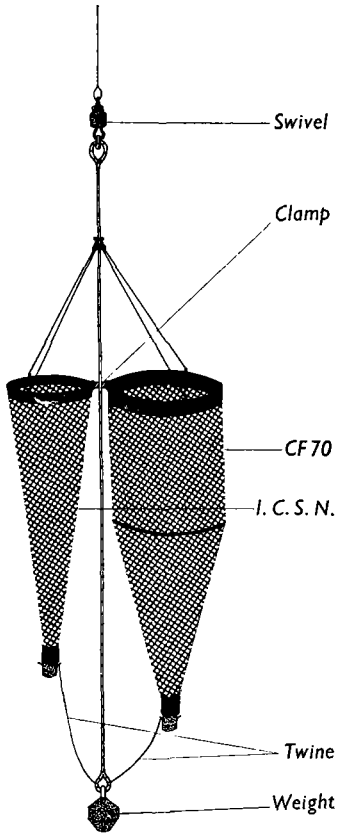


Fig. 1 —Diagram to show how the vertical plankton nets were assembled.

No previous systematic plankton work has been done in these waters. Some random samples were taken during various expeditions, e.g. " Valdivia " 1898–99, " Dana " 1928–30 and " John Murray " 1933–34, but these were very limited in numbers. Thus the area covered can be regarded, planktologically, as unexplored ground.

Systematic sampling of tropical plankton from fixed stations for extended periods has been limited, being restricted generally to such surveys as the Great Barrier Reef (Russell & Colman, 1931, etc.) and the Malacca Strait–Singapore Strait–South China Sea area (Tham, 1953 ; Wickstead, 1961). The present survey is of rather different scope from these,

but since the nets used were either the same, or one from which a relationship can be estimated directly, the results will be comparable from various aspects.

THE STATIONS

For this section of the plankton survey three " Permanent Stations " were chosen ; these will be referred to as P.S.1, P.S.2 and P.S.3 (Fig. 2).

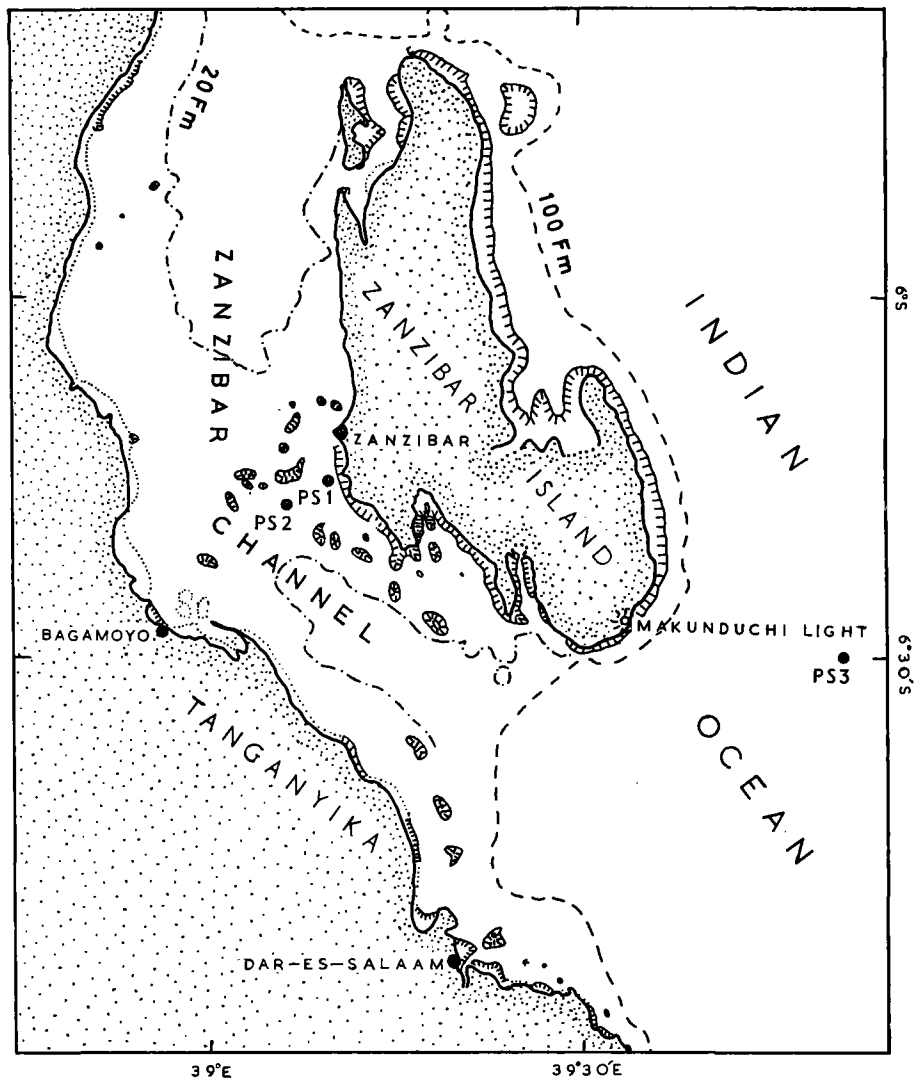


Fig. 2—Map of Zanzibar to show the locality of the three plankton stations.

*P.S.*1

Position 6° 13′ 30″ S, 39° 11′ 30″ E. This is between 400–700 yards off the western coast of Zanzibar, in Zanzibar Channel, in a mean depth of 12 m (see note about tides). The bottom is of fairly clean sand with some

mud patches, these latter being more extensive closer in-shore ; the bottom deposits are rich in Foraminifera, with a typical shallow water assemblage, including *Elphidium*. *Tretomphalus* was abundant and small globigerinacids fairly common. There were isolated patches of coral, with more continuous growths off-shore and surrounding the islands and sand-banks. Some *Sargassum* weed was present and there were fairly extensive areas of an " *Enhalus* " type of plant between and just below tide levels.

*P.S.*2

Position 6° 17′ S., 39° 7′ E. This is also off the western coast of Zanzibar, but farther out in the Zanzibar Channel ; mean depth is 40 m. The bottom appeared to be of fairly clean sand, with some mud. Bottom deposits are again rich in Foraminifera constituting a shallow water assemblage characterized by in-shore forms including *Ammonia beccarii*, peneroplids, alveolinids, miliolacids and *Elphidium* (*striatopunctatum* ?). Some of the larger specimens are abraded (operculinids and alveolinids). Pelagic species are rare, but include *Tretomphalus*. Dredges and trawls brought up amounts of seaweed and small sponges.

*P.S.*3

Position 6° 30′ S., 39° 48′ E. This is a little under 20 miles just south of east from the southern tip of Zanzibar, situated in clear oceanic water having a total depth of 750 m. The bottom deposit is a grey mud, rich in Foraminifera. These were of a deep-water assemblage with no obvious in-shore forms except possibly a few miliolacids. The benthonic agglutinated forms are typical deep-water species. Radiolaria were rarely present ; adult pelagic Foraminifera were abundant.

Note.—The Zanzibar tidal range is not very extensive. During the plankton survey the average high tide was about 10′–11′, with minimum 7·6′, maximum 14·4′. Average low tide was about 2′–3′, with minimum −0·6′, maximum 5·8′. These heights refer to the datum of Admiralty Chart No. 3211.

CLIMATIC ASPECTS

The three stations are directly affected by the monsoon conditions of the Indian Ocean, the North-east monsoon from about December to March, and the South-east monsoon from about June to October. It must be noted that the duration of either monsoon is not constant from year to year.

There are two main periods of rainfall, the so-called long rains in March–April–May, and the so-called short rains in October–November. Newell (1957) says " Heavy rains occur all along the coast (*of East Africa—Auth.*) between March and May, and light rains in October, so that the outflow from the five principal rivers (the Ruvuma, Rufiji, Pangani, Sabaki and Tana) is at a maximum from April to June. However, it has been found that the brackish outflow from these rivers is kept close inshore by the prevailing natural forces, and only rarely are isolated patches of water of low salinity found out to sea ".

Fig. 3 shows the monthly total rainfall, in inches, and the mean maximum air temperature for a twelve-month period during which the plankton survey was being made.

A point which might affect P.S.1 and P.S.2 : as a general statement it can be said that Zanzibar is mainly of limestone with no surface drainage system, but with a well-defined water table. At low tides, particularly on the eastern coast between the shore and the barrier reef, numerous tiny springs can be found coming up through the sand marking the entry of fresh water into the sea. This local dilution might affect the plankton at P.S.1 and possibly at P.S.2.

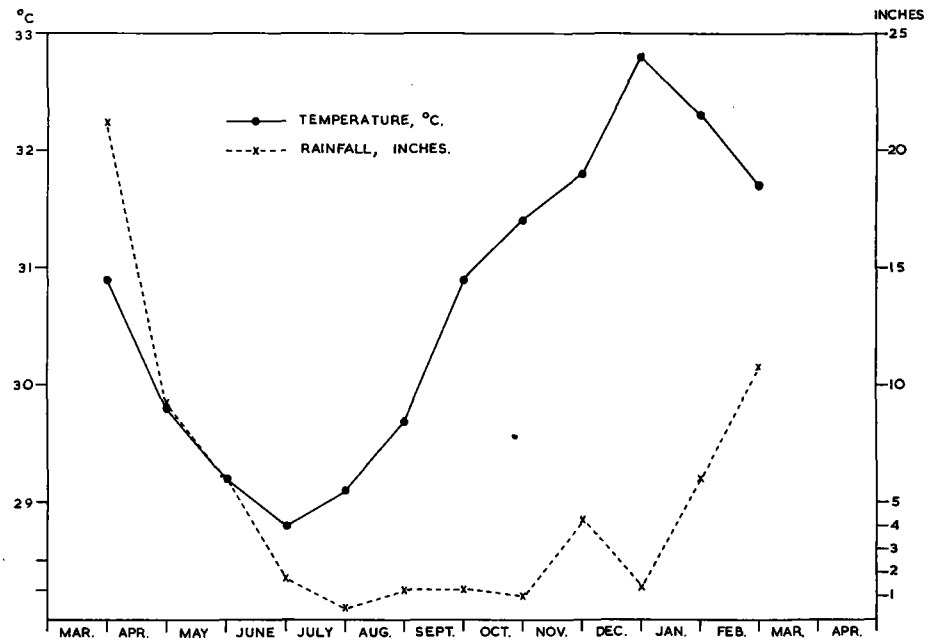


Fig. 3—Monthly total rainfall, in inches, and mean maximum air temperature in the Zanzibar area for twelve months of the plankton survey.

Full details of the general weather conditions of the area can be seen in Williams (1956), Newell (1957) and the Africa Pilot (1954).

HYDROGRAPHY

The only systematic work that has been done with particular reference to the coasts of Kenya and Tanganyika is that carried out by the East African Marine Fisheries Research Organization (Newell, 1957, 1959).

*P.S.*1 (Fig. 4)

The data are insufficient to show if there is a regular cycle in the salinity, but the temperatures suggest regularity, with the lowest at the end of the South-east monsoon and the highest at the end of the North-east monsoon. The annual range of *ca.* 4·5° C is not very great for a station so close to the shore. Secchi disc readings do not show any marked periodicity. It must be

noted that some of these readings, where the disc was actually resting on the bottom, are either extrapolations (when the disc was almost invisible), or taken in slightly deeper water (when the disc was plainly visible on the bottom).

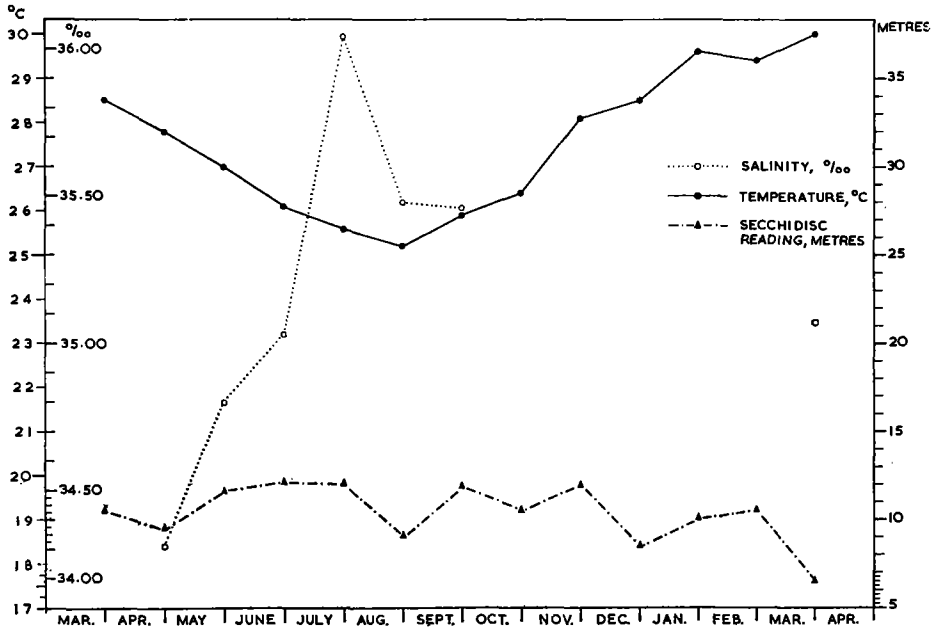


Fig. 4—Salinity, temperature and Secchi disc readings at P.S.1.

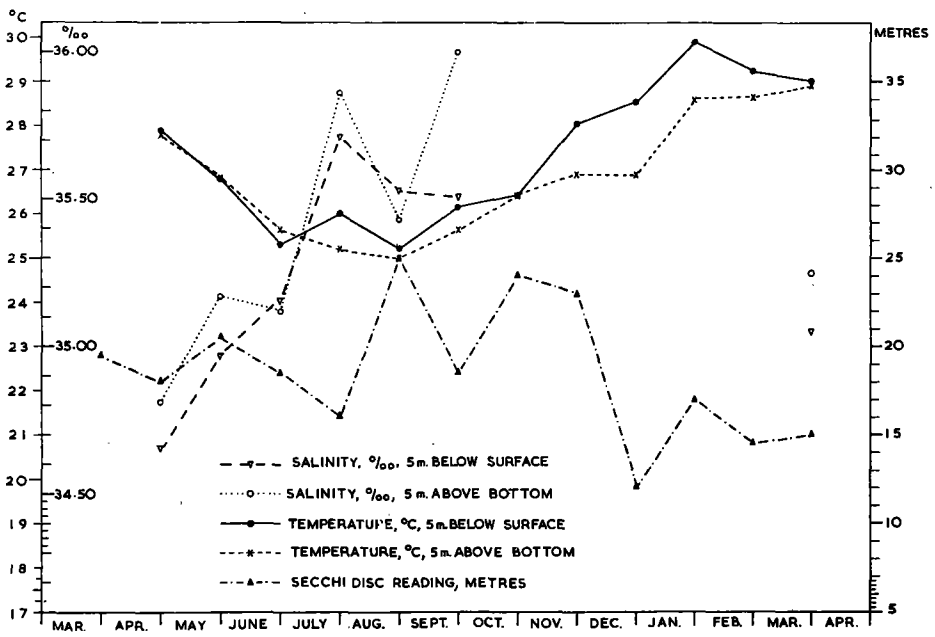


Fig. 5—Salinity, temperature and Secchi disc readings at P.S.2.

The absence of any river system on the island, or any close mainland river system, makes for conditions more than usually stable for stations so close in-shore.

*P.S.*2 (Fig. 5)

Regarding salinity, the same remarks apply here as to P.S.1.

The general pattern of temperature variations is similar to that at P.S.1. The difference between the temperature at 5 m below the surface and 5 m above the bottom is much more pronounced during the North-east monsoon ; no indications of a thermocline were found.

There appears to be no definite cycle of Secchi disc readings, but the general transparency is fairly high ; greater than Singapore Strait or the English Channel off Plymouth for instance.

Zanzibar Channel appears to be open to a constant through flow of water from south to north (the coastal currents of this part of East Africa move in a northerly direction throughout the year). However, it is clear from the plankton that the inflow of oceanic water into the channel is very limited. In samples taken from P.S.1 at the end of May some species of *Lucicutia* and *Pleuromamma* were recorded. This was the only time that these typical Slope/deep-water copepods were recorded here. Similarly, such indicators of oceanic water as *Sapphirina* spp. and the long eye-stalked species of *Lucifer* were taken but rarely in the Channel.

*P.S.*3 (Fig. 6)

The same remarks concerning salinity apply here as to P.S.1.

A thermocline was always present here, and there was never any overlap between the temperatures at 30 m and at 150 m. The general pattern of temperatures at the two depths was similar during the South-east monsoon, but not so during the North-east. In neither case was it similar to P.S.1 or P.S.2. On three occasions the temperature at 200 m was taken ; these were 14·63° C on 30 xii 60, 15·20° C on 10 i 61 and 14·98° C on 22 ii 61.

The Secchi disc readings showed two peaks, each at an interim monsoon period.

For the plankton analyses there is no doubt that P.S.3 can be regarded as an oceanic station beyond the influence of coastal variations.

APPARATUS AND METHODS OF SAMPLING

Two boats were used, a 28-foot launch, the " Chermin ", and a 119-foot converted trawler, the " Manihine ". Fuller descriptions and pictures of these can be seen in another publication (Wickstead, 1961). The " Chermin " was used for some series of samples at P.S.1 and P.S.2 ; the " Manihine " was used for some of the series of samples at P.S.1 and P.S.2 and for all those taken at P.S.3.

For the quantitative work vertical samples were taken using the two nets clamped side by side (Fig. 1) ; thus the two nets sampled simultaneously the same body of water, and the varying results from the two nets could be compared directly.

The two types of net used were the International Coarse Silk Net (hereafter called the I.C.S.N.) and the Currie & Foxton quantitative net (hereafter called the CF 70), this latter with some qualifications. A full description of the I.C.S.N. can be seen in Russell & Colman (1931). Briefly, it has an aperture of 50 cm, length of 2 m, mesh of 58 per inch (23 per cm), aperture size of 0·288 mm and the open area of mesh is 47 per cent. A full description of the CF 70 has been given by Currie & Foxton (1957), but for this survey it was not possible to have the canvas fore-section and the brass drum with its contained flow-meter and depth gauge. However, this was not considered serious since it was not used as a closing net for mid-water samples, and the maximum amount of warp used for quantitative work was 200 m. Thus the results should be comparable with those from a complete CF 70 net.

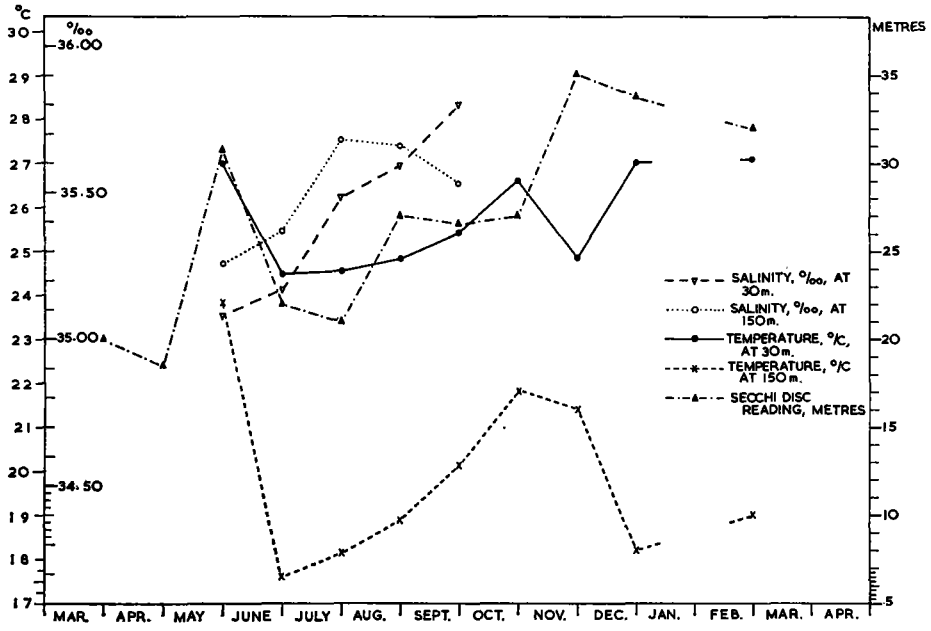


Fig. 6—Salinity, temperature and Secchi disc readings at P.S.3.

Briefly, as used, the CF 70 had an aperture of 70 cm and consisted of a 6-inch wide band of canvas, a 1 m cylindrical length of nylon mesh and a 1·5 m conical length of the same nylon mesh. Mesh throughout was 74 per inch (29 per cm), aperture size of 0·205 mm and the open area of mesh is 34 per cent.

Both nets were rigged and used as shown in Fig. 1 with a 70 lb (32 kg) weight. The catch was put through a concentrator (Wickstead, 1961).

It is important to note that at P.S.1 and P.S.2 all vertical samples started from the very bottom of the water column. At neither of these two stations was a thermocline found to be present. At P.S.3 a thermocline was always present, usually well defined, but, particularly from the end of December to February, sometimes in a series of small steps ; this was a major consideration when deciding upon a scheme of sampling. It was decided to take a double

series of vertical samples, one from above the thermocline to the surface, the other from below to the surface. For the former there was, from the surface, 50 m of warp out ; for the latter, 200 m. It was ensured at every sample that one sample was from above and the other from below the thermocline. The depth of the thermocline itself was variable, but it was usually at *ca.* 80 m (a more detailed account of this, and of the general hydrography, will be published at a later date by Mr B. E. Bell, hydrographer to the East African Marine Fisheries Research Organization). Owing to varying undercurrents, wind-induced drift, etc., the warp was usually at some angle from the vertical. Checks on the vertical depth of the net were made from time to time with Kelvin sounding tubes ; with 200 m of warp out it was usually *ca.* 175 m ; with 50 m out it was usually *ca.* 44 m. Calculations of plankton concentration were based on the amount of warp out, not on the vertical depth of the nets. It is considered that deviations from the true vertical sampling at P.S.3 were not significant for the purposes of this survey.

Rate of hauling has an important bearing on the efficiency of plankton nets. Every effort was made to ensure that the nets were hauled through the water at a consistent speed at all three stations and from both boats. The mean rate of hauling was 0·86 m/sec.

The object was to estimate the total plankton in terms of numbers, volume and dry weight per m^3. The volumes were measured from the preserved samples after counting ; the dry weights were measured from duplicates of the samples taken for numerical estimations.

At each station, on each sampling day, two consecutive samples were taken, mixed, and put aside for numerical analysis. Immediately afterwards another two consecutive samples were taken and put aside for dry weight measurements.

Since night plankton can vary so much from day plankton, particularly in tropical areas, it was decided to take samples at about midnight in addition to those taken at about midday.

The length of the survey was fixed for thirteen months. All the samples would be grouped and analysed as monthly means, from mid-March/mid-April 1960 to mid-March/mid-April 1961. In practice continuous sampling throughout the thirteen months was not completely possible, due mostly to engine troubles. Thus, as shown on the graphs, at P.S.1 all daylight samples are present, but the thirteenth night sample is missing. Similarly with P.S.2. At P.S.3 the eleventh and thirteenth daylight samples are missing and the first, eleventh and thirteenth night samples.

Water samples were taken with an Ekman reversing bottle ; temperature readings with the attached, paired, protected thermometers.

Thermocline and continuous temperature recordings were taken with a Spilhaus bathythermograph. This instrument was, unfortunately, out of action from the middle of August until the middle of December.

A measure of the water transparency was obtained with a 50 cm Secchi disc.

APPARATUS AND METHODS OF ANALYSIS

The plankton was analysed in three ways, numerically, volume and dry weight. The method used for the numerical estimations was the same as

used previously (Wickstead, 1961). For this survey a 1/10 sub-sample was used for all the animal groups excepting the cyclopoid and calanoid copepods from the CF 70 samples. Here a " 1/100 " sub-sample was taken, the resultant counts being multiplied by a factor to bring them to a 1/10 sub-sample. While it was straightforward to take accurately a 1/10 sub-sample (500 cm^3 from 5,000 cm^3), this was not so with a 1/100 sub-sample (50 cm^3), since small errors would result in significant differences in the final figure per m^3. A scoop was made approximating to 50 cm^3 and the results of 200 comparative 1/10 and " 1/100 " sub-samples analysed statistically. It was found that to bring the copepod " 1/100 " sub-samples up to a 1/10 sub-sample they had to be multiplied by a factor of 8·17.

The total numbers of the animal groups were found by multiplying the 1/10 sub-samples by 10. These totals were then divided by the number of cubic metres through which the appropriate net was hauled ; this gave the numbers per m^3.

These calculations were based on a filtration ratio of 1 : 1. This is not unreasonable in view of the short distance through which the nets were hauled and the lack of clogging due to the short period of hauling.

Measurements of volume, by displacement, were made on the preserved samples after they had been counted, using the container shown in Fig. 7.

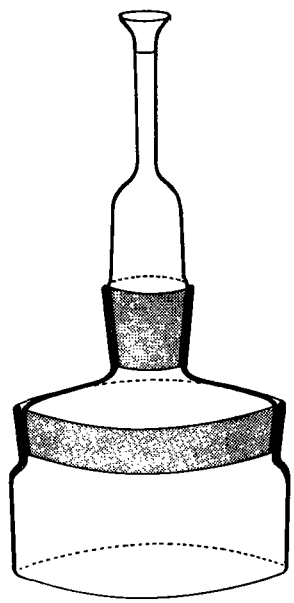


Fig. 7—Container used for measuring the plankton displacement volumes ; for explanation see text.

This container held a known volume of water, measured accurately at the mark on the narrow stem (actual volume 59·00 cm^3). Surplus liquid was removed from the sample by using a vacuum pump, filtering through 600 m.p.i. nylon. The plankton was then " peeled " off the nylon and put into the bottom part of the container via the large ground glass joint. The

container was assembled, keeping to the same alignment each time, and water run in from a burette up to the mark. The displacement volume was found by difference. Large solitary salps which were occasionally present were removed before the volume measurements. The resulting plankton volume was divided by the number of cubic metres filtered by the nets, the resulting figure being the displacement volume/m^3.

This container was convenient, quick and accurate for plankton volumes up to 10 cm^3. The few total volumes which exceeded this had to be divided into two or more parts.

For the dry weight samples the first stage of preparation was on the boat. When the two consecutive plankton samples were filtered through the concentrators the plankton was washed with distilled water to remove surplus sea water. The resulting " pat " of plankton was put directly into a wide-necked weighing bottle, and the ground glass lid put in place. In the prevailing climatic conditions decomposition of the plankton would begin very rapidly indeed. Therefore, in the " Chermin " the weighing bottles, plus plankton, were put into a wide-necked vacuum flask containing ice ; in the " Manihine " they were put into a refrigerator, the temperature being held at a little above freezing point. Back at the laboratory the plankton and weighing bottles, lids removed but present, were dried to a constant weight at a constant temperature of 50° C. The plankton and weighing bottles, with lids securely replaced, were allowed to cool to room temperature. The use of a desiccator to dry plankton samples is not very effective in such high temperatures and humidities. The weighing bottles were then weighed as rapidly as possible. The bottles were cleaned out and then re-weighed. The weight of the plankton was found by difference. As with the volumes, the occasional large salp was removed before measurement. The resulting total plankton dry weight was divided by the number of cubic metres through which the nets were hauled to give the dry weight of plankton per m^3.

Salinities were determined by Mr B. E. Bell by the chloride titration method, using Knudsen burettes and pipettes. Standard sea water was provided by the Association d'Océanographie Physique, Charlottenlund, Denmark. Unfortunately, due to accidents, no burettes, and hence no salinities, were available for half the period of the survey. Water samples were stored with a view to analysis at a later date, but the results were clearly highly inaccurate. Fortunately some data in Newell (1959) will be relevant to P.S.3.

PLANKTON ESTIMATES

The graphs representing these show the *total* plankton in terms of numbers, volume and dry weight per m^3 by day and by night for each of the two types of net used and for each of the three stations. Each graph has been drawn to the same scale, therefore each can be compared directly with another.

*P.S.*1 (Figs. 8A, 8B, 8C & 8D)

All three measures of the plankton follow a similar pattern for the daylight samples, rather less so with the night samples.

There is some difference between the numbers taken in the I.C.S.N. and CF 70 catches, due mainly to the different stages and numbers of some of the different groups of animals caught ; e.g. when significant numbers of copepod nauplii were taken with the CF 70 relatively few were taken with the I.C.S.N. Also considerably more copepods were taken with the finer mesh net.

Greater differences are apparent with the volumes and dry weights due, mainly, to the very many fewer, but larger, animals involved. As was particularly noticeable at this station, less so at P.S.2 and not at all at P.S.3, many relatively large larval and adult forms of Crustacea were present in the plankton at night which were virtually absent during the day. As one example, the addition of about fifty *Leptochaela* larvae per m^3 in the plankton at night would affect the numbers but little, the volume more so and the dry weight the most. Conversely, other types of animals which are present in greater numbers during the day would similarly affect the results. Throughout the year these differences were balanced out (see p. 589).

In general it can be said that the total numbers reflect largely the numbers of copepods present since these formed, numerically, the greatest part of the plankton (one notable exception was Jan./Feb. when many of the cladoceran *Penilia avirostris* were present) ; the volume, the numbers of siphonophores, salps and medusae present, and the dry weight, the numbers of decapod larvae and copepods by day, and decapod larvae, gammarid amphipods, mysids and ostracods by night.

A factor which affected the CF 70 samples in varying degrees was the phytoplankton. While the amount taken with the 58 m.p.i. net could be usually ignored, the amount taken with the 74 m.p.i. net, although of just a little finer mesh, was, at times, considerable. From the July/August period up to the November/December period the phytoplankton, according to the net samples, was present in very small amounts or virtually absent. For the remainder of the year it was present in much greater quantities, and at times was very thick. It consisted mainly of *Bacillaria* and small *Rhizosolenia* spp., and at times was sufficiently common to give the water, throughout the visible depth, a distinct silky sheen. A settled, preserved, zooplankton sample taken in such conditions would be overlain by a deposit of diatom frustules. This did not affect the numerical analysis of course, but did contribute a significant amount to the volume and dry weight. Dinoflagellates excepted, the larger phytoplankton can be considered absent from P.S.3 throughout the year.

*P.S.*2 (Figs. 9A, 9B, 9C & 9D)

The remarks which applied to numbers, volumes and dry weights at P.S.1 are generally applicable here. There were fewer larval types present and the plankton was rather more constant than at P.S.1, However, there is still the well-marked peak during February/March.

*P.S.*3 (Figs. 10A, 10B, 10C & 10D ; 11A, 11B, 11C & 11D ; 12A, 12B, 12C & 12D)

The plankton here clearly follows a different pattern from both P.S.1 and P.S.2. The differences between the catches of the two different types of nets are not so marked (see below) due to the generally larger sizes of the plankton animals.

There was a marked increase in the night plankton due to the upward migration of various animals ; no larval types or animals entered the plankton from the sea-bed as was the case with the other two stations.

The night samples show clearly that, in the topmost 200 m at least, the plankton is richer in the South-east monsoon than in the North-east monsoon. The night samples will give a better indication of this since the day plankton will vary according to the water transparency (Wickstead, 1963). There is a much greater variation between the day and night volumes and dry weights than in the numbers. This is due to the upward migration of larger planktonic forms such as euphasiid larvae and adults, large copepods such as *Pleuromamma xiphias, Scottocalanus, Gaetanus*, etc. Given below are the mean figures per m^3 for the period of the survey, for numbers, volume and dry weight, for day and night samples, according to the CF 70, at P.S.1, 2 and 3.

	P.S.1		P.S.2		P.S.3 (50 m ↑)		P.S.3 (200 m ↑)	
	Day	Night	Day	Night	Day	Night	Day	Night
Numbers	2,770	3,194	2,439	2,443	1,096	1,482	693	1,170
Volume (cm^3)	0·206	0·258	0·206	0·203	0·106	0·167	0·072	0·133
Dry weight (mg)	49·50	47·17	47·21	47·28	18·26	38·34	12·58	23·19

This shows clearly that, when taken over the whole year, the relative increase of the night plankton over the day plankton is much greater than at the coastal stations.

DISCUSSION

All the figures per m^3 quoted are representative of a uniform distribution of the plankton throughout the water column ; this uniform distribution would be exceptional. Thus, from the Singapore survey (Wickstead, 1961), it is most probable that, at least at P.S.2, the station most comparable with Singapore, the greater part of the plankton, numerically, would be towards the surface. An overall concentration of, say, 2,000/m^3 will probably indicate a concentration of 6–8,000/m^3 in the upper layers. This uneven distribution in depth must be borne in mind continually when making any relative assessment of the plankton.

From these results of the three methods of assessing the plankton it is clearly impossible to establish any constant relationship between any two methods. Of the three, the volumes and dry weights have the most similar trends. For P.S.1 and P.S.2 each method has its disadvantages, and no one method appears markedly superior to another. If it is possible to use a single method only, this must be chosen with due regard to the purpose of the investigation.

With oceanic stations, as shown by P.S.3, volumes and dry weights agree fairly reasonably, both forming rather different graphs from the numbers. From these results it would seem that, for any survey of an oceanic area with a large number of stations, the simplest and most revealing estimations of the *total* plankton would be dry weight estimations based on night samples. However, all three would undoubtedly be better.

Comparing the yearly mean of each of the three stations (see above) it will be seen that, superficially, P.S.1 and P.S.2 are much the same, both appearing richer than P.S.3. Numerically speaking this is an undoubted fact. However, it has been pointed out above that the general size of the plankton at P.S.3 is larger than at the other two stations. Comparing then the dry weights, the night plankton in the top 50 m at P.S.3 appears to be a little over 75 per cent of that at the other two stations. Considering the heavy phytoplankton populations at times present at P.S.1 and P.S.2, plus the greater amounts of detritus and suspended matter, I consider that the amount of zooplankton in the topmost 50 m during darkness at P.S.3 is very little, if at all, less than that at the other two stations. In my opinion, contrary to generally accepted ideas (e.g. Sverdrup, Johnson & Fleming, 1942, pp. 783–4), for this area it is not true to say that the sea becomes increasingly barren the farther off-shore one goes ; it may be a little less rich, but by only a small amount. From my surveys along this part of the East African coast, this statement appears valid up to *ca.* 40–50 miles from the coast. When considering this statement it must be remembered how narrow the Continental Shelf is here ; at this distance off-shore the depth would be *ca.* 1,000–1,500 fathoms.

Qualitatively, P.S.3 is quite distinct from the other two ; there appears to be no overlapping. As can be expected there is more similarity between P.S.1 and P.S.2, but even so, the plankton communities are different in both types of animals and differing proportions of animals present. An unlabelled sample from one of these three stations could be placed in its correct station with little difficulty.

Valid comparisons with total plankton data from other areas are difficult owing to the different methods and apparatus used. Fig. 13 does, however, give numerical estimations which are directly comparable in that the same net and methods of sampling were used. Even so, care must be taken in considering which areas are relatively richer than others, as not all the stations are really comparable, the plankton communities being therefore different. I have noted before (Wickstead, 1961, p. 184) that a single *Bathycalanus* copepod per m^3 is the equivalent in biomass of *ca.* 725 other calanoid copepods per m^3 of the type found at the Singapore station. In Fig. 13 three stations

which can be reasonably directly and validly compared numerically are P.S.2, Great Barrier Reef (G.B.R.) and Singapore ; a closely similar plankton population was present at each. Thus, the volumes and dry weights from the G.B.R. and Singapore would no doubt have a similar relationship with the numbers as at P.S.2.

From Fig. 13 P.S.2 is richer than the G.B.R., which in turn is richer than Singapore. These figures relate to standing crops only. The higher temperatures of the Singapore waters would probably mean a rather more rapid rate of turnover, which would make it richer relative to the other two.

The proximity of deep oceanic water might well influence the richness of coastal plankton. Thus, oceanic water was very much removed from the Singapore station, close to P.S.2 and rather more distant from the G.B.R. station. This last station also had small reefs and the barrier reef interposed.

THE RELATIVE CATCHING POWERS OF THE I.C.S.N. AND THE CF 70 NET

All the information obtained from this survey is expressed graphically in Figs. 14, 15 and 16. As was to be expected the most variation about the means was at P.S.1, the least at P.S.3.

Numbers

With the exception of P.S.2 daylight, all the yearly mean percentage increases were greater during the night samples than during the day. It is clear that the 74 m.p.i. net, although but a little finer mesh than the 58 m.p.i. net, will catch considerably more animals ; *ca.* 60 per cent at oceanic stations, rather more at in-shore stations.

From the analysis of the animal groups of plankton samples from East Africa, Singapore and other tropical areas the following observations can be made on sampling tropical plankton.

Coastal and shallow water

For general plankton sampling a mesh size of *ca.* 150–160 μ would be the best. This would have the disadvantage, at times, of taking large amounts of phytoplankton. Most of the developmental stages of most of the copepod species would pass through this mesh in addition to some small animals such as some chaetognaths, appendicularians and *Amphioxus* larvae. For the collection of life-history and developmental material a mesh size of *ca.* 70–75 μ will be necessary. Stramin nets, or other nets having a large mesh size, would be of little use other than for the collection of specific types of animals. If it is possible to ignore the loss of many of the smaller organisms, including some adult forms, using a 58 m.p.i. net does have the advantage of not taking large quantities of phytoplankton, and there is the important point that it is of international size and mesh.

Oceanic water

For general plankton sampling a mesh size of 200 μ is about the best ; even so this mesh size would take inadequate samples of certain adult copepod

species. As before, any adequate sampling for life-history and developmental material would require a mesh size of *ca.* 70–75 μ. Most of the forms migrating up towards the surface at night are robust animals ; a coarse net with apertures of *ca.* 500 μ is very useful here. Sampling for such animals would be best done with such a net. This mesh would exclude a large part of the plankton which lives always at the surface. Forms such as the deep-water sergestids and carideans, medusae such as *Atolla,* and other such types of animals are best taken with a still larger mesh.

Volume and dry weight

The yearly mean catches of the two nets generally conformed quite closely. Some variability in the in-shore samples will be due to phytoplankton, detritus, etc. For all practical purposes oceanic samples taken with these two nets may be considered directly comparable.

ACKNOWLEDGMENTS

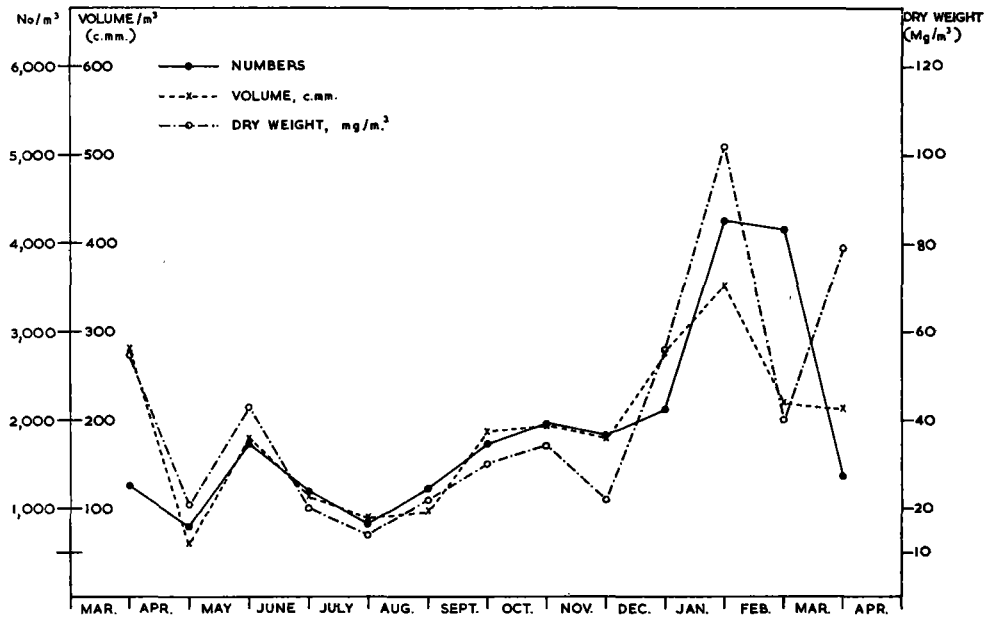
I would like to thank Mr D. N. F. Hall, Director of the East African Marine Fisheries Research Organization, for the use of the facilities of his Organization while in Zanzibar, and to Dr F. S. Russell, F.R.S., Director of the Marine Biological Association Laboratory at Plymouth, for permission to work on the East African material in the Plymouth Laboratory, and the use of the facilities of the Laboratory.

I would also like to thank Dr J. Murray of Bristol University, for his notes on the Foraminifera in the bottom deposits.

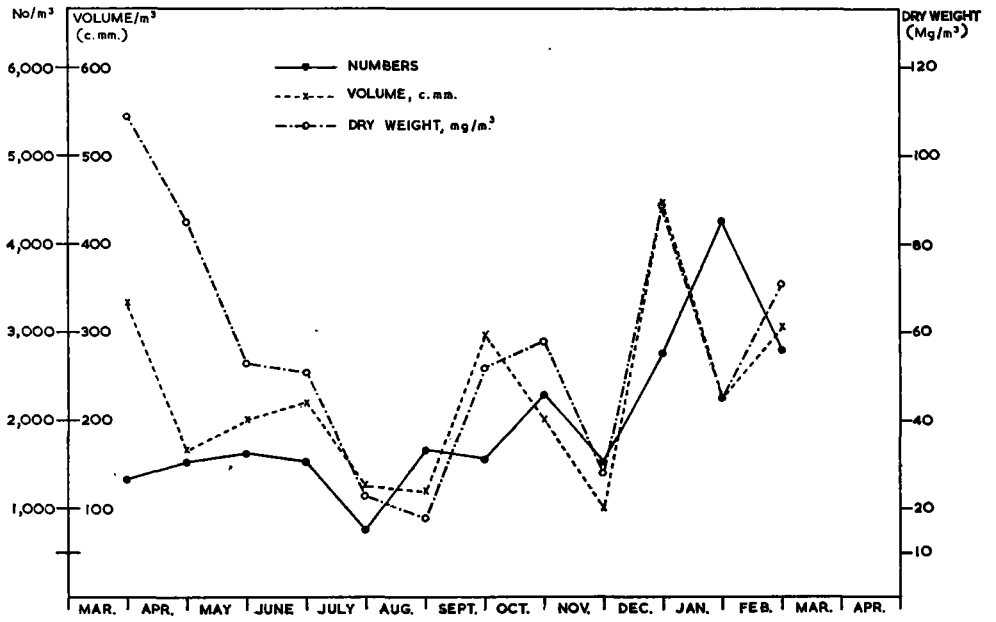
SUMMARY

Three stations were chosen in the Zanzibar area : P.S.1, depth 12 m, *ca.* $\frac{1}{4}$-mile off-shore ; P.S.2, depth 40 m, *ca.* 7 miles off-shore ; P.S.3, total depth 750 m, *ca.* 20 miles off-shore. Vertical plankton samples were taken by day and by night at each station throughout a period of thirteen months using both a 50 cm, 58 m.p.i. and a 70 cm, 74 m.p.i. net clamped together. At P.S.1 and P.S.2 sampling was from bottom to surface ; at P.S.3 it was from both 200 m and 50 m to the surface, i.e. from both below and above the thermocline to the surface. Total plankton was estimated as numbers, volume and dry weight per m^3. All the results are presented graphically, each station and each measure being compared with the other two. Some comparison of numbers is made with plankton from other areas. Some relevant hydrographic data are shown.

The mean monthly catches of the 74 m.p.i. net are shown as a percentage increase or decrease above or below the catch of the 58 m.p.i. net at each station. The mean variation throughout the period of the survey is shown and the conclusions are given.

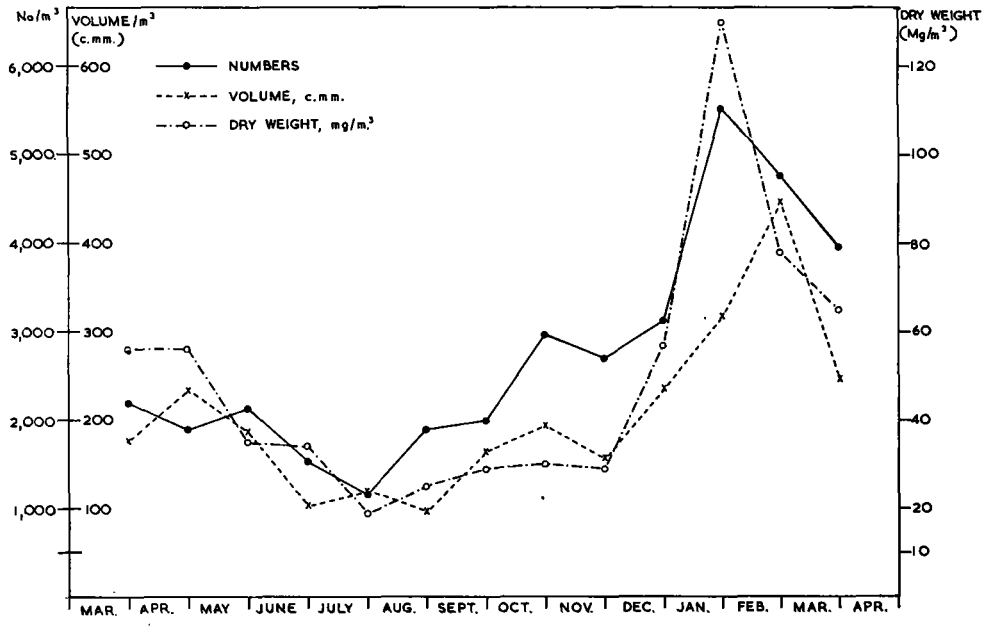


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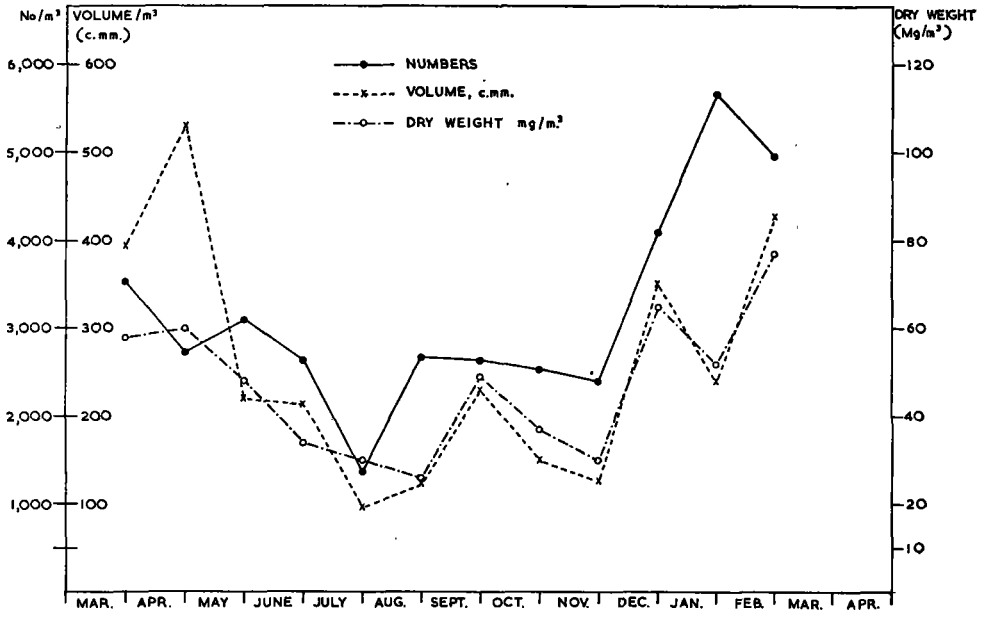


B

Fig. 8—Total plankton at P.S.1. 8A=taken with I.C.S.N. *ca.* midday; 8B=taken with I.C.S.N. *ca.* midnight.



C



D

8C=taken with CF 70 *ca.* midday ; 8D=taken with CF 70 *ca.* midnight.

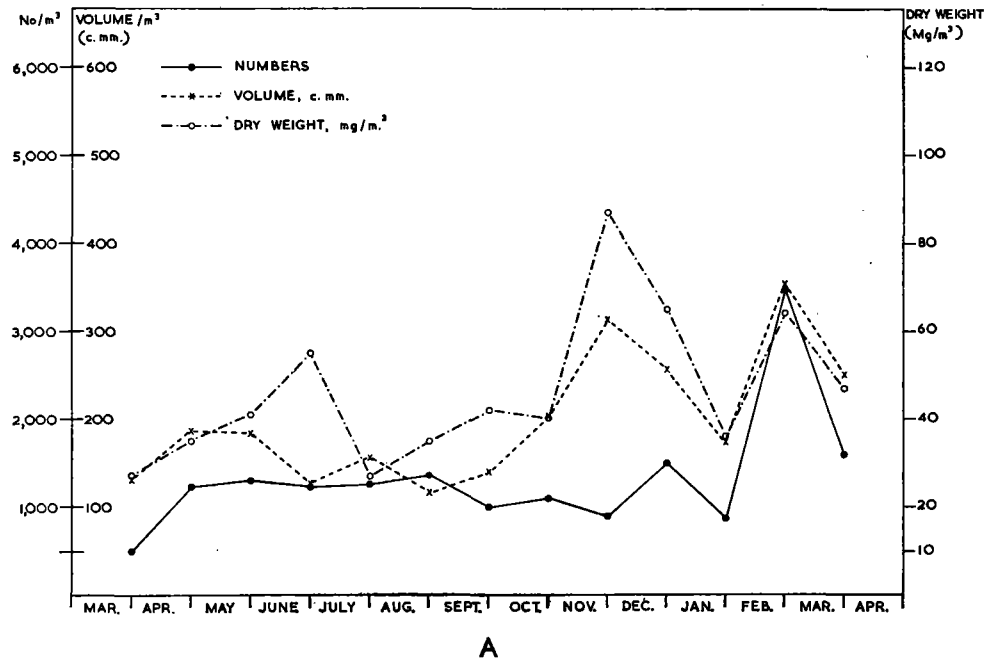
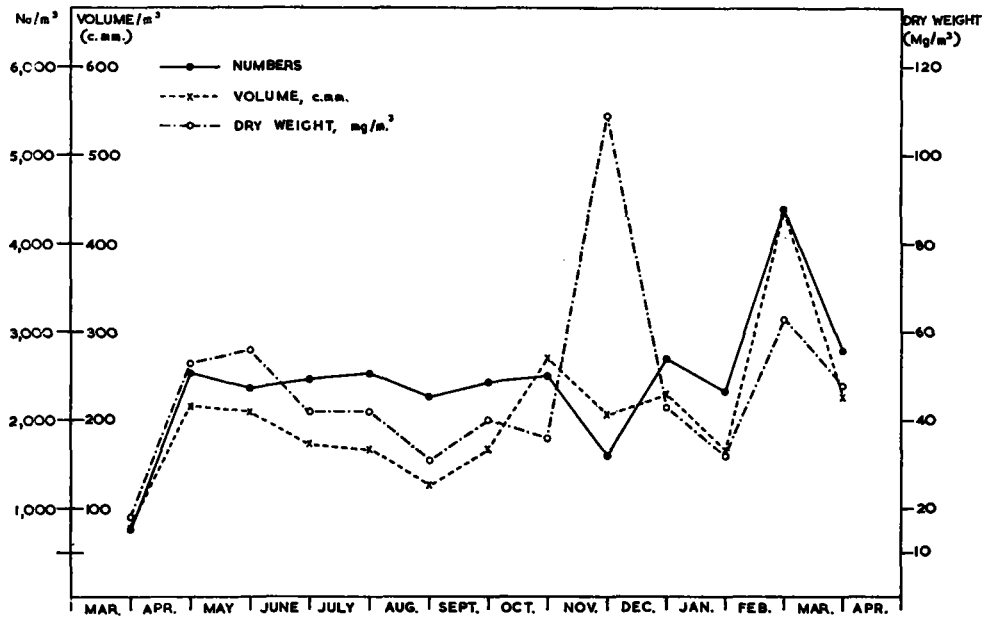
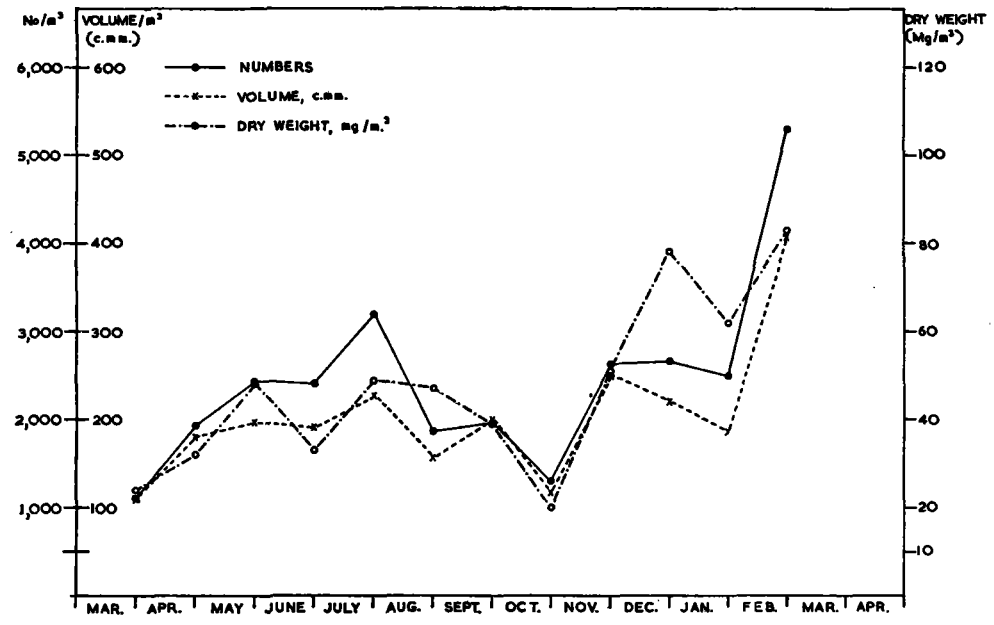


Fig. 9—Total plankton at P.S.2. 9A=taken with I.C.S.N. *ca.* midday; 9B=taken with I.C.S.N. *ca.* midnight.

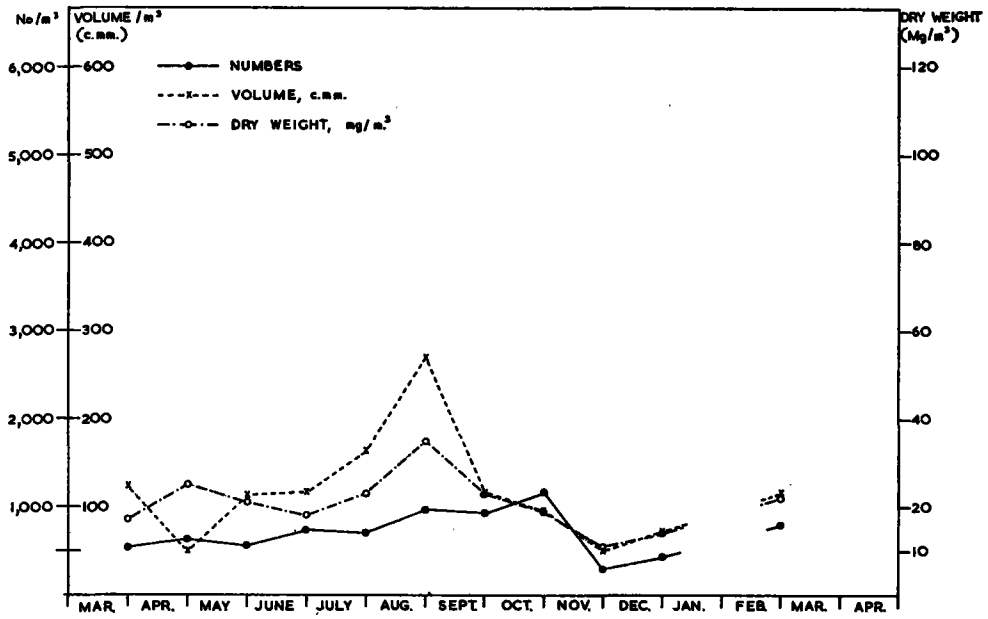


C

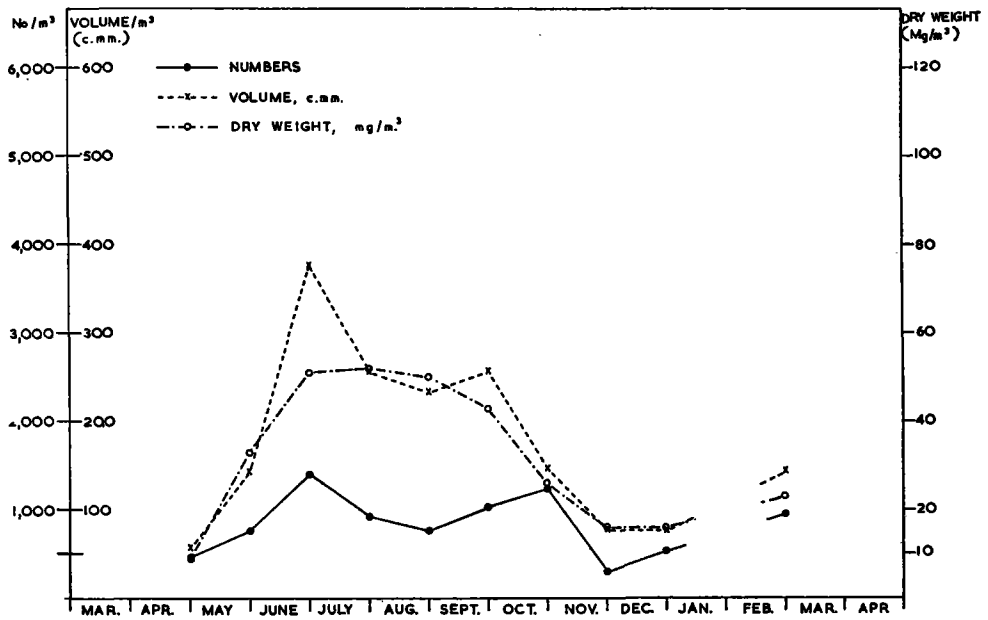


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9C=taken with CF 70 *ca.* midday ; 9D=taken with CF 60 *ca.* midnight.

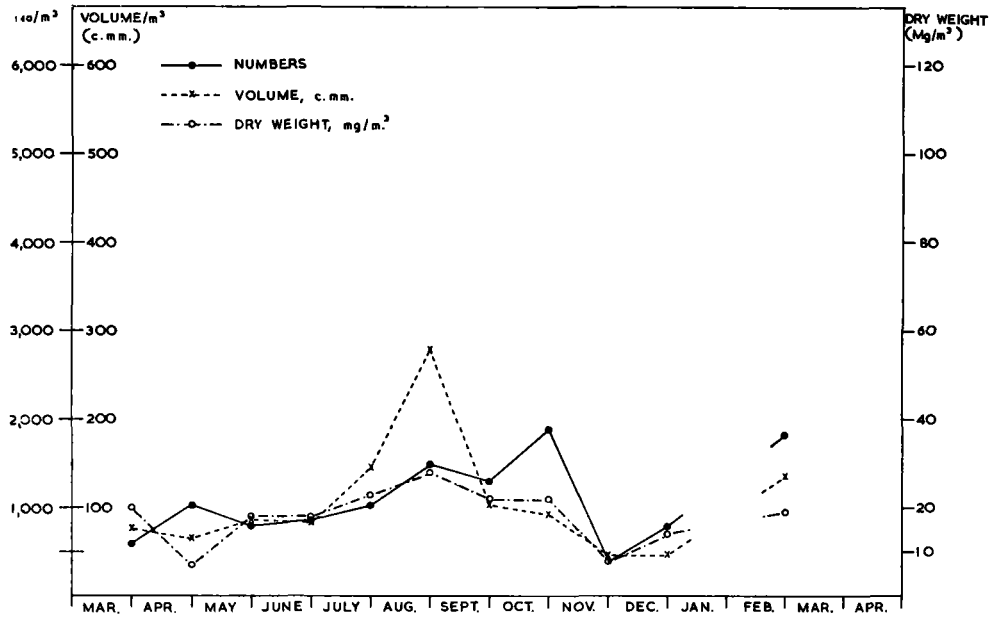


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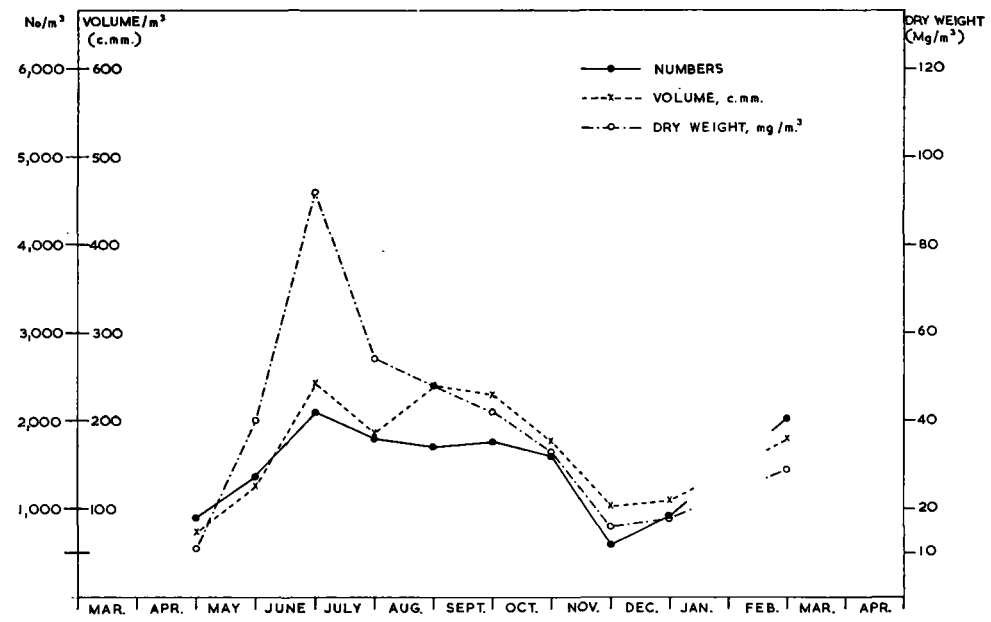


B

Fig. 10—Total plankton at P.S.3, samples taken from *ca.* 50 m to the surface, i.e. from above the thermocline to the surface. 10A=taken with I.C.S.N. *ca.* midday; 10B=taken with I.C.S.N. *ca.* midnight.

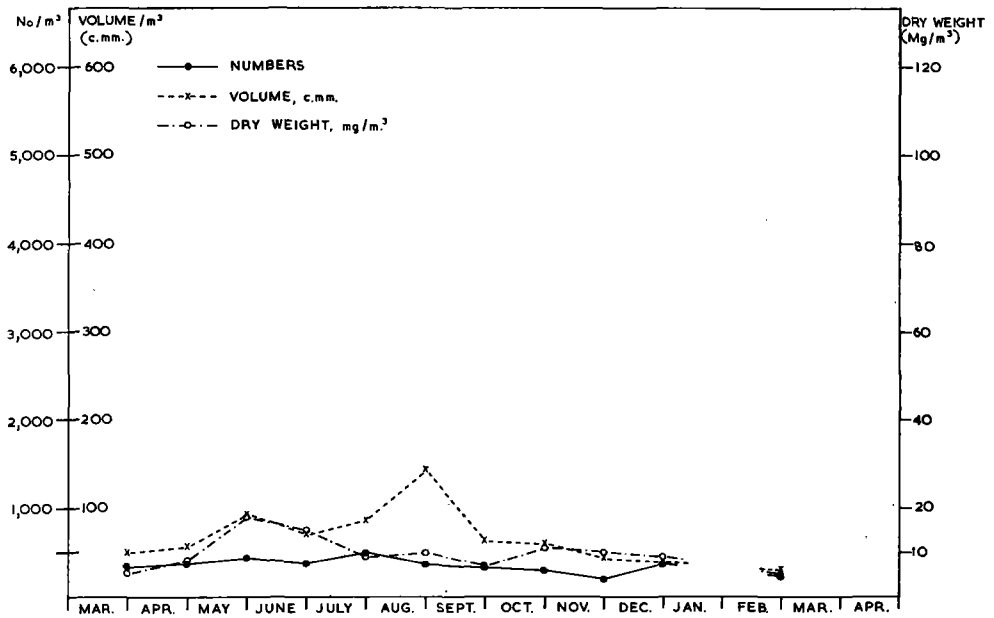


C



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10C = taken with CF 70 *ca.* midday ; 10D = taken with CF 70 *ca.* midnight.



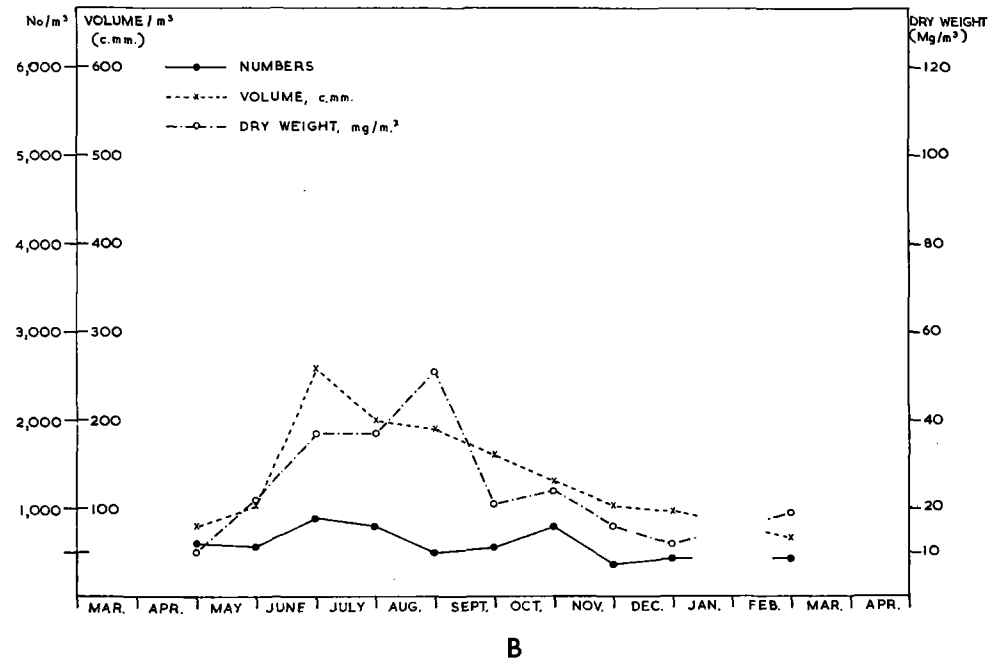
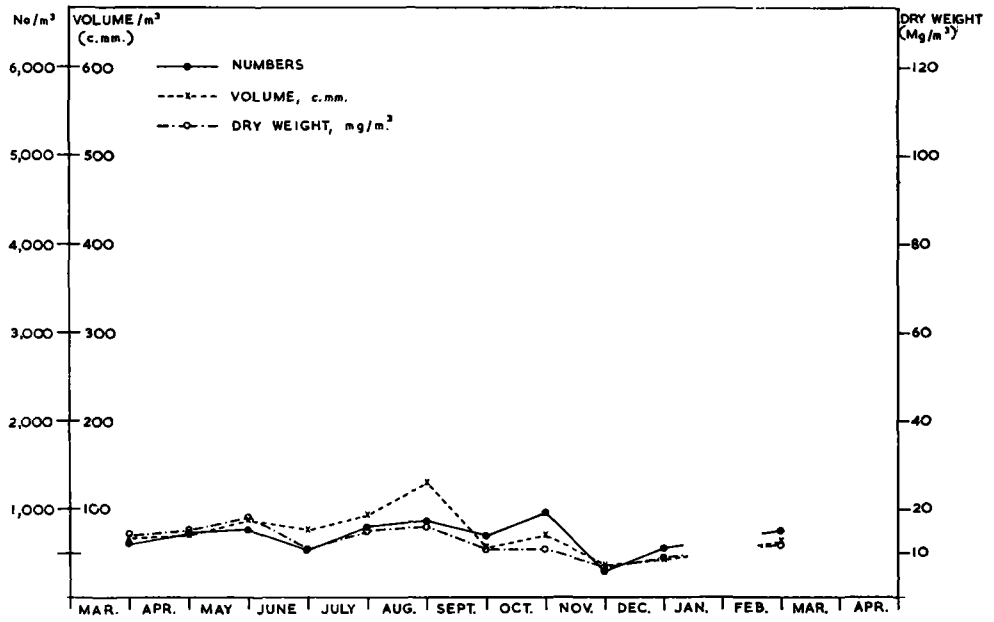
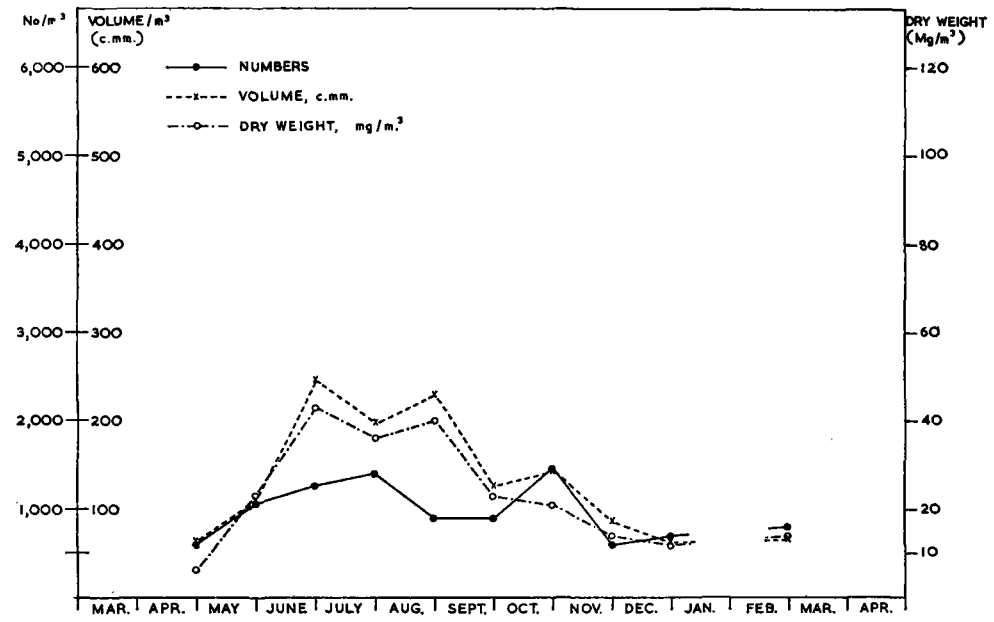


Fig. 11—Total plankton at P.S.3, samples taken from *ca.* 200 m to the surface, i.e. from below the thermocline to the surface. 11A=taken with I.C.S.N. *ca.* midday; 11B=taken with I.C.S.N. *ca.* midnight.

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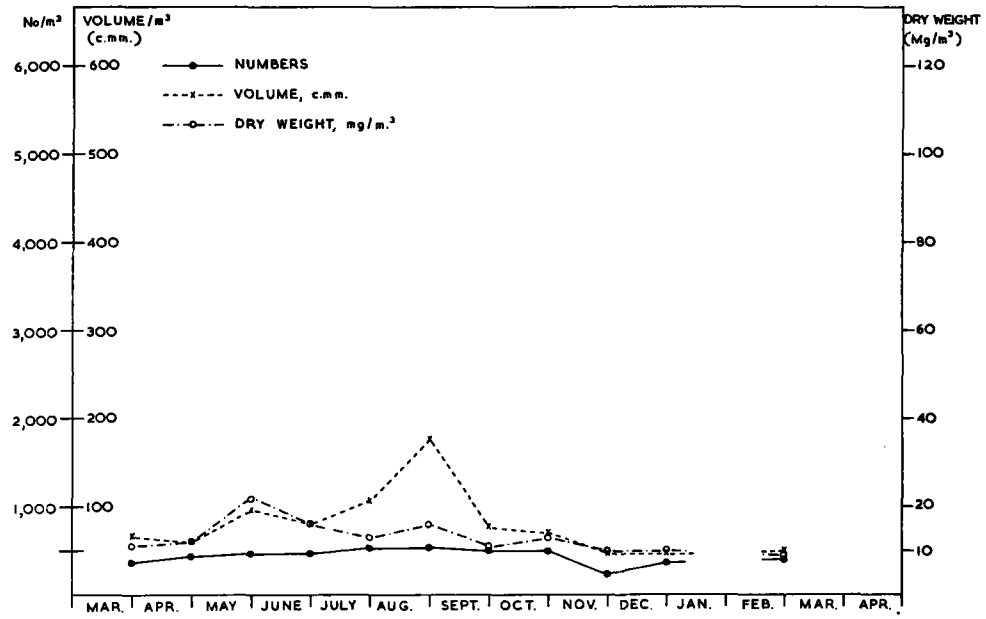


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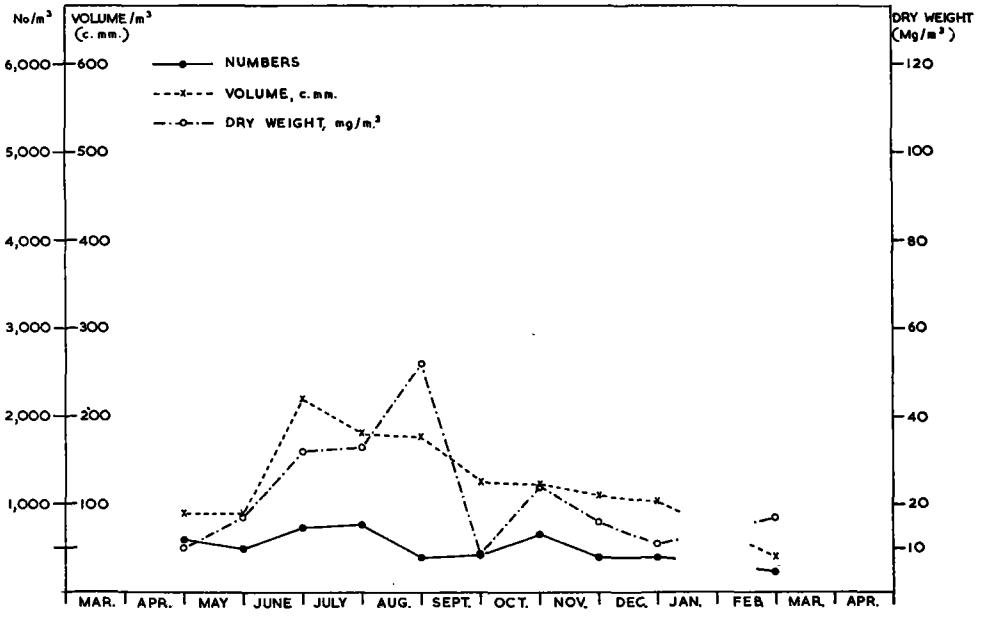


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11C=taken with CF 70 *ca.* midday ; 11D=taken with CF 70 *ca.* midnight.

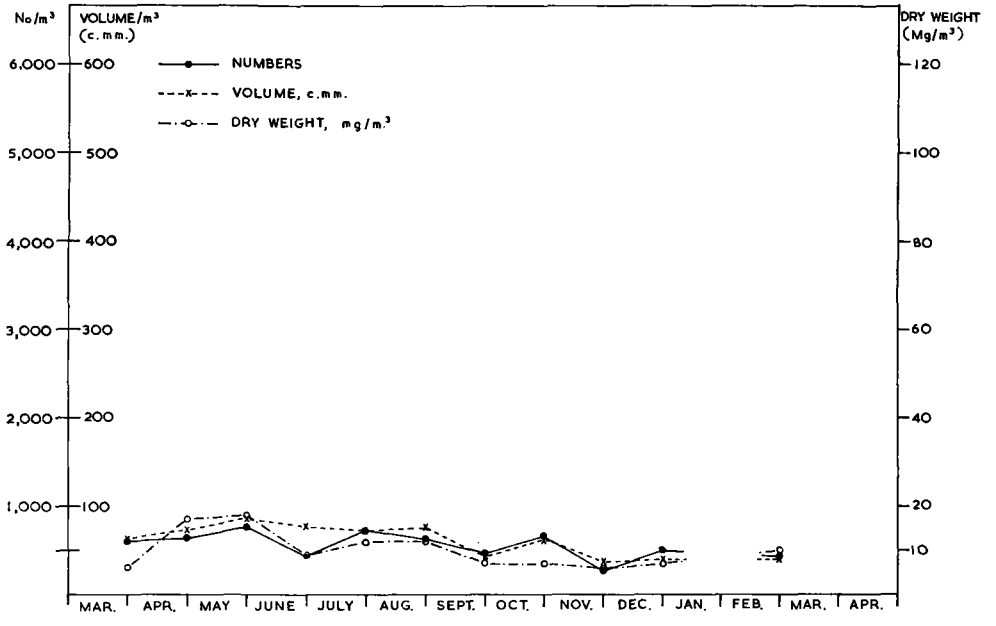


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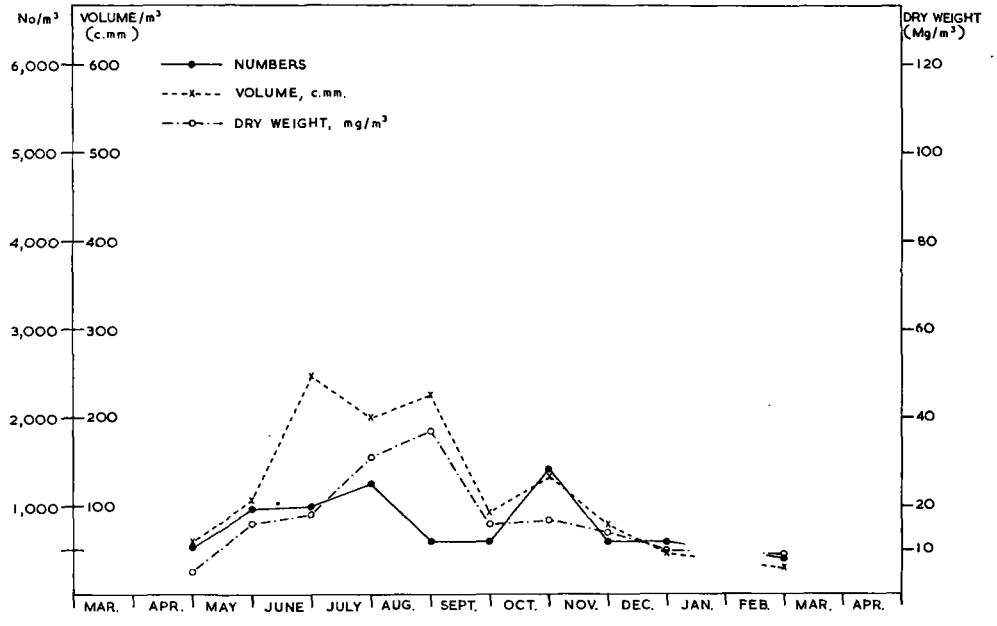


B

Fig. 12—Total plankton at P.S.3 in the zone from *ca.* 200 m to *ca.* 50 m depth, i.e. the layer of water in which the thermocline lies, but excluding the surface 50 m. 12A = taken with I.C.S.N. *ca.* midday ; 12B = taken with I.C.S.N. *ca.* midnight.



C



D

12C=taken with CF 70 *ca.* midday ; 12D=taken with CF 70 *ca.* midnight.

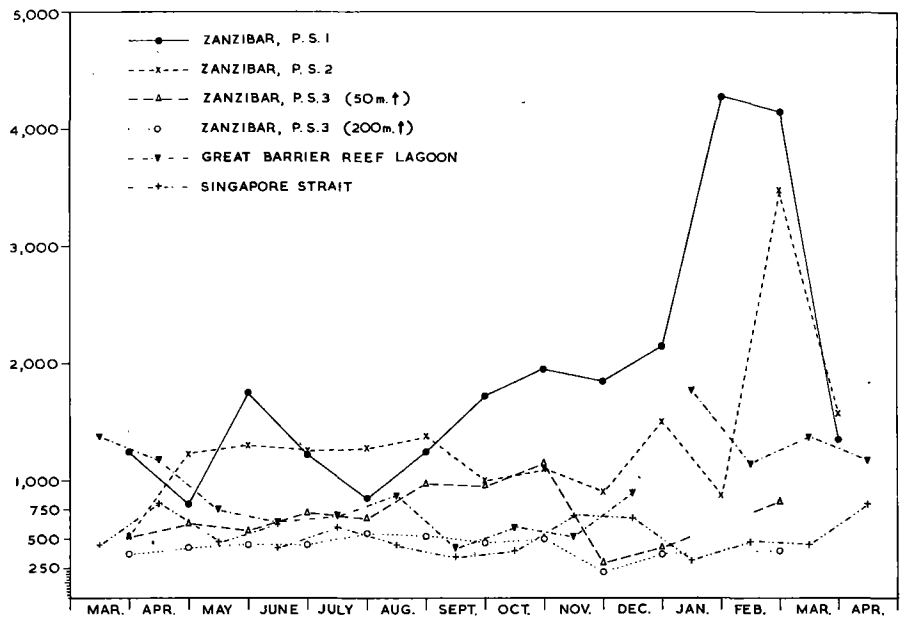
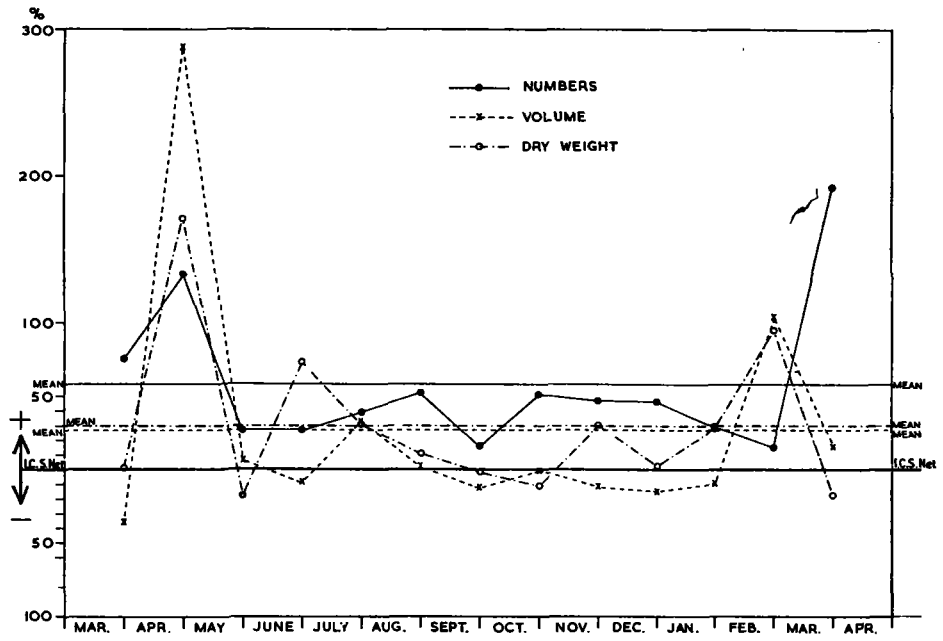
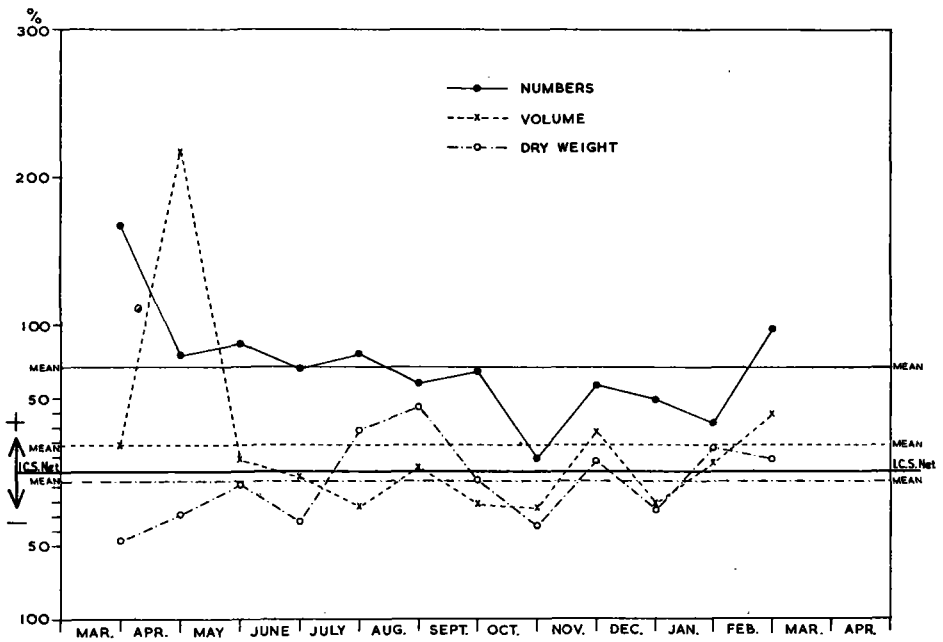


Fig. 13—The plankton numbers per m^3, according to the I.C.S.N., from P.S.1, P.S.2, P.S.3 (*ca.* 50 m to the surface), P.S.3 (*ca.* 200 m to the surface) Great Barrier Reef Lagoon and Singapore Strait. All are daylight samples.

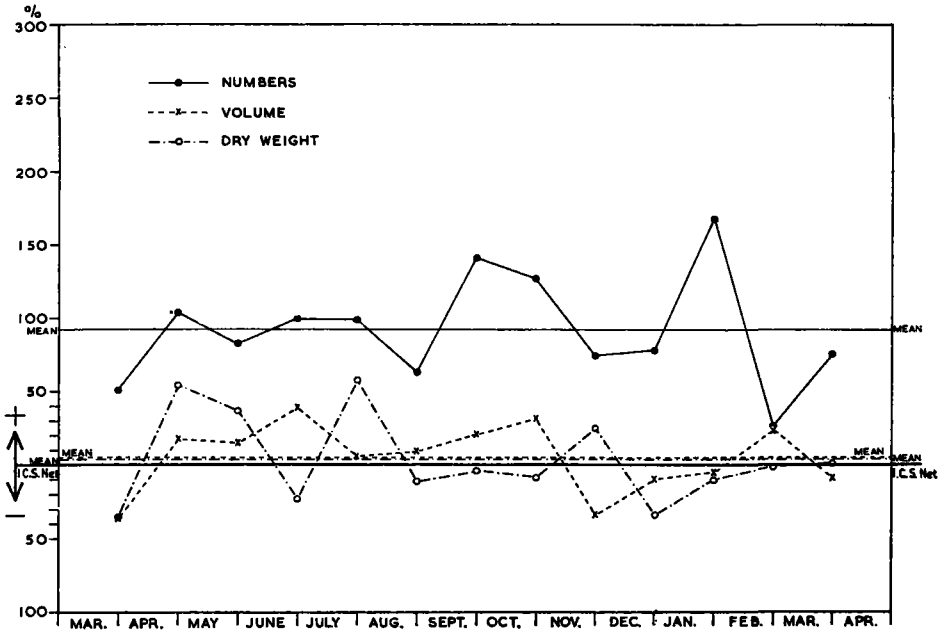


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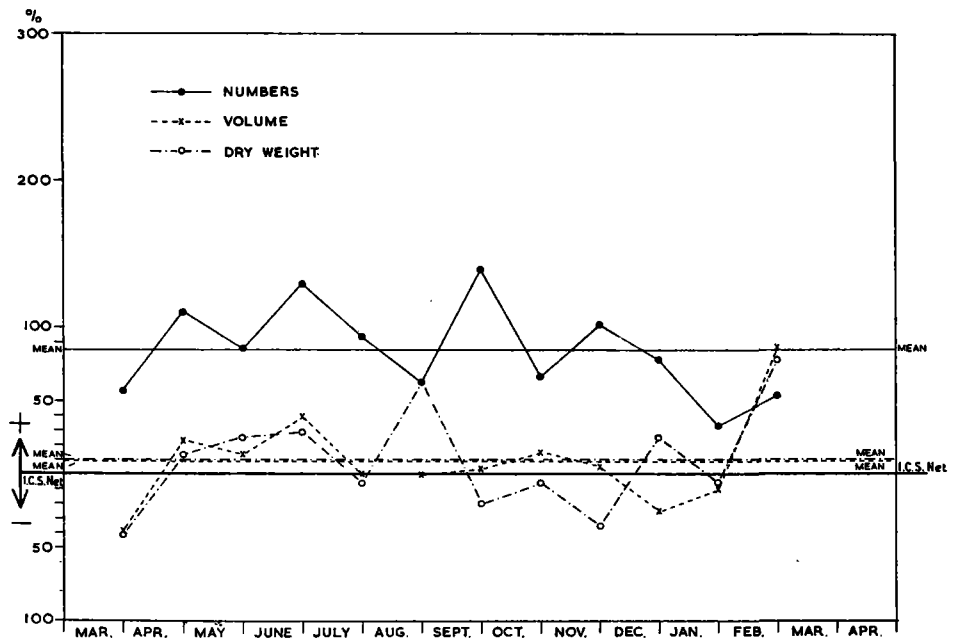


B

Fig. 14—The percentage of the catch of the CF 70 above or below that of the I.C.S.N. at P.S.1. 14A = *ca.* midday samples ; 14B = *ca.* midnight samples.

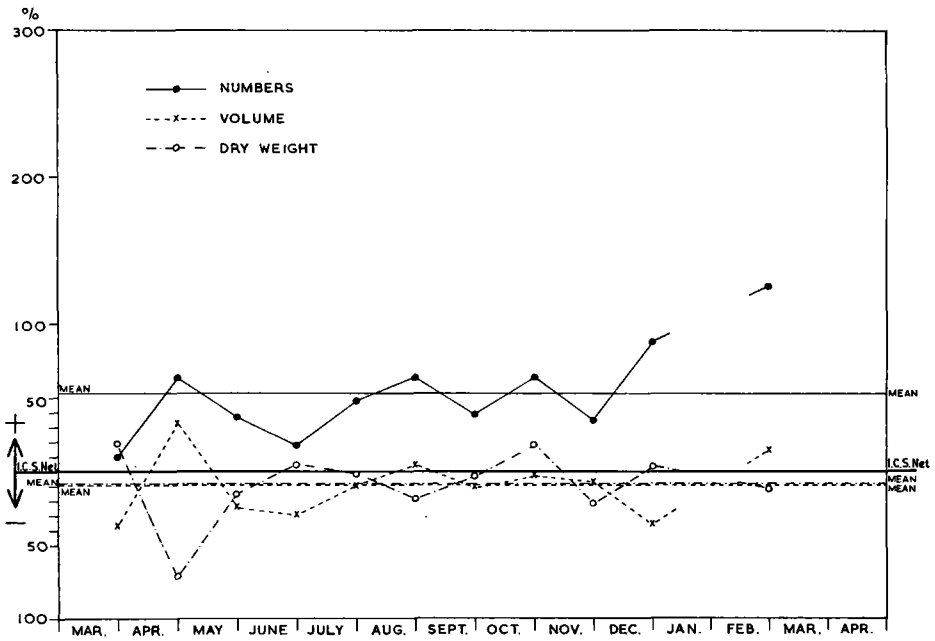


A

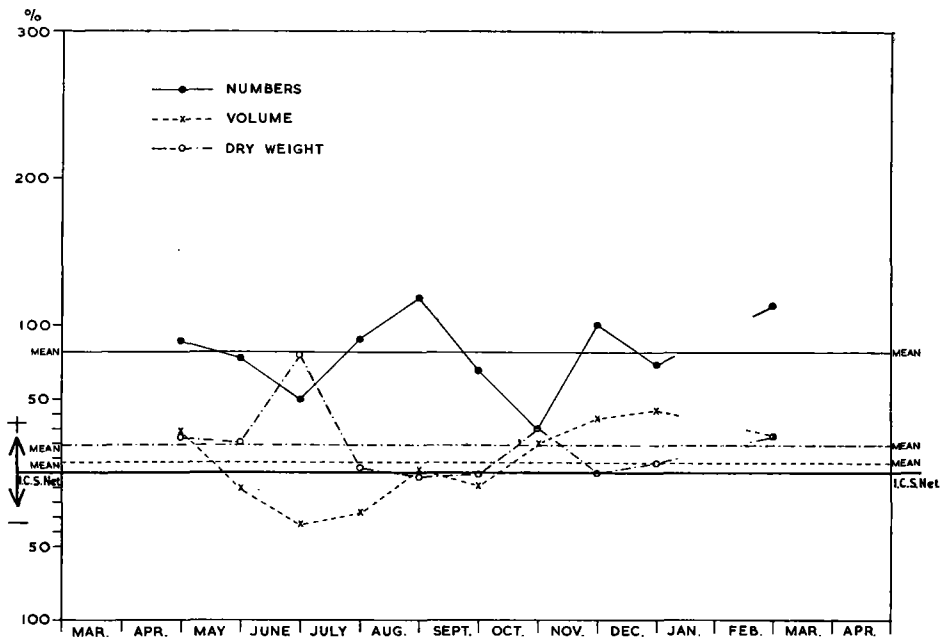


B

Fig. 15—The percentage of the catch of the CF 70 above or below that of the I.C.S.N. at P.S.2. 15A=*ca.* midday samples ; 15B=*ca.* midnight samples.

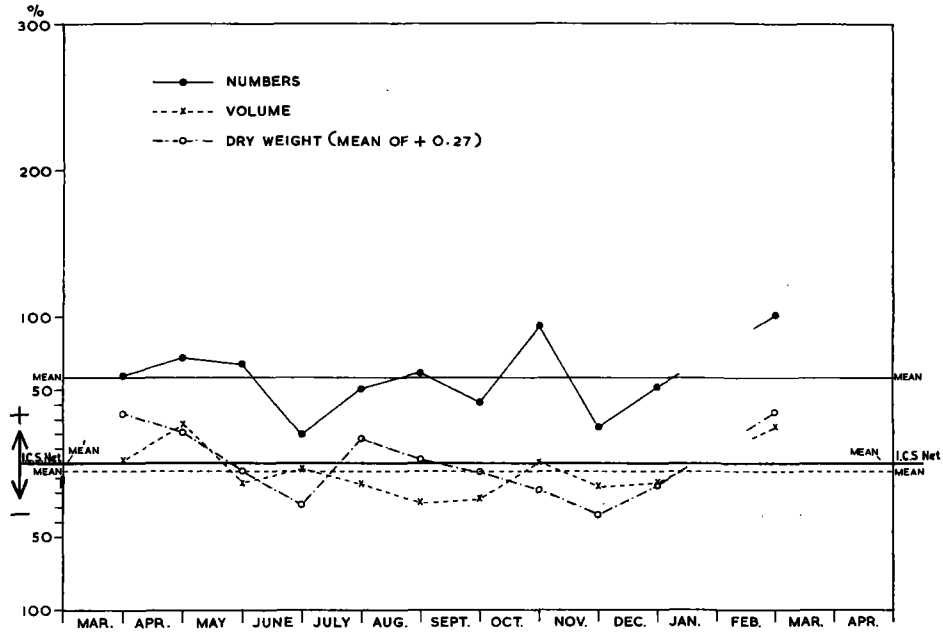


A

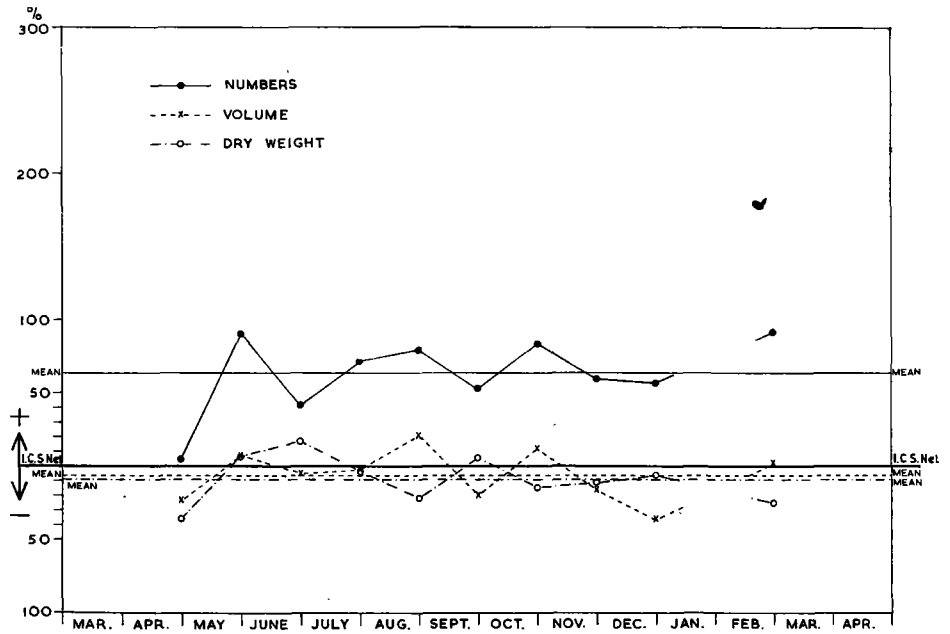


B

Fig. 16—The percentage of the catch of the CF 70 above or below that of the I.C.S.N. at P.S.3. 16A=*ca.* midday samples, 50 m to the surface ; 16B=*ca.* midnight samples, 50 m to the surface.



C



D

16C=*ca.* midday samples, 200 m to the surface ; 16D=*ca.* midnight samples from 200 m to the surface.

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PELAGIC POLYCHAETES FROM WATERS OFF THE COASTS OF KENYA AND TANGANYIKA.

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THIRTY-FOUR samples were chosen at random from a plankton survey of the waters off the Kenya-Tanganyika coasts made during 1960 (Wickstead 1961), and all the pelagic polychaetes they contained removed and identified. I am indebted to Dr. J. H. Wickstead for allowing me to do this, and for supplying the collection data. Samples sorted were taken within the area extending from 1° 40′ S, 41° 37′ E in the north, to 10° 41′ S, 40° 39′ E in the south. The whole sample was sorted and all contained at least some polychaetes. The samples were collected with a Currie & Foxton net (Currie & Foxton 1957) used without the fore-section and its contained flow-meter and depth gauge. This net has an aperture of 70 cm and a constant mesh aperture throughout of 205 μ (29 meshes per cm, or 74 per inch). All the hauls were vertical and were taken either from 150–200 m (below the thermocline) to the surface, or from 30–50 m (above the thermocline) to the surface. Where the water was shallow hauls were taken from the bottom to the surface. Samples were taken at various times during the day and night. The collection is of interest in that there are no previous records of pelagic polychætes from this region.

Family **Phyllodocidae** Grube.

Subfamily LOPADORHYNCHINAE Clarapède *sensu* Reibisch.

Lopadorhynchus (*Lopadorhynchus*) *brevis* Grube.

One specimen taken at 7° 25′ S, 40° 20′ E during daylight in a haul from above the thermocline from 35 m, and several others from 9° 10′ S, 39° 49′ E during daylight in a deeper haul (145 m) from below the thermocline.

Lopadorhynchus (*Lopadorhynchus*) *krohnii* (Clarapède).

Collected more often than *L. brevis* though usually singly in samples taken over the whole area.

Pelagobia longicirrata Greeff.

Several specimens taken from each of five samples from 1° 53′ S to 10° 39′ S and probably not uncommon over the whole area studied.

Maupasia coeca Viguier.

Only two specimens, one from 2° 30′ S, 41° 18′ E, the other from 3° 25′ S, 40° 02′ E, both in hauls taken from 140–150 m and starting below the thermocline.

Subfamily IOSPILINAE Bergström.

Phalacrophorus uniformis Reibisch.

Only three specimens collected, one at 1° 40′ S, 41° 37′ E, one at 9° 15′ S, 39° 40′ E and the third at a station in between, so that the species may be sparsely distributed over the whole area.

Family **Alciopidae** Ehlers.

Naiades cantrainii Delle Chiaje.

Only one specimen was found in the samples sorted, and this was collected from 10° 40′ S, 41° 10′ E in a deep haul made from 170 m during daylight.

Vanadis minuta Treadwell.

Perhaps the most numerous polychæte, at least one occurring in half the samples sorted and often several found together. No other species of *Vanadis* was encountered.

Plotohelmis capitata (Greeff).

Fairly common, especially in the more northern part of the area although several occurred together in a sample as far south as 7° 32′ S, 39° 53′ E.

Alciopina parasitica Clarapède and Panceri.

Four specimens taken singly from stations between 1° 53′ S, 41° 36′ E and 5° 05′ S, 40° 05′ E, all from deeper hauls starting from below the thermocline.

Rhynchonerella petersii (Langerhans).

Several specimens from different samples collected throughout the area. Of two specimens from 5° 26′ S, 40° 05′ E, one had some acicular chætæ unserrated, the other had the end-pieces simple so that it could have been mistaken for *R. angelini* (Kinberg). These were very small specimens.

Family **Tomopteridae** Grube.

Tomopteris membranacea Caroli.

Three specimens which came closest to Caroli's (1928) species were collected on consecutive days (24, 25, 26-4-1960) from 2° 30′ S, 41° 45′ E, 2° 40′ S, 41° 20′ E and 3° 30′ S, 40° 25′ E. The form of the parapodia and glands were identical with Caroli's Tav. I, fig. 8, and the gonads were present in the dorsal rami only, unlike *T. nationalis* Apstein *amend.* Terio 1950, to which the specimens showed some resemblance. They were more like *T. nationalis* in the smaller number of segments in the body (16–18 in these specimens as compared with 28 described by Caroli for *membranacea*) and in having relatively prominent eyes, but the position of

the rosettes on the trunks of the first two parapodia was more like that of *membranacea*, which they resemble also in the form of the body and tail. *T. membranacea* was described from specimens collected in the Red Sea but has not been found since.

Tomopteris nisseni Rosa.

Only two specimens, both in a sample collected from 9° 20′ 30″ S, 40° 58′ E in a night haul from a depth of 150–160 m on 21-7-1960.

Tomopteris planktonis Apstein.

Four specimens, each collected on different occasions. Many of the *Tomopteris* too poorly preserved to enable their identity to be determined may have belonged to this species. Three of the four certainly attributable to this species occurred at stations south of 9° 00′ S.

Tomopteris elegans Chun.

Two specimens only, from 1° 53′ S, 41° 36′ E and 9° 20′ S, 40° 58′ E in hauls made from about 160 m.

Family **Typhloscolecidae** Uljanin.

Typhloscolex mülleri Busch.

Common throughout the area.

Sagitella kowalevskii Wagner.

Occasionally represented in samples collected throughout the area.

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ON THE OCCURRENCE OF 'RED WATER' PHENOMENON ON THE WEST COAST OF INDIA*

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THE phenomenon of discoloured sea-water, which owes its origin mainly to a very high and localized concentration of marine phytoplankton, has been observed in various parts of the world. Such discolourations may be of any shade between red, brown, yellow and green, depending upon the causative organism involved. Although the term 'red tide' has often been used rather indiscriminately to describe discolourations which are not necessarily red and may not be of biological origin, the characteristic red water is caused primarily by the dinoflagellates. Various genera like *Cochlodinium, Gonyaulax, Gymnodinium, Noctiluca* and *Peridinium* have been implicated.

The study of red water phenomenon is of considerable interest not only from the biological standpoint, but also due to economic reasons since mass mortalities of commercially important fish and shellfish have been caused by red water outbreaks in diverse geographic locations. On the west coast of India, discoloured water caused by a variety of organisms and sometimes associated with mass mortality of local marine fauna, has been reported from several localities (refer Hayes and Austin, 1951; Brongersma-Sanders, 1957 and Subrahmanyan, 1959 for bibliography). The dinoflagellates associated with red discolourations in the coastal waters have been identified as *Noctiluca miliaris* (Bhimachar and George, 1950); *Gymnodinium* sp. (Subrahmanyan, 1959); two species of *Cochlodinium* (Hornell and Nayudu, 1923); and an unidentified Peridinian (Hornell, 1917). Recently, while participating in the International Indian Ocean Expedition Programme, an interesting phenomenon of red water caused by a different dinoflagellate species was observed on the west coast of India. Details are given below :

On November 5, 1963, while on a collection trip on board the Indo-Norwegian Project vessel 'KALAVA', an extensive patch of red water was sighted about eight miles north-west of Cochin Harbour. Being a bright sunny day with an extremely calm sea, it was possible to see rust-red or brick-red water for miles around. At our request the Commander, Naval Air Station at Cochin, arranged to send a few reconnaissance flights over the red water area that evening and also on subsequent days. The purpose of these flights was to get an idea of the exact locations, configurations, and the spread of discoloured water patches. The Pilots reported sighting a few red water patches along the coast, the largest patch being about 10 miles wide and drifting in a north-westerly direction away from the coast.

Microscopic examination of the red water samples collected that day revealed that the discolouration was caused by an extensive bloom of *Gonyaulax polygramma* Stein—a common tropical and sub-tropical dinoflagellate, hitherto not recorded from the west coast of India. *G. polygramma* was present in very high concentrations and cell counts of the bloom samples using Utermohl's method gave the density as high as 11,000,000 cells per litre of sea-water. This species presented an almost monospecific natural culture comprising about 99% of the total number of organisms present in the bloom samples. Other phytoplankton species were very insignificant in numbers and there was a virtual exclusion of zooplankters (Table I).

Except for *G. polygramma* all the other species listed in Table I have already been recorded from the west coast of India (Subrahmanyan, 1958). Only two species of *Gonyaulax*, viz., *G. diegensis* and *G. scrippsæ* have been included in Subrahmanyan's list of the phytoplankton organisms of the west coast of India and none of these have been known to occur in such high concentrations as to cause red water.

G. polygramma is essentially a warm water species and has been reported from many areas in the tropics and sub-tropics. It is of common

* Contribution from the Indian Ocean Biological Centre, Ernakulam, India.

occurrence in the Indian Ocean and has been recorded from the Gulf of Aden, Arabian Sea,

TABLE I
Composition of the red water

Component organisms	Cell count/litre	Percentage
DINOFLAGELLATES		
Gonyaulax polygramma ..	10,828,000	99·00
Peridinium steinii ..	9,000	0·08
Prorocentrum micans ..	8,000	0·07
Ornithocercus magnificus ..	7,000	0·06
Peridinium crassipes ..	7,000	0·06
Peridinium granii ..	4,000	0·04
Peridinium pentagonum ..	3,000	0·03
Peridinium depressum ..	2,000	0·02
DIATOMS		
Sceletnoema costatum ..	63,000	0·57
Rhizosolenia styliformis ..	2,000	0·02
Navicula sp. ..	2,000	0·02
Corethron hystrix ..	1,000	0·01
Nitzschia seriata ..	1,000	0·01
MICROFLAGELLATES—unidentified	?	?

eastern and southern coasts of Africa, off the Maldives and Australia (Wood, 1963). Therefore, the occurrence of this species on the west coast of India is by no means unique, nevertheless, its presence in the form of vast monospecific bloom in the coastal waters is certainly of interest because of the reported ill-effects of its blooms on marine life. Nishikawa (1901) reported that 'red tide' caused by *G. polygramma* bloom in the Bay of Agu in Japan was responsible for considerable destruction of oysters and was generally toxic to other organisms. Mass mortality of fish and marine invertebrates near Cape Town, South Africa, has been attributed to red water bloom of *G. polygramma* by Grindley and Taylor (1962). It is not clear from Nishikawa's account if the mass destruction of marine life in Japan was due to actual release of the toxic principle by the dinoflagellates into the surrounding water. In the case of South African mortality, however, Grindley and Taylor are of the opinion that the death of fish and invertebrates was due to lack of oxygen in the water which had resulted from mass decay of the red plankton and was aggravated by the release of decay products.

Since a number of *Gonyaulax* species, *viz.*, *G. tamarensis*, *G. catenella* and *G. polyedra* are capable of producing extremely potent toxins lethal to various animal groups as well as to human beings, it was decided to test the toxicity, if any, in the case of *G. polygramma*. Attempts to raise *G. polygramma* in axenic unialgal cultures in the laboratory had to be abandoned due to lack of proper facilities, but it was possible to prepare 'acid extract' of the cells concentrated from fresh red water samples for bioassay. Procedures for the preparation of extract and for bioassay were similar to those adopted for *G. tamarensis* by Prakash (1963). A series of toxicity tests were conducted on white mice at the Haffkine Institute, Bombay, and in each case the characteristic neurotoxic symptoms leading to death of the mice were missing. Based on these observations, we are of the opinion that *G. polygramma* bloom off Cochin was non-toxic. No fish or other mortality as a result of red water bloom was observed or reported from the surrounding areas. However, there was some evidence from the fishing log of R.V. 'KALAVA' that fish seemed to avoid the bloom area but appeared again in the same area after two days when the bloom had drifted away.

Based on the positions of the various red water patches given by Naval aircrafts, we have attempted to determine the average rates of surface drift in the coastal water off Cochin for the two consecutive days. The general direction of wind during the bloom period was westerly (270°) and that of the red water drift was north-westerly (325°). Table II summarises the main meteorological conditions at the time of red water bloom and the calculated rates of surface drift.

TABLE II
Meteorological conditions at Cochin during red water bloom

Date	Air Temp. °C. (Surface) Max.	Min.	Sky	Wind speed (knots) Max.	Mean	Calculated drift rate (miles/hr.)
November 4	31·8	24·5	clear	14	7	..
November 5	32·0	23·7	clear	11*	9	0·67
November 6	31·6	22·7	clear	7*	variable	0·53

* Reported calm after 6 p.m.

Since red water blooms are largely a surface phenomenon and winds and currents are primary factors governing their distribution, the use of aircrafts in locating and regularly following such discoloured water patches over a certain time period suggests an interesting possibility of estimating the rate and direction of the surface water drift. Of course, for a more refined estimation the growth potential or the generation time of the causative species must be taken into account.

The exact mechanism of the development of a monospecific dinoflagellate bloom causing red water is not fully understood. Primary factors like light, temperature and nutrients which control the production of phytoplankton in the sea are not the only necessary conditions for the establishment and subsequent development of a monospecific bloom. Probably certain other factors or a combination of factors is involved. The period of maximum phytoplankton production on the west coast of India is during the south-west monsoon months, May-September, with production peak occurring in July or August (Subrahmanyan, 1959). But most red water blooms on the west coast of India have been observed during September-November, and according to Bhimachar and George (1950) there appears to be a periodicity in the occurrence of such blooms. The obvious explanation for this periodicity appears to be the onset of north-east monsoon. There is also a suggestion that during this period water of lower salinity from the Bay of Bengal enters the coastal circulation on the west coast of India and probably favours development of blooms of certain species (Subrahmanyan, 1960). While certain dinoflagellate species are known to require a discrete mass of water of relatively low salinity for their growth, it does not imply that salinity difference is the sole requirement for the development of a monospecific bloom. Laboratory studies on dinoflagellate cultures have provided some clues to what makes the water physiologically suitable for growth, but this is still a very open question and more work is needed in this field. Hydrographic information from the west coast of India, particularly that concerning the origin and characteristics of the coastal water masses, is at present too sketchy to put forward a reasonable hypothesis. A study of the physiological ecology of the causative organism in relation to physical and chemical characteristics of the coastal waters would be a right step towards understanding the phenomenon of blooms causing red water.

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Variation in Transparency and in Bioluminescence on Longitudinal Transects in the Western Indian Ocean *

by

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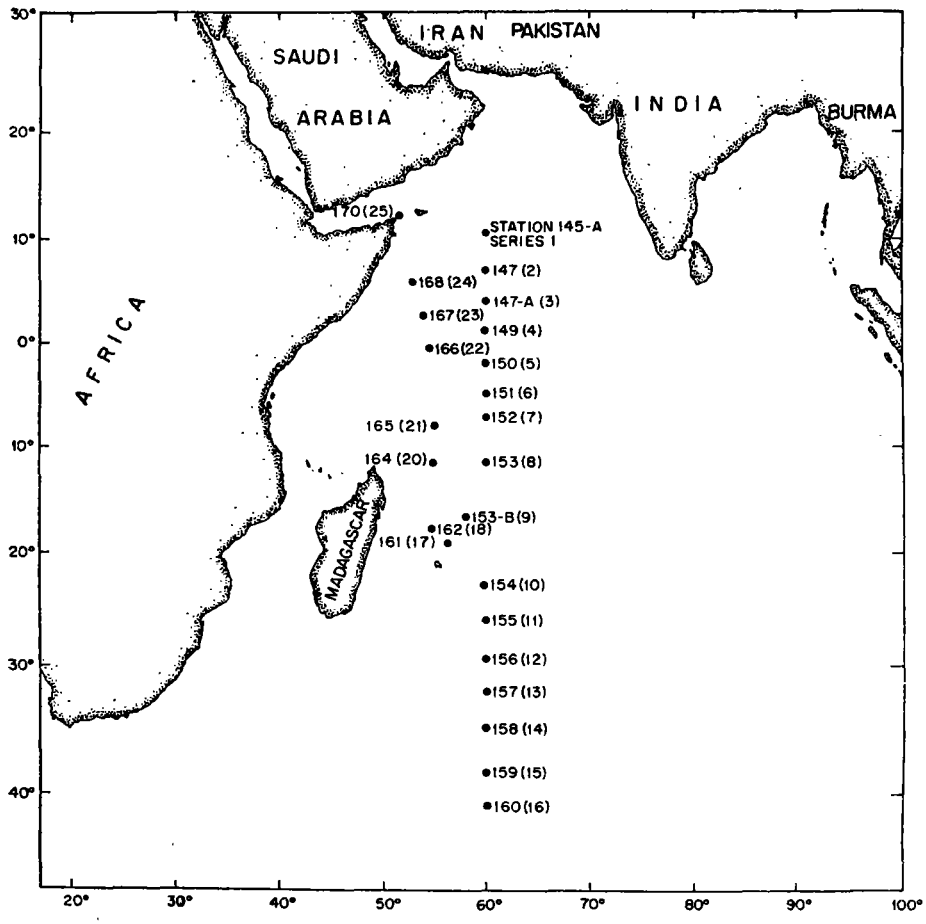


FIG. 1. — Positions of stations occupied on *Anton Bruun* Cruises 3 and 4 in August and September, 1963, with series numbers for photometer casts.

Measurements of the penetration of surface light, transparency, and bioluminescent flashing were carried out on north-south transects in the western Indian Ocean made by the Research Vessel *Anton Bruun* during August and September, 1963, as a part of the U.S. Program in Biology of the International Indian Ocean Expedition. Very little was known previously of the light conditions in this ocean. Information on the rate of daylight penetration was sought primarily in relation to the photic reactions of animals [CLARKE & DENTON, 1962; CLARKE & BACKUS, 1964], but it was also desired to supplement near-surface measurements made by others in studies of phytoplankton productivity. Transparency values, determined from the foregoing as attenuation coefficients, were needed to determine the maximum depths both by day and by night at which animals with eyes could see objects, and the depths at which these and other animals could detect the daily cycle of light, carry out diurnal migrations, or respond to light in other ways. No knowledge existed heretofore as to the occurrence of bioluminescence at sub-surface levels in the Indian Ocean. Quantitative records were desired on the frequency and intensity of flashing. This information in combination with transparency values may be used to approximate the distance over which one animal would be able to respond to the luminescence of another.

Procedure

The instruments and methods used were described by CLARKE and WERTHEIM [1956], CLARKE and HUBBARD [1959], and CLARKE and BRESLAU [1959]. The deep-sea photometer contains a photomultiplier tube which has a spectral sensitivity extending from 320 to 650 mμ with a maximum at 480 mμ. A pressure-potentiometer depth sensor is attached to the photometer. The instrument is suspended by a 4-conductor steel-armored cable and the signals relating to light and depth register on a dual-channel Sanborn recorder. During daylight hours the photometer was used in the upright position, i.e. with sensing surface upward, for the purpose of determining transparency to the greatest depth possible. For the measurements in the upper few hundred meters a filter holder, containing a diffusing disc of plexiglass and neutral filters, was placed over the receiving window. These reduced the incident irradiance by a factor of about 10^6 and thus avoided saturation of the phototube in strong daylight. For measurements at greater depths and at night the filter holder was removed.

For the investigation of bioluminescence the photometer was usually employed in the inverted position (sensing surface downward) to reduce interference by ambient light from the surface. During the later part of the investigation Nansen water bottles were placed at

intervals on the photometer cable, thus combining the hydrographic cast with the photometer cast and saving a corresponding amount of time. The depth sensor was attached in the "off" position to the lowest water bottle. When this bottle was reversed by its messenger, the depth meter was turned on by its mercury switch and thus indicated to the operator the moment when the messenger had reached the lowest bottle as well as the depth. The incident surface light was reported by an Eppley Pyranometer mounted on the upper deck and connected to a "Speedomax" Recorder in the ship's laboratory.

The stations occupied fell on a transect running south on the 60°E meridian from latitude 11°N to 41°S (Cruise 3) and on a second transect running north from Mauritius Island (20°S) to the eastern tip of Somalia (12°N) following roughly the 55°E meridian (Cruise 4) as shown in Figure 1 with pertinent station data in Table 1. The ship's schedule was such that transparency measurements were confined chiefly to Cruise 3, but bioluminescence was recorded on both transects.

TABLE 1

Summary of Station Data and Measurements
Anton Bruun *Cruises* 3 *and* 4

Station	Date 1963	Latitude	Longitude	Bottom Depth (m)	Series	Time (Local)	Wind Force
145A	Aug. 14	10°39′ N	60°07′ E	4355	1 a,b	1513-1645	6
147	Aug. 16	07°04′ N	60°01′ E	2049	2 a,b	0138-0347	4
147A	Aug. 17	04°09′ N	59°52′ E	——	3 a,b	1535-1930	—
149	Aug. 19	01°16′ N	60°08′ E	4385	4 a,b	1236-1500	4
150	Aug. 21	02°02′ S	60°00′ E	4315	5 a,b	1127-1340	3
151	Aug. 22	05°05′ S	60°05′ E	3950	6 a,b	1440-1626	5
152	Aug. 24	07°21′ S	59°44′ E	2926	7 a,b,c	1435-1631	6
153	Aug. 26	11°39′ S	58°02′ E	2246	8 a,b	1938-2248	5
153B	Aug. 28	16°26′ S	58°02′ E	——	9 a,b	1128-1305	—
154	Sept. 4	22°58′ S	59°45′ E	4243	10 a,b	0943-1217	4
155	Sept. 5	25°55′ S	60°01′ E	4846	11 a,b	1721-2100	2
156	Sept. 7	29°24′ S	60°03′ E	4627	12 a,b	0749-1016	3
157	Sept. 8	31°58′ S	59°51′ E	4792	13 a,b	0725-0939	4
158	Sept. 9	34°54′ S	60°06′ E	4828	14	1502-1550	3
159	Sept. 11	38°22′ S	59°51′ E	3219	15 a,b	0846-1122	4
160	Sept. 12	40°54′ S	60°01′ E	4974	16	0800-0850	4
161	Sept. 25	19°14′ S	56°27′ E	4224	17	1819-1920	4
162	Sept. 26	17°47′ S	55°00′ E	4480	18 a,b	1410-1618	4
164	Sept. 29	11°37′ S	54°57′ E	4252	20	0040-0135	5
165	Sept. 30	08°12′ S	55°00′ E	3828	21	0128-0200	5
166	Oct. 5	00°24′ S	54°33′ E	4682	22	0530-0622	2
167	Oct. 6	02°45′ N	53°51′ E	4929	23	0720-0802	4
168	Oct. 7	05°52′ N	52°57′ E	4953	24	0721-0828	3
170	Oct. 9	12°06′ N	51°31′ E	667	25	0415-0438	4

Hydrography

The hydrography of the region studied is presented here primarily on the basis of the section made on Cruise 3 (60°E long). The measurements at the offshore stations of Cruise 4 are consistent with the general picture obtained from Cruise 3. The temperature at the surface varied from 26.6°C at the northern end of the section, through a maximum of 28.1°C near the equator, to a minimum of 13.4°C at the southern end of the section. The temperature at 2000 m remained between 2° and 3° throughout the section. At stations from the northern limit of the section south to about 15°S a sharp thermocline was found between the bottom of the mixed surface layer and a depth of about 200 m, with a more gradual reduction of temperature below. Near the equator the temperature dropped from 27.6°C at 75 m to 14.0°C at 200 m. From about 15°S to the southern end of the section the thermocline became progressively more spread out and deeper. At the last two stations thermally uniform water was found to a depth of 500 m and the thermocline layer extended from 500 m to 1200 m.

The salinity profile for Cruise 3 revealed high values at the surface, ranging between 36.1‰ and 35.0‰, and generally lower values at deeper levels, as shown in Fig. 2. Certain water masses were identified on the following basis : The upper and lower limits for temperature and salinity as reported by DEFANT [1961, vol. 1, p. 217] were used for the delineation of the " Indian Ocean Central Water " and the " Indian Ocean Equatorial Water ". T-S curve envelopes were drawn from these values and the portions of the water column at each of our stations whose characteristics fell within these envelopes were considered to be part of the designated water masses. However, since the T-S values obtained before and after the present study at stations in the Arabian Sea east of the Red Sea did not agree with the values given by DEFANT for " Red Sea Water ", an envelope for this part of the Arabian Sea was drawn with upper limits of 13.6°C and 35.86‰ and lower limits of 3°C and 34.85‰ and designated as "Northern Boundary Water". (Water of these characteristics has been called "Arabian Sea Water" by MENZEL, 1964.) This water mass appeared below 600 m, or deeper, in the northern stations of Cruise 3 (A in Fig. 2). Indian Ocean Equatorial Water (B in Fig. 2) was found between 1°S and 8°S at depths of 200 to 1700 m. Indian Ocean Central Water (C in Fig. 2) occurred as a wedge with its base at 40°S, where it extended from the surface to 1400 m, and its apex at 4°S where it lay between 300 m and 600 m.

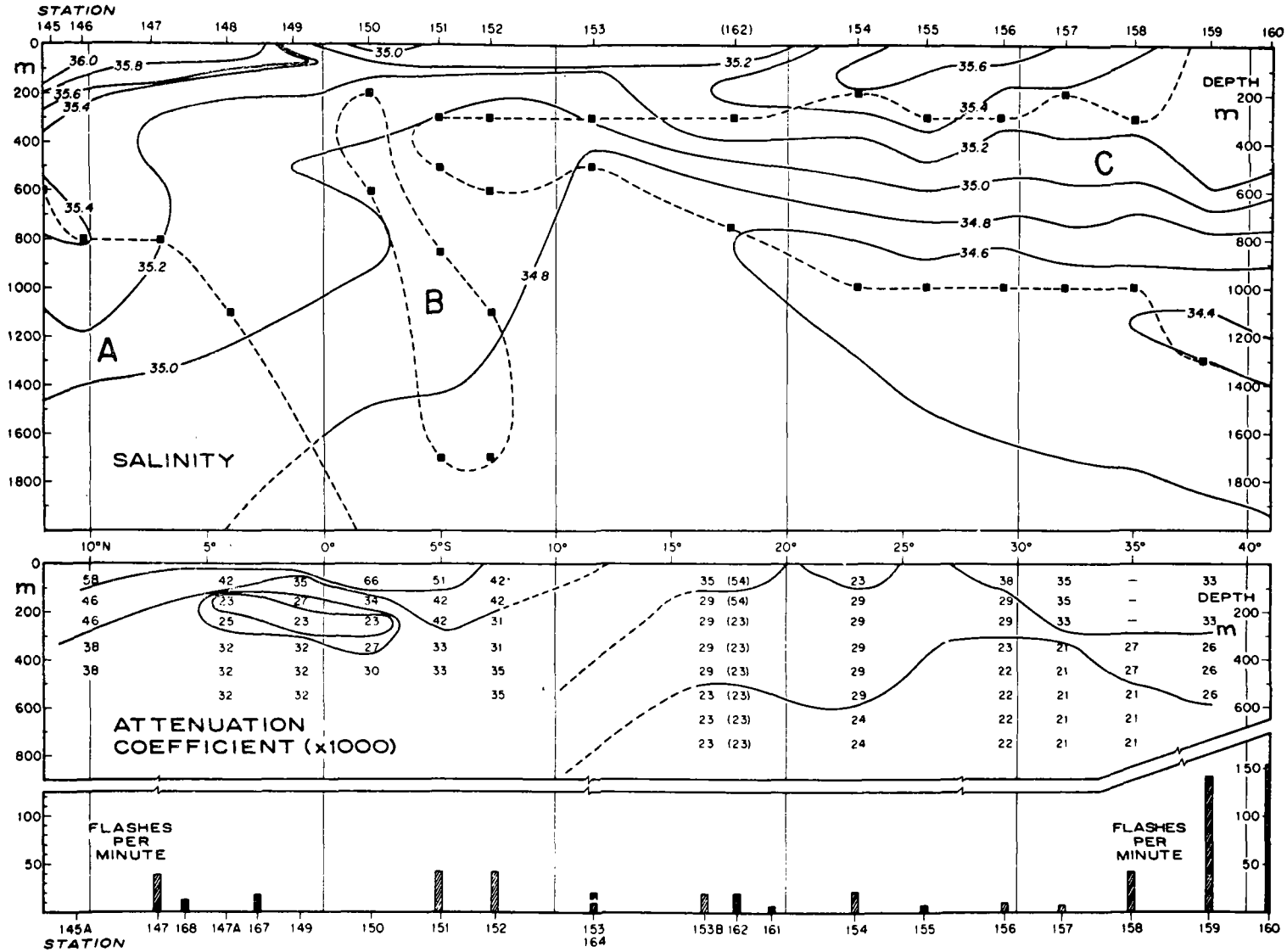

STATION
145 146 147 148 149 150 151 152 153 (162) 154 155 156 157 158 159 160
m
DEPTH
m
SALINITY
A
B
C
36.0
35.8
35.6
35.4
35.2
35.0
34.8
34.6
34.4
10°N 5° 0° 5°S 10° 15° 20° 25° 30° 35° 40°
ATTENUATION
COEFFICIENT (x1000)
FLASHES
PER
MINUTE
145A 147 168 147A 167 149 150 151 152 153 164 153B 162 161 154 155 156 157 158 159 160
STATION

Fig. 2

Light Penetration and Transparency

Measurement of the penetration of light during the day at 14 stations in Cruise 3 permitted the calculation of attenuation coefficients for various strata. The visible irradiance reported by the deck photometer reached daily maxima ranging from 8×10^3 $\mu W/cm^2$ to 5×10^4 $\mu W/cm^2$ at stations on this transect. Irradiance at night at the surface was too low to be recorded by the Eppley Pyranometer and no special study was made of it with the photomultiplier photometer due to interference from the ship's lights. However, for purposes of calculations of light penetration at night, we may use the values of 3×10^{-1} $\mu W/cm^2$ for a clear sky with a full moon and 3×10^{-3} $\mu W/cm^2$ for a clear sky with no moon [U.S. Navy, 1952] and 3×10^{-4} $\mu W/cm^2$ for a dark night [CLARKE & WERTHEIM, 1956].

In the present study attenuation coefficients in the upper 30 m ranged from $k = .070$ to .192 (Table 2). In the stratum below this, extending to about 100 m, the values ranged from $k = .023$ to .066, and in the deeper strata they were generally lower with a minimum of $k = .021$. The relatively high coefficients found in the upper strata are partly due to the fact that the deep-sea photometer has a broad spectral sensitivity. The effect of the selective absorption of the water itself, with the ends of the spectrum being more rapidly attenuated, is thus included in the values obtained. Absorbing and scattering material present also contributed to the high coefficients of the upper layers, particularly at stations in the northern part of the transect. The rate of attenuation for the whole of the visible spectrum, due both to the water and to material in the water, was thus revealed by the measurements.

Appreciable changes in attenuation coefficient due to the selective action of water itself is limited to the upper 30 m; at greater depths differences in attenuation coefficients are due to differences in material in the water affecting the most penetrating wavelengths (centered near 475 mμ). A transect showing the vertical distribution of coefficients for

FIG. 2. — Sections showing variations in salinity, transparency, and bioluminescence on north-south transects with station numbers indicated at top and bottom and latitudes shown in the middle of the figure.

Upper : Salinity profile for Cruise 3 on longitude 60°E.
A = " Northern Boundary Water ",
B = " Indian Ocean Equatorial Water ", and
C = " Indian Ocean Central Water ".

Middle : Attenuation coefficients at indicated depths on longitude 60°E with contour lines every 5 units; parentheses refer to one station on longitude 55°E.

Lower : Average number of luminescent flashes/min received by photometer at depths between 1000 and 1500 m. Crosshatched columns for stations on longitude 60°E; black columns for stations to the west.

TABLE 2

Summary of Measurements of Light Penetration and Transparency

Series	Station	Depth range (m)	Attenuation Coefficient, k^*
1	145A	0-20	.153
		20-100	.058
		100-350	.046
		350-450	.038
3	147A	0-20	.079
		20-75	.042
		75-200	.023
		260-558	.032
4	149	0-30	.077
		30-125	.035
		300-450	.033
5	150	0-10	.192
		10-100	.066
		100-150	.046
		150-350	.023
		350-600	.030
6	151	0-10	.150
		10-75	.051
		75-175	.046
		175-600	.033
7	152	0-20	.115
		20-200	.042
		200-400	.031
		400-600	.035
9	153B	0-10	.115
		10-40	.046
		40-100	.035
		100-450	.029
		500-800	.023
10	154	25-100	.023
		100-600	.029
		600-800	.024
12	156	25-150	.038
		150-250	.023
		600-800	.022
13	157	0-25	.070
		25-75	.041
		75-300	.035
		300-700	.021
14	158	300-500	.027
		500-800	.021

Series	Station	Depth range (m)	Attenuation Coefficient, k*
15	159	0-100	.033
		125-200	.023
		225-325	.033
		325-675	.026
16	160	300-530	.023
18	162	50-200	.054
		200-800	.023

* Attenuation coefficient = k in equation $\frac{I}{I_0} = e^{-kL}$ where light is reduced from I_0 to I by a stratum of water L meters thick.

depths below 30 m is plotted below the salinity transect in Fig. 2 and reveals the relation of these values to the hydrography. Relatively high coefficients (low transparency) were found in the water of high salinity down to a depth of 400 m at Station 145 A. High values also occurred in the upper 100 m at Stations 147 A to 150, and extended to greater depths at Stations 151 and 152. A bubble of very clear water was detected at about 250 m at Stations 147 A to 150. The occurrence of clear water here was not reflected in a salinity change but was just below the sharp thermocline occurring at these stations. This phenomenon may be related to the complex of water movements in the equatorial region. Farther south along the transect transparency was generally higher with less of a difference between the upper and lower levels. From 15°S to the end of the section attenuation coefficients were generally below $k = .038$ at depths greater than 75 m and no coefficient greater than .029 was recorded below 300 m. The occurrence of extremely clear water ($k = .025$) was found to occupy the stratum from about 500 m to 800 m in this region. The position of this clear water corresponded roughly with the tongue of Indian Ocean Central water (C in Fig. 2).

Curves showing the relation between depth and percentage of downwelling surface light for 9 stations are presented in Fig. 3. The tendency for rates of attenuation of visible light to become less with increasing depth is again indicated. In most instances there is no further change in transparency below 300 m. The highest average transparency for the whole stratum measured was found at Station 154. Here measurable daylight was detected at 900 m where the irradiance was 6×10^{-9} % of the surface value, equivalent to an intensity of about 6×10^{-6} $\mu W/cm^2$ at noon (assuming a surface value of 10^5 $\mu W/cm^2$). This is more than $10 \times$ the value of the irradiance at 900 m reported by CLARKE and BACKUS [1964] for the clearest water observed in the Brownson Deep, north of Puerto Rico. If we take 3×10^{-10} $\mu W/cm^2$ as the threshold for vision for deep-sea fishes [CLARKE & DENTON, 1962], and if we extra-

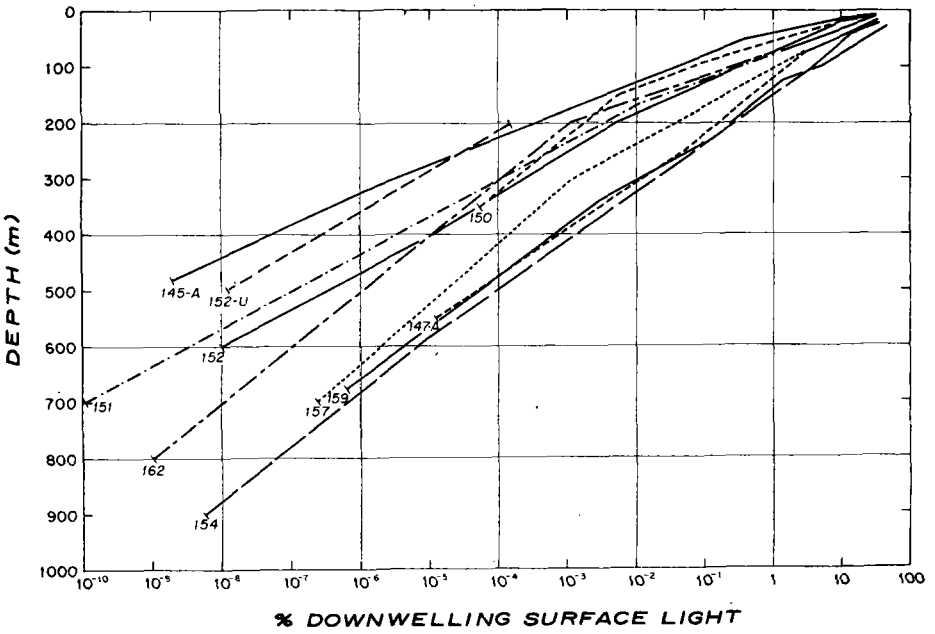


FIG. 3. — Semilogarithmic plot for penetration of daylight into the sea at the indicated stations. All curves are for downwelling light except curve 152 U represents upwelling light as a percentage of downwelling surface light, and curve 157 represents upwelling light as a percentage of upwelling surface light. Curve 150 followed the slope of curve 152 extended to 700 m. Attenuation coefficients are given in Table 2.

polate the curve for Station 154, we find that a deep-sea fish could probably detect the presence of daylight at 1300 m at noon in this part of the Indian Ocean. At Station 145 A, where the least transparent water was observed, the irradiance at 400 m was about $10^{-4}\times$ the value at Station 154 at the same depth. Extrapolating this curve gives us a maximum depth of about 700 m for a deep-sea fish to perceive daylight at Station 145 A. These values indicate the ranges of depths down to which daylight would be sufficient for vision and for the control of vertical diurnal migration.

The only previously published observations on transparency of the Indian Ocean are those of the Swedish Deep-Sea Expedition [JERLOV, 1951, Table 5]. Stations were made between 104°E and 59°E longitude and between 11°S and 02°S latitude. Three stations were located south of Sumatra, two were southeast of Ceylon, and two were in the Western Indian Ocean, of which one (Sta 227) was 70 miles west of our Sta 150 and 170 miles northwest of our Sta 151. At this station JERLOV reported a value of $k = .031$ for the stratum 20 to 50 m and $k = .062$ for 50 to 70 m. Since his photometer had a spectral sensitivity only 40 mμ wide with a " center of gravity " at 465 mμ, JERLOV's results may be compared only with our deep measurements, and in addition, the depth strata considered

are not the same. Nevertheless our values $k = .066$ for 10 to 100 m at Sta 150 and $k = .051$ for 10 to 75 m at Sta 151 are similar to his value for 50 to 70 m. The deepest stratum which JERLOV measured in the Indian Ocean was 75 to 100 m (at Sta 192) where he found $k = .036$ and his values are very irregular. For example at Sta 201 he reported $k = .018$ for 10-25 m and $k = .063$ for 50-75 m. Our results extended to far greater depths and showed a more gradual change in transparency. Our value of $k = .021$ for the stratum 300-700 m at Sta 157 and for 500-800 m at Sta 158 is the lowest value ever reported for depths greater than 100 m. In general our results indicate the presence of extremely clear water at depths from 300 to 900 m in the western part of the Indian Ocean. This region may thus be added to those previously reported in which the transparency of the deep water has been measured and found to be high [JERLOV & KOCZY, 1951; CLARKE & WERTHEIM, 1956; CLARKE & BRESLAU, 1959; and CLARKE & BACKUS, 1964]. All measurements thus far made in any part of any ocean within the stratum from 300 to 1000 m have yielded consistently low attenuation coefficients which fall within the range $k = .021$ to .042.

Bioluminescence

The deep-sea photometer recorded flashes of bioluminescence at every station at all depths during the night, and at depths below the level at which light from the surface interfered during the day. As in other oceans considerable differences were found from station to station and from one depth to another. Previous observations have shown that increase in the movement of the photometer due to the roll of the ship, or to raising or lowering the cable, causes an increase in the number of flashes recorded due to the stimulation of the luminescent organisms by turbulence or by actual contact with the photometer. Stabilizing the photometer by suspending it from an underwater parachute drogue, or in shallow water from a line held taut between a float and an anchor [unpublished report by J. R. PRINGLE] has noticeably reduced the flashing rate observed. Furthermore, a mathematical analysis of the relative numbers of flashes of different intensities recorded with the photometer suspended from the ship in the usual manner, shows that the number of weak flashes is much smaller than it would be if the flashing animals were uniformly distributed at all distances from the photometer. The probable explanation is that most of the flashes are usually produced within a meter or less from the photometer and are evoked to a large degree by the presence of the instrument. Our records, then, reveal a luminescent potential of the organisms present rather than the amount of flashing which would occur if the organisms were undisturbed . In interpreting the records allowance must be made for any important differences in the amount of the ship's roll, but comparisons may be made of records taken at different depths at the station or at different stations with about the same amount of ship motion. During the present investigation the sea conditions were fairly uniform.

Considering first the depths between 1000 and 1500 m, the average number/min of flashes more intense than 10^{-6} $\mu W/cm^2$ are shown in the bottom portion of Fig. 2. The flashing rate in this stratum tended to be low in the northern and central regions except at three stations where it rose to about 40 flashes/min. However, the rate increased greatly at the southern end of the 60°E transect to about 150 flashes/min at Sta 159 and 160. In this region the Indian Ocean Central Water extended from the surface to 1400 m. Also the catches of invertebrates taken by the mid-water trawl were much larger at these stations than farther north. For these transects there was no close correlation between the flashing rate recorded in Fig. 2 and the motion of the ship which is indicated roughly by the wind force (Table 1). The increase in flashing was thus associated with the presence of a greater abundance of luminescent organisms and probably also of different species. The identification of the animals taken by the trawl at these stations is being carried out by other investigators, and is not yet available.

Turning now to the whole range of depths at which flashes were recorded at each station, the daytime observations may be considered first. Most of these were made with the photometer in the upright position and flashes of luminescence could not be recorded at depths shallower than 400 m. Below that depth increasingly weaker flashes were recorded as shown for the Stations 157 and 159 (Tables 3 & 4) which were selected as representing localities with low and high amounts of luminescence respectively. At Sta 157 a maximum of 60 flashes/min occurred at 750 m and at 1110 m, and a minimum of 22 flashes/min at 1310 m. At Sta 159, about 390 miles to the south, a maximum of more than 202 flashes/min was recorded at 670 m and at 820 m and minimum of 94 flashes/min at 1730 m. At these and all other stations flashing rates tended to drop off progressively at levels deeper than 1100 m.

The five stations occupied during twilight hours showed results intermediate between those made during the day and the night. The four night stations were made with the photometer in the inverted position. As an example, the tally for Sta 147 is presented in Table 5. Here a high frequency of flashing was recorded in the upper layers with a maximum of more than 284 flashes/min at 28 m. Rates greater than 100/min occurred at all levels down to 200 m below which rates dropped off rapidly to 16 flashes/min at 1500 m. A high instrument dark level prevented the recording of flashes of 10^{-6} $\mu W/cm^2$ and lower at this station. Closely parallel results were obtained at Sta 153 and Sta 164 except that at the latter station rates above 100/min extended to 400 m. The ship's schedule did not permit making both day and night observations at the same station but neighboring stations showed no diurnal difference in the rate or intensity of flashing below 700 m where flashes of all intensities could be recorded at any hour of the day. Some flashing was found at every level at every station down to the maximum depth sampled of 2000 m.

At all stations not only did the total number of flashes/min tend to be greater in the upper layers than in the deeper layers (at night, much greater), but also the rates dropped off with depth in each of the ranges

TABLE 3

Relation between depth and occurrence of flashes as received by the upright photometer, Sept. 9, 1963, Sta. 157. Ambient light obscured all flashes in categories marked with a dash and some of the flashes in the next higher intensity range.

Time	Depth	No. of flashes per min. in indicated range					Total flashes per min.
Local	m	10^{-2} to 10^{-3} $\mu W/cm^2$	10^{-3} to 10^{-4} $\mu W/cm^2$	10^{-4} to 10^{-5} $\mu W/cm^2$	10^{-5} to 10^{-6} $\mu W/cm^2$	10^{-6} to DL $\mu W/cm^2$	
0808	500	0	> 8	—	—	—	> 8
0805	590	0	0	> 12	—	—	> 12
0803	660	0	2	10	> 32	—	> 44
0800	750	0	0	8	12	40	60
0756	960	0	0	4	6	46	56
0752	1030	0	0	2	8	44	54
0750	1110	0	0	2	6	52	60
0749	1200	0	2	4	12	24	42
0748	1270	0	0	2	12	22	36
0741	1310	0	0	0	0	22	22
0738	1310	0	0	1	1	20	22
0734	1400	0	0	0	6	22	28
0731	1600	0	0	0	0	32	32
0725	1870	0	0	0	6	38	44

TABLE 4

Relation between depth and occurrence of flashes as received by the upright photometer, Sept. 11, 1963, Sta. 159.

Time	Depth	No. of flashes per min. in indicated range					Total flashes per min.
Local	m	10^{-2} to 10^{-3} $\mu W/cm^2$	10^{-3} to 10^{-4} $\mu W/cm^2$	10^{-4} to 10^{-5} $\mu W/cm^2$	10^{-5} to 10^{-6} $\mu W/cm^2$	10^{-6} to DL $\mu W/cm^2$	
0937	590	0	>100	—	—	—	> 100
0934	670	0	18	>184	—	—	> 202
0930	820	2	16	80	> 98	—	> 196
0927	900	2	16	64	>108	—	> 190
0923	1020	0	6	42	110	16	174
0920	1070	0	24	90	46	0	160
0917	1220	2	4	50	96	4	156
0914	1290	1	5	46	86	4	142
0911	1360	2	6	32	104	4	148
0907	1460	0	8	38	78	10	134
0905	1560	0	4	10	94	20	128
0846	1730	0	2	16	46	30	94

of flash intensity. For example, at Sta 147 (Table 5) flashes greater in intensity than 10^{-3} μW/cm² were found only in the upper 100 m and flashes in the range 10^{-3} to 10^{-4} μW/cm² dropped in frequency from 249/min at 28 m to less than 7/min below 200 m. In general at each depth flashes were more frequent in the progressively lower intensity categories, although at some stations at certain depths brighter flashes occurred at a higher rate. At all times of day at depths at which the ambient light is above the dark level of the photometer, the highest flashing rate is characteristically found in the intensity category just above the ambient light level. Thus at Sta 157 (Table 3) 8 flashes of 10^{-3} to 10^{-4} μW/cm² were recorded at 500 m and the next highest number for flashes of this intensity was 2.

TABLE 5

Relation between depth and occurrence of flashes as received by the upright photometer, Aug. 16, 1963, Sta. 147.

Time	Depth	No. of flashes per min. in indicated range				Total
		10^{-2} to 10^{-3}	10^{-3} to 10^{-4}	10^{-4} to 10^{-5}	10^{-5} to DL	flashes
Local	m	μW/cm²	μW/cm²	μW/cm²	μW/cm²	per min.
0138	5	0	> 164	—	—	> 164
	10	1	> 142	—	—	> 143
	20	4	155	> 34	—	> 193
	28	8	249	> 37	—	> 294
0147	39	2	121	> 99	—	> 222
	50	0	87	> 110	—	> 197
	70	0	40	126	> 16	> 182
	80	0	31	157	> 28	> 216
	100	1	13	64	87	165
0156	125	0	8	40	112	160
	150	0	6	33	101	140
	175	0	12	62	64	138
	200	0	2	19	91	112
0209	250	0	0	18	80	98
	300	0	5	14	40	59
	350	0	2	17	23	42
	400	0	6	9	35	50
	500	0	4	7	31	42
0224	600	0	0	10	36	46
	700	0	0	5	18	23
	800	0	0	11	34	45
0234	900	0	0	3	34	37
	1000	0	1	3	21	25
	1100	0	3	9	33	45
	1200	0	1	2	35	38
0247	1300	0	0	11	35	46
	1400	0	0	3	30	33
0257	1500	0	0	2	14	16

At 590 m no flashes in this category were recorded but 12 were found in the 10^{-4} to 10^{-5} $\mu W/cm^2$ range. The same situation occurred at 660 m and at the first few sampling levels at Sta 159 (Table 4). Similar relationships have been reported earlier [CLARKE & HUBBARD, 1959; CLARKE & BRESLAU, 1959; CLARKE & BACKUS, 1964]. In all regions thus far investigated the brighter flashes have generally been found to occur more frequently in the upper layers of the depth range measured. This must mean that individual organisms of species having brighter luminescence must be present and flashing in the upper layers with greater frequency than in the deeper layers. The findings could not be accounted for by a larger number of weakly flashing organisms since we cannot suppose that the flashing of enough organisms would be synchronized so as to sum the energy of their short flashes simultaneously. These brighter organisms in each of the levels may or may not be more abundant than weaker flashers within the same layers. It is possible that they are in fact more numerous at these levels (and less numerous than the weaker ones at deeper levels) but it is also possible that organisms with weaker flashes are more abundant, but undetected because of the interference of the ambient light.

At Station 155 on Sept. 5 the numbers of luminescent flashes were recorded at 8 depths from the surface to 300 m and the observations were repeated as the photometer was brought back to the surface (Fig. 4). The moon (3 days past full) rose as the series began and was well above the horizon when the series finished, 1 hr 24 min later. The difference in the moon's altitude caused a two-fold increase in the ambient light at each depth as is shown by the two curves in Fig. 4. During the first half of the series the total number of flashes/min reached a maximum of 156 at 100 m, whereas in the second half a maximum of 192 flashes/min occurred at 175 m. Insofar as reliance may be placed on this one series of observations, there is evidence either that some luminescent organisms moved downward from about 100 m to about 180 m as the ambient light increased or that the amount of flashing of stationary populations changed correspondingly. It is to be noted that no significant change in flashing rates occured at levels from 220 to 300 m where the intensity of the ambient light was less than 1×10^{-6} $\mu W/cm^2$.

A comparison with previous studies of the rate and intensity of luminescent flashing showed general similarities but also certain specific differences. The most intense flashes received by the photometer in the Indian Ocean ranged between 10^{-2} and 10^{-3} $\mu W/cm^2$ with a maximum of 8 flashes/min. In the Atlantic Ocean CLARKE and BACKUS [1964] reported a maximum of 20 flashes/min in the same highest intensity range, and CLARKE and BRESLAU [1959] found a maximum of 14 flashes/min in this category in the Mediterranean Sea. Higher rates for the occurrence of weaker flashes were observed in each of the three regions with the largest number of bright flashes occurring in the upper layers, frequently just below the corresponding intensity of the ambient light. The highest total number of flashes/min of all intensities at any one depth were recorded in the upper layers at night. In the Atlantic slope water off

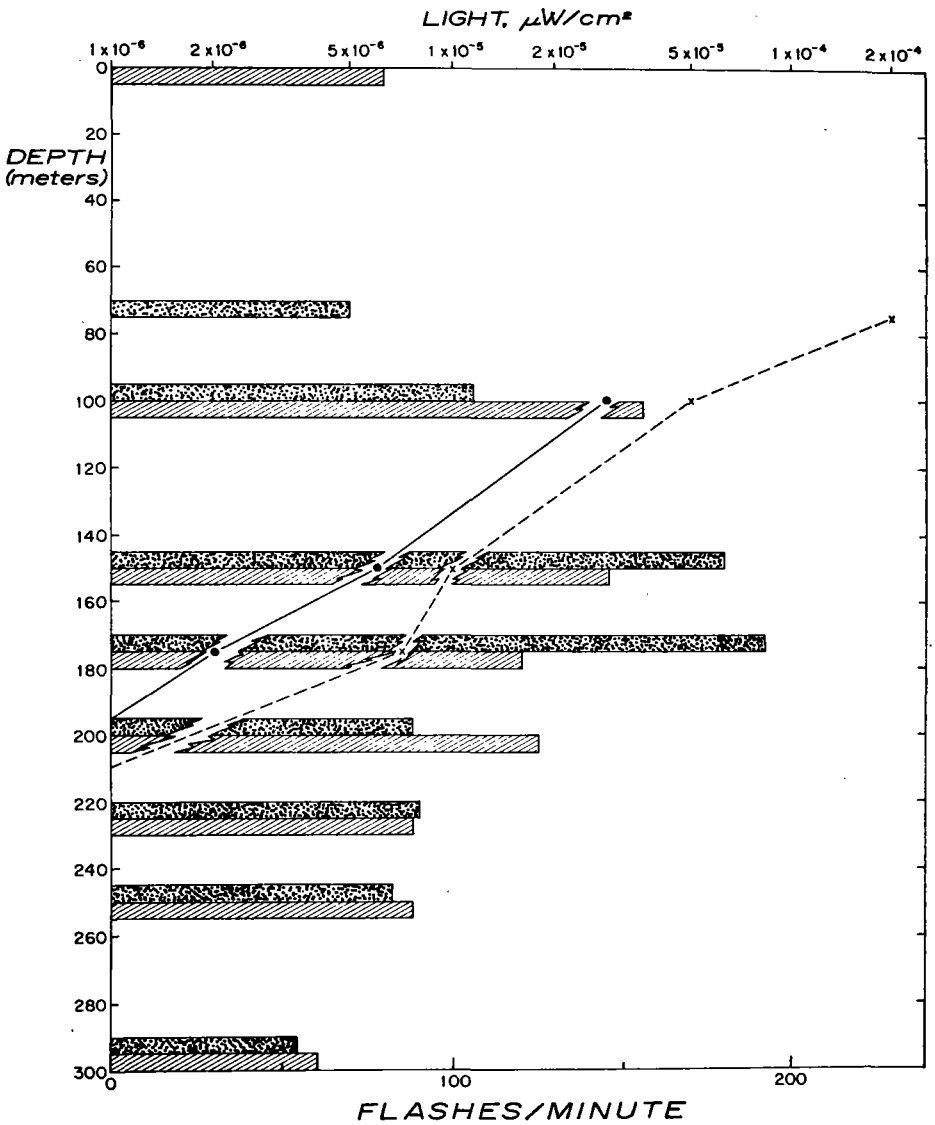


FIG. 4. — Comparison of the intensity of moonlight and the numbers of luminescent flashes at the indicated depths for two periods at Sta. 155. Solid curve and cross-hatched histograms for moonlight and flashes at 1920 hrs. to 2032 hrs. Broken curve and stippled histograms at 2050 hrs. to 2110 hrs. when the moon was higher.

New York maximum totals ranged from 140 to 187 flashes/min and off the Virgin Islands the maximum value was 140 flashes/min [CLARKE & HUBBARD, 1959; and CLARKE & BACKUS, 1964]. In the Mediterranean total flash frequency at each depth was generally lower and the maximum rate observed was 116 flashes/min. In the Indian Ocean maxima of just over 200 flashes/min were recorded during the day at 700 to 800 m and

values ranged from 206 to 284 flashes/min in the upper 100 m at night. Thus, at the stations occupied, frequency of flashing tended to be higher in the Indian Ocean both by day and by night, although the number of the most intense flashes was generally less than in the other areas investigated. In the western part of the Indian Ocean bioluminescence tended to diminish rapidly below 1100 m. Similar reduction with depth was observed below about 900 m to 1000 m in other seas in which the water was not quite as transparent as that reported here.

The present study thus extends our knowledge on the relationships between luminescence and ambient light in the sea. Evidence indicates that in the Indian Ocean, as in other regions, the largest number of bright flashes occurs near or just below the level where ambient light of the same intensity as these flashes is found. This is in the upper 100 m at night and from about 500 m to 600 m at noon. It is possible that organisms with the brightest flashes tend to congregate at this light level and follow it down and up as the sun rises and sets, or if the animals themselves do not migrate vertically, a wave of increased flashing may follow the vertical movement of a stimulating or controlling intensity of the ambient light. In either case the ambient light in these upper layers, controlled by surface intensity and transparency, is of ecological significance to the luminescent organisms living there. Furthermore, the diminution of luminescence below about 1100 m occurred at the approximate depth at which daylight is reduced to the minimum for the vision of deep-sea fishes [CLARKE & DENTON, 1962]. This is therefore probably the maximum depth at which the vertical migration of pelagic animals could be controlled by the diurnal changes in daylight, and the greatest depth at which animals with eyes could see others by means of light penetrating from the surface in relation to finding prey, avoiding predators, mating, or schooling. This depth is therefore another level of ecological significance.

Summary

Measurements of light penetration and luminescent flashing were made at 24 stations occupied by the R/V *Anton Bruun* on north-south transects in the Western Indian Ocean between 51° and 60° East longitude. Northern Boundary Water, Indian Ocean Equatorial Water, and Indian Ocean Central Water, were delineated from the hydrography. A deep-sea photomultiplier photometer capable of recording irradiance as low as 10^{-8} $\mu W/cm^2$ was employed together with a depth sensor.

Transparency for radiation of wavelengths centering at 480 mμ was determined during the middle of the day at 14 stations. Attenuation coefficients were found as follows : from 0 to 30 m, $k = .070$ to .192; from 30 to 100 m, $k = .023$ to .066, and from 100 m to 900 m generally lower with a minimum of $k = .021$, representing the most transparent water ever recorded below 100 m. At noon at the clearest station deep-sea fishes could probably detect daylight at 1300 m.

Luminescent flashing was found at every station and at every depth investigated below those at which light from the surface interfered. Between 1000 to 1500 m the average flashing rate was low in the northern and central regions but rose to about 150 flashes/min at the southern end of the transect where much larger catches of invertebrate plankton were taken.

The total number of flashes tended to be greatest in the upper layers, especially at night when as many as 284 flashes/min were recorded. In general the frequency of flashing tended to be higher in the Indian Ocean, although the number of the most intense flashes was generally less than in other seas where measurements have been made. The largest number of bright flashes occurred near, or just below, the level (changing during the course of the day) where ambient light of the same intensity was found. Evidence was found for the influence of moonlight on the flashing rate. Frequency of flashing dropped markedly at levels deeper than about 1000 m.

Résumé

Des mesures de la pénétration de la lumière et des éclairs luminescents ont été faites en 24 stations du navire océanographique *Anton-Bruun*, le long de coupes nord-sud de l'océan Indien occidental, entre 51° et 60° de longitude est. L'hydrographie a permis de délimiter « les eaux de la limite nord », « les eaux équatoriales de l'océan Indien » et « les eaux centrales de l'océan Indien ». Un photomètre photomultiplicateur, capable d'enregistrer le rayonnement jusqu'à 10^{-8} $\mu W/cm^2$ a été utilisé en même temps qu'un indicateur de profondeur.

La transparence pour un rayonnement dont la bande de longueurs d'onde est centrée sur 480 mμ a été déterminée au milieu du jour en 14 stations. Les valeurs suivantes ont été trouvées pour le coefficient d'atténuation : de 0 à 30 m, $k = 0{,}070$ à $0{,}192$; de 30 à 100 m, $k = 0{,}023$ à $0{,}066$; de 100 à 900 m, généralement plus bas avec un minimum de $k = 0{,}021$, représentant l'eau la plus transparente jamais enregistrée au-dessous de 100 m. A midi, à la station la plus claire, les poissons de profondeur pourraient probablement distinguer la lumière du jour à 1 300 m.

L'émission d'éclairs luminescents s'est rencontrée à toutes les stations et à toutes les profondeurs examinées au-dessous de celle où la lumière provenant de la surface interfère. De 1 000 à 1 500 m, le taux moyen d'émission d'éclairs a été peu élevé dans les régions du nord et du centre mais a augmenté jusqu'à 150 éclairs par minute, environ, à l'extrémité sud de la coupe où des prélèvements beaucoup plus importants d'invertébrés planctoniques ont été effectués.

Le nombre total d'éclairs tend à être plus grand dans les couches supérieures, spécialement la nuit, où il a été enregistré jusqu'à 284 éclairs par minute. Dans l'ensemble, la fréquence des éclairs tend à être plus

haute dans l'océan Indien, bien que le nombre des éclairs les plus intenses ait été généralement moindre que dans d'autres mers où des mesures ont été faites. Les éclairs brillants se produisent en plus grand nombre à proximité ou juste au-dessous du niveau — variable au cours de la journée — d'égale intensité de la lumière ambiante. L'influence de la lumière de la lune sur le taux des éclairs a été démontrée. La fréquence des éclairs diminue brutalement au-dessous de 1 000 m environ.

Изменения прозрачности и биологического светоизлучения вдоль продольных профилей в западной части Индийского Океана

Георгий Л. КЛАРК и Малон Г. КЕЛЛИ

Краткое содержание

Во время 24 остановок океанографического корабля "Антон Бруун", вдоль северо-южных профилей западной части Индийского океана, между 51° и 60° восточной долготы, были произведены измерения проникновения света и световых вспышек. Гидрография позволила установить границы "северных приграничных вод", "экваториальных вод Индийского океана" и "центральных вод Индийского океана." Был использован фотомножительный фотометр, способный регистрировать излучение до 10^{-8} мквт/см^2 одновременно с глубинным указателем.

Прозрачность для окружности, лента которой охватывала длинну волн в 480 ммк, была определена по середине дня на 14 остановках. Были найдены следующие значения для коэффициента уменьшения : от 0 до 30 м, κ = 0,070 до 0,192 ; от 30 до 100 м, κ = 0,023 до 0,066; от 100 до 900 м, большей частью ниже с минимумом κ = 0,021, соответствующим воде наибольшей прозрачности, когда-либо зарегистрированной ниже 100 м. В полдень, на наиболее прозрачной станции, глубинные рыбы могли, вероятно, различать дневной свет на глубине 1 300 м.

Появление световых вспышек встречалось во время всех стоянок и на всех глубинах, исследованных ниже той, где проявляется свет, проникающий с поверхности. От 1 000 до 1 500 м, средняя норма появлений выспышек была невысока в северном и центральном районах, но возросла до 150 примерно вспышек в минуту в южной части профили, где планктонические безпозвоночные были получены в значительно большом количестве.

Общее количество вспышек возростает в верхних слоях, в особенности, ночью, когда было зарегистрировано до 284 вспышек в минуту. В общем итоге частота вспышек возростает в Индийском океане, хотя количество наиболее сильных вспышек, в общем, ниже количества их в других исследованных морях. Яркие вспышки происходят в большом количестве по близости

или как раз ниже меняющегося в течение дня уровня окружающего света одинаковой силы. Влияние лунного света на силу вспышек уже было объяснено. Частота вспышек резко уменьшается, примерно, ниже 1 000м.

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MARINE BIOLOGICAL RESEARCH

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Investigational Report No. 8

Preliminary guide to the sharks found off the east coast of South Africa

by

Jeannette D. D'Aubrey

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INTRODUCTION

THE INCIDENCE of shark attack on humans off the east coast of the Republic of South Africa is high and, with a view to preventing attacks in the future, an extensive programme of research on protective measures is being conducted by the Oceanographic Research Institute in Durban. The first requirement in this investigation of the problem of shark attack was to determine the species responsible for attacking humans in this area and, in order to accomplish this, a survey of the potentially dangerous shark families was begun in 1959. Families in which the species grow to a large size and possess well-developed cutting or tearing teeth were considered to be potentially dangerous. These families include the *Carchariidae* (Ragged Tooth Sharks), *Isuridae* (Blue Pointer and Mako Sharks), *Alopiidae* (Thresher Sharks), *Carcharhinidae* (Tiger, Soupfin, Blue, Milk, Lemon, White-tipped, Black-tailed Grey, Sandbar, Bronze, Ridge-backed Grey, Silky, Bignose, Galapagos, Black, Zambezi, Java, Blackspot, Blackfin and Black-tipped Sharks) and *Sphyrnidae* (Hammerhead Sharks). Study material was collected from coastal and offshore waters between Lourenco Marques and Cape Town. The majority of specimens was obtained from coastal waters in the Durban area.

During the early part of the survey it became evident that considerable confusion existed in the identification of sharks and that, in view of this, a simplified method of identifying the sharks caught in this area might be of considerable value to anglers and spearfishermen. This preliminary guide has been compiled in an attempt to help in the identification of sharks belonging to the families included in the survey. The survey has recently been extended to include all sharks, rays, sawfishes and sandsharks and it is hoped that a comprehensive guide on these groups will be produced in the future. Before this is possible, however, it is necessary to examine large numbers of specimens of each species. This can only be done with the full co-operation

of anglers in making specimens (dead as well as alive) available to the Institute. It is therefore urgently requested that anglers should make *any sharks, rays, sawfishes or sandsharks* caught, available to the Institute for research.

Arrangements can be made for sharks caught within the Durban area to be collected by the Institute (Phone 68374 or 23432). Otherwise specimens can be brought to the Aquarium, 2 West Street, Durban or sent to the Oceanographic Research Institute, Box 736, Durban. Postage costs will be refunded. Should it be impossible to send complete specimens to the Institute, photographs similar to those included in this guide should be taken and sent to the Institute together with information as to when and where the specimen was caught, the dried jaws of the specimen (or detailed notes on the nature and number of teeth on each jaw), and measurements of the body length (from the tip of the snout to the beginning of the tail) and total length (from the tip of the snout to the tip of the tail when held in its natural position). It is hoped that this much-needed assistance in the collection of material and data will be forthcoming.

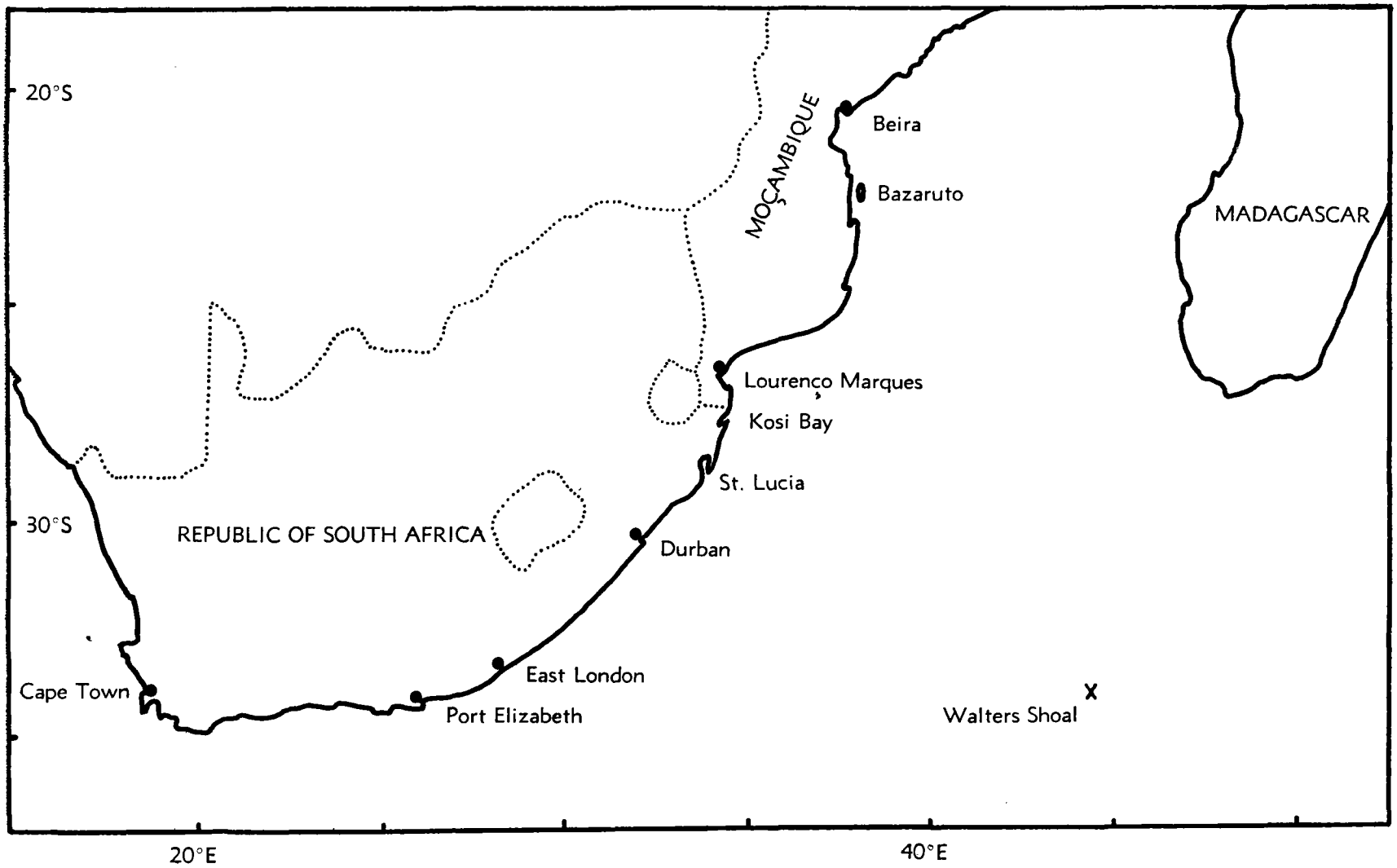


Fig. 1 — The East Coast of South Africa.

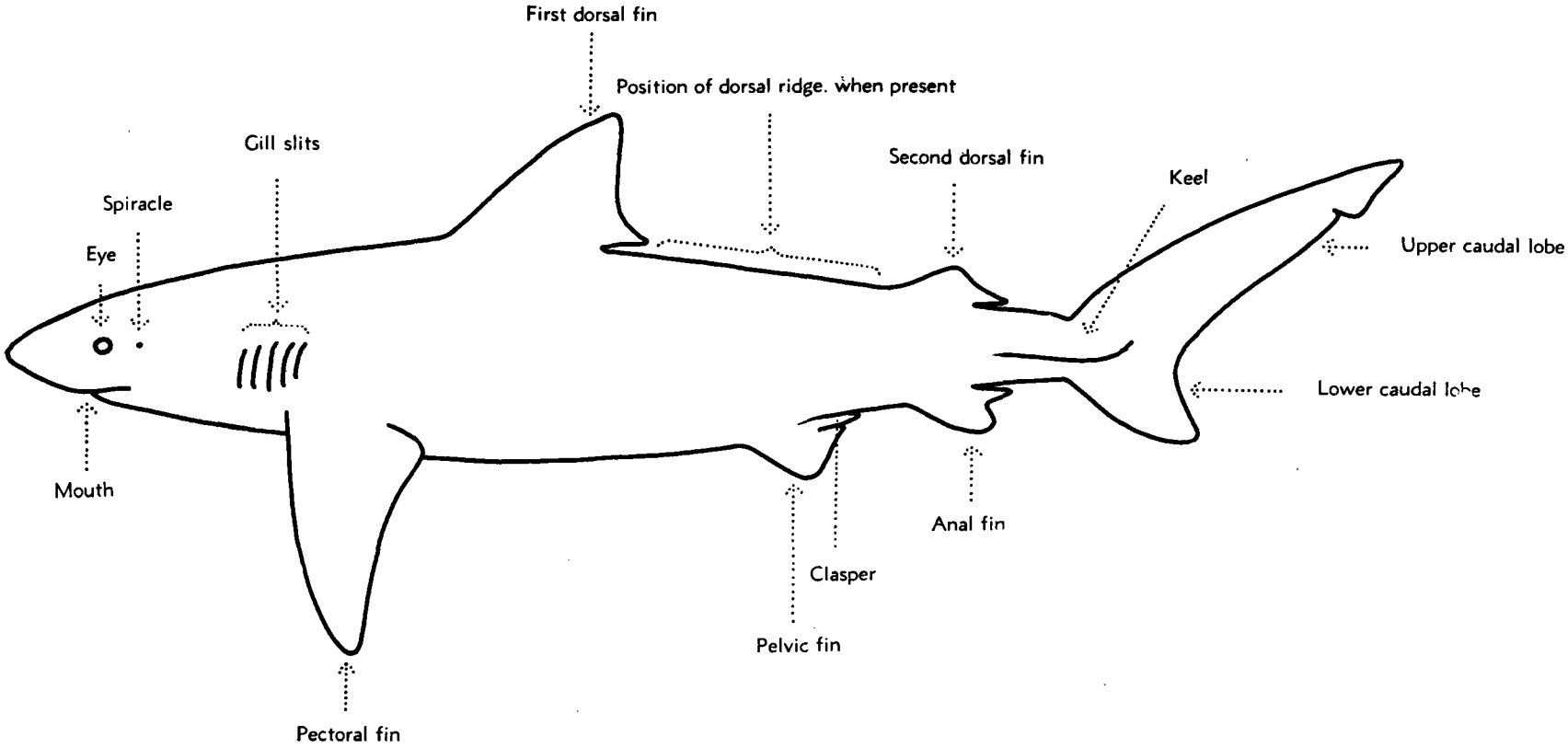


Fig. 2 — Diagram of a Typical Shark.

MAIN FEATURES USED IN IDENTIFICATION OF SHARKS

These are illustrated in Figs. 3 to 22 and consist of the following:

Head: Normal or hammershaped.

Snout: Long or short.
Pointed or rounded tip.

Nasal lobe: Long or short.

Teeth: Edges smooth or serrated
Shape
Basal denticles present or absent

Dental formula: The dental formula enables the number of rows of teeth on each side of each jaw to be simply expressed. It is written as follows:

$$\frac{\text{No. of teeth on left side of upper jaw} \quad \text{No. of central teeth} \quad \text{No. of teeth on right side of upper jaw}}{\text{No. of teeth on left side of lower jaw} \quad \text{No. of central teeth} \quad \text{No. of teeth on right side of lower jaw}}$$

Hence a dental formula of $\frac{16 - 2 - 16}{15 - 1 - 15}$ indicates that the specimen has 16 teeth on the left side of the upper jaw, 2 teeth in the centre of the jaw, 16 teeth on the right side of the upper jaw, 15 teeth on the left side of the lower jaw, 1 tooth in the centre of the lower jaw and 15 teeth on the right side of the lower jaw.

Spiracles: Present or absent.
When present these are very small in the species described. They consist of a small hole on each side situated between the eye and the first gill slit but nearer the eye than the first gill slit. They are only slightly larger than the pores found on the head in this region but may be distinguished from them as they do not exude mucus when squeezed.

Gill slits: Position of 5th gill slit (above or in front of pectoral fin).

Dorsal ridge: Present or absent.

Fins: Position, shape and size (particularly the two dorsal fins).

Caudal fin: Proportion of the lower lobe to the upper lobe (i.e. whether the lower lobe is almost as long as, or considerably shorter than the upper lobe).

Keel: Present or absent.

Colour: Although this is not always reliable it may be of some use in identification.

The overall colour of sharks may show considerable variation within the same species when alive or freshly caught. After death further colour changes take place. For this reason overall colour is usually an unreliable feature in the identification of sharks.

Markings on the fins or body may also vary. For example, adult specimens of the Black-tipped Shark *(Carcharhinus maculipinnis)* have very distinct black tips on their fins while the young have no markings at all. In a few species, e.g. the Black Shark *(Carcharhinus melanopterus)* and the Black-tailed Grey *(Carcharhinus spallanzani)*, the markings are more reliable and may be used for identification.

HOW TO IDENTIFY THE SPECIES

The general appearance of many species of shark may be closely similar. As the differences between species are not always apparent in photographs, a brief description of each species has been included in this guide. Each description gives the main features by means of which each species can be identified but identification should be made by using the keys. Identification is likely to be more accurate when keys are used and, with a little practice, will be far quicker. The descriptions should be used as a means of checking the identification. If the identification is correct, the description should agree on every point for the shark concerned.

HOW TO USE THE KEYS

Each key consists of a number of paired statements. In order to identify a specimen, start with the first pair of statements (numbers 1a and 1b) and decide which of the two statements (a or b) applies to the specimen being identified. Should the statement chosen be directly followed by block type, this is the name of the group to which the specimen belongs. If the statement chosen is not followed directly by block type, refer to the pair of statements directly beneath and repeat the process.

This process of elimination is continued until the statement chosen is directly followed by a group name (in block type). Whenever a statement that is not followed by a group name is

chosen, refer to the pair of statements directly below and repeat the process.

For example: To identify a shark of the family *Carcharhinidae,* turn to the key to the genera of the family *Carcharhinidae* on page 19. If the shark in question has the following features: no spiracles, the midpoint of the base of the first dorsal nearer the pectorals than the pelvics, the cusps of the upper teeth serrated and a large first dorsal fin with a very broadly rounded apex, the identification will be made as follows:

The first pair of statements is always 1. Therefore choose between 1a and 1b, and, as the above described shark has **no** spiracles, 1b must be chosen.

There is no group name opposite 1b, so proceed to the pair of statements directly beneath it — in this case 3. Choose between 3a and 3b and, as the midpoint of the first dorsal is nearer the pectorals than the pelvics, the choice will be 3b.

There is no group name opposite 3b, so proceed to the pair of statements directly beneath — in this case, 4. Choose between 4 a and 4 b and, as the cusps of the upper teeth are serrated, the choice will be 4a.

There is a group name opposite 4a — in this case *Carcharhinus.* The specimen in question therefore belongs to the genus *Carcharhinus* (Grey Sharks). To determine which species of *Carcharhinus* it is, use the key to the species of the genus *Carcharhinus* on page 26—identification LONGIMANUS.

It is not necessary to use more than three keys to identify any one of the species described in this guide. The first key in the guide will indicate the family to which the species belongs. In the section dealing with the family there may be another key by means of which, except in the case of the genera *Carcharhinus* and *Galeorhinus,* it is possible to identify the species. To find the species of the genus *Carcharhinus* or *Galeorhinus* it is necessary to use a third key which is found at the beginning of the subsection dealing with the genus.

KEY TO THE FAMILIES CARCHARIIDAE, ISURIDAE, ALOPIIDAE, CARCHARHINIDAE AND SPHYRNIDAE.

1a HEAD hammer-shaped .... **SPHYRNIDAE (26-28)**
1b HEAD normal, not hammer-shaped
  2a CAUDAL FIN lunate, the lower lobe being almost as long as the upper lobe ..... **ISURIDAE (3-4)**

2b CAUDAL FIN not lunate, the lower lobe being considerably shorter than the upper lobe.
3a UPPER CAUDAL LOBE very long being equal in length to the distance from the tip of the snout to the beginning of the caudal ..... **ALOPIIDAE (5)**
3b UPPER CAUDAL LOBE less than ½ the length from the snout to the beginning of the caudal.
4a 5th GILL SLIT in front of the pectoral fin .... **CARCHARIIDAE (1-2)**
4b 5th GILL SLIT above the pectoral fin **CARCHARHINIDAE (6-25)**

FAMILY: CARCHARIIDAE

Key to the Species

1a EYE SMALL, the diameter considerably less than twice the length of the longest tooth **CARCHARIAS TAURUS (1)**
1b EYE LARGE, the diameter twice the length of the longest tooth or more ..... **CARCHARIAS KAMOHARAI (2)**

1. CARCHARIAS TAURUS

(PLATE 1)

Common Names:

RAGGED TOOTH SHARK, Sand Shark, Grey Nurse Shark, Sand Tiger, Brown Shark, Yellow Shark, Yellow Belly, Sarda.

Description:

Head: Normal, not hammer-shaped. (Fig. 3a).

Eye: Small, the diameter considerably less than twice the length of the longest tooth.

Gill slits: Fifth gill slit in front of the pectoral fin. (Fig. 13b).

First dorsal: Midpoint of base considerably nearer the pelvics than the pectorals. (Fig. 15a).

Second dorsal: Almost as large as the first dorsal.

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe (Fig. 20b).
Length of upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal (Fig. 21a).

Teeth: A small basal denticle is present on each side of the cusp (Fig. 11a).
In both jaws the teeth are long in front but decrease in size towards the sides of the jaws where they form a cobblestone-like surface.

Dental formula:

$$\frac{17 \text{ to } 27 \ — \ 0 \ — \ 17 \text{ to } 27}{16 \text{ to } 25 \ — \ 0 \ — \ 16 \text{ to } 25}$$

Colour: Greyish-brown to yellowish-brown above and paler below. In young specimens the posterior part of the body is marked with irregular dark spots but these fade with age and are not always visible in large specimens.

Size: Reaches 10½ feet in length.

Habitat: They live on the bottom in shallow water and are usually found close inshore.

Locality: Not uncommon off the east coast of South Africa. Also found in the Mediterranean, eastern and western Atlantic.

***Season:** In Durban this species is most frequently caught between June and November although specimens have also been obtained in January and March. Gravid females have been caught in March, June and July.

Development: Ovoviviparous—the young are born alive and, prior to their birth, are nourished first on their yolk and later feed on the eggs lying near them in the uterus. Each female bears only two young which are born at a length of approximately 36 inches.

Habits: They are usually solitary and sluggish but are more active at night. They feed in inshore areas on fish and crabs.

Commercial importance: None.

†Records:

Natal Angling Board of Control:
55 lb. Line Test: 649 lbs. E. Scott, 1946.

---

*SEASON: The seasonal notes are based on the specimens obtained by this Institute and the accuracy of these notes therefore rests mainly on the number of specimens obtained by the Institute from anglers. It is hoped that future co-operation of anglers and spearfishermen will enable greater accuracy in the records to be included in the more comprehensive guide to be compiled.

†RECORDS: The records of the Natal Angling Board of Control are as of November, 1963. Those of the South African Anglers Union are as of September, 1963. Those of the Game Fish Union of Africa are as of 31st December, 1963. Those of the International Game Fish Association are as of 31st December, 1963. The records of the Natal Underwater Union are as of October, 1963.

South African Angler's Union:
Caught by members from shore: 649 lbs. E. Scott.
Game Fish Union of Africa:
130 lb. Line Test: 649 lbs. E. Scott 1946.
Natal Underwater: 39 lbs. E. Franken.

2. CARCHARIAS KAMOHARAI

(PLATE 2)

Common names:
JAPANESE RAGGED TOOTH SHARK, Mizuwani.

Description:
Head: Normal, not hammer-shaped. (Fig 3a).
Eye: Large, the diameter twice the length of the longest tooth or more.
Gill slits: Fifth gill slit in front of the pectoral fin. (Fig. 13b).
First dorsal: Midpoint of base at least as near to the pelvics as the pectorals. (Fig. 15a).
Second dorsal: Considerably smaller than the first dorsal fin.
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).
Teeth: No small basal denticle on each side of the cusp. (Fig. 11a).
In both jaws the teeth are long and smooth-edged. They decrease in size towards the sides of the jaws.
Dental formula:

$$\frac{13 \text{ or } 14 \text{ — } 0 \text{ — } 13 \text{ or } 14}{12 \text{ or } 13 \text{ — } 0 \text{ — } 12 \text{ or } 13}$$

Colour: Brownish-grey above, paler beneath.

Size: Probably does not reach much more than 3 to 4 feet in length.

Habitat: Probably warm temperate waters.

Locality: One specimen caught close inshore at Clifton Beach. Cape Town. Also found in Japanese waters and off West Africa.

Season: The only specimen examined was caught off Cape Town in November.

Development: Unknown. Possibly similar to the Ragged Tooth Shark *(C. taurus)*.

Habits: Unknown. The South African specimen was found close inshore swimming feebly.

Commercial importance: Probably marketed as food in Japanese waters.

Records:

No official South African or international angling records for this species could be found.

FAMILY: ISURIDAE

Key to the Species

1a TOOTH MARGINS smooth .... **ISURUS GLAUCUS (3)**

1b TOOTH MARGINS coarsely serrated .... **CARCHARODON CARCHARIAS (4)**

3. ISURUS GLAUCUS

(PLATE 3)

Common Names:

MAKO, Mambone, Sharp-nosed Mackerel Shark, Blue Pointer, Blue Porpoise Shark, Snapper Shark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Mouth: Narrow, the height being more than $\frac{2}{3}$ of the width.

Gill slits: Fifth gill slit in front of the pectoral fin. (Fig. 13b).

Caudal: Lunate, the lower lobe being almost as long as the upper lobe. (Fig. 20a).

Keels: Present. (Fig. 22a).

Teeth: Tooth margins smooth. (Fig. 9b).

No small basal denticles on each side of the cusp. (Fig. 11b).

Dental formula:

$$\frac{11 \text{ to } 13 \text{ — } 0 \text{ — } 11 \text{ to } 13}{12 \text{ to } 15 \text{ — } 0 \text{ — } 12 \text{ to } 15}$$

Colour: Deep blue above, white beneath.

Size: Probably reaches 12 feet in length.

Habitat: Usually found near the surface in warm, deep waters.

Locality: This species is found off the east coast of South Africa and off Madagascar but does not often come inshore. It is also found in tropical, sub-tropical and warm-temperate waters in the Pacific and Indian Oceans.

Season: Off Durban, specimens are usually caught between August and November although one specimen was obtained by this Institute in January. No gravid females have been obtained.

Development: Development is similar to that of the Ragged Tooth Shark *(Carcharias taurus)*.

Habits: This solitary, fast-swimming species is well known as a game-fish and is noted for leaping out of the water when hooked as well as under natural conditions. Feeds on fish and squid. Said to be responsible for attacks on boats.

Commercial importance: Marketed as food.

Records:

Natal Angling Board of Control:

Deep Sea: 18⅜ lbs. R. Nipper 1960.

South African Angler's Union:

Caught by members from shore: 75 lbs. K. J. Lilliecrona.

Caught by non-members from craft at sea: 18⅜ lbs. R. Nipper.

Game Fish Union of Africa:

130 lb. Line Test: 602 lbs. Mrs. M. Marot 1962.

International Game Fish Association:

All Tackle: 1,000 lbs. B. Ross 1943 (New Zealand).

4. CARCHARODON CARCHARIAS

(PLATE 4)

Common Names:

MANEATER, Blue Pointer, Death Shark, White Death Shark, Great White Shark, White Shark, White Pointer, Tommy, Uptail, Sarda, Cowshark, Mudshark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Mouth: Broad, the height being less than ⅔ of the width.

Gill slits: Fifth gill slit in front of the pectoral fin. (Fig. 13b).

Caudal: Lunate, the lower lobe being almost as long as the upper lobe. (Fig. 20a).

Keels: Present. (Fig. 22a).

Teeth: Tooth margins coarsely serrated. (Fig. 9a).

Dental formula:

$$\frac{12 \text{ to } 14 \text{ — } 0 \text{ — } 12 \text{ to } 14}{10 \text{ to } 13 \text{ — } 0 \text{ — } 10 \text{ to } 13}$$

Colour: Blue-black above and white beneath; the undertips of the pectorals are black. This is the colouration observed at this Institute but this species has also been reported as being "slaty-brown" and, in large specimens, "leaden-white" above.

Size: May reach 40 feet in length. Large fossil teeth similar to those of this species come from an extinct species, *Carcharodon megalodon,* which is estimated to have reached 90 feet in length.

Habitat: The Maneater *(Carcharodon carcharias)* is a deep water species, where it is usually found near the surface, but may frequently come inshore, sometimes even into very shallow water.

Locality: Specimens are caught in the Durban area (from South Pier and in the shark nets) and elsewhere off the east coast of South Africa but are nowhere abundant. This species is widely distributed in tropical and warm temperate waters and is found in the Mediterranean, the Atlantic and off Australia.

Season: Off Durban, specimens are usually caught between July and December but they have also been obtained in February and March. No gravid females have been caught.

Development: No account of the developmental stages of this species has been published. Unborn young are said to reach 48 inches in length.

Habits: Usually solitary but sometimes found in groups, this is a swift, strong-swimming species. It feeds on a wide variety of prey including other sharks, large and small fish, seals, turtles, squid and crabs. It is also a scavenger and eats a wide variety of dead animals washed from the shore. Strange objects such as potatoes, coal, etc., have also been found in their stomachs. This species has been proved responsible for attacks on humans and attacks on small boats. In both cases identification has been made possible by tooth fragments broken off in the attack.

Commercial importance: May be eaten.

Records:

Natal Angling Board of Control:

55 lb. Line Test: 880 lbs. M. Geerdts 1934.
All Tackle: 1660 lbs. R. Harrison 1953.

South African Angler's Union:

Caught by members from shore: 880 lbs. M. R. Geerdts and G. T. Bush.
Caught by non-members from shore: 1660 lbs. R. S. Harrison.

Game Fish Union of Africa:

130 lb. Line Test: 1660 lbs. R. Harrison 1953.

International Game Fish Association:

All Tackle: 2664 lbs. A. Dean 1959 (Australia).

FAMILY: ALOPIIDAE

Only one species of this family has been found off the east coast of South Africa.

5. ALOPIAS PELAGICUS

(PLATE 5)

Common Names:

THRESHER SHARK, Thrasher Shark, Whiptail, Fox Shark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Upper lobe very long, being equal in length to the distance from the tip of the snout to the beginning of the caudal. (Fig. 21b).

Teeth: Smooth-edged (Fig. 9b) with one or two small lateral denticles towards the edge of the base on each side of the cusp. (Fig. 11a).

Dental formula:

$$\frac{21 - 2 - 20}{24 - 2 - 22}$$ but may vary slightly.

Colour: Dark blue-grey above, white beneath.

Size: Probably reaches 18 feet in length.

Habitat: A deep water species, found near the surface in tropical and sub-tropical areas but very seldom comes inshore.

Locality: Found off the East Coast of South Africa and off Japan. Probably also occurs elsewhere in the Pacific and Indian Oceans.

Season: The only specimen obtained by this Institute was caught off Margate, Natal South Coast in February.

Development: Ovoviviparous—the young are born alive but do not have a placental connection with their mother. It is said that small numbers of large young are born but no evidence is available.

Habits: An active species, which preys mainly on small shoal fish which it rounds up into tight, easily-attacked shoals using its elongated tail.

Commercial importance: None.

Records: There are apparently no official South African or International angling records for this species.

FAMILY: CARCHARHINIDAE

In this family a number of species are found in South Africa. These are grouped into 5 genera, the key to which is shown below:—

Key to the Genera

1a SPIRACLES present
  2a SNOUT very short and blunt ..... **GALEOCERDO (6)**
  2b SNOUT pointed at tip and of moderate length ..... **GALEORHINUS (7-8)**
1b SPIRACLES absent
  3a MIDPOINT OF THE FIRST DORSAL FIN BASE is considerably nearer to the pelvics than the pectorals .... **PRIONACE (10)**
  3b MIDPOINT OF THE FIRST DORSAL FIN BASE is as close (or closer) to the pectorals as the pelvics.
    4a CUSPS of the upper teeth serrated ..... **CARCHARHINUS (12-25)**
    4b CUSPS of upper teeth smooth-edged.
      5a SECOND DORSAL BASE at least ¾ length of first dorsal base .... **NEGAPRION (9)**
      5b SECOND DORSAL BASE less than ½ as long as first dorsal base ..... **RHIZOPRIONODON (11)**

GENUS: GALEOCERDO

Only one species found off South Africa.

6. GALEOCERDO CUVIERI

(PLATE 6)

Common Names:

TIGER SHARK, Leopard Shark, Requin Renard, Requin demoiselle, Sora Min, Pez Zorro.

Description:

Head: Normal, not hammershaped. (Fig 3a).
Snout: Short and blunt. (Fig. 5a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Present. (Fig. 12b).
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Characteristically cockscomb-shaped. (Plate 6c).

Dental formula:

$$\frac{10 \text{ to } 12 \text{ — } 1 \text{ or } 2 \text{ — } 10 \text{ to } 12}{10 \text{ to } 12 \text{ —— } 1 \text{ —— } 10 \text{ to } 12}$$

Colour: Greyish-brown above with darker markings in the form of spots or bands giving a "tiger-like" appearance. These markings fade with age and may not be apparent in very large specimens. The lower surface is white or off-white.

Size: Reaches at least 18 feet in length.

Habitat: Found in tropical and sub-tropical waters both off-shore and inshore where it may enter bays and river mouths and sometimes very shallow water.

Locality: Found off the east coast of Africa but is not very common. This species is widely distributed and is also found on the east and west coasts of North and South America, in the eastern Atlantic and from Japan to New Zealand.

Season: Has been caught in Durban between May and December. No gravid females have been obtained.

Development: Ovoviviparous—the young are born alive but do not have a placental connection with their mother. There may be from 10 to 82 young in a litter. It is likely that the number of young in the litter increases with the size of the mother. The young are relatively small and may be 18 to 28 inches in length at birth.

Habits: Apparently solitary, these are strong-swimming, active sharks. They are voracious and omnivorous and feed on fish, sharks, rays, squid and crabs. They are also well known for the wide variety of dead animals and extraneous articles found in their stomachs. They are reputed to attack man.

Commercial importance: The liver oil contains a higher vitamin A content than that of most other warm water sharks. Excellent leather can be made from the skin.

Records:

Natal Angling Board of Control:

55 lb. Line Test: 680 lbs. D. Boyes 1963.

All Tackle: 1034 lbs. H. Roseveare 1954.

South African Angler's Union:
Caught by members from shore: 680 lbs. D. L. Boyes.
Caught by non-members from shore: 1034 lbs. H. Roseveare.
Game Fish Union of Africa:
130 lb. Line Test: 1034 lbs. H. Roseveare 1954.
International Game Fish Association:
All Tackle: 1422 lbs. J. Robinson 1958 (Australia).

GENUS: GALEORHINUS

Key to the Species

1a SECOND DORSAL and anal fins about equal in size ..... **GALEUS (7)**

1b SECOND DORSAL about twice the size of the anal ..... **ZANZIBARENSIS (8)**

7. GALEORHINUS GALEUS

(PLATE 7)

Common Names:
SOUPFIN, Liver Oil Shark, Oil Shark, School Shark, Tope, Speareye, Spierhaai, Vaalhaai.

Description:
Head: Normal, not hammershaped. (Fig. 3a).
Snout: Moderately long and pointed. (Fig. 6b).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Present. (Fig. 12b).
Second dorsal: About equal in size to anal.
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).
Teeth: Oblique, but noticeably different from those of the Tiger Shark *(Galeocerdo cuvier)*.
Dental formula:

$$\frac{16 \text{ to } 22 \text{ — } 0 \text{ to } 2 \text{ — } 16 \text{ to } 22}{16 \text{ to } 18 \text{ — } 1 \text{ or } 2 \text{ — } 16 \text{ to } 18}$$

Colour: Dark grey above and whitish beneath. The fins may be dusky tipped.

Size: May attain 6 feet in length.

Habitat: Usually found in deep water.

Locality: Common off Port Elizabeth and the south eastern coast of South Africa. Also found off the west coast of South Africa, the east coast of South America and from Japan to New Zealand. It is also common off Lower California.

Development: No account of the development of this species has been obtained.

Habits: This species is found in groups when pursuing food and is said to be more active at night. It feeds on small fish including bottom-dwelling fish, squid and crustaceans (crabs, etc.). It is almost certainly harmless to humans.

Commercial importance: This is one of the most important commercial species. Its fins are used in the preparation of shark fin soup by the Chinese, the liver oil is rich in Vitamin A and its hide may be used for leather.

Records: There are apparently no official South African or International angling records for this species.

8. GALEORHINUS ZANZIBARENSIS

(PLATE 8)

Common Names:

ZANZIBAR SOUPFIN.

Description:

Head: Normal, not hammershaped. (Fig 3a).

Snout: Moderately long and pointed. (Fig. 6b).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Present. (Fig. 12b).

Second dorsal: About twice the size of the anal.

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal (Fig. 21a).

Teeth: Oblique, but noticeably different from those of the Tiger Shark *(Galeocerdo cuvier)*.

Dental formula:

$$\frac{23 \text{ to } 25 \text{ —— } 2 \text{ —— } 23 \text{ to } 25}{20 \text{ to } 21 \text{ — } 1 \text{ or } 2 \text{ — } 20 \text{ to } 21}$$

Colour: Grey above, lighter beneath. Rear margin of dorsals dark and that of pectorals, pelvics and anal light.

Size: Does not reach 6½ feet in length.

Habitat: Probably in slightly offshore waters.

Locality: Recorded from off Zanzibar and off the Durban and Kenya coasts.

Development: No account of the developmental stages of this species has been obtained.

Habits: Probably similar to those of the Soupfin *(Galeorhinus galeus)*.

Records: There are apparently no official South African or International Angling records for this species.

GENUS: NEGAPRION

Only one species has been found off South Africa.

9. NEGAPRION ACUTIDENS

(PLATE 9)

Common Names:

LEMON SHARK, Kosi Bay Shark, Kosi Shark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
First dorsal: Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).
Second dorsal: Base is at least $\frac{3}{4}$ the length of the first dorsal base.
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of upper lobe less than $\frac{1}{2}$ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).
Teeth: Cusps of the upper teeth are smooth-edged. The teeth are slender and may have a basal denticle (Fig. 11a) on the outer side of the cusp.
Dental formula:

$$\frac{13 \text{ to } 15 \text{ — } 1 \text{ — } 13 \text{ to } 15}{13 \text{ or } 14 \text{ — } 1 \text{ — } 13 \text{ or } 14}$$

Colour: Grey above, white beneath.

Size: Reaches 10 feet in length.

Habitat: Found inshore in warm seas.

Locality: Specimens have been caught at Kosi Bay and Mapelane, Zululand. It is unlikely that this species is found as far south as Durban.

Season: The specimen from Mapelane was caught in May.

Development: No account of the developmental stages of this species has been obtained.

Habits: Nothing is known of the habits or diet of this species.

Commercial importance: Apparently none.

Records:

South African Angler's Union:
Caught by members from shore: 253 lbs. H. E. Keen.

GENUS: PRIONACE

Only one species is found off South Africa.

10. PRIONACE GLAUCA

(Also known as Glyphis glaucus)

(PLATE 10)

Common Names:

BLUE SHARK, Great Blue Shark, Blue Whaler, Requin Bleu, Janiquin.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

First dorsal: Midpoint of base nearer to the pelvics than the pectorals. (Fig. 15a).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Tooth margins coarsely serrated. (Fig. 9a).

Dental formula:

$$\frac{12 \text{ to } 15 \text{ — } 0 \text{ or } 1 \text{ — } 12 \text{ to } 15}{12 \text{ to } 14 \text{ — } 1 \text{ or } 2 \text{ — } 12 \text{ to } 14}$$

Colour: Deep blue above becoming black on death, white beneath. The pectorals may be dusky tipped.

Size: Said to reach 20 feet in length but there is no positive evidence for this. It does, however, reach a length of 13 feet.

Habitat: Found in tropical to warm temperate offshore waters near the surface.

Locality: Off the east and west coasts of South Africa where it is probably one of the most abundant offshore species. It is widely distributed in all oceans, being found off the east coast of America from Newfoundland to Brazil, off the west coast of America near California, Chile, Hawaii and off Japan and Australia.

Season: Owing to the lack of regular offshore shark-catching activities the exact season in the Durban area is not known.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be from 28 to 58 young in a litter and these are born at a length of not less than 20 inches.

Habits: Solitary. Said to be sluggish except when in pursuit of prey when it is a strong, fast swimmer. It usually feeds on small fish and squid but may cause considerable

damage to whales killed by whaling ships. There is no authenticated evidence of this species being responsible for attacks on humans, and as these sharks do not come inshore it is most unlikely that they are responsible for attacks on bathers.

Commercial importance: The meat is smoked and marketed in California. It is also eaten in Japan and Morocco.

Records:

International Game Fish Association:

All Tackle: 410 lbs. R. Webster 1960 (U.S.A.)

GENUS: RHIZOPRIONODON

Only one species has been found off South Africa.

11. RHIZOPRIONODON ACUTUS

(Also known as Scoliodon walbeehmi)

(PLATE 11)

Common Names:

MILK SHARK, Milky, Sharpnosed Shark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

First dorsal: Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Base less than ½ the length of the first dorsal base.

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth smooth-edged. (Fig. 10b).

Dental formula:

$$\frac{12 \text{ or } 13 - 0 \text{ or } 1 - 12 \text{ or } 13}{10 \text{ to } 12 - 2 - 10 \text{ to } 12}$$

Colour: Light to dark grey above, white beneath. There are no conspicuous markings.

Size: Specimens seldom reach more than 3 feet in length.

Habitat: Close inshore in warm waters.

Locality: Common off Durban. Also caught off Lourenco Marques and probably Madagascar. The distribution of this species is probably fairly wide but cannot be ascertained until its nomenclature has been settled.

Season: Caught off Durban throughout the year. Gravid females have been caught in May, July, August and September.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. The litters are small, there being 3 and 5 embryos respectively in each of the two gravid females examined. The young are born at a length of approximately 12 inches.

Habits: Often found in groups and generally active. They feed on small fish and squid. Too small to inflict severe wounds on humans.

Commercial importance: May be eaten.

Records:

Natal Angling Board of Control:

55 lb. Line Test: 10¾ lbs. J. Blamey 1953.

South African Anglers Union:

Caught by members from shore: 10¾ lbs. J. O. Blamey.

GENUS: CARCHARHINUS

15 species belonging to this genus are found off South Africa.

Key to the Species

1a FIRST DORSAL noticeably large with a very broadly rounded apex ..... **LONGIMANUS (12)**

1b FIRST DORSAL with a pointed or moderately rounded apex.

2a FIRST DORSAL white-tipped and the entire trailing edge of caudals deep black ..... **SPALLANZANI (13)**

2b FIRST DORSAL may be white-tipped or not or the trailing edge deep black or not but these do not occur in combination.

3a RIDGE on back between the dorsal fins.

4a FIRST DORSAL vertical height twice the length of the snout or more ... **MILBERTI (14)**

4b FIRST DORSAL vertical height less than twice the length of the snout.

5a SECOND DORSAL low, its posterior margin almost straight.

6a UPPER TEETH consist of narrow cusps on broad bases... **AHENEA (15)**

6b UPPER TEETH triangular, the cusps not distinct from their bases.
7a SNOUT broadly rounded at tip .... **OBSCURUS (16)**
7b SNOUT pointed or narrowly rounded at tip ....
FALCIFORMIS (17)

5b SECOND DORSAL erect, its posterior margin concave.
8a NASAL FLAP long ... **ALTIMUS (18)**
8b NASAL FLAP short ....
GALAPAGENSIS (19)

3b NO RIDGE on back between dorsal fins.
9a SNOUT very short and blunt.
10a TIPS of all fins deep black ....
MELANOPTERUS (20)

10b TIPS of fins may be dark but not deep black.
11a FIRST DORSAL vertical height less than 3½ times that of second dorsal .... **LEUCAS (21)**
11b FIRST DORSAL vertical height more than 3½ times that of second dorsal .... **AMBOINENSIS (22)**

9b SNOUT long to moderately long.
12a SNOUT moderately rounded at tip.
13a SECOND DORSAL erect, its posterior margin concave .....
TJUTJOT (23)

13b SECOND DORSAL low, its posterior margin almost straight
AHENEA (15)

12b SNOUT pointed or narrowly rounded at tip.
14a SECOND DORSAL erect, its posterior margin deeply concave
LIMBATUS (24)

14b SECOND DORSAL low, its posterior margin almost straight
MACULIPINNIS (25)

12. CARCHARHINUS LONGIMANUS

(Also known as Pterolamiops magnipinnis)

(PLATE 12)

Common Name:

WHITE TIPPED SHARK, Requin Canal.

Description:

Head: Normal, not hammershaped. (Fig. 3a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
First dorsal: Noticeably large with a very broadly rounded apex. (Fig. 16a).
Midpoint of the base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).
Teeth: Cusps of the upper teeth are serrated as well as the bases. (Fig. 10a).
Dental formula:

$$\frac{14 \text{ or } 15 \text{ — } 1 \text{ or } 2 \text{ — } 13 \text{ to } 15}{13 \text{ or } 14 \text{ — } 1 \text{ or } 2 \text{ — } 13 \text{ or } 14}$$

Colour: Grey to brown above, off-white beneath. In adults the first dorsal, lower caudal and pectoral fins are tipped with white but in young specimens the fins are tipped with dark grey or black.

Size: Reaches at least 13 feet in length.

Habitat: This species is found near the surface in deep water. It is seldom found in less than 100 fathoms of water.

Locality: Specimens have been caught at the surface approximately 40 miles east of Durban and off Lourenco Marques. A cosmopolitan species, it also occurs in the Mediterranean, Red and Australian Seas and the tropical and sub-tropical Atlantic, Pacific and Indian Oceans.

Season: Owing to lack of regular offshore shark-catching activities the exact season off Durban is not known.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There are 6 to 9 young in a litter and these are born at approximately 27 inches in length.

Habits: Because this species is found so far offshore, little is known of its habits. However, it is probably solitary and active. It feeds on both large and small fish and is

also said to feed on turtles. Said to attack humans but there is no definite evidence. As it does not come inshore it is unlikely to be responsible for attacks on bathers.

Commercial importance: Has not been used commercially.

Records: There are apparently no official South African or International records for this species.

13. CARCHARHINUS SPALLANZANI

(PLATE 13)

Common Names:

BLACK-TAILED GREY, Black Shark, Requin Bar.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

First dorsal: Apex pointed or moderately rounded. (Fig. 16b).

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth are serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{13 \text{ or } 14 \text{ — } 1 \text{ — } 13 \text{ or } 14}{12 \text{ or } 13 \text{ — } 1 \text{ — } 12 \text{ or } 13}$$

Colour: The colour is distinctive for this species in that the posterior part of the lower caudal and the entire rear margin of the upper and lower caudal lobes are deep black and the first dorsal is tipped with white. The body is grey above, white beneath but, when freshly caught, the upper surface is bronze.

Note: This species is most easily distinguished by the white-tipped first dorsal—black-edged caudal colour combination.

Size: Reaches at least 5½ feet in length.

Habitat: Found inshore in warm shallow waters where it may be found in the vicinity of reefs. Also enters deep water where it is quite common between 40 to 50 fathoms.

Locality: Specimens have been recorded from Madagascar, the Mauritius-Seychelles area, Bazaruto and Sordwana Bay. It is unlikely that this species is found as far south as Durban.

It is found in the Red Sea as well as the Indian Ocean.

Season: The only specimen obtained at this Institute was speared at Sordwana Bay in January.

Development: Probably viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 1 to 4 young in a litter and it is likely that the number of young in a litter increases with the size of the mother. The young are born at a length of 20 to 28 inches.

Habits: Unlike most sharks, this species is said to be more active during the day. It is a strong fighter when hooked. It feeds on both surface and bottom-dwelling fish and on squid and octopus.

Commercial importance: It is not known whether the flesh of this shark is marketed.

Records: There are apparently no official South African or International angling records for this species.

14. CARCHARHINUS MILBERTI

(PLATE 14)

Common Names:

SANDBAR SHARK, Brown Shark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
Ridge: Present on the back between the dorsal fins. (Fig. 14a).
First dorsal: Vertical height twice the length of the snout or more.
Apex pointed or moderately rounded. (Fig. 16b).
Midpoint of the base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than $\frac{1}{2}$ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).
Teeth: Cusps of the upper teeth are serrated as well as the bases. (Fig. 10a).
Dental formula:

$$\frac{14 \text{ to } 16 \text{ — } 1 \text{ or } 2 \text{ — } 14 \text{ to } 16}{12 \text{ to } 15 \text{ —— } 1 \text{ —— } 12 \text{ to } 15}$$

Colour: Grey to brown above, off-white beneath. There are no conspicuous markings.

Size: May reach 8 feet in length.

Habitat: Found in warm waters. This is an inshore species which enters bays and river mouths, sometimes coming right into very shallow water. Except in shallow water it rarely occurs near the surface.

Locality: Caught off Durban. Also found off Madagascar, Mauritius and the Seychelles as well as off the east coast of America from New England to Brazil, in the Mediterranean Sea and off the west coast of Africa.

Season: Only 3 specimens have been obtained, one of which was caught in April while the other two were caught in December.

Development: Probably viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. The gestation period is estimated as 8 - 12 months. There may be 1 to 27 young in a litter. They are born at approximately 24 inches in length.

Habits: Mainly solitary but may congregate in schools at times. Said to be more active at night and feed mainly on small bottom fish and invertebrates.

Commercial importance: Vitamin A may be obtained from the liver oil and good quality leather from the skin.

Records: There are apparently no official South African or International angling records for this species.

15. CARCHARHINUS AHENEA

(Also known as Carcharhinus improvisus)

(PLATE 15)

Common Names:

BRONZE SHARK, Bronze Whaler, Spear-eye, Spierhaai, Requin.

Description:

Head: Normal, not hammershaped. (Fig. 3a).
Snout: Moderately long and rounded at the tip. (Fig. 5b).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
Ridge: May or may not be present on the back between the dorsal fins. (Fig. 14).
First dorsal: Vertical height less than twice the length of the snout.
Apex pointed or moderately rounded. (Fig. 16b).
Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Low (Fig. 18b), its posterior margin almost straight. (Fig. 19b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth serrated as well as the bases. (Fig. 10a).
Upper, as well as lower, teeth consist of narrow cusps on broad bases. (Fig. 8a).

Dental formula:

$$\frac{15 \text{ or } 16 \text{ — } 2 \text{ — } 15 \text{ or } 16}{14 \text{ or } 15 \text{ — } 1 \text{ — } 14 \text{ or } 15}$$

Colour: When fresh, bronze above and cream beneath. Later becomes grey-brown above and off-white beneath. There are no conspicuous markings.

Size: The largest specimen recorded was 9 feet in length.

Habitat: Found offshore in warm seas.

Locality: Rare off Durban but more common in the Port Elizabeth area. Also found in False Bay in the Cape, off the Seychelles, Australia and the Philippines.

Season: The only specimen obtained off Durban was a gravid female caught in March.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 10 to 20 young which are born at a length of approximately 24 inches.

Habits: Solitary or found in small groups. Said to be a strong fighter when hooked. Feeds on fish (including bottom-dwelling fish), small sharks and squid.

Commercial importance: Apparently none.

Records: There are apparently no official South African or International angling records for this species.
The 364 lb. and 722 lb. "Square-nose" specimens caught by D. E. Damp and G. J. Schmidt are incorrectly recorded by the South African Anglers Union as Smith No. 6a.

16. CARCHARHINUS OBSCURUS

(PLATE 16)

Common Names:
DUSKY SHARK, Ridge-Backed Grey, Lazy Grey, Brown Shark (Cape Town), Shovelnose (U.S.A.), Farqueita, Tiburon.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Snout: Broadly rounded at tip. (Fig. 6a).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

Ridge: Present on back between the dorsal fins. (Fig. 14a).

First dorsal: Vertical height less than twice the length of the snout.

Apex pointed or moderately rounded. (Fig. 16b).

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Low (Fig. 18b) its posterior margin almost straight. (Fig. 19b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of upper teeth serrated as well as the bases. (Fig 10a).

Upper teeth triangular, the cusps not distinct from the bases. (Fig. 10a).

Dental formula:

$$\frac{14 \text{ or } 15 \text{ — } 2 \text{ — } 14 \text{ or } 15}{13 \text{ to } 15 \text{ — } 1 \text{ — } 13 \text{ to } 15}$$

Colour: Grey to grey-brown above and white to off-white beneath. Adults usually appear darker than juveniles. The fins are dusky-tipped.

Size: Reaches 12 feet in length and is reputed to grow longer although there is no positive evidence for this.

Habitat: A warm water shark which is found both inshore and offshore.

Locality: Off Durban specimens of less than 4 feet are common in the Umgeni mouth area and along the coast, while females of over 10 feet are caught in the shark nets and from the South Pier. The intermediate sizes, however, are rare and no adult males have been recorded at this Institute. This species is also found in tropical and sub-tropical waters off the east coast of Africa, Madagascar and both sides of the Atlantic.

Season: Caught off Durban mainly between July and December. Specimens have also been obtained in January, April and June. Gravid females have been caught in April, September (1 in each) and 2 in December.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 9 to 12 young (usually 10) which are born at a length of approximately.36 inches. As adult females, some of

which are gravid, and very young specimens are common in Durban, while intermediate sizes and males are absent, it is assumed that this species drops its young near Durban.

Habits: Young specimens usually occur in groups although the adults may be solitary. Feeds on fish (including bottom-dwelling fish), sharks and squid.

Commercial importance: May be utilized for leather.

Records:

Natal Angling Board of Control:
55 lb. Line Test: 620 lbs. G. Ledingham 1956.
All Tackle: 720 lbs. T. Low 1946.
South African Anglers Union:
Caught by members from shore: 625 lbs. E. B. Downing.
Caught by non-members from shore: 720 lbs. T. Low.
Game Fish Union of Africa:
130 lbs. Line Test: 257 lbs. T. D. van der Merwe 1962.
Note: At least some of the early records for "Black Sharks" probably refer to this species.

17. CARCHARHINUS FALCIFORMIS

(PLATE 17)

Common Name:

SILKY SHARK.

Description:

Head: Normal, not hammershaped. (Fig. 3a).
Snout: Pointed or narrowly rounded at tip. (Fig. 6b).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
Ridge: Present on back between the dorsal fins. (Fig. 14a).
First dorsal: Vertical height less than twice the length of the snout.
Apex pointed or moderately rounded. (Fig. 16b).
Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).
Second dorsal: Low (Fig. 18b) its posterior margin almost straight. (Fig. 19b).
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).
Teeth: Cusps of upper teeth serrated as well as the bases. (Fig. 10a).
Upper teeth triangular, the cusps not distinct from the bases. (Fig. 8a).

Dental formula:

$$\frac{14 \text{ to } 16 \text{ — } 1 \text{ to } 3 \text{ — } 14 \text{ to } 16}{14 \text{ or } 15 \text{ — } 1 \text{ to } 3 \text{ — } 14 \text{ or } 15}$$

Colour: Dark grey above, off-white beneath. The fins may be dusky-tipped.

Size: May reach a length of 10 feet.

Habitat: Found in tropical and sub-tropical waters. This is an offshore species but occasionally enters inshore waters. Young specimens may occur near shallow offshore banks.

Locality: Only one specimen has been obtained from the Durban area. Also found off West Africa and from Delaware Bay in the U.S.A., to the West Indies.

Season: The only specimen examined at this Institute was 4 feet in length and was caught in September.

Development: The young are born at approximately 30 inches in length. No further details of the development of this species have been obtained.

Habits: Nothing definite known of its habits or diet.

Commercial importance: Used for leather and Vitamin A.

Records: There are apparently no official South African or International records for this species.

18. CARCHARHINUS ALTIMUS

(PLATE 18)

Common Name:
BIGNOSE SHARK.

Description:
Head: Normal, not hammershaped. (Fig. 3a).
Nasal flap: Long. (Fig. 7a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
Ridge: Present on the back between the dorsal fins. (Fig. 14a).
First dorsal: Vertical height less than twice the length of the snout.
Apex pointed or moderately rounded. (Fig. 16b).
Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).
Second dorsal: Erect (Fig. 18a), its posterior margin concave. (Fig. 19a).
Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{14 \text{ to } 16 \text{ — } 1 \text{ or } 2 \text{ — } 14 \text{ to } 16}{14 \text{ or } 15 \text{ —— } 1 \text{ —— } 14 \text{ or } 15}$$

Colour: Light grey above, off-white beneath. The fins may be dusky-tipped.

Size: This species may reach over 11 feet in length.

Habitat: Towards the edge of continental shelves in tropical and sub-tropical waters.

Locality: This species has been caught in 50 fathoms off Durban where specimens of less than 5 feet in length are not uncommon. Also found off Madagascar, West Africa and in the West Indian region.

Season: Owing to the lack of regular fishing activities in this area no exact season is known. In three years, however, all specimens obtained at this Institute were caught between the months of July and November. No gravid females have been obtained.

Development: There are 6 to 8 young in a litter and they are born at a length of approximately 26 inches. No further details of the development have been obtained.

Habits: Feeds largely on fish and small sharks.

Commercial importance: May be utilised for leather and Vitamin A.

Records: There are apparently no official South African or International angling records for this species.

19. CARCHARHINUS GALAPAGENSIS

(PLATE 19)

Common Name:

GALAPAGOS SHARK.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Nasal flap: Short. (Fig. 7b).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

Ridge: Present on the back between the dorsal fins. (Fig. 14a).

First dorsal: Vertical height less than twice the length of the snout.

Apex pointed or moderately rounded. (Fig. 16b).

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Erect (Fig. 18a), its posterior margin concave. (Fig. 19a).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{14 - 1 - 14}{14 - 1 - 14}$$ but may vary slightly.

Colour: Grey above, off-white beneath. Often mottled with grey. The fins may be dusky-tipped.

Size: Attains a length of 11 feet or more.

Habitat: This species is typically found in warm waters surrounding oceanic islands of volcanic origin. Usually found 3 to 10 feet above the sea bottom.

Locality: The only known locality off the east coast of South Africa is in the region of the Walters Shoal in the South Madagascar Ridge. It is also found in the eastern Pacific in the vicinity of the Revilla Gigedo, Clipperton, Coco and Galapagos Islands off the west coast of Central America.

Season: Only 4 specimens have been obtained by this Institute and these were caught on the Walters Shoal in February 1963.

Development: No account of the development of this species has been obtained.

Habits: Although often present in large numbers, there appears to be no schooling behaviour. Said to feed at the surface and at midwater but not on the sea bottom where they often swim. May act aggressively towards divers.

Commercial importance: Probably do not occur in sufficient numbers within reach of shark fisheries to be of much importance.

Records: There are no official South African or International angling records for this species.

20. CARCHARHINUS MELANOPTERUS

(PLATE 20)

Common names:
BLACK SHARK, Blackfin Shark, Nilow, Requin noir.

Description:
Head: Normal, not hammershaped. (Fig. 3a).
Snout: Short and blunt. (Fig. 5a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).

Ridge: No ridge on the back between the dorsal fins. (Fig 14b).

First dorsal: Apex pointed or moderately rounded. (Fig. 16b). Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than $\frac{1}{2}$ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: The cusps of the upper teeth are serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{13 - 2 - 13}{12 - 1 - 12}$$ but may vary slightly.

Colour: The colour is characteristic of this species in that the tips of all the fins are dark black. The lower caudal lobe may be almost entirely black.

Size: Seldom exceeds 5 feet in length.

Habitat: Found in warm waters, both shallow (in the vicinity of coral reefs and inside harbours) and deep, where it is often found at 25 fathoms.

Locality: The only specimen examined at this Institute was caught at Bazaruto and it seems unlikely that this species occurs as far south as Durban. It is likely that the "Black Sharks" repeatedly recorded before World War II were what are known today as "Grey Sharks", viz. Ridge-backed-grey *(Carcharhinus obscurus)* and Slipway-grey or Zambezi Sharks *(Carcharhinus leucas)*. It is found off the tropical east coast of Africa, Madagascar, Hawaiian Islands, western Pacific and Australia.

Season: Only one specimen has been obtained by this Institute. It was caught off Bazaruto in November 1960.

Development: There are 2 to 4 young in a litter and these are born at 18 to 20 inches in length.

Habits: Said to be migratory and to swim strongly. Feeds on fish. Is said to be aggressive and a nuisance to shell collectors near coral reefs.

Commercial importance: Too small to be of commercial importance off Madagascar. Its importance elsewhere is not known.

Records: The Natal Angling Board of Control and South African Anglers Union records for this species probably apply to *C. obscurus* and possibly *C. leucas* (see locality notes).

21. CARCHARHINUS LEUCAS

(Also known as Carcharhinus zambezensis and Carcharhinus vanrooyeni)

(PLATE 21)

Common Names:

ZAMBEZI SHARK, Shovelnose Grey, Slipway Grey (Durban), Bull Shark, Cub Shark, Ground Shark, River Shark, Lake Nicaragua Shark, Van Rooyen's Shark, Square-nose Shark.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Snout: Short and blunt. (Fig. 5a).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

Ridge: No ridge on the back between the dorsal fins. (Fig. 14b).

First dorsal: Vertical height less than $3\frac{1}{2}$ times that of the second dorsal.*

Apex pointed or moderately rounded. (Fig. 16b).

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than $\frac{1}{2}$ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{12 \text{ or } 13 \text{ — } 1 \text{ — } 12 \text{ to } 14}{12 \text{ or } 13 - 1 \text{ or } 2 - 12 \text{ or } 13}$$

Colour: Grey above, off-white beneath. The fins are dusky-tipped, more darkly so in juveniles.

Size: Reaches 10 feet in length. Probably does not exceed 450lb.

Habitat: Found close inshore often in shoal water. They enter harbours, estuaries and may be found in fresh water.

Locality: Specimens longer than 5 feet are common off Durban while smaller specimens are caught at St. Lucia Estuary. It has been caught off the east coast of Africa from the Zambezi River to Algoa Bay and has been reported from Knysna. Small specimens have been caught over 300 miles from the sea in the Zambezi River. It is also found off Madagascar, Australia and in the western Atlantic from Brazil to the vicinity of New York.

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*This proportion is the feature which distinguishes *C. amboinensis* from *C. leucas*.

Season: Specimens are caught off Durban throughout the year, the catches being higher between December and March. The only gravid female obtained by this Institute was caught in June 1963.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There are 5 or 6 young in a litter and they are born at a little more than 24 inches in length.

Habits: Feeds on fish, other sharks, rays, squid, and is a scavenger feeding on dead animals and whale meat washed from the shore. An aggressive species, has been proved responsible for an attack on a human off the Natal South Coast and is probably responsible for most of the attacks in this area.

Commercial importance: May be utilized for fish meal, leather and liver oil.

Records:

The Natal Angling Board of Control:
55 lb. Line Test: 518 lbs. G. Ledingham 1956.
All Tackle: 722 lbs. G. Schmidt 1950.

South African Anglers Union:
Caught by members from shore: 364 lbs. D. E. Damp.
Caught by non-members from shore: 722 lbs. G. J. Schmidt.

There is some doubt concerning the identification of the 518 lb. and 722 lb. specimens as the Zambezi Shark *(C. leucas)*.

22. CARCHARHINUS AMBOINENSIS

(Also known as Carcharhinus zambezensis)

(PLATE 22)

Common Name:
JAVA SHARK.

Description:

Head: Normal, not hammershaped. (Fig. 3a).
Snout: Short and blunt. (Fig 5a).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracles: Absent. (Fig. 12a).
Ridge: No ridge on the back between the dorsal fins. (Fig. 14b).
First dorsal: Vertical height more than $3\frac{1}{2}$ times that of the second dorsal.*
Apex pointed or moderately rounded. (Fig. 16b).

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*This proportion is the feature which distinguishes *C. amboinensis* from *C. leucas*.

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{12 \text{ or } 13 \text{ — } 1 \text{ — } 12 \text{ or } 13}{11 \text{ or } 12 \text{ — } 1 \text{ — } 11 \text{ or } 12}$$

Colour: Grey above, off-white beneath. The fins are dusky-tipped.

Habitat: Found in warm waters and may come inshore. Otherwise not known.

Locality: This species has been caught in the Swartkops River, Algoa Bay and off Durban and Winklespruit. It also occurs in the Batavian Seas and off Java.

Season: Specimens have been caught off Durban in every month except April, October and November. There have been no gravid females.

Development: No account of the development has been obtained.

Habits: Feeds on fish, other sharks and squid.

Commercial importance: No records are available.

Records: There are no official angling records for this species.

23. CARCHARHINUS TJUTJOT

(PLATE 23)

Common Names:

BLACKSPOT SHARK, Lesser Black Shark, Requin nene pointe.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Snout: Long and broadly rounded at the tip. (Fig. 5b).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracles: Absent. (Fig. 12a).

Ridge: No ridge on back between the dorsal fins. (Fig. 14b).

First dorsal: Apex pointed or moderately rounded. (Fig. 16b).
Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Erect, (Fig. 18a) its posterior margin concave. (Fig 19a).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).
Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: The cusps of the upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{11 \text{ to } 13 \text{ — } 2 \text{ or } 3 \text{ — } 11 \text{ to } 13}{11 \text{ to } 13 \text{ — } 1 \text{ — } 11 \text{ to } 13}$$

Colour: Pale grey above, white beneath. The apex of the second dorsal is black.

Size: These are small sharks and it is unlikely that they reach 4 feet in length.

Habitat: Found close inshore in warm waters.

Locality: Occasionally caught off Durban. Also found off Zanzibar and Bazaruto.

Season: Specimens have only been caught off Durban during August and September. There have been no gravid females.

Development: The young are born at a length greater than 9 inches. No further details of the development have been obtained.

Habits: No account of its habits or diet has been obtained.

Commercial importance: Probably marketed as food.

Records: Included in the records of the Natal Angling Board of Control is a 9lb. specimen caught off the Seychelles.
South African Anglers Union:
Caught by members from shore: 9 lbs. A. R. Thorpe.
The South African Angler's Union record this specimen as Smith No. 7a. This is incorrect for the new edition of Smith "The Sea Fishes of Southern Africa" in which no number is given for this species.

24. CARCHARHINUS LIMBATUS

(PLATE 24)

Common Names:
BLACK FIN, Small Black-tipped Shark, Lesser Black-tipped Shark, Spierhaai.

Description:
Head: Normal, not hammershaped. (Fig. 3a).
Snout: Long to moderately long and pointed or narrowly rounded at tip. (Fig 6b).
Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).
Spiracle: Absent. (Fig. 12a).
Ridge: No ridge on back between dorsal fins. (Fig. 14b).

First dorsal: Apex pointed or moderately rounded. (Fig 16b).

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Erect (Fig. 18a) its posterior margin concave. (Fig. 19a).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than ½ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{15 \text{ or } 16 - 2 \text{ or more} - 15 \text{ or } 16}{14 \text{ to } 16 \text{ —— } 1 \text{ —— } 14 \text{ to } 16}$$

Colour: Grey above, off-white beneath. The fins are dusky-tipped, more darkly so in juveniles.

Size: Reaches 8 feet in length.

Habitat: Found in warm waters both inshore and offshore.

Locality: Caught from Durban to Knysna. Also found in tropical and sub-tropical seas off Madagascar, the Canaries, Cape Verde Islands and West Africa and in the western Atlantic and eastern Pacific Oceans.

Season: Specimens have been caught off Durban throughout the year. Gravid females have been caught in August, September and November.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 3 to 10 young in a litter and they are born at a length of about 27 inches.

Habits: These sharks often school; they are active and swift-swimming and may leap out of the water. They feed on fish, sharks, rays and squid.

Commercial importance: Can be eaten and are used for hides and oil.

Records:

Natal Angling Board of Control:

55 lb. Line Test: 320 lbs. G. Germishuys 1949.

South African Anglers Union:

Caught by members from shore: 340 lbs. W. H. Berndt.

The 735 lb. specimen caught by J. B. Steek is incorrectly recorded by the South African Angler's Union as a Blackfin, Smith No. 5. This specimen has previously been recorded as a "Black Shark", the identity of which is probably the Dusky Shark *(C. obscurus)*—see locality notes of the Black Shark *(C. melanopterus)*.

Natal Underwater: 44 lbs. P. N. Malherbe.

25. CARCHARHINUS MACULIPINNIS

(Also known as Carcharhinus johnsoni)

(PLATE 25)

Common Names:

BLACK TIPPED SHARK, Long Nosed Grey, Long Nosed Blackfin, Sharp-nosed Blackfin, Requin nene pointe.

Description:

Head: Normal, not hammershaped. (Fig. 3a).

Snout: Long to moderately long and pointed to narrowly rounded at tip. (Fig. 6b).

Gill slits: Fifth gill slit above the pectoral fin. (Fig. 13a).

Spiracle: Absent. (Fig. 12a).

Ridge: No ridge on back between dorsal fins. (Fig. 14b).

First dorsal: Apex pointed or moderately rounded. (Fig 16b).

Midpoint of base is as close (or closer) to the pectorals as the pelvics. (Fig. 15b).

Second dorsal: Low (Fig 18b) its posterior margin almost straight. (Fig. 19b).

Caudal: Not lunate, the lower lobe being considerably shorter than the upper lobe. (Fig. 20b).

Length of the upper lobe less than $\frac{1}{2}$ the distance from the tip of the snout to the beginning of the caudal. (Fig. 21a).

Teeth: Cusps of the upper teeth serrated as well as the bases. (Fig. 10a).

Dental formula:

$$\frac{16 \text{ to } 18 \text{ — } 1 \text{ or } 2 \text{ — } 16 \text{ to } 18}{15 \text{ to } 17 \text{ — } 1 \text{ or } 2 \text{ — } 15 \text{ to } 17}$$

Colour: Grey above off-white beneath. In young specimens there are no markings but in specimens of between 2 and 3 feet in length the second dorsal becomes tipped with black while the anal, lower caudal and pectoral fins are dusky-tipped. In specimens of over 4 feet in length the tips of the second dorsal, anal, lower caudal and underside of the pectorals are black. The pelvics usually have no markings.

Size: Specimens may reach 9 feet in length.

Habitat: Found in warm waters apparently both inshore and offshore.

Locality: Caught off Durban but not abundant. Also found off Port Elizabeth, Madagascar, Southern Florida, Cuba and possibly Puerto Rico.

Season: Specimens have been caught off Durban in every month except February. Gravid females have been caught in April and September.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 6 to 15 young in a litter and they are born at 24 to 31 inches in length.

Habits: May be seen in schools, leaping at the surface. It feeds on fish. Other prey have not been reported.

Commercial importance: May be utilised for fishmeal, hides and liver oil.

Records:

Natal Angling Board of Control:
55 lb. Line Test: 142 lbs. R. Heslop 1954.
South African Anglers Union:
Caught by members from shore: 142 lbs. R. M. Heslop.
Natal Underwater: 64 lbs. G. Askew.

FAMILY: SPHYRNIDAE

Key to the Species

1a CENTRE of anterior edge of hammer not notched ..... **SPHYRNA ZYGAENA (26)**

1b CENTRE of anterior edge of hammer notched

2a CUSPS of upper teeth smooth-edged ..... **SPHYRNA LEWINI (27)**

2b CUSPS of upper teeth serrated ..... **SPHYRNA MOKARRAN (28)**

26. SPHYRNA ZYGAENA

(PLATE 26)

Common Names:

HAMMERHEAD, Balance Fish, Cornuda.

Description:

Head: Hammershaped. (Fig. 3b).
Centre of anterior edge of hammer not notched. (Fig. 4b).

Dental formula:

$$\frac{13 \text{ to } 15 \text{ — } 0 \text{ or } 1 \text{ — } 13 \text{ to } 15}{12 \text{ to } 14 \text{ —— } 1 \text{ —— } 12 \text{ to } 14}$$

Colour: Grey above, white beneath. The fins may be dusky-tipped.

Size: May reach 13 feet in length.

Habitat: Are found in tropical to warm temperate seas and may be found inshore but more commonly offshore. Usually swim near the surface.

Locality: Specimens have been obtained from off Lourenco Marques, Durban and Port Elizabeth. It is also found in tropical and warm temperate waters in the Atlantic and Pacific Oceans.

Season: Specimens have been caught off Durban from May to January. No adult specimens have been obtained.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 29 to 37 young in a litter. They are born at about 19 inches in length.

Habits: This is a strong-swimming species, which feeds on fish, sharks, rays, crustaceans (crabs, etc.) and squid. At least one Hammerhead species is known to attack man.

Commercial importance: May be used for fish meal, leather and liver oil.

Records: There are apparently no official International angling records for this species. The South African record hammerhead was misidentified as the Hammerhead *(S. zygaena)* and is actually the Great Hammerhead *(S. mokarran)*.

27. SPHYRNA LEWINI

(Also confused with Sphyrna zygaena)

(PLATE 27)

Common Name:

BRONZE HAMMERHEAD.

Description:

Head: Hammershaped. (Fig. 3b).

Centre of anterior edge of hammer notched. (Fig. 4a).

Teeth: Cusps of upper teeth smooth-edged. (Fig. 10b).

Dental formula:

$$\frac{15 \text{ or } 16 \text{ — } 0 \text{ to } 2 \text{ — } 15 \text{ or } 16}{15 \text{ or } 16 \text{ — } 1 \text{ or } 2 \text{ — } 15 \text{ or } 16}$$

Colour: Bronze when fresh, or grey above, white beneath. The pectorals and lower caudal may be dark-tipped.

Size: Reaches at least 10 feet in length.

Habitat: Are found in tropical to warm temperate seas and may be found inshore and offshore. Usually swim near the surface.

Locality: In Durban, males are caught off the South Pier while small specimens are not uncommon off the Umgeni mouth. This species is also found off Madagascar and in the tropical and warm temperate waters of the Atlantic and Indo-Pacific Oceans.

Season: Specimens have been caught off Durban from May to January. The maximum number of specimens being caught in December. No adult females have been obtained.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. The number of young in a litter is not known. At birth they may be about 15 inches in length.

Habits: This is a fast-swimming species. It feeds on fish, crustaceans (crabs, etc.) and squid. Large specimens also probably feed on other sharks and rays. At least one Hammerhead species is known to attack man.

Commercial importance: Probably used for fish meal, leather and liver oil as well as for food.

Records: No records have been claimed for this species.

28. SPHYRNA MOKARRAN

(PLATE 28)

Common Name:
GREAT HAMMERHEAD.

Description:
Head: Hammershaped. (Fig. 3b).
Centre of anterior edge of hammer notched. (Fig. 4a).
Adult specimens can be distinguished from both the Bronze Hammerhead *(lewini)* and the Hammerhead *(zygaena)* by means of the very straight hammer the edges of which are on a level with, and not behind the centre of the hammer. In young specimens, however, the hammer is very similar to that of the Bronze Hammerhead *(lewini)*.
Teeth: Cusps of upper teeth finely serrated. (Fig. 10a).
Dental formula:

$$\frac{17 \text{ —— } 2 \text{ or } 3 \text{ —— } 17}{16 \text{ or } 17 \text{ — } 1 \text{ to } 3 \text{ — } 16 \text{ or } 17}$$

Colour: Very dark above, white beneath. Has also been described as "brownish" and "dark olive" above.

Size: Reaches at least 15 feet in length.

Habitat: Found in tropical to warm-temperate seas and may be found both inshore and offshore. Usually swims near the surface.

Locality: In the Durban area this species is not uncommon off the South Pier, although only one specimen has been obtained by this Institute. Also found off Madagascar and in the tropical and subtropical areas of the Atlantic.

Season: The only specimen obtained by this Institute was caught in August.

Development: Viviparous—the unborn young absorb nutriment from their mother by means of a yolk sac placenta. There may be 30 to 38 young in a litter. They are born at about 24 inches in length.

Habits: These are strong-swimming sharks. Their diet is probably similar to that of the Bronze Hammerhead *(S. lewini)* and the Hammerhead *(S. zygaena)*. At least one Hammerhead species is known to attack man.

Commercial importance: Some specimens are very rich in Vitamin A. Can also be utilized for leather, fish-meal, etc.

Records:

Natal Angling Board of Control:

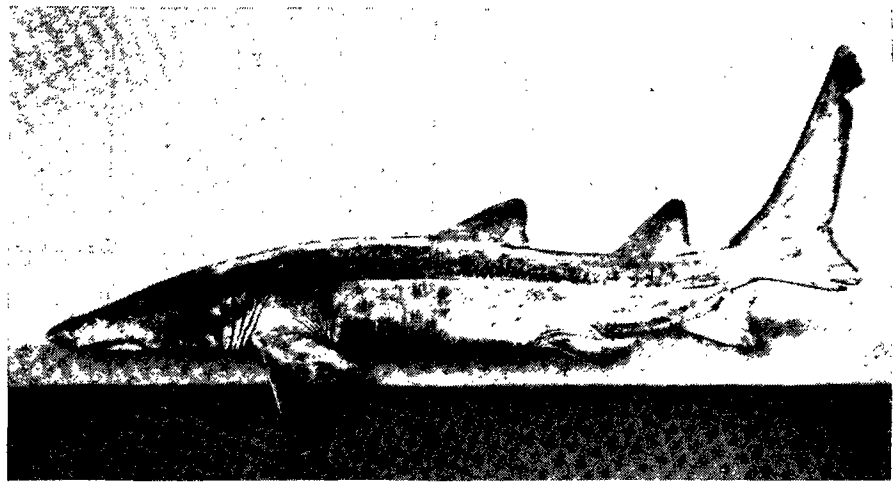
55 lb. Line Test: 295 lbs. G. Ledingham 1962.

All Tackle: 664 lbs. B. Blaine 1936.

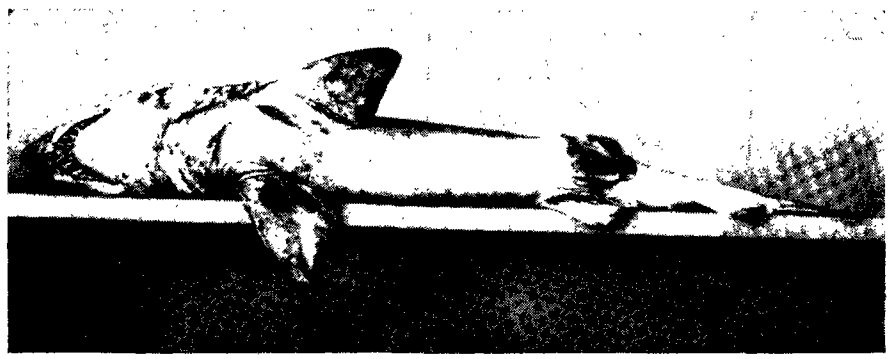
Game Fish Union of South Africa:

130 lb. Line Test: 664 lbs. B. Blaine 1936.

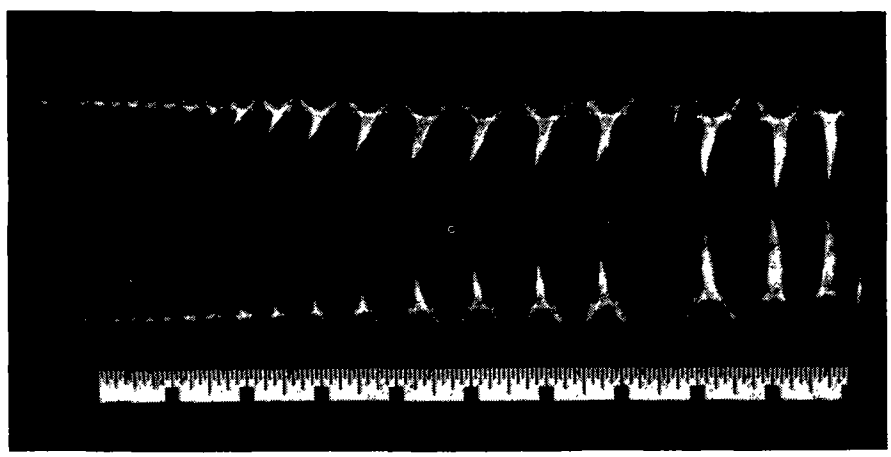
(This shark was misidentified as the Hammerhead, *S. zygaena)*.



(a) Lateral view. Total length 9 feet.

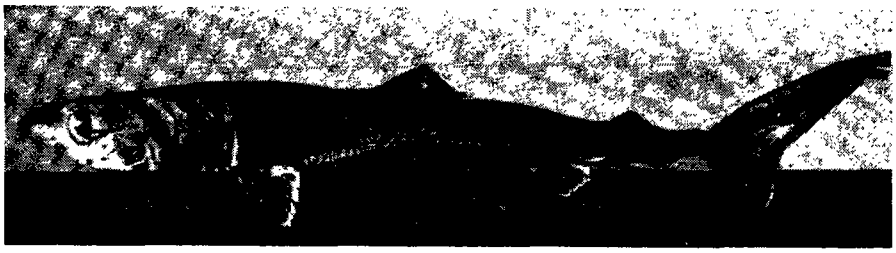


(b) Ventral view. Total length 9 feet.



(c) Teeth of left side of upper and lower jaws.

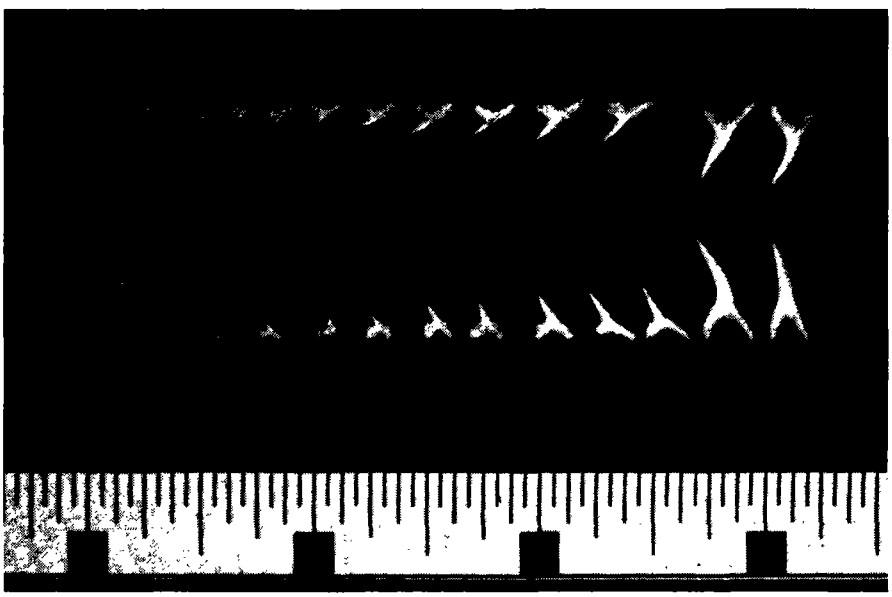
PLATE 1 — **CARCHARIAS TAURUS.**
THE RAGGED TOOTH SHARK



(a) Lateral view. Total length 2 feet 8 inches.

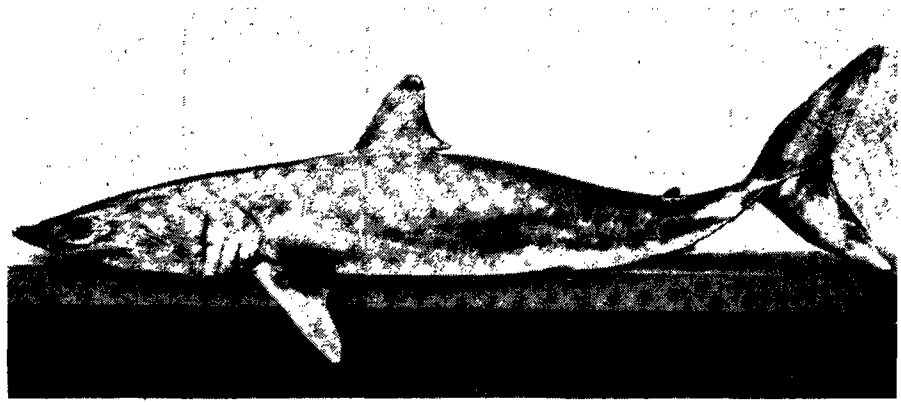


(b) Ventral view. Total length 2 feet 8 inches.

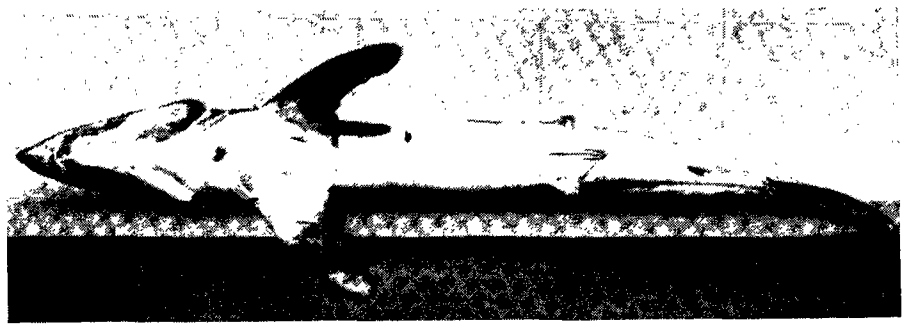


(c) Teeth of left side of upper and lower jaws.

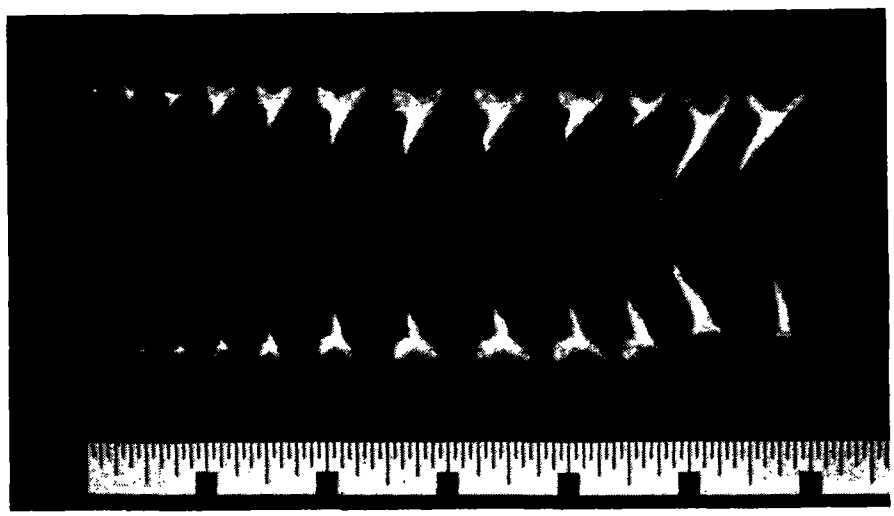
PLATE 2 — **CARCHARIAS KAMOHARAI.** MIZUWANI



(a) Lateral view. Total length 3 feet 10 inches.

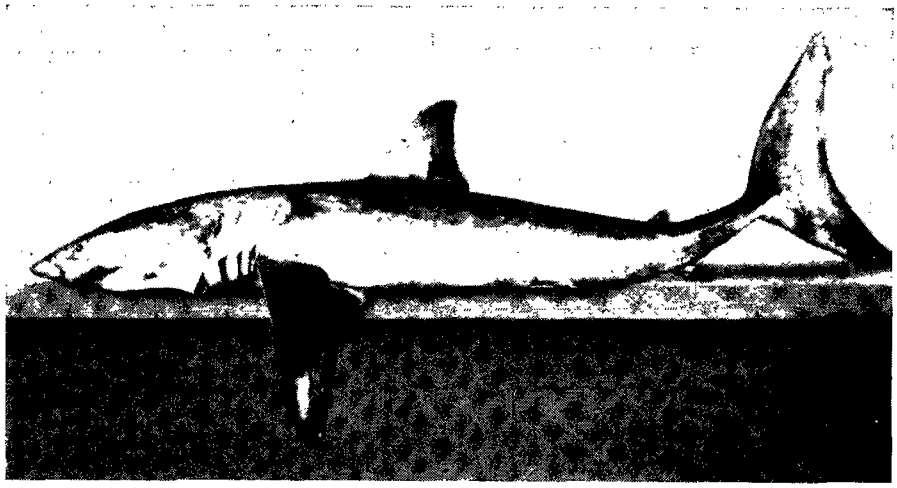


(b) Ventral view. Total length 3 feet 4 inches.

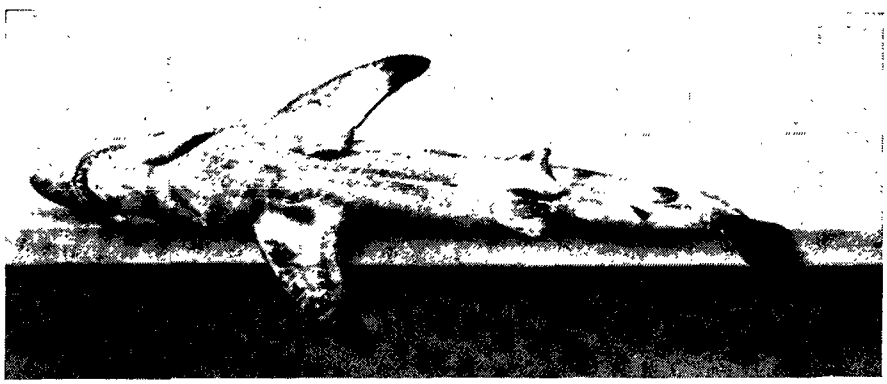


(c) Teeth of left side of upper and lower jaws.

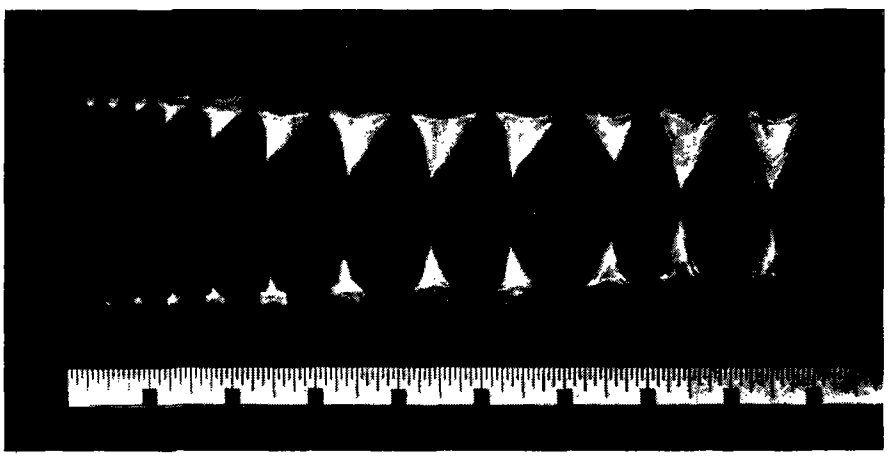
PLATE 3 — **ISURUS GLAUCUS.** MAKO



(a) Lateral view. Total length 7 feet 3 inches.

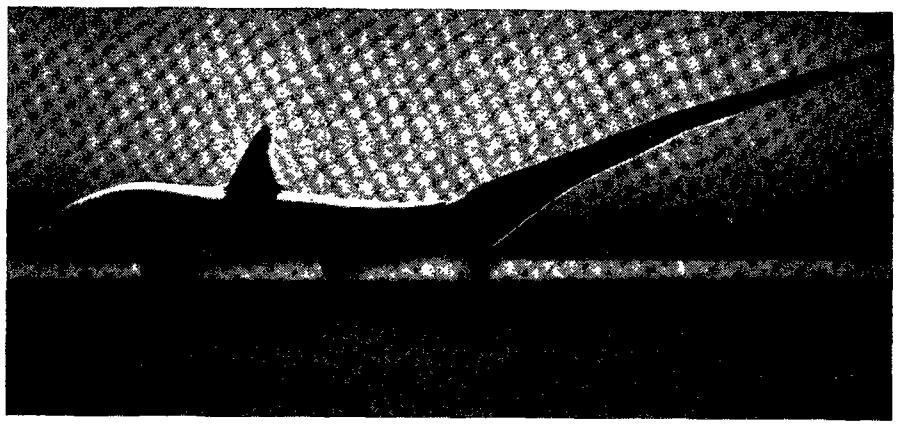


(b) Ventral view. Total length 7 feet 3 inches.

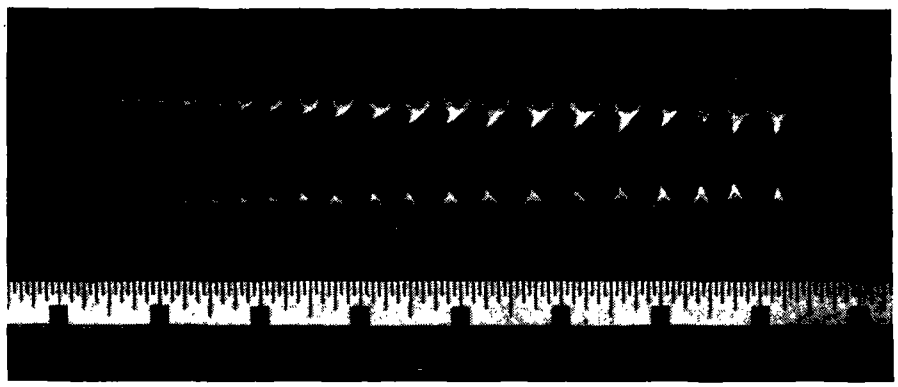


(c) Teeth of left side of upper and lower jaws.

PLATE 4 — **CARCHARODON CARCHARIAS.** MANEATER

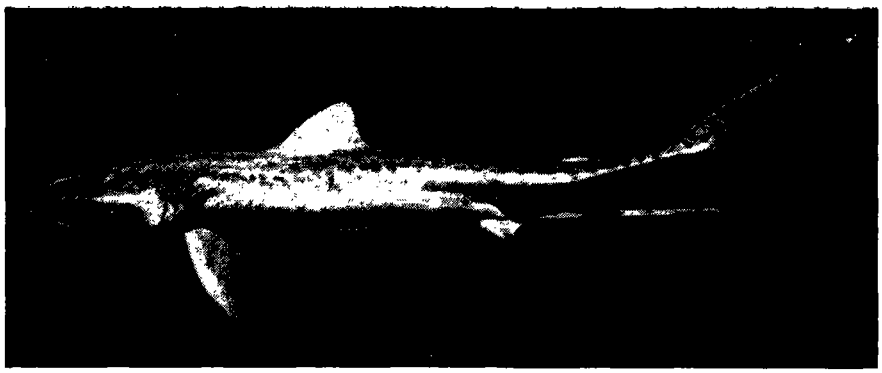


(a) Lateral view. Total length 12 feet 6 inches.

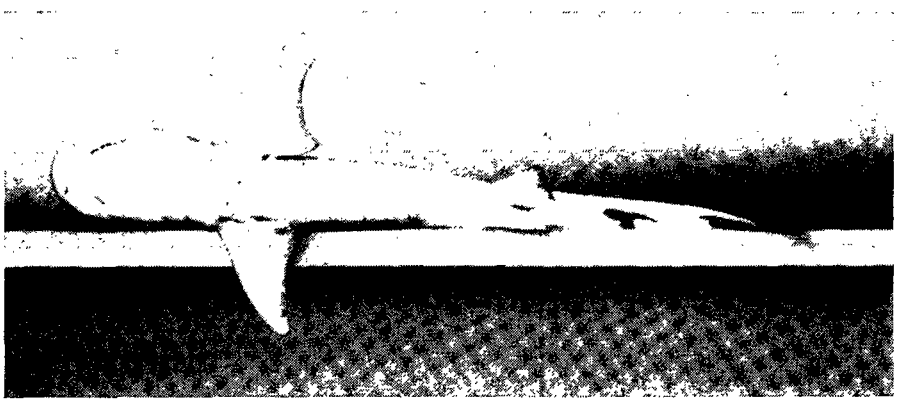


(c) Teeth of left side of upper and lower jaws.

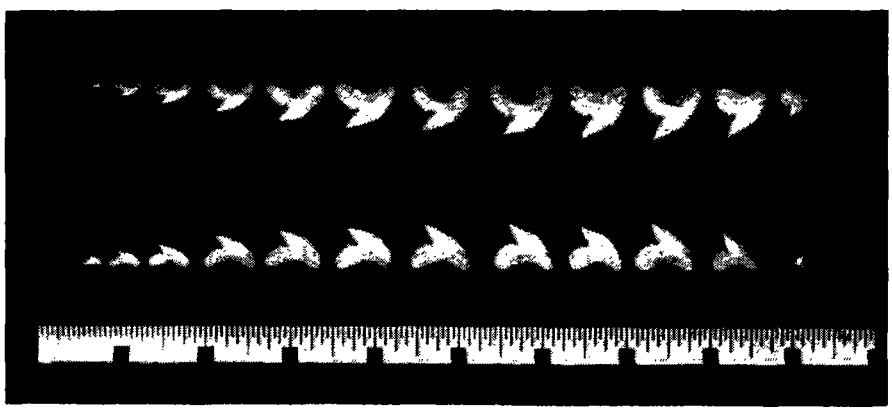
PLATE 5 — **ALOPIAS PELAGICUS.** THRESHER SHARK



(a) Lateral view. Total length 5 feet.

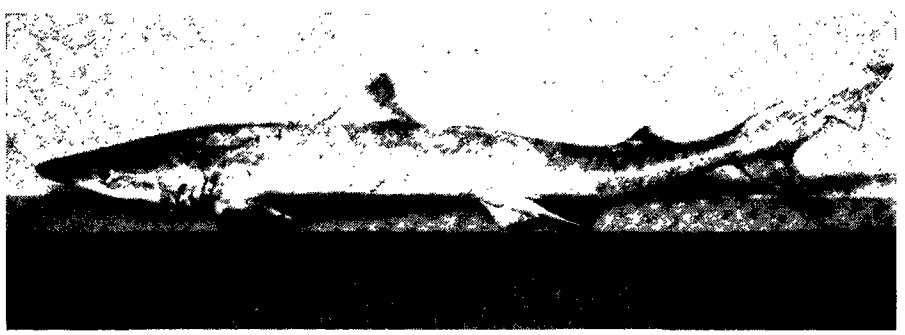


(b) Ventral view. Total length 5 feet 6 inches.

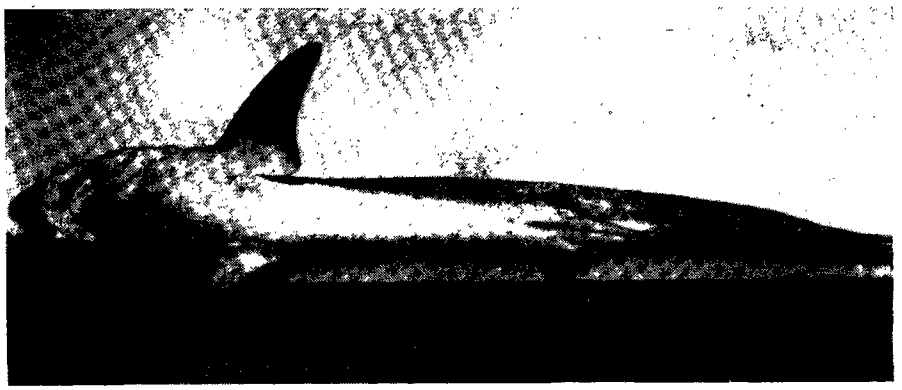


(c) Teeth of left side of upper and lower jaws.

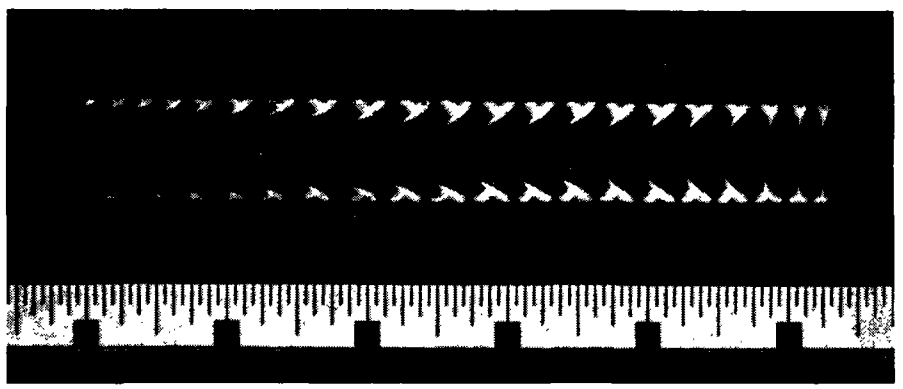
PLATE 6 — **GALEORCERDO CUVIERI.** TIGER SHARK



(a) Lateral view. Total length 4 feet 6 inches



(b) Ventral view. Total length 4 feet 6 inches.

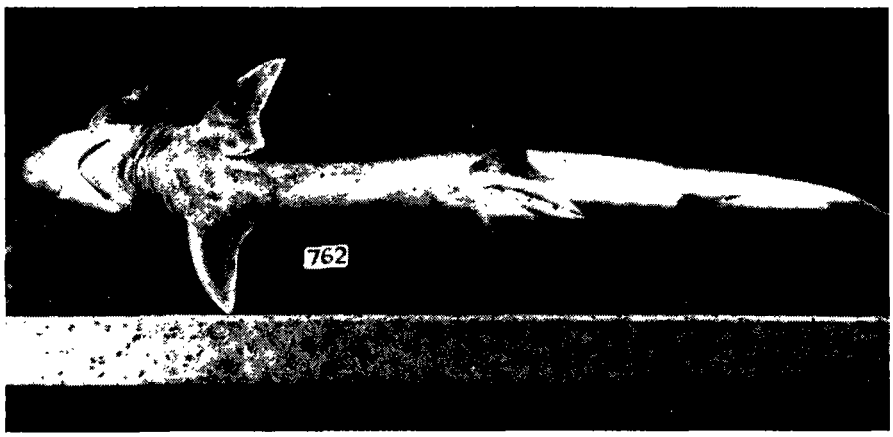


(c) Teeth of left side of upper and lower jaws.

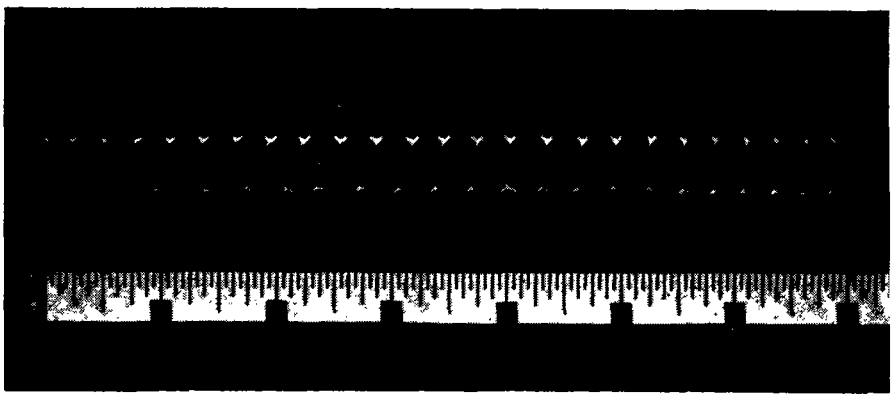
PLATE 7 — **GALEORHINUS GALEUS.** SOUPFIN SHARK



(a) Lateral view. Total length 4 feet.

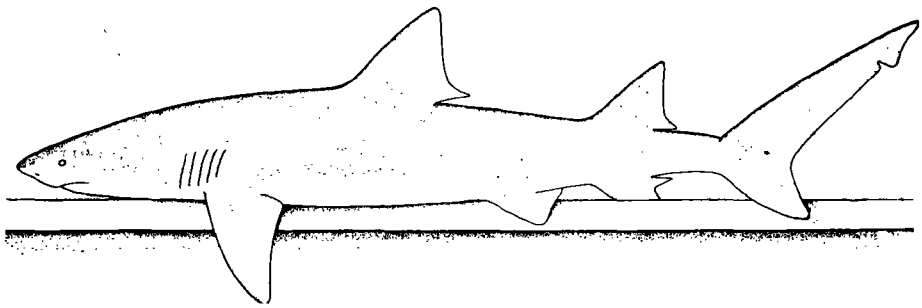


(b) Ventral view. Total length 4 feet.



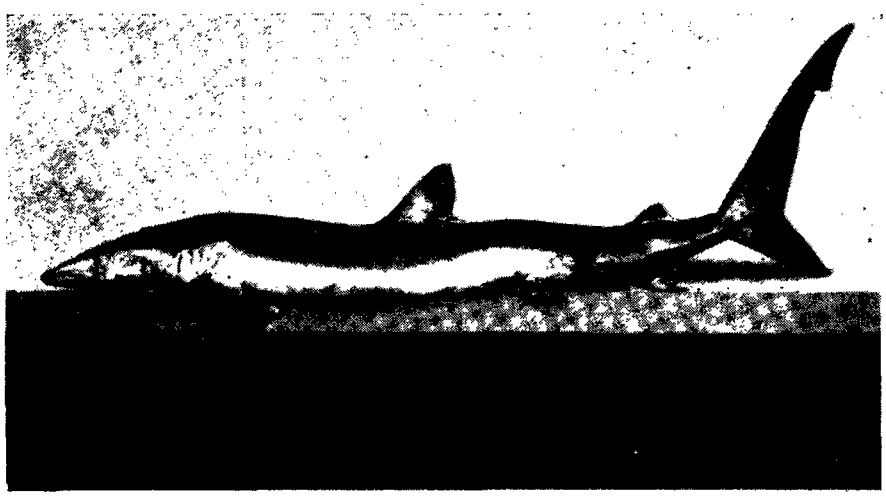
(c) Teeth of left side of upper and lower jaws.

PLATE 8 — **GALEORHINUS ZANZIBARENSIS.**
ZANZIBAR SOUPFIN

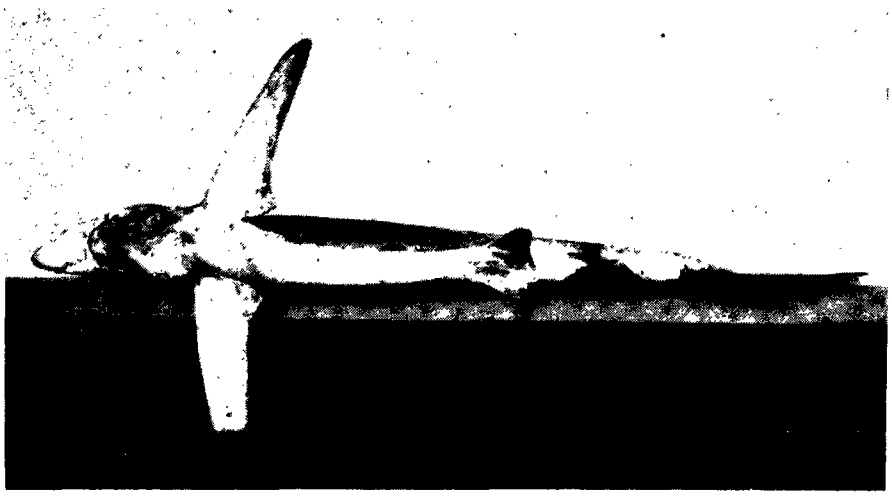


(a) Lateral view.

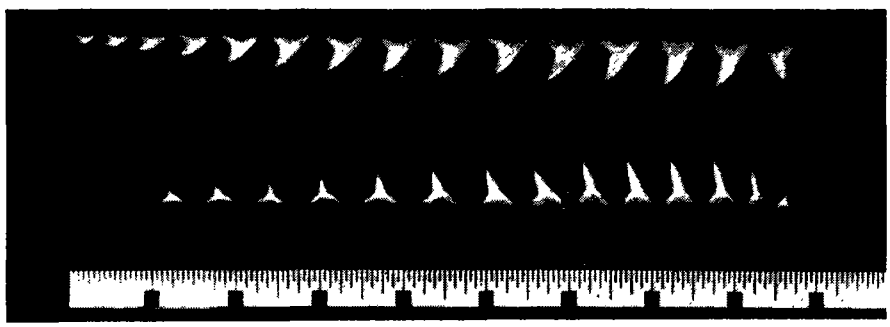
PLATE 9 — **NEGAPRION ACUTIDENS.** LEMON SHARK



(a) Lateral view. Total length 9 feet 4 inches.

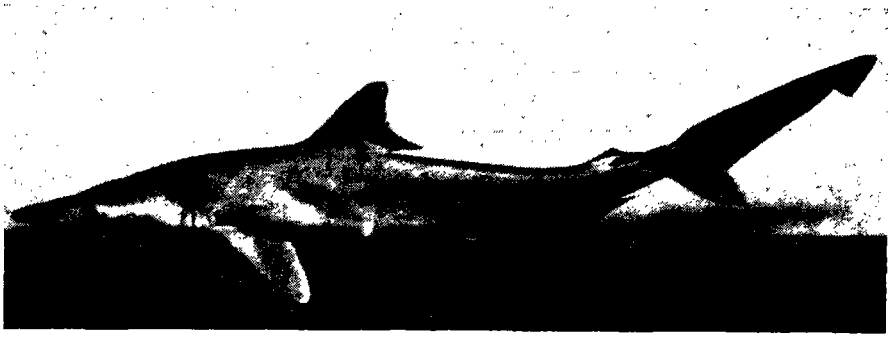


(b) Ventral view. Total length 9 feet 4 inches.

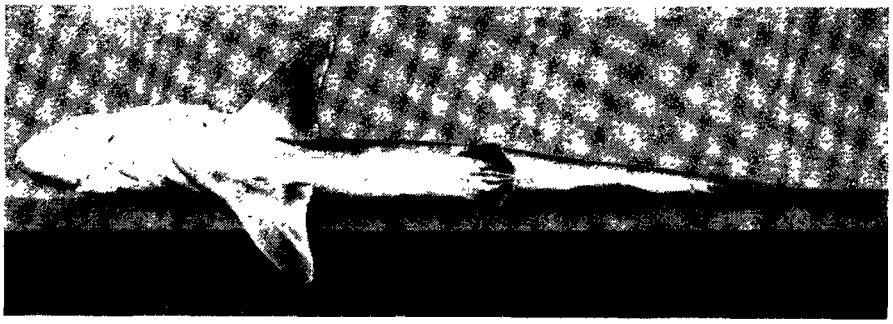


(c) Teeth of left side of upper and lower jaws.

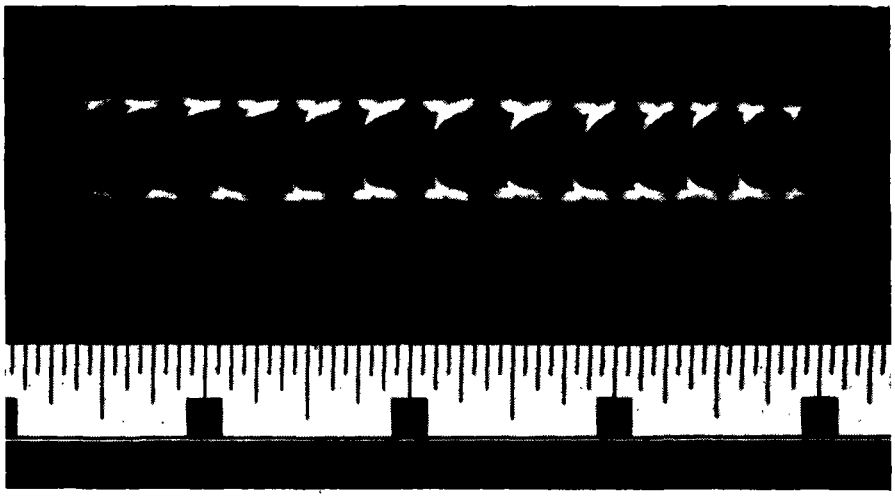
PLATE 10 — **PRIONACE GLAUCA.** BLUE SHARK



(a) Lateral view. Total length 1 ft. 9 inches.

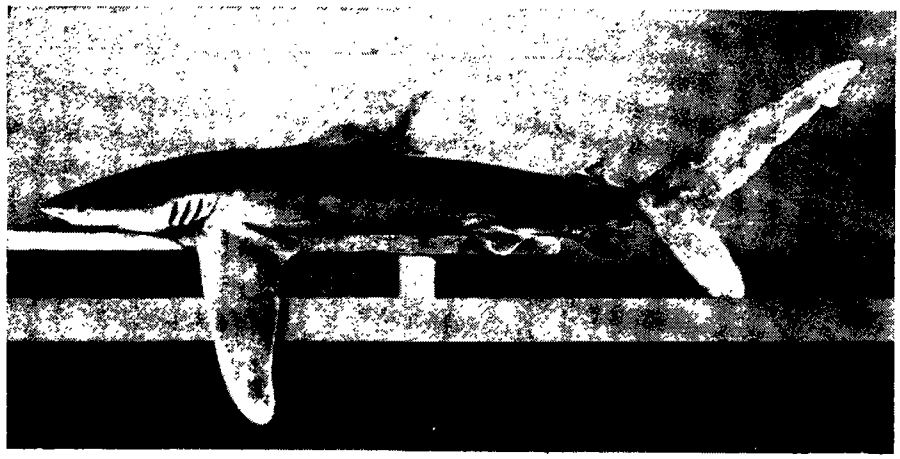


(b) Ventral view. Total length 2 feet.

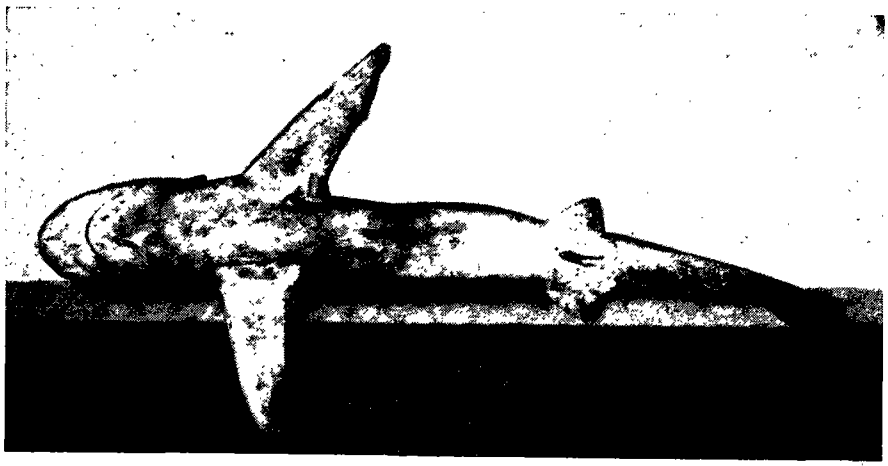


(c) Teeth of left side of upper and lower jaws.

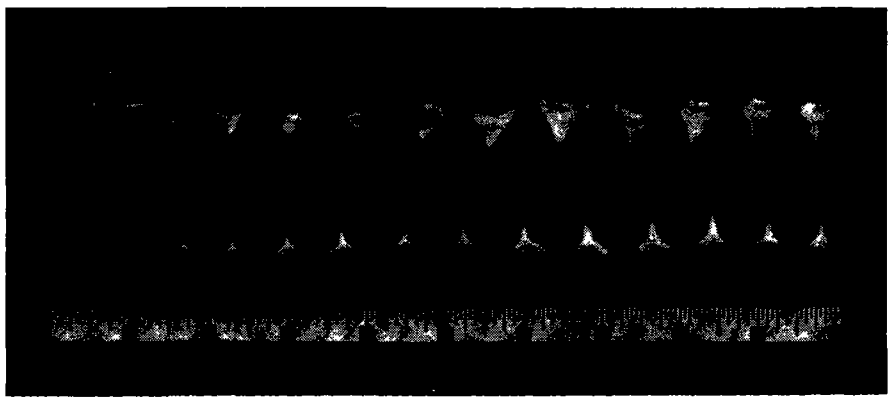
PLATE 11 — **RHIZOPRIONODON ACUTUS.** MILK SHARK



(a) Lateral view. Total length 5 feet.

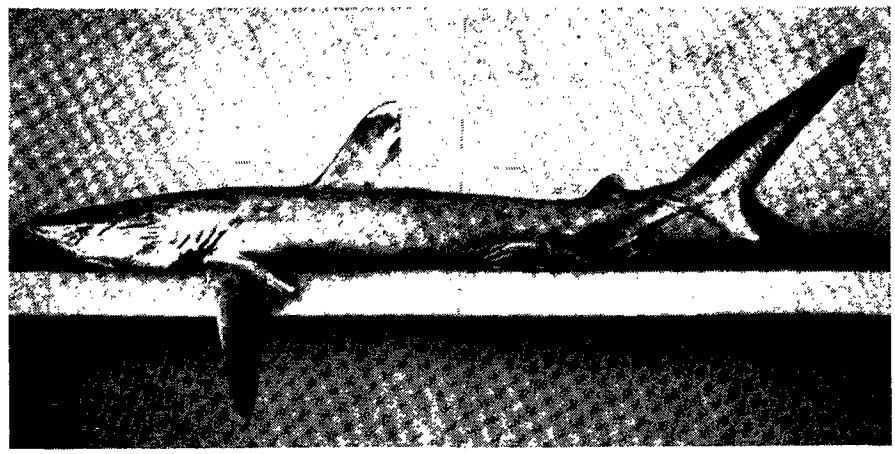


(b) Ventral view. Total length 7 feet 8 inches.

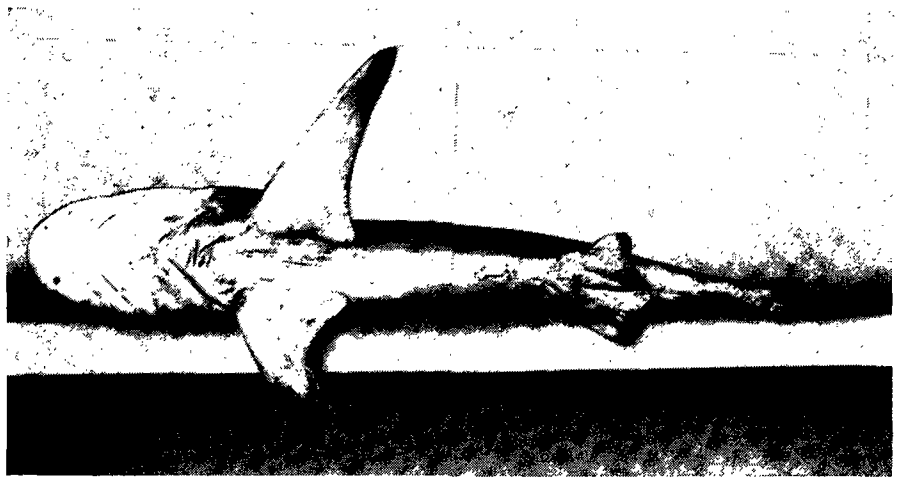


(c) Teeth of left side of upper and lower jaws.

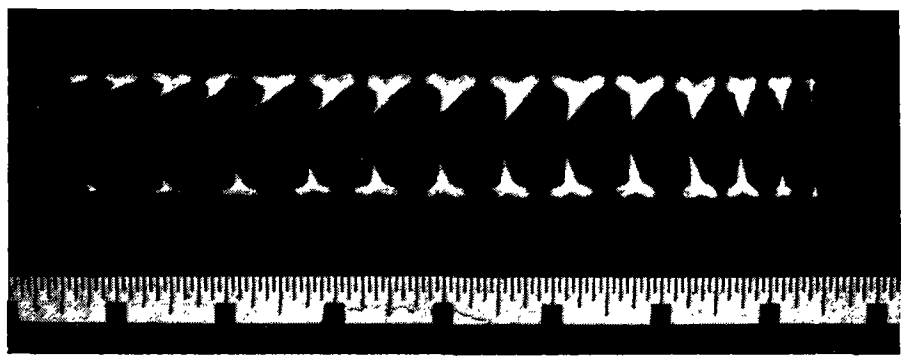
PLATE 12 — **CARCHARHINUS LONGIMANUS**
WHITE TIPPED SHARK



(a) Lateral view. Total length 4 feet 8 inches.

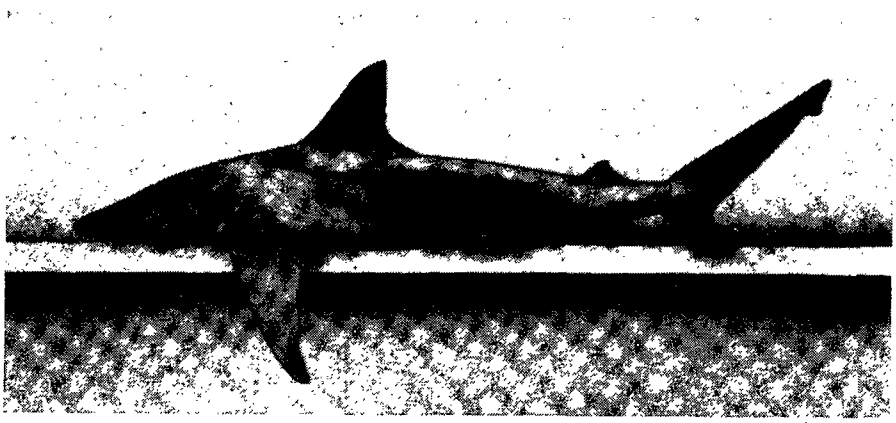


(b) Ventral view. Total length 4 feet 8 inches.

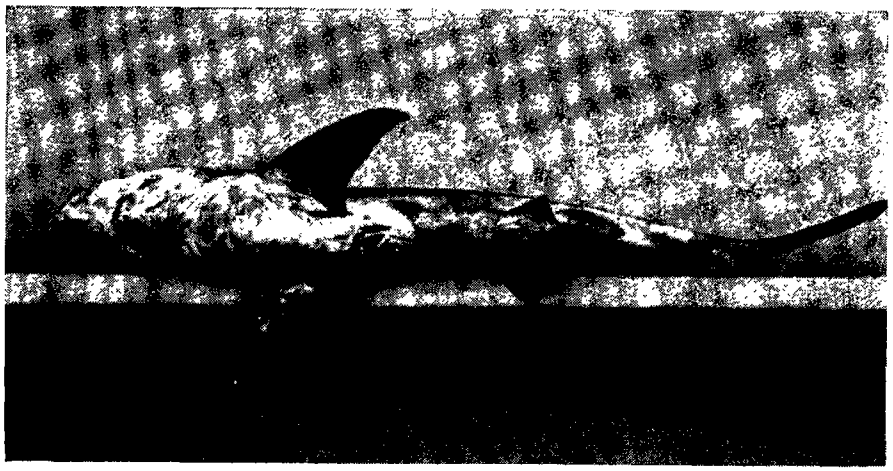


(c) Teeth of left side of upper and lower jaws.

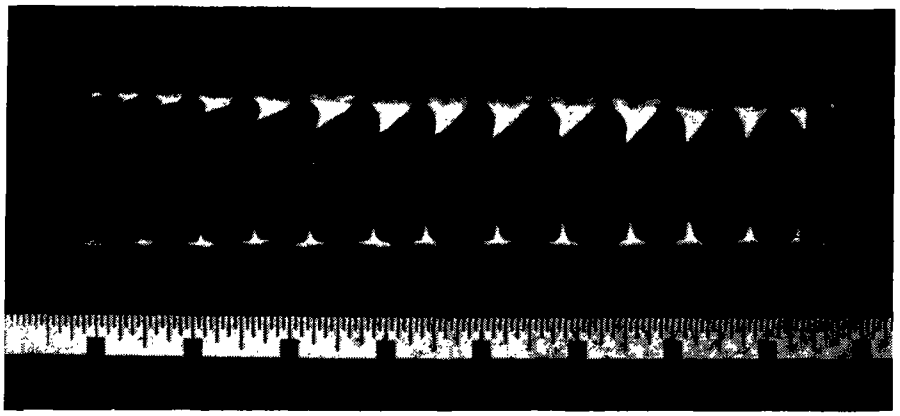
PLATE 13 — **CARCHARHINUS SPALLANZANI.**
BLACK-TAILED GREY



(a) Lateral view. Total length 6 feet.

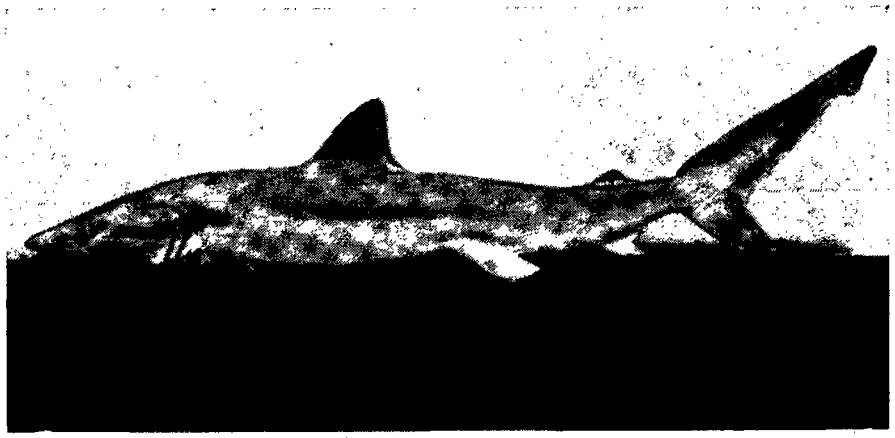


(b) Ventral view. Total length 6 feet.

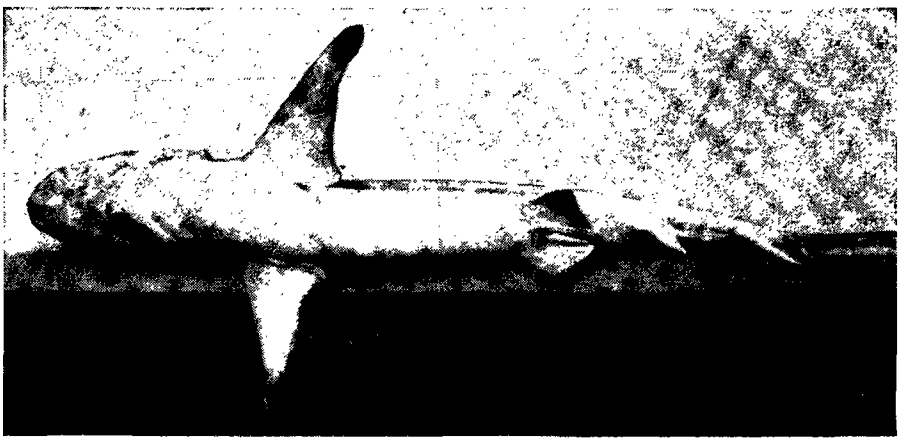


(c) Teeth of left side of upper and lower jaws.

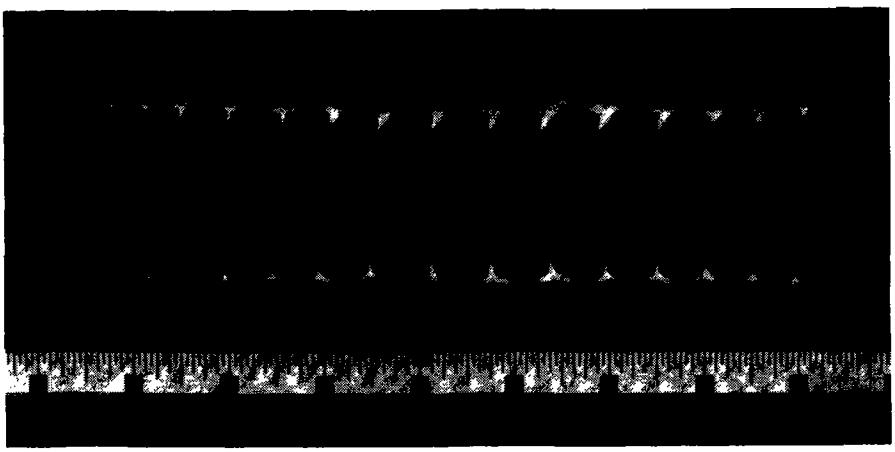
PLATE 14 — **CARCHARHINUS MILBERTI.** SANDBAR SHARK



(a) Lateral view. Total length 5 feet.

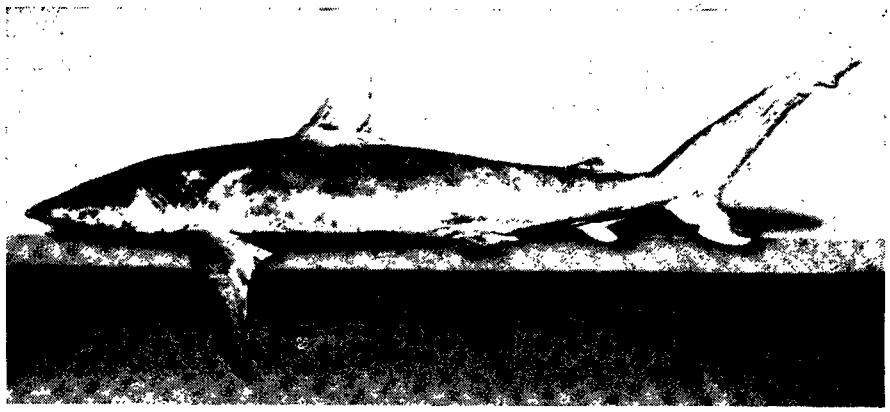


(b) Ventral view. Total length 5 feet.

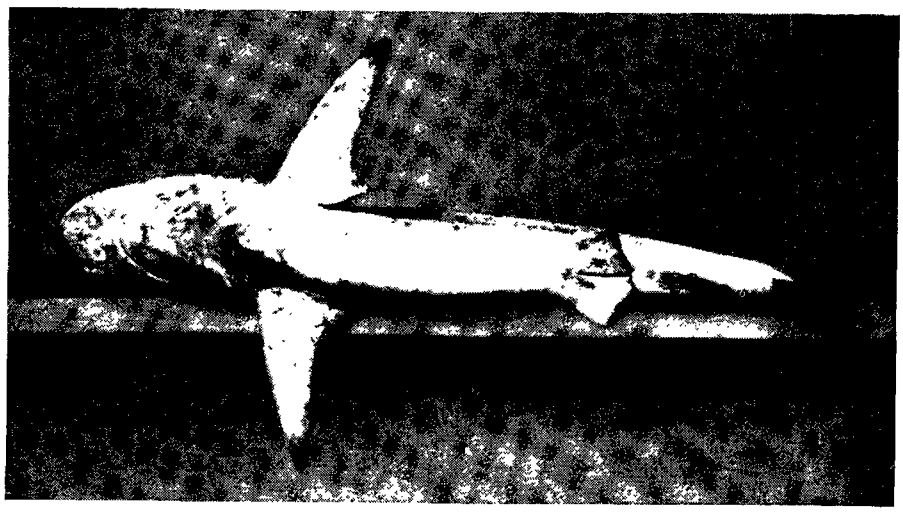


(c) Teeth of left side of upper and lower jaws.

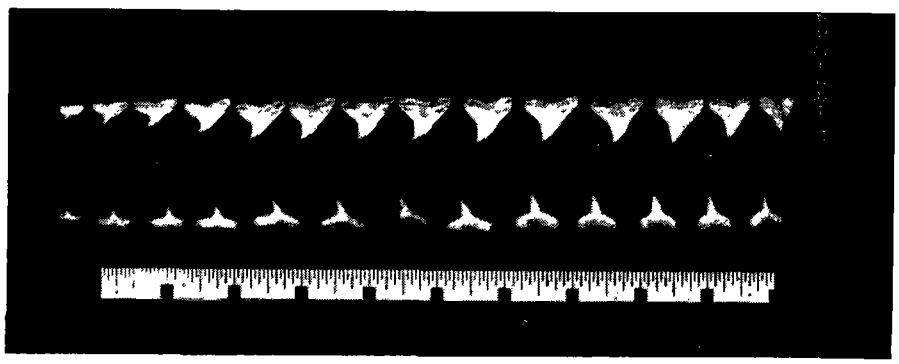
PLATE 15 — **CARCHARHINUS AHENEA.** BRONZE SHARK



(a) Lateral view. Total length 5 feet 6 inches.

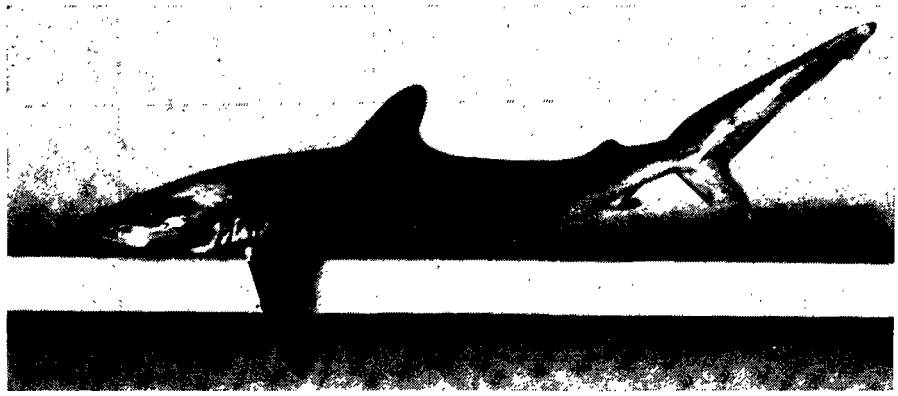


(b) Ventral view. Total length 5 feet 6 inches.

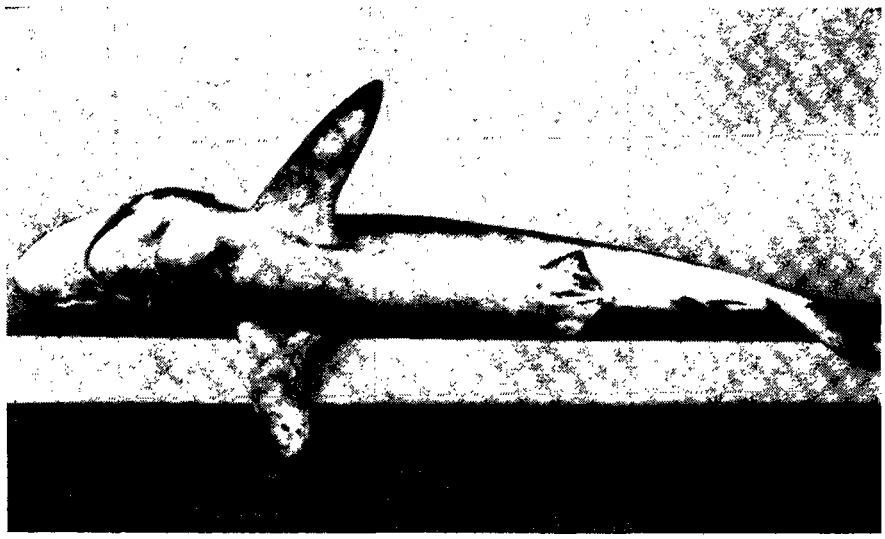


(c) Teeth of left side of upper and lower jaws.

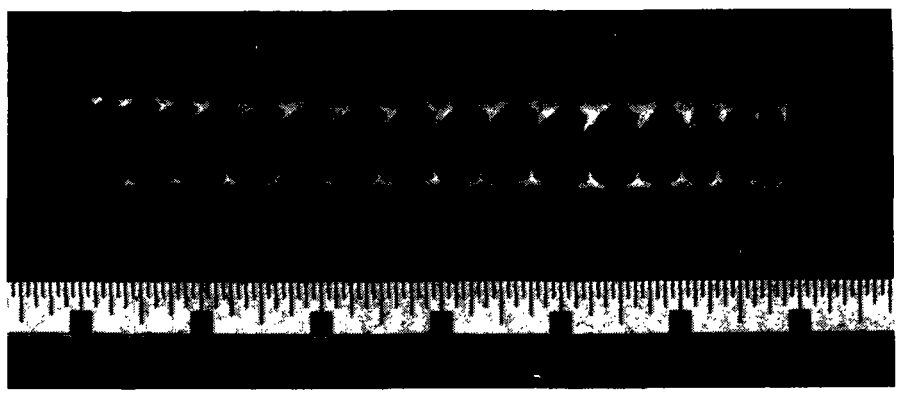
PLATE 16 — **CARCHARHINUS OBSCURUS.**
RIDGE-BACKED GREY



(a) Lateral view. Total length 4 feet.



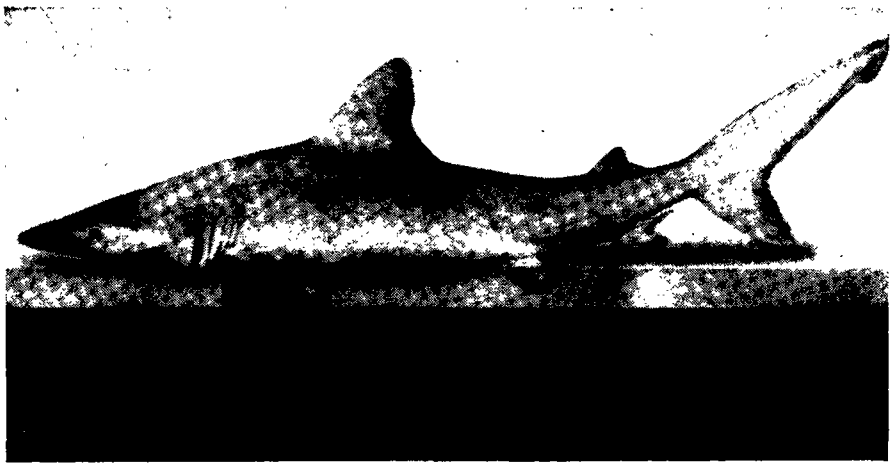
(b) Ventral view. Total length 4 feet.



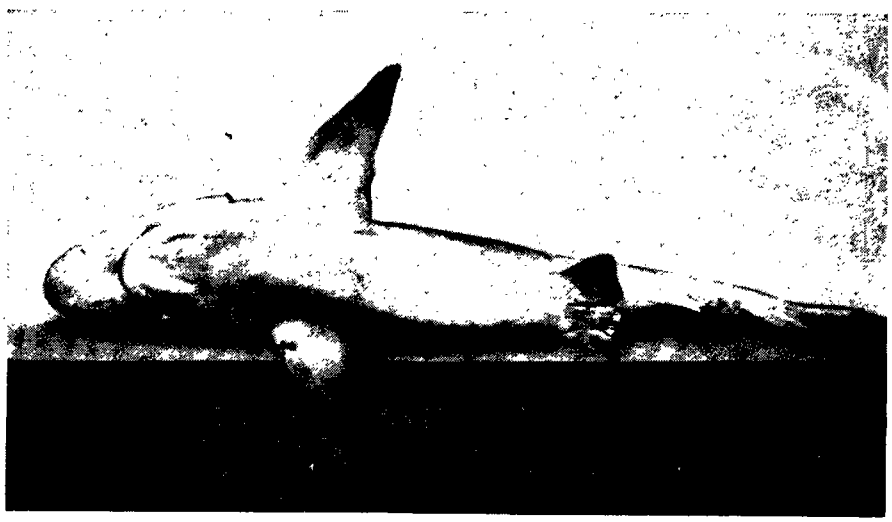
(c) Teeth of left side of upper and lower jaws.

PLATE 17 — **CARCHARHINUS FALCIFORMIS.** SILKY SHARK

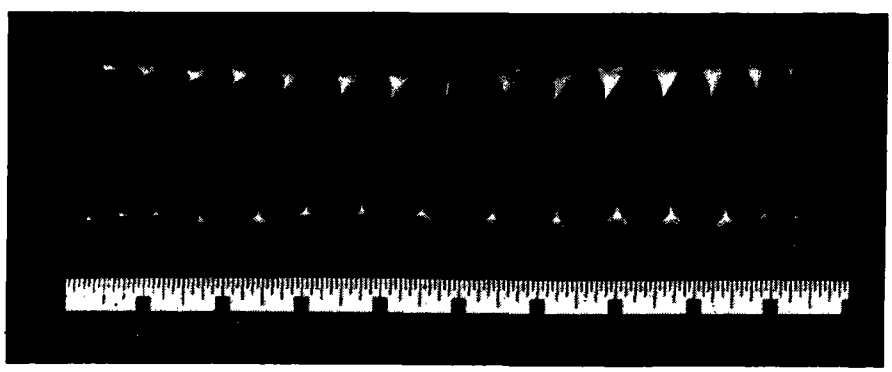
UNESCO ARCHIVES



(a) Lateral view. Total length 4 feet.

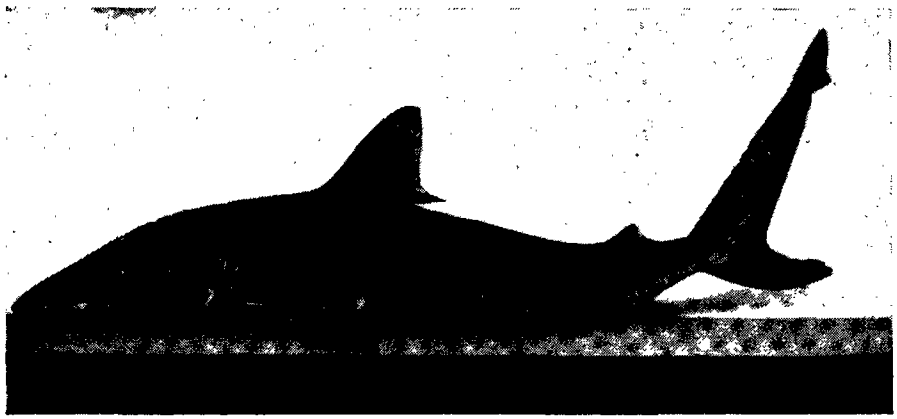


(b) Ventral view. Total length 4 feet.

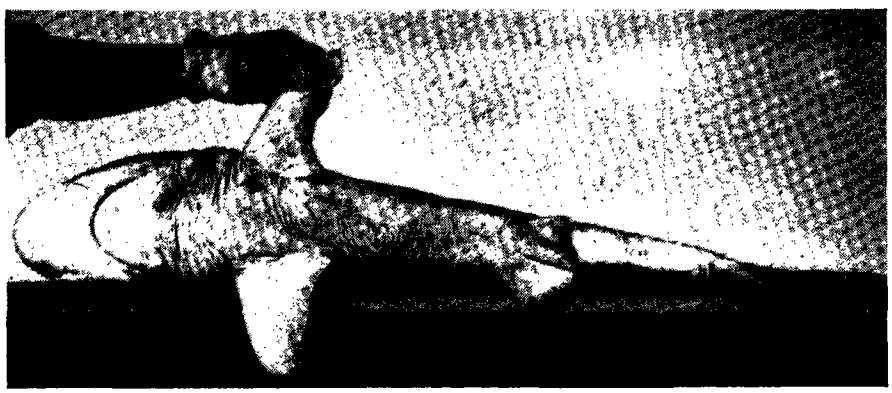


(c) Teeth of left side of upper and lower jaws.

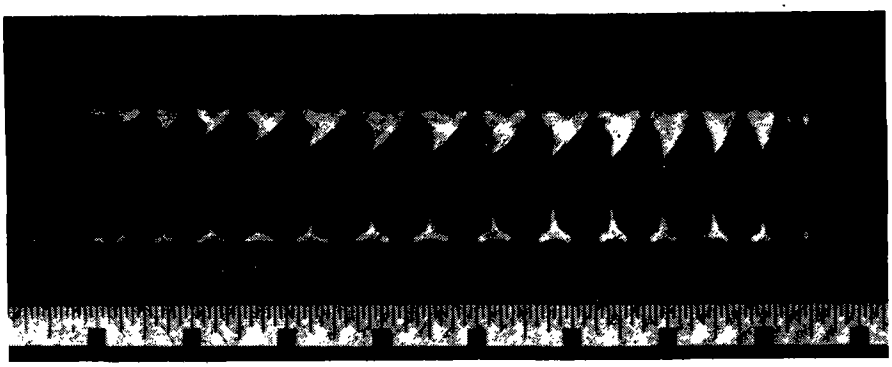
PLATE 18 — **CARCHARHINUS ALTIMUS.** BIGNOSE SHARK



(a) Lateral view. Total length 3 feet.

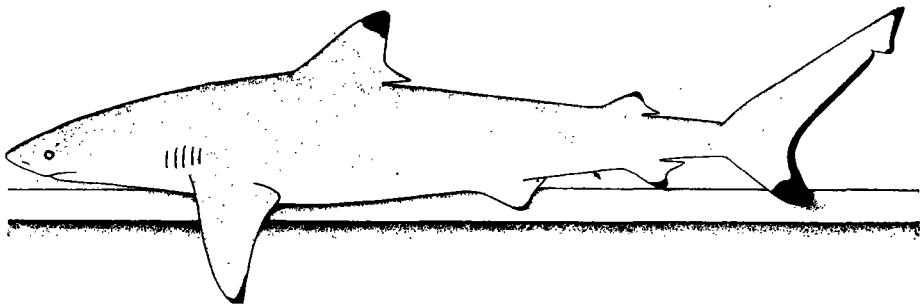


(b) Ventral view. Total length 3 feet.



(c) Teeth of left side of upper and lower jaws.

PLATE 19 — **CARCHARHINUS GALAPAGENSIS.**
GALAPAGOS SHARK



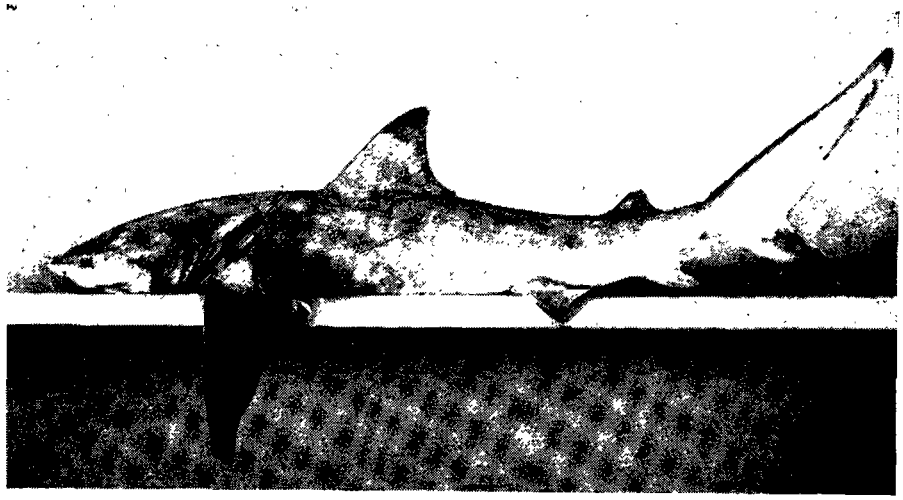
(a) Lateral view.



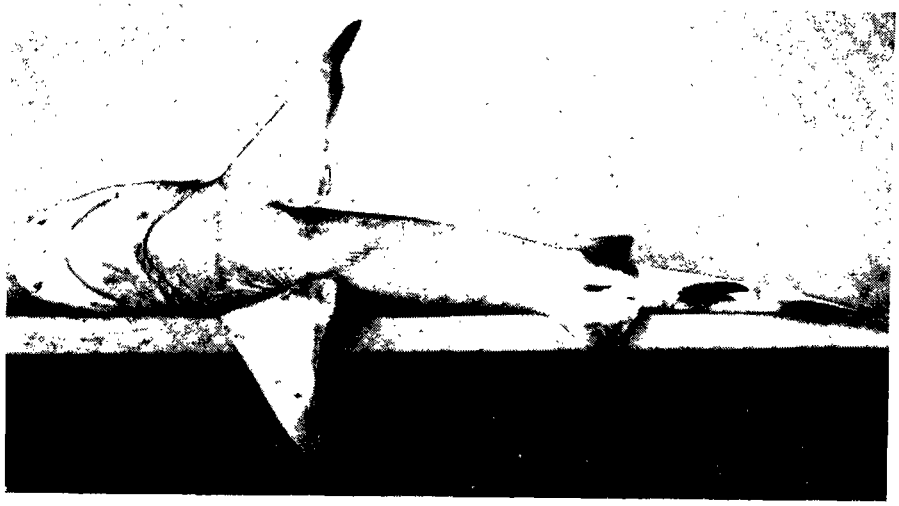
(c) Teeth of left side of upper jaw.

PLATE 20 — **CARCHARHINUS MELANOPTERUS.**

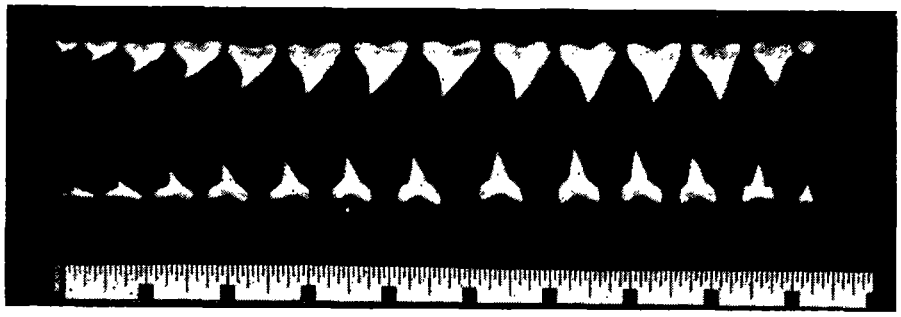
BLACK SHARK



(a) Lateral view. Total length 6 feet.

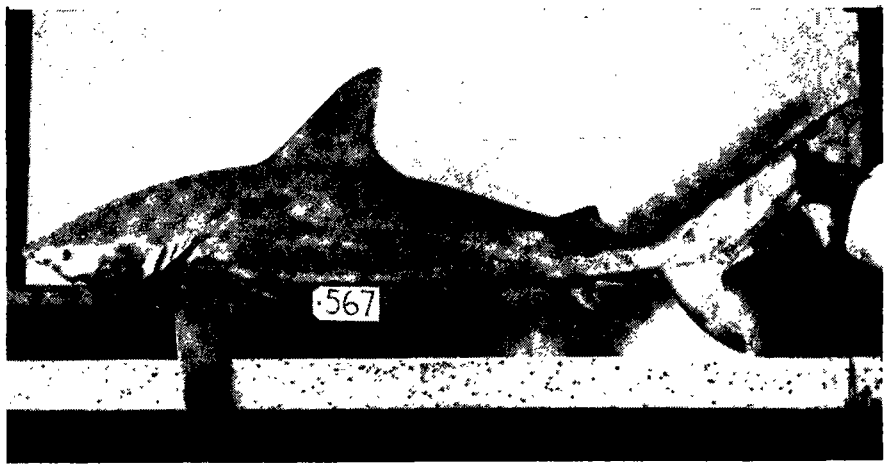


(b) Ventral view. Total length 6 feet.

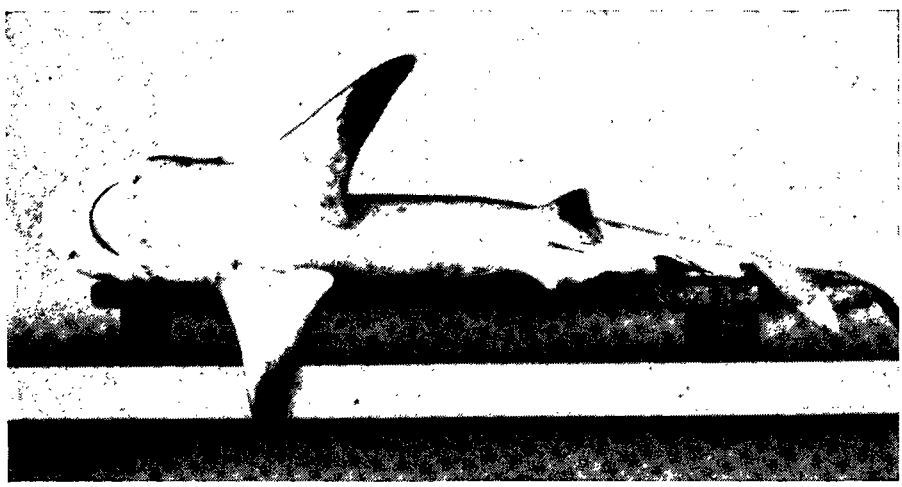


(c) Teeth of left side of upper and lower jaws.

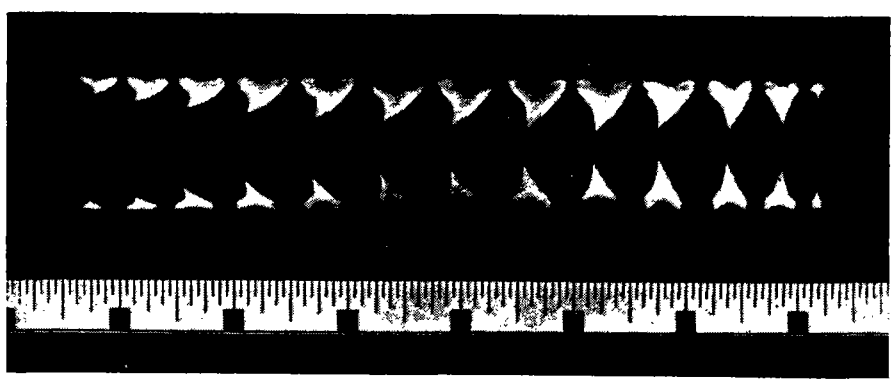
PLATE 21 — **CARCHARHINUS LEUCAS.** ZAMBEZI SHARK



(a) Lateral view. Total length 4 feet 7 inches.

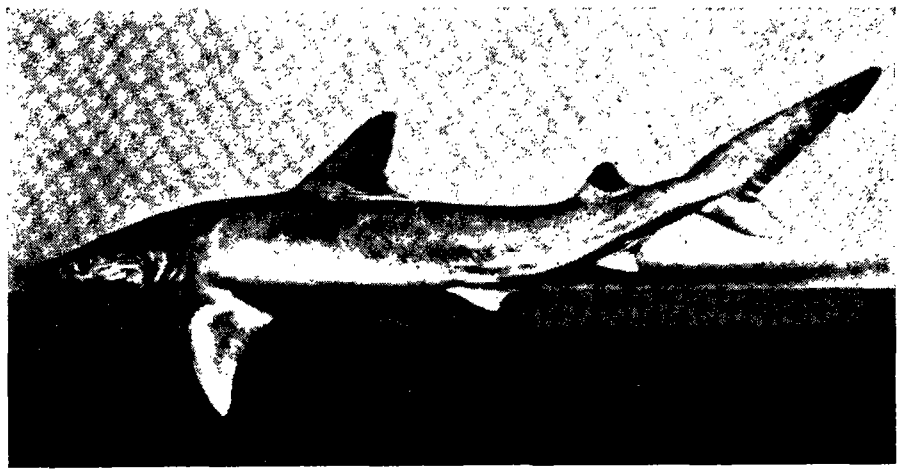


(b) Ventral view. Total length 4 feet 7 inches.

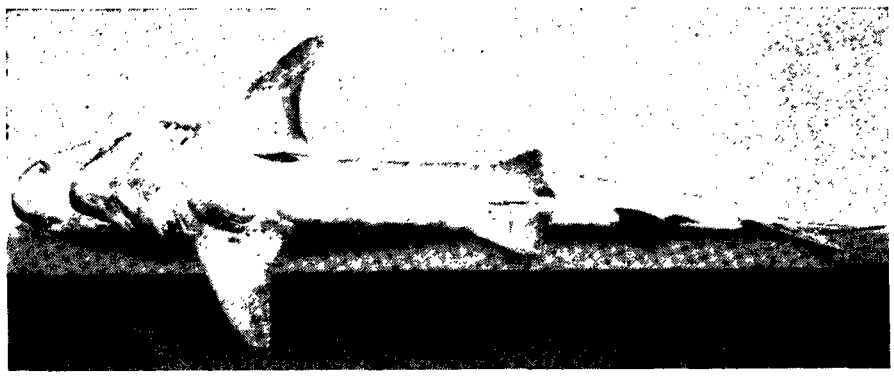


(c) Teeth of left side of upper and lower jaws.

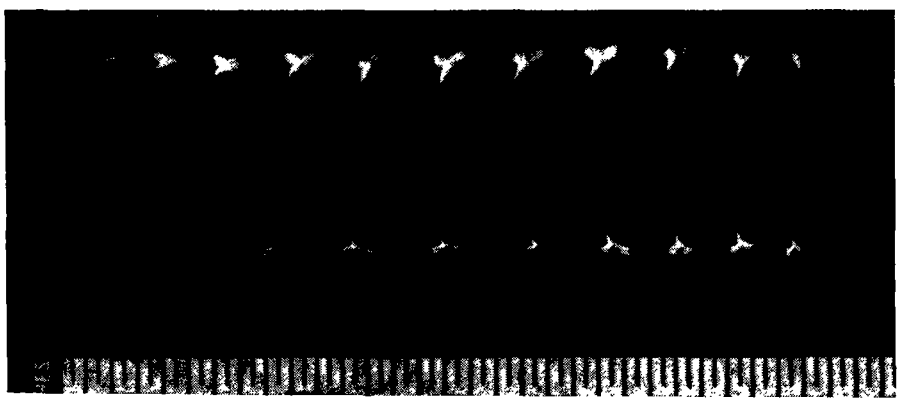
PLATE 22 — **CARCHARHINUS AMBOINENSIS.** JAVA SHARK



(a) Lateral view. Total length 2 feet 9 inches.



(b) Ventral view. Total length 2 feet 9 inches.

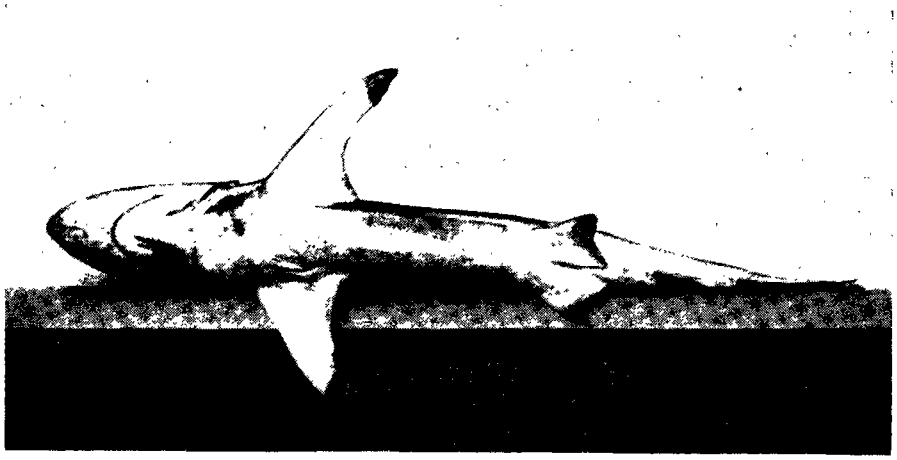


(c) Teeth of left side of upper and lower jaws.

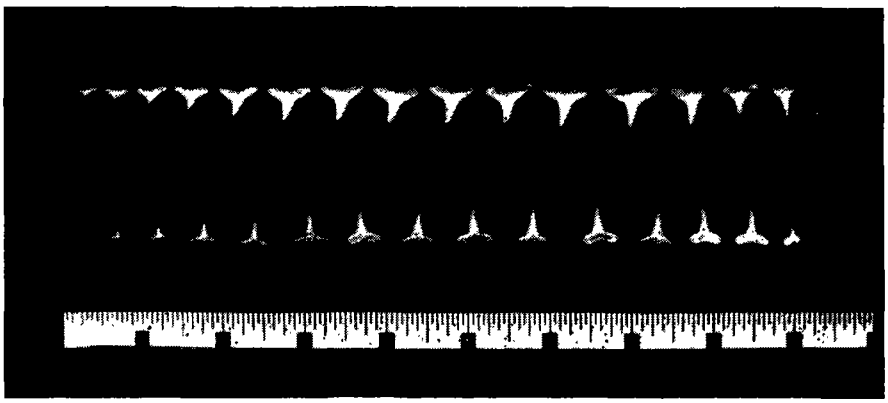
PLATE 23 — **CARCHARHINUS TJUTJOT.** BLACKSPOT SHARK



(a) Lateral view. Total length 4 feet 6 inches.

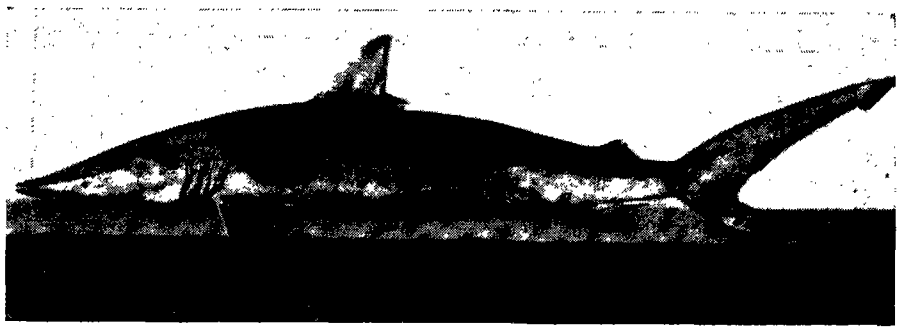


(b) Ventral view. Total length 5 feet.

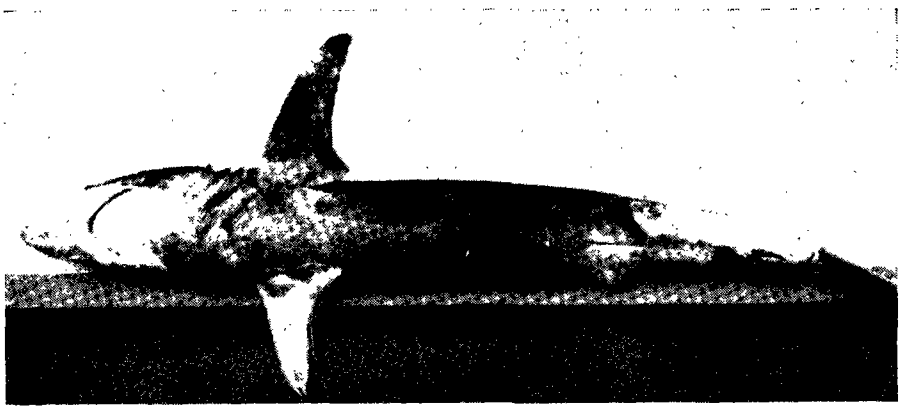


(c) Teeth of left side of upper and lower jaws.

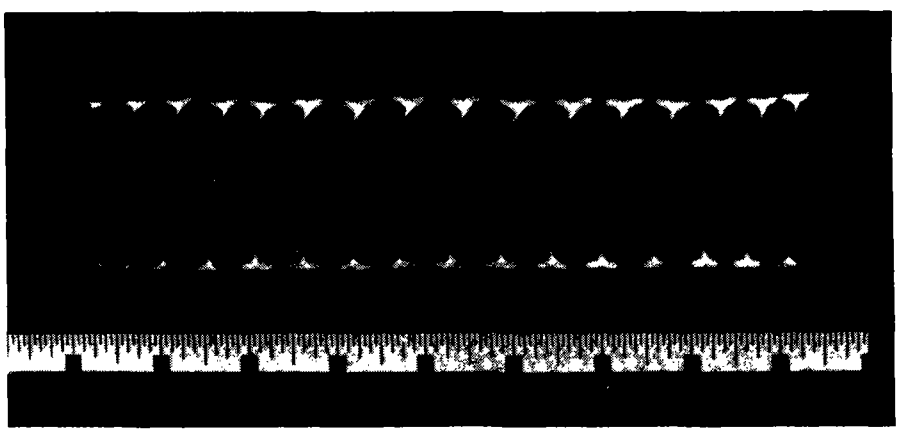
PLATE 24 — **CARCHARHINUS LIMBATUS.** BLACK FIN



(a) Lateral view. Total length 6 feet.

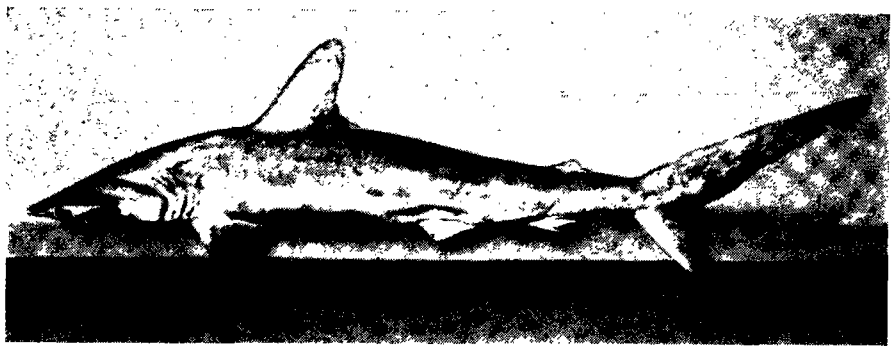


(b) Ventral view. Total length 6 feet.

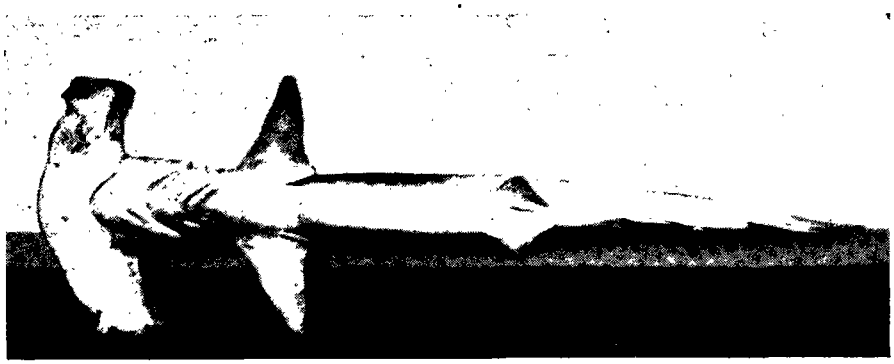


(c) Teeth of left side of upper and lower jaws.

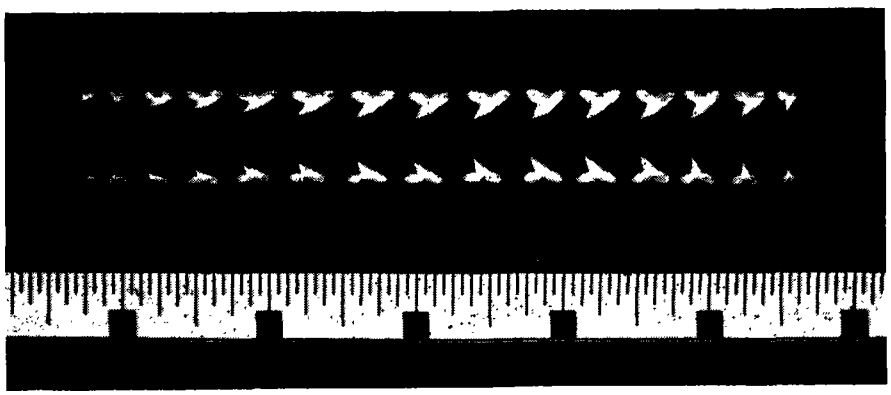
PLATE 25 — **CARCHARHINUS MACULIPINNIS.**
BLACK-TIPPED SHARK



(a) Lateral view. Total length 2 feet 6 inches.

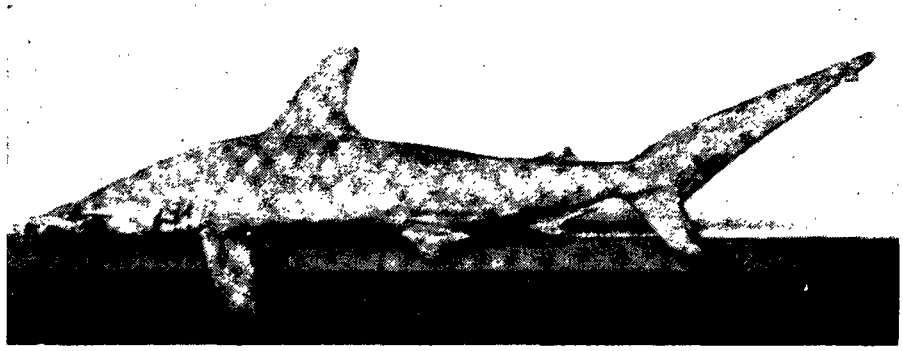


(b) Ventral view. Total length 3 feet.

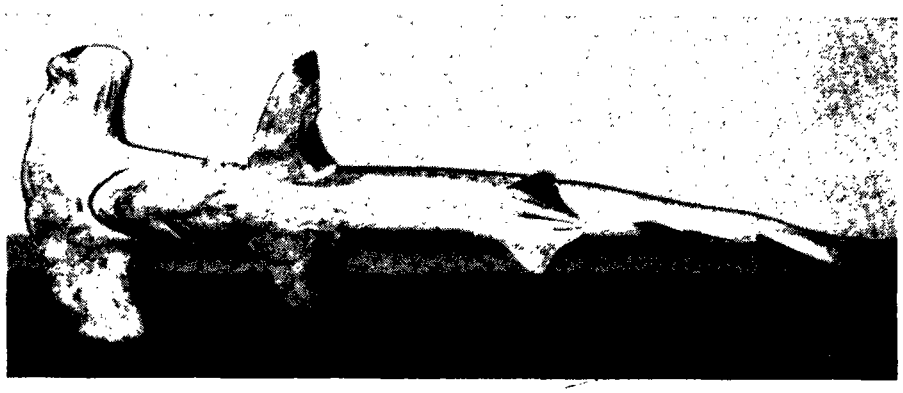


(c) Teeth of left side of upper and lower jaws.

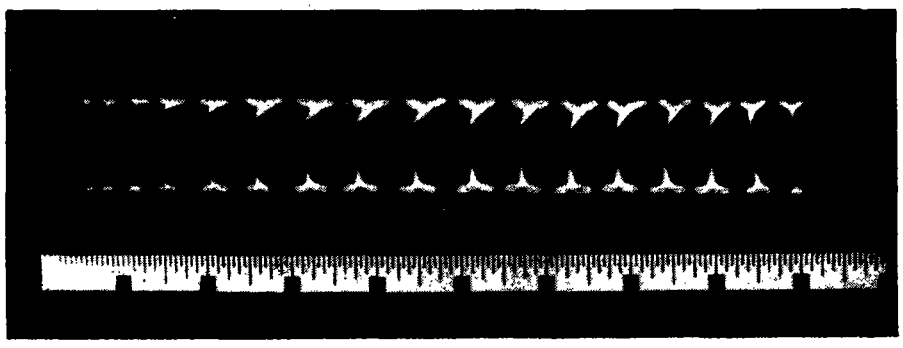
PLATE 26 — **SPHYRNA ZYGAENA.** HAMMERHEAD



(a) Lateral view. Total length 4 feet 6 inches.

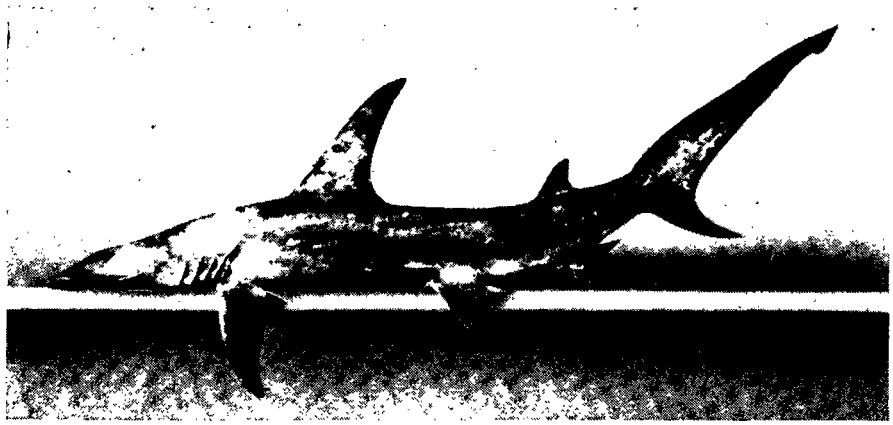


(b) Ventral view. Total length 3 feet 6 inches.



(c) Teeth of left side of upper and lower jaws.

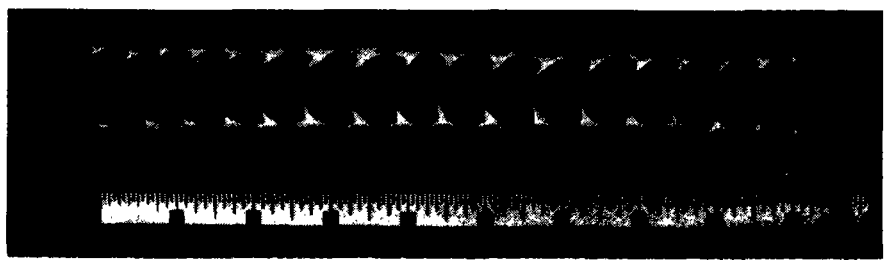
PLATE 27 — **SPHYRNA LEWINI.** BRONZE HAMMERHEAD



(a) Lateral view. Total length 9 feet 8 inches.



(b) Ventral view. Total length 9 feet 8 inches.



(c) Teeth of left side of upper and lower jaws.

PLATE 28 — **SPHYRNA MOKARRAN.** GREAT HAMMERHEAD

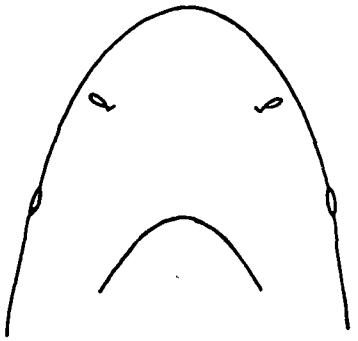


Fig. 3a—HEAD: Normal, not hammershaped.

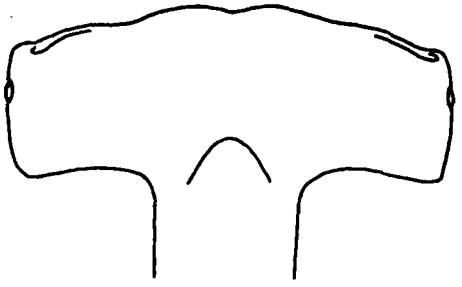


Fig. 3b—HEAD: Hammershaped.

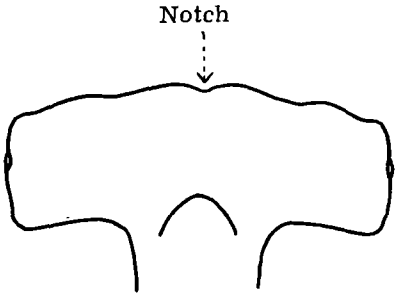


Fig. 4a—HEAD: Centre of anterior edge of "hammer" notched.

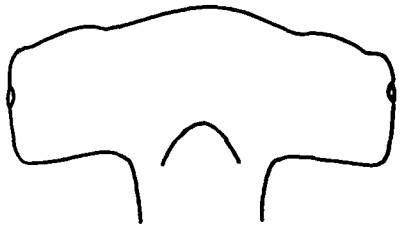


Fig. 4b—HEAD: Centre of anterior edge of "hammer" not notched.



Fig. 5a—SNOUT, short.

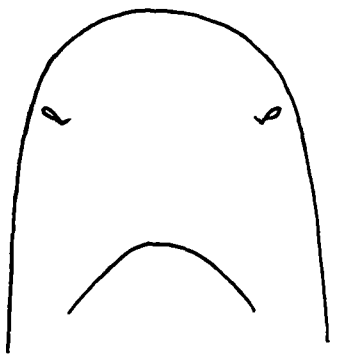


Fig. 5b—SNOUT, long.

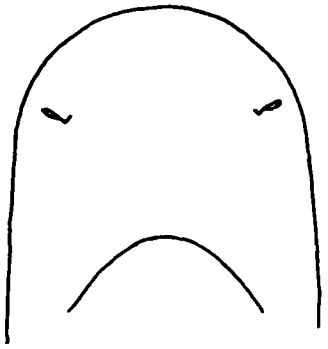


Fig. 6a—SNOUT: Broadly rounded at tip.

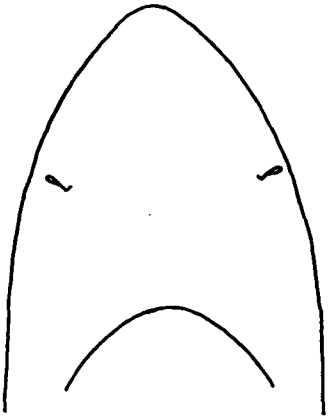


Fig. 6b—SNOUT: Pointed at tip.

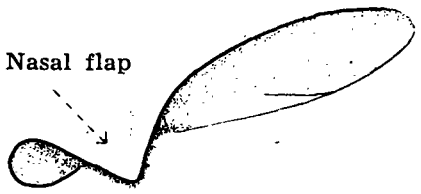


Fig. 7a—NOSTRIL with long nasal flap.

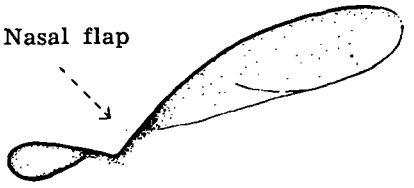


Fig. 7b—NOSTRIL with short nasal flap.

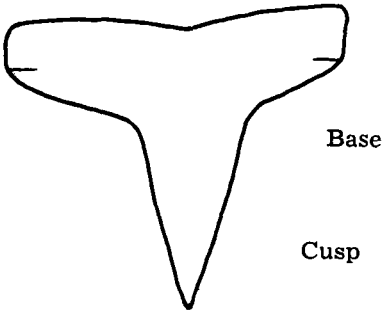


Fig. 8a—TEETH: Upper, as well as lower, teeth consist of narrow cusps on broad bases.

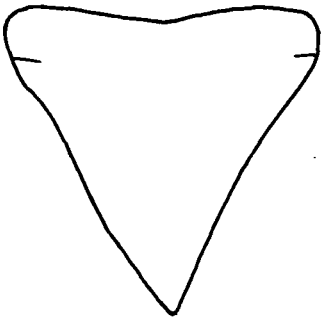


Fig. 8b—TEETH: Upper teeth triangular, the cusps not distinct from their bases.

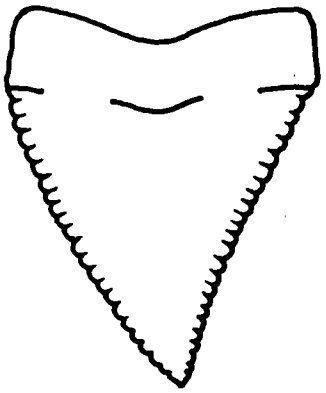


Fig. 9a—TEETH: Tooth margins coarsely serrated.

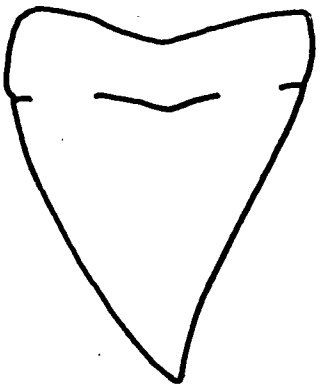


Fig. 9b—TEETH: Tooth margins smooth.

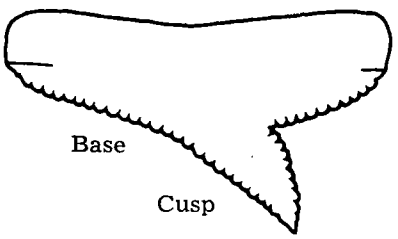


Fig. 10a—TEETH: Cusps of upper teeth serrated as well as bases.

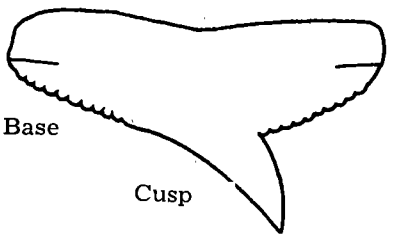


Fig. 10b—TEETH: Cusps of upper teeth smooth-edged.

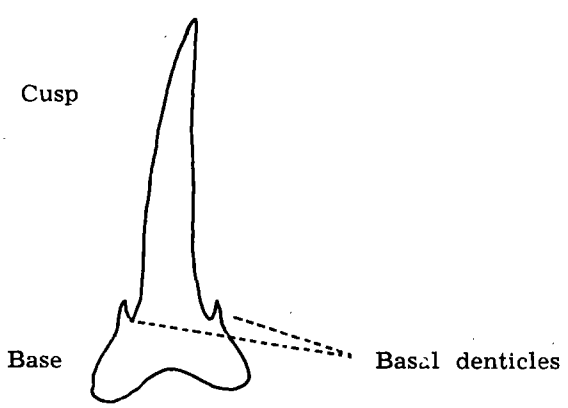


Fig. 11a—TEETH: A small basal denticle present on each side of the cusp.

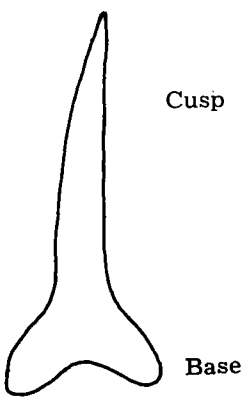


Fig. 11b—TEETH: No small basal denticle on each side of the cusp.

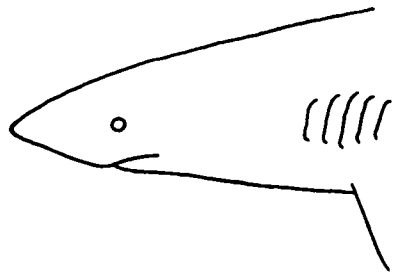


Fig. 12a—SPIRACLE: Absent.

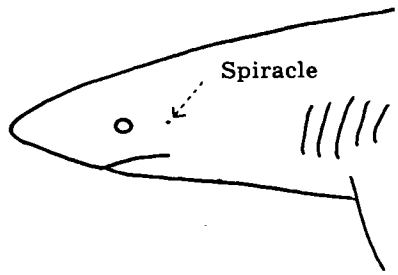


Fig. 12b—SPIRACLE: Present.

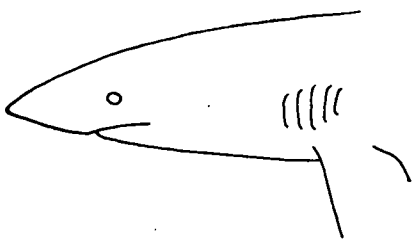


Fig. 13a—FIFTH GILL slit above the pectoral fin.

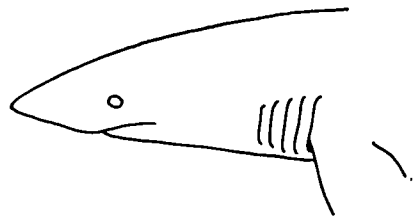


Fig. 13b—FIFTH GILL slit in front of pectoral fin.

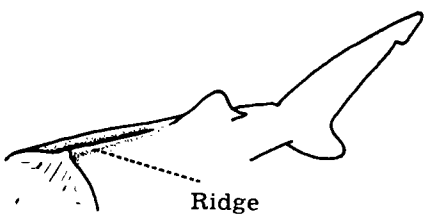


Fig. 14a—RIDGE: Present on back between the dorsal fins.

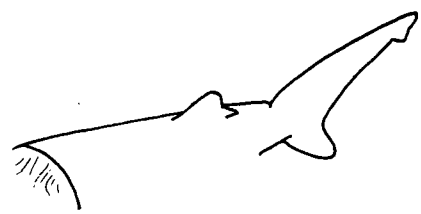


Fig. 14b—No Ridge on back between dorsal fins.

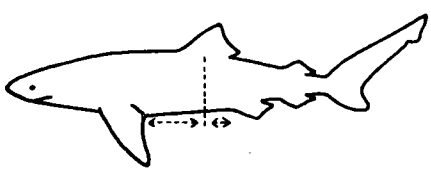


Fig. 15a—FIRST DORSAL: Midpoint of base considerably nearer the pelvics than the pectorals.

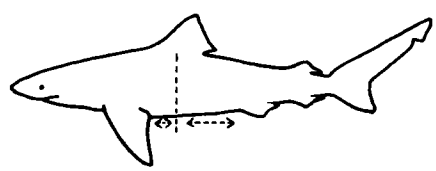


Fig. 15b—FIRST DORSAL: Midpoint of base as close (or closer) to the pectorals as the pelvics.



Fig. 16a—FIRST DORSAL: Noticeably large with a very broadly rounded apex.



Fig. 16b—FIRST DORSAL: Apex pointed or moderately rounded.



Fig. 17a—FIRST DORSAL: High.



Fig. 17b—FIRST DORSAL: Low.



Fig. 18a—SECOND DORSAL: Erect.



Fig. 18b—SECOND DORSAL: Low.



Fig. 19a — SECOND DORSAL: Posterior margin concave.

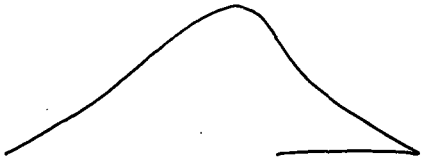


Fig. 19b — SECOND DORSAL: Posterior margin almost straight.

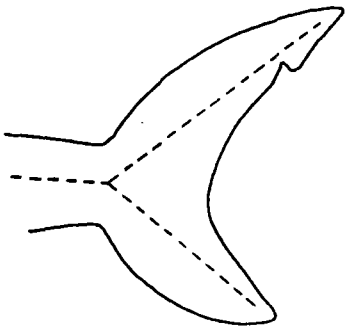


Fig. 20a—CAUDAL: Lunate, the lower lobe being almost as long as the upper lobe.

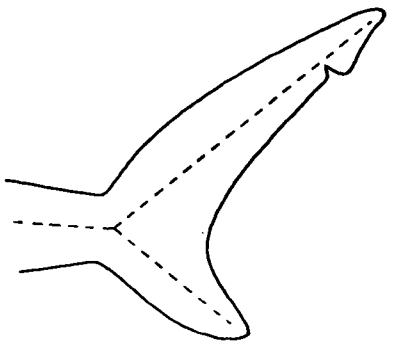


Fig. 20b—CAUDAL: Not lunate, the lower lobe being considerably shorter than the upper lobe.

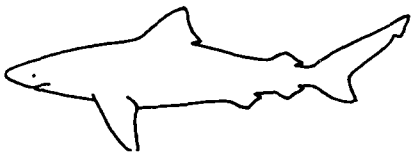


Fig. 21a—CAUDAL: Length of upper lobe less than half the distance from the tip of the snout to the beginning of the caudal.



Fig. 21b—CAUDAL: Upper lobe very long being equal in length to the distance from the tip of the snout to the beginning of the caudal.

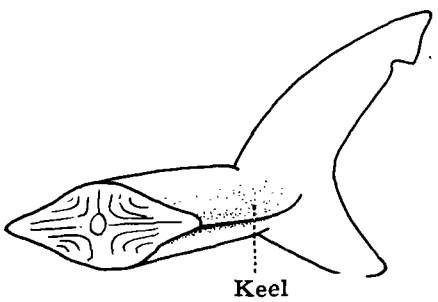


Fig. 22a—KEELS: Present.

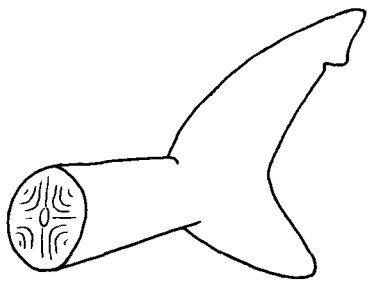


Fig. 22b—KEELS: Absent.

ACKNOWLEDGMENTS

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SOUTH AFRICAN ASSOCIATION FOR
MARINE BIOLOGICAL RESEARCH

OCEANOGRAPHIC RESEARCH INSTITUTE

Investigational Report No. 9

A Carchariid Shark new to South African waters

by

Jeannette D. D'Aubrey

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Introduction

In December, 1961 a mature male specimen of total length 814 mm. belonging to the genus *Carcharias* was obtained by the Division of Sea Fisheries, Cape Town, and was sent to this Institute for further identification.

The characteristics of this specimen differed from those of *Carcharias ferox*, *platensis*, *arenarius*, *tricuspidatus*, *owstoni*, *taurus*, *herbsti* and *noronhai* but agreed with those of *Carcharias kamoharai* Matsubara 1936 in almost every respect except in possessing spiracles, lacking a prominent white spot behind the eye and in that the longest tooth is only slightly greater than half the diameter of the eye.

Since there is close agreement in every other respect, these differences are considered to be insufficient to exclude the specimen from the species *Carcharias kamoharai*. It seems likely that there was some error concerning the recording of an absence of spiracles in the description by Matsubara.

The characteristics of the South African specimen also agreed with those of *Pseodocarcharias pelagicus* Cadenat 1963 in every respect except for a marked difference in first dorsal height and shape and in that *P.pelagicus* has basal denticles on some of the teeth. From the figure of *P.pelagicus*, however, it appears likely that the apical portion of the first dorsal had been lost due to an early injury and, as this specimen had only one tooth with a basal denticle, these differences are not considered sufficient to exclude the South African specimen from this species.

As the South African specimen cannot be excluded from either *C.kamoharai* or *P.pelagicus* these species are considered to be synonymous.

In his description of *C.yangi* Teng 1959, Chen mentions that it closely resembles *C.kamoharai* but differs from it in possessing the following:

1. Spiracles.
2. Basal cusps on the teeth.
3. No white spot behind the eye.
4. Weakly developed lateral keels.

On comparison with the specimens examined by Cadenat and that examined at this Institute, Nos. 1-3 become invalid as specific differences. As the longitudinal thickenings on the caudal peduncle may be interpreted as lateral keels, No. 4 is probably a difference in interpretation rather than a specific difference. *C.yangi* may therefore be considered synonymous with *C.kamoharai*.

The synonymy of *P.pelagicus*, *C.yangi* and *C.kamoharai* is confirmed by their dimensional proportions (Table I) and, according to nomenclatural law, the specific name *kamoharai* has priority.

TABLE 1

COMPARISON OF THE SOUTH AFRICAN SPECIMEN WITH THOSE OF THE TYPES OF CARCHARIAS KAMOHARAI, PSEUDOCARCHARIAS PELAGICUS AND CARCHARIAS YANGI

	Type C.kamoharai	S.A. Specimen	Type P.pelagicus	Type C.yangi
According to description by	Matsubara	D'Aubrey	Cadenat	Chen
Sex	♂	♂	♂	
Total length in mm.	735	814	975	1000
Head† in total length	5.14	5.4	5.4	—
Head in precaudal length	3.84	4.3	4.1	—
Distance from snout to pelvic in total length	—	1.7	1.8	—
Distance from snout to pelvic in precaudal	1.38	1.3	1.3	—
Distance from snout to first dorsal in precaudal	2.0	2.0	1.9	± 2
Distance from snout to fifth gill slit in precaudal	—	3.1	3.4	3.2
Depth in precaudal	6.53	—	5.6	7
Horizontal diameter eye in interorbital	2	2.5	2	—
Horizontal diameter eye in preoral	>2	2.9	2.4	2
Horizontal diameter eye in head	6.50	6.6	6.2	—
Horizontal diameter eye in distance from snout to fifth gill slit	—	9.2	7.4	8
Interorbital distance in head	3.12	2.6	(3.1)*	—
Interorbital in distance from snout to fifth gill slit	—	3.7	(3.7)*	4.2
Preoral in head	2.75	2.3	2.5	—
Mouth height in head	4.0	4.6	3.2	—
Mouth width in head	3.18	3.0	3.4	—
First gill slit length in head	>3.3	3.0	3.5	—
First gill slit length in distance from snout to fifth gill slit	—	4.2	4.2	4.30
Second gill slit length in distance from snout to fifth gill slit	—	4.2	—	4.0
Third gill slit length in distance from snout to fifth gill slit	—	4.2	—	4.0
Fifth gill slit length in distance from snout to fifth gill slit	—	4.8	3.9	4.30
Pectoral length in head	±2.0	1.9	1.9	—
Pectoral length in distance from snout to fifth gill slit	—	2.7	2.2	2.5
Caudal peduncle length§ in head	3.06	2.3	(2.5)*	—
Caudal peduncle depth in head	6.10	6.9	7.5	—
Interdorsal distance in head	1.13	1.0	(1.1)*	—
First dorsal height in base	—	2.1	3.5‡	—
First dorsal height in free rear lobe	—	0.6	1.5‡	—
Second dorsal height in base	—	1.7	2.0	—
Second dorsal height in free rear lobe	—	1.3	2.2	—
Second dorsal base in interdorsal	>4.0	4.5	(4.8)*	4.0
Anal height in base	—	2.2	1.8	—
Anal height in free rear lobe	—	1.9	1.4	—
Dental formula	14-0-14 / 13-0-13	13-0-14 / 12-0-12	13-0-13 / 12-0-12	14-0-15 / 13-0-13
Relative lengths of 2 anterior upper teeth	—	Subequal	Subequal	—
Relative lengths of 2 anterior lower teeth	—	Subequal	Subequal	—
No. of teeth anterior to gap or small teeth	—	2	2	3
No. of small teeth in gap	—	0 or 1	1	
No. of basal denticles on each side of tooth	0	0	0 or 1	0 or 1
Diameter eye in longest tooth	>½	>½	±½ (from fig.)	—
Eye in internarial	—	0.9	>1	>1
Eye nearer snout than fifth gill slit	Yes	Yes	(Yes)*	Yes
Longer lip groove	Upper	Upper	—	Upper

TABLE 1 (Cont.)

	Type C.kamoharai	S.A. Specimen	Type P.pelagicus	Type C.yangi
Relative sizes of fins	DI>DII>Anal	DI>DII>Anal	DI>DII>Anal	DI>DII>Anal
Position of pelvic origin	Behind DI base	Behind DI base	Behind DI base	Behind DI base
Position of anal origin	Behind DII base	Behind DII base	Opp. post DII base	Behind DII base
Spiracles	Absent	Present	Present	Present
White spot behind eye	Present	Absent	Absent	Absent

* based on measurements estimated from those given in Cadenat's description.

† Head length=distance from snout to upper end first gill slit.**

§ Caudal peduncle length=distance from posterior end of second dorsal base to origin upper caudal.**

** These are the measurements given for the South African specimen and the type of P.pelagicus. It is probable that these are the measurements for the type of C.kamoharai but Matsubara does not specify how they were taken.

‡ The proportional discrepancies between the S.A. specimen and P.pelagicus have arisen due to the absence of the apical portion of the first dorsal of P.pelagicus.

Note: DI=first dorsal
DII=second dorsal

Cadenat has proposed a new subgenus for this species based on the following characteristics:

1. First dorsal low and different in shape to the second dorsal and anal.
2. Lengths of posterior lobes of second dorsal and anal greater than their respective heights.
3. Teeth with very few basal denticles.
4. Very low tooth count.
5. Only two anteriors (teeth anterior to the gap or small teeth on each side of the jaw).
6. No symphysials (small teeth on either side of the symphysis).

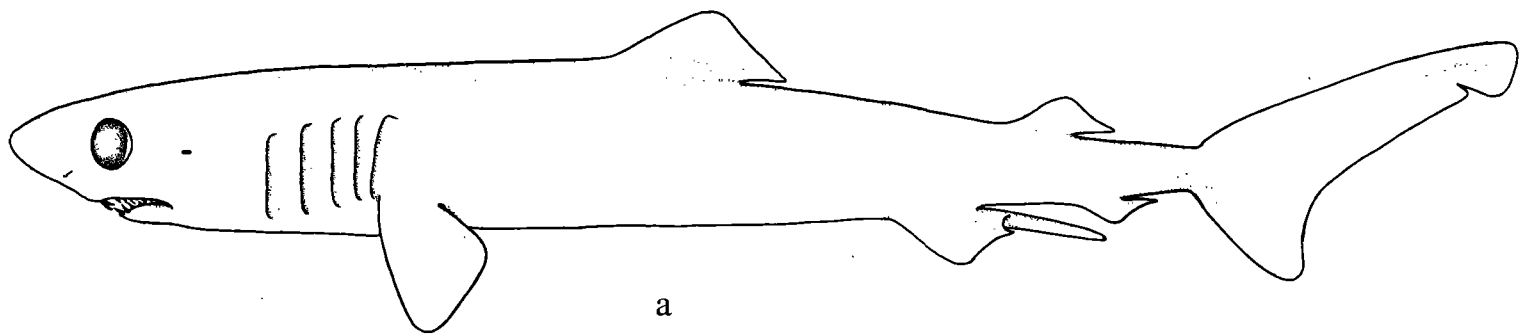
Of these, No. 1 has already been shown to be the result of damage and No. 3 does not exclude *owstoni*. It has not been possible to confirm that the dimensional proportions of the second dorsal and anal of *kamoharai* differ from those of all other *Carcharias* species as, other than in Cadenat's paper, no references to this characteristic have been found. The subgeneric status of *Pseudocarcharias* rests, therefore, only on the low tooth count, the number of teeth anterior to the gap (or small teeth) and the lack of small anterior teeth. The greater length of the upper lip groove in relation to the lower also appears to separate *kamoharai* from the other species of *Carcharias*.

However, in view of the variability of the teeth within a single species of *Carcharias*, as seen in *taurus*, these four characteristics are not considered sufficient to justify subgeneric status for *kamoharai*. This is confirmed by a comparison of the species of *Carcharias* (Table 2).

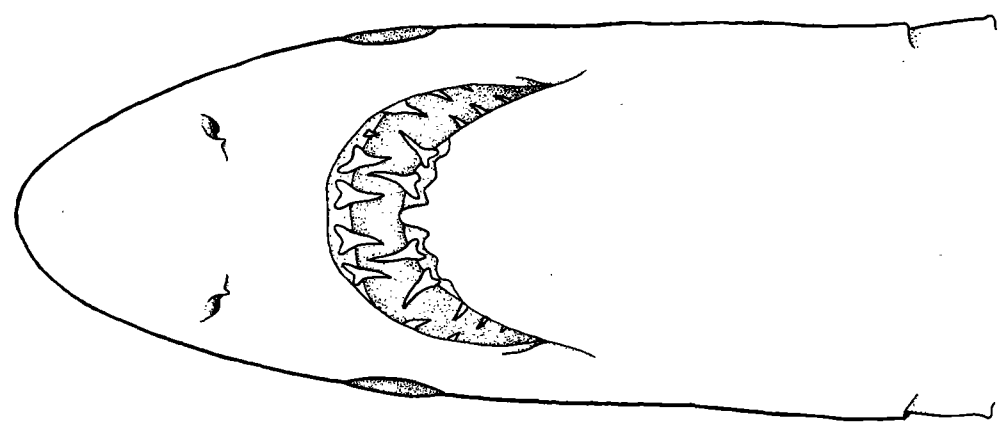
TABLE 2 **COMPARISON OF C.KAMOHARAI WITH OTHER SPECIES OF CARCHARIAS**

	taurus	**tricuspidatus**	**noronhai**	**arenarius**	**herbsti**	**ferox**	**owstoni**	**kamoharai**
According to description by	Bigelow & Schroeder	Day	Maul	Whitley	Whitley	Daugherty	Garman	4 authors*
Relative lengths of 2 anterior upper teeth	Subequal		First smaller	Subequal	Subequal	First smaller	Subequal	Subequal
Relative lengths of 2 anterior lower teeth	First smaller	First smaller	First smaller	First smaller	First smaller	First smaller	First smaller	Subequal
No. of teeth anterior to gap or small teeth	3	3	3	3	3	3	3	2
No. of small teeth in gap	1	1	1	1	4	4	1	0 or 1
No. of basal denticles on each side of tooth	0 or 1 or 2	1	1	1	2 or 3	1 or 2 or 3	0	0 or 1
Diameter of eye in longest tooth	$>\frac{2}{3}$		$<\frac{1}{2}$			$\frac{2}{5}$	$<\frac{1}{2}$	$>\frac{1}{2}$
Longer lip groove	Lower	Lip grooves absent	Lower	Lower	Lip grooves equal in length	Lower	Lower	Upper
Dental formula	$\frac{44 \text{ to } 48}{41 \text{ to } 46}$	$\frac{32 \text{ to } 34}{30 \text{ to } 34}$	$\frac{38}{40}$	$\frac{49}{40}$	$\frac{48}{40}$	$\frac{46 \text{ to } 54}{36 \text{ to } 48}$		$\frac{26 \text{ to } 29}{24 \text{ to } 26}$
Preoral in head to first gill slit	4 or 5		3.8	4.4	2.7	2.6		2.3–2.75
Horizontal diameter eye in preoral	2.5–3.3		2.7	5	3.4	3.7	3	2
Horizontal diameter eye in interorbital			±2.7		2.9	2.75		2
Relative sizes of fins	Subequal	Subequal	DI>DII>Anal	Subequal	Subequal	Subequal	Subequal	DI>DII>Anal
Interdorsal distance in 2nd dorsal base	0.6–0.7			0.5	0.4	0.3	0.75	0.25
Anterior margin pectoral in rear lobe	0.4	0.2	0.3			0.3		0.5
Position of pelvic origin	Behind DI base			Behind DI base	Behind DI base	Behind DI base	Behind DI base	Behind DI base
Position of anal origin	Opposite last ½ DII base	Behind DII origin	Behind DII origin	Opposite Last ½ DII base	Behind DII base	Behind DII base	Opposite last ⅓ DII base	Behind DII base
					It appears likely that Maul is correct in suggesting that these two species are synonymous			

*Matsubara, Chen, Cadenat and D'Aubrey.



a



b

FIG. 1. *Carcharias kamoharai*, mature male, 814 mm. in total length.

a. Lateral view.

b. Ventral View of head.

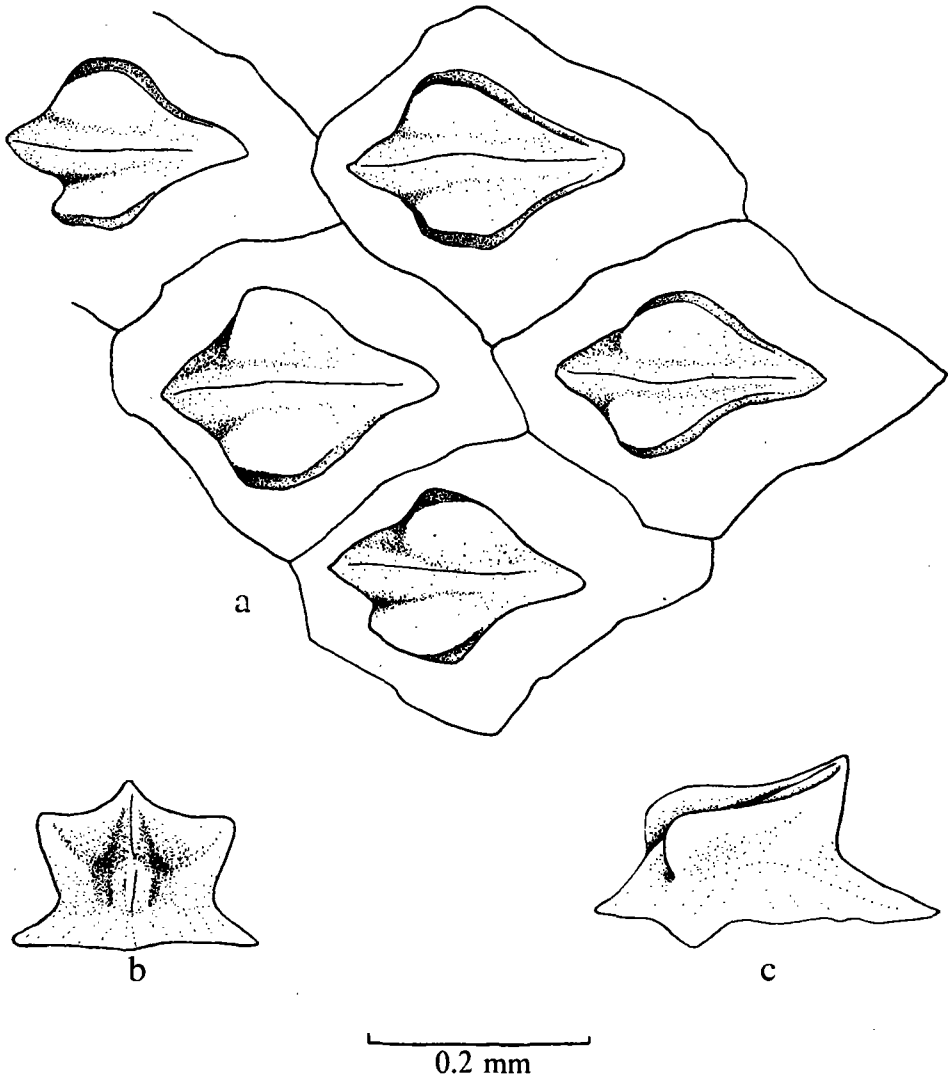


FIG. 2. *Carcharias kamoharai*, mature male, 814 mm. in total length.
a. Dorsal view of dermal denticles. b. Anterior view of dermal denticle.
c. Lateral view of dermal denticle.

Description

Carcharias kamoharai was first described from Japanese waters and descriptions have since been included in other works on the fishes of Japan. It has been described off Taiwan by Teng (1959) and off West Africa by Cadenat (1963). There is no previous record of it in South African waters and a description of the South African specimen is given as follows:

CARCHARIAS KAMOHARAI Matsubara 1936

Material

One mature male specimen of 814 mm. in total length. Preserved in formalin. Unfortunately the specimen had been gutted before it was examined and no data for the total weight or the greatest width and depth could be obtained.

MEASUREMENTS IN mm. OF CARCHARIAS KAMOHARAI MALE 814 mm. IN TOTAL LENGTH, AND AS PERCENTAGES OF THE TOTAL LENGTH

	mm.	%
From snout to origin of pelvic	484	59.5
,, ,, pectoral	202	24.8
,, ,, first dorsal	328	40.3
,, upper end first gill slit	152	18.7
,, anterior margin of eye	52	6.4
,, inner end of nostril	45	5.5
,, mandible (mouth closed)	66	8.1
Length nostril	12	1.5
Between inner ends nostrils	21	2.6
From inner end nostril to mandible (least)	22	2.7
,, ,, orbit (least)	29	3.6
Horizontal diameter orbit	23	2.8
Vertical diameter orbit	28	3.4
Interorbital distance	58	7.1
From orbit to mandible (least)	20	2.5
Mouth width	51	6.3
Mouth height	33	4.1
Length upper lip groove	26	3.2
,, lower lip groove	20	2.5
From orbit to spiracle	31	3.8
Length spiracle	4	0.5
,, first gill slit	51	6.3
,, second gill slit	50	6.1
,, third gill slit	50	6.1
,, fourth gill slit	47	5.8
,, fifth gill slit	44	5.4
Between upper ends first to fifth gill slit	60	7.4
,, ,, first to second gill slit	15	1.8
Interdorsal distance	150	18.4
Between fin fronts first to second dorsal	231	28.4
,, ,, second dorsal to origin caudal	98	12.0
,, ,, pectoral to pelvic	283	34.8
,, ,, pelvic to anal	105	12.9
,, ,, anal to origin lower caudal	62	7.6
Least depth before caudal grooves	22	2.7
,, width before caudal grooves	22	2.7
First dorsal base	81	10.0

	mm.	%
First dorsal height	38	4.7
„ „ length anterior margin	71	8.7
„ „ rear lobe	21	2.6
Second dorsal base	33	4.1
„ „ height	19	2.3
„ „ length anterior margin	32	3.9
„ „ rear lobe	24	2.9
Anal base	24	2.9
„ height	11	1.4
„ length anterior margin	27	3.3
„ rear lobe	21	2.6
Pectoral length from origin to outer tip	81	10.0
„ base	32	3.9
„ rear lobe	37	4.5
Pelvic origin to lateral corner	46	5.7
„ „ median tip	67	8.2
Length claspers (cloaca to tip)	95	11.7
Caudal upper lobe from origin to tip	202	24.8
„ lower lobe from origin to tip	83	10.2
„ terminal lobe from notch to tip	40	4.9
„ upper origin to concavity	79	9.7
Standard length	652	80.1

Description

Trunk slender, caudal peduncle moderately slender and without keels but a slight longitudinal thickening evident on each side; upper caudal groove present, lower slight; dorsal midline not ridged.

Dermal denticles widely spaced and not overlapping. They are small, 0.21 - 0.25 mm. in length and 0.15 - 0.18 mm. in width. Three longitudinal ridges present, all of which are strongly keeled anteriorly. The lateral ridges lie close to the edges of each denticle and converge posteriorly to form one posterior marginal tooth.

Head (from the snout to the first gill slit) 4.3 in precaudal length. Snout long, slightly depressed and broadly tipped in profile. Preorbital distance 1.1 in interorbital and 2.9 in head. Eye large (horizontal diameter 6.6 in head); circular; anterior margin almost opposite anterior margin of mouth. Eye nearer tip of snout than first gill slit. No *nictitans* present. Spiracle well developed and situated level with and posterior to eye. Gill slits long (longest 3.0 in head) and anterior to origin of pectoral. Their ventral ends extend beneath level of pectoral origin. Nostrils much nearer mouth than tip of snout (prenarial distance nearly two-thirds preoral distance and a little more than twice internarial distance). Nostrils almost horizontal, small and slit-like; their anterior edge nearly straight but for a short, narrow nasal lobe. Preoral distance 2.3 in head or three times eye diameter. Mouth narrowly arched but wider than high (height 1.5 in width which is 3.0 in head); corners of mouth deeply sunken, upper lip groove longer than lower.

Teeth long, narrow, awl-shaped and similar in both jaws; longest tooth approximately equal to half eye diameter; no lateral basal denticles.

Dental formula $\frac{13-14}{12-12}$ $\left(\frac{11::2-2:1::11}{10:2-2:10}\right)$

First two teeth on each side of centre are longest. Adjacent to these, on the upper jaw, there is a gap in which there may be one very small tooth. Teeth following the gap are smaller than first two teeth and decrease in size towards side of jaw. Situation of teeth on lower jaw same as on upper jaw, except no gap or small tooth between large central and smaller lateral teeth.

First dorsal origin midway between tip of snout and caudal origin, posterior to pectorals even when outer corner of pectoral is adpressed laterally. Rear tip of first dorsal well anterior to origin of pelvics. First dorsal low (height 2.1 in base) and triangular; posterior margin nearly straight; apical tip rounded and rear lobe stout.

Second dorsal of same shape as first (height 1.7 in base) but considerably smaller (base and height being 2.5 and 2.0 in those of first dorsal respectively). Base less than quarter of interdorsal distance; origin just posterior to rear end of pelvics; rear lobe terminates opposite posterior end of anal base.

Anal of same shape as first and second dorsals (height 2.2 in base) but considerably smaller than either (base and height 1.4 and 1.7 in those of second dorsal respectively); base 1.6 in distance from origin to rear tips of pelvics; anal opposite posterior end of second dorsal base; rear lobe terminates anterior to caudal origin by a distance nearly equal to length of base.

Pectorals short, quadrilateral in shape; slightly convex anterior margin; posterior margin almost straight; anterior (outer) and posterior (inner) corners rounded; inner margin slightly convex and almost equal in length to base or 2.2 in anterior margin. Anterior margin 1.9 in head.

Pelvics triangular and smaller than first dorsal but larger than second; anterior (outer) corner rounded but posterior corner pointed just outside of claspers. In this specimen claspers reach beyond anal origin.

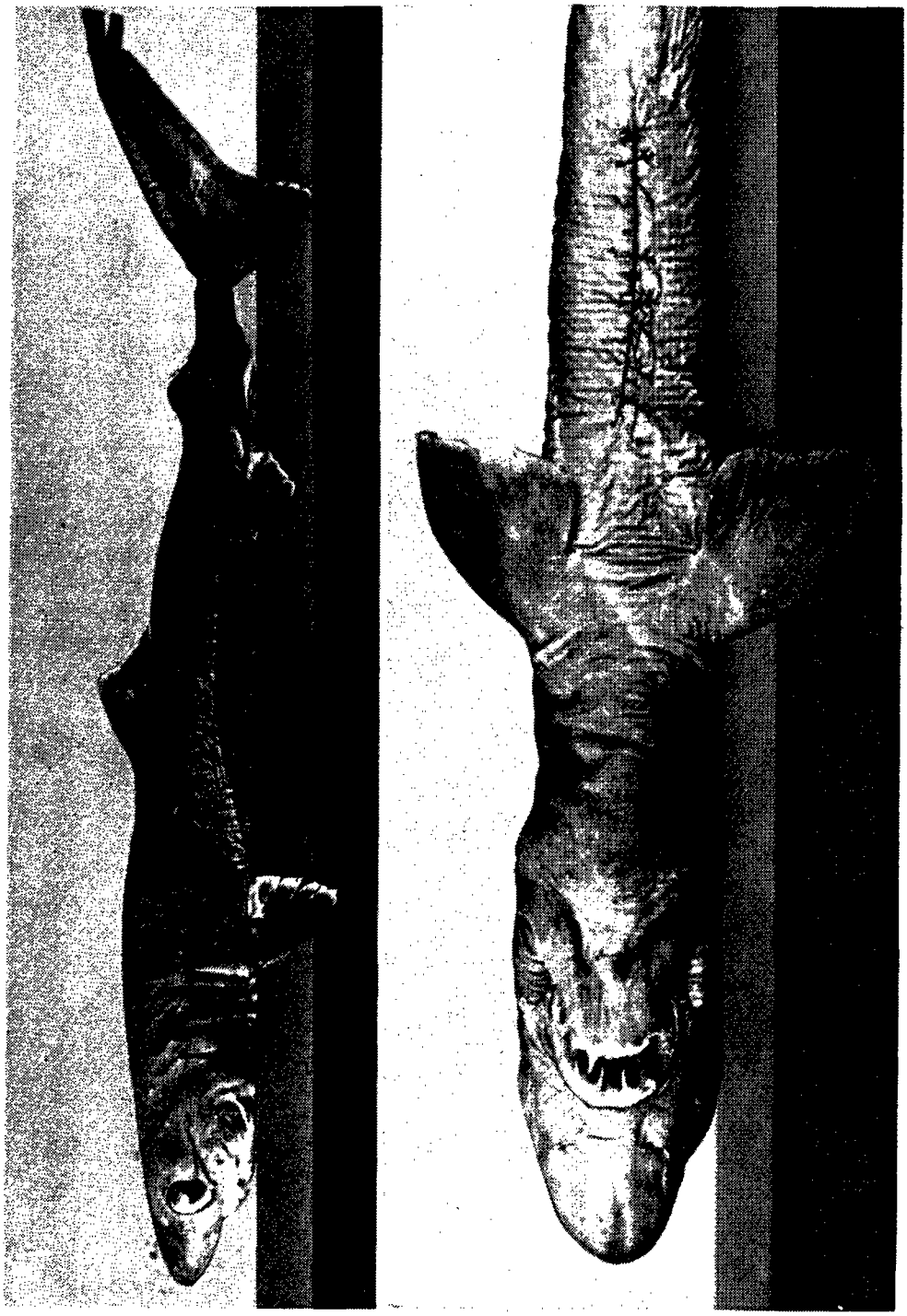
Upper caudal short, length less than one third of precaudal length or less than quarter of total length. Length of terminal lobe from notch to apex 5.1 in upper caudal length and length of lower caudal 2.4.

Colour

After preservation in formalin the colour is dark brown above and on the sides and light brownish grey on the ventral surface. Fins dark brown except for the undersides of the paired fins which become paler towards the base. With the exception of the upper caudal, the posterior margin of each fin is narrowly edged with white or appears transparent. There is no conspicuous white spot between the mouth and first gill slit as described by Matsubara. This area is, however, slightly paler than the lateral colour and appears to be a slightly darker extension of the ventral colour.

Vertebral counts

Total count	153
Precaudal count	84



a b

FIG. 3. *Carcharias kamoharai*, mature male, 814 mm. in total length.
a. Lateral view. b. Ventral view.

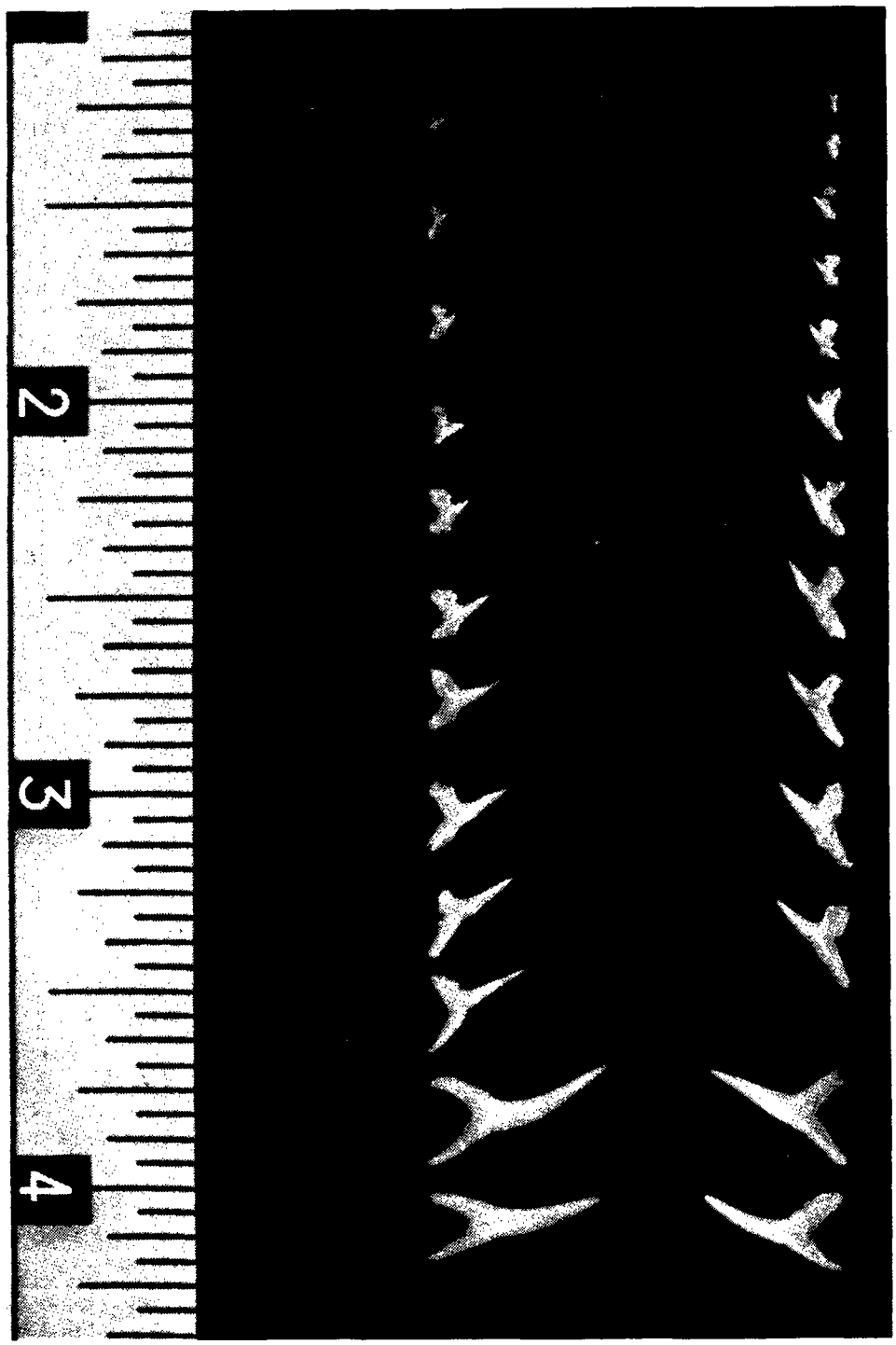


FIG. 4. *Carcharias kamoharai*, mature male, 814 mm. in total length. Teeth of left side of upper and lower jaws.

General

In spite of the apparent rarity of this species (only 21 specimens are known to have been recorded), *C.kamoharai* is widely distributed and is found in the Atlantic, Pacific and Indian Oceans from approximately 33° N. to 35° S. The localities from which specimens have been recorded are as follows:

Specimen	Locality	Date	Remarks
C.kamoharai (holotype)	Kochi, S.W. Japan	–	–
C.yangi (holotype)	Taiwan	–	–
S.A. specimen	Cape Town, S. Africa	Dec 1961	Swimming feebly in shallow water
P.pelagicus (paratype)	Luanda, Angola	April 1962	Between 250–300 m. in depth
P.pelagicus (holotype)	Guinea Coast	Aug–Sept	–
16 specimens recorded by N. Merritt	S.W. of Madagascar 23–28°S 38–41°E	June 1964	Caught on long lines

The type of *C.kamoharai*, the S.A. specimen and the paratype of *P. pelagicus* (males of 735, 814 and 975 mm. in total length respectively) had well developed claspers, which reached beyond the origin of the anal, and it is assumed that *C.kamoharai* matures at a length of approximately 735 mm.

Summary

1. *Carcharias kamoharai* is recorded for the first time from South African waters.
2. *Pseudocarcharias pelagicus* and *Carcharias yangi* are synonymous with *Carcharias kamoharai*.
3. *Pseudocarcharias* is not considered to be of subgeneric status.

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The Miocene Shark Fauna of the Southern St. Lucia Area

by

David H. Davies

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Introduction

A marine fauna belonging to the Lower* Miocene from Uloa, Zululand (Fig. 1) was discovered in July 1952 and has been described in considerable detail by Professor Lester King of the University of Natal (1953). A total of 103 metazoan species was described from a number of extremely rich fossiliferous sandstone blocks which were removed from the area and examined in the laboratory. King considered the fauna to be typically sub-tropical Indo-Pacific and he found that there were many similarities between the fauna of the Uloa deposits and the Tertiary faunas of East Africa and India. He found the fauna to be widely different from the more temperate Tertiary faunas of the Cape Province in South Africa.

The Uloa outcrop and the neighbouring hills at Sapolwana (Fig. 2) are situated on the coastal plain of Zululand and are located 6 to 7 miles inland at a height of approximately 60 feet above sea level. King (1953) considered the geomorphological implications of the fossiliferous deposit and his views are summarised in the two paragraphs which follow:

The coastal plain in which St. Lucia Lake and the Umfolozi River are situated has had a varied history. Twice, in the late Cretaceous and in Miocene time, the entire plain has been submerged beneath the sea and marine fossiliferous deposits of these ages are to be found along the western side of Lake Eteza (Fig. 1) near the main road. At other times it has been exposed as low-lying land. During the early Miocene period, with which we are concerned, the shoreline lay probably not far inland from the marked ridge of Miocene fossiliferous sandstones (now seven miles inland) upon which stands the headquarters of the Uloa sugar plantations (Fig. 1).

After the withdrawal of the transgressive Pliocene sea, caused by an uplift of the land, the lower Umfolozi — St. Lucia drainage carved channels through the several fossiliferous series to depths of more than 100 feet below the present river beds. Quaternary tilting of the landscape drowned these channels below sea level and they have since been filled in with alluvium to form the present extensive lands upon which sugarcane is grown.

A good description of the geological and fossiliferous composition of the deposits has been given by King (1953), but only brief mention has been made of sharks' teeth from one species (*Carcharodon megalodon*) belonging in all probability, to a single specimen which became stranded at Uloa. During 1964 it was learned that work had been started on the removal of the smallest of three fossiliferous hills (Sapolwana 3) at Sapolwana with the aid of a bulldozer in order to create an additional area for the planting of sugarcane and to provide hard material for the laying of the tracks of a cane railway.

* According to the shark fauna this could be Middle Miocene rather than Lower Miocene.

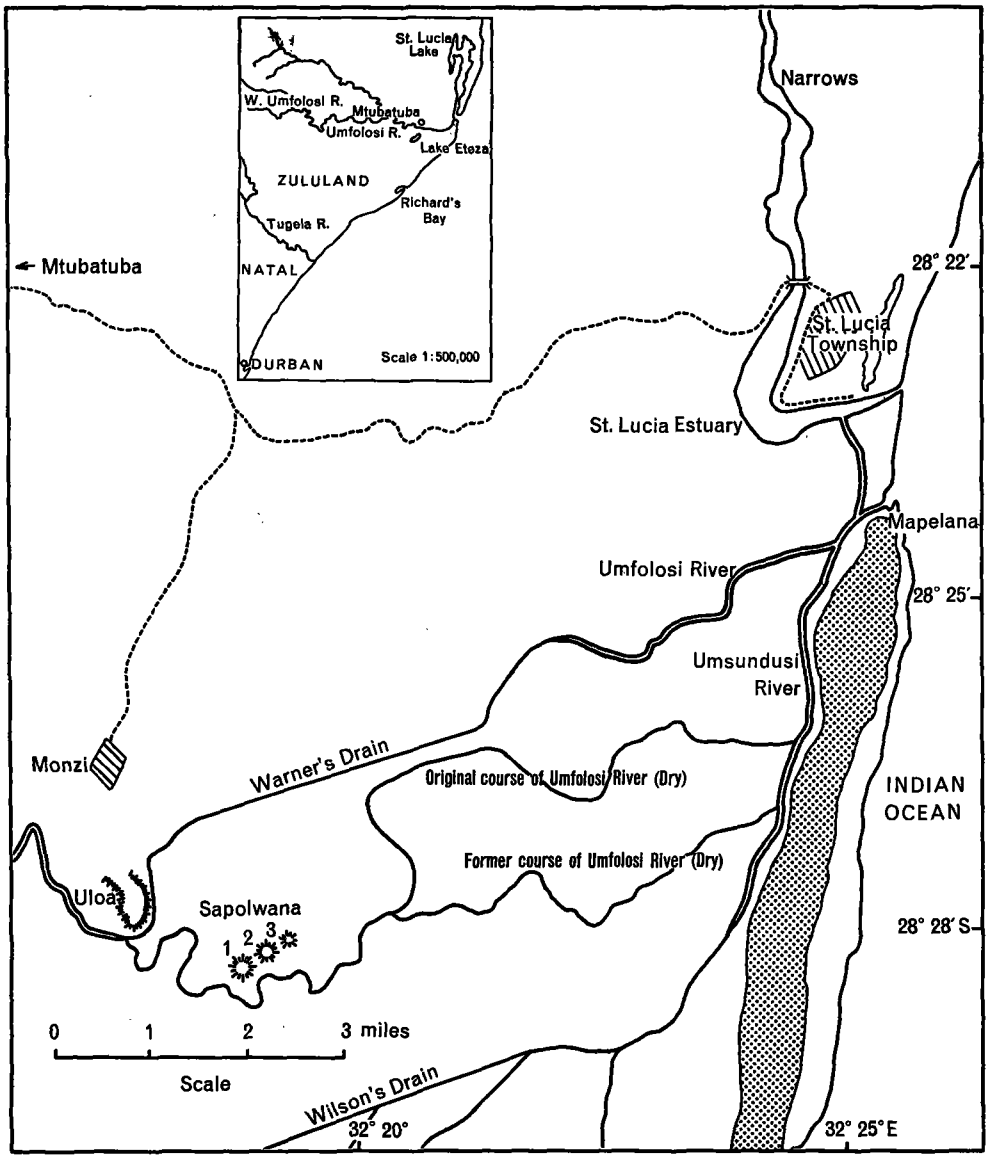


FIG 1. The southern St. Lucia area showing location of Fossil Beds at Uloa and Sapolwana

With the assistance of Mr. Errol Harrison, a farmer in the Mtubatuba district, a search for sharks' teeth was made in the Miocene deposits in order to establish the composition of the shark fauna of the area to the south of Lake St. Lucia during Miocene times. The Uloa deposits yielded two *Carcharodon sulcidens* teeth in addition to the specimens of *C.megalodon* teeth described by King, together with a single broken *C.megalodon* tooth obtained by us in 1964. Large numbers of teeth belonging to a number of different species of sharks were obtained from Sapolwana 3 during the course of the examination of the bulldozed material.

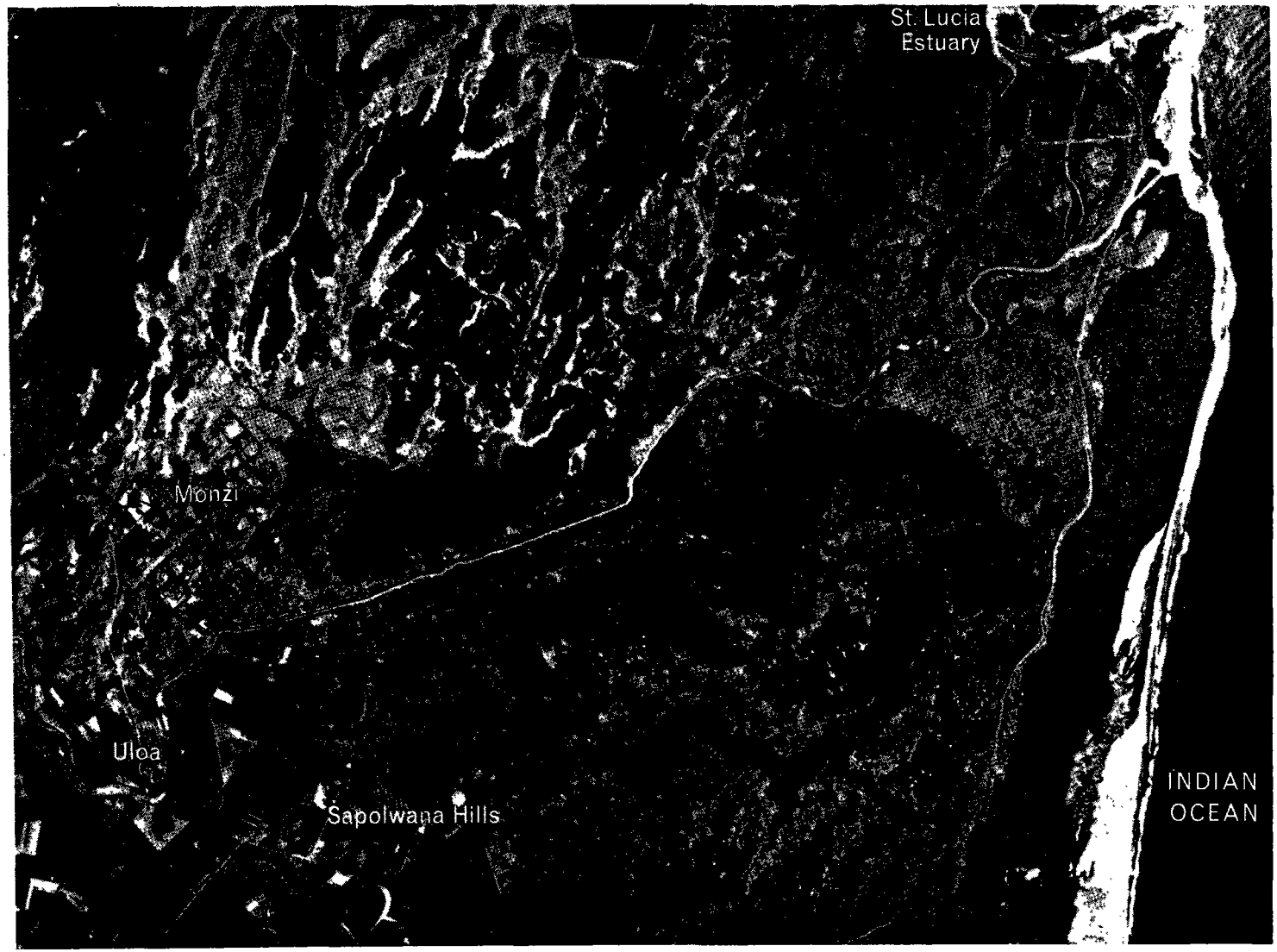


FIG. 2. Aerial photograph showing Uloa and the Sapolwana Hills in relation to the Lake St. Lucia Estuary and the Coast

Locality and Description of Sites

The two sites at which fossil sharks' teeth were found are Uloa and Sapolwana (Figs. 1 and 2). The general area of the two sites is on the coastal plain approximately 160 road miles north of Durban in Zululand. The Uloa site lies to the south of the village of Monzi at a point where the narrow gauge cane railway enters a cutting (Fig. 3) before crossing the Umfolozi River by means of a high level bridge.

The Sapolwana site is the most northerly situated of three hills designated Sapolwana 1, 2 and 3 (Figs. 1 and 2). Although the hills Sapolwana 1 and 2 are large and richly fossiliferous, they are thickly overgrown with bush and natural forest and have not been examined for sharks' teeth or other fossils. Sapolwana 3 was the principal source of sharks' teeth which were obtained as a result of the bulldozing of the hill. A general view of the three hills at Sapolwana is seen in Fig. 4, the razed hill Sapolwana 3 in Fig. 5 and the rich fossiliferous sandstone obtained from Sapolwana 3 is shown being used as a foundation for the cane railway in Fig. 6. A typical example of the extremely high density of fossil organisms found at both the Uloa and the Sapolwana deposits is seen in Fig. 7. Here the dominant fossil is the Scallop *Aequipecten uloa* King.

The general composition of both the Uloa and the Sapolwana deposits is similar, the lowest beds consisting of yellow sandy clays overlain by richly fossiliferous sandstone in a layer which varies from 20 to 30 feet in thickness. *Aequipecten uloa* is extraordinarily abundant in this layer. [The presence of scallops is characteristic of Miocene and later deposits and the phenomenon of *swarming* is characteristic of several Miocene deposits in various parts of the world, King (1953)]. Above the sandstone are flaggy Pliocene sandstones and succeeding layers of yellow sand, followed by grey sand and a layer of ironstone two to three feet thick.

According to King, the fossil beds comprise the remains of a Miocene sandbank which was once situated at the mouth of the Umfolozi river. Enormous numbers of littoral and sub-littoral organisms were associated with the sandbank. These organisms, according to the record obtained from the fossil beds investigated, are typically marine and consist of corals, *polyzoa, brachiopoda, pelecypoda, gastropoda, cirripedia, crustacea* and include neritic vertebrates in the form of sharks.

King states that from the point of view of the variety of fauna and number of species, the Uloa beds are by far the most important Tertiary locality so far found in South and East Africa. He also draws attention to the fact that a large proportion of the organisms found at Uloa are either identical with or closely similar to existing forms, showing that there has been relatively little change in the littoral sub-tropical Indo-Pacific type fauna of this area from Miocene to recent times. The survival of so large a variety of invertebrates from these deposits together with the remarkable survival of the Coelacanth *Latimeria chalumnae* Smith since Cretaceous time in the Comores Islands region is indicative of a slow rate of evolution in this area.



FIG. 3. The Fossil Beds at Uloa



FIG. 4. General view showing Sapolwana Hills, bush covered in middle distance



FIG. 5. Sapolwana 3 after bulldozing



FIG. 6. Fossiliferous sandstone from Sapolwana 3 being used on cane railway



FIG. 7. Section of fossiliferous sandstone showing extremely high density of organisms taken from Uloa

The Sharks' Teeth

Uloa

According to King (1953) many large teeth belonging to the extinct shark *Carcharodon megalodon* have been found in one section of the north side of the cutting at Uloa. Tooth counts made from the jaws of the existing form *Carcharodon carcharias* in the collection of jaws in the Oceanographic Research Institute in Durban showed that there are approximately 130 fully formed teeth in the upper jaw and 120 teeth in the lower jaw. Further excavation and systematic searching during a period of two weeks in June 1964 yielded no additional *C.megalodon* teeth, but four smaller specimens identified as belonging to *Carcharodon sulcidens Agassiz* were taken from the cutting site at Uloa. It is evident therefore that a single large *C.megalodon* and a smaller *C.sulcidens* became stranded in the Uloa beds. Details of the teeth obtained from Uloa are given in Table 1.

TABLE 1. **SHARK TEETH FOUND AT ULOA, ZULULAND**

Species	Number of Teeth	Total Length (range) mm.	Remarks
Carcharodon megalodon	13	99 – 130	Teeth from upper jaw of single shark.
Carcharodon sulcidens	2	32, 25	Damaged teeth from upper jaw.
	2	16, 21	Very worn teeth from lower jaw.

Certain of the *C.megalodon* teeth found were extremely large and measured up to 120 mm. in total length according to King (1953). The damaged specimen obtained by us in 1964 was 90 mm. in total length but the tip had

been broken off. Other specimens (13 in number) taken from the Uloa bed and now in the possession of the Durban Museum were examined and measured. The largest of these was found to be 125 mm. in total length (Fig. 8). Two additional specimens obtained at Uloa, one loaned by Prof. King and the other by Mr. Mill-Colman of Durban, measured 115 mm. and 130 mm. in total length respectively.

A large specimen of *C.megalodon's* nearest living relative the Blue Pointer *Carcharodon carcharias* was harpooned in the whaling grounds approximately 100 miles off Durban on 29 June 1962. The largest teeth in the upper jaw of this specimen measured 55 mm. in total length, the total length of the shark was 19 ft. and the estimated weight was 3,000 lbs. Assuming that the



FIG. 8. Teeth of *Carcharodon megaladon* found at the Uloa Fossil Beds

growth of *C.megalodon* was approximately proportional to that of *C.carcharias*, the Uloa specimen would have measured nearly 45 ft. in length and would have weighed several tons. Estimates of size made from the fossil teeth of this wide-ranging shark obtained in various parts of the world indicate that it may have reached 60 to 80 ft. in total length. The record for the largest specimen of *C.carcharias* obtained by Bigelow and Schroeder

(1948) measured 36½ ft. in length — there is, however, some doubt as to the authenticity of the length measurement of this specimen. Reliable records of *C.carcharias* 17 to 20 ft. in total length are fairly numerous and the largest specimen, listed in Bigelow and Schroeder's authenticated records of this species, which was taken off Havana in Cuba, was 21 ft. in length and weighed 7,100 lbs. Unfortunately no mention of the tooth size of this specimen is made.

The distribution of *C.megalodon* according to fossil teeth found in various parts of the world is much the same as the present distribution of the existing *C.carcharias*, viz. world-wide, mainly in tropical and sub-tropical seas, but found at times in temperate areas as well. Records of fossil teeth of the genus *Carcharodon* are as follows: Europe (Upper Cretaceous–Pleistocene), Africa (Eocene — Pliocene), North America (Eocene — Pleistocene), South America (Miocene), New Zealand (Miocene — Pliocene) and Eastern Asia (Pliocene) according to Bigelow and Schroeder (1948). These records doubtless include both *C.megalodon* and *C.sulcidens* and in the case of these investigations, the teeth of both *C.megalodon* and *C.sulcidens* were found in the Uloa deposits. At Sapolwana 3 large numbers of *C.sulcidens* teeth were found but no *C.megalodon* teeth were obtained.

A comparison was made between fossil teeth of *C.sulcidens* and teeth belonging to a freshly caught specimen of *C.carcharias* possessing teeth of similar size. Although there was close similarity between the fossil teeth and fresh teeth certain differences were noticed. These included differences in axial symmetry of the teeth of the two species and the presence of coarser and less regular serrations together with greater lateral concavity in the teeth of existing *C.carcharias*. The larger teeth of *C.megalodon* appeared to differ mainly in relation to size and in possessing finer and more numerous serrations although in existing specimens of *C.carcharias* the number of serrations was found to increase with the size of the specimen.

Sapolwana 3

As far as is known, no fossil shark teeth have previously been described from the fossil beds of Sapolwana 3. Examination of bulldozed material from the site revealed the presence of large numbers of teeth belonging to five species of shark: *Carcharodon sulcidens*, *Galeocerdo cuvieri*, *Isurus benedictus*, *Carcharias taurus* and *Hemipristis serra*. Details of the shark teeth obtained at Sapolwana 3 are given in Table 2.

An attempt was made to reconstruct the dental lay-out of the *C.sulcidens* teeth (Fig. 9) applying the known dental formula of the existing species. The first and second rows for the upper jaw and the first and second rows for the lower jaw were partially obtained together with large numbers of teeth without bases indicating that they came from immature back rows. It is likely that the teeth came from a single specimen of estimated total length 21 ft. and approximate weight 7,000 lbs. The presence of a small number of teeth in the collection from Sapolwana 3 which did not conform particularly well with the other specimens suggests that a second smaller *C.sulcidens* could have been stranded there as well.

A single large tooth in excellent condition belonging to the genus *Isurus*

benedictus was found at Sapolwana 3 (Fig. 10). It was matched with a corresponding tooth in a set of jaws belonging to a Mako Shark *Isurus glaucus* in the collection of jaws in the Oceanographic Research Institute. The jaws had been obtained from a specimen 8 ft. 8 ins. in length, weighing 290 lbs. Based on these data, the single tooth obtained from Sapolwana 3 belonged to a shark of estimated length 14 ft. and estimated weight over 1,000 lbs. Existing *Isurus* are said to reach 12 to 13 ft. in length and a weight of 1,000 lbs., Bigelow and Schroeder (1948). Fossil teeth belonging to the genus *Isurus* have been found in deposits dating back to the late Oligocene, Gregory (1957).

TABLE 2. **SHARK TEETH FOUND AT SAPOLWANA 3, ZULULAND**

Species	Number of Teeth	Total Length (range) mm.	Remarks
Carcharodon sulcidens	75	10 - 61	Upper Jaw – probably from 2 sharks.
	61	18 – 54	Lower Jaw – probably from 2 sharks.
Isurus benedirtus	1	50	Single tooth in excellent condition.
Carcharias taurus	17	15 - 24	Majority of teeth well worn.
Galeocerdo cuvieri	6	10 - 30	1 from Upper Jaw (large), 1 from Lower Jaw (small) remainder broken.
Hemipristis serra	2	21 - 24	Upper Jaw.

Seventeen slender teeth of length range 15 to 24 mm. were obtained at Sapolwana 3; the majority of these were in an extremely worn condition but two possessed well marked lateral denticles and were identified as belonging to the Ragged Tooth Shark *Carcharias taurus*. It is likely that the teeth came from a single specimen of moderate size.

A large tooth from the upper jaw, a small tooth from the lower jaw and four tooth fragments belonging to the Tiger Shark *Galeocerdo cuvieri** were found at Sapolwana 3 (Fig. 10). The two intact teeth were in excellent condition and, based on teeth in specimen jaws in the Oceanographic Research Institute, the total length of the shark from which they came was estimated to have been approximately 10 ft. and its weight about 220 lbs. Fossil teeth of this genus have been described from the following areas: North America (Cretaceous — Miocene), South America (Miocene), Europe (Eocene — Pliocene), Asia (Miocene), West Indies (Miocene) and Africa (Eocene — Miocene), Bigelow and Schroeder (1948).

Two teeth, one intact and one damaged, belonging to the Carcharinid species *Hemipristis serra* Agassiz were obtained at Sapolwana 3 (Fig. 10). The genus *Hemipristis* was considered to be extinct until 1871 when a specimen was caught in the Red Sea. Since then specimens have been found in deep water off Bombay, Zanzibar and northern Moçambique, Fourmanoir (1961). Fossil teeth of this species have been described from the following areas: North America (Cretaceous — Pliocene), South America (Miocene), Europe (Pliocene), Asia (Miocene), West Indies (Tertiary), and Africa (Eocene and Miocene), Bigelow and Schroeder (1948).

* The two teeth obtained were indistinguishable from *G.cuvieri*. If a sufficient number of teeth are obtained for comparison in the future, it is possible that this species will be found to be *G.aduncus* Agassiz.



FIG. 9. Teeth of *Carcharodon sulcidens* (upper and lower jaw) found at Sapolwana 3

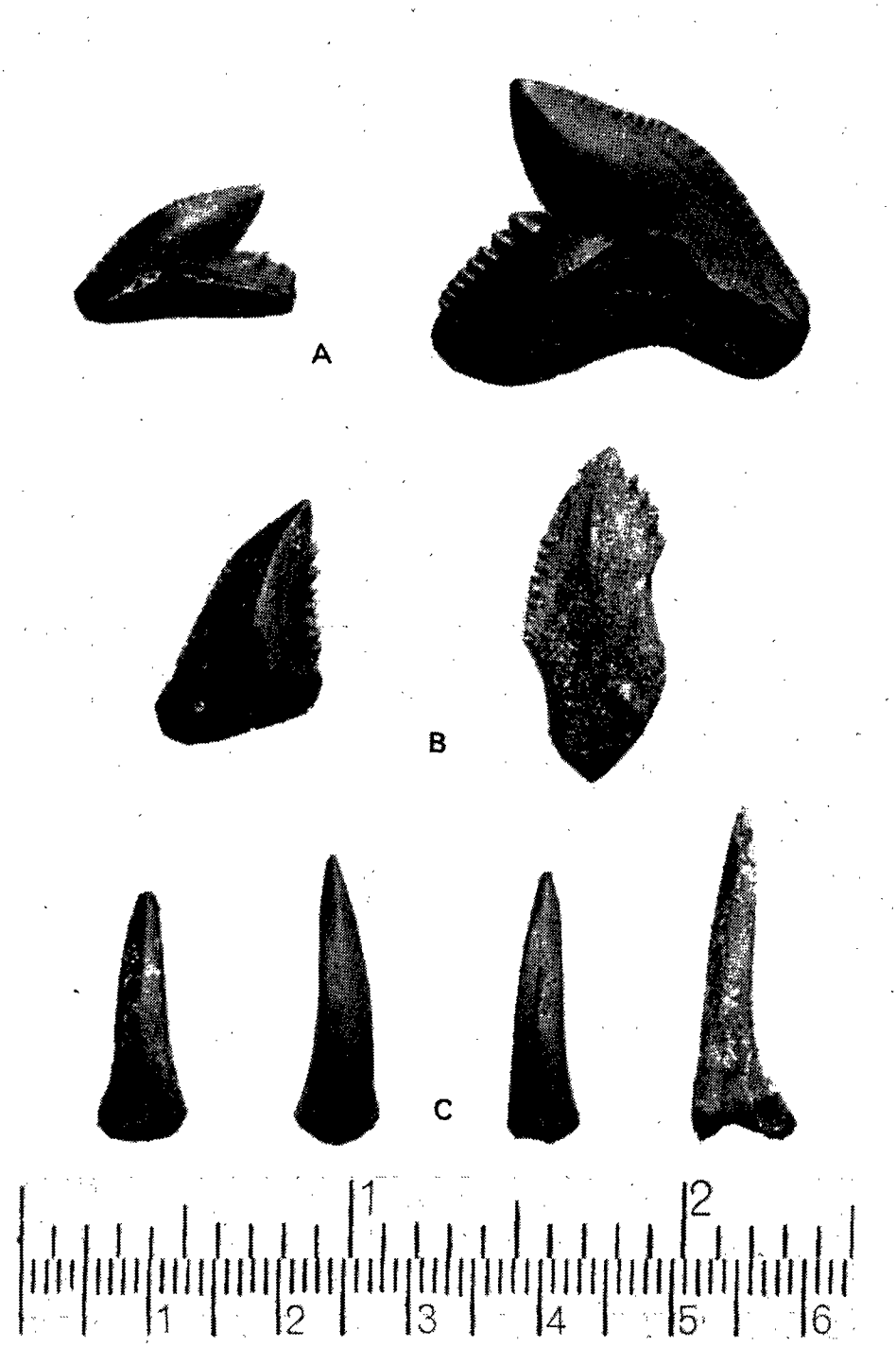


FIG. 10. Teeth of (A) Tiger Shark *Galeocerdo cuvieri* (B) *Hemipristis serra* and (C) Ragged Tooth Shark *Carcharias taurus* taken from Sapolwana 3

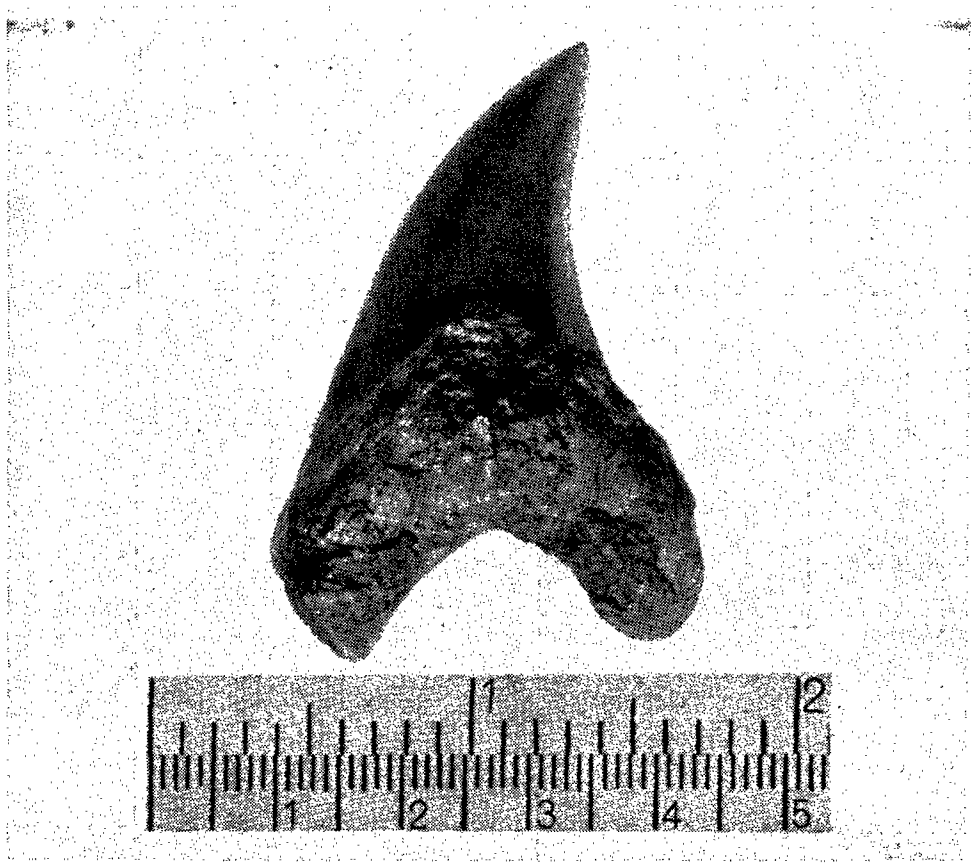


FIG. 11. Tooth of Mako Shark *Isurus benedictus* taken from Sapolwana 3

Summary

A provisional determination of the Miocene shark fauna of the area south of Lake St. Lucia based on the recovery of fossil teeth from extensive excavations of fossiliferous sandstone of Middle Miocene origin from two sites in Zululand revealed the presence of fossil teeth belonging to the following sharks: *Carcharodon megalodon* Agassiz, *Carcharodon sulcidens* Agassiz, the Mako *Isurus benedictus*, the Ragged Tooth Shark *Carcharias taurus* Rafinesque, the Tiger Shark *Galeocerdo cuvieri* (Lesueur) and *Hemipristis serra* Agassiz. Four genera, viz. *Carcharodon*, *Isurus*, *Geleocerdo* and *Carcharias* are still found off the coasts of Zululand and Natal, one species, *C.megalodon* is extinct and the existing *Hemipristis* is found in the northern Indian Ocean and the Red Sea.

The examination of material from this area for the purpose of locating additional shark teeth is being continued.

Acknowledgments

I am much indebted to Prof. Lester King of the Geology Department, University of Natal for his critical reading of the manuscript of this paper and for the loan of a *Carcharodon megalodon* tooth. I am grateful to Mr. Mill-Colman of Durban for the loan of a *C.megalodon* tooth.

It gives me great pleasure to acknowledge the important part played by Mr. Errol Harrison of Mtubatuba in organising the collection of sharks' teeth from Uloa and Sapolwana and in providing enthusiastic and valuable assistance in many different ways.

The photograph appearing in Fig. 2 was taken from a mosaic of the St. Lucia area prepared by Mr. Paul Dutton of the Natal Parks, Game and Fish Preservation Board.

I wish to acknowledge the assistance provided by my colleagues in this project, in particular Mr. K. H. Cooper, Miss J. d'Aubrey, Miss R. Ahrens and Miss L. Joubert.

Finally, I wish to acknowledge the very great assistance provided by Dr. Shelton Applegate of the Los Angeles County Museum, U.S.A. during a short visit to South Africa in November 1964. Dr. Applegate visited the Uloa and Sapolwana deposits, examined the material, checked and, in certain cases re-identified the teeth and offered many valuable suggestions for future work on fossil shark teeth.

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REEF CORAL TOLERANCE OF HIGH TEMPERATURES AND SALINITIES

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THE purpose of this article is to bring revised data to the attention of geologists and others interested in the distribution of coral reefs, concerning the temperature and salinity conditions under which reef corals may grow.

During the past three years I have been engaged in the investigation of Recent limestones and calcareous sediments near the town of Abu Dhabi, Trucial Coast, Persian Gulf. The area comprises a series of coastal islands and lagoons at the southern margin of a broad shelf, the Trucial Coast embayment. Field studies have revealed the presence of coral reefs, along the inner margin of the shelf, at its junction with the coastal island and lagoon complex. The reefs are associated with areas of oolite and skeletal sands, and farther back in the lagoons are extensive spreads of pellet sands and aragonite muds. Early diagenetic dolomite and evaporite deposits exist in many of the innermost areas.

Reef or hermatypic corals are distinguished by the presence of symbiotic, unicellular, dinoflagellate algae or zooxanthellæ in their endodermal tissues. 'Deep-sea' or ahermatypic corals lack zooxanthellæ and can withstand a much wider range of environmental conditions than can reef corals. Reef corals are limited in their habitats largely because of the mutual interdependence of the coral polyps and their algal symbionts.

Limitations on reef coral growth include factors such as water circulation, illumination, temperature, and salinity:

(*a*) *Water circulation :* fairly vigorous water circulation is required to ensure the necessary supply of oxygen and nutrients.

(*b*) *Illumination :* reef corals generally live in depths of less than 50 m and most vigorous growth takes place in depths of less than 20 m. The depth control is a reflexion of the depth to which light may penetrate in sufficient amount to maintain the metabolic processes of the zooxanthellæ. The upper limit of coral growth is normally close to low water mark, as death ensues by desiccation if exposure is too prolonged.

(*c*) *Temperature :* water temperature is an important control and reef corals flourish best in the range 25°–29° C. They can withstand limited exposure to temperatures as low as 16°–17° C, and in the West Indies the maximum endurable temperature for survival and continued growth has been found to be about 36° C. Because of its high rate of metabolism, *Acropora* is thought to be the most sensitive and can endure a maximum temperature of only 32° C (Wells, personal communication).

(*d*) *Salinity :* average tropical ocean water has a salinity of 35 parts per thousand and reef corals flourish best within the range 34–36 parts per thousand. How-

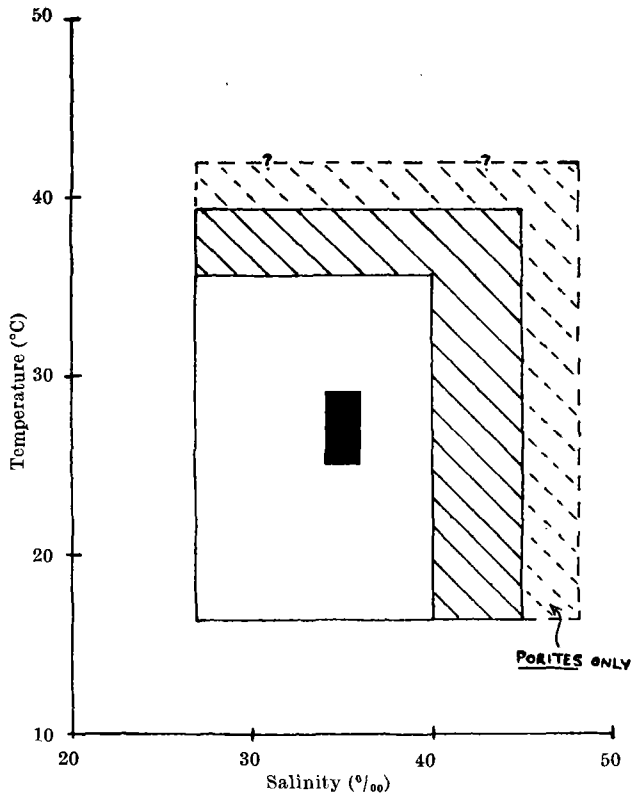


Fig. 1. Temperature and salinity tolerances of reef corals. Black, optimum conditions; white, previously accepted limits; hatched, extended limits derived from Persian Gulf investigations; broken hatched, extreme limits—boundaries uncertain

ever, they can tolerate dilution to 27 parts per thousand or concentration to 40 parts per thousand. In the West Indies it is found that *Acropora* can withstand salinities of 40 parts per thousand for only a few hours, although *Porites* can survive salinities of up to 48 parts per thousand. Above 48 parts per thousand all forms die or are damaged.

Along the Trucial Coast reef corals grow between low water mark and about 10–15 m depth. However, sea-water temperatures and salinities have been found to exceed those recorded in other regions of reef coral growth. Surface and shallow sea-water temperatures range seasonally from a minimum of 16° C to a maximum of over 40° C; deeper than 4–5 m the seasonal temperature range is about 20°–36° C. Average surface water temperatures from May to October are in excess of 30° C. In late July, August and early September air temperatures over the adjoining islands reach at least 47° C, and during this period shallow water temperatures in excess of 35° C are commonly encountered. Previous authors[1] have found that a large diurnal range in water temperature has drastically affected the distribution of corals on reef flats and other very shoal areas. Along the Trucial Coast corals in very shallow depths endure diurnal temperature ranges in excess of 10° C and a total seasonal range of over 20° C. The Trucial Coast reefs are composed dominantly of *Acropora*, even in very shoal areas which suffer maximum temperature changes; yet *Acro-*

pora is a form found to be extremely temperature sensitive in the West Indies.

Sea-water salinities along the Arabian shore of the Persian Gulf are everywhere high and near Abu Dhabi the open coast salinities are always in excess of 42 parts per thousand. Salinities in the reef areas range from 42 to 45 parts per thousand and in the seaward parts of the lagoons large *Porites* colonies, up to 3 m in diameter, occur where salinities reach 48 parts per thousand. As in the West Indies, it is the massive coral *Porites* which is capable of withstanding the highest salinities, although above ·48 parts per thousand even this form cannot survive. Other genera apparently cannot tolerate salinities much in excess of 45 parts per thousand.

The optimum and previously determined temperature and salinity limits of reef coral growth are indicated in Fig. 1; also shown are the extensions of the limits determined from the Trucial Coast reef coral environment.

The reef coral fauna from the Abu Dhabi area comprises:

vc *Acropora* sp. cf. *A. pharaonis* (Milne Edwards and Haime)
vc *Porites* sp. cf. *P. lutea*—Milne Edwards and Haime
c *Platygyra lamellina*—Ehrenberg
c *Cyphastrea microphthalma* (Lamark)
c *Stylophora pistillata* (Esper)
u *Favia favus* (Forskaal)
r *Coscinaria monile* (Forskaal)
Siderastrea liliacea (Klunzinger)
r *Psammocora* (*Stephanaria*) *planipora*—Milne Edwards and Haime
r *Turbinaria* sp.
r *Plesiastrea* sp. nov.

vc, very common (dominant reef builders); c, common; u, uncommon; r, rare.

With the exception of the new species of *Plesiastrea*, all the foregoing forms are known to occur in the Red Sea and Indian Ocean faunas, and most of these species have been previously recorded in the northern Persian Gulf. The genus *Psammocora* is uncommon but widespread in the Red Sea and Indo-Pacific faunas, but this is the first recorded occurrence from the Persian Gulf. The presence of *Siderastrea* is also of interest as it is extremely rare in the living Indo-Pacific fauna, being typically an Atlantic genus.

The total number of reef coral genera now recorded from the Persian Gulf is fifteen, and eleven of these have been found in the Abu Dhabi area. The full Indo-Pacific fauna numbers over 80 genera. The attenuation in the number of genera between the Indo-Pacific and Persian Gulf regions may be explained either as a result of geographical isolation or because of the extreme temperatures and salinities experienced in the latter region. Even within the Persian Gulf the number of genera would appear to be lower along the Trucial Coast than in the northern parts of the Gulf, where water salinities are less than 39–40 parts per thousand and summer water temperatures probably do not exceed 35° C. It is therefore probable that the further reduction of genera along the Trucial Coast is a result of the higher water temperatures and salinities of this area.

The distribution of reef corals in areas affected by low temperatures has been remarked on by several authors[1]. Below 18° C the number of genera and species falls and reef development as a whole is less strong than in areas of higher temperatures. In the Abu Dhabi area reef

structures are fairly well developed, though probably inferior to those formed under less extreme conditions of temperature and salinity. Despite the reduction in the number of reef coral genera, reef structures formed of several coral genera are still developed where salinities do not exceed 45 parts per thousand. Above 45 parts per thousand reefs are no longer formed and only lone colonies of *Porites*, often of large size, are to be found.

In the geological record the presence of coral reefs is usually taken as good evidence that the environment was one in which sea-water salinities were close to normal (35 parts per thousand). However, in the Abu Dhabi area coral reefs are growing under conditions of elevated temperature and salinity. The only indication of extreme conditions is the reduction in the number of genera. Those genera which are present show "no noticeable differences or effects—they might all have come from waters of usual salinity and temperature" (Wells, personal communication).

Lying close behind the reefs are the lagoonal carbonate sediments together with early diagenetic dolomite and evaporite deposits. The close juxtaposition of coral reefs, apparently indicating normal salinity waters, and of evaporites and lagoonal 'back-reef' dolomites, normally considered indicative of elevated salinities, is of fairly frequent occurrence in the geological record. But investigations on the Trucial Coast have shown that the back-reef dolomite and evaporite deposits are a diagenetic development and that excessively high salinities in this environment are not attained by free-standing bodies of lagoon waters but by pore fluids within the sediments. Thus the concept of a back-reef lagoon with waters of salinity greater than 100 parts per thousand will in many instances be almost certainly incorrect. However, in order to produce high salinities in the interstitial fluids within the sediments, an area must be one of high net evaporation. High net evaporation will tend to produce higher than normal salinity waters in shallow shelf and lagoon environments, as occurs along the Trucial Coast. If offshore depths are fairly great and water circulation unrestricted, then salinities at the seaward edge of the lagoon barrier might rise little higher than those of normal ocean water. Thus, in any area, if fairly deep water conditions can be proved to have existed seaward of the coral reefs, then the corals probably lived in waters with salinities close to normal, even though shallow back lagoonal waters might have been fairly saline. But if evidence is found of coral reefs growing at the inner margins of a broad, shallow shelf, with saline lagoons behind, then it is quite possible that the corals themselves were living under fairly saline conditions. The latter type of occurrence is exemplified by the present-day Trucial Coast environment.

I thank Dr. J. W. Wells of Cornell University and Dr. W. J. Rees and Mr. E. White of the British Museum (Natural History) for identification of the corals and for their advice. This work forms part of a programme of research in the Persian Gulf, supported by the Department of Scientific and Industrial Research.

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インド洋ココス・キーリング諸島附近の植物プランクトンの垂直分布

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Abstract

The present paper deals with a study of the vertical distribution of phytoplankton in an area near Cocos-Keeling Islands in the Indian Ocean. Collections were made at three stations in this area, on the 13th, 15th and 16th of January 1963 on board the "Umitaka Maru," Training Ship of Tokyo University of Fisheries, during her cruise from Colombo to Singapore. During this cruise collections of surface plankton were also made at several other stations between 5°S and 25°S along 78°E (Fig. 1). Taxonomic study of diatoms collected at all these stations including those near Cocos-Keeling Islands will be dealt with in another paper.

Vertical hauls were made with a Hart type closing net (25 cm in diameter of mouth ring; 30 cm in diameter of trunk ring; 0.094 mm mesh, XX 13, Japanese bolting silk). No flow-meter was attached to the net. Depths of zones where collections were made were 200–100 m, 100–50 m, 50–20 m, and 20–0 m. Details of collections are shown in Table 1.

Number of phytoplankton species identified from the samples are as follows: Cyanophyceae: 2 species; Bacillariophyceae: 30 species. One species is divided into two forms; Dinoflagellata: 52 species and one variety. Two species are divided into two forms each.

Only 6 species of diatoms were found in the 50–100 m zone, another 4 species of diatoms in the 100–200 zone, and the rest (nearly 75 per cent of the diatoms) were confined to the upper 50 m zone. Total number of the diatom cells also apparently decreased with increase in depth. Some species of diatoms namely, *Planktoniella sol*, *Asteromphalus flabellatus*, *A. wyvillei* and *Gossleriella tropica*, seem to prefer the dim light of the disphotic zone as they were found in the 100–200 m zone.

The bulk of the phytoplankton consisted of dinoflagellates. The species most commonly found were *Pyrophacus horologicum*, *Ceratium carriense* forma *ceylanicum*, *C. carriense* forma *hundhansenii* and *Pyrocystis* (*Dissodinium*) *hamulus* var. *inaequalis*. As in the case of the diatoms most of the dinoflagellates were confined to the 0–50 m zone. It was observed that the amount of dinoflagellates in the 50–100 m and 100–200 m zones was much more than the amount of diatoms. As with diatoms the number of dinoflagellates was very few in the 100–200 m zone, and they were represented by *Amphisolenia bidenta*, *Pyrophacus horologicum* var. *steinii*, *Ceratium brave*, *C. lunula*, *C. vultur*, *C. carriense* forma *volans*, *C. carriense* forma *ceylanicum*, *C. carriense* forma *hundhausenii*, *C. trichoceros* forma *claviceps* and *C. cephalatum*.

I wish to express my sincere thanks to Dr. Takashi Sekine, President of Tokyo University of Fisheries, for granting me permission to join the cruise of "Umitaka Maru" from Colombo to Singapore. I am grateful to professor Hiroshi Niino, Tokyo Universty of Fisheries, Expedition Leader on that cruise, and Captain Keijiro Ozawa of the "Umitaka Maru" for making my trip comfortable and granting me all facilities to work. My sincere thanks are due to Professor Sigeru Motoda, Hokkaido University, who was on board on that cruise, not only for assisting me in collecting materials at sea, but also arranging my paper to be published in this journal.

要　　約

筆者は昭和37年12月26日より同38年1月21日まで，東京水産大学練習船海鷹丸のコロンボ，シンガポール間航海に便乗し，1月13，15，16日に亘り3回ココス・キーリング諸島附近で植物プランクトンの垂直分布を観察する機会を得た。採集は口径25cmの垂直閉鎖ネットにより0～20m，20～50m，50～100m，100～200mの層別に行なつた。得られた標本より藍藻類2種，硅藻類30種（1種は2型を含む），双鞭毛類52種1変種（2種は夫々2型を含む）を同定した。珪藻類，双鞭毛類何れも種量ともに大部分は0～50m層に分布し，以深に急減する。100～200mの薄光層に分布する蔭性種と思われるものは，*Planktoniella sol*, *Asteromphalus flabelletus*, *A. wyvillei*, *Gossleriella tropica* 等の硅藻類，*Amphisolenia bidenta*, *Pyrophacus horologicum* var. *steinii*, *Ceratium brave*, *C. lunula*, *C. vultur* *C. carriense* forma *volans*, *C. carriense* forma *ceylanicum*, *C. carriense* forma *hundhausenii*, *C. trichoceros* forma *claviceps*, *C. cephalatum* 等の双鞭毛類である。

Table 1. Data on sampling

Station	Postion	Date	Time	Wire run out (m)	Wire angle (degree)	Estimated depth (m)
1	97°19′E 12°46′S	Jan. 13 (1963)	9:56 a.m.	340 & 175	55	200—100
				131 & 65	40	100—50
				58 & 23	30	50—20
			10:26 a.m.	23 & 0	30	20—0
2	98°42′E 10°11′S	Jan. 15 (1963)	10:20 a.m.	247 & 124	36	200—100
				111 & 56	26	100—50
				56 & 22	26	50—20
			10:45 a.m.	21 & 0	26	20—0
3	100°05′E 8°15′S	Jan. 16 (1963)	10:02 a.m.	278 & 159	44	200—100
				118 & 59	32	100—50
				53 & 21	20	50—20
			10:26 a.m.	20 & 0	16	20—0

Table 2. Occurrence of phytoplankton at various depths in an area near Cocos-Keeling Islands, Indian Ocean

Date and position of collection	13 January 1963 12°46′S,97°19′E				15 January 1963 10°01′S,98°42′E				16 January 1963 8°15′S,100°05′E			
Depths of collection	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m
CLASS : CYANOPHYCEAE												
Oscillatoria laetevirens Crouan	+				+				+	+		
Trichodesmium erythraeum Ehrenberg et Gomont	+				+	+			+			
CLASS: BACILLARIOPHYCEAE												

Date and position of collection	13 January 1963 12°46′S,97°19′E				15 January 1963 10°01′S,98°42′E				16 January 1963 8°15′S,100°05′E			
Depths of collection	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m
Order: Centrales												
Skeletonema costatum (Greville) Cleve		+			+	+			+	+		
Melosira sulcata (Ehrenberg) Kuetzing	+	+			+	+			+			
Thalassiosira decipiens (Grunow) Jörgensen	+				+	+			+			
Coscinodiscus lineatus Ehrenberg	+						+					
Coscinodiscus marginatus Ehrenberg						+			+			
Planktoniella sol (Wallich) Schutt			+	+		+		+		+	+	+
Asteromphalus wyvillei Castracane		+			+	+	+	+				+
Asteromophalus flabellatus (Brébisson) Greville		+		+		+	+	+				+
Gossleriella tropica Schutt			+	+			+	+			+	+
Actinocyclus ehrenbergii Ralfs		+				+	+			+	+	
Corethron hystrix Hensen		+								+		
Rhizosolenia setigera Brightwell	+				+							
Rhizosolenia robusta Norman					+							
Rhizosolenia styliformis Brightwell					+	+			+			
Rhizosolenia alata Brightwell forma *gracillima* (Cleve) Grunow	+	+				+						
Rhizosolenia alata Brightwell forma *indica* (Peragallo) Ostenfeld	+				+				+			
Chaetoceros pervianus Brightwell					+				+			
Chaetoceros didymus Ehrenberg var *protuberans* (Lauder) Gran et Gendo						+						
Chaetoceros affinis Lauder		+	+			+				+		
Chaetoceros diversus Cleve	+					+				+		
Eucampia zoodiacus Ehrenberg	+				+				+			
Climacodium Frauenfeldianum Grunow	+								+	+		
Order: Pennales												
Fragilaria oceanica Cleve		+										
Synedra formosa Hantzsch	+	+										
Thalassiothrix longissima Cleve and Grunow		+			+				+	+		
Pleurosigma angulatum (Quekett) W. Smith		+				+						
Nitzchia longissima (Brob.) Ralfs	+	+				+			+	+		
Nitzschia seriata Cleve	+	+				+			+			
Nitzschia closterium (Ehrenberg) Smith			+				+				+	

Date and position of collection	13 January 1963 12°46′S,97°19′E				15 January 1963 10°01′S,98°42′E				16 January 1963 8°15′S,100°05′E			
Depths of collection	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m
Amphiprora gigentia Grunow var. *sulcata* (O'Meara) Cleve									+			
Navicula Hennedyii W. Smith		+			+				+			
CLASS: DINOPHYCEAE												
Order: Diniferidea												
Dinophysis miles Cleve	+						+					
Amphisolenia bispinosa Kofoid		+				+	+					+
Amphisolenia bidenta Schroder		+	+	+	+	+		+	+			
Amphisolenia thrinax Schutt		+			+	+	+			+	+	
Ornithocercus steinii Schutt	+	+	+			+	+		+		+	
Pyrophacus horologicum var. *steinii* Schiller	+	+	+	+	+	+			+	+		+
Peridinium thorianum Paulsen		+				+		+				
Peridinium steinii Jörgensen					+	+			+			
Peridinium diabolus Cleve		+				+			+			
Peridinium brochii forma *inflatum* (Okamura) Schiller							+			+		
Peridinium depressum Bailey	+				+		+			+		
Goniaulax birostris Stein		+			+				+	+		
Goniaulax pacifica Kofoid					+	+						
Goniaulax minima Matzenauer		+			+	+						
Ceratium incisum (Karsten) Jörgensen		+			+							
Ceratium teres Kofoid	+	+				+			+			
Ceratium Kofoidii Jörgensen		+			+	+						
Ceratium Schmidtii Jörgensen	+				+	+			+			
Ceratium inflatum (Kofoid) Jörgensen					+				+			
Ceratium reticulatum (Pouchet) Cleve	+					+			+			
Ceratium strictum (Okamura et Nishik.) Kofoid			+				+					
Ceratium oxtensum (Gourret) Cleve		+			+	+						
Ceratium breve (Ostenfeld and Schmidt) Schroder					+		+		+			+
Ceratium karstenii Pavillard	+	+					+			+	+	
Ceratium contortum forma *subcontortum* (Schroder) Steeman Nielsen					+	+			+		+	
Ceratium furca (Ehrenberg) Clap and Lach.	+								+			
Ceratium gibberum forma *sucaequale* Jörgensen			+									

Date and position of collection	13 January 1963 12°46′S,97°19′E				15 January 1963 10°01′S,98°42′E				16 January 1963 8°15′S,100°05′E			
Depths of collection	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m	20–0m	50–20m	100–50m	200–100m
Ceratium lunula Schimper				+			+					
Ceratium Schmidtii Jörgensen	+				+							
Ceratium symmetricum Pavillard	+	+	+									
Ceratium limulus Gourret					+							
Ceratium buceros forma *tenue* (Ostenfeld and Schmidt) Schiller	+						+					
Ceratium buceros forma *molle* (Kofoid) Schiller	+		+			+	+		+			
Ceratium arietinum Cleve	+				+	+						
Ceratium fusus (Ehrenberg) Dujardin	+				+	+			+			
Ceratium Pavillardii Jörgensen	+		+		+		+		+			
Ceratium vultur var. *sumatranum* (Karsten) Steeman Nielsen	+	+		+	+	+			+		+	+
Ceratium deflexum (Kofoid) Jörgensen	+				+				+	+		
Ceratium hexacanthum Gourret						+				+		
Ceratium massiliense (Gourret) Jörgensen	+		+		+	+			+	+		
Ceratium pentagonum Gourret	+				+		+		+			
Ceratium carriense forma *volans* (Cleve) Jörgensen		+		+				+		+		
Ceratium carriense forma *ceylanicum* (B.Schroder) Jörgensen	+	+	+	+	+	+	+	+	+			+
Ceratium carriense forma *hundhausenii* (Schroder)		+	+	+	+	+	+	+	+		+	+
Ceratium deflexum (Kofoid) Jörgensen	+				+				+			
Ccratium gibberum Gourret	+		+			+			+		+	
Ceratium macroceros subsp. *gallicum* (Kofoid) Jörgensen					+					+	+	
Ceratium trichoceros (Ehrenberg) Kofoid		+								+		
Ceratium trichoceros var. *contrarium* (Gourret) Schiller	+				+	+		+	+	+	+	
Ceratium trichoceros forma *claviceps* Schroder	+	+	+		+			+	+			+
Ceratium cephalotum (Lemmermann) Jörgensen		+		+		+	+	+				
Ceratium longinum Karsten	+					+			+			
Ceratium euarcuatum Jörgensen	+	+				+			+			
Ceratium reticulatum (Pouchet) Cleve	+	+				+				+		
Goniodoma acuminatum Stein	+				+							

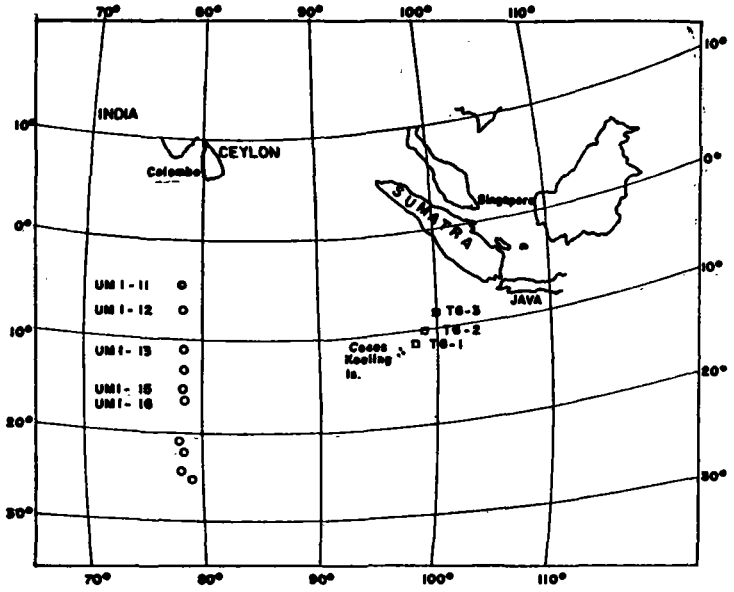


Fig. 1. Umitaka Maru cruise of Indian Ocean, December 26, 1962, to January 20, 1963.
tg=tuna grounds.
O=stations covered in connection with I. I. O. E.

インド洋標準ネットの濾水率，標本量変動，濾水直線等について

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Filtration Ratio, Variance of Samples and Estimated Distance of Haul in Vertical Hauls with Indian Ocean Standard Net

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インド洋標準ネットの濾水率，標本量変動，濾水直線等について *

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Filtration ratio, variance of samples and estimated distance of haul in vertical hauls with Indian Ocean standard net

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Abstract

I. Filtration ratio of Indian Ocean standard net

In previous paper (Motoda *et al.*, 1963a) filtration ratio of the Indian Ocean standard net was reported to be 0.70 (Umitaka Maru) and 0.72 (Oshoro Maru). On the cruise in the Indian Ocean 1963-64 filtration ratio of this net was again measured on the "Umiatka Maru" and "Oshoro Maru" (Tables 1, 2), with the results of 0.86 and 1.0 respectively. High value obtained by the experiment on the "Oshoro Maru" was probably due to the fact that the experiment with net was made at a station when the angles of wire were considerably great (15-24°), while the experiment without net was made at one other station on calm day. The filtration ratio of the Indian Ocean standard net may be presumed

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as 0.7-0.9.

II. Variance of samples in vertical haul with Indian Ocean standard net

In previous paper (Motoda *et al.*, 1963a) it was reported that in 0-200 m vertical haul with an Indian Ocean standard net, the standard deviation percentage of samples was 30.2 % (displacement), 39.6 % (wet weight) in 99 % fiducial limit; 18.4 % (displacement), 23.9 % (wet weight) in 95 % fiducial limit in the experiments on the "Umitaka Maru," and 34.4 % (displacement), 41.4 % (wet weight) in 99 % fiducial limit; 18.7 % (displacement), 21.4 % (wet weight) in 95 % fiducial limit in the experiment on the "Oshoro Maru." On the 1963-64 cruise by the "Umitaka Maru" and "Oshoro Maru" in the Indian Ocean, experiments were again made (Tables 3, 4). From the above-mentioned four series of experiments, it can be said that the variance of samples in 0-200 m haul with Indian Ocean standard net will be as follows:

Standard deviation percentage. 99 % fiducial limit:
30～75% (displacement)
40～66% (wet weight)
Standard deviation percentage. 95 % fiducial limit:
18～45% (displacement)
21～40% (wet weight)

III. Estimation of distance of haul in vertical sampling with Indian Ocean standard net

The writers proposed a method of estimation of the distance of haul of plankton net in vertical haul, which will differ with drifting velocity of the ship (Motoda *et al.*, 1963b). Plotting the data on flow-meter readings in the standard zooplankton samplings obtained during the cruises of the "Kagoshima Maru" and "Oshoro Maru" in the Indian Ocean, from November 1963 to January 1964, in the previous figure of filtration line (Motoda *et al.*, 1963, Fig. 3), Fig. 1 is obtained. It is found that the newly plotted dots generally satisfy the filtration line previously drawn, $y = 0.482\,x + 130$, where y is length (m) of wire cable extended long enough for the net to reach 200 m depth, and x is volume (m^3) of water filtered by the net that originally calculated by flow-meter readings. Applying this line for calculation of volume of water filtered by the net in standard samplings made by the "Umitaka Maru," "Koyo Maru" and "Oshoro Maru" on 1962-63 cruises, and "Kagoshima Maru," "Koyo Maru," "Umitaka Maru" and "Oshoro Maru" on 1963-64 cruises, the distribution charts of zooplankton biomass in the upper 200 m zone in the eastern Indian Ocean are illustrated in Figs. 2-5.

IV. Estimation of underwater wire angles in vertical plankton net haul

Using an underwater wire clinometer (Fig. 6) (Motoda, 1963, p. 159, Pl. 4, Fig. 4) an experiment was made to observe the line of wire cable underwater when the ship was drifting considerably due to wind. A Norpac plankton net with a sinker was repeatedly lowered to the depth by running out the wire cable as a length of 200 metres. One underwater wire clinometer was attached to different positions on the wire cable each time. The results (Table 7, Fig. 7) indicate that the wire cable suspending the plankton net and sinker did not extend in a straight line, but curved to a certain degree. The position of the net is shown to be about 184 m depth. If the depth at which net was positioned is simply estimated by length of wire run out and angle of wire on deck, it amounts to 112 m approximately. The error is remarkably great.

前報にインド洋標準ネット（網目0.33mm）の濾水率並びに採集標本量の変動についてのべ，（元田外1963a）又垂直採集に於て船の標流による濾水量増加の推定方法について提案を行ったが（元田外1963b），其の後の資料を加えて再び考察してみたい。本報告のため未発表資料の使用を許された海鷹丸，耕洋丸，かごしま丸の各担当者に深く感謝する。

I. インド洋標準ネットの濾水率

濾水量の測定は，ネット濾過布を取外して口輪だけにしたものと，ネット濾過布をとりつけたものとの2種を，海上平穏でワイヤ傾角の少い時に，くりかえし垂直引上を行って，口輪中央に装着した濾水計の示度を読み，両者を比較して求められる。インド洋標準ネットは口輪に続いて 70cm の長さの粗網部があるが，

垂直引上に於て，口輪から入った水はこの部分から殆ど外部に溢れ出すことはないと想像される（Currie 1962，元田 1962)。従って粗網部の存在による影響は無視することとする。ネットの濾水率測定は，プランクトン及び懸濁細片を含まない海で実施することが理想である。

前報（元田外1963 a）に於て述べた，インド洋標準ネットの濾水率は0.70（海鷹丸），0.72（おしよろ丸）であった。海鷹丸の実験は東支那海で行われ当時のプランクトン量は 0-200m 層平均排水量 5.1cc/0-200m haul，湿重量 1.51gr/0-200m haul であった。又おしよろ丸の実験は津軽海峡西方で行われたが，プランクトン量は多く，0-200m層平均排水量47.24cc/0-200m haul，湿重量 47.8gr/0-200m haul であった。併し上記の如く結果に表われた濾水率は両実験の間に大きな差はなく，却って反対におしよろ丸の場合の方が少しばかり濾水率が高くなっている。

1963－64年度航海に於ける海鷹丸（妹尾次郎氏による）並びにおしよろ丸で行った，インド洋標準ネットの濾水率検定結果は Tables 1，2 の如く夫々0.86及び

Table 1. Estimation of filtration ratio of Indian Ocean standard net; 1963-64 cruise of the "Umitaka Maru" in the Indian Ocean.
Flow-meter: TSK 710.
Locality of observations: Sta. Um-I-28, 03°55′S, 99°35′E.

Date and time	January 22, 1964, 1131-1159	January 22, 1964, 1034-1111
Mean velocity of haul	0.83 m/sec.	0.84 m/sec.
Mounted on	Mouth ring without net	Mouth ring with net

No. of haul	Angle of wire	Length of wire (m)	Revolutions of flow-meter	Angle of wire	Length of wire (m)	Revolutions of flow-meter
1	3	200	1111	1	200	929
2	0	200	1102	3	200	970
3	2	200	930	4	200	916
4	3	200	1190	4	200	924
Mean			1083.		200	935
Ratio			1			0.86

Measurement was made by Mr. J. Seno.

1.0の値が得られた。当時の標本量は夫々排水量 2.2cc/0-200m haul，湿重量2.2gr/0-200m haul 及び排水量 22.6cc/0-200m haul，湿重量 22.4gr/0-200m haul であって，おしよろ丸の場合の採集量は極めて多い。それにも拘らずおしよろ丸の場合は clogging のために濾水率が低下せずに却って濾水率 1.0 という値が示されている。之はおしよろ丸の実験が無網試験と有網試験と異なる時と場所で行われ，有網試験を行った時のワイヤ傾角は 15～24° に及び，曳網距離はワイヤの長さよりも相当増加したと想像される。従って上記の4回の実験で得られた値の中0.70，0.72，0.86をとり，インド洋標準ネットの濾水率は0.7～0.9と推定するのが適当であろう。

II. インド洋標準ネット垂直引上げによる採集量の変動

インド洋標準ネットの採集量変動については前報（元田外1963 a）に次の結果を報告した。

標準偏差百分率		標本排水量	標本湿重量
海鷹丸実験	99%信頼限界	30.2%	39.6%
	95%信頼限界	18.4%	23.9%
おしよろ丸実験	99%信頼限界	34.4%	41.4%
	95%信頼限界	18.7%	21.4%

1963～64年インド洋航海における海鷹丸並びにおしよろ丸の実験結果は Tables 3，4 の如くである。

Table 2. Estimation of filtration ratio of Indian Ocean standard net; 1963-64 cruise of the "Oshoro Maru" in the Indian Ocean.

Flow-meter: RGS 292.

Velocity of haul: about 1 m/sec.

Locality	Sta. Os 5, 12°54′S, 109°04′E	Sta. Os 8, 10°12′S, 110°50′E
Date and time	December 17, 1963, 0712-0752	December 20, 1963, 1029-1125
Mounted on	Mouth ring without net	Mouth ring with net

No. of haul	Angle of wire	Length of wire (m)	Revolutions of flow-meter	Angle of wire	Length of wire (m)	Revolutions of flow-meter
1	13	200	2961	18	202	2868
2	13	205	3052	18	202	2800
3	16	198	2784	24	203	3130
4	13	201	2848	22	203	2805
5	14	201	2837	15	203	2880
6	14	201	2870			
7	11	211	2957			
Mean revolutions per one metre			14.3			14.3
Ratio			1			1

Table 3. Estimation of variance of samples taken by 0-200 m vertical hauls with Indian Ocean standard net; 1963-64 cruise of the "Umitaka Maru" in the Indian Ocean.

Sta. Um-I-28, 03°55′S, 99°35′E.

January 22, 1964, 1034-1111.

No. of haul	Velocity of haul (m/sec.)	Angle of wire	Length of wire (m)	Displacement of sample (cc)	Wet weight of sample (gr)
1	0.81	1	200	2.2	2.4
2	0.83	3	200	2.3	2.5
3	0.89	4	200	2.3	2.1
4	0.84	4	200	2.0	1.8
Mean				2.2	2.2
Standard deviation. 99% fiducial limit				0.41	0.94
Standard deviation. 95% fiducial limit				0.23	0.51
Standard deviation percentage. 99% fiducial limit				18.64%	42.73%
Standard deviation percentage. 95% fiducial limit				10.45%	23.18%

Sampling and measurement of displacement and wet weight of samples were made by Mr. J. Seno.

Table 4. Estimation of variance of samples taken by 0-200 m vertical hauls with Indian Ocean standard net; 1963-64 cruise of the "Oshoro Maru" in the Indian Ocean.

Sta. Os 8, 10°12'S, 110°50'E.

December 20, 1963, 1029-1125.

Velocity of haul: about 1 m/sec.

No. of haul	Sample No.	Angle of wire	Length of wire run out (m)	Sample per 0-200 m	
				Displacement (cc)	Wet weight (gr)
1	63188	18	202	13.9	14.9
2	63189	18	202	19.8	19.8
3	63190	24	203	31.9	33.9
4	63191	22	203	24.7	24.2
5	63192	15	203	22.6	19.4
Mean				22.6	22.4
Standard deviation. 99% fiducial limit				17.02	14.82
Standard deviation. 95% fiducial limit				10.26	8.94
Standard deviation percentage. 99% fiducial limit				75.3%	66.2%
Standard deviation percentage. 95% fiducial limit				45.4%	39.9%

Large organisms such as fish larvae, salps, doliolids, etc. were removed before measurement.

以上の両年の実験結果により，インド洋標準ネットの0-200m垂直採集における採集量の変動は99%信頼限界に於て標準偏差百分率は30～75%（排水量），40～66%（湿重量），95%信頼限界に於て18～45%（排水量），21～40%（湿重量）となる。

III. インド洋標準ネット垂直引網におけるネット通過距離（濾水量）の推定

前報（元田外1963）に於てインド洋標準ネット0-200m垂直採集に於けるネット通過距離の推定によって濾水量を計算する方法を述べたが，今回1963～64年（4mmワイヤ，40kg錘使用）のおしよろ丸による採集，1963～64年のかごしま丸による採集，の結果を前報 Fig. 3 にプロットしてみたところ（Fig. 1），大体前回と同じ傾向を示し，前報で述べた濾水量推定直線式 $y=0.482x+130$ 〔y はワイヤ傾角に応じて200m層にネットが達するまで繰出したワイヤの長さ（m），x はネットが濾過した水量（m^3）〕をそのまま使用し得るものと認められた。海鷹丸 1962～63年，1963～64年航海，耕洋丸1962～63年，1963～64年航海の結果は点のばらつきが甚しいので用いなかった。Fig. 1 の濾水直線はワイヤ角度（ワイヤ角度に応じてワイヤの長さをのばして）に対応する引網距離を示すものであるが，之には当然濾水計示度を基礎にしたネットの濾水率も含まれて了っている。

今上記の濾水直線によって1962～63年の海鷹丸，耕洋丸，おしよろ丸の結果，1963～64年のかごしま丸，耕洋丸，海鷹丸，おしよろ丸の結果につき，濾水量を計算し，両年のインド洋東部に於ける0-200m層の動物プランクトンビオマス（標本排水量cc/1000m^3，標本湿重量 gr/1000m^3）の分布を示してみると Tables 5, 6, Figs. 2～5の如くなる。

IV. プランクトンネット垂直引上における水中ワイヤ傾度測定

従来プランクトンネットによる垂直採集に於て，ネットの下降深度は甲板上で測定したワイヤ傾角と，くり出したワイヤの長さから簡単に算定していた。従って若し水中に於けるワイヤの形状が直線をなさない場合は，この計算ではネットの到達深度の推定に誤りを生ずる。1963～64年インド洋航海の帰途スルー海で水中ワイヤ傾角計（Fig. 6）（Motoda 1963, p. 159, pl. 4. Fig. 4）を用い，ネットを吊した200mのワイヤの水中に於ける形状を測定してみた。ただしこの時はインド洋標準ネットは破損して了ったので，北太平洋標

Table 5. Mean displacement volume (cc/1000 m³) and mean wet weight (gr/1000 m³)

Ref. to A-J in Figs. 2, 3.	A			B			C			D			E			F		
Latitude	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³
08°N～06°N	2	74.5	74.9															
06°N～04°N	1	38.0	38.1				3	16.9	16.7									
04°N～02°N	1	46.0	46.0				2	21.4	19.0									
02°N～00°	3	101.1	103.6	1	51.9	49.4	3	42.1	28.7									
00° ～02°S	2	72.9	73.4				2	33.7	28.6									
02°S～04°S	1	65.7	72.7				3	31.0	29.3									
04°S～06°S	1	101.5	102.3				1	24.1	40.8									
06°S～08°S	1	78.9	79.3				2	63.1	48.2	2	19.9	15.3						
08°S～10°S	1	24.9	28.7				1	34.0	30.0	2	33.2	29.9				1	47.3	113.0
10°S～12°S	1	21.7	20.3				1	20.8	18.7	1	31.0	23.2	4	42.5	40.9	3	29.3	24.8
12°S～14°S	1	38.4	38.4				2	22.4	23.9				2	48.8	42.8	2	33.1	31.8
14°S～16°S	1	49.8	49.8				1	18.4	11.4									
16°S～18°S	1	28.1	29.3				1	13.8	12.4				4	37.5	39.8	1	40.3	35.2
18°S～20°S	1	8.5	9.5				2	16.0	12.3							1	58.2	67.8
20°S～22°S																2	57.4	42.3
22°S～24°S	1	24.4	25.5															
24°S～26°S	1	16.5	16.2															
31°S～33°S																		
Longitude	77°E～79°E			90°E～92°E			93°E～95°E			104°E～106°E			106°E～108°E			108°E～110°E		

of zooplankton samples (IOSN) in grid areas based on IIOE of Japan 1962–63.

G			H			I			J		
Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³
2	19.9	25.8	3	55.8	48.9				2	36.3	31.5
			2	51.3	45.8				2	17.7	24.9
			1	52.8	67.8				2	23.3	15.5
1	40.2	36.2	1	36.6	48.2				2	35.0	23.0
			1	62.9	51.5	1	60.6	49.8			
			1	80.5	45.6						
2	45.7	43.1	1	133.0	48.9						
			2	26.0	20.6						
110° E ~ 112° E			112° E ~ 114° E			114° E ~ 116° E			117° E ~ 119° E		

Table 6. Mean displacement volume (cc/1000 m³) and mean wet weight (gr/1000 m³) of

Ref. to A-I in Figs. 4, 5.	A			B			C			D			E			F		
Latitude	Number of stations	Mean displacement cc/1000m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³
10°N～08°N							1	90.4	85.1									
08°N～06°N	1	48.1	47.4	1	92.5	102.5	1	61.0	49.1									
06°N～04°N	1	57.1	56.9	1	75.3	73.5	1	61.9	51.4									
04°N～02°N	2	76.8	79.3	2	53.5	52.3	2	31.3	27.8									
02°N～00°	2	91.1	95.9	2	39.9	39.3	1	32.0	30.9									
00° ～02°S	2	121.1	128.5	2	47.7	48.7	1	51.3	46.1									
02°S～04°S	1	168.5	70.3	1	50.5	51.5	1	42.9	37.0	1	19.8	20.4						
04°S～06°S	1	85.3	86.1				2	30.1	26.5	1	19.3	20.0						
06°S～08°S	1	96.1	98.8				1	25.8	25.3	2	17.8	19.3						
08°S～10°S	2	61.0	33.4				2	35.5	26.1	2	11.1	11.5	2	33.0	34.7	1	24.1	28.9
10°S～12°S	1	35.0	36.4										3	58.2	56.7	1	14.3	15.4
12°S～14°S	2	30.6	31.8							2	27.7	15.9	2	22.7	24.8	1	59.4	64.4
14°S～16°S	1	43.6	44.4							1	24.9	38.3	1	14.1	14.0			
16°S～18°S	1	37.3	36.3							1	40.2	31.3	1	18.2	20.3			
18°S～20°S	2	31.8	31.6							2	46.0	26.3	1	21.2	21.5			
20°S～22°S	1	34.0	33.3							1	42.5	37.1	1	15.9	16.2			
22°S～24°S	1	34.4	36.1										1	24.5	27.4			
24°S～26°S	1	26.3	24.7										1	16.8	16.1			
Longitude	77°E～79°E			85°E～87°E			93°E～95°E			99°E～101°E			106°E～108°E			108°E～110°E		

zooplankton samples (IOSN) in grid areas based on IIOE of Japan 1963–64.

G			H			I		
Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³	Number of stations	Mean displacement cc/1000 m³	Mean wet weight gr/1000 m³
2	64.3	64.3	3	44.1	47.5	1	25.0	25.1
2	80.8	62.7	2	37.8	47.6	2	18.2	17.7
			1	21.0	21.5	1	16.3	18.3
			1	27.7	28.8	1	11.6	10.0
			1	18.9	19.5			
			1	27.2	28.7			
			1	22.4	22.6			
110° E ~ 112° E			113° E ~ 115° E			119° E ~ 121° E		

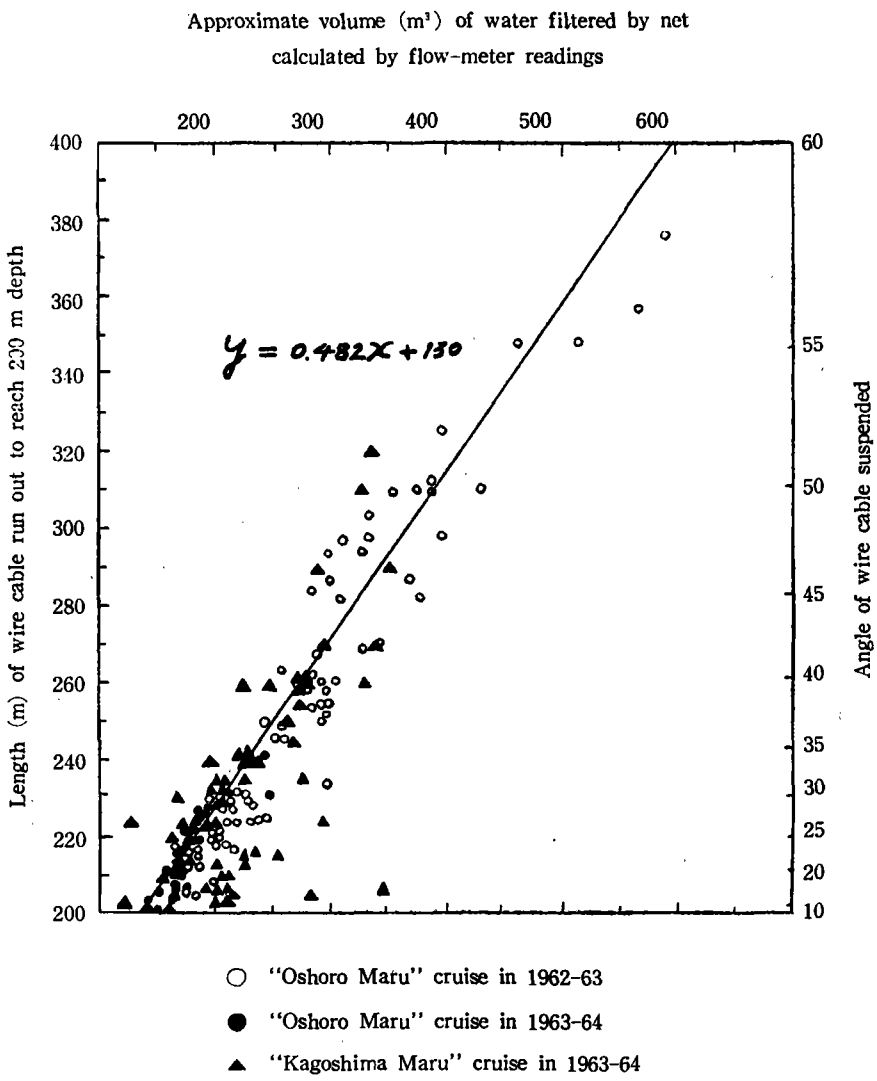


Fig. 1. Mean volume of water filtered in vertical haul with Indian Ocean standard net.

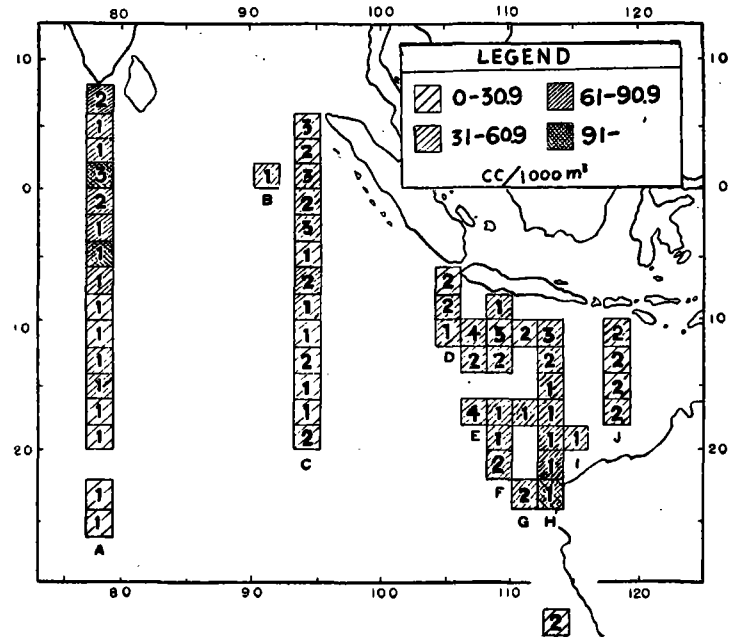


Fig. 2. Distribution of zooplankton biomass (displacement cc/1000 m³)
in the eastern Indian Ocean. IIOE of Japan 1962-63.
A-J correspond to those in Table 5.
Figure in a grid indicates the number of observations inside the grid.

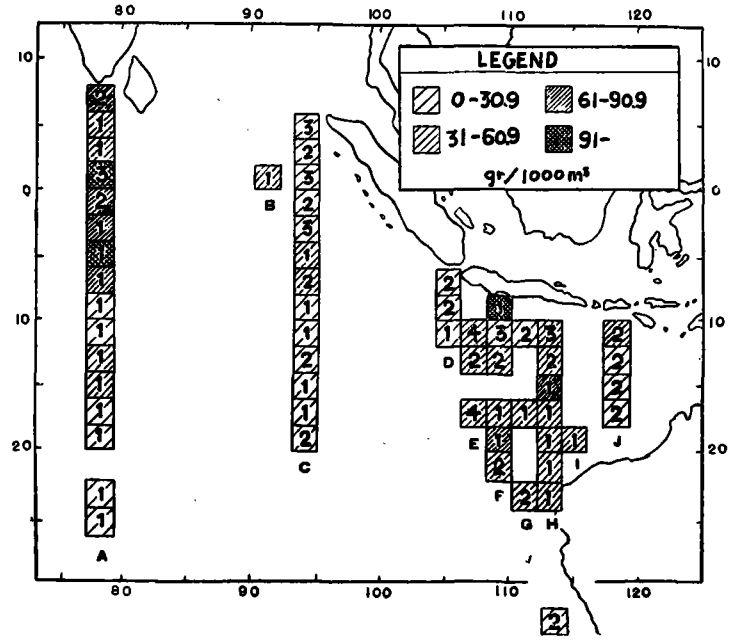
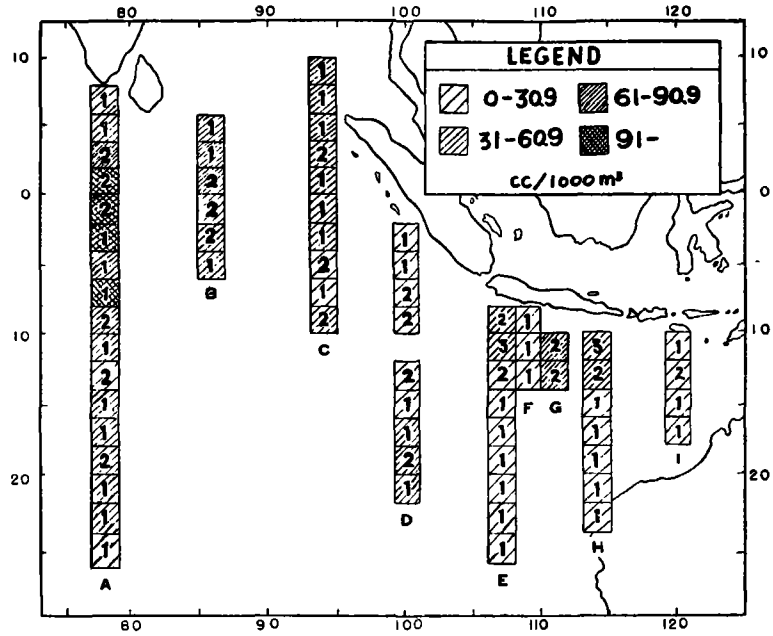


Fig. 3. Distribution of zooplankton biomass (wet weight gr/1000 m³)
in the eastern Indian Ocean. IIOE of Japan 1962-63.
A-J correspond to those in Table 5.
Figure in a grid indicates the number of observations inside the grid.



Eig. 4. Distribution of zooplankton biomass (displacement cc/1000 m³)
in the eastern Indian Ocean. IIOE of Japan 1963-64.
A-I correspond to those in Table 6.
Figure in a grid indicates the number of observations inside the grid.

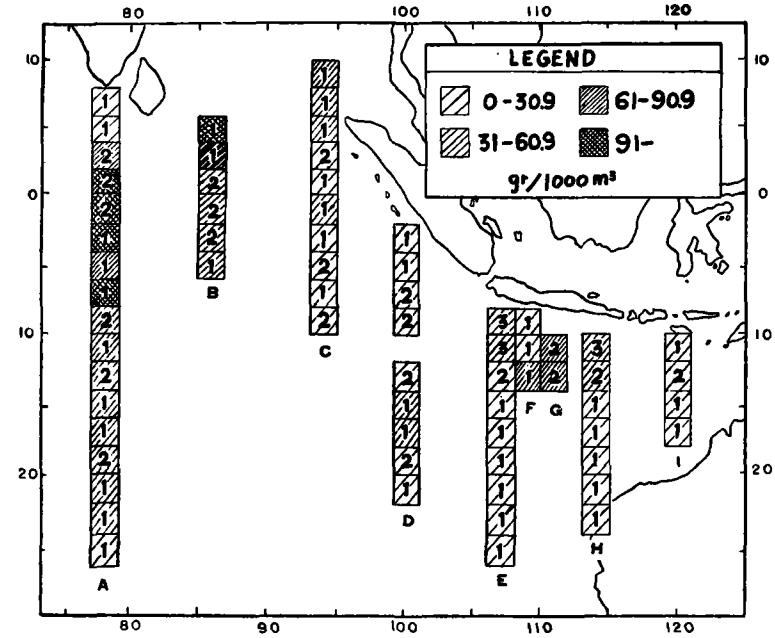


Fig. 5. Distribution of zooplankton biomass (wet weight gr/1000 m³)
in the eastern Indian Ocean. IIOE of Japan 1963-64.
A-I correspond to those in Table 6.
Figure in a grid indicates the number of observations inside the grid.

Table 7. Estimation of underwater wire angles in vertical haul with plankton net.

Ship and cruise No: "Oshoro Maru" Cruise 6.
Date and time: January 19, 1964, 0930-1300.
Location: 07° 45'N, 121°36'E, in Sulu Sea, about 29 miles west to Duluguin Point, Zamboganga Peninsula, Mindanao Island.
Wind velocity: 10 m/sec.
Net used: Norpac net (45 cm in mouth diametre, 180 cm in length, pylen cloth, having 0.35 mm mesh apertures).
Sinker: 40 kg.
Wire cable: 4 mm diameter, steel wire.

Length of wire cable run out (m)	Position of underwater wire-clinometer on the wire cable (m)	Angle of wire cable on deck	Angle of wire cable underwater as measured with underwater wire-clinometer
200	10	60	42
200	20	58	36
200	30	58	33
200	40	58	30
200	50	58	24
200	60	58	24
200	80	58	18*
200	80	58	25
200	100	55	8*
200	100	53	13
200	125	55	14
200	150	52	6
200	150	51	6
200	200	53	9*
200	200	53	4
		Mean 56	(*discarded)

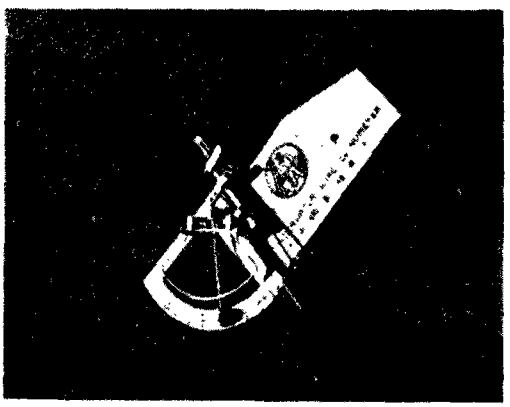


Fig. 6. Underwater wire-clinometer (Motoda, 1963). A wooden vane which is not shown in original design was attached to the clinometer.

準ネットを用いて試験した。実験は風速10m/secで船が漂流している際，北太平洋標準ネットと40kgの錘をつけた 4 mm 径ワイヤを 200m のばして，垂直引上をくりかえし，各回順次水中ワイヤ傾角計の位置をかえてワイヤ上各点の傾角測定を行った。測定された結果をみると水中に於けるワイヤは著しい曲線を呈し，ネットの達した深さは約 184mと測定された (Table 7, Fig. 7)。甲板上のワイヤ傾角とくり出したワイヤの長さによって計算したネットの深さ 112mと比べ著しい差がある。

各種の型のネット，重錘，ワイヤについて，いろいろの風速のときに上のように測定を行っておけば，甲板上のワイヤ角度を測るだけで，ネットの真の到達深度を推定することが可能となるであろう。

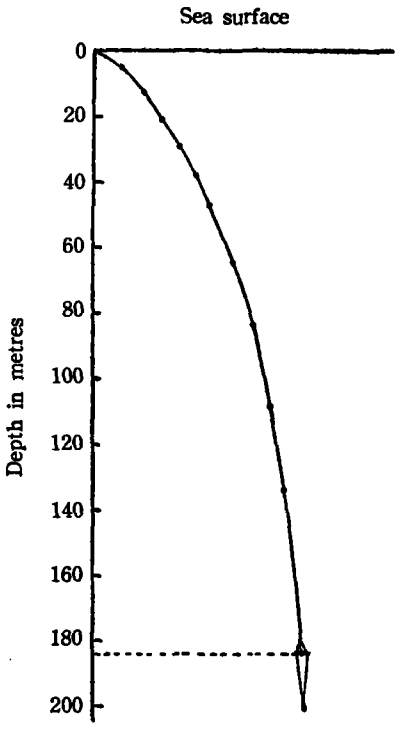


Fig. 7. Observed line of wire cable suspending a plankton net.

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The Chaetognatha of the Monsoon Expedition in the Indian Ocean[1]

ANGELES ALVARIÑO

THIS REPORT deals with the chaetognaths collected by the "R/V Argo" during the Monsoon Expedition in the Indian Ocean in 1960 and 1961. The Monsoon collections extended from about 8° S to 42° S (Fig. 1); that is, the region roughly limited by the Equatorial Countercurrent and the Subantarctic West Wind Drift (the Indian Central waters extending to the Subtropical Convergence); and also the Indonesian seas and the South Australian waters. This report includes only data from the Indian Ocean. Data from collections made by the same Expedition in the Pacific have been added to the study of the chaetognaths of the Pacific. However, data derived from the Pacific are used here also in discussing the distribution of the species. The Monsoon Expedition covered in part the regions surveyed for chaetognaths by the Gazelle, Gauss, Sealark, Siboga, and Snellius expeditions, with the following exceptions: the Bay of Bengal, west coast of Ceylon, and waters of Somalia and eastern Africa.

The samples were taken with a 1-m open net, towed obliquely from a depth of 200 or 360 m to the surface; and several mid-water trawls are also included (see Table I).

It is well known that the hydrographic changes taking place in the Indian Ocean are influenced by the monsoon regime. The sampling extended from November 1960 to January 1961. This is the season of the northeast monsoon (Mattheus, 1926).

Two well-defined zoogeographical boundaries were indicated in the Indian Ocean by the study of the Chaetognatha population: (1) the equatorial boundary extending south of the equator (from about 5° S in the West to 15° S in the East), and (2) the Subtropical Convergence region (at about 40° S). These well-defined boundaries frame latitudinally three main regions: Equatorial, Central, and Subantarctic.

Typical equatorial species of the Pacific that occur also in the Indian Ocean appear to be restricted to the Equatorial waters. Warm-water species that are cosmopolitan in distribution, extend along the Equatorial and Central Indian waters, while cold-water species do not extend to the Central waters. The Subtropical Convergence appears to be the fluctuating northern boundary for the latter.

The data obtained aid in filling the gap that existed in the zoogeography of the chaetognaths by adding information from the Indian Ocean. These observations make it easy to compare the relationships found in the distributional pattern shown by each of the species in the Indian Ocean and their respective allies in the Atlantic and Pacific oceans.

The Indian Ocean collection contains 23 oceanic species of chaetognaths, already known from the Atlantic and the Pacific oceans.

The following species were observed in the samples from the Monsoon Expedition in the Indian Ocean:

Eukrohnia bathypelagica Alvariño
E. fowleri Ritter-Zahony
E. hamata (Möbius)
Krohnitta pacifica (Aida)
K. subtilis (Grassi)
Pterosagitta draco (Krohn)
Sagitta bedoti Béraneck
S. bipunctata d'Orbigny
S. decipiens Fowler
S. enflata Grassi
S. ferox Doncaster
S. gazellae Ritter-Zahony
S. hexaptera Quoy and Gaimard
S. lyra Krohn
S. minima Grassi
S. neglecta Aida
S. pacifica Tokioka

[1] Contribution from the Scripps Institution of Oceanography, University of California, San Diego.
Manuscript received May 13, 1963.

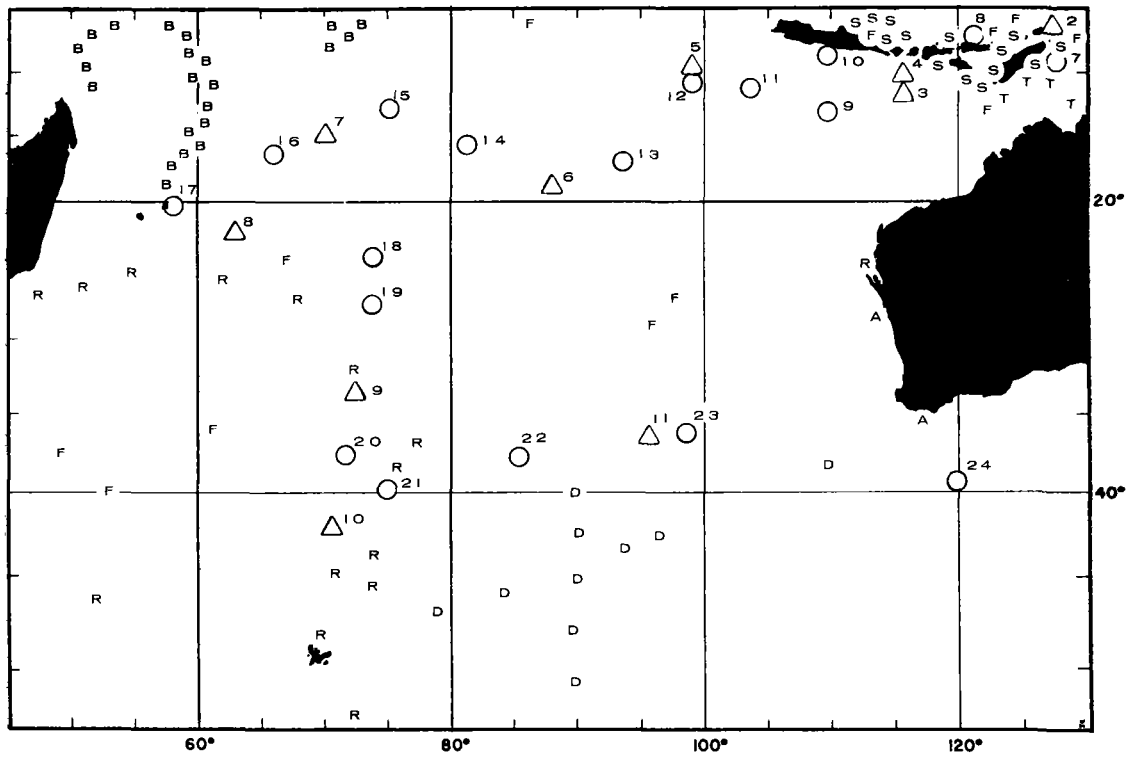


FIG. 1. Stations plan for the zooplankton collections of the Monsoon Expedition in the Indian Ocean.
O — 1-m net
Δ — mid-water trawl

Stations corresponding to previous work in this region are:
F — Siboga Expedition (Fowler, 1906)
R — Gazelle Expedition, Fauna Southwestern Australia, Deutsche Südpolar Expedition (Ritter-Zahony, 1909, 1910, 1911)
B — Sealark Expedition (Burfield and Harvey, 1926)
S — Snellius Expedition (Schilp, 1941)
T — (Tokioka, 1956*b*)
D — (David, 1958, 1959)

S. planctonis Steinhaus
S. pulchra Doncaster
S. regularis Aida
S. robusta Doncaster
S. tasmanica Thomson
S. zetesios Fowler

Seventeen of the 23 species recorded are epiplanktonic. Ten of these are cosmopolitan and seven are Indo-Pacific. Fifteen of the 17 epiplanktonic species in the Indian Ocean connect with their respective regions of distribution in the Pacific Ocean along the Indonesian seas. The mesoplanktonic species *S. decipiens* and *S. zetesios* apparently connect with the Pacific population along the same route, while *S. planctonis* extends into the Pacific following the South Australian waters. These mesoplanktonic species are also cosmopolitan. However, *E. bathypelagica,* obtained previously only in the Pacific at great depths, was recorded here once at the northern part of the region covered by the "R/V Argo" in the Indian Ocean (mid-water trawl no. 3, at 11° 56′ 42″ S—115° 22′

TABLE 1

LIST OF STATIONS OF THE MONSOON EXPEDITION IN THE INDIAN OCEAN

STATION NUMBER	DATE	1 M OPEN NET OBLIQUE TOW				
		Time		Position		Depth (meters)
		Start	End			
	1960					
7	X–22	1745	1811	9° 11.5′ S	127° 33.5′ E	305
8	X–26	2109	2135	7° 47.0′ S	121° 16.5′ E	200
9	XI–7	2012	2037	13° 19.5′ S	109° 35.5′ E	240
10	XI–11	0437	0501	8° 53.0′ S	109° 38′ E	271
11	XI–20	2203	2227	11° 15′ S	103° 32′ E	297
12	XI–22	1929	1950	10° 30.0′ S	98° 59.0′ E	339
13	XI–25	2300	2327	17° 01′ S	93° 28.6′ E	278
14	XI–29	2213	2249	15° 51.0′ S	81° 10.3′ E	335
15	XII–1	2108	2134	12° 57.9′ S	75° 13.6′ E	356
16	XII–5	0319	0346	16° 24.5′ S	66° 02.4′ E	235
17	XII–11	1753	1819	20° 18.9′ S	58° 09.6′ E	328
18	XII–15	0044	0109	23° 59.4′ S	73° 57.5′ E	283
19	XII–17	0313	0342	27° 48.6′ S	73° 51.5′ E	273
20	XII–20	0435	0507	37° 40.1′ S	71° 41′ E	283
21	XII–22	1150	1216	39° 50′ S	75° 03.7′ E	362
22	XII–26	0509	0540	37° 49.6′ S	85° 21.7′ E	283
23	XII–30	0013	0041	36° 18.7′ S	98° 41.1′ E	235
	1961					
24	IX–1	1733	1806	39° 18′ S	119° 51′ E	269
	MID-WATER TRAWLS					
2	24–25–X–1960	2339	0259	7° 10′ 00″ S 7° 09′ 00″ S	127° 22′ 00″ E 126° 58′ 54″ E	2121
3	29–30–X–1960	2157	0359	11° 56′ 42″ S 12° 15′ 30″ S	115° 22′ 12″ E 115° 30′ 06″ E	2179
4	2–XI–1960	0121	0451	10° 10′ 00″ S 10° 43′ 00″ S	115° 17′ 12″ E 115° 14′ 54″ E	1721
5	22–23–XI–1960	2239	0235	10° 39′ 00″ S 10° 50′ 00″ S	98° 50′ 36″ E 98° 43′ 42″ E	1408
6	27–XI–1960	1817	2300	18° 49′ 24″ S 18° 41′ 06″ S	88° 05′ 42″ E 87° 51′ 30″ E	1643
7	3–XII–1960	1649	2128	14° 54′ 00″ S 15° 01′ 24″ S	70° 12′ 00″ E 69° 52′ 00″ E	2000
8	12–XII–1960	1910	2342	22° 04′ 18″ S 22° 15′ 30″ S	63° 02′ 00″ E 63° 19′ 00″ E	2000
9	19–XII–1960	0324	0829	33° 19′ 18″ S 33° 38′ 06″ S	72° 34′ 24″ E 72° 31′ 00″ E	1878
10	21–22–XII–1960	2326	0415	42° 03′ 48″ S 42° 01′ 06″ S	70° 39′ 54″ E 71° 00′ 18″ E	2060
11	28–XII–1960	1738	2312	36° 35′ 00″ S 36° 32′ 18″ S	95° 28′ 00″ E 95° 52′ 30″ E	2000

12″ E, from 2179 m depth). No typical Indian Ocean species was found. The sampling only covered the oceanic regions, and it is assumed that some neritic species of chaetognaths may be restricted to the Indian waters.

Important previous works on the Chaetognatha in the Indian Ocean and adjacent waters include:

Authority	*Number of valid species observed*
Béraneck (1895), Bay of Amboine	5
Burfield and Harvey (1926), Indian Ocean	15
Doncaster (1903), Maldive-Laccadive Archipelago	11
Fowler (1906), Indian Ocean	18
George (1952), Indian coastal waters	12
Lele and Gae (1936), Bombay harbor	3
Oye (1918), Java Sea	12
Rao (1958), Lawson's Bay, Waltair, Bay of Bengal	13
Rao and Ganapati (1958), off east coast of India and Ceylon	12
Ritter-Zahony (1909), southern Indian Ocean	6
(1910), southwest Australia	10
(1911), Deutsche Südpolar Expedition	17
Schilp (1941), Indian Ocean	19
Tokioka (1940), New South Wales	8
(1955), NE Indian Ocean	13
(1956), Central Indian Ocean	13
(1956), Arafura Sea	9

The chaetognaths observed in the Indian Ocean can be grouped as follows:

a) Cosmopolitan (common to Atlantic, Indian, and Pacific oceans): *S. lyra, S. enflata, S. hexaptera, S. minima, S. bipunctata, K. subtilis, K. pacifica, P. draco, S. gazellae, S. tasmanica.*

b) Cold-water representants: *S. gazellae, S. tasmanica, E. hamata.*

c) Tropical–equatorial, and restricted to the Indo-Pacific waters: *S. ferox, S. robusta, S. pacifica, S. pulchra, S. neglecta, S. bedoti, S. regularis.*

d) Mesoplanktonic: *S. decipiens, S. planctonis, S. zetesios.*

e) Deep water: *E. hamata* (in low latitudes), *E. fowleri, E. bathypelagica.*

It is important to notice that *Sagitta macrocephala* Fowler was not recorded here. The absence of this species from the samples may be due to its scarcity and to the small number of deep samplings. It was previously recorded in the Indian Ocean by Fowler (1906), Burfield and Harvey (1926), and Schilp (1941).

Sagitta gazellae, an oceanic species with a circumpolar distribution in the Antarctic and Subantarctic waters, enters the Atlantic, Indian, and Pacific oceans up to the Subtropical Convergence, often extending further north in deep levels in the Atlantic and Pacific (Alvariño, 1964*b*). In the Monsoon collections (Fig. 2), *S. gazellae* occurred as far north as 36° S—98° E and 37° S—71° E; whereas David (1958) reported it extending along the 90° E meridian from 63° S to approximately 41° 30′ S (Fig. 2), and David (1959) from 66° 35′ S to 42° 35′ S (south of the Indian Ocean). The specimens of *S. gazellae* recorded in the Monsoon region might very well represent penetrations of the Subantarctic waters below the Subtropical. The penetration apparently does not extend farther north, because none were recorded at the mid-water trawl station 9 situated north of the septentrional boundary of this species in the Indian Ocean, although the sampling went to 1878–2000 m deep. The northernmost records of *S. gazellae* in the Indian Ocean (David, 1955) were at 40° 30′ S—90° E, and in the Pacific at 39° 20′ S—180° E and 38° 30′ S—126° W.

At station 22 (37° 49.6′ S—85° 21.7′ E) only young specimens 28–30 mm long at early maturity stage 1 were found; while at station 25 (57° 43′ S—169° 12′ E) some were 50–60 mm long and still at maturity stage 1. In the Pacific, at station 29 (40° 37′ S—164° 08′ W) the specimens were 20–30 mm in length, and at station 32 (28° 35.3′ S—158° 57.5′ W) they were 20–30 mm long and at maturity stage 1.

David (1955) points out that *S. gazellae* was occasionally taken north of the Subtropical Convergence at 41° 49.7′ S—18° 49.9′ E, and that the hydrographical data showed a northward extension of the Subantarctic waters. The observations in the Pacific (Alvariño, 1964*b*) showed the progression of the Subantarctic waters at deep levels far north of the Subtropical Con-

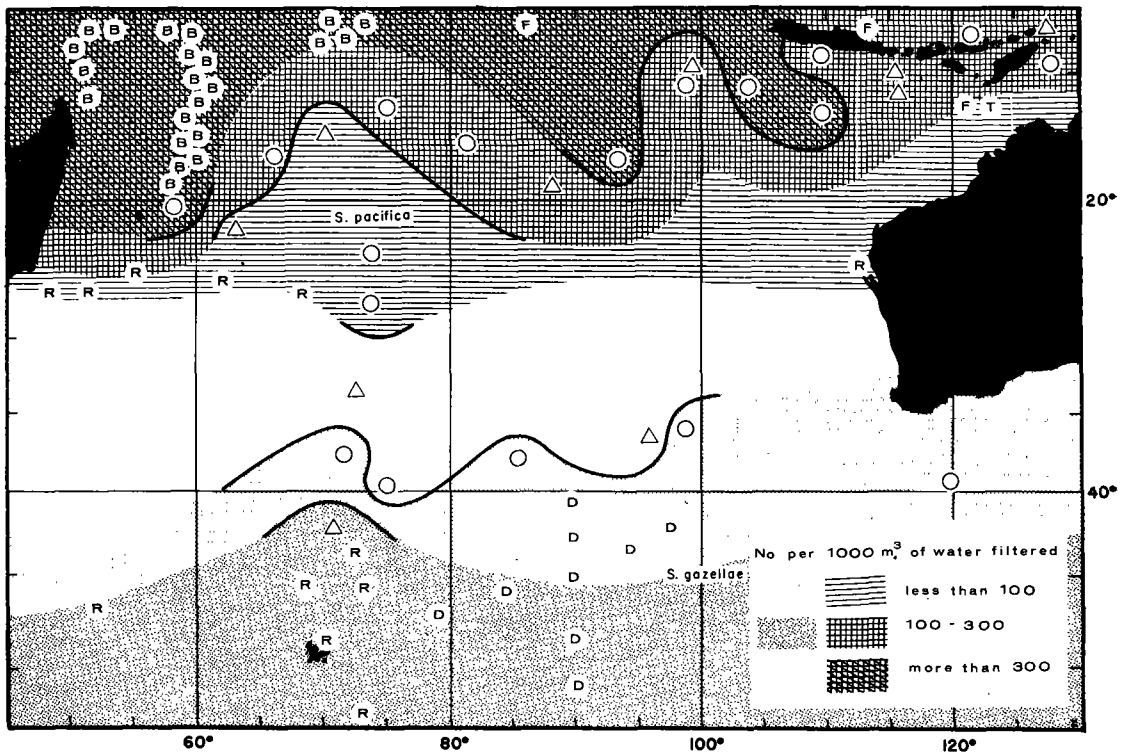


FIG. 2. Distribution of *S. gazellae* and *S. pacifica* in the Indian Ocean, including positive records from previous expeditions.

vergence. In the Pacific (Alvariño, loc. cit.), at about 35° S—21° S, there is an overlapping of the populations of *S. gazellae* and *S. pacifica* at about 200–400 m depth. In the Indian Ocean, the northern boundary of *S. gazellae* and the southern boundary of *S. pacifica* did not overlap, and do not even appear well juxtaposed. However, this pattern cannot be admitted as definitive; it may be due to scarcity of sampling in these localities. More data from this region will eventually show if this distributional pattern persists, or if both species occur in a pattern similar to that shown in the Pacific.

S. lyra recorded by Tokioka (1940) is most probably *S. gazellae* because of the geographic localities of the records (33° and 35° S and 151° E); and the *S. lyra* recorded by David (1959) and by Johnson and Taylor (1921) may also be *S. gazellae.*

S. pacifica populations of the Pacific and Indian oceans connect along the Indonesian seas (author's records; Tokioka, 1955, 1956*b;* and possibly also the report of Béraneck, 1895). It appears to extend with the South Equatorial Current to the Indonesian seas and then into the Indian Ocean (Fig. 2). It cannot be ascertained if some representatives of this species enter the Agulhas Current, since they have not yet been observed in the Atlantic.

Previous records of *S. serratodentata* in the Indian Ocean by Burfield and Harvey (1926), Doncaster (1903), Fowler (1906), John (1937), Ritter-Zahony (1910, 1911), and Schilp (1941), could be considered to be *S. pacifica.* Baldasseroni (1915) was the first to distinguish Atlantic specimens of *serratodentata* from those of the Pacific; he gave a short diagnosis and published drawings of the seminal vesicles of the species. Tokioka (1940) published a complete diagnosis and named the species. Cleve's (1901) records of *S. serratodentata* Krohn should correspond to *S. pacifica.* The John (1937),

Rao (1958*a*, *b*) Rao and Ganapati (1958), and Ritter-Zahony (1910, 1911) records of *S. serratodentata* correspond to *S. pacifica.* Other records of *S. pacifica* in the Indian Ocean are given by Tokioka (1940, 1955, 1956*a*, *b*).

S. tasmanica populates the Atlantic and the southernmost part of both the Indian and Pacific oceans up to the Subtropical Convergence. The northern boundary follows a pattern similar to that of *S. gazellae,* although it does not progress northward in deep layers as *S. gazellae* does. More data are needed to establish the extension of the distribution.

This species extends along southern Australia into the Pacific (Alvariño, 1964*b*); and it appears from the *S. tasmanica* records in the Pacific and Indian oceans that the Subtropical Convergence acts as a barrier which interrupts the distribution of the species northward from that boundary. With these findings in mind, and the fact that this species is recorded widely in the Atlantic, more data are needed before definitive conclusions may be drawn (Fig. 3).

Unfortunately, some of the expeditions in the Indian Ocean did not cover the distributional region of *S. tasmanica,* and most of the data from the Atlantic are difficult to interpret, because this species has been recorded together with *S. serratodentata* under Krohn's synonymy.

David's (1958, 1959) records of *S. serratodentata* Krohn refer probably to both *S. tasmanica* and *S. pacifica* and to *S. tasmanica* respectively.

S. lyra, a typical Atlantic chaetognath, appeared in small numbers and only in the West-Central Indian waters (Fig. 3). Other records are given by Baldasseroni (1915), Burfield and Harvey (1926), Fowler (1906) as *S. furcata,* Oye (1918), Ritter-Zahony (1911), Schilp (1941), and Tokioka (1956*a*).

S. enflata extends along the Indian Equatorial waters. It is heavily distributed in the eastern

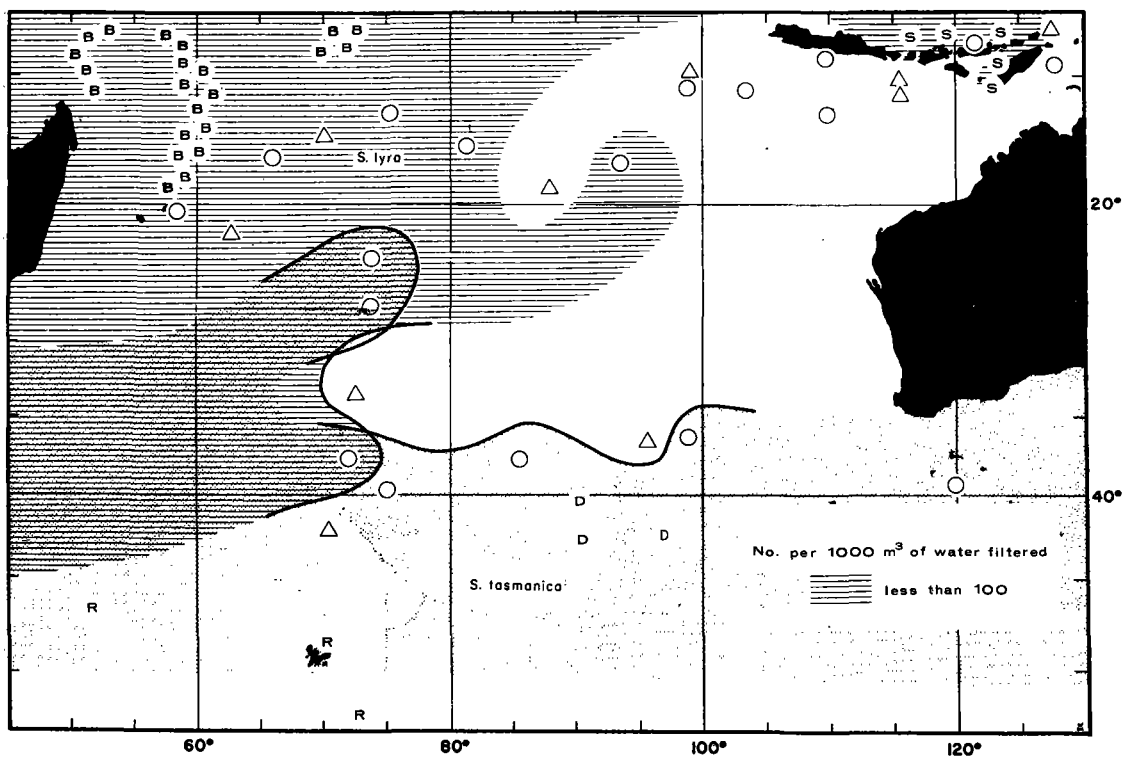


FIG. 3. Distribution of *S. lyra* and *S. tasmanica* in the Indian Ocean, including positive records from previous expeditions.

part of these waters and in the Sunda Sea. I suspect that it will also extend along the Indian Central waters, but lack of sampling in the East-Central Indian Ocean does not permit a complete picture of the distribution of this species (Fig. 4). Other records in the Indian Ocean: Baldasseroni (1915), Béraneck (1895), Burfield and Harvey (1926), Chacko (1950), Cleve (1901), Doncaster (1903), Fowler (1906), George (1952), John (1933, 1937), Lele and Gae (1936) as *S. gardineri,* Menon (1945), Oye (1918), Pillai (1944), Rao (1958*a, b*), Rao and Ganapati (1958), Ritter-Zahony (1909, 1910, 1911), Schilp (1941), Tokioka (1940, 1955, 1956*a, b*), and Varadarajan and Chacko (1943).

S. hexaptera was observed at each of the stations of the Monsoon Expedition in the Indian Ocean and the Indonesian seas, though it was less abundant in the southernmost stations. As in the Pacific, this species extends into colder regions than does *S. enflata* (Fig. 4), (Alvariño, 1964*a* and other unpublished data; Bieri, 1959). Other records in the Indian Ocean: Baldasseroni (1915), Burfield and Harvey (1926), Doncaster (1903) as *S. tricuspidata* and *S. magna,* Langerhans, Fowler (1906), Oye (1918), Ritter-Zahony (1909, 1910, 1911), Schilp (1941), and Tokioka (1940, 1955, 1956*a*).

S. robusta was observed in the Indonesian seas and at the northeastern stations in the Equatorial Indian Ocean. It apparently remains (Fig. 5) restricted to the Equatorial waters, whereas *S. ferox* (also an Equatorial species) spreads further south into the Tropical region. A similar pattern was observed in the Pacific (Alvariño, 1962*b*). It is obvious that the populations of both the Pacific and the Indian oceans connect along the Indonesian seas. Other records in the Indian Ocean: Baldasseroni (1915, *S. robusta*), Doncaster (1903), and Fowler (1906), recorded both species. Burfield and Harvey

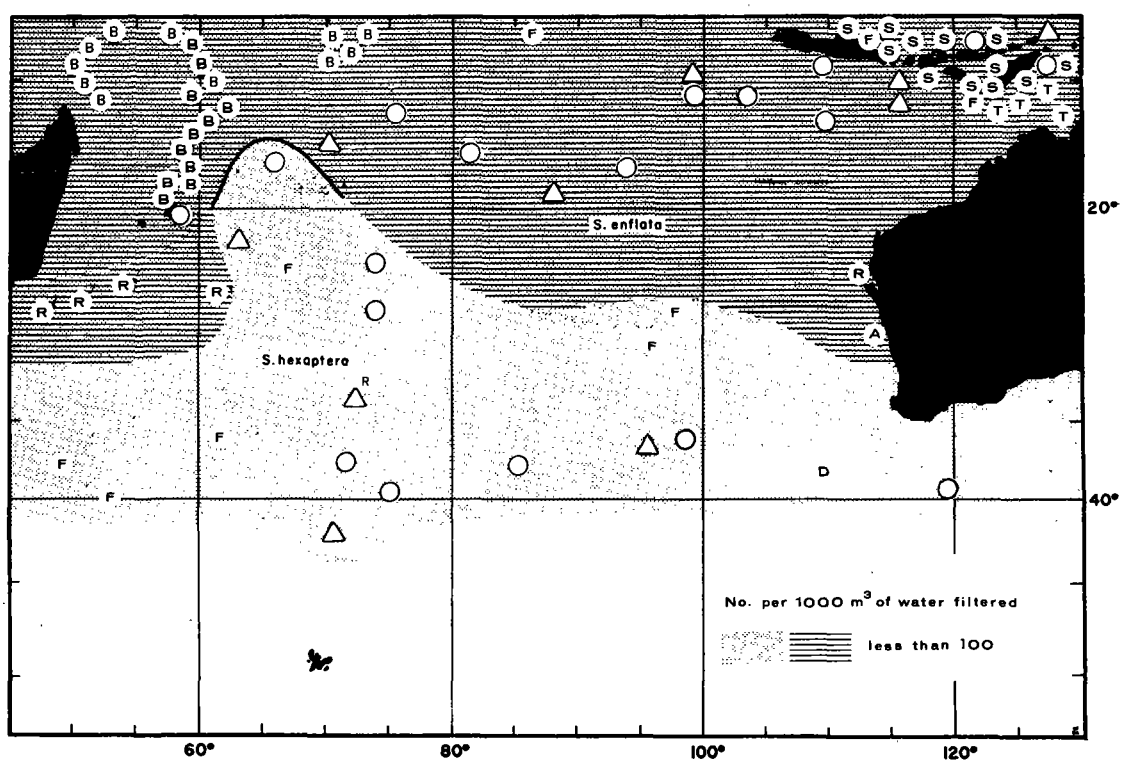


FIG. 4. Distribution of *S. enflata* and *S. hexaptera* in the Indian Ocean, including positive records from previous expeditions.

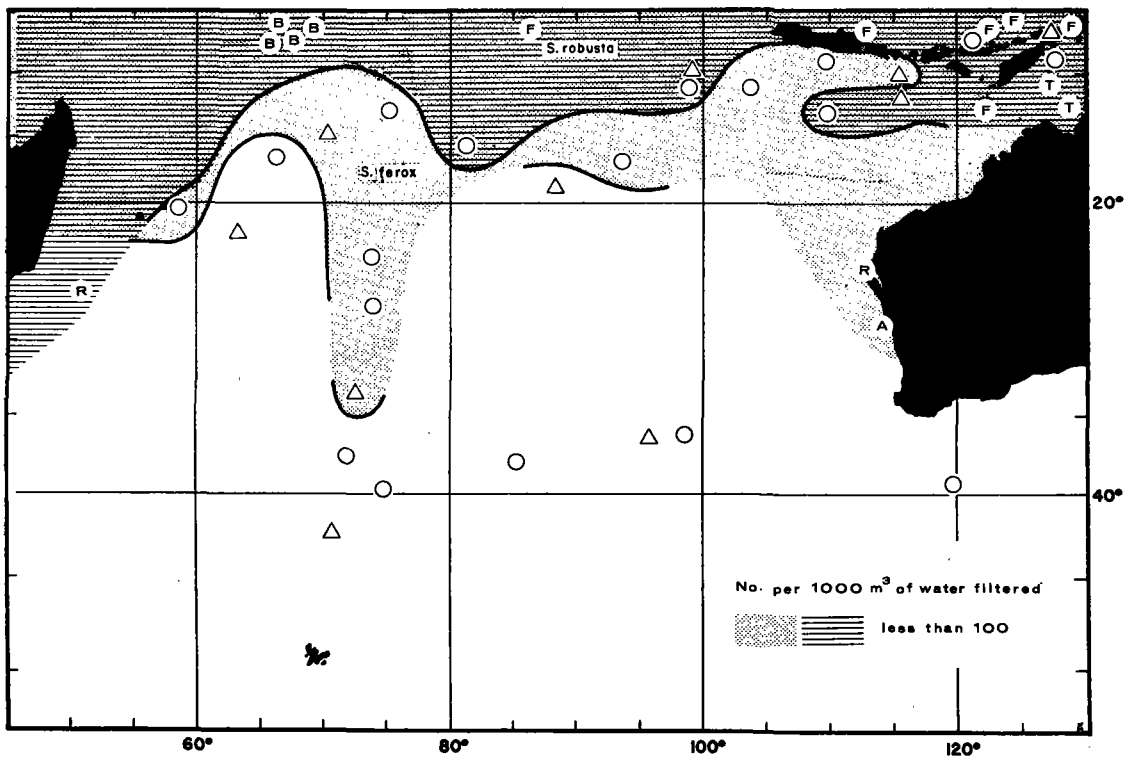


FIG. 5. Distribution of *S. robusta* and *S. ferox* in the Indian Ocean, including positive records from previous expeditions.

(1926), George (1949, 1952), Oye (1918), Ritter-Zahony (1909, 1910, 1911), and Schilp (1941) recorded both under the *S. robusta* synonymy. Rao (1958*a*, *b*) and Rao and Ganapati (1958) records of *S. robusta* probably correspond to *S. ferox* and those of *S. hispida* to *S. robusta*. Tokioka (1940) recorded both species in 1955, and in 1956*b* only *S. robusta*, in 1956*a*, both species, although *S. ferox* is recorded under the *S. ai* Tokioka synonymy. Other records: Chacko (1950), John (1933, 1937), and Varadarajan and Chacko (1943).

S. bipunctata was abundant in the stations north of 30° S. According to the data obtained, it appears that the populations of *S. bipunctata* of the Indian and Pacific oceans connect along the Indonesian seas, as no *S. bipunctata* was observed south of parallel 30° S; while the 35° S parallel appears to be the southern boundary for this species in the Pacific (Alvariño, 1964*a*, and other unpublished data; Bieri, 1959). It inhabits the Tropical Equatorial and Central Pacific waters. Other records in the Indian Ocean: Baldasseroni (1915), Béraneck (1895), Cleve (1901), Oye (1918), Rao (1958*a*), Rao and Ganapati (1958), Ritter-Zahony (1910, 1911), Schilp (1941), Thomson (1948), and Tokioka (1940, 1955, 1956*b*). The Burfield and Harvey (1926) and George (1952) drawings of *S. hispida* are more likely to be of *S. bipunctata*.

S. bedoti appeared abundantly in the Indonesian seas to the southwest of Java, a position between Cocos Keeling Isl. and the Christmas Islands. Other records in the Indian Ocean: Baldasseroni (1915), Béraneck (1895), Burfield and Harvey (1926), Doncaster (1903, as *S. polydon*), Fowler (1906), George (1952), Lele and Gae (1936), Pillai (1944), Rao (1958*a*), Rao and Ganapati (1958), Ritter-Zahony (1910) Schilp (1941), Subramanian (1940), and Tokioka (1955, 1956*a*, *b*).

S. neglecta was recorded only at station 11 (11° 15′ S—103° 32′ E). Other records in the Indian Ocean: Baldasseroni (1915), Burfield

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and Harvey (1926), Chacko (1950), Doncaster (1903, as *S. septata*), Fowler (1906), George (1949, 1952), John (1933, 1937), Oye (1918), Rao (1958*a*, *b*), Rao and Ganapati (1958), Schilp (1941), Tokioka (1955, 1956*b*), Varadarajan and Chacko (1943).

S. pulchra was observed in the Indonesian seas and in the Equatorial Indian waters as far as the Mauritius Islands. Other records in the Indian Ocean: Baldasseroni (1915), Burfield and Harvey (1926), Doncaster (1903), Fowler (1906), George (1949, 1952), Oye (1918), Rao (1958*a*, *b*), Rao and Ganapati (1958), Ritter-Zahony (1910), Schilp (1941) and Tokioka (1955).

S. minima, cosmopolitan in the warm and temperate waters, should be expected in the Central Indian Ocean waters. However, it was only observed in very small numbers at stations 11, 13, 15 (11° 15′ S—103° 32′ E, 17° 01′ S—93° 28.6′ E, 12° 57.9′ S—75° 13.6′ E) respectively. The samples studied showed an abundance of *S. bipunctata* and a scarcity of *S. minima,* whereas the opposite was found by Tokioka (1956*a*). The samples examined by Tokioka (loc. cit.) were taken on December 11, 1954—January 16, 1955, and the Monsoon samples from October 22, 1960—January 9, 1961, which is practically during the same monsoon regimen. Therefore, no speculation could be made based on the monsoon influence in the distribution of these species. In the samples from the Naga Expedition in the South China Sea and the Gulf of Siam (Alvariño, unpublished data), *S. bipunctata* appeared also more abundant than *S. minima,* unlike the quantitative pattern shown by both species in the North Pacific. Other records of *S. minima* in this ocean: Ritter-Zahony (1910, 1911), Schilp (1941), Thomson (1948), and Tokioka (1955, 1956*a*).

S. regularis extended in the Equatorial waters as far as the Mauritius Islands. Although no specimens of *S. regularis* were observed at the stations in the Indonesian seas, it is reasonable to assume that the species extends along those paths to the Pacific. Large numbers of *S. regularis* were observed in the samples of the Naga Expedition, from the Gulf of Thailand and the South China Sea (Alvariño, unpublished data). The lack of positive records in regions where the presence of this species is to be expected, is likely due to the small size of the *S. regularis* which could easily escape owing to the size of the mesh used in the nets. The species has been recorded by previous workers in the Indonesian region. Other records in the Indian Ocean: Burfield and Harvey (1926), Doncaster (1903), Fowler (1906), George (1952), Menon (1945), Oye (1918), Rao (1958*a*, *b*), Rao and Ganapati (1958), Ritter-Zahony (1910, 1911), Schilp (1941), and Tokioka (1955, 1956*a*, *b*).

S. decipiens extended along the strata below 250 m from the northern part of the region covered in the Indian Ocean to 37° S. In the Pacific it extended along those strata from 40° S (Alvariño, 1964*b*; Bieri, 1959). Other records in the Indian Ocean: Burfield and Harvey (1926), David (1958), Fowler (1906) as *S. sibogae,* Rao and Ganapati (1958), Ritter-Zahony (1911), and Schilp (1941).

S. planctonis was observed along the northern part of the Subantarctic West Wind Drift extending into the Subtropical Convergence in the Indian Ocean. It was found below the 200-m level up to 36° S, and in deeper waters up to 22° S (mid-water trawl from 2000 m deep, one specimen). The connection of the populations of *S. planctonis* of the Indian and Pacific oceans evidently occurs along the south Australian seas. Its distribution in the Pacific was also found limited by the Subtropical Convergence towards the north (Alvariño, 1964*b*). *S. zetesios,* a species closely related to *S. planctonis,* extends along the mesoplanktonic domain of the Tropical, Equatorial, and Central Indian waters. The two-dimensional pattern of distribution for *S. zetesios* overlaps that of *S. planctonis* at mid-water trawl station 8 (22° 04′ S—63° 02′ E), where one specimen of *S. planctonis* and two of *S. zetesios* were observed in a haul taken from 2000 m. At mid-water trawl 9 (33° 19′ S—72° 34′ E) taken from 1878 m, 38 specimen of *S. zetesios* were recorded with only three specimens of *S. planctonis.* The *S. planctonis* domain, then, extended south of that boundary.

The Burfield and Harvey (1926), George (1952), and John (1937) records of *S. planctonis* are most likely to be *S. zetesios* in view of the location of the observations and the drawings and descriptions of the species included in the

respective publications. David's (1959) records of *S. zetesios* should have included *S. planctonis*. Fowler (1906) recorded *S. zetesios* and, in species "incertae," *S. planctonis*. Schilp's (1941) records of *S. planctonis* may apply to *S. zetesios*. Ritter-Zahony (1911) observed *S. planctonis* at about 44° S in the Southwest Indian Ocean and in the Subantarctic-Antarctic waters of the Southwest Indian Ocean. Tokioka's (1940) records of *S. planctonis* from Australian waters are accurate, but those of *S. planctonis* from Japanese waters may apply to *S. zetesios*. The discrepancy Tokioka refers to in relation to the percentage of the length of the tail segment to the total length between those populations indicates that he was dealing with two different species: *S. zetesios* in the Japanese waters and *S. planctonis* in the New South Wales region. This is also understood when observing the drawings that appear on page 374 (loc. cit.): Fig. 8A is *S. planctonis* (the anterior end of the anterior fins reaches the level of the middle of the ventral ganglion); and Fig. 8D is *S. zetesios* (the anterior end of the anterior fins reaches the level of the posterior end of the ventral ganglion). (See original descriptions of Steinhaus, 1896, and Fowler, 1905.)

Krohnitta subtilis populates the Equatorial and Central Indian Ocean, and does not reach the boundaries of the Subtropical Convergence. The Indo-Pacific populations connect through the Indonesian seas. Other records in the Indian Ocean: Burfield and Harvey (1926), Fowler (1906), George (1952), Rao (1958*a*), Ritter-Zahony (1910, 1911), Schilp (1941), and Tokioka (1940, 1955, 1956*a, b*).

K. pacifica was observed only at station 8 (north of Flores Island). This species is not so widely distributed as is its congeneric *K. subtilis*, and is for the most part restricted to the Equatorial waters. This is the only equatorial-tropical species of chaetognath common to these regions in the Atlantic, Indian, and Pacific oceans. The presence of this species in the Equatorial-Tropical Atlantic suggested one of two hypotheses: either it is conveyed by the Agulhas Current into the Benguella Current and assimilated by the Equatorial Current, or the populations of *K. pacifica* at both sides of Central America, although long isolated, still somehow remain unchanged morphologically, but the process of divergence is noticed. There are no conveniently available samples and data from the Atlantic to explain this problem. However, Heydorn (1959) did not observe it in the Benguella region.

Other records in the Indian Ocean: Burfield and Harvey (1926) under the *K. subtilis* synonymy; Chacko (1950), Doncaster (1903), Fowler (1906), George (1952), Oye (1918) as *K. kerberti*; Pillai (1945), Rao (1958*a, b*) Rao and Ganapati (1958), Ritter-Zahony (1910), Schilp (1941), Tokioka (1955, 1956*a, b*), and Varadarajan and Chacko (1943).

Pterosagitta draco inhabits the Equatorial and Central Indian waters, and its extension southward is apparently limited by the Subtropical Convergence. Other records in the Indian Ocean: Baldasseroni (1915), Béraneck (1895), Burfield and Harvey (1926), Doncaster (1903), Fowler (1906), George (1952), Rao (1958*a, b*), Rao and Ganapati (1958), Ritter-Zahony (1910, 1911), Schilp (1941), and Tokioka (1940, 1955, 1956*a, b*).

Eukrohnia hamata was recorded at the stations along the southernmost part of the region sampled, in hauls taken from 283 and 268 m deep, and the records taken in the central gyral were from 1878 m deep. There are two possible alternatives: (1) *E. hamata* does not progress northward from the boundary of the Subtropical Convergence in the Indian Ocean, or (2) if it does progress northward it is not very abundant and hence is missed by the sampling, or it may appear in layers deeper than those mostly sampled. Other records in the Indian Ocean: Burfield and Harvey (1926), Fowler (1906), Ritter-Zahony (1911), and Schilp (1941).

E. fowleri was recorded at the mid-water trawls 2, 3, 4, and 10, taken from 2121, 2179, 1721, and 2060 m deep, respectively. In all probability, *E. fowleri* populates the deep layers (below 1600 m) of the Indian Ocean, as it does in the Pacific and Atlantic. The species *E. fowleri* was only recorded at the boundary of the Indian Ocean and the Indonesian seas. A peculiarity of this species is that it emerges to higher levels in the Equatorial regions than in others in the Pacific (author's unpublished data), and that the populations extend along deeper levels in other parts of the oceans. Other records

in this region: Ritter-Zahony (1911), and Schilp (1941).

E. bathypelagica was represented by only one specimen at mid-water trawl 3 (11° 56′ S—115° 22′ E) taken from 2179 m. This single record could be considered as a stray of the population extending along deeper levels. This is the first record of the species occurring other than in the Pacific Ocean (Alvariño, 1962*a*). This species could not be the spent stage of *E. hamata,* in view of the morphological characteristics and the size reached at maturity (*E. bathypelagica* 23 mm, and *E. hamata* 43 mm).

Sagitta hexaptera is the most common species in the region of the Indian Ocean covered by the Monsoon Expedition, followed by *P. draco, S. pacifica, S. ferox, S. bipunctata,* and *K. subtilis.* The species appearing in the highest number relative to the frequency were, in regressive order: *S. gazellae, S. bedoti, S. enflata, S. pacifica,* and *S. tasmanica.*

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TRAWLING RESULTS OF THE R/V ANTON BRUUN IN THE BAY OF BENGAL AND ARABIAN SEA

By A. T. Pruter*

SUMMARY

Trawling surveys in the Bay of Bengal and in the Arabian Sea were conducted in 1963 from the National Science Foundation research vessel Anton Bruun as part of the United States contribution to the International Indian Ocean Expedition. Relatively small shrimp catches obtained may reflect a distribution of shrimp concentrations in shallower waters than were surveyed. Demersal fish in the Bay of Bengal generally were similar to those observed in the Arabian Sea. Stingray dominated the catches in all regions at depths less than 50 fathoms.

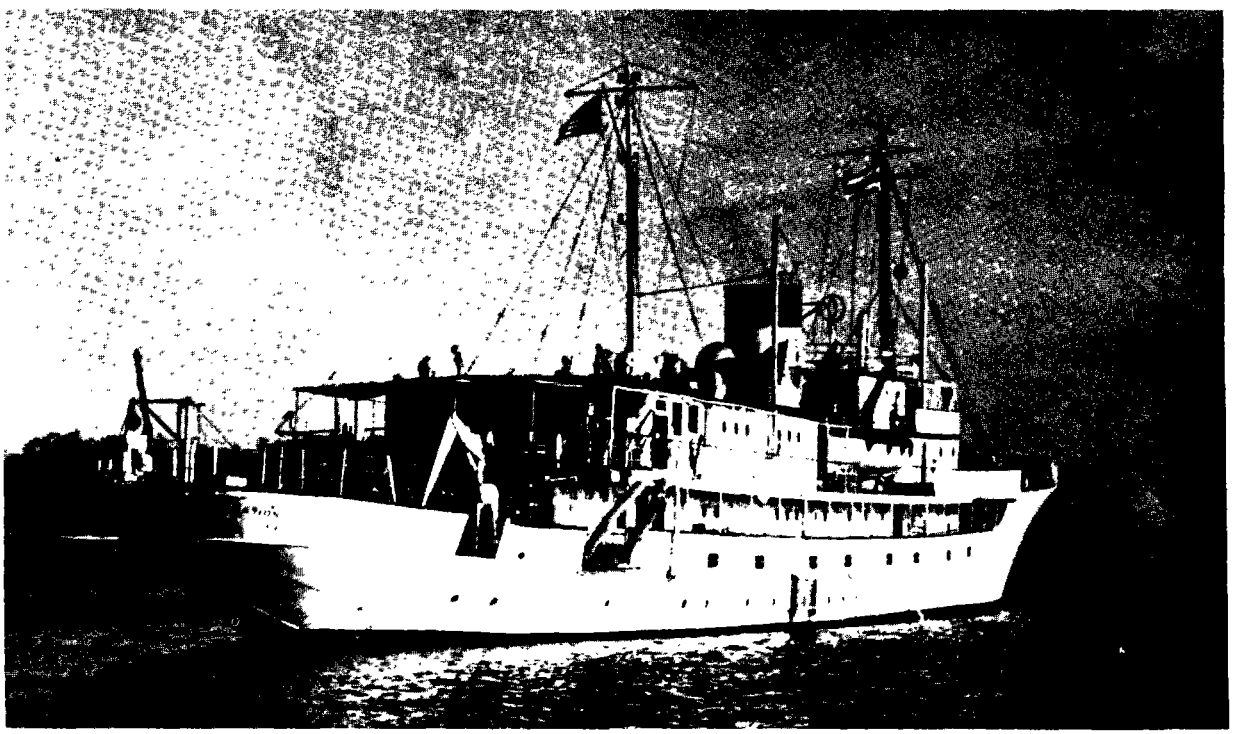


Fig. 1 - United States National Science Foundation research vessel Anton Bruun at anchor off Phuket, Thailand, during Cruise 1 in the Bay of Bengal.

Largest fish catches were taken off Muscat and Oman (Arabia). The precipitous and uneven ocean bottom at depths greater than about 100 fathoms in both the Bay of Bengal and the Arabian Sea, together with relatively few demersal fish at such depths, would seem to hinder if not preclude developing deep-water trawl fisheries.

INTRODUCTION

The International Indian Ocean Expedition (I.I.O.E.) is sponsored by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) with the cooperation of the Inter-

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national Council of Scientific Unions. It is an unprecedented, cooperative, international study of the seas, and represents the first attempt to study scientifically an entire ocean. More than 40 vessels and several hundred scientists from many nations are participating in the 3-year program. Information on the Indian Ocean will permit more accurate weather forecasting, charting sea currents, and more economical navigational routes, locating latent fisheries resources, and compiling new hydrographic charts.

From March 12 to May 10, 1963, and from November 12 to December 10, 1963, trawling surveys of the Bay of Bengal and the Arabian Sea, respectively, were conducted from the National Science Foundation research vessel Anton Bruun (fig. 1). Those surveys were part of the participation in the I.I.O.E. in which various governmental groups and educational and private institutions are participating.

The scientific program from the 243-foot Anton Bruun (formerly the Presidential yacht Williamsburg) is directed by the Woods Hole Oceanographic Institution. During its 2-year assignment in the Indian Ocean, the Anton Bruun has a permanent staff of oceanographers to provide continuity in the basic oceanographic program. Visiting scientists from the United States and other countries participate in individual cruises. Personnel from the U. S. Fish and Wildlife Service's Bureau of Commercial Fisheries participate in most of the cruises from the Anton Bruun, and on 4 of the cruises involving fisheries surveys[1/] they direct the fishing activities. Overall direction and coordination of the Bureau of Commercial Fisheries participation in the Indian Ocean program is being provided by the Bureau's Biological Laboratory in Honolulu. Scientists and fishermen from the Bureau's Exploratory Fishing and Gear Research Base at Seattle and from the Biological Laboratory in Honolulu directed exploratory trawling activities on Cruises 1 and 4B. This report discusses the trawling results of those two cruises. Reports on hydrographic, ichthyological, and other activities during the cruises will be published elsewhere by the investigators concerned with such studies.

Thirty-one exploratory hauls with a Gulf of Mexico shrimp trawl were made on Cruise 1 in the Bay of Bengal. Hauls were made off the west coast of Thailand, near the Andaman Islands, off Burma, and off East Pakistan. The trawling phase of Cruise 1 ended 1 month earlier than planned due to malfunction of the trawl winch. On Cruise 4B, 86 trawl hauls were made in the Arabian Sea off northwest India, off West Pakistan, in the Gulf of Oman, and off Muscat and Oman (Arabia).

Commercial trawl fisheries for shrimp and fish in the Bay of Bengal and in the Arabian Sea are restricted to relatively shallow waters of a maximum depth of about 40 fathoms and generally less than 20 fathoms. Exploratory trawling on Cruises 1 and 4B was primarily designed to provide information on fish and shrimp resources in regions and at depths not presently exploited.

On Cruise 1 in the Bay of Bengal the vessel track was chosen to accommodate both oceanography and exploratory fishing; on Cruise 4B in the Arabian Sea, exploratory fishing only.

GEAR AND METHODS

Nylon Gulf of Mexico shrimp trawls (Schaefers and Johnson 1957) measuring 42 feet along the footrope and having a mesh size of $1\frac{1}{2}$ inches (stretched measurement, opening including one knot) were used on both cruises. The trawl was connected by a 25-fathom-long bridle to a single towing warp. A rectangular otter board measuring $2\frac{1}{2}$ feet by 5 feet and weighing 160 pounds was attached to each wing of the net when trawling to depths of 200 fathoms. Below 200 fathoms heavier boards (260 pounds each) were used.

The shrimp trawl was towed from an A-frame on the starboard side of the Anton Brunn. A hydraulic crane located aft of the A-frame lifted the net and doors outboard and inboard and lifted the cod end of the net aboard after each haul. A "lazy line"--a nylon rope with a loop on one end passing through puckering rings on the forward portion of the cod end--was used to pull the net alongside the Anton Bruun and to lift the cod end aboard.

1/Cruises 2 and 5 are tuna surveys employing pelagic long-line gear; Cruises 1 and 4B are bottom-trawling surveys.

Echo-sounding tracings of the ocean bottom were obtained whenever the Anton Bruun was under way. They were supplemented by more detailed soundings prior to trawling and by samples of bottom sediments obtained with a small dredge or a spring-loaded bottom grab.

The Anton Bruun is powered by two main engines supplemented by an active rudder. Using the port engine the vessel moved at 6 to 8 knots during setting of the trawl. When approximately 50 to 100 fathoms of cable remained to be let out on each haul, the vessel was slowed by reducing speed of the port engine as low as possible and running the active rudder in reverse. This was done in an attempt to have the vessel proceeding at standard trawling speed when the trawl reached the ocean bottom. Either the port engine, the active rudder, or a combination of both was used to maintain trawling speed after the net reached the ocean bottom. Trawling speed ranged between 2 and $3\frac{1}{2}$ knots.

The ratio between the amount of towing warp out and the depth to bottom was greater in shallow water than in deep water, ranging from 6 to 1 (6 fathoms of cable to 1 fathom of depth) in less than 20 fathoms to approximately $2\frac{1}{2}$ to 1 at 1,000 fathoms. To ensure that the trawl reached bottom, a practice was followed of using slightly higher ratios than were found satisfactory in exploratory trawling with identical gear in the northeastern Pacific Ocean (Pereyra 1963).

Duration of the hauls varied between 30 and 60 minutes, counted as the time the net was on the bottom. Catches were emptied onto a sorting table and separated by family (genera or species when possible). Each group was examined (1) to determine the number of individuals present and their total weight, and (2) to estimate their range in length by measuring the total lengths of the smallest and largest individuals present. Length frequencies were obtained from representative samples of some groups of fishes. For the larger shrimp catches, estimates of the number of whole (heads on) shrimp per pound were recorded.

REGIONS SURVEYED

Locations of trawl stations in the Bay Bengal and in the Arabian Sea are shown in figures 2 and 3. The topography of the continental shelf (depths to 100 fathoms) in all regions surveyed was generally suitable for trawling except off Muscat and Oman and in the Gulf of Oman where numerous coral outcroppings were encountered. Green mud was the dominant bottom sediment in both the Bay of Bengal and the Arabian Sea. The continental slope was precipitous and uneven in all regions surveyed. This precluded much trawling at depths greater than about 100 fathoms.

For convenience in analyzing the distribution and relative abundance of fish and shrimp encountered, the survey regions were divided into the following areas: Andaman Islands, Thailand, Burma, East Pakistan, northwest India, West Pakistan, Gulf of Oman, and Muscat and Oman (Arabia). Areas were subdivided into the following depth intervals: 8-49 fathoms, 50-99 fathoms, 100-199 fathoms, 200-299 fathoms, and 1,000-1,099 fathoms (no trawling from 300 to 999 fathoms).

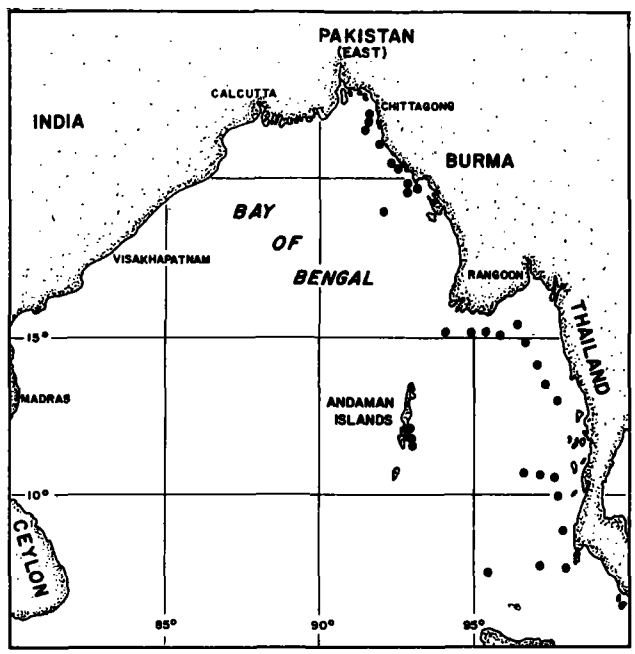


Fig. 2 - Location of trawl stations, cruise 1 of R/V Anton Bruun.

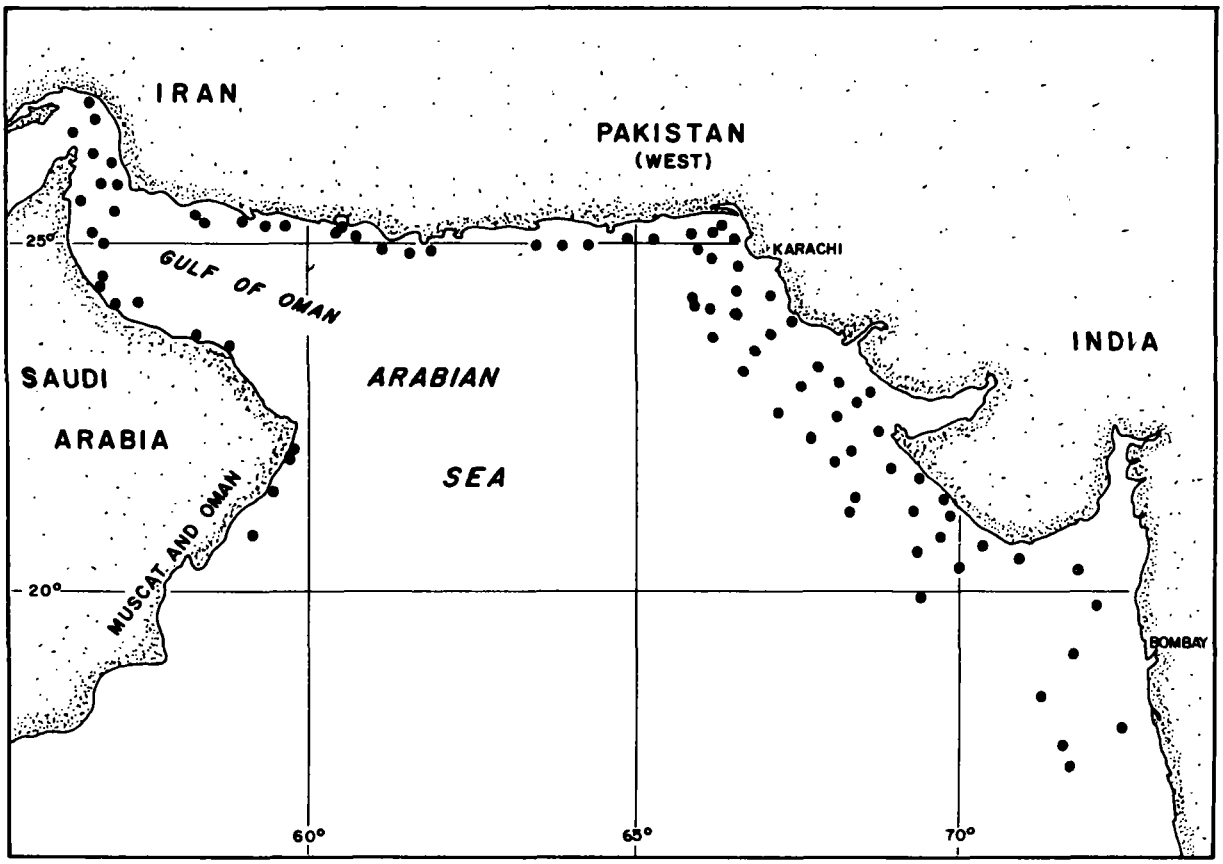


Fig. 3 - Location of trawl stations, Cruise 4B of R/V Anton Bruun.

RESULTS

Thirty-one trawl hauls were made in the Bay of Bengal; 27 were successful and 4 resulted in extensive damage to the nets. In the Arabian Sea 86 trawl hauls were completed; 77 were successful and 9 resulted in extensive damage to nets. The highest incidence of gear damage occurred off Muscat and Oman where one-half of the hauls were unsuccessful and in the Gulf of Oman where the nets were extensively damaged in one-quarter of the hauls.

Fishing effort and catch rates for fish and shrimp by areas and depth intervals in the Bay of Bengal and the Arabian Sea are shown in tables 1 and 2. Because of the few trawl hauls and the probable low catching efficiency of the shrimp trawl, it is impossible to assess the commercial potential of fish and shrimp inhabiting the various areas. The surveys do provide, however, an indication of the relative abundance of fish and shrimp between areas.

Greatest survey effort was expended in the depth range 8-49 fathoms, the shallowest zone surveyed. Within this depth range best coverage was attained off northwest India and off West Pakistan, where totals of 22 and 16 successful trawl hauls were completed (table 2).

In the depth zone 50-99 fathoms, best survey coverage was attained off northwest India, off West Pakistan, and in the Gulf of Oman where from six to seven successful trawl hauls were completed in each area (table 2).

Maximum survey effort in the depth range 100-199 fathoms was expended in the Gulf of Oman (four successful hauls) and off northwest India and West Pakistan (two successful hauls

in each region). Only one successful haul was made in the depth interval 200-299 fathoms and one in the 1,000- to 1,099-fathom interval. Both of the latter hauls were made off Burma.

Table 1 - Number of Successful Trawl Hauls, Fishing Effort, and Catch Rates by Areas and Depth Zones in the Bay of Bengal, R/V Anton Bruun, March-April 1963

Depth Interval, Fishing Effort, and Catch Rates	Andaman Islands	Thailand	Burma	East Pakistan
8-49 fathoms				
Number of hauls	2	2	12	6
Hours trawled	1.0	1.0	8.0	3.9
Pounds fish/hour trawled	58	50	107	157
Pounds shrimp/hour trawled	0	1	6	5
50-99 fathoms				
Number of hauls	1	0	0	0
Hours trawled	0.5	-	-	-
Pounds fish/hour trawled	4	-	-	-
Pounds shrimp/hour trawled	0	-	-	-
100-199 fathoms				
Number of hauls	0	0	1	0
Hours trawled	-	-	0.5	-
Pounds fish/hour trawled	-	-	68	-
Pounds shrimp/hour trawled	-	-	56	-
200-299 fathoms				
Number of hauls	0	1	1	0
Hours trawled	-	0.6	0.5	-
Pounds fish/hour trawled	-	21	80	-
Pounds shrimp/hour trawled	-	9	34	-
1,000-1,099 fathoms				
Number of hauls	0	0	1	0
Hours trawled	-	-	1.0	-
Pounds fish/hour trawled	-	-	2	-
Pounds shrimp/hour trawled	-	-	trace	-

BAY OF BENGAL: Fish: 8- to 49-Fathom Interval: Highest catch rates of fish in the Bay of Bengal occurred in the 8- to 49-fathom depth interval off Burma and off East Pakistan where 107 and 157 pounds of fish, respectively, were caught per hour of trawling (table 1). In those regions and in this depth interval, stingray (Dasyatidae) and guitarfish (Rhinobatidae) dominated the catches. Other fish which comprised an important part of the catches were drum (Sciaenidae), lizardfish (Synodontidae), and snapper (Lutjanidae). Some miscellaneous fish taken included sea catfish (Ariidae), threadfin (Polynemidae), and tonguefish (Cynoglossidae).

50- to 99-Fathom Interval: The only haul in this depth interval was made in the Andaman Islands area and was unproductive, yielding only 4 pounds of fish per hour of trawling (table 1). Included in the catch were a number of small threadfin-bream (Nemipteridae), cardinalfish (Apogonidae), lizardfish, goatfish (Mullidae), and mackerel (Scombridae).

100- to 199-Fathom Interval: The single haul in this depth interval was made off Burma and provided 68 pounds of fish per hour of trawling. Chlorophthalmid (Chlorophthalmidae) was the dominant group encountered, accounting for over one-half the total fish catch by weight. Chlorophthalmid were followed in order of abundance by scorpionfish (Scorpaenidae) and butterfish (Stromateidae). Miscellaneous species taken included bembropsid (Bembropsidae), requiem shark (Carcharinidae), grenadier (Macruridae), bigeyes (Priacanthidae), and tripodfish (Triacanthidae).

200- to 299-Fathom Interval: Single hauls were made off Thailand and Burma in this depth interval. Off Burma, hatchetfish (Sternoptychidae) were the dominant group encountered, accounting for over 70 percent of the total fish catch by weight. Hatchetfish were followed by requiem shark, grenadier, cutlassfish (Trichiuridae), and chlorophthalmids. Off Thailand, skate (Rajidae), sea robbin (Peristediidae), and boafish (Stomiatidae) dominated the catches.

1,000- to 1,099-Fathom Interval: The one successful trawl haul made in the 1,000- to 1,099-fathom interval off Burma yielded a catch rate of 2 pounds per hour of trawling. The catch consisted of one snipe eel (Nemichthyidae), four boafish, several eel larvae, and a number of unidentified fish.

The largest fish encountered in the Bay of Bengal were stingray and guitarfish which attained maximum estimated weights of 200 and 225 pounds, respectively.



Fig. 4 - Shrimp-trawl catch in Bay of Bengal, Cruise 1 of R/V Anton Bruun.

Shrimp: With the exception of the Andaman Islands area, shrimp were taken in all depth zones and in all areas surveyed in the Bay of Bengal. However, no large catches were obtained in any area. Off Burma, several individual hauls made at depths between 14 and 35 fathoms yielded from 10 to 20 pounds of shrimp per hour of trawling. Two ½-hour hauls off Burma in 165 and 200 fathoms of water yielded 28 and 17 pounds of shrimp, respectively.

Most of the shrimp belonged to the family Penaeidae (genera Penaeus and Metapenaeus) and to the tribe Caridea. They generally were small, ranging from 200 to 300 heads-on count per pound, although a few penaeid shrimp weighing over one-half pound each were caught.

ARABIAN SEA: Fish: 8-to 49-Fathom Interval: Highest catch rates of fish in the Arabian Sea occurred off Muscat and Oman in the 8- to 49-fathom depth interval (table 2) where four trawl hauls were made. Numerous coral outcroppings in that area resulted in extensive damage to the trawl nets on 2 of the 4 hauls. Of the two successful hauls, one of 30 minutes made at 23 fathoms yielded an estimated 5,500 pounds of stingray plus 100 pounds of other fish; the other (45 minutes) made at 25 fathoms yielded 1,700 pounds of fish--primarily grunt (Pomadasyidae), stingray, and cardinal fish--and 1,840 pounds of swimming crab (Portunidae).

Table 2 - Number of Successful Trawl Hauls, Fishing Effort and Catch Rates by Areas and Depth Zones in the Arabian Sea, R/V Anton Bruun, November-December 1963

Depth Interval, Fishing Effort, and Catch Rates	Northwest India	West Pakistan	Gulf of Oman	Muscat & Oman (Arabia)
8-49 fathoms				
Number of hauls	22	16	9	2
Hours trawled	16.4	11.9	6.5	1.3
Pounds fish/hour trawled	214	137	64	5,840
Pounds shrimp/hour trawled	8	trace	1	trace
50-99 fathoms				
Number of hauls	7	7	6	0
Hours trawled	5.5	6.1	4.1	-
Pounds fish/hour trawled	132	246	118	-
Pounds shrimp/hour trawled	1	1	1	-
100-199 fathoms				
Number of hauls	2	2	4	0
Hours trawled	2.0	2.0	4.0	-
Pounds fish/hour trawled	22	2	45	-
Pounds shrimp/hour trawled	trace	6	8	-

Catch rates in the 8- to 49-fathom depth interval off northwest India, West Pakistan, and in the Gulf of Oman were much lower than off Muscat and Oman, ranging from 64 to 214 pounds of fish per hour of trawling (table 2). Stingray again were dominant, accounting for from one-half to one-third of the total fish catches by weight. Other important species in all areas were threadfin-bream and drum. Grunt were numerous off West Pakistan and off Muscat and Oman. The apparent distribution of Bombay duck (Harpadontidae), a commercially important group in India, was interesting in that they were caught in substantial numbers in the Arabian Sea only off northwest India in the Gulfs of Kutch and Cambay and only in relatively shallow water (8-20 fathoms).



Fig. 5 - Catch of fish and swimming crabs taken in shrimp trawl off Muscat and Oman (Arabia), Cruise 4B of R/V Anton Bruun.

50- to 99-Fathom Interval: No trawling was conducted below 49 fathoms off Muscat and Oman. Catch rates in the depth interval 50-99 fathoms off West Pakistan and in the Gulf of Oman were higher than in the shallower interval surveyed in these regions. In contrast, off northwest India the catch rate in this interval was less than that in the shallower 8- to 49-fathom interval. Within the 50- to 99-fathom interval, stingray comprised an important part of the catches only off West Pakistan. Threadfin-bream were as important in the catches in all areas surveyed as in shallower water. Although drum and grunt were taken, they occurred less often in most areas than in the shallower 8- to 49-fathom interval. Other fish accounting for much of the catches in this interval included jack (Carangidae), sea bass (Serranidae), and lizardfish. Off West Pakistan and in the Gulf of Oman, monocle-bream (Scolopsidae) were important in the catches; however, relatively few were caught in other areas.

100- to 199-Fathom Interval: Off northwest India, West Pakistan, and in the Gulf of Oman, the catch rates declined markedly in this interval compared to those in shallower intervals (table 2). Drum and cardinalfish formed important parts of the catches in all areas. Stingray were not taken in this depth interval in any area. Off northwest India, Champsodontidae was the dominant family of fish encountered but they were virtually absent from catches off West Pakistan and in the Gulf of Oman. Threadfin-bream comprised an important part of the catches off northwest India.

The largest fish captured in the Arabian Sea were stingray, which attained a maximum estimated weight of 450 pounds. One haul made off Muscat and Oman contained approximately 5,500 pounds of stingray estimated at 40 pounds each. Occasional large guitarfish (approximately 400 pounds) were caught. Some other relatively large fish caught during the survey were false conger eel (Muraenesocidae) which ranged up to 14 pounds in weight apiece, drum of up to 22 pounds each, and threadfin of up to 15 pounds each. Many of the more abundant fish in the catches were relatively small. Grunt averaged about one-half pound and attained a maximum weight of approximately 4 pounds. Threadfin-bream averaged about one-tenth pound each. Lizardfish averaged only a few ounces, but occasional specimens ranged up to $1\frac{1}{2}$ pounds. Monocle-bream, cardinalfish, and flathead (Platycephalidae) all averaged only a few ounces in weight.

Shrimp: Shrimp were taken in all depth zones and in all regions surveyed in the Arabian Sea. Catches in all regions and depth zones, however, were disappointingly small. Best catches were taken off northwest India in the 8- to 49-fathom depth interval, and in the Gulf of Oman and off West Pakistan in the 100- to 199-fathom depth interval (table 2). The largest single haul of shrimp taken in the Arabian Sea survey was 66 pounds, caught in a 45-minute haul off northwest India at a depth of 18 fathoms. The next largest single haul was 30 pounds taken in a 1-hour haul in the Gulf of Oman at a depth of 163-170 fathoms. A 40-minute haul off northwest India in the Gulf of Cambay in 15 fathoms produced 28 pounds of Caridean shrimp (Paleomon).

Most of the shrimp belonged to the family Penaeidae (genera Penaeus, Metapenaeus, and Solenocerina) and to the tribe Caridea. As in the Bay of Bengal survey, the shrimp generally were small, although occasional hauls yielded fair numbers of 40 to 50 heads-on count per pound.

Many sea snake (Hydrophidae) were caught in the small-mesh shrimp trawls in both the Bay of Bengal and in the Arabian Sea. Because they are extremely poisonous, the snakes must be handled with care when removing them from the net or from the catches. Use of larger-mesh trawls should reduce the catch of snakes.

DISCUSSION

Catching ability of the Anton Bruun may have been impaired in shallow water due to mud being stirred up from the ocean bottom by the vessel's wake. This was noticeable in depths of about 12 fathoms and less and may have frightened some shallow-water animals away from the path of the trawl. At those depths, the catching efficiency of a smaller vessel with a shallower draft might have been higher than that of the Anton Bruun.

Shrimp catches in the Bay of Bengal and in the Arabian Sea were surprisingly small in view of the large commercial shrimp fisheries there. The commercial fisheries, however, occur in shallower waters than were explored from the Anton Bruun. Shrimp appeared about equally available throughout all depth intervals surveyed out to a depth of 299 fathoms. The larger penaeid shrimp, however, were caught in the shallower depth intervals.

Largest fish catches were taken off Muscat and Oman where two successful trawl hauls in the depth interval 8-49 fathoms yielded a catch rate over 20 times as high as that obtained in any other region or depth interval. Although catches off Muscat and Oman primarily consisted of stingray and swimming crab for which there is no market, one 45-minute haul yielded 980 pounds of grunt. It seems probable that further explorations there would locate large populations of other more desirable species.

Off northwest India, West Pakistan, and in the Gulf of Oman, demersal fish appeared as abundant in the 50- to 99-fathom interval as in the shallower 8- to 49-fathom interval. Trawling effort in other areas was too inadequate in the 50- to 99-fathom interval to provide a meaningful comparison. Relative abundance of fishes at depths greater than 99 fathoms declined markedly in all areas surveyed.

Within the depth interval 8-49 fathoms in all areas surveyed, elasmobranchs, primarily stingray, dominated the catches. The relative importance of stingray in the catches decreased greatly in the 50- to 99-fathom interval and they were virtually absent in hauls made below 99 fathoms.

Demersal fish in the Bay of Bengal generally appeared similar to those observed in the Arabian Sea. In both regions, stingray, guitarfish, threadfin-bream, drum, lizardfish, threadfin, and cardinalfish were among the dominant groups encountered on the continental shelf. Grunt were important constituents of the fish fauna throughout most of the Arabian Sea; however, in the Bay of Bengal they were caught only off Burma and only in small quantities.

Throughout most of the Bay of Bengal and Arabian Sea, the precipitous and uneven ocean bottom at depths greater than 100 fathoms prevented trawling. This factor, together with an apparent reduction in abundance of demersal fishes, would seem to hinder if not preclude future development of major commercial trawl fisheries at depths greater than about 100 fathoms.

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Woronina pythii Goldie-Smith in India

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Woronina pythii Goldie-Smith in India[1]

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KARLING, JOHN S. (Purdue Univ., Lafayette, Indiana). **Woronina pythii** *Goldie-Smith in India.* Bull. Torrey Bot. Club 91: 224–227. 1964.—*Woronina pythii* Goldie-Smith was observed as a parasite of *Pythium* sp., which had been isolated from dry brackish soil at Mandapam Camp, Rhamnad District, Madras State, and grown in brackish tap water. The life cycle, development and general morphology of the Indian isolate of this parasite conforms to those described previously in the literature, but the cytosori exhibit a higher degree of variation. No evidence of fusion of zoospores produced by the zoosporangia or the germinated resting spores was observed. In addition to this species two other members of the Plasmodiophoraceae were found in India, *Sorodiscus cokeri* Goldie-Smith and *Woronina polycystis* Cornu as parasites of *Pythium* and *Saprolegnia*, respectively.

Woronina pythii is a plasmodiophorous parasite of *Pythium* which Goldie-Smith mentioned briefly in 1951 and subsequently (1956) described fully from Florida, Louisiana, and Texas, U.S.A. It occurs in the soil, and as conditions become favorable for the development and growth of its hosts

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it parasitizes them. Subsequent to its discovery by Goldie-Smith, the author (1960) reported its occurrence in Brazil, Jamaica, and Connecticut, Indiana and Louisiana, U.S.A. Since then he has found it in soil from Georgia, Maryland, New Jersey, New York, Oregon and Washington, U.S.A. In 1960 Persiel reported its occurrence in the Alps, and later (1962) Miller found it in Texas. According to these reports, *W. pythii* appears to be widely distributed and is particularly common in the soil in the United States.

The present contribution concerns the discovery of its occurrence in another part of the world as well as observations on the variations exhibited by its cystosori. While participating as a marine mycologist with the International Indian Expedition the author isolated a large number of species of *Pythium* (as yet not identified fully) and other zoosporic fungi from soil and water in various parts of India, and one isolate of *Pythium* on hemp seed from dry brackish soil collected at Mandapam Camp, Rhamnad District, Madras State, became parasitized by an organism which was tentatively identified as *W. pythii.* Subsequent study of the parasite revealed that it has the same cycle of development as Goldie-Smith's species and conforms fairly closely with it in size and general morphology. Accordingly, no basic differences have been observed in the Indian isolate which would warrant the creation of a different species. However, some marked variations have been noted which extend and add to the excellent observations and description of Goldie-Smith (1956). These relate primarily to the cystosori.

These variations as well as the complete life cycle of *W. pythii* are illustrated in figures 1 to 39, and inasmuch as the general developmental cycle is well known it is not necessary to describe it in detail. Also, the legends accompanying illustrations are sufficiently detailed to explain fully the life cycle of the Indian isolate.

Goldie-Smith (1956) reported that elongate, irregular cystosori did not occur in her material of *W. pythii,* "and that it seems that the parasite cannot complete its development without some lateral extension into a swelling, although this may be quite small." However, in the Indian material greatly elongate cystosori consisting of linear series of cysts (fig. 28, 35) were fairly common and similar to those which the author illustrated in the Indiana, U.S.A. isolate. Also, irregular and almost spongy (fig. 36), subhemispherical (fig. 30), slightly dumb-bell, (fig. 34), flattened and almost circular (fig. 33) cystosori were observed. Although most of the cystosori were ovoid to slightly elongate (fig. 31, 32), subspherical ones also occurred. Occasionally, the cystosori were quite small and consisted only of diads, triads, and tetrads of cysts (fig. 29). Other large ones consisted of nearly 200 cysts (fig. 31). Accordingly, the cystosori of this species are indefinite in size and shape like those of *Woronina polycystis* and members of *Ligniera* and *Polymyxa,* and it is difficult to distinguish *W. pythii* solely by the type of its cystosori.

The cysts may be separated quite readily by pressure on the coverglass

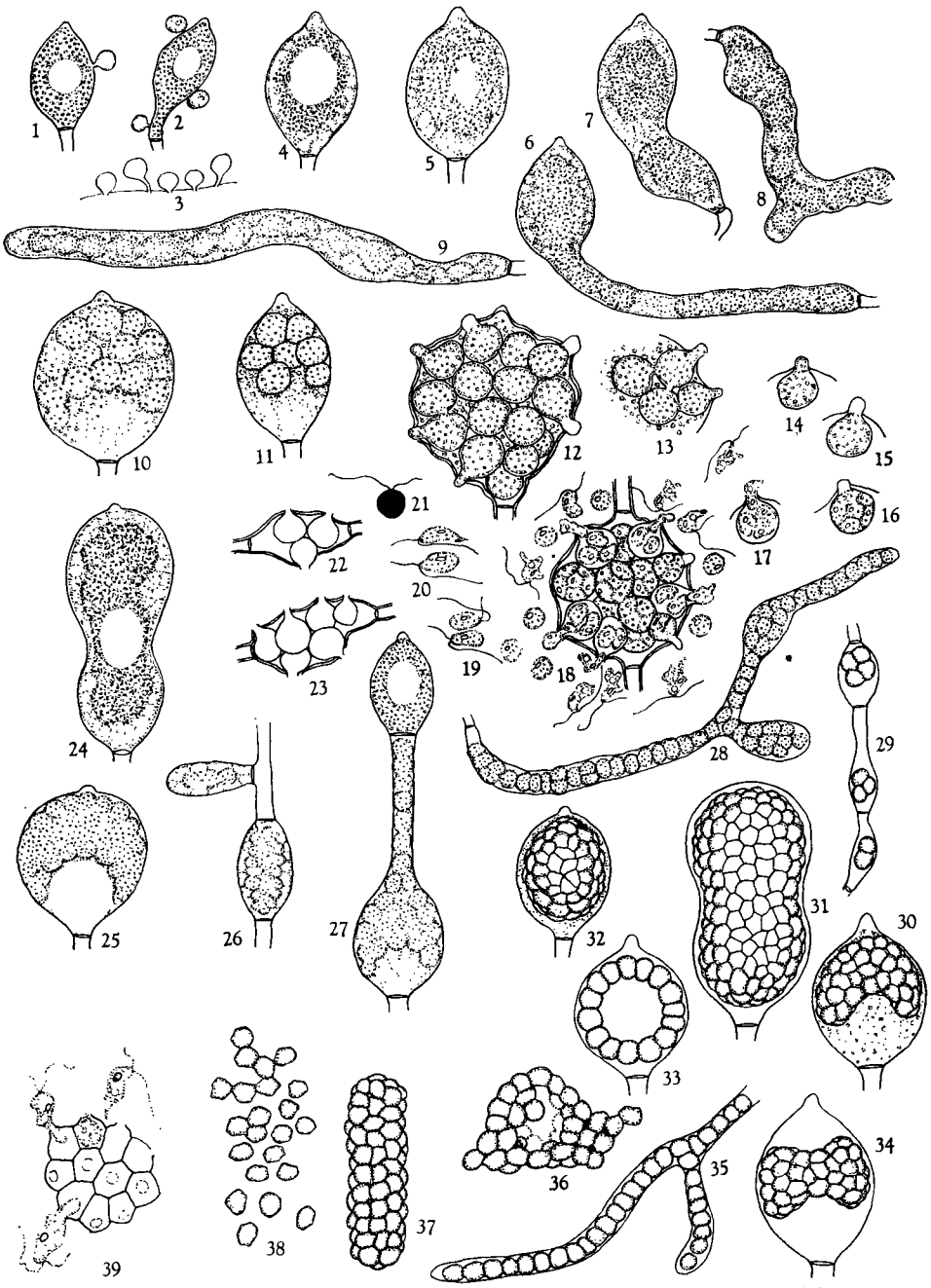


Fig. 1–39. *Woronina pythii* from living material.—Fig. 1, 2. Single and multiple infection of incipient sporangia of *Pythium* sp.; zoospore cysts persistent.—Fig. 3. Empty persistent zoospore cysts on a hypha.—Fig. 4, 5. Later stages of development of the sporangial plasmodium in hypertrophied tips of the host hyphae.—Fig. 6, 7. Enlarged hyphal tips with two sporangial plasmodia.—Fig. 8. Irregularly enlarged hyphal tip with sporangial plasmodium undergoing cleavage.—Fig. 9. Elongate swollen hyphal tip with an extended plasmodium undergoing cleavage.—Fig. 10, 11. Completion of cleavage to form sporangiosori.—Fig. 12. Sporangiosorus, sporangia with short broad exit tubes. —Fig. 13. Small sporangiosorus of four sporangia connected by isthmuses.—Fig. 14–17. Single sporangia showing structure, cleavage, and dehiscence.—Fig. 18. Sporangiosorus with dehiscing sporangia; anteriorly biflagellate heterocont zoospores amoeboid immedi-

(fig. 38), which indicates that they are not tightly united. Heavily infected hyphae of *Pythium* with cystosori were accumulated in a dish during the course of several weeks and stored for study of cyst germination. As the host hyphae degenerated the cystosori were freed, and by this process a high number of them was obtained. By alternate drying and wetting, freezing and thawing over a period of 5 months a few of them were stimulated to germinate, and in these cystosori each cyst formed a single anteriorly biflagellate heterocont zoospore (fig. 39). Such zoospores were kept under observation for the length of their life to determine whether or not they function as gametes and fuse, but no fusions were observed. For the same reason careful watch was kept on the zoospores produced by the zoosporangia (fig. 18). Occasional pairings of zoospores (fig. 19, 20) were observed, but here also no fusions occurred. Accordingly, no evidence of sexuality has yet been observed in this species.

In relation to the above account of *W. pythii,* it may be noted that *Sorodiscus cokeri* Goldie-Smith also was found as a parasite of *Pythium* species, and *Woronina polycystis* occurred fairly commonly in species of *Saprolegnia.* No significant differences in development and general morphology from the descriptions given by Goldie-Smith (1954, 1956) were noted in these species; accordingly they are not described here. In addition to the above-recorded species three other members of the Plasmodiophoraceae, *Plasmodiophora brassicae Spongospora subterranea,* and *Sorodiscus radicicolus* Cook (1931), have been found in India. *Sorodiscus radicicolus* was discovered by M. S. Ghemawat at Jodhpur on the roots of *Gynandropsis pentaphylla* where it causes conspicuous galls. Thus, six species of the Plasmodiophoraceae have been reported so far from India.

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ately after emerging.—Fig. 19, 20. Paired zoospores.—Fig. 21. Fixed and stained zoospore.—Fig. 22, 23. Small sporangiosori with three and six empty sporangia, respectively. —Fig. 24. Cystogenous plasmodium.—Fig. 25–28. Cleavage of cystogenous plasmodium. —Fig. 29. Cystosori consisting of diads, triads and tetrads of cysts.—Fig. 30–37. Variations in the size and shape of cystosori.—Fig. 38. Separated cysts.—Fig. 39. Germination of cysts to form anteriorly biflagellate hetercont zoospores.

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Indian Anisochytrids *)

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(With 6 figures).

In connection with the author's (1964) studies on the chytrid flora of India several anisochytrids were trapped on various substrata such as bleached corn leaves, bits of hemp seed and fibrin film from soil in numerous parts of the country. These fungi are strikingly similar in structure and development to many of the true chytrids, but are distinguishable from them by the presence of an anterior tinsel-type flagellum on their zoospores. Comparatively few species are known so far, and these have been classified (Karling, 1943) into three families, *Anisolpidiaceae, Rhizidiomycetaceae,* and *Hyphochytriaceae,* on the basis of thallus structure and organization. In this respect the three families correspond with and are fairly similar, respectively, to the families *Olpidiaceae, Rhizidiaceae* and *Cladochytriaceae* of the true chytrids.

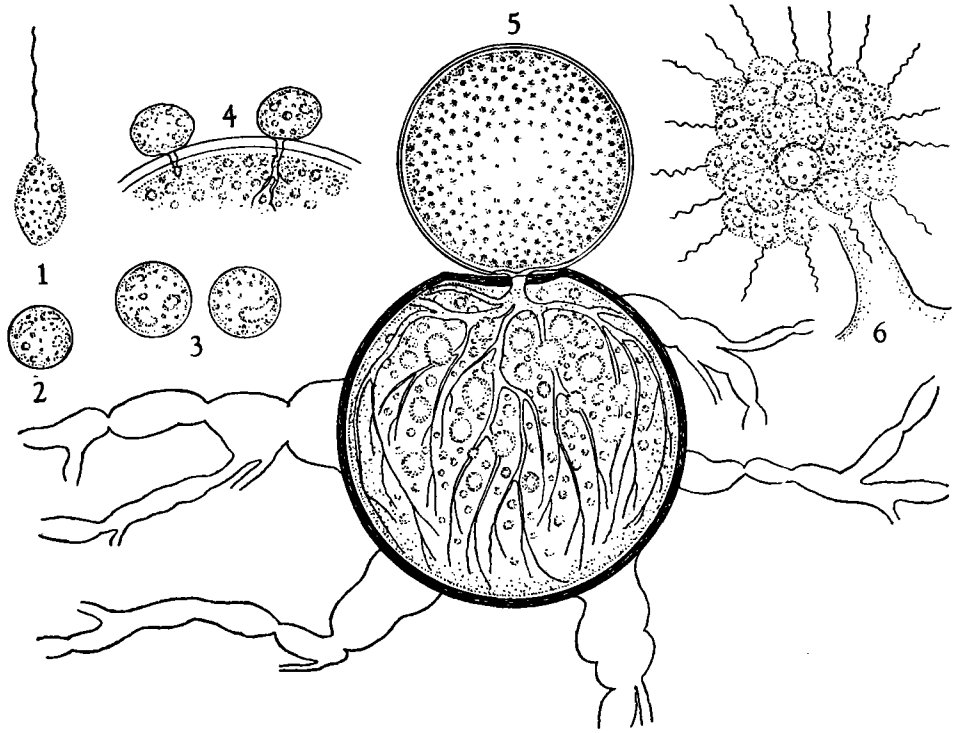
Among the anisochytrids isolated in the manner noted above occurred a species of *Rhizidiomyces* which parasitized virulently the thick-walled sporangia of *Rhizophlyctis* sp., a true chytrid. The only other species of this genus reported to be parasitic is *R. apophysatus* which occurs on the oogonia of *Achlya* and *Saprolegnia.* Apparently, it is a facultative parasite which can be cultured readily on synthetic media (Couch, 1939) and also occurs on pollen grains when they are used to bait soil samples (Gaertner, 1954). The present species, on the other hand, appears to be a virulent parasite with a limited host range. So far all attempts to infect the sporangia of *Karlingia rosea, Phlyctorhiza variabilis, Allomyces arbuscula, Catenaria anguillulae, Nowakowskiella elegans* and *N. ramosa* as well as the oogonia of *Achlya* and *Saprolegnia* have been unsuccessful. Also, attempts to grow it on nutrient agar have failed. Furthermore, it is non-apophsate, has slightly larger zoospores, and lacks the short spines which are frequently present on the sporangia of *R. apophy-*

*) This study has been supported by the U. S. Program in Biology, International Indian Ocean Expedition and conducted at the Central Marine Fisheries Research Institute, Mandapman Camp, Madras State. I am very grateful to Dr. S. Jones, Director of the Institute, for research facilities and assistance.

satus. For these reasons the author believes it is distinct from *R. apophysatus* and the other species of this genus. Accordingly, it is diagnosed here as a new species for which the name *R. parasiticus* is proposed.

Rhizidiomyces parasiticus sp. nov.

Fungus parasiticus. Sporangiis extramatricaliis, non-apophysatis, levibus, hyalinis, sphaericis, 20—40 μ diam. ovalibus, 12—21 × 30



Figs. 1—6. *Rhizidiomyces parasiticus*. Fig. 1. Anteriorly uniflagellate zoospore. Fig. 2. Zoospore after coming to rest. Fig. 3. Encysted and enlarged zoospores 24 hours after coming to rest. Fig. 4. Infection stages. Fig. 5. Mature thallus on and in sporangium of (?). *Rhizophlyctis* sp. Fig. 6. Completion of cleavage of sporeplasm outside of sporangium.

—42 μ diam. Zoosporis ovalibus aut oblongatis 3.5—4.2 × 5.7—7 μ; flagello 14—16 μ longo. Sporis perdurantibus non notis.

Sporangia non-apophysate, smooth, hyaline, with a wall 2—3 μ thick, spherical, 20—40 μ diam., or ovoid. 12—21 × 30—42 μ diam.; content emerging slowly through an exit tube, 12 μ broad by 18—25 μ long, and usually undergoing cleavage outside of sporangium; vesicular membrane around sporeplasm lacking. Zoospores ovoid to oblong, 3.5—4.2 × 5.7—7 μ diam. with coarsely granular refractive content; flagellum 14—16 μ long. Resting spores unknown.

Parasitic on the sporangia of *Rhizophlyctis* sp., isolated from brackish soil at Mandapam Camp, and non-brackish soil at Madurai, Madas State. Type slide no. 120 PU.

The distinguishing structural features of this species are shown in figures 1 to 6. Its development, the dehiscence of the sporangia, and the cleavage of the sporeplasm after emergence are so similar to those of other species described by the author (1944, 1945) and Fuller (1962) that it is not necessary to describe them again. Careful observations and plasmolytic experiments have been made on the emerged sporeplasm of this species, and these have confirmed the previous observations of the author that it is not enveloped by a distinct wall or membrane. Nabel (1939) and Fuller (1962) reported the presence of a membrane around the sporeplasm of the species which they studied, but the author is confident that it does not exist.

Occasionally, a portion of the sporeplasm may remain in the sporangium, as reported by the author, (1939, 1944) in *Hyphochytrium catenoides, Rhizidiomyces bivellatus* and *R. hansonii,* and undergoes cleavage to produce zoospores which then swim out. Also, on rare occasions the development of the exit tube may be arrested, with the result that the sporeplasm does not emerge but cleaves into zoospores within the spoangium as in *R. hansonii* (Karling, 1944, fig. 60).

So far the only anisochytrid reported previously from India is *R. apophysatus* which Chaudhuri and Kochar (1935) found on the oogonia of *Achlya klebsiana.* However, as noted above, the author isolated several other species, as is indicated below.

Rhizidiomyces hirsutus Karling, 1945. Bull. Torrey Bot. Club 72: 47, 19 figs.

Saprophytic on and around bits of hemp seed, from brackish soil at Mandapam Camp, Rhamnad District, Madras State.

Rhizidiomyces bivellatus Nabel, 1939. Ark. Mikrobiol. 10: 515—541.

Saprophytic on wings of mosquito, from non-brackish soil 10 km. south of Madurai along the Rhamnad Road, Madras State, and Calcutta, Bengal State.

Rhizidiomyces hansonii Karling, 1944. Amer J. Bot. 31: 396, figs. 35—64.

Saprophitic on bleached corn leaves from soil 2 km. north of Rhamnad, Madras State.

Rhizidiomyces apophysatus Zopf, 1884. Nova Acta Acad. Leop. Carol. 47: 188, pl. 20, figs. 1—7.

Parasitic on the oogonia of *Achlya* sp., from soil in a cotton paddy at Bodinakayanur, Madras Staate.

Hyphochytrium catenoides Karling, 1939. Amer. J. Bot. 26: 513, 19 figs.

Saprophytic in bleached corn leaves from soil in the Thalayar Tea Estate, near Munnar, Kerala State.

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Indian Chytrids I. Eucarpic Monocentric Species,*)

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(31 text-figures)

In addition to the species of the *Plasmodiophoraceae* and *Rhizidiomycetaceae* reported by the author (1964a, b) from India, several eucarpic, monocentric chytrids were isolated on various substrata from soil and water samples during 1963. These include two new species and several other well-known operculate and inoperculate species which have been reported previously from other parts of the world.

Rhizophydium collapsum sp. nov.

Fungus saprophyticus. Sporangiis extramatricalibus, laevibus, hyalinis, subsphaericis aut sphaericis, 14—27 μ diam., obpyriformibus, 14—16×18—20 μ diam. Zoosporis sphaericis, 2,5—3 μ diam. Sporis perdurantibus subsphaericis, sphaericis, 5,2—9 μ diam., ovalibus, 5—6,3×6—7,8 μ diam., fuscis.

Thalli solitary or up to 7 on a host cell. Sporangia extramatrical, usually sessile, hyaline, smooth, slightly subspherical to spherical, 14—27 μ diam., or broadly obpyriform, 14—16×18—20 μ diam., with a thin, 0,8—1,2 μ, wall which collapses and partially dissolves as the zoospores emerge; basal portion of wall slightly thickened; exit papillae lacking. Rhizoids intramatrical, main axis narrow and finely branched at base. Zoospores spherical, 2,5—3 μ diam., with a small hyaline refractive globule and a 12—14 μ long flagellum; a few emerging singly in succession through a single minute apical, subapical or lateral pore. Resting spores subspherical to spherical, 5,2 to 9,5 μ diam., or slightly ovoid, 5—6,3×6—7,8 μ, with a light-brown wall which is usually smooth or occasionally slightly rough or verrucose; functioning as prosporangia in germination.

On dead pollen of *Pinus silvestris*, from brackish soil at Mandapam Camp and near Valantarvai along the Rhamnad Road, Madras State.

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As noted in the diagnosis above the species is characterized primarily by a very thin sporangium wall which collapses and dissolves partially as the zoospores emerge, and by the lack of discernable exit papillae. In these respects it differs from other chytrids which have been reported to occur on pine pollen. Its developmental stages (figs. 1—15) are basically similar to those of other *Rhizophydium* species, and for this reason it is not necessary to describe them in detail. Suffice it to note that the incipient sporangia are highly vacuolate and include numerous large glistening globules (fig. 3). As the sporangia mature they may be readily separated from the host cell by pressure on the cover glass, and float free in the water (fig. 4). In such sporangia a slight thickening of the basal portion of the wall is sometimes visible, but the remaining portion of the wall is quite thin, 0,8—1,2 μ. No exit papillae are visible, but a narrow pore or tear is formed in the wall for the discharge of the zoospores. The first visible indication of dehiscence is an instantaneous discharge of a mass of fluid at the point where the exit pore occurs (fig. 5), and this is followed by the emergence of a few zoospores. As a result the sporangium loses turgidity and begins to shrink quite perceptably in diameter (fig. 6) in much the same manner as Canter (1959) described it in *R. contractophilum*. As more zoospores emerge the wall collapses around those still within the sporangium (fig. 7, 8) and within 35 to 70 minutes it is frequently no longer visible except for the slightly thickened basal portion (fig. 9). Such persistent portions are somewhat similar to those illustrated by Whiffen (1942) for *Solutoparies pythii*. In other dehisced sporangia, shriveled remanents of the upper portion of the wall may persist.

Complete dissolution or deliquescence of the sporangium wall upon dehiscing has been reported to occur in other chytrids such as *Nowakowskia hormothecae* Borzi (1885), *Hapalopera piriformis* Fott (1942), *Rhizophydium sphaerocystidis* Canter (1950), *R. difficile* Canter (1954), *R. achanthis*, and *R. melosirae* Friedman (1952). Also, in *R. pelagicum* Patterson (1948), the upper portion of the sporangium wall deliquesces, leaving the lower half intact, while in *Solutoparis pythii* Whiffen (1942) and *R. contractophilum* Canter (1959) only a small basal portion remains intact. Accordingly, complete or partial dissolution of the sporangium wall during dehiscence is not uncommon in the chytrids, and its occurrence alone does not distinguish *R. collapsum* sharply from the above-named species of *Rhizophydium*. However, these species are parasites of algae in contrast to *R. collapsum* which is a saprophyte. Other characteristcs as well distinguish it from the species reported to occur on pollen grains.

The zoospores which emerge singly through the exit orifice lie quiescent in a loose mass for a while or float away slowly, after which they become dartingly motile. Usually, a fairly large number fail to

emerge in this manner and are held in a central mass by the collapsing sporangium wall (fig. 8). These may degenerate unless freed, or they become motile and swim away if the wall dissolves completely.

The resting spores develop in the same manner as the sporangia with the exception that they soon form a thicker wall and contain numerous refractive globules. So far no evidence of sexual fusions has been observed in relation to their development. The wall of the spores is usually smooth (fig. 10, 11), but occasionally it may be slightly rough or verrucose (fig. 12, 13). As in other species of *Rhizophydium* these spores function as prosporangia in germination (fig. 14, 15).

In the same culture with *R. collapsum* occured another eucarpic monocentric chytrid which obviously belong in the genus *Phlyctochytrium*. The author has been unable to identify it with any of the other known species of the genus, and for reasons which will become apparent below he is diagnosing it as a new species and proposing the name, *P. indicum*, for it.

Phlyctochytrium indicum sp. nov.

Fungus saprophyticus. Sporangiis hyalinis, laevibus, pyriformibus, 18—28 × 24—38 μ diam. citriformibus, subsphaericis, 22—29 μ diam., Zoosporis sphaericis, 2,5—3 μ diam. Apophysis subsphaericis, 8—12 μ diam., ovalibus, elongatis, irregularibus. Rhizoidis ramosis. Sporis perdurantibus, hyalinis, laevibus, subsphaericis, sphaericis, 16—20 μ diam.

Sporangia hyaline, smooth, broadly pyriform with a slightly flattened base, 18—28 μ broad by 24—38 μ high, occasionally broadly citriform, or almost spherical, 22—29 μ diam., with one broad apical exit papilla, 7—14 μ diam. Apophysis subspherical, 8—12 μ diam., ovoid, slightly elongate, or irregular; rhizoids branched, main axes arising at 1 to 3 points on surface of apophysis. Zoospores spherical, 2,5—3 μ diam., with a minute refractive globule; flagellum 11—13 μ long. Resting spores hyaline, smooth, subspherical to spherical, 16—20 μ diam., with a large, somewhat angular, refractive body and several smaller ones; functioning as prosporangia in germination.

Saprophytic on dead pollen of *Pinus silvestris*, from brackish soil at Mandapam Camp, Rhamnad District, Madras State.

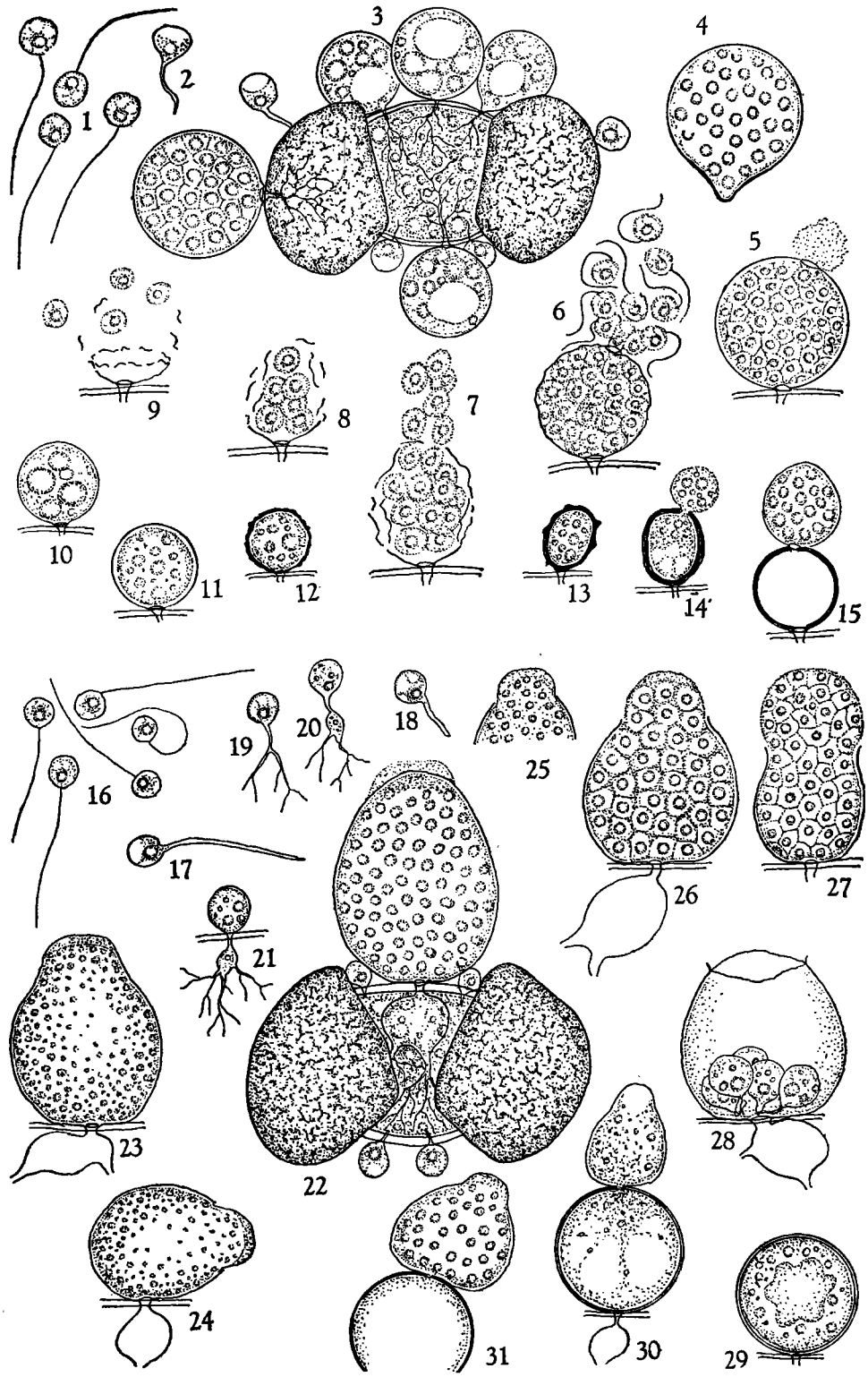
The life cycle and development of this species are illustrated in figs. 16 to 31, and it is evident that they do not differ significantly from those of most other known species of *Phlyctochytrium*. Hence, detailed descriptions of these processes are omitted. This species differs primarily from the other members of the genus which occur on pollen by a single, unusually broad apical exit papilla. So far, several species of *Phlyctochytrium*, including *P. biporosum* Couch (1932), *P. papillatum* Sparrow (1952), *P. palustre* Gaertner (1954),

P. africanum Gaertner (1954), *P. semiglobiferum* Uebelmesser (1956), *P. spectabile* Uebelmesser (1956), *Phlyctochytrium* n. sp. Reinboldt (1951), or *P. reinboldtae* Persiel (1956), have been reported to occur on pine pollen. All of these species except one have from 2 to 5 small or broad and elevated exit papillae, and in *P. spectabile* 15 to 20 may be present on the sporangia. In *P. indicum*, however, only one exit papilla per sporangium has been found, and this one occurs apically and may be up to 14 μ in diameter. How significant and specific the number of exit papillae may be as a diagnostic criterion in *Phlyctochytrium* remains to be proven, in the author's opinion, but it is noteworthy that in the hundreds of sporangia observed in the present species only one broad papilla occured. Also, in *P. palustre*, according to Gaertner (1954), there was no increase beyond 5 in number of papillae when he grew it on agar where the sporangia attained a diameter of 55 μ. In these two species, at least, the number appears to be specific. More recently Paterson (1963) reported that the number of papillae in the two species of *Rhizophydium* which he studied is constant on all substrata.

Although generally smaller, the sporangium of *P. indicum* with its large apical papilla and the presence of a visible inner sporangial wall around the protruding papilla shortly before dehiscence is strikingly similar to that of *Phlyctidium megastomum* Sparrow (1943), a species which Raitchenko (1902) described as *Rhizophydium sphaerocarpum* on *Anabaena flos-aquae* in Russia. Miller (1961) rediscovered this species on *Liquidamber styraciflua* pollen in Lake Texoma, bordering Texas and Oklahoma, and except for the increase in size of the zoospores during motility and the occurrence of "false proliferation" of the sporangia, he confirmed in general Raitchenko's observations and the presence of an intramatrical, non-rhizoidal peg or apophysis. Germination of some zoospores within the sporangia occurs commonly in *Phlyctochytrium indicum* also, and its zoospores may increase in size as in *Phylctidium megastomum* but only after they

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Figs. 1—15. *Rhizophidium collapsum*. Figs. 16—31. *Phlyctochytrium indicum*. Fig. 1. Zoospores. Fig. 2. Germinating zoospore on agar. Fig. 3. Heavily infested pollen grain with thalli in various stages of development. Fig. 4. Free-floating broadly obpyridorm sporangium with slightly thickened basal wall. Fig. 5. Sporangium showing first visible evidence of dehiscence. Fig. 6. Same sporangium showing marked contraction in diameter as zoospores emerge. Fig. 7—9. Same sporangium showing collapse and partial disappearance of wall. Fig. 10, 11. Stages in development of resting spore. Fig. 12, 13. Slightly rough and verrucose resting spores. Fig. 14, 15. Germination stages. Fig. 16. Zoospores. Fig. 17—20. Germination of zoospores and early stages of thallus development on agar. Fig. 21. Young thallus. Fig. 22. Pollen grain infected by zoospores and a large mature thallus. Fig. 23, 24. Variations in size, shape and position of sporangia relative to substratum. Fig. 25—27. Stages in dehiscence of sporangium. Fig. 28. Dehisced sporangium with zoospores germinating within it. Fig. 29. Resting spore. Fig. 30, 31. Germination stages of resting spore.


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have come to rest. Furthermore, the resting spores of these two chytrids vary similarly in size. However, these species differ markedly by the sizes of their zoospores and by the presence of rhizoids on the apophysis of the Indian chytrid, as noted previously. Such rhizoids are clearly evident on thalli which develop in water or agar cultures (fig. 19, 20) as well as in pollen grains which have been cleared by various agents.

In addition to the new monocentric, eucarpic species described above several others were isolated in India, including operculate and inoperculate species.

Rhizophydium sphaerotheca Zopf, 1887. Abhand. Naturf. Gesell. Halle 17: 92, pl. 2, figs. 33—41.

On dead pollen of *Pinus sylvestris* from brackish soil, Mandapam Camp, Madras State.

Rhizophydium keratinophilum Karling, 1946. Amer. J. Bot. 33: 753, 43 figs.

On human hair from soil in a dry rice paddy near Uttarkosamanga along the Rhamnad Road, Madras State.

Rhizophydium sp.

This species occurred in abundance on bleached corn leaves in watered soil samples from Panakudi, 15 km. from Nagercoil, and Virudunagar, Madras State. No resting spores were formed during the brief period of existence of this fungus, and the author is, thusly, unable to identify it with any of the known members of the genus. Nevertheless, it is described here insofar as it is known.

Sporangia extramatrical, spherical, 25—60 μ diam., hyaline, smooth, wall persistent after dehiscence, with 5 to 8 almost equally distributed exit papillae which are 3 to 4 in diam. and filled with broadly conical, protruding, 4 μ high by 5 μ diam. at base, plugs of slightly opaque and homogeneous material. Main rhizoidal axis 3,5—4 μ diam., occasionally slightly inflated and almost apophysis-like. Zoospores spherical, 3—3,8 μ diam., with a small refrigent globule, emerging simultaneously and singly from several exit papillae.

Phlyctochytrium chaetiferum Karling. 1937. Mycologia 29: 179, fig. 1—3.

In association with *Phlyctochytrium indicum* another species occurred fairly often on dead pine pollen in the Mandapam Camp culture. This species is identified as *Phlyctochytrium chaetiferum* Karling which the author found as a saprophyte on dead cells of *Hydrodictyon reticulatum* and *Oedongonium* sp. in New York City. Although the Indian isolate occurred on pine pollen and differs in

some minor respects, these differences are not sufficient enough to warrant the creation of another species. Usually, the hairs on the sporangia are not as numerous as in the American material and do not become as long (only up to 88 μ). Also, they are usually narrower or finer. The walls of the resting spores are thinner than reported for the American isolate, and the zoospore vary only from 2,5 to 3,2 μ in diameter. Germination of zoospores or "false proliferation" in the sporangia occurs commonly in the Indian material, and the single, apical exit orifice may be up to 20 μ in diameter. Otherwise, it is identical with the American species.

Phlyctochytrium sp.

This species occurred as a saprophyte on bleached corn leaves in a watered brackish soil sample at Mandapam Camp, Rhamnad District, Madras State. Its extramatrical sporangia are spherical, 20—42 μ diam., with a thin hyaline and smooth wall and numerous (5—12) small and hardly discernable exit papillae which are fairly evenly distributed. The intramatrical portion of the thallus consists usually of a small, 3,2—5 μ diam., apophysis from which arise 1 to 3 branched rhizoids. Occasionally, the apophysis may be lacking, and the species resembles members of *Rhizophydium*. In such thalli the main rhizoidal axis may be 2,8 to 4 μ in diameter. The zoospores are small, spherical 2—2,5 μ diam., and lack a distinct refractive globule. Instead, they contain a minute droplet or body which appears dark to black by transmitted light. No resting spores were observed in this species, and for this reason it is difficult to identify it. In general appearance, it resembles *Phlyctochytrium spectabile* Uebelmesser (1956), but its sporangia, zoospores, apophysis and rhizoids are markedly smaller.

Entophlyctis texana Karling, 1941. Torreya 41: 106.

In bleached corn leaves from soil in a tea estate 39 kms. west of Munnar, Kerala State, at an altitude of about 3500 ft.

Diplophlyctis intestina (Schenk) Schroeter, 1893. Engler and Prantl, Natürlichen Pflanzenf. (1) 1: 78.

Rhizidium intestinum Schenk, (pro part), 1858. Über das Vorkommen contractiler Zellen im Pflanzenreich, p. 5, figs. 1—9, Würzburg.

In dead cortical cells of *Chara delicatula* from a freshwater lake about 4 kms. west of Uchippuli, Madras State.

Phlyctorhiza variabilis Karling, 1947. Amer. J. Bot. 38: 722—777, 3 figs.

This is one of the most common fungi encountered by the author in India. It was found in all 56 soil collections from India as well as

in collections in Ceylon, Thailand, Hong Kong and Japan. In India it occurred in brackish soil at sea level as well as in nonbrackish soils up to an elevation of over 6000 ft. Monocentric and polycentric thalli were present, and the latter, particularly, grew equally well in bleached corn leaves as in keratinized substrata which suggests that the Indian collections might be different from those reported by the author, Gaertner (1954) and Willoughby (1962) from other parts of the world. The majority of the Indian thalli were polycentric and very extensive like those shown previously by the author (1951, figs. 1—3) for the Israelian strain, particularly when grown on human fibrin film. The zoospores of such thalli gave rise to both monocentric and polycentric thalli. These strains are being investigated more intensively in pure culture at the present time. Present studies indicate that this fungus should be removed from *Phlyctorhiza* as Hanson (1946) defined this genus, and as the author (1951) stated previously it may be closely related to *Catenaria*.

Rhizidium verrucosum Karling, 1944. Amer. J. Bot. 31: 255, figs. 34—63.

In snake skin from soil in Maden Park along Chowringee Street, Calcutta, Bengal State.

Karlingia rosea (DeBary and Woronin) Johanson, 1944. Amer. J. Bot. 31: 399, 37 figs.

Chytridium roseum DeBary and Woronin, 1865. Ber. Verhandl. Naturf. Gesell. Freiburg 3 (2): 52, pl. 2, figs. 17—20.

Rhizoplyctis rosea (DeBary and Woronin) Fischer, 1892. Rabenhorst's Kryptogamen-Fl. 1 (4): 122.

In bleached corn leaves, cellophane and onion skin from all soil collections made in India as well as in Ceylon, Thailand, Hong Kong and Japan.

Like *Phlyctorhiza variabilis* this species occurred in brackish soil at sea level as well as in non-brackish soil up to 6000 ft. in India and Ceylon. Variations in size, structure and pigmentation were noted in the collections, and these variations suggest that more than one strain of K. *rosea* is present in India.

Some workers, Haskins (1950) and Haskins and Weston (1950), have contended that dehiscence in this species is inoperculate and maintained that the presence of endo-opercula does not indicate that a species is operculate. Willoughby (1958) made an intensive study of this species in England and found that dehiscence was always operculate as described by Johanson (1940). Careful observations over long periods of time on the development of the sporangia, exit tubes and endo-opercula were made on the Indian collections, and in no cases was inoperculate dehiscense seen. Obviously, K. *rosea* is

operculate and does not belong in the genus *Rhizophlyctis* as some writers claim.

Karlingia marilandica Karling, 1949. Mycologia 41: 51, figs. 70—80.

Karlingiomyces marilandicus (Karling) Sparrow, 1960. Aquatic phycomycetes, 2nd. ed. p. 562.

Isolated on bleached corn leaves and strips of cellophane from soil 39 km. west of Munar, Kerala State at an elevation of 3500 ft., and at sea level in brackish soil 14 km. north of Mandapam Camp along the Rhamnad Road, Madras State. The majority of the sporangia observed in the Indian collections were exo-operculate, but fairly often they were endo-operculate also as the author described them from Maryland, USA. Careful and continuous observations of the development and dehiscence of endo-operculate sporangia were made to determine whether or not they dehisce without the extrusion of an operculum, and in no instance was this observed to occur. As in the Maryland material (fig. 72) the sporangia were sometimes monorhizoidal, and the exit canal extended up to distances of 228 μ. No resting spores were observed in the Indian collections.

Chytridium parasiticum Willoughby, 1956. Trans. Brit. Mycol. Soc. 39: 135, figs. 5—7.

Parasitic on *Karlingia rosea* which was isolated on bleached corn leaves from soil 14 kms. north of Mandapam Camp along the Rhamnad Road, Madras State. Although this is a new host, the author believes that this parasite is the same as *C. parasiticum*, and it is identified as such. No resting spores were found in the Indian material.

Chytriomyces hyalinus Karling, 1945. Amer. J. Bot. 32: 363, figs. 46—61.

Chytriomyces nodulatus Haskins, 1946. Trans. Brit. Mycol. Soc. 29: 131, 8 figs.

On purified shrimp chitin in water from the Pulviar River on the Ghat Road. Madras State.

So far, the author has found that chitinophilic species are rare in India, and this is the only such species he has found to date.

Chytriomyces verrucosus Karling, 1960. Bull. Torrey Bot. Club 87: 327, figs. 1—19.

Parasitic on *Karlingia rosea* from brackish soil at Mandapam Camp, Madras State.

Nephrochytrium appendiculatum Karling, 1938. Amer. J. Bot. 25: 507, 509, 34 figs.

On bleached corn leaves from soil in a tea estate, 39 kms. west of Munnar, Kerala State.

In the diagnosis of this species the author (1938) omitted mention of the fact that the sporangia are operculate. This characteristic has been observed by him in all subsequent collections of this species.

Nephrochytrium aurantium Whiffen, 1941. Amer. J. Bot. 28: 41, 26 figs.

On bleached corn leaves from soil in a tea estate, 39 kms. west of Munnar, Kerala State.

Cylindrochytridium Johnstonii Karling, 1941. Bull. Torrey Bot. Club 68: 383, 16 figs.

On bleached corn leaves from soil in a tea estate 45 kms. west of Munnar, Kerala State.

Summary

Two new chytrids, *Rhizophydium collapsum* and *Phlyctochytrium indicum*, occurred on dead pine pollen when it was used as a bait in watered brackish soil samples at Mandapam Camp. In addition numerous other eucarpic monocentric species were isolated on various substrata. These include *Rhizophydium* sp., *R. sphaerotheca*, *R. keratinophilum*, *Phlyctochytrium chaetiferum*, *Phlyctochytrium* sp., *Entophlyctis texana*, *Diplophlyctis intestina*, *Phlyctorhiza variabilis*, *Rhizidium verrucosum*, *Karlingia rosea*, *K. marilandica*, *Chytridium parasiticum*, *Chytriomyces hyalinus*, *C. verrucosus*, *Nephrochytrium appendiculatum*, *N. aurantium* and *Cylindrochytridium johnstonii*.

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Indian Chytrids. II. Olpidium indianum sp. nov. *)

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(21 text-figures).

In 1963 while participating as a mycologist in the UNESCO-sponsored International Indian Ocean Expedition the author isolated numerous chytrids from soil, pools and lakes in various parts of India. Some of the monocentric eucarpic species were described in an earlier paper (Karling, 1964 a). In addition to these, a large *Olpidium* species was found which parasitized the thalli and sporangia of *Phlyctorhiza variabilis* and the sporangia of *Rhizophlyctis fuscis* Karling (1964 b). These host had been isolated from soil at the edge of a slightly brackish pool at Mandapam Camp, Rhamnad District, and grown on bleached corn leaves in tap water whose salt content varied from 0.3 to 1.0 per cent. Under such conditions they became so abundantly parasitized by the *Olpidium* species that after two weeks it was difficult to find any thalli which were not attacked. Subsequently, it was found in isolates of the same hosts from soil in dry rice paddies 10 and 51 kilometers south of Madurai along the Rhamnad Road where the soil is non-brackish.

The sporangia of the parasite vary markedly in size and shape, depending to some degree on the number present in a host cell, but when they occur singly in a large sporangium of *Rhyzophlyctis fuscis* they may fill it and attain a diameter of 150 μ, the largest size reported so far for any species of *Olpidium*. Such large sporangia of the parasite may develop exit tubes which vary from 8 to 12 μ in diameter and 28 to 48 μ in length. The hyaline to light amber resting spores develop by the contraction of the thallus content (fig. 14—16) and its investment by a faily thick wall. As a result, the spores occupy only a portion of the thallus in which they develop and are usually enveloped by a thin hyaline membrane as in *Olpidium allomycetos* Karling (1948) and other species. No evidence of fusion of

*) This study was supported by the U. S. Program in Biology, International Indian Ocean Expedition and conducted at the Central Marine Fisheries Research Institute, Mandapam Camp. I am very grateful to Dr. S. Jones, Director of the Institute for research facilities and assistance and to Dr. Eric Silas for collecting numerous soil samples near the southern tip of India.

gametes prior to resting spore development, such as Sahityance (1962) found in *Pleotrachelus,* has been observed so far. Occasional biflagellate zoospores (fig. 2) may occur, but these appear to be the result of unequal cleavage instead of fused gametes.

Although the Indian species of *Olpidium* occurred so abundantly in the hosts mentioned above, it appears to have a limited host range. Other aquatic fungi such as, *Catenaria anguillulae, Nowakowskiella elegans, N. ramosa, Karlingia rosea* and *Pythium* spp. were abundant in the parasitized cultures of *P. variabilis* and *Rhizophlyctis fuscis,* but none of these were attacked during the course of this study. Subsequent attempts to infect these and other aquatic fungi with *O. indianum* in the laboratory at Purdue University were unsuccessful. However, the sporangia and resting spores of *Allomyces arbuscula* and the resting sporangia of *Physoderma pluriannulata* on *Kundmannia sicula* became densely infected when these fungi were added to a parasitized culture of *P. variabilis.* In these additional hosts also, a single to several parasites occurred in the host cells, and the exit canals were usually quite long and contorted.

Olpidium indianum sp. nov.

Fungus parasiticus, sporangiis hyalinis, laevibus, sphaericis, 30—150 μ, ovalibus, 22—40 × 38—60 μ, oblongatis, 20—30 × 40—52 μ, hemisphaericis aut angularibus; tubulum exeuntibus 5—12 × 8—48 μ. Zoosporis sphaericis, 3—4 μ singulis globulis refringentibus instructis; flagello 18—22 μ longo. Sporis perdurantibus laevibus, sphaericis, 12—28 μ, ovalibus, 8—12 × 15—20 μ, granulis globulis refractivis numerosis dense instructis; zoosporis germinatione ortis.

Sporangia 1 to 18 in a host cell and filling it partly or completely, hyaline, smoth, spherical, 30—150 μ, ovoid, 22—40 × 38—60 μ, oblong, 20—30 × 40—52 μ, hemispherical to polyhedral when 2 and a large number, respectively, fill a host cell. Exit tubes usually solitary, rarely 2 per sporangium, 5—12 μ in diameter by 8—48 μ in length, penetrating and cracking the host wall locally. Zoospores numerous, spherical, 3—4 μ, with a hyaline, brilliantly refractive globule and an 18—22 μ long flagellum; remaining spherical throughout motile period. Resting spores, 1 to 25 in a host cell, spherical, 12—18 μ, ovoid, 8—12 × 15—20 μ, with a hyaline to light amber, smooth wall, 1—8 to 3.2 μ thick, and containing 1 to several large refractive globules; formed by contraction of thallus content and lying in a hyaline vesicle; forming zoospores directly in germination and discharging them through a broad exit tube.

Parasitic in the thalli and sporangia of *Phlyctorhiza variabilis* and *Rhizophlyctis fuscis,* Rhamnad District, Madras State. Type spec. slide, PU, no. 103.

The life cycle and development of *O. indicum* are basically

similar to those of other known species of the genus, and it is not essential that they be described in detail. They are illustrated fully in figures 1 to 21, and the descriptive legends of the figures are sufficient for an understanding of the developmental stages.

Rhizophlyctis fuscis is a species whose sporangia develop an unusually thick, up to 8 μ, reddish-brown wall, but the exit tube of *O. indicum* readily cracks this wall locally and penetrates to the outside as shown in fig. 13. Likewise, the relatively thick-walled sporangia of polycentric strains of *Phylctorhiza variabilis* Karling (1951) and resting sporangia of *Allomyces arbuscula* and *Physoderma pluriannulata* are penetrated in the same manner.

So far only two members of the family *Olpidiaceae* has been reported from India as far as I am aware. Thirumalachar (1942) reported *Olpidum uredinis* as a parasite of the uredospores of *Hemileia canthii,* and Lacy reported *Olpidium entophytum* in *Spirogyra* from Patna in 1955. However, during the course of this study several members of this family were found in India in addition to *O. indicum.* These include the following species:

Olpidium gregarium (Nowakowski) Schroeter, 1885. Cohn, Krypt. — Fl. Schlesiens 3 (1): 182.

Chytridium gregarium Nowakowski, 1876, Cohn, Beitr. Biol. Pflanz. 2: 77.

Parasitic in rotifer eggs. This species occurs commonly as a parasite of rotifer eggs, and this is the first report of its occurrence in India so far as I know. It was found frequently in rotifer eggs in the cultures which contained *O. indianum* from Mandapman Camp.

Olpidium entophytum (Braun) Rabenhorst, 1868. Flora Europ. Algarum 3: 283.

Chytridium entophytum Braun, 1856. Monatsber. Berlin Akad. 1856: 589.

Parasitic in *Spirogyra* sp. This species occurred in a large species of *Spyrogyra* which was collected in a freshwater lake about 4 kilometers west of Uchippuli in the Rhamnad district.

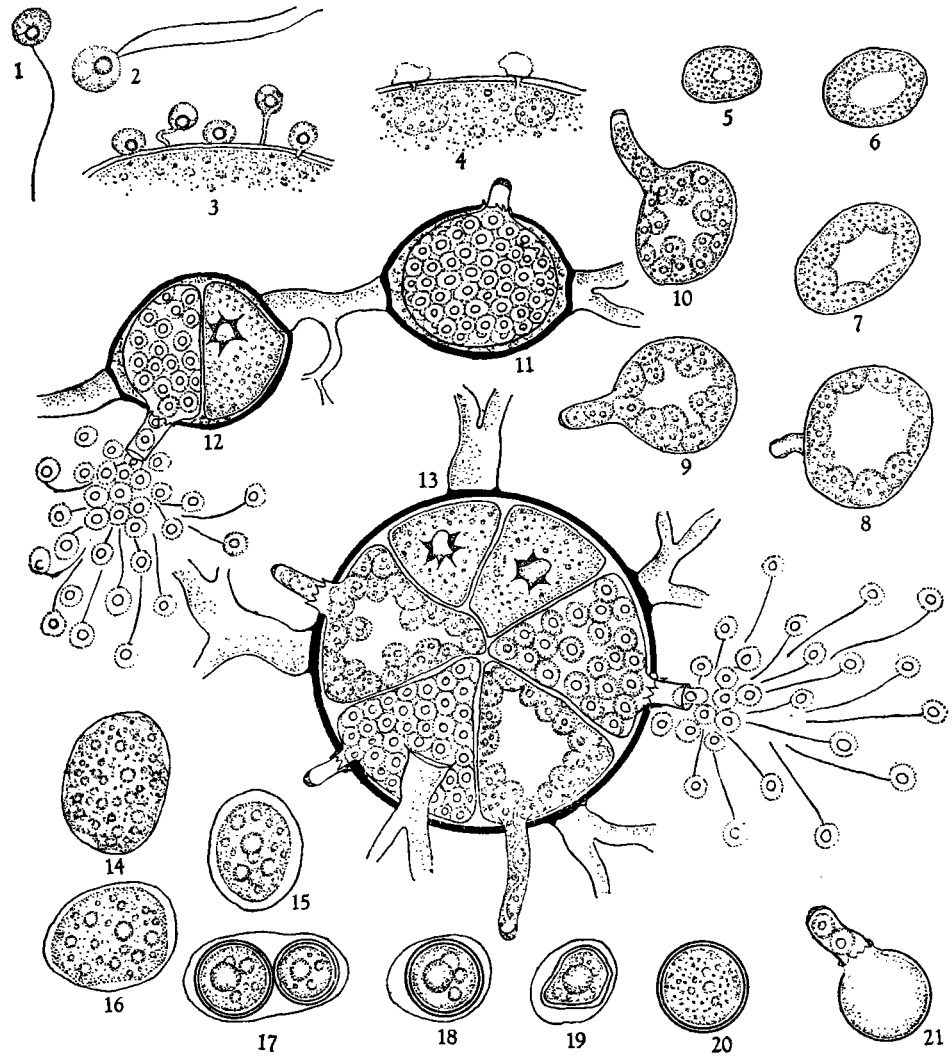
Olpidium allomycetos Karling, 1948. Amer. J. Bot, **35**: 503—510, fig. 1—32.

Parasitic in *Allomyces arbuscula* which was isolated from dry soil along the Rhamnad Road near Valantarayai, Rhamnad District, Madras State.

Rozella allomycis Foust, 1937. J. Elisha Mitchell Sci. Soc. **53**: 198, pls. 22, 23.

Parasitic in *Allomyces arbuscula.* This host was isolated on hemp seed from soil in a slightly brackish pond 8 kilometers north of Man-

dapam Camp along the Rhamnad Road, and within a few days it became so heavily parasitized that nearly all of thalli were killed. The zoosporangial phase of the parasite occasionally caused septation of the hyphae and incipient zoosporangia of the host, as described by Foust, but only rarely did it induce slight cell enlargement. The re-



Figs. 1—21. *Olpidium indianum.* Fig. 1. Normale Zoospore. Fig. 2. Abnormal biflagellate zoospore. Fig. 3. Multiple infection of host cell. Fig. 4. Young parasites in host protoplasm. Figs. 5—7. Development of thallus. Figs. 7—10. Stages in cleavage and zoosporogenesis. Fig. 11. Ovoid sporangium in thick-walled sporangium of *Phlyctorhiza variabilis*. Fig. 12. Two almost hemispherical sporangia in same host. Fig. 13. Median view of large sporangium of *Rhizophlyctis fuscis* with six polyhedral sporangia of *O. indianum in* various stages of development and dehiscence. Figs. 14—16. Stages in contraction of thallus content to form resting spores. Fig. 17. Thallus with 2 resting spores. Figs. 18—20. Mature resting spores. Fig. 21. Germination of resting spore.

sting spore phase, on the other hand, caused considerable cell enlargement, particularly when several spores were present in a cell. In some sporangia and hyphal cells of the host as many as 12 resting spores were present.

Rozella cladochytrii Karling, 1941. Torreya 41: 105; 1942 a, Amer J. Bot. **29**: 25, figs. 1—24.

Parasitic in *Nowakowskiella ramosa* and *N. elegans,* isolated on bleached corn leaves from a freshwater lake approximately 4 kilometers west of Uchippuli, Rhamnad District.

Rozella rhizophlyctii Karling, 1942. Amer. J. Bot. **29**: 32, figs 37—47.

Parasitic in the sporangia of *Karlingia rosea* which was isolated on bleached corn leaves from soil at the edge of a brackish ditch on Mandapam Camp, Rhamnad District.

Rozella laevis Karling, 1942. Mycologia **34**: 201; 1944, Mycologia 36: 638, figs. 1—19.

Parasitic in the sporangia and hyphae of *Pythium* sp. causing marked hypertrophy of the host cells, Mandapam Camp, Madras State, Jodhpur, Rajasthan State, Calcutta, Bengal State and Munnar, Kerala State.

One of the hosts of this parasite was isolated on corn leaves from brackish soil in a dry ditch and cultured in brackish tap water at Mandapam Camp. Apparently, the resting spores of the parasite were present in the brackish soil with the oospores of the host. Subsequently, it was found in numerous non-brackish soil collections as noted above, and appears to be a common parasite in India.

Rozella sp. Karling, 1947. Amer. J. Bot. 34: 31, figs. 44—48.

Parasitic in the sporangia of *Phlyctorhiza variabilis,* Mandapam Camp, Madras State and Jodhpur, Rajasthan State. Apparently, the Indian parasite is the same one which the author (1947) found in America because it conforms closely with it. So far no resting spores have been observed.

Summary.

Olpidium indianum sp. nov. is a virulent parasite of *Phlyctorhiza variabilis* Karling and *Rhizophlyctis fuscis* which occur in the brackish soil at Mandapam Camp, Madras State, and non-brachish soil in other parts of India. It is characterized by unusually large sporangia with long or short exit tubes, minute spherical zoospores which contain a hyaline, brilliantly refractive globule, and resting spores which are formed by the contraction of the thallus content and its

investment by a relatively thick, hyaline wall. These spores function as sporangia in germination. Other members of the family Olpidiaceae found in India include *Olpidium gregarium* (Nowakowski) Schroeter, *O. entophytum* (Braun) Rabenhorst, *O. allomycetos* Karling, *Rozella allomycis* Foust, *R. cladochytrii* Karling, *R. rhizophlyctii* Karling and *R. laevis* Karling which parasitized, respectively, rotifer eggs, *Spirogyra* sp., *Allomyces arbuscula, Nowakowskiella ramosa* and *N. elegans, Karlingia rosea* and *Pythium* spp.

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Indian Chytrids. IV. Nowakowskiella Multispora Sp. Nov. and other Polycentric Species.*)

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(8 text-figures).

Previous publications by the author (1964 a—e) on the aquatic zoosporic fungi of India related to members of the families *Plasmodiophoraceae, Olpidiaceae, Rhizidiaceae* and *Rhizidiomycetaceae.* The present contribution concerns the aquatic polycentric chytrids which were isolated from soil and water samples in various parts of India in 1963. Small soil samples were covered with boiled tap water and baited with bits of various substrata such as bleached corn leaves, onion skin, cellophane, chitin, skin, hair, and hemp seed in the manner which has become almost standarized for the trapping, isolation and study of aquatic zoosporic fungi. In addition to these substrata human fibrin film was used as a bait in most soil cultures, and several new chytrids were isolated on this substratum.

Among the numerous chytrids trapped on bleached corn leaves, cellophane and onion skin occurred a species of *Nowakowskiella* which the author has been unable to identify with the other eleven species of this genus. It is characterized principally by an unusually abundant production of resting spores and by small zoospores. Accordingly, it is diagnosed as a new species and named *multispora.*

Nowakowskiella multispora sp. nov.

Fungus saprophyticus. Rhizomycelio hyalino, profuso, copiose ramoso, partibus tenuibus, 2—5 μ diam., incrementis pluribus non septatis, ovalibus, fusiformibus, 10—15 × 17—30 μ, aut elongatis. Sporangiis terminalibus aut intercalaribus, 12—16 × 20—32 μ diam., elongatis aut cylindris, 10—14 × 32—40 μ diam., oblongatis, ovalibus aut sphericis, 8—26 μ diam. Zoosporis sphaericis, 3—3.9 μ diam., unico globulo refringenti; flagello 12—14 μ longo. Sporis perdurantibus numerosis, intercalaribus, laevibus, hyalinis, ovalibus, 12—15 ×

* This study was supported by the U. S. program in Biology, International Indian Ocean Expedition and conducted at the Central Marine Fisheries Research Institute, Mandapam Camp. I am very grateful to Dr. S. Jones, Director of the Institute for research facilities and assistance.

15—30 μ, oblongatis aut elongatis, 8—10 × 17—22 μ; germinantibus ut prosporangio membrano tenui ad superficium sporae.

Rhizomycelium profose, tenuous portions 2—5 μ diam.; spindle-shaped enlargements numerous and frequently in tandem, non-septate, narrowly ovoid, fusiform, 10—15 × 17—30 μ diam., or elongate, 8—10 × 17—22 μ diam. Sporangia usually terminal, sometimes intercalary, non-apophysate, hyaline, smooth, predominantly fusiform 12—16 × 20—32 μ diam., with long exit tubes, frequently elongate and almost cylindrical, ovoid or spherical, 8—26 μ diam., endo- or exo-operculate. Zoospores small, spherical, 3—3.9 μ diam., with a minute refringent globule; flagellum 12—14 μ long. Resting spores unusually abundant, usually intercalarly; formed by transformation of intercalary enlargements into fairly thick-walled structures, hyaline, smooth, almost spherical, 15—30 μ, broodly to narrowly ovoid, 12—15 × 15—30 μ, oblong or elongate 8—10 × 17—22 μ diam., with truncate ends, containing numerous large refractive globules; functioning as prosporangia in germination.

Saprophytic in bleached corn leaves, and on cellophane from non-brackish soil in a dry catch basin along the Rhamnad Road near Valantaravai, Rhamnad District, Madras State.

Type slide no. 104, P. U. L.

The structure and distinguishing characteristics of this species are illustrated in figs. 1 to 8. Its development from zoospore to rhizomycelium, sporangium and resting spore is basically similar to that of other species; hence it is not described further. As noted earlier, attempts to identify this species with any of the 11 other known members of *Nowakowskiella* have been unsuccessful. In *N. elegans, N. ramosa, N. hemisphaerospora, N. elongata, N. profosa, N. atkinsii* and *N. macrospora* the zoospores are reported to be 5—7.5 μ, 6.6—8.8 μ, 4.4—6.3 μ, 5—6 μ, 4.5—5 μ 5.7—7.5 μ, 5—6.6 μ, 4.5—5.5 μ, 5 × 3 μ and 10—12 in diameter, respectively, while in *N. multispora* they are only 3—3.9 μ in diameter. In this respect *N. multispora* is more similar to *N. sculptura* in which the zoospores are 3—3.8 μ in diameter, but the two species differ markedly by the manner of development and structure of the resting spores.

Except for *N. ramosa* and *N. sculptura* in which the resting spores are formed at the end of buds on pseudoparenchymatous intercalary enlargements, resting spore development in *N. multispora* is similar to that of the other species in that the spores develop by direct transformation of the enlargements into thicker-walled sructures in which numerous refractive globules have accumulated. However, in these other species resting spore production is sparse, and in *N. elegans,* particularly, they are rarely formed, according to the author's observations. In *N. multispora,* on the other hand, their development may occur so soon and abundantly that zoosporangia may be com-

paratively few or almost completely lacking. Sometimes strips of cellophane may contain almost nothing more than the tenous rhizomycelium and mature and developing resting spores (fig. 1). Usually, the resting spores are more abundant than is shown in figure 1. The sporangia usually occur at the edge of the cellophane, and immediately beneath is a relatively clear area of tenuous filaments, rhizoids and almost empty enlargements. Then follow inwardly the dense areas of resting spores.

The structure and appearance of the tenous portions of the rhizomycelium, intercalary enlargements, and sporangia are not specifically characteristic for *N. multispora.* The sporangia vary markedly in size and shape as indicated in the diagnoses above and fig. 1, and the majority of them develop long necks on cellophane. These may be endo- or exo-operculate. In light of Haskins (1950) and Haskin's and Weston's (1950) contention that the presence of endo-opercula is not a decisive criterion of whether or not a species is operculate, particular attention was given to the development and dehiscence of the sporangia of *N. multispora.* Most of the sporangia along the edge of cellophane strips were exo-operculate but quite a few were endo-operculate. In the latter, the development of the endo-operculum occurred in much the same manner as the author (1944, 1945, 1961) described it for *N. granulata, N. macrospora,* and *N. sculptura,* and in no instance was inoperculate dehiscence observed.

So far only one other species of *Nowakowskiella, N. ramosa* Butler, has been reported in India, but during this study several other aquatic polycentric species were isolated from brackish and non-brackish soils at sea level and up to an altitude of 4000 feet. These include:

Nowakowskiella elegans (Nowak.) Schroeter, 1893. Engler and Prantl, Natürlich. Pflanzenf. 1, (1): 82.

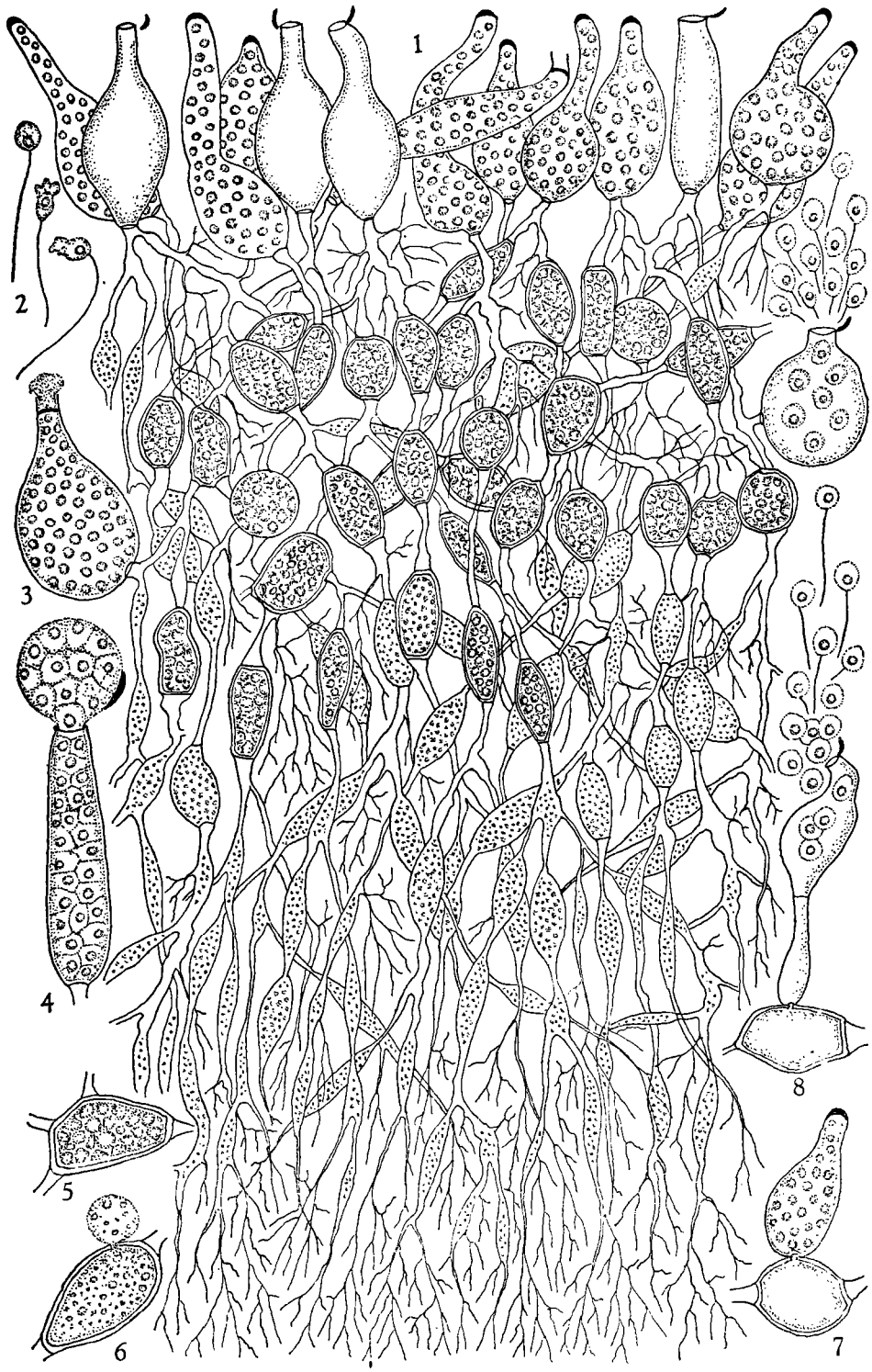
Cladochytrium elegans Nowakowski, 1876. (pro parte) in Cohn, Beitr. Biol. Pflanz. 2: 95, pl. 6, figs. 14—17.

Nowakowskiella endogena Constantineanu, 1901. Rev. Gen. Bot. 13: 387, fig. 83.

Saprophytic in bleached corn leaves, cellophane and fibrin film from dry non-brackish soil at Satur; 10 km., 30 km., and 60 km. south of Madurai along the Rhamnad Road, Virudunagar, and brackish soil at Mandapam Camp, Madras State. Also, this species occurred abun-

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Figs. 1—8. *Nowakowskiella multispora.* Fig. 1. Portion of thallus on cellophane; sporangia at edge of substratum, resting spores within. Fig. 2. Zoospores. Fig. 3. Endo-operculate sporangium. Fig. 4. Dehiscence of almost cylindrical sporangium. Fig. 5. Mature polyhedral resting spore filled with globules. Figs. 6, 7, 8. Germination stages of resting spores.


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dantly in soil collections in Ceylon, Thailand, Victoria Peak, Hong-Kong and Tokyo, Japan.

Nowakowskiella ramosa Butler, 1907. Mem. Dept. Agr. India, Bot. Ser..1: 141, p. 10, figs. 3—10.

Saprophytic in bleached corn leaves, cellophane and fibrin film, from non-brackish soil and water at Satur, Uttarakosamangai, Virudunagar, and Rhamnad, Madras State, and Calcutta, Bengal State. Resting spore development was unusually abundant in all of these collections.

Nowakowskiella elongata Karling, 1944. Bull. Torrey Bot. Club 71: 375, figs. 30—44.

Saprophytic in bleached corn leaves, from non-brackish soil in a dry catch basin 5 km. north of Rhamnad along the Rhamnad Road, Madras State.

Cladochytrium replicatum Karling, 1931. Amer. J. Bot. 18: 538, pls. 42—44.

Cladochytrium hyalinum Berda, 1941. Amer. J. Bot. 28: 425, figs. 1—84.

Both of these *Cladochytrium* spezies were trapped on bleached corn leaves and onion skin from soil in a tea estate 39 km. west of Munnar. Kerala State, at an altitude of about 3500 ft. It is significant that neither of these species were found in brackish soil where *N. elegans* was usually abundant.

Septochytrium variabile Berdan, 1942. Amer. J. Bot. 29: 461, fig. 2.

Saprophytic in bleached corn leaves, from non-brackish soil in a dry catch basin near Valantarvai along the Rhamnad Road, Madras State.

It is significant to note that none of these polycentric species developed prolifically on human fibrin film. Sporadic infections occurred, but the rhizomycelia developed only sparingly.

Summary.

Nowakowskiella multispora sp. nov. is characterized primarily by a minute zoospores and an unusually abundant production of resting spores. In addition to this species *Cladochytrium replicatum* Karling, *C. hyalinum* Berdan, *Nowakowskiella elegans* (Nowa.) Schroeter, *N. ramosa* Butler, *N. elongata* Karling, and *Septochytrium variabile* Berdan were isolated from soil and water samples in India.

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Blue Pigment of a Surface-living Oceanic Copepod

THE development of special nets has made it possible to sample specifically the plankton living in the uppermost layers of the sea. Routine sampling with such a net, designed by P. M. David at the National Institute of Oceanography, to fish only in the top 4 in. of the water, has been carried out during the present cruise of the R.R.S. *Discovery* in the Indian Ocean. One of the most striking features of the living hauls is the predominance of blue pigmented organisms, and these have been seen in a wide diversity of groups, among them copepods, mysids, decapods, stomatopod larvæ, siphonophores, chætognaths, salps, doliolids and appendicularians. The most typical members of the catch are pontellid copepods, and these show a blue colour more intense than most other groups. Since blue is a colour almost completely absent in deeper-living plankton, it was considered to be of interest to make a closer examination of this typical feature of the tropical surface plankton. Using the surface net it was possible to capture very large numbers of *Pontella fera* Dana and carry out a simple analysis of its pigment.

Three surface hauls were made in different regions and a few hundred *P. fera* were either picked out individually or, on one occasion when several thousands were caught, the other components of the catch were removed. Having separated animals of both sexes, excess water was removed on filter paper, and the animals were ground up with a little distilled water until a satisfactory homogenate was obtained. Further distilled water was added, and the suspension was centrifuged for 10 min at approximately 4,000 r.p.m. This caused a layer of solid carapace pieces to separate out at the bottom, above it a fatty layer, and above this an opaque blue liquid. This supernatant liquid was pipetted off and filtered through a Whatman No. 42 filter paper, the solids being discarded. The filtered liquid was a clear blue solution which was very stable on one occasion but rather more unstable on the two subsequent occasions, tending to precipitate out after some time. This is probably due to changes of *p*H occurring in the solution. The blue solution was examined in a spectrophotometer between 400 and 1,000 mμ using a 1-cm cuvette—the high organic content of the solution ruling out any useful examination in the ultra-violet region. The result is given in Fig. 1*A*, the curves being almost identical on each occasion, and showing a broad absorption band with a peak at about 640 mμ.

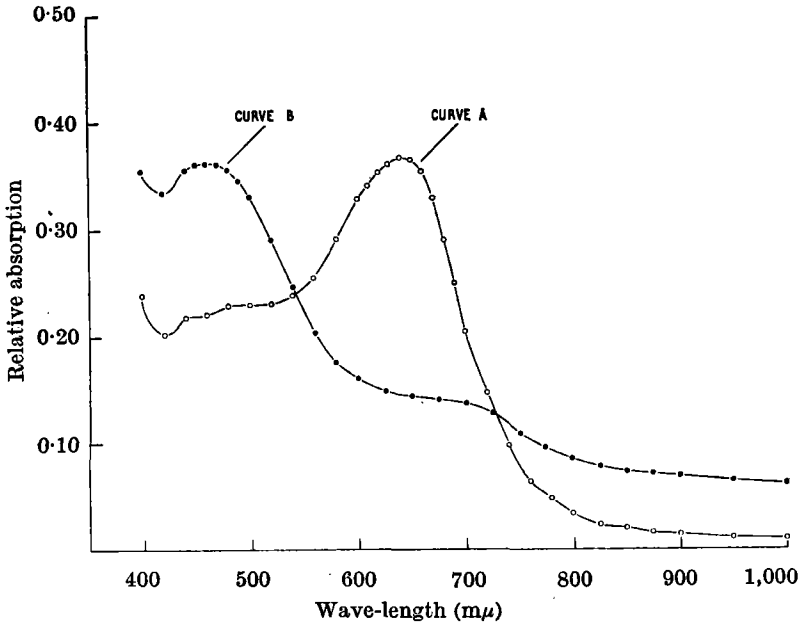


Fig. 1. Spectral absorption of the initial extract of blue pigment (curve *A*) and after treatment with citric acid (curve *B*)

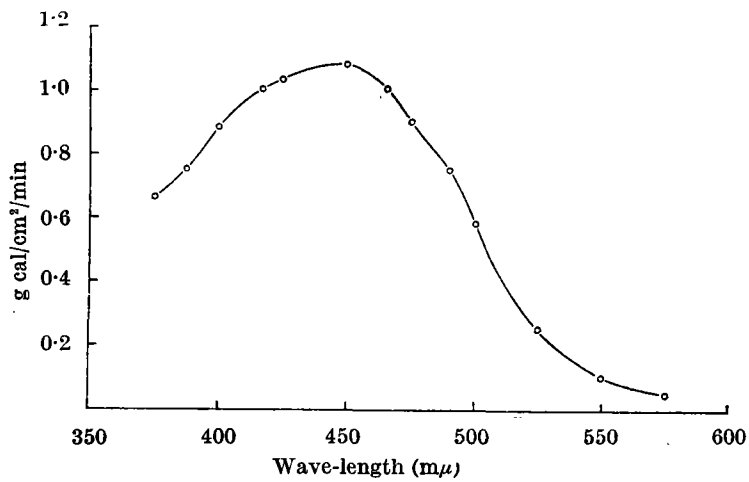


Fig. 2. Spectral energy curve of the upward illumination at the Swedish Deep Sea Expedition station 192 in the eastern Indian Ocean (after Jerlov)

The blue pigment is insoluble in ether, benzene and carbon tetrachloride, and treatment with these agents accentuates the peak but does not alter its position. Treatment of the blue pigment with alkali, organic or mineral acids, alcohol or acetone permanently decolorizes it, giving a reddish-yellow solution, the characteristic absorption curve of which is shown in Fig. 1*B*. The blue colour is similarly lost on heating the solution slowly to about 65° C. After freezing the solution, precipitation occurs when it is subsequently thawed. Passage through

activated charcoal completely removes the colour of the solution. When the pigment is allowed to decay by standing for a day or more there is a tendency for a transient greenish tinge to appear and the solution becomes cloudy.

It seems probable that the pigment is a chromoprotein complex of a carotenoid and a protein. This is suggested by its initial insolubility in fat solvents, the ease by which it is denatured, particularly when *p*H changes occur, and the fact that the peak absorption after denaturation (presumed to involve breakage of the carotenoid-protein link) is at 450–475 mμ, a region characteristic of the carotenoid pigments commonly found in planktonic animals. In the living animal the pigment appears to be uniformly distributed over the body, both in the exoskeleton and in the underlying epidermis. There are three main sites where it appears to be more concentrated, namely, the thickened grasping portion of the male right antenna, on the inside of the base of the first antennæ in both sexes, and over the ventral eye. The latter, particularly, appears deep blue, but dissection shows that a thickened layer of deep blue chitin overlies a red fat-soluble pigment spot.

The reason for the preponderance of blue in the tropical surface plankton is not immediately clear. The background colour of clear oceanic water is a deep blue, as can be seen from Fig. 2, showing the spectral energy of upward illumination at 2 m depth at the Albatross station 192 in the eastern Indian Ocean according to Jerlov[1]. It will be noted that the spectral transmission of the pigment is relatively high over the same region and only decreases at about 550 mμ, above which the background energy is exceedingly low. The pigment, therefore, transmits the ambient light with little wave-length change and the animal matches the background very well. This will only apply when it is viewed from above or from the side, but the main predators of surface-living copepods are probably flying-fish which are found at approximately the same horizontal level. Similarly, the blue of *Porpita* and other siphonophores may be a camouflage for the predator. This argument, however, would not seem to hold good for animals which are more usually transparent, for example, the chætognaths, stomatopod larvæ and doliolids. In some species, such as the copepods, it may be that there is an obligatory accumulation of carotenoids, the basic red colour of which is masked by the linkage with a protein so that the animal becomes much less conspicuous.

The diffuse distribution of the pigment in almost every case, and its appearance in widely separate taxonomic groups, makes it seem more likely that it is, as Heinrich[2] has suggested, a protection against the strong solar radiation to which the tropical surface plankton is exposed. The ultra-violet wave-lengths are generally considered as the most biologically harmful, but it is not known whether the blue pigments do strongly absorb these wave-lengths.

Though the penetration of the longer wave-lengths, particularly the infra-red, is very small, they may be an important factor in the top few inches of the surface of the sea, and the pigment with the peak absorption at 640 mμ would screen the organs from much of this energy. None of these explanations seems wholly satisfactory, however, and it is hoped that further work will make the reasons clearer. Preliminary work on another species of *Pontella* has given similar results and it is hoped to carry out further analysis of the pigment of this and other species of surface plankton.

I thank Mr. R. I. Currie and Mr. P. M. David for their interest and assistance in this work.

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SOUTHERN BLUEFIN TUNA POPULATIONS IN SOUTH-WEST AUSTRALIA

By J. S. HYND*

[*Manuscript received September* 17, 1963]

Summary

Length–frequency histograms of southern bluefin tuna caught for tagging and other purposes by F.V. *Estelle Star* in the course of survey operations showed heterogeneity in that the catches contained size groups, the differences between which could not be regarded as simply those to be expected between the age groups of a single stock. The times at which these groups appeared in the catches showed that the groups were characterized by distinct distributional behaviour, and this was confirmed by the results of the tagging operations. However, the groups are indistinguishable in their growth rate, so far as this has been shown by the present work, and no evidence is yet available as to the origins or status of these groups.

I. INTRODUCTION

From July 1961 to July 1962 the tuna fishing vessel *Estelle Star* operated under charter to the Australian Government in the coastal waters off south-western Australia. The objective of the survey was to locate commercial quantities of tuna, accessible either to trolling and poling vessels, or to longline vessels.

The principal species taken was southern bluefin. In all, about 6000 of these were trolled or poled but none was taken by longline. All were small immature specimens. The largest specimen measured 80 cm L.C.F. (length to caudal fork) and the smallest 33 cm. In most catches two size groups could be distinguished. Scales from 50 fish from the larger-size group were examined for growth rings; in 46 instances two rings were found, in two instances three rings, in one instance one ring, and in one the scales were unreadable. Scales from 16 fish from the smaller-size group all had one ring only. Hence, it was concluded that the larger-size group were 2+ age group fish and the smaller were 1+ age group fish. An attempt was made to construct an age–length curve following the Petersen method of tracing the progression of modes but it was found that length distributions within the 2+ age group were often bimodal. These distributions were subjected to further analysis.

II. SIZE CHARACTERISTICS OF THE POPULATIONS

(*a*) *Fish Taken in the Vicinity of Albany*

Most specimens (some 5000, odd) were taken between West Cape Howe and Bald I. in the months May, June, and July, 1962 (see Fig. 1 for these and other localities). The length frequencies of the 2+ age group of these specimens are given in Figure 2. The distribution of L.C.F. of fish taken on cruise 6 is unimodal, of fish taken on cruises 7 and 8 bimodal, and of fish taken on cruise 9 unimodal. Also the mode seen in cruise 6 data corresponds in location to the right hand modes seen in the data of cruises 7 and 8 while the mode seen in cruise 9 data corresponds to the

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left hand modes seen in the data of cruises 7 and 8. A plausible explanation of this disposition of modes is that two distinct groups of fish were present, one replacing the other over the period of the observations.

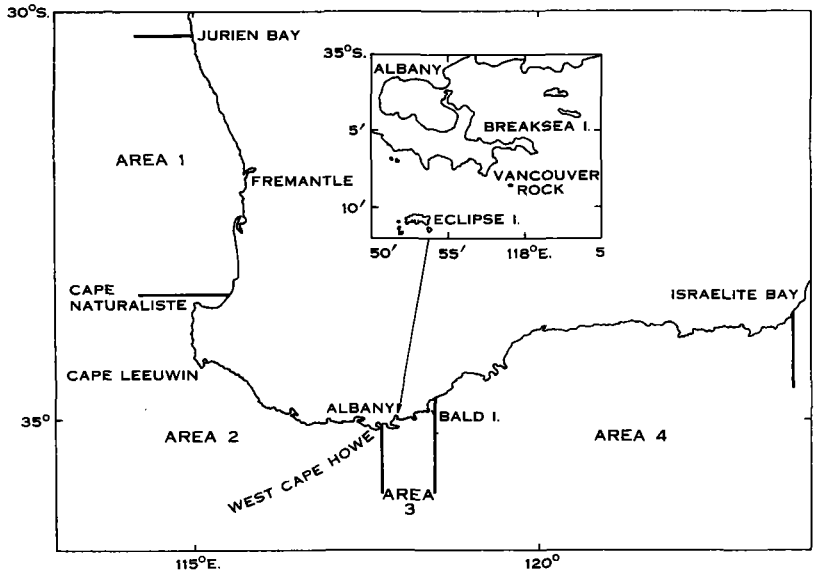


Fig. 1.—Areas into which the survey area was divided for record purposes.

On the last 2 days of cruise 9 (July 4 and 5, 1962) 1295 fish were taken. These fish were located in the vicinity of Vancouver Rock in an area less than 1 square mile. Their length frequencies are plotted in Figure 3. Inspection shows a near

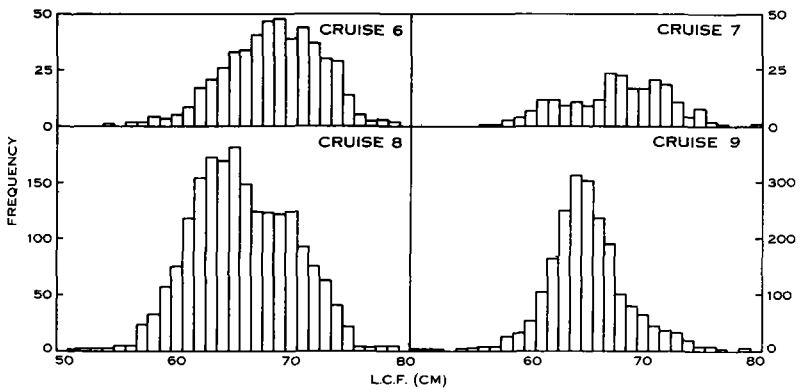


Fig. 2.—Length–frequency histogram of the L.C.F. of the 2+ age group of southern bluefin tuna taken by F.V. *Estelle Star* in the vicinity of Albany, W.A. (West Cape Howe–Bald I.) on cruises 6–9, inclusive, 1962.

symmetrical bell-shaped distribution with mode of 65 cm. Mean and standard deviation were 64·91 cm and 3·34 cm, respectively. A normal curve was fitted and is shown in Figure 3. The observed distribution was found to differ from the expected (normal) distribution at the 0·1% level. The major contribution to χ^2 derived from

the fact that the observed distribution is leptokurtic with respect to the normal, the contribution from the high observed frequencies in the 73 and 74 cm class intervals being negligible. Therefore, the distribution of L.C.F. in the parent population is fundamentally symmetrical, leptokurtic with respect to the normal, and has estimated parameters of mean 64·91 cm, standard deviation 3·34 cm, and 95% confidence range (1·96 times S.D.) ±6·56 cm about the mean.

Applying these criteria of homogeneity to the histograms in Figure 2 the distributions of L.C.F. in the populations from which fish were taken on cruises 6, 7, and 8 are seen to be widely different from that in the population fished on cruise 9 on July 4 and 5, 1962.

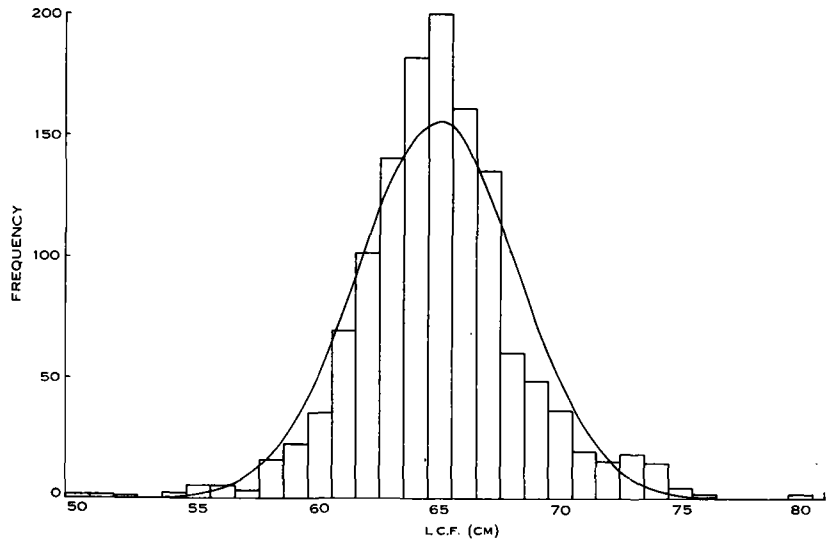


Fig. 3.—Length–frequency histogram of the L.C.F. of the 2+ age group of southern bluefin tuna taken by F.V. *Estelle Star* around Vancouver Rock, W.A., on July 4 and 5, 1962. The curve shown is the normal curve fitted to the data.

To investigate this difference further, frequency histograms of catches taken on single days or groups of not more than 3 consecutive days separated by approximately weekly intervals were constructed. These histograms are shown in Figures 4*a*–4*i*. The distribution in Figure 4*a* is practically identical with that in Figure 3. In Figures 4*b*–4*d* inclusive, the distributions are, in general, right skewed with the same mode as in Figure 4*a*. Figures 4*e* and 4*f* show approximately symmetrical flat-topped distributions with appreciably higher means than that of Figure 4*a*. In Figures 4*h* and 4*i* the distributions are left skewed with modes at approximately 70 cm. This sequence of length–frequency distributions is consistent with the hypothesis that at the beginning of the investigation period two distinct groups of fish were present in the area; that their modal sizes were approximately 70 and 65 cm; that the group with the greater modal size outnumbered the other by 3 or 4 to 1; and that over the period of the investigation the numbers of the larger-size group decreased relative to those of the smaller-size group until finally only the smaller-size group was present.

These fish were all taken from an area of approximately 30 square miles lying between Breaksea I. and Eclipse I. Vessel movements were such that the whole of

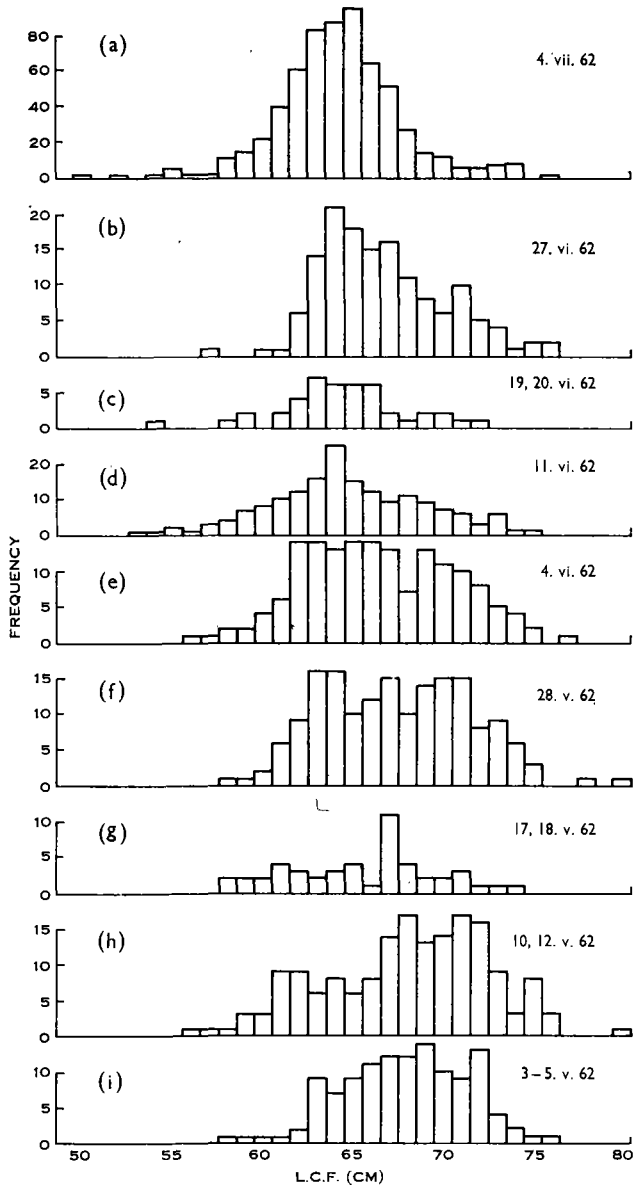


Fig. 4.—Length-frequency histograms of the 2+ age group of southern bluefin tuna taken by F.V. *Estelle Star* in the vicinity of Albany, W.A. (Eclipse I.–Breaksea I.) in May, June, and July, 1962. The data were selected to show the size composition at approximately weekly intervals.

the area investigated was covered each day, effort being concentrated in places where schools were located. Investigations of the composition of individual schools (as judged by the lengths of the fish taken from them) showed that except at the end

of the period of investigation fish from both groups schooled together. Thus, the observed sequence of length–frequency distributions could not have arisen by fortuitous application of fishing effort to schools composed of fish segregated by size within the area.

Confirmation of this hypothesis of replacement of one group of fish by another comes from the results of the tagging programme carried out in connection with the survey. In all, 241 fish measuring more than 70 cm L.C.F. and therefore belonging almost certainly to the larger-size group were tagged and released during cruises 6 and 7. Nine were recovered by June 11, one more on June 24, but none between June 25 and July 7 when tagging ceased. In contrast, 69 of the other tagged fish at large in the area were recovered between June 25 and July 7. The average number at large during this period, assuming no mortality and no emigration, was 3905. Therefore, the expected number of recaptures from the 241 fish of the larger-size group is:

$$(69 \times 241)/3905 = 4{\cdot}258.$$

The difference between this and the observed value of zero is significant at the 1 % level.

This low return from the larger-size group could be due either to relatively higher mortality following on the tagging operation, greater loss of tags by shedding, or emigration from the fishing area. Schaefer, Chatwin, and Broadhead (1961) investigated mortality in yellowfin and skipjack following on tagging. They considered this mortality as consisting of an initial, short-term mortality operating in a matter of hours or at most days, and long-term mortality (including loss of tags) operating over a period of months or years. For yellowfin, short-term mortality was found to be of the order of 80 % and long-term mortality of the order of 5 % per year. In the present experiment short-term mortality will have operated equally on all fish except perhaps for the last few hundred tagged, and hence should not have produced differential survival in the two groups. Apart from tag losses, long-term mortality could have arisen from increased predation (e.g. through slower movement of the tagged fish or attractiveness of the tag) and increased susceptibility to disease. Evidence is that the effects of these were slight or absent.

Fish newly released appeared to swim normally though somewhat faster than usual. Some were observed to rejoin the school around the stern of the boat. (In subsequent experiments conducted under similar conditions two tagged fish were recaptured less than 20 sec after release.) Towards the end of the experiment, schools of fish attracted to the boat by live bait were observed to contain an appreciable proportion of tagged fish. It is thus evident that the tagging operation did not produce any obvious change in swimming power or behaviour. Robins (1963, p. 570) lists sharks, dolphins, and seals as predators of southern bluefin. None of these animals were observed in the area where bluefin were being caught. Some tags in recaptured fish were found to be relatively loose in the flesh though still held by the barb. This indicates that some tag loss by shedding might have occurred. However, evidence from double tagging experiments (Hynd, unpublished data) shows that this loss is negligible in the first month and can therefore be ignored in this case. Tag wounds in fish with loose tags were not observed to be heavily infected. In view of all these

facts it is inferred that the low return from the larger-size group was due to emigration from the fishing area, this emigration being substantially complete by June 25.

Thus the evidence is conclusive that two distinct groups of 2+ fish were fished during the period May 3–July 4 in the area between Breaksea I. and Eclipse I. These groups differed in their size distributions and behaviour patterns. Parameters of the size distribution of the smaller-size group are given above. Corresponding parameters cannot be estimated with the same accuracy from these data for the larger-size group

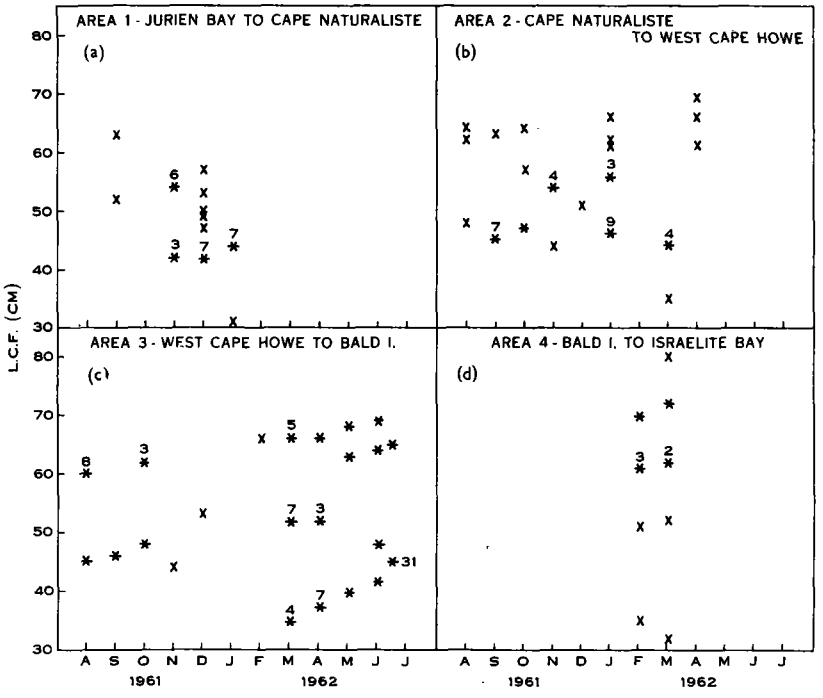


Fig. 5.—Length–frequency distribution of southern bluefin tuna in Western Australia. Data from F.V. *Estelle Star* cruises 1961 and 1962. An asterisk indicates the modal size of a group of 10 or more specimens; an asterisk with superscript indicates mean length of a group with no prominent mode; the superscript shows the number of specimens; ×, individual lengths.

since this group was always mixed with the smaller-size group whenever it was sampled. However, the modal value was approximately 70 cm and judging from the slope of the right hand side of the frequency distributions in Figures 4*e*, 4*f*, 4*h*, and 4*i*, the standard deviation and therefore 95% confidence limits are of the same order of magnitude as those of the smaller-size group. For identification purposes the group with the larger modal size is designated "W.A. Group I" and that with the smaller modal size "W.A. Group II".

The length–frequency distributions of the 1+ age group taken in the vicinity of Albany in the months May, June, and July were also examined. Numbers involved were small but, nevertheless, two modes were detected in June.

Having determined that two different groups of fish were present during May, June, and July, attention was then directed to the length–frequency distributions of fish taken in the other 9 months. Figure 5*c* shows the modal sizes or mean lengths of the various groups month by month. The two groups distinguished above appear at top right, bottom right, and bottom left of the figure. The remaining points at right centre and top left represent a third group quite distinct from the other two. For identification purposes this is called "W.A. Group III".

(*b*) *Fish Taken other than in the Vicinity of Albany*

Figures 5*a*, 5*b*, and 5*d* show the modal sizes or mean lengths of the various groups of fish taken in the areas Jurien Bay–Cape Naturaliste, Cape Naturaliste–West Cape Howe, and Bald I.–Israelite Bay, respectively. The data are somewhat scanty but suggest that all three groups are present in all areas at one time or another during the year.

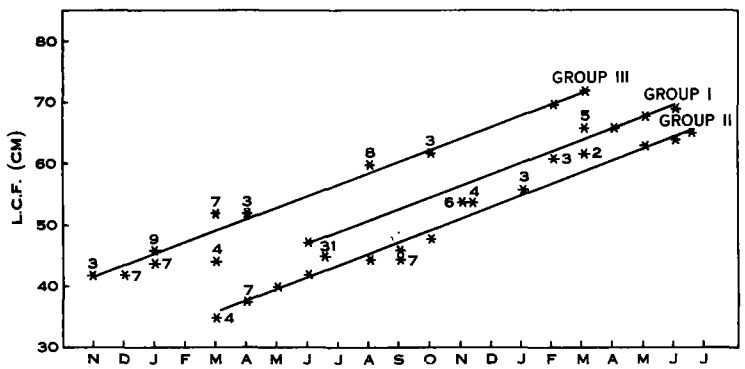


Fig. 6.—Modal lengths, month by month, of the three Western Australian groups of southern bluefin tuna (symbols as for Fig. 5).

III. Growth Rates

The relation between modal length and time of year for each group is shown in Figure 6. This figure was obtained by combining the data of Figures 5*a*–5*d*, omitting single measurements and plotting 1+ fish 12 months to the left of 2+ fish. Parallel straight lines have been fitted by eye to each set of data and give reasonably good representation of the growth.

IV. Discussion

The question we now ask is—what status should these groups be given? Figure 6 shows that from just over 1 to nearly 3 years of age the growth rates of the three groups are identical. It is unlikely that there would be major differences in growth rate during the first year so it may reasonably be assumed that each group is the result of a separate spawning. These spawnings could be repeated spawnings of the one stock or single spawnings of three stocks or some combination of these. Robins (1963, p. 571) states that there are at least two breeding peaks in the one spawning

season in the Indian Ocean off the west coast of Australia and infers (op. cit., p. 568) that there is another spawning in eastern Australian waters. Whether this is the correct solution or not will probably be decided if and when some of the fish tagged are recovered in the Japanese longline fisheries in the Indian Ocean and the Tasman Sea.

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DYNAMICS OF TWO POPULATIONS OF THE HUMPBACK WHALE, *MEGAPTERA NOVAEANGLIAE* (BOROWSKI)

By R. G. CHITTLEBOROUGH*

[*Manuscript received November* 22, 1963]

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Summary

Results of studies of the structure and dynamics of two humpback whale stocks of the southern hemisphere (group IV, 70°E.–130°E.; group V, 130°E.–170°W.) are drawn together. Estimates are made of recruitment and mortality rates, and an assessment is made of the yields to be taken from these stocks under various conditions.

The two stocks are shown to be, in the main, independent of one another although there is a negligible sporadic exchange between them. The group V stock is shown to fragment, but probably randomly, in its northern migration.

Reproduction, nutrition, and growth are described. Birth rate of females is estimated to be 0·186, and since the sex ratio is approximately 1, the total birth rate is about 0·37. Parameters (von Bertalanffy) for growth are L_∞ 42·58 ft for males, 45·21 ft for females; $k♂ = 0·266$, $k♀ = 0·205$.

The history of exploitation is reported.

Population structure is described from evidence drawn from examination of commercial catches; substantial changes in recent years (reduction of the numbers in older groups) are described.

Measurement of effort, and an analysis of variations in selectivity of the killings are reported in detail.

Decline in the abundance of these groups, group IV steadily since 1954 and group V sharply since 1959, is described.

Total mortality, natural mortality, fishing mortality, and recruitment rates are estimated and are used in estimating stock numbers and sustainable yields. The group IV stock probably consisted of 12,000–17,000 individuals in its unfished state, of about 10,000 individuals in 1949, and no more than 800 in 1962. The group V stock probably contained about 10,000 individuals in its unfished state, but only 500 or less in 1962. In its present state, group IV could give a sustainable yield of 18 (range 4–32) whales, and group V of 12 (range 3–21) whales. The maximum yields these stocks could sustain in completely regenerated state are: group IV, 390 whales per year; group V, 330 whales per year. Group IV would require 28–49 years to reach that state, group V would require 36–63 years.

I. Introduction

(*a*) *Objectives*

When postwar whaling was re-opened on the Australian coast, in 1949 on the west coast, and in 1952 on the east coast, a programme of research was commenced upon the two populations of humpback whales being fished. While the ultimate objectives of this research were the estimation of population size and assessment of maximum yields under various exploitation regimes, the parameters of the populations first had to be determined. Information concerning some of these parameters, i.e. migration, reproduction, age, growth, and population structure, has already appeared in various publications to which reference will be made in the relevant sections.

The present paper brings together all the available data (both published and unpublished) relating to these two populations, to measure the parameters more precisely, and to assess stock sizes and maximum yields at various levels of fishing.

(*b*) *Material*

(i) *Commercial Catches*

Apart from a few specimens killed under special licence for research purposes, material for the study of these populations has been obtained from humpback whales killed during commercial whaling operations. These operations were centred

around shore-based whaling stations at Point Cloates, Carnarvon, and Albany on the west coast, at Tangalooma (Moreton I.), and Byron Bay on the east coast of Australia, at Norfolk I., and in Cook Strait, N.Z., the locality of each station being shown in Figure 1. Catches of humpback whales were also taken by whaling fleets operating in Antarctic waters to the south of Australia and New Zealand.

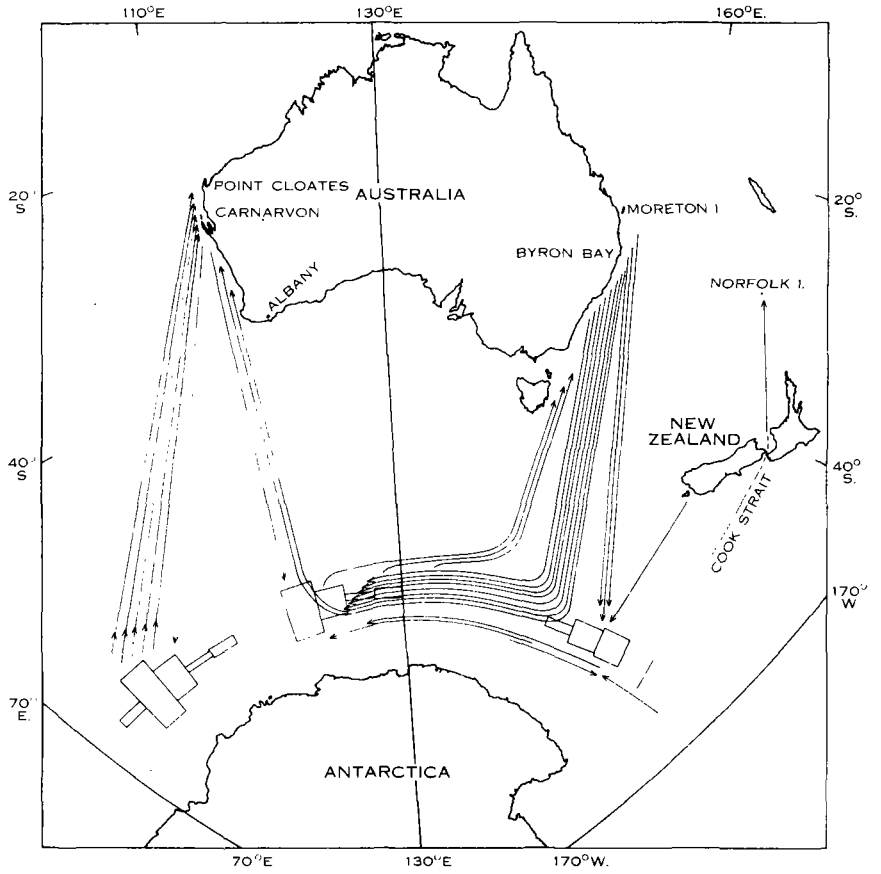


Fig. 1.—Individual movements (simplified) by 27 marked whales whose recapture provided evidence of migrating behaviour in 1958–59. Rectangles indicate location of Antarctic humpback whale catch in February 1959.

Commercial catches of whales are seldom (if ever) random samples of the populations from which they were drawn; in this case the following factors were of importance in the relationship between the commercial catch and the population.

The minimum legal length (35 ft) renders the young whales invulnerable to commercial operations. This regulation does not impose a knife-edge selection of the whales to be killed. Varying degrees of selectivity are applied by individual gunners. The level of selection may vary with the abundance of whales. When whales are plentiful, individuals of approximately 36 or 37 ft may be approached but passed by in favour of larger specimens.

The method and level of catch limitation may influence the degree of selection applied by gunners. In waters south of 40°S., where an overall catch limit has been applied, the competition for catch in the short season permitted has left little time for discriminating between whales, with the result that there has been very little selection of large whales. Each expedition has competed for the greatest proportion of the total limit. The allocation of separate quotas to each Australian station reduced the competition between these stations so that they could afford to be selective. Gunners were encouraged to take large whales so that the highest possible

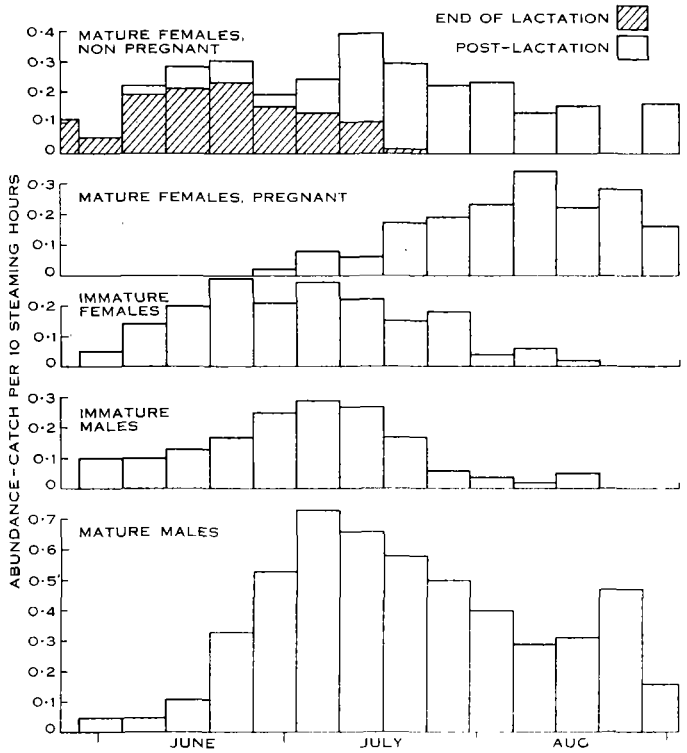


Fig. 2.—Abundance (at weekly intervals) of various categories of humpback whales during northward migration past Albany (35°05'S.).

yield of oil could be obtained from the allotted quota. In some instances, gunners were offered bonus payments based on the lengths of the whales killed. On occasion, gunners have been instructed to take (where possible) only whales exceeding 40 ft in length. The allocation of separate quotas to each Australian station led to some competition between stations for the highest average oil yield per whale killed.

A change in the quota can result in a change in the level of selection; for example, a reduction in the quota is likely to lead to the average size of the catch being somewhat higher than it would have been if the quota had remained unchanged, provided there are sufficient whales from which to select.

The protection of female whales accompanied by calves imposes another type of selection, a considerable proportion of the mature females being invulnerable at most times since lactation continues for nearly 11 months. Calves are weaned

in June and early July (Chittleborough 1958*c*), such females and their "yearling" offspring being amongst the first to reach the Australian coast during the northward migration (Fig. 2). Although there is little doubt that the " yearling" offspring could survive even if its parent was killed just prior to, or during weaning, interpretation of the regulation protecting lactating females has varied from station to station and from year to year. At some stations, gunners have spared females accompanied by yearlings, or have taken these females only when no other whales could be found. Lactating females would then be absent, or under-represented in the commercial catch.

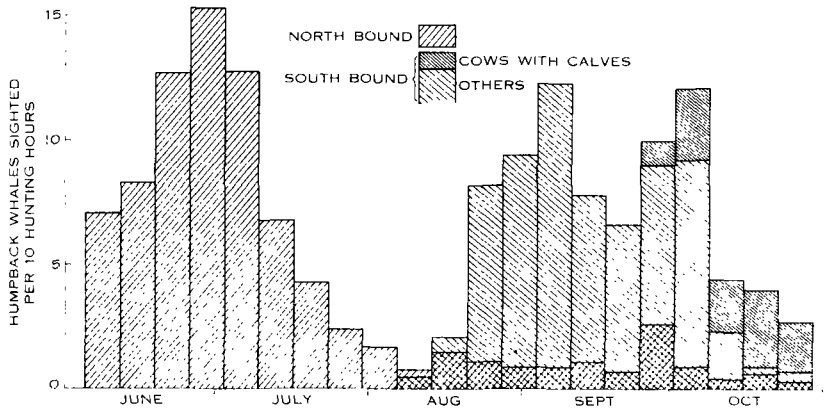


Fig. 3.—Average weekly density (sightings per unit effort) of humpback whales migrating north and south on the east coast of Australia in the vicinity of 28°S. latitude during 1961.

At Australian whaling stations the availability of whales changes as the migrating stream passes during the northward and southward migrations (Figs. 3 and 4). Within the migrating stream there is some segregation of the various categories of humpback whales (Fig. 2). The period of commercial operations is then of importance to the question of whether the commercial catch samples the population fully. A whaling station with a small quota might fill its quota rapidly by operating only during the height of the migration past that station, and in consequence the beginning and end of the migrating stream might not be sampled.

On the other hand, an increase in the quota could extend the season so that a much more intensive effort would be required in order to locate sufficient whales. The station in Cook Strait, N.Z., has not been limited by a quota, and operated throughout the period of (northward) migration every year, so that its catch could be expected to have been more representative of the accessible population than the catches taken by stations operating under more restrictive conditions.

Commercial catches may vary in composition from one locality to another. For example, during the northward migration, pregnant females are carrying near-term foetuses, and the majority give birth soon after reaching the vicinity of 35°S. Thus the catches at the more southerly stations, such as that at Albany, Western Australia, and at Cook Strait, N.Z., include high proportions of pregnant females in their catches. By the time these females pass the more northerly whaling stations, most are lactating and are, therefore, protected.

Since all factory ships and shore stations are required to send details of their catches to the Bureau of International Whaling Statistics, the records of humpback whales taken from these populations in recent years should be complete. However, there is evidence that not all catches of humpback whales taken in recent years have been reported to International Whaling Statistics.

During the summer of 1954–55, the factory ship *Olympic Challenger* apparently slaughtered humpback whales in the Antarctic without regard for the time of open season, or the minimum legal length. The Panamanian whaling inspectors on board attempted to cover these infringements by submitting falsified statistics of catches

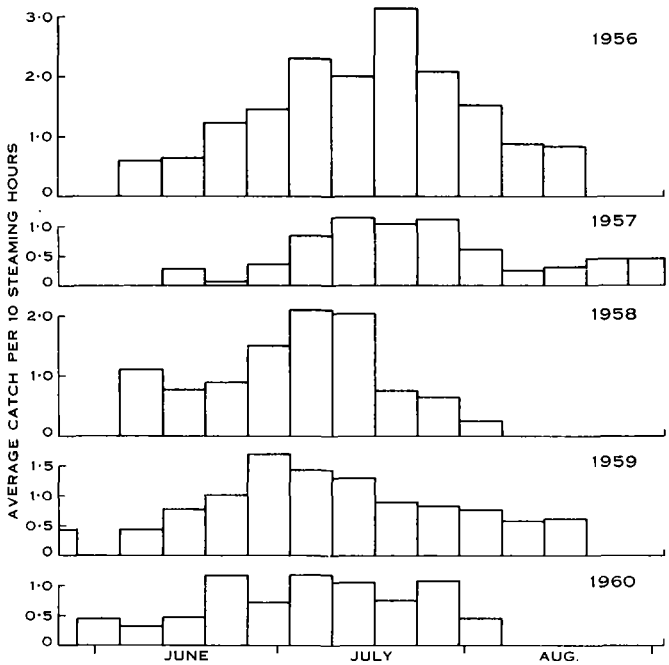


Fig. 4.—Relative abundance (catch per unit effort) of catchable humpback whales each week off Albany (35 °S.); northbound migration.

to the Bureau of International Whaling Statistics (Ruud 1956). In all, 1097 humpback whales were taken from the group V population, but 170 were reported to International Whaling Statistics, and 28 were taken from the group IV population although none was reported. These illegal catches are included in the total catches listed in Tables 1 and 2. There are grounds, reported later, for believing the records to be incomplete in other respects.

(ii) *Sampling of Catch*

Whaling inspectors on each shore station and Antarctic factory ship are required to record, with respect to each whale in the catch, the date and location of killing, the sex and total length, and in the case of females, the presence or absence of milk, and the sex and length of foetuses. These data are available for all humpback whales reported to the Bureau of International Whaling Statistics as having been taken from the group IV and V populations since 1949.

At Australian whaling stations further material and data were collected from humpback whales by the author, other members of CSIRO, and the whaling inspectors. The most important of these items were the gonads and ear plugs required for studies of reproduction and age determination. The numbers of these collected in each year, and the percentage of the catch sampled for these organs, are shown in Table 3. Efforts were made to avoid bias in the sampling of the catches. During the earlier years most of the collections were made by a few research staff, seldom more

TABLE 1

HUMPBACK WHALES OF THE GROUP IV (70°E.–130°E.) POPULATION

Catches reported from 1949 to 1962

Year	Australian Shore Stations (quotas in parentheses)						Antarctic (pelagic)	Total Recorded Catch
	Point Cloates (22° 35′S., 113° 40′E.)		Carnarvon (24° 53′S., 113° 38′E.)		Albany (35° 05′S., 117° 56′E.)			
1949	(600)	190					0	190
1950	(600)	348	(600)	40			779	1167
1951	(600)	574	(650)	650			1112	2336
1952	(600)	536	(600)	600	(50)	51	1127	2314
1953	(603)	603	(600)	600	(100)	100	193	1496
1954	(600)	600	(600)	600	(120)	120	258	1578
1955	(500)	500	(500)	500	(126)	126	28*	1154
1956	Transferred to Carnarvon		(1000)	1000	(120)	119	832	1951
1957			(1000)	1018	(120)	102	0	1120
1958			(1000)	885	(120)	82	0	967
1959			(1000)	541	(175)	159	1413†	2113
1960			(750)	440	(120)	105	66	611
1961			(475)	475	(105)	105	4	584
1962			(540)	503	(100)	40	56	599
Total	West coast of Australia, 12,312						5868	18,180

* Reported as being killed illegally by F. F. *Olympic Challenger*.

† Redistributed after considering intermingling of populations IV and V (Chittleborough 1959).

than one member at a particular whaling station, so that it was not possible to examine all whales. Generally, whales processed during daylight and early evening were examined, without any preference being given to any particular category of whale. In recent years, the close cooperation of whaling inspectors has made it possible to examine the majority of the whales caught.

The length frequency distribution of the whales examined generally did not differ significantly from the length frequency distribution of the catch from which the sample was taken, indicating that a representative sample of the catch had been taken. The ear plugs of the small whales were often soft and more difficult to remove intact than those of large whales. Consequently, the samples of ear plugs were less

representative of the small whales (those less than 39 ft in length) as shown in Figure 5. This bias did not reach significant levels, except for the male ear plugs sampled on the east coast of Australia during 1961 (Fig. 5). In this case the length frequency distribution of the sample aged from ear plugs differed at the 1% level from that of the total catch of males.

Because of the difficulty of collecting ear plugs from the small (young) whales, the distribution of ages in the sample should not be stepped up by a constant ratio (total catch : number in sample) in order to obtain the distribution of ages in the

TABLE 2

HUMPBACK WHALES OF THE GROUP V (130°E.–170°W.) POPULATION

Catches reported from 1949 to 1962

Year	Australian Stations (quotas in parentheses)						New Zealand	Antarctic (pelagic)	Total Recorded Catch
	Tangalooma (27° 11′S., 153° 23′E.)		Byron Bay (28° 37′S., 153° 38′E.)		Norfolk I. (29° 01′S., 167° 58′E.)				
1949							141	0	141
1950							79	903	982
1951							111	162	273
1952	(600)	600					122	146	868
1953	(700)	700					109	504	1313
1954	(600)	598	(120)	120			180	0	898
1955	(600)	600	(120)	120			112	1097*	1929
1956	(600)	600	(120)	120	(150)	150	143	194	1207
1957	(600)	600	(121)	121	(120)	120	184	0	1025
1958	(600)	600	(120)	120	(120)	120	183	0	1023
1959	(660)	660	(150)	150	(150)	150	318	885†	2163
1960	(660)	660	(150)	150	(170)	170	361	931	2272
1961	(660)	591	(150)	140	(170)	170	80	293	1274
1962	(600)	68	(150)	105	(170)	4	32	0	209
Total	Australia, 8307						2155	5115	15,577

* Reported as being killed illegally by F. F. *Olympic Challenger*.

† Redistributed after considering intermingling of populations IV and V (Chittleborough 1959).

whole catch. The best estimate of age distribution of the whole catch is obtained by applying the age to length key, derived from the sample, to the length frequency distribution of the whole catch. This technique has been applied in the estimation of age distribution of all catches from these populations (see Section V (*c*)).

(iii) *Treatment of Material*

Accounts have already been given of the methods used for the examination and interpretation of ovaries (Chittleborough 1954), testes, vertebral epiphyses (Chittleborough 1955), ear plugs, and baleen (Chittleborough 1959*c*).

In the description of ovarian changes, Chittleborough (1954) stated, with little supporting evidence, that Graafian follicles exceeding 30 mm in diameter were approaching ovulation. As this is an important criterion in distinguishing phases within the reproductive cycle, further corroboration is given in Figure 6

TABLE 3

SAMPLES OF GONADS AND EAR PLUGS COLLECTED FROM AUSTRALIAN HUMPBACK WHALE CATCHES

West coast of Australia (group IV population)

Year	Males					Females				
		Testis Weight		Ear Plugs			Ovaries		Ear Plugs	
	Total Catch	Number	Percentage of Catch	Number	Percentage of Catch	Total Catch	Number	Percentage of Catch	Number	Percentage of Catch
1949	135	0	—	0	—	55	27	49·1	0	—
1950	250	0	—	0	—	137	32	23·4	0	—
1951	907	395	43·6	0	—	310	92	29·7	0	—
1952	666	161	24·2	0	—	516	278	53·9	0	—
1953	726	111	15·3	0	—	572	246	43·0	0	—
1954	692	7	1·0	0	—	617	150	24·3	0	—
1955	581	0	—	0	—	543	8	1·5	0	—
1956	676	110	16·3	32	4·7	443	279	63·0	12	2·7
1957	583	488	83·7	182	31·2	536	521	97·2	187	34·9
1958	509	439	86·2	233	45·8	458	438	95·6	219	47·8
1959	331	254	76·7	179	54·1	369	353	95·7	221	59·9
1960	271	208	76·8	139	51·3	274	263	96·0	155	56·6
1961	306	291	95·1	217	70·9	272	263	96·7	195	71·7
1962	304	280	92·1	186	61·2	239	230	96·2	134	56·1
Total	6937	2744		1168		5341	3180		1123	

East coast of Australia and Norfolk I. (group V population)

1952	449	233	51·9	—	—	150	104	69·3	—	—
1953	509	200	39·3	—	—	191	121	63·4	—	—
1954	511	298	58·3	—	—	207	148	71·5	—	—
1955	494	37	7·5	—	—	226	118	52·2	—	—
1956	577	190	18·0	—	—	293	195	66·6	—	—
1957	585	267	45·6	204	34·9	256	198	77·3	94	36·7
1958	574	205	35·7	93	16·2	266	121	45·5	57	21·4
1959	633	273	43·1	236	37·3	327	252	77·1	125	38·2
1960	592	319	53·9	276	46·6	388	282	72·7	198	51·0
1961	572	569	99·5	379	66·3	329	304	92·4	197	59·9
1962	103	103	100·0	79	76·7	74	73	98·6	53	71·6
Total	5599	2698		1267		2707	1916		724	

which shows the diameter of the largest follicle in 938 female humpback whales taken off the west coast of Australia from June to October. The modal diameter of 20 mm, characteristic of immature females, as well as of those in anoestrus and

metoestrus is clearly illustrated. A second peak at a follicle diameter of 42–45 mm which is shown in the results from mature (non-pregnant) females which did not carry a newly ruptured follicle nor a recently formed corpus luetum, was not present in the histogram for females which had recently ovulated. Maturation of a follicle

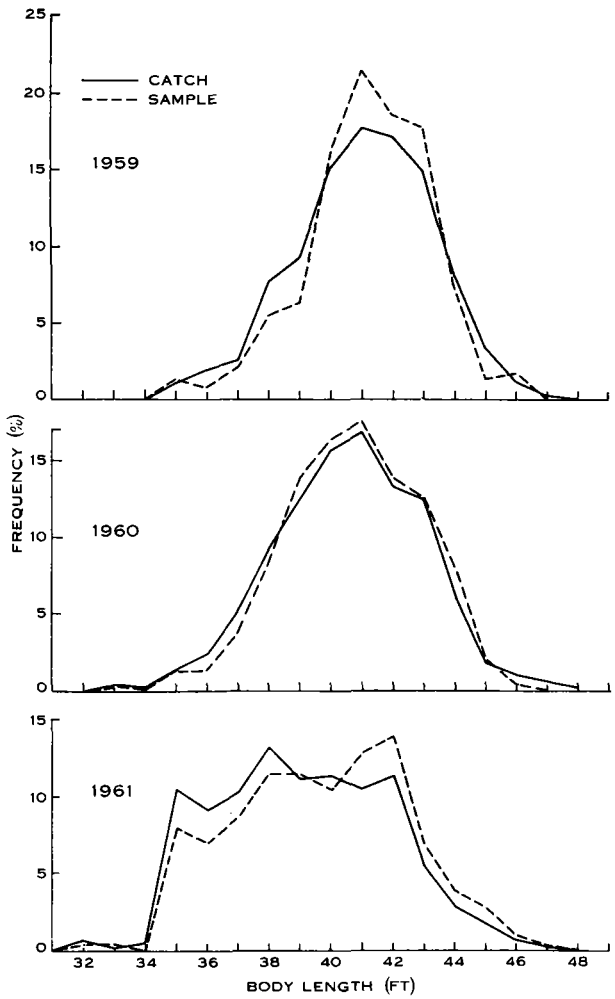


Fig. 5.—Male humpback whales from the east coast of Australia, 1959–61. Length frequency distribution of catch and of sample aged from ear plugs.

from the resting (anoestrous) phase is apparently a rapid process, as there are few follicles from 27 to 36 mm in diameter (Fig. 6*b*). Females carrying a follicle exceeding 30 mm in diameter are approaching ovulation. On this basis, some of those females included in Figure 6*a* as immature, were in fact diagnosed as pubertal females killed during their first pro-oestrus.

II. Identity of Populations

(*a*) *Geographic Limits, Ranges, and Migrations*

As reviewed by Mackintosh (1942), five more or less self-contained populations of humpback whales have been recognized in the southern hemisphere. Two of these are accessible to Australian shore-based whaling stations.

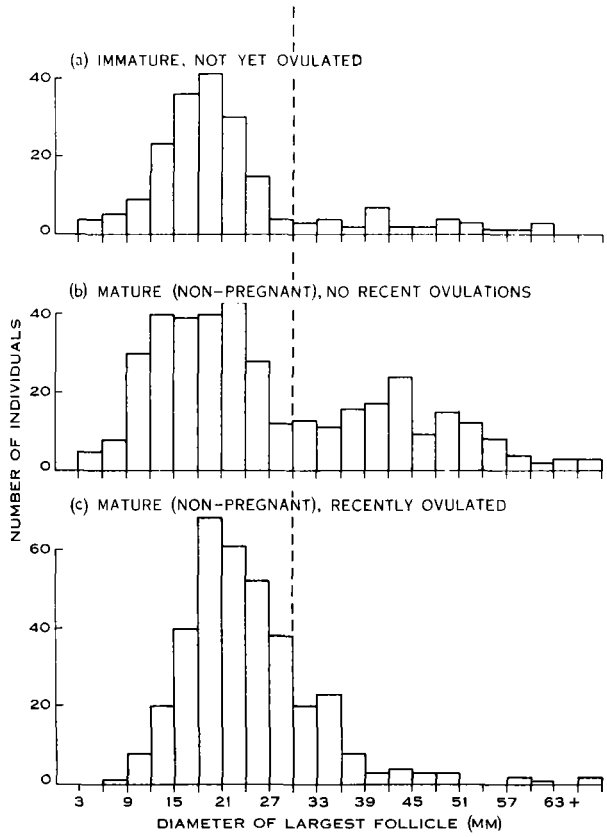


Fig. 6.—Diameter of largest Graafian follicle in each of 938 female humpback whales taken on the west coast of Australia between June and October.

Humpback whales which spend the winter months off the west coast of Australia, and the summer months concentrated in Antarctic waters in the vicinity of 80°E.–110°E. are known as the group IV population. The migration of these whales between the summer feeding grounds and the winter breeding grounds has been amply demonstrated by recapture of marked whales (Rayner 1940; Chittleborough 1959*a*). The meridional limits of this population are given as 70°E. and 130°E., but these cannot be regarded as rigid boundaries.

Humpback whales which in the summer months are concentrated in the Antarctic in the vicinity of 150°E.–180°E., and which migrate in the autumn to the east coast of Australia (Chittleborough 1959*a*) and the islands in the south-west

Pacific Ocean (Dawbin 1959), comprise the group V population. The meridional limits of this population are given as 130°E and 170°W., but there is some doubt as to the eastern limit of this range.

During the winter (breeding) season the majority of these humpback whales reach 20°S. latitude; Dawbin (1956) considers that most of the group V population reach 15°S. However, there is no particular latitude along the west and east coasts of Australia where migration ceases and breeding commences. Some individuals may migrate north of 10°S., while a few (late in their northward migration) may not reach 30°S. Parturition has been recorded as far south as Albany (35°S.); such females continue to move northwards during the first few weeks of lactation.

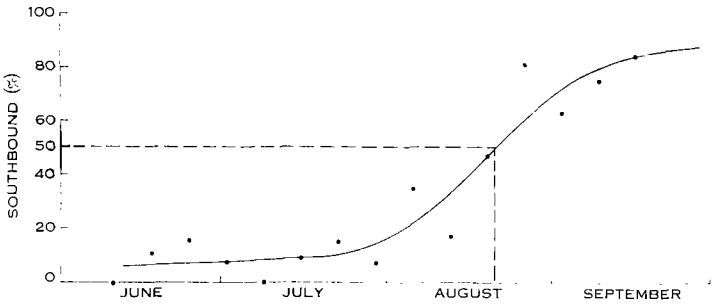


Fig. 7.—Proportions of southbound humpback whales in weekly sightings from the spotting aircraft operating from Point Cloates in 1953.

A few of those in the extreme vanguard of the northward migration may reach the Australian coast in April but the main part of the north-bound stream arrives in June. Figure 3 shows that on the east coast of Australia (in 1961) most of the north-bound humpback whales passed 28°S. latitude during June and July, while a few stragglers were still making their way northwards as late as October. The south-ward migration took place mainly from the latter part of August until mid-October. The mid-point (in time) between the northward and southward migration (in that year) was close to August 15.

The group IV population migrates along the west coast of Australia at times similar to those at which migration occurs on the east coast. The northward migration past Albany (35°S.) is shown in Figure 4 (humpback whales do not pass Albany on their southward migration). At Point Cloates (22½°S.), the point in time mid-way between the northward and southward migration was close to August 24 in 1952 (Chittleborough 1953), and August 20 in 1953, as shown in Figure 7.

The time at which the migrating stream of humpback whales passes a particular locality varies slightly from year to year, as shown by Dawbin (1956) who compared the times at which the peak of the northward migration passed through Cook Strait, N.Z., in each of 35 years. The difference between the earliest of these (June 21 in 1947 and 1950) and the latest (July 29 in 1933) was 38 days. In the northward migration of group IV humpback whales past Albany (Fig. 4), the peak density was approximately 3 weeks earlier in 1959 than in 1956. Annual variation in the

availability of food in the Antarctic (either by behaviour of the *Euphausia* themselves, or by climatic changes such as the formation of sea ice making the *Euphausia* inaccessible) might be responsible for these annual variations in the time of the northward migration, but there are no precise data concerning these conditions in the Antarctic.

The speeds at which individual humpback whales travel during undisturbed migration have been measured by direct (aerial) observations over periods of a few hours, giving speeds from 2·6 to 7·7 knots (Chittleborough 1953), the mean of the values being 4·3 knots. Similar speeds have been maintained for longer periods by humpback whales marked during their migration along the Australian coast; one travelled a minimum of 520 nautical miles during 6 days subsequent to marking (average speed 3·6 knots), while another travelled at least 430 nautical miles in 7 days (average speed 2·5 knots). That these speeds can be maintained over very considerable distances was demonstrated by a humpback whale marked when passing through Cook Strait, N.Z., on June 15, 1960, and shot 20 days later off Moreton I., on the east coast of Australia. The shortest distance between these points is 1350 nautical miles, so that this whale must have averaged at least 2·8 knots.

In contrast to these relatively rapid movements by individual whales are those of whales seen idling or playing with little active migration. Some whales may spend several days in one locality before continuing their migration. For example, a humpback whale marked on July 30, 1960, close to Norfolk I., was killed 10 days later in the same locality.

Dawbin (1956) calculated the average rate of progression of the whole population during migration from the times at which the maximum density of the northbound whales passed widely separated observation points. His figure of 1·3 knots is the rate of progression of the whole population in the course of its northward migration. Individuals may vary their speed from time to time, and sometimes change their direction temporarily. Some of the individuals shown in Figure 3 as migrating northwards during September and October may actually have been southbound whales which were milling around at the time observed.

Although most humpback whales have left the Australian coast by the end of October, some have been sighted in these waters in November and December. Three separate females seen migrating southwards along the west coast during December had probably been late in making the northward migration, each being accompanied by a calf (see Section II (*d*)). The appearance of such whales, late in making their way south, and of others exceptionally early in migrating from the southern feeding grounds, might have been what led Mackintosh to suggest (Mackintosh 1942, p. 238) that a few humpback whales remain in subtropical waters throughout the summer.

During the summer the group IV population feeds in the Antarctic between 56°S. and 66°S. latitude, and the group V population from 59°S. to 68°S. (Omura 1953).

(*b*) *Discreteness of Populations*

Very few humpback whales winter off the south coast of Australia. Occasionally an individual may terminate its northward migration at the head of the Great Australian Bight. Calaby (personal communication) sighted a humpback whale there (at 130° 30'E.) on August 3, 1952. A female humpback whale and its newborn calf were reported in St. Vincent Gulf, South Australia (138½°E.) during the winter of 1961. On the western side of Australia some humpback whales meet the south coast during their northward migration, but they then follow the coastline to the west and south-west (passing the whaling station at Albany) until they can continue their northward migration up the west coast. Humpback whales do not pass the station at Albany at the time of the southward migration.

Since almost all members of these populations are distributed along the coastlines to the north of 30°S. during the winter (breeding) season, there is complete reproductive isolation, as the two populations are separated at that time by the Australian continent.

The geographic distribution of catches from these populations during the summer (feeding) season (Omura 1953, fig. 9; Chittleborough 1959*b*, Table 3) would indicate that there is generally little exchange of individuals between these populations in Antarctic waters. Humpback whales are seldom captured in the region from 120°E. to 140°E. A reservation which must be made here is that in recent years the period of open season for humpback whales in the Antarctic has been so brief (4 days) that the location of catches reflects the positions of factory ships at that time. Whaling masters endeavour to place their vessels in regions of greatest density of whales, and if already operating successfully on fin whales, they would not move the fleet for the short season on humpback whales.

The composition of the catches taken from the group IV and V populations from 1949 to 1954 affords evidence that there was little interchange between these populations. During this period the lengths of males and females taken each year decreased both in the catches from the northern (west coast of Australia) and southern (Antarctic area IV) ranges of the group IV population (Chittleborough 1958*a*). On the other hand, the sizes of whales taken from both the east coast of Australia and from Antarctic area V remained at similar high levels during those years.

The migrations by individuals from these populations are demonstrated from the subsequent recapture of humpback whales marked off the Australian coast (Table 4, and also Chittleborough 1959*a*), near islands in the south-west Pacific Ocean (Dawbin 1959), and in Antarctic waters (Rayner 1940). The intervals between marking and recapture of these whales ranged from a few days up to 17½ years. Only those killed 6 months or more after marking can be considered to have had an opportunity to move from one population to another.

Of the humpback whales marked when within the territory of the group IV population (70°E.–130°E.), 56 have been recaptured after 6 months or more. Of these, 54 (96·4%) had remained in the group IV population, while the remaining two had entered the confines of the group V population.

Of the humpback whales marked when within the territory of the group V population (130°E.–170°W.), 84 have been recaptured after 6 months or more. Of

TABLE 4

HUMPBACK WHALES MARKED OFF AUSTRALIA AND ALL KNOWN RECAPTURES FROM THESE UP TO 1962

Marked Whales		Recaptured Whales (number of years after marking)																
Year	Number Marked	Locality	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	9
(A) Humpback whales marked off east coast of Australia (group V population)																		
1950	4	—																
1952	4	—																
1953	14	Eastern Australia	1						1									
1954	66	Eastern Australia	1		1		2											
		Antarctic Area V										1				1		
		Western Australia											1					
1955	180	Eastern Australia	3		3		1		9		3							
		New Zealand											1					
		Antarctic Area V												1				
		Antarctic Area IV								2								
		Western Australia									1							
1956	376	Eastern Australia					2		3		3		2					
		New Zealand			1													
		Antarctic Area V						2				1						
		Antarctic Area IV						3										
1957	63	Eastern Australia	1															
		New Zealand					1											
1958	123	Eastern Australia	1		2		1		1									
		Antarctic Area IV		1														
1959	57	Eastern Australia			1		1											
		Antarctic Area V				1												
1960	116	Eastern Australia					1											
		Antarctic Area V		1														
1961	34	Eastern Australia	1															
1962	4	Eastern Australia	1															
(B) Humpback whales marked off west coast of Australia (group IV population)																		
1949	16	Western Australia					1											1
1954	21	Western Australia					1											
1955	69	Western Australia	1				1		1						1			
		Antarctic Area IV		1														
1956	6	Western Australia							1									
1957	80	Western Australia			1						1							
		Antarctic Area IV				2												
1958	46	Western Australia									1							
1960	12	—																
1961	20	—																
1962	17	—																

these, 73 (86·9%) had remained in the group V population, 10 (11·9%) had moved into the area of the group IV population, while one had joined the group I population (120°W.–60°W.).

During the period of study the exchange between the group IV and group V population took place mainly in the summer feeding season of 1958–59. Chittleborough (1959*b*) has shown that catches of humpback whales taken during February 1959 from the eastern portion of the Antarctic feeding grounds of the group IV population (i.e. from 110°E. to 130°E.), comprised approximately equal numbers of individuals from the group IV and group V populations. That there had been an expansion of the feeding area of the group V population in that summer was confirmed by the capture in the eastern part of the group IV sector, of eight humpback whales marked when in the normal range of the group V population.

The movement between these two populations during the summer of 1958–59 has been further clarified by the results from the recoveries of marks fired during that summer. Figure 1 illustrates the movements of marked whales which were either marked or killed in the summer of 1958–59 or the following winter. During the summer of 1958–59 the group V population extended its feeding range to overlap the feeding area of the group IV population (which apparently had not been dispersed any more widely than usual). During the autumn, the majority of the members of the group V population which had penetrated the eastern part of the feeding grounds of the group IV population, returned to the normal range of the group V population, migrating to the east coast of Australia. However, some (at least two) of the group V population remained with the group IV population and migrated to the west coast of Australia (Fig. 1). The differences in abundance of whales, and in the composition of catches on the west and east coasts of Australia during the winter of 1959 (Chittleborough 1960), suggest that very few individuals from the group V population had remained with the group IV population during the autumn northward migration.

The evidence of humpback whale sightings, catches, catch composition, and of movements of marked whales, indicates that these populations remain separate in most years. Intermingling occurs occasionally in the southern feeding grounds, but this does not lead to much permanent exchange between the populations (perhaps because of some inherent instinct of individuals to return to the locality where they were born).

Little is known of the factors responsible for maintaining the discreteness of southern humpback whale population in Antarctic waters during the summer feeding season. Beklemishev (1960, 1961) has postulated that humpback whales gather to feed on concentrations of *Euphausia superba* brought to the surface in centres of upwelling induced in the Antarctic Divergence by atmospheric cyclones. These cyclones are reputed to be quasi-stationary and to re-form in the same localities, concentrations of krill being brought to the surface in the centres of upwelling so produced. If this is the mechanism by which populations of humpback whales remain separated during the feeding season, we might interpret the wider dispersion of the group V population during the summer of 1958–59 as having been caused by poor development of the system of quasi-stationary cyclones in the vicinity of the Balleny Is. (160°E.) at that time.

(c) *Morphological Differences*

Lillie (1915) distinguished seven colour patterns (four main and three intermediate groups) in humpback whales, these patterns ranging from completely black bodies (given as group 4) to individuals having white skin on the abdomen and sides (group 1). By comparing the frequency of occurrence of the various colour patterns, Matthews (1938) showed that humpback whales from South Georgia and South Africa (populations II and III) were predominantly of the darker patterns, while those from new Zealand (population V) were generally less pigmented. Using these seven colour patterns, Omura (1953) produced further evidence of a progressive decrease in pigmentation amongst Antarctic humpback whales from the South Atlantic eastwards towards the Ross Sea.

TABLE 5

FREQUENCY OF OCCURRENCE OF FOUR COLOUR PATTERNS IN HUMPBACK WHALES SAMPLED FROM VARIOUS LOCALITIES

Locality	Sample		Frequency of Colour Pattern (%)			
	Sex	Number	1	2	3	4
S. Georgia and S. Africa (Matthews 1938)	Male	25	4·0	12·0	16·0	68·0
	Female	28	0·0	3·6	17·9	78·6
West coast of Australia	Male	599	16·2	34·1	32·9	16·9
	Female	428	13·8	36·2	32·0	18·0
East coast of Australia	Male	619	29·4	36·9	19·9	13·7
	Female	281	30·5	39·9	15·1	14·4

Because observers differed in their interpretation of the ill-defined intermediate patterns, only the four main colour patterns figured by Lillie and Matthews are used in comparison of Australian samples (Table 5). Figure 8 shows that although the complete range of colour patterns is found in each population, the less pigmented individuals are more plentiful in the group V population (east coast of Australia) than in the group IV population (west coast of Australia), while in the South Atlantic Ocean (group II and III populations) most individuals are heavily pigmented ventrally as well as dorsally.

Measurements were made of various parts of the bodies of humpback whales killed on the west and east coast of Australia, in order to determine whether members of these two populations differed significantly in body form. Statistical analysis of these measurements showed greater differences between the measurements taken by two observers measuring whales from the same population than between measurements from whales of the two populations.

Although these two populations of humpback whales are separate entities, there is apparently sufficient interchange between them to prevent genetic differences from reaching significant levels. Thus there is little justification for the separation of races or subspecies of humpback whales within the southern hemisphere, as has been done by Ivashin (1958).

(d) Segregation within Populations

(i) *Sub-division of Breeding Grounds*

While the group IV population has only one breeding area (along the west coast of Australia), the group V population is widely dispersed during the breeding season. A large portion of the group V population breeds along the east

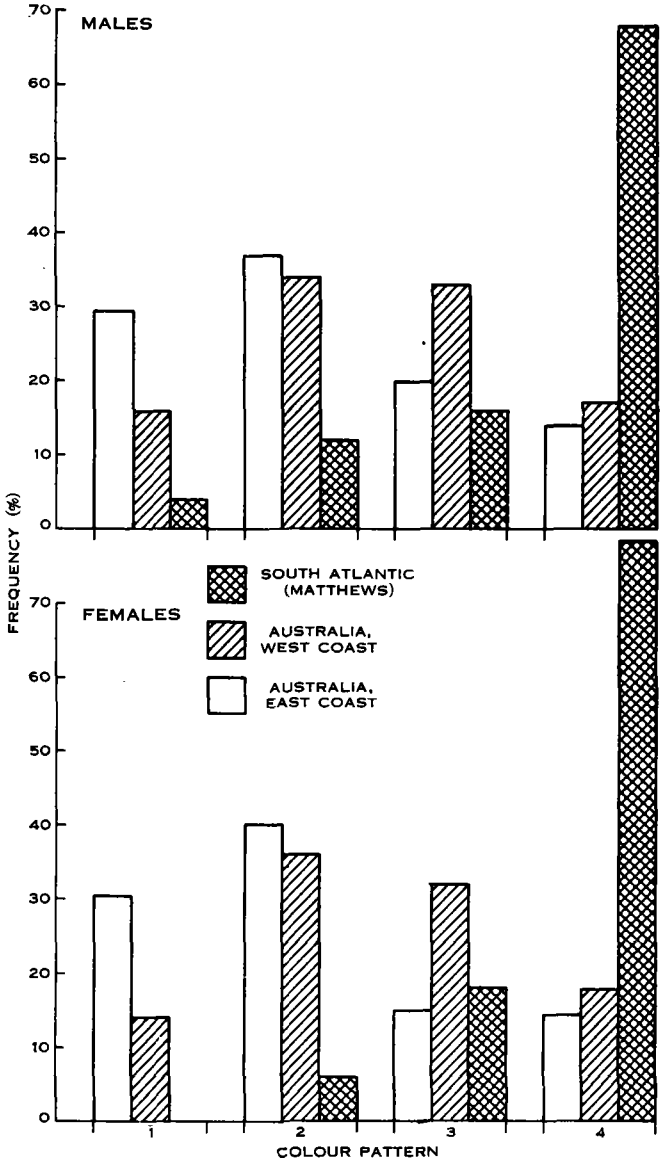


Fig. 8.—Frequency distribution of four colour patterns amongst humpback whales sampled from populations II–III (South Atlantic), IV (west coast of Australia), and V (east coast of Australia).

coast of Australia, but other members gather around island groups of the south-west Pacific Ocean. Dawbin (1959) postulated from the movements of marked

whales recaptured up to 1958, that this population of humpback whales did not disperse at random across the width of the tropical breeding zone, but that individuals generally returned to the same coastline or island group year after year. From these results, Dawbin suggested that the population was segregated to some extent into a number of breeding units and that the individuals usually returned to breed in the locality where they had been born and weaned.

The total numbers of humpback whales marked (up to 1960) in the northern area of distribution of this population were 946 on the east coast of Australia and 875 off the south-west Pacific islands. If these whales returned to the locality of marking (after mingling freely in the Antarctic feeding area), then whaling on the east coast of Australia should recover only marks implanted off that coast. However, if the whales remained randomly dispersed in their northward migration, whaling on the east coast of Australia should yield marks from both the east coast of Australia and the south-west Pacific islands, in the proportion 946 : 875. Table 6 shows the recoveries of marks on the east coast of Australia in recent years and compares their origins, as observed, with what would be expected by the hypothesis that the marks from the two regions would be randomly distributed. Recoveries on the east coast of Australia during 1959 would support the theory of segregation of breeding grounds within this population, whereas the recoveries on this coast in 1960 and 1961 support the hypothesis of random distribution during the breeding season.

From the recoveries of marks up to 1959 there may have been partial segregation of breeding grounds within the group V population, but this appears to have broken down in 1960 and 1961.

(ii) *Segregation during Migration*

Chittleborough (1958*b*) and Dawbin (1960) showed that during the northward migration the whales of certain categories within the population travel ahead of others. These authors were not able to measure the abundance of one category relative to another throughout the migration past the particular points. This is now shown in Figure 2 for the population passing Albany (35°05′S.) on the south-west coast of Australia during the combined northbound migrations from 1952 to 1961. As set out in Table 7, the mean catch per 10 steaming hours within 7-day periods is used as an index of the abundance of each category. Because of the minimum legal length (35 ft), the immature groups are not fully vulnerable, so that the values shown in Figure 2 and Table 7 for immature groups are instead the abundance of those exceeding 35 ft.

Figure 2 shows that sexually immature individuals and mature females terminating lactation are in the vanguard of the northward migration. Non-pregnant mature females (those which had been in non-lactation anoestrus, and others which had completed lactation) continue to pass throughout the period of the northward migration, while pregnant females (carrying near-term foetuses) are in the rear of the northward migration. Adult males are most abundant in the centre of the migration, and continue to be relatively plentiful in the latter portion of the migrating stream.

Segregation of the various categories during the northward migration may be the result of each leaving the Antarctic feeding grounds at a different time. There is no indication that individuals within a particular category travel at a higher average speed than those in any other.

Partial segregation of the various categories of humpback whales is apparently continued during the southward migration, those which were first to arrive in temperate and tropical waters being the first to depart on the southward migration. The pregnant females, which were amongst the last to migrate northwards (Fig. 2), gave birth on reaching warmer waters (Chittleborough 1958*c*), and were then amongst the last to migrate southwards (Chittleborough 1953, and also Fig. 3 above).

TABLE 6

RECENT RECOVERIES ON THE EAST COAST OF AUSTRALIA OF MARKS FIRED ON OR NEAR THE BREEDING GROUNDS OF THIS POPULATION

Year of Capture	Total Marks Recovered	Origin of Marks			
		East Coast of Australia		S.W. Pacific Is.	
		Observed	Expected*	Observed	Expected*
1959	8	8	4·16	0	3·84
1960	9	5	4·68	4	4·32
1961	7	4	3·64	3	3·36

* On the hypothesis of random distribution.

The main stream of humpback whales migrating past Australian shore stations passes within 10 miles of the coast; few humpback whales are seen or captured more than 20 miles from land in the vicinity of these stations, in spite of much wider ranging of searching aircraft and vessels operating from these stations in recent years. The various categories of humpback whales listed in Table 7 are dispersed across the width of the migrating stream, no group being confined either inshore or staying further offshore than any other group.

III. Life History

(*a*) *Reproduction*

(i) *Puberty*

From the histological examination of testes, Chittleborough (1955*a*) showed that the length of the males at puberty ranged from 33·3 to 40·8 ft with a mean of 36·75 ft. The average weight of the paired testes at this stage was 4·0 kg.

From the ages determined from baleen traces of 238 male humpback whales, Chittleborough (1959*c*) showed that the mean age of males at puberty was between 4 and 5 years, more males reaching puberty at 5 than at 4 years of age. Further evidence upon the ages of males at puberty is given in Figure 9 which shows the growth of testes (by weight), based on the data from 1067 males. Using the testes weight

TABLE 7

RELATIVE ABUNDANCE, AS INDICATED BY CATCH PER UNIT EFFORT, OF VARIOUS CATEGORIES OF HUMPBACK WHALES THROUGHOUT THE NORTHWARD MIGRATION PAST ALBANY (35°05'S.)

Combined data from 1064 humpback whales taken from 1952 to 1961

Week Ending:	Total Effort (steaming hours)	Total Catch (humpback whales)	Catch per 10 Steaming Hours	Catch Cagetory											
				Mature Females						Immature Females		Immature Males		Mature Males	
				Non-pregnant				Pregnant (near-term)							
				Terminating Lactation		Post-lactation									
				Number Killed	Catch per 10 Steaming Hours	Number Killed	Catch per 10 Steaming Hours	Number Killed	Catch per 10 Steaming Hours	Number Killed	Catch per 10 Steaming Hours	Number Killed	Catch per 10 Steaming Hours	Number Killed	Catch per 10 Steaming Hours
May 28	87·5	1	0·11	1	0·11	0	0	0	0	0	0	0	0	0	0
June 4	204·2	5	0·24	1	0·05	0	0	0	0	1	0·05	2	0·10	1	0·05
11	584·8	30	0·51	11	0·19	2	0·03	0	0	8	0·14	6	0·10	3	0·05
18	915·2	65	0·71	19	0·21	6	0·07	0	0	18	0·20	12	0·13	10	0·11
25	1038·2	113	1·09	24	0·23	7	0·07	0	0	30	0·29	18	0·17	34	0·33
July 2	962·8	115	1·19	14	0·15	4	0·04	2	0·02	20	0·21	24	0·25	51	0·53
9	1051·2	170	1·62	14	0·13	12	0·11	8	0·08	29	0·28	30	0·29	77	0·73
16	1090·2	174	1·60	11	0·10	32	0·29	6	0·06	24	0·22	29	0·27	72	0·66
23	883·2	120	1·36	1	0·01	25	0·28	15	0·17	13	0·15	15	0·17	51	0·58
30	946·2	109	1·15	0	0	21	0·22	18	0·19	17	0·18	6	0·06	47	0·50
Aug. 6	854·0	80	0·94	0	0	20	0·23	20	0·23	3	0·04	3	0·04	34	0·40
13	477·2	40	0·84	0	0	6	0·13	16	0·34	3	0·06	1	0·02	14	0·29
20	413·2	31	0·75	0	0	6	0·15	9	0·22	1	0·02	2	0·05	13	0·31
27	106·2	8	0·75	0	0	0	0	3	0·28	0	0	0	0	5	0·47
Sept. 3	62·5	3	0·48	0	0	1	0·16	1	0·16	0	0	0	0	1	0·16
Total		1064		96	1·18	142	1·78	98	1·75	167	1·84	148	1·65	413	5·17

of 4·0 kg as a criterion, puberty can be said to be reached at 3–6 years of age, 11·8% being mature at 3 years, 33·0% at 4 years, 85·4% at 5 years, and 95·0% at 6 years.

From an examination of females captured during their first oestrous cycle, Chittleborough (1955*b*) found that females at puberty ranged in size from 35·2 ft to 43·5 ft, with a mean length of 38·50 ft. Subsequently, Chittleborough (1960*b*) showed that the mean length of pubertal females taken in the catch varied with the degree of selection applied by gunners, and that after a period of intensive and selective killing, the capture of the slower growing individuals remaining in the population, resulted in an apparent decrease in the mean length at puberty.

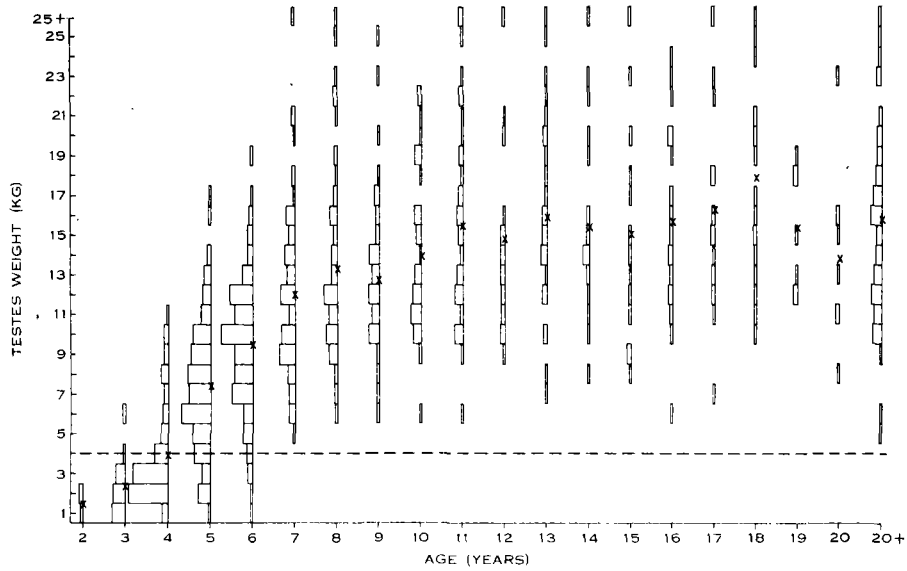


Fig. 9.—Distribution of testes weights and mean of each age group (×) in 1067 male humpback whales from Australia. Ages by ear plugs.

In New Zealand, under conditions of minimum selectivity, Dawbin (1960) estimated the average length at the attainment of sexual maturity to be 38 ft for males and 39·5 ft for females. These whales were killed early in the northward migration, so that pubertal whales were not available for study. Chittleborough (1955*b*, p. 318) showed that the mean length of females reaching sexual maturity (1 year after puberty), on the west coast of Australia, was 39·66 ft.

From the ages determined from the baleen traces of 391 female humpback whales, Chittleborough (1959*c*) showed that the majority of females reach puberty at 4 and 5 years of age. Further evidence upon the ages of females at puberty is given in Figure 10, which is based upon the data from 1603 females whose ovaries and ear plugs were examined at Australian stations. While the ages at puberty range from 2 years to a (doubtful) extreme of 12 years, the majority of individuals (70%) attain puberty at 4 and 5 years of age. No indication has been found of any significant variation in age at puberty from year to year or between the group IV and group V populations.

(ii) *Breeding Season*

Male humpback whales undergo a seasonal sexual cycle, as evidenced by changes in testes weight and spermatogenesis. Chittleborough (1955*a*), Symons and Weston (1958), and Nishiwaki (1959) have shown that testes weights are lower in males taken in polar waters during the summer (feeding season) than in those captured in temperate and subtropical waters during winter months (breeding season). Matthews (1938) and also Symons and Weston found very little testicular activity during summer months when the males were in Antarctic waters, while spermatozoa were plentiful both in testes tubules and in vasa deferentia of adult males taken off the Australian coast from June to October (Chittleborough 1955*a*).

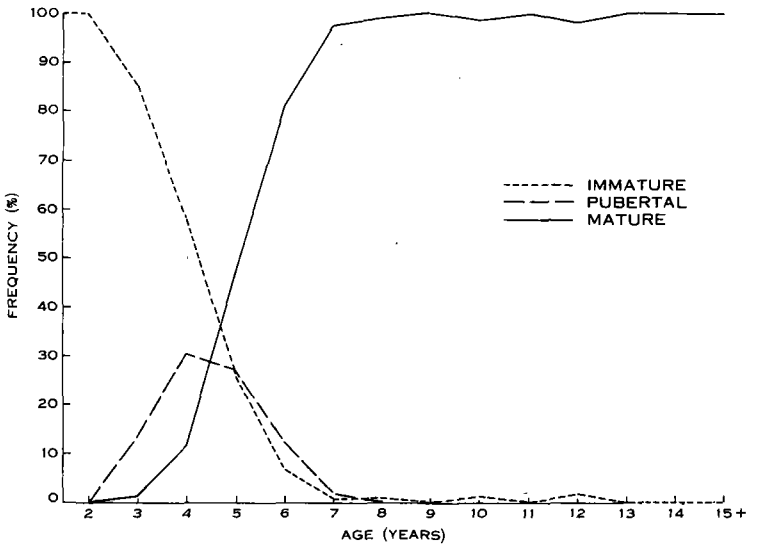


Fig. 10.—Percentages of sexually immature, pubertal, and mature females in each age group; data from 1603 female humpback whales from Australian stations.

Because of this seasonal activity of testes, the relationship between testes weight and age, shown in Figure 9, is valid only for the duration of the breeding season. The mean testes weight of 4·0 kg at puberty may not be applicable to males taken in polar waters, or even in New Zealand during the early part of the northward migration. This may account for the somewhat higher lengths of males at maturity estimated by Dawbin (1960) in New Zealand and by Omura (1953) in the Antarctic both of whom used the testes weight of 4 kg as the criterion of maturity.

Contrary to Harvey's (1963) interpretation of the evidence given by Chittleborough (1954), female humpback whales are seasonally polyoestrus. Most oestrous cycles occur during the winter and early spring (June–October in the southern hemisphere) when the whales are in temperate and subtropical waters. There may be one or several successive cycles, terminated when conception succeeds or when the female migrates to the polar feeding grounds. In each oestrous cycle there is generally a single ovulation but multiple ovulations (seldom involving more than two follicles) occur occasionally.

The average rate of ovulation is 1·1 ovulations per year (Chittleborough 1959*c*), but the distribution (in time) of ovulations during the 2-year breeding cycle has not been fully elucidated. Chittleborough (1959*c*, Table 5) estimated that during the first ovulatory season of the 2-year breeding cycle, there was an average of 1·2 ovulations per mature female. If this were so, a very high percentage of females should have a post-partum ovulation in order to achieve an average annual rate of 1·1 ovulations per year. However, Dawbin (personal communication) who has examined the ovaries of female humpback whales killed (by Tongan natives) soon after parturition, found no evidence that post-partum ovulation is of frequent occurrence in this species. Because of this, the actual rate of ovulation at the commencement of a 2-year breeding cycle may be higher than 1·2 ovulations per female.

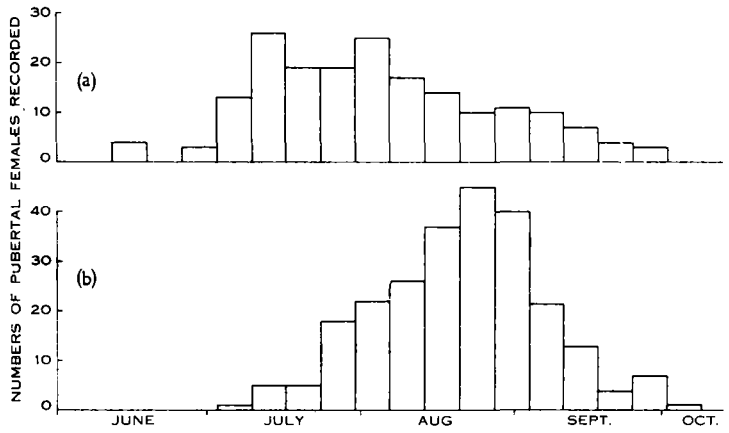


Fig. 11.—Distribution in time of 432 pubertal females killed (*a*) shortly before, (*b*) soon after the first ovulation, during operations throughout the Australian season.

Re-examination of ovarian material collected during the ovulatory period has led to the conclusion that in the ovaries of a female killed during the second or third successive oestrous cycle of a season, involution of the first corpus luteum had in many cases proceeded to the extent that it was classed as a corpus albicans (of an ovulation in a previous season). Robins (1960) presented evidence that an average of 1·48 ovulations occurred in females during the breeding season at the commencements of the 2-year breeding cycle, but he then regarded this as the average annual rate of ovulation.

Laws (1961) suggested (from indirect evidence) that oestrus and pairing in the fin whale took place later in the season for primiparous females than for multiparous females. This can be checked by direct observation in the case of humpback whales taken at Australian shore stations. Although immature females (of all sizes) are present in Australian catches during June (Fig. 2), very few have the maturing follicle which would indicate prooestrus of the first oestrous cycle. Females in this condition (approaching their first ovulation) are taken more frequently during July and in early August (Fig. 11). Most of the pubertal females had ovulated by mid-August, although a few did not ovulate until October. From this evidence, obtained

from 432 pubertal females, the first ovulation can occur between June and October, but most ovulate early in August. This is almost the same result as that obtained by Chittleborough (1956) for multiparous female humpback whales.

The timing of the first ovulation did not vary from year to year, nor did it differ in the two breeding regions under study (west and east coasts of Australia).

(iii) *Pregnancy and Lactation*

The gestation period is of approximately 11½ months, conception generally occurring early in August, and parturition at the end of the following July or the beginning of August (Chittleborough 1958*c*), both conception and parturition taking place along the coasts of Australia. Embryonic and early foetal stages have been described by Stump, Robins, and Garde (1960). A foetal growth curve for this species is given by Laws (1959). Generally a single foetus is carried; Chittleborough (1958*c*) recorded twins in 0·28% of pregnancies. The modal length at birth is 14 ft (4·3 m) (Chittleborough 1958*c*). Caudal presentation at birth has been described by Dunstan (1957).

Lactation extends over 10½–11 months (Chittleborough 1958*c*), weaning taking place during June and early July as the whales reach temperate latitudes (Fig. 2 of this paper). During their first Antarctic summer, calves from 6 to 9 months of age might supplement their milk diet with euphausiids, but there is no definite evidence of this.

Sharks and killer whales are probable causes of mortality among calves (Chittleborough 1953). If the calf is lost at or close to the time of parturition, oestrous cycles recommence (Chittleborough 1958*c*). Oestrus can follow parturition while the female is suckling a calf but, as discussed in the previous section, post-partum ovulation is probably not of regular occurrence in this species.

(iv) *Rate of Reproduction*

The breeding cycle of the female humpback whale is basically a 2-year one (Chittleborough 1958*c*), variations of which can result in either one or two calves being born in that time. However, successive breeding cycles do not necessarily follow immediately one after another; a resting year (when a female is neither pregnant nor lactating) may intervene between two cycles.

The reproductive rate could be measured if the corpora albicantia derived from previous pregnancies could be distinguished from those of ovulations which did not lead to pregnancy. Various attempts have been made to separate corpora albicantia into these two categories. Robins (1954) suggested that corpora albicantia from an earlier pregnancy are characterized by a central cavity or capsule of connective tissue. However, Laws (1958) and Ivashin (1957) do not accept this theory. Ivashin claimed that the two types of corpora albicantia could be distinguished by size, density, texture, and content of connective tissue, but his descriptions are very similar to the "young" and "old" stages of corpora albicantia involution described by Laws. To date, there is no reliable method by which corpora albicantia can be separated into those derived from pregnancy and those from unsuccessful ovulations.

A direct measure of the birth rate is the percentage of mature females found to be pregnant among those killed just prior to the period when parturition occurs. The whaling station at Albany is suitably located for such observations, as the population passes shortly before parturition occurs. The fishing effort expended has fluctuated from week to week during a season, and also from one season to another, operations sometimes terminating before the pregnant females had passed. These difficulties were resolved by expressing the abundance of pregnant and non-pregnant mature females in weekly periods throughout the season, in terms of catch per unit of effort, as shown in Table 7. From these values, the total relative abundance of non-pregnant mature females was 2·96 units, and that of pregnant females was 1·75 units. Then, 1·75 : 4·71 or 37·2% of the mature females give birth each year, i.e. the average annual birth rate is 0·37 in this species.

(*b*) *Nutrition*

(i) *Food and Feeding*

The most important item in the diet of humpback whales is *Euphausia superba* which is taken in large quantities in Antarctic waters during summer and autumn (Matthews 1938; Mackintosh 1942; Mizue and Murata 1951; Nemoto 1959). Nemoto and Nasu (1958) found that *Thysanoessa macrura* was of some importance in the diet of humpback whales in Antarctic waters between 130°W. and 100°W.

According to Beklemishev (1960, 1961) humpback whales gather to feed upon late larval and adolescent *Euphausia superba* which are concentrated in regions of upwelling along the Antarctic Divergence. These centres of upwelling are considered to be produced by quasi-stationary cyclonic depressions which re-form in the same localities. Klumov (1961) estimated that humpback whales feeding in polar waters consume 1–1·5 tons of euphausiids per day. He postulated that dense concentrations (exceeding 2000 mg/m^3) of these organisms are actively sought by the whales using echolocation, vision, and touch.

Fish have been recorded occasionally in the stomachs of humpback whales (Matthews 1937; Nishiwaki 1959; Nemoto 1959) but in these instances the fish may have been swallowed accidentally by the whale while both fish and whale were feeding on the plankton.

In somewhat warmer waters, the pelagic *Grimothea* post-larvae of *Munida gregaria* are eaten while humpback whales are migrating along the coast of Patagonia (Matthews 1932) and New Zealand (Dawbin and Falla 1949; Dawbin 1956). Dawbin points out that off New Zealand the humpback whales could feed on *Grimothea* only during the southward migration of the whales, as shoaling of these post-larvae does not commence until late in the spring. During their northward migration past New Zealand, humpback whales occasionally take *Nyctiphanes australis.*

Humpback whales seldom find sufficiently dense swarms of plankton off the Australian coast to stimulate feeding. Dall and Dunstan (1957) recorded food present in only one of over 2000 humpback whales examined at Tangalooma. However, the stomachs of these whales were examined rather superficially; when only small amounts of foods are present, the remnants of this food may escape recognition

unless the stomach contents are strained and the residues examined minutely. Close examination of the stomach contents from 197 humpback whales sampled at Carnarvon and Point Cloates (west coast of Australia) showed food remains in five of those taken off Point Cloates. In each of these whales the quantity of food ingested was small (probably less than 2 kg before decomposition began). Several species of food organisms were present in each case indicating that a small swarm of mixed plankton had been eaten. The most common species were *Euphausia hemigibba* and *Pseudeuphausia latifrons*. Other organisms noted were alima larvae of a stomatopod, probably *Gonodactylus* sp., megalopa larvae, a large caridean larva, and salps—*Ghalia democratica*.

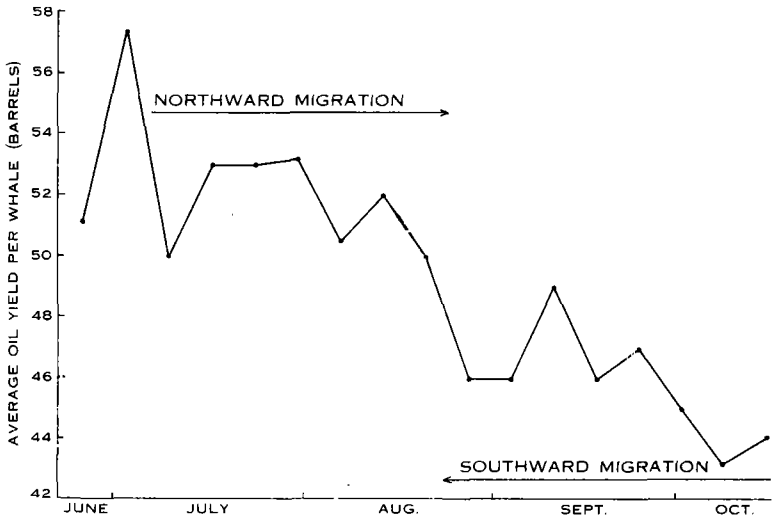


Fig. 12.—Average weekly oil yield per whale at Carnarvon in the 1958 season.

A female humpback whale taken off Albany in July, 1955, carried approximately 10 kg of *Euphasia spinifera* in very fresh condition.

The discovery of a large mass of semi-digested *Euphausia superba* in the stomach of a humpback whale at Tangalooma (27°S.) in July, 1956 (Dall and Dunstan 1957), stimulated some debate (Jonsgård 1957; Marr 1957) as to whether the bathypelagic range of this Antarctic euphausiid should be extended, or whether the whale had carried this large sample 2400 miles from the Antarctic feeding grounds (the latter possibility appears to be the more favoured).

Humpback whales may occasionally ingest some plankton during their winter migration to temperate and subtropical waters but the total food intake is negligible for at least 4 months of each year. During this period the whales subsist on stored fat reserves, with the result that oil yields decline progressively at whaling stations in low latitudes, as demonstrated in Figure 12.

(ii) *Oil Yield*

The quantity of oil which can be extracted from each whale is influenced by the following factors:

(1) The efficiency of the factory. Factory efficiency varies not only from one shore station or factory ship to another but may also vary at a particular factory from one season to another, due to changes in equipment (e.g. depreciation on the one hand, or more skilful operation of the plant, or addition and replacement of machinery on the other).

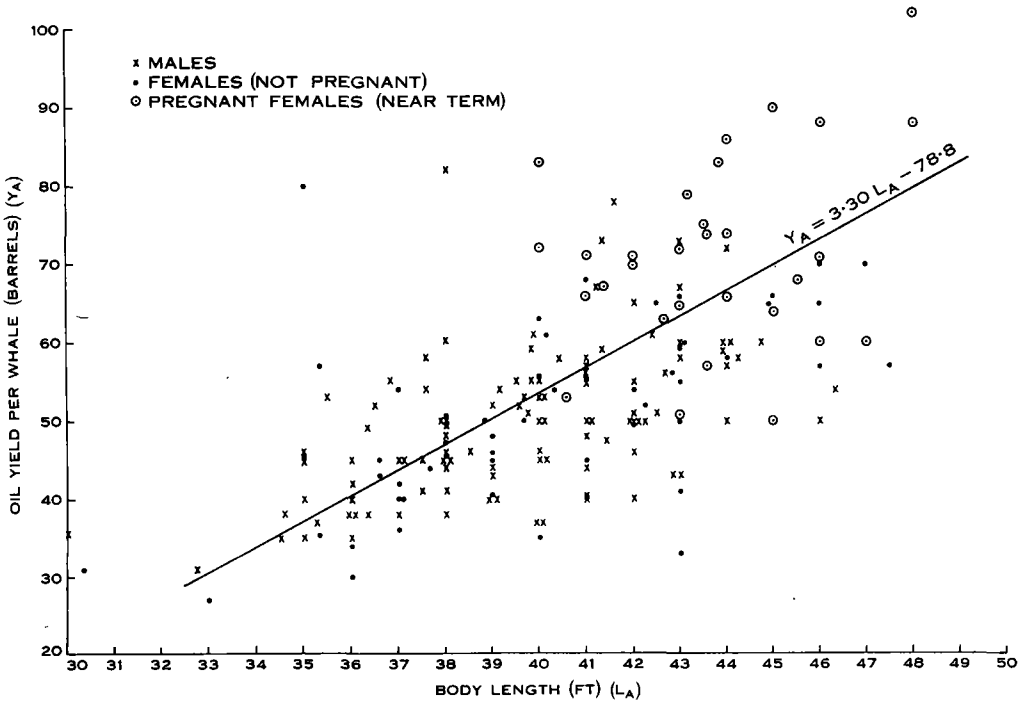


Fig. 13.—Oil yield and body length of individual humpback whales processed at Albany during 1953 and 1954.

(2) The size of the whale. Larger whales obviously carry more oil, as shown in Figure 13.

(3) Time and place of capture. The highest oil yields could be expected from whales killed when they have spent the summer feeding in the Antarctic, just before they depart on the northward migration. In temperate regions, whales are fatter as they pass a station on their northward migration, than when returning southwards at the end of a breeding season, as shown in Figure 12.

(4) Sex or phase of breeding cycle. Female humpback whales grow to larger size, and hence yield more oil, than males of similar ages. Mature females carrying near-term foetuses have been considered by whalers to yield more oil than other mature females.

(5) Availability of food. Humpback whales feeding in one area of the Antarctic may have access to more food (*Euphausia* more abundant, or less intraspecific or interspecific competition for food) than is the case in an adjacent population of humpback whales. Food supply may fluctuate from one year to another, so that whales from a particular population may be fatter in one season than in another.

The effects of these variables could only be measured if the oil yield had been recorded for each whale processed, together with details of the size, sex, breeding phase, date, and locality when killed. However, processing of whales at most factories has been rapid and continuous, so that the yield could not be measured for each whale.

TABLE 8

MEAN LENGTH AND AVERAGE OIL YIELD PER WHALE FROM ANNUAL CATCHES OF HUMPBACK WHALES AT VARIOUS WHALING STATIONS

Year	Point Cloates		Carnarvon		Albany		Tangalooma		Byron Bay		Norfolk I.		Cook Strait (N.Z.)
	Mean Length (ft)	Oil (barrels per whale)	Mean Length (ft)	Oil (barrels per whale)	Mean Length (ft)	Oil (barrels per whale)	Mean Length (ft)	Oil (barrels per whale)	Mean Length (ft)	Oil (barrels per whale)	Mean Length (ft)	Oil (barrels per whale)	Oil (barrels per whale)
1950	40·35	42·7	41·48	41·3	—	—	—	—	—	—	—	—	36·0
1951	40·27	43·2	40·31	47·8	—	—	—	—	—	—	—	—	40·4
1952	40·30	52·4	40·16	52·5	42·07	62·9	40·45	48·3	—	—	—	—	39·3
1953	39·91	50·7	39·59	50·6	39·86	51·9	40·36	51·4	—	—	—	—	41·8
1954	39·57	47·0	39·48	48·3	40·30	52·1	40·26	53·4	40·71	42·5	—	—	49·0
1955	40·35	49·8	41·32	50·6	40·20	47·6	40·70	54·5	42·10	57·2	—	—	44·8
1956	Closed		41·23	50·1	40·25	49·3	40·98	54·5	41·32	53·2	41·61	45·5	43·3
1957	—	—	40·77	50·6	39·56	49·4	40·89	57·5	39·91	42·1	41·52	55·1	46·5
1958	—	—	40·43	49·6	38·74	47·1	41·18	59·8	41·93	59·9	42·32	51·0	45·0
1959	—	—	38·76	45·1	39·63	49·8	41·17	59·1	42·44	58·1	41·34	52·0	50·3
1960	—	—	38·94	47·0	38·50	47·4	40·81	55·3	41·95	52·0	41·18	46·9	37·6
1961	—	—	37·54	45·8	37·94	48·0	38·76	42·8	40·68	49·1	41·01	44·4	47·8
1962	—	—	38·27	44·0	38·63	46·4	37·95	41·0	38·51	35·3	*	—	†

* Only four humpback whales taken.

† Data not available.

The station at Albany was unique in this regard. Having a small quota of humpback whales and very limited factory capacity (at least in the early years of operations), approximate quantities of oil extracted from individual whales were sometimes estimated at this station. Oil yield (Y_A) plotted against length of whale (L_A), as shown in Figure 13, gave the relation:

$$Y_A = 3{\cdot}30\ L_A - 78{\cdot}8.$$

For the reasons discussed above, this result is applicable only to humpback whales taken by that station (35°05'S.) during the northward migration of the group IV population in 1953 and 1954. Most of the pregnant females represented in Figure 13 would have given birth (and hence become protected by law) before migrating much further north. With those females no longer vulnerable, and assuming that there had

been no other change in the catch or factory efficiency, the relation between oil yield and length would then have been:

$$Y_A = 2{\cdot}85\ L_A - 60{\cdot}5.$$

At other whaling stations, oil yields from individual whales could not be determined. From the total oil produced each season, the mean production per whale could be estimated (Table 8). At most stations the average oil production per whale was less in the first season of operation than in the second, and thereafter varied with the mean length of the catch. Other factors, such as length of catching period, sex ratio, breeding season, fluctuations in food supply, etc., appear to have been of less importance, but the degree of influence of these factors could not be measured.

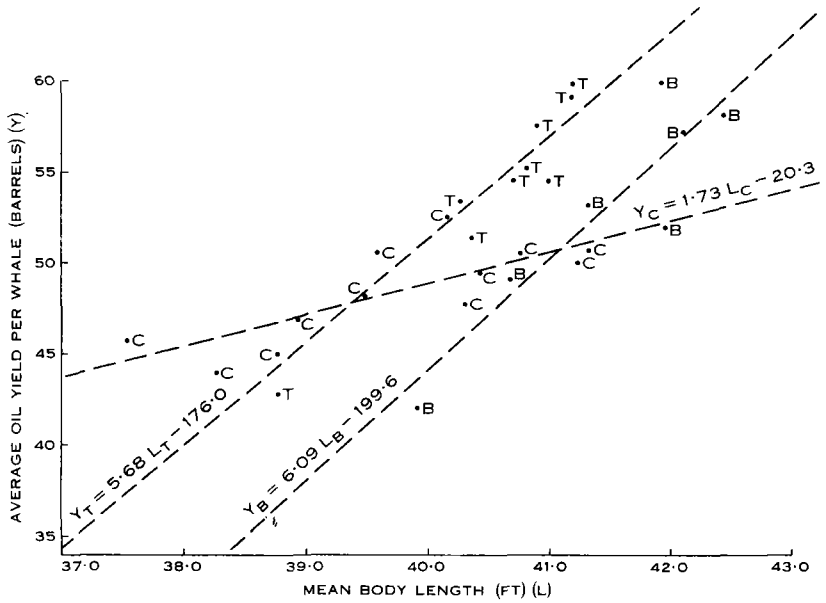


Fig. 14.—Regression of oil yield on body length for average seasonal values at Tangalooma (*T*), Byron Bay (*B*), and Carnarvon (*C*) stations (data for first season omitted).

The regressions of average annual oil yield per whale against mean body length of that season's catch, calculated by least squares, differed from one station to another (Fig. 14). Similar slopes of the regressions estimated from catch data at Byron Bay (28°37'S.) and Tangalooma (27°11'S.) indicate that these stations differed in only the first two of the five variables listed above as affecting oil yield. Less steeply inclined regressions derived from data collected at whaling stations on the west coast than the regressions from data on the east coast of Australia result from the influence of some factor or factors operating in addition to factory efficiency and sizes of whales killed. The group IV and V populations of humpback whales appear to differ in oil yield to body length relation, quite apart from any differences in factory efficiency or the time and location of commercial operations. There may be a difference in the availability of food to individual humpback whales within Antarctic areas IV and V. At present these possibilities cannot be explored owing to lack of data.

(*c*) *Growth*

Chittleborough (*1955b*) studied the growth of mature female humpback whales taken on the west coast of Australia from 1949 to 1954, using numbers of previous ovulations as an index of age. Although the numbers of ovulations did not give an absolute measure of age, the shape of the growth curve was shown. The data showed that growth ceased at an average length of a little over 45 ft.

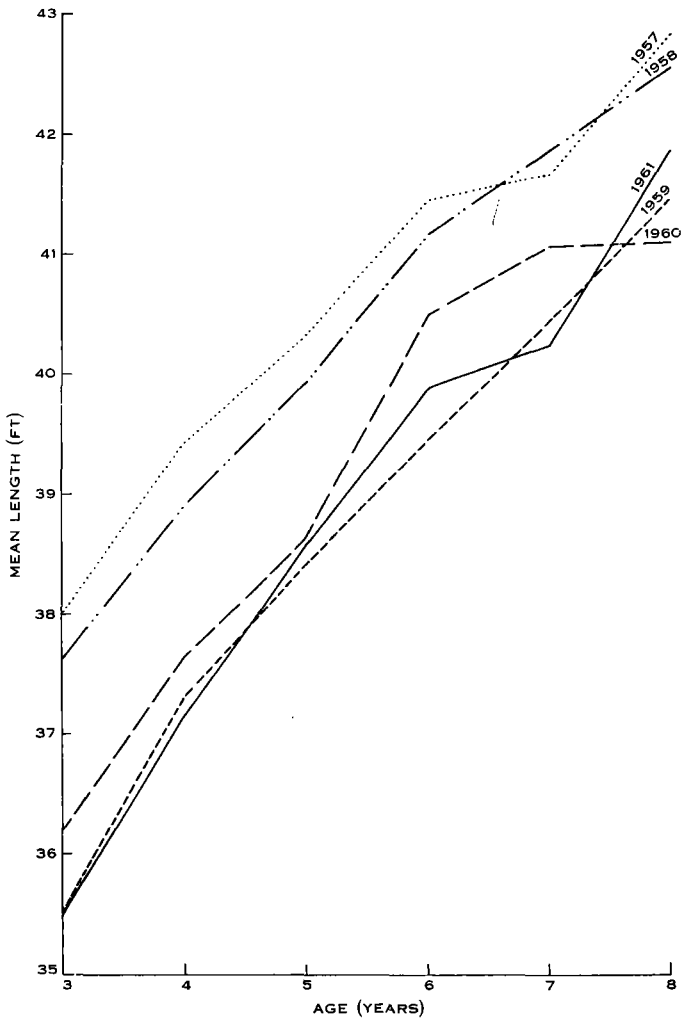


Fig. 15.—Mean lengths of females in age groups 3–8 years sampled off the west coast of Australia, 1957–61; ages from ear plugs.

Chittleborough (1958*b*) gave evidence of an apparent increase in the growth rate of pubertal and young mature females taken on the west coast of Australia in 1956 and 1957, compared with that measured in females of similar ages taken in the period 1949–1954. Although he noted the possibility that this was the result of more stringent selection of large whales by the gunners in 1956 and 1957, Chittleborough

suggested that young whales were actually growing faster than previously, as a result of the decrease in numbers of baleen whales competing for food in Antarctic waters.

However, the growth rate (as determined from the age–length relationship in the catch) of young females from the west coast of Australia has apparently decreased

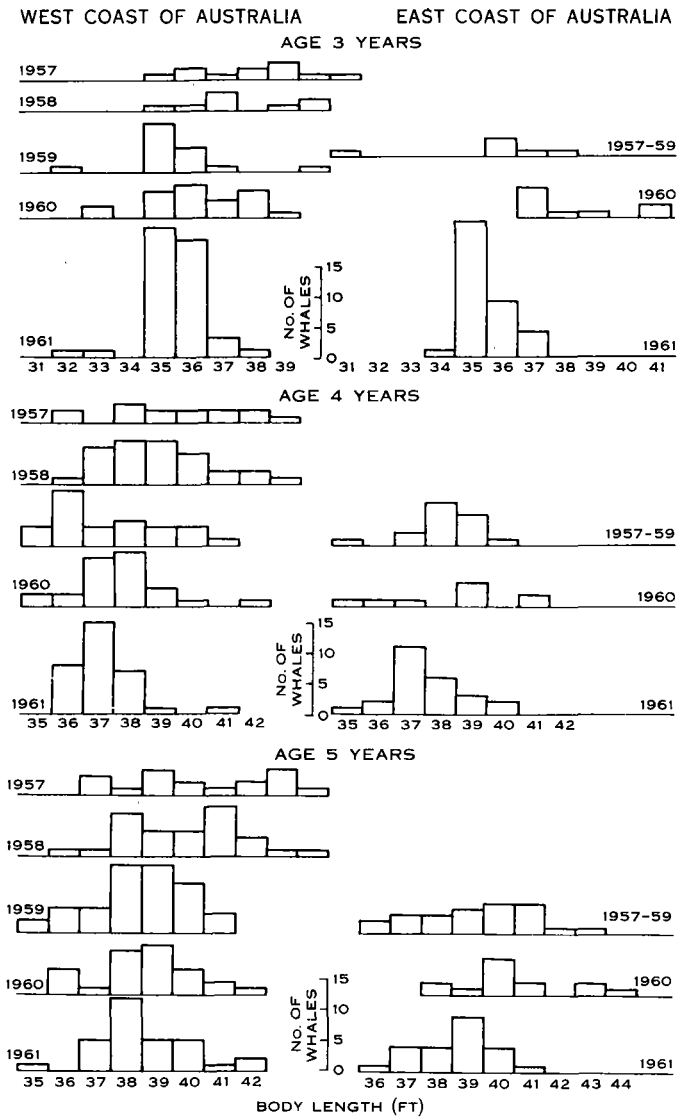


Fig. 16(*a*).—Distribution of lengths in annual samples of females aged 3, 4 anp 5 years (aged from ear plugs).

since 1957, this being most marked from 1959, as shown in Figures 15 and 16. From the length frequency distribution within age groups 3–6 years (Fig. 16), there was also an apparent decrease from 1960 to 1961 in the growth rate of females sampled by the gunners on the east coast of Australia.

This appearance of change in growth rates has resulted from changes in the level of selection of the catch by Australian gunners. Chittleborough (1960*b*) has shown that the mean length of pubertal females in annual catches varied with the level of selection applied by gunners in each year. The full series of samples of pubertal

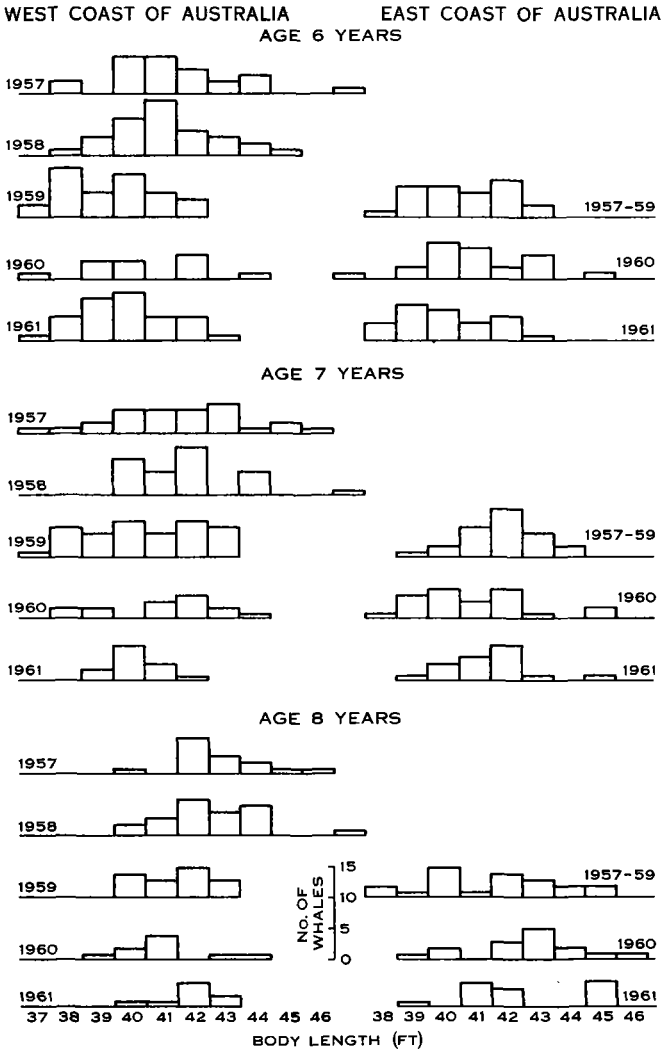


Fig. 16(*b*).—Distribution of lengths in annual samples of females aged 6, 7, and 8 years (aged from ear plugs).

females is shown in Table 9. The more careful selection of large whales applied since 1955 following the slight reduction of quotas (see Table 1) resulted in the capture of only the largest (and fastest growing) pubertal females in the following seasons, so that the mean length of pubertal females was higher in 1956 and 1957 than in the period 1949–54. However, as the populations decreased in size, gunners were obliged to take smaller whales, with the result that the mean length of the pubertal females in the catch decreased. The juvenile (immature) section of the population also had been

subject to selective hunting, only the largest being killed. Hence, when these young whales reached puberty in following years, the faster growing individuals had already been eliminated so that the mean length of the pubertal females captured was lower than that of the pubertal females of the original (unfished) population of whales.

Table 9 shows that the fall in the level of selection, brought about by the decline of that population, occurred earlier in the case of the group IV than in the group V population.

TABLE 9

LENGTHS OF PUBERTAL FEMALE HUMPBACK WHALES FROM CATCHES ON AUSTRALIAN COASTS

Year	Number Sampled	Range (ft)	Mean (ft)	S.D.	S.E.
West coast (group IV population)					
1949–54	77	35·25–43·50	38·50	1·66	0·18
1956	17	35·25–45·50	40·15	3·04	0·74
1957	42	35·75–44·50	39·49	2·18	0·34
1958	59	35·00–43·25	39·08	1·11	0·14
1959	43	35·00–40·50	37·96	1·45	0·22
1960	33	35·75–40·50	38·00	1·29	0·23
1961	42	34·50–40·50	37·29	1·43	0·22
1962	44	35·00–40·50	37·75	1·17	0·18
East coast (group V population)					
1952–54	60	34·50–42·17	38·51	1·73	0·22
1956–59	15	36·33–43·00	39·38	1·81	0·47
1960	11	37·17–40·67	39·21	1·27	0·38
1961	39	35·17–40·50	38·09	1·50	0·24

The evidence given above shows that no growth curve constructed from data on the age and length of whales in the commercial catches will accurately represent the growth of the younger year classes. If the samples obtained in the various years are pooled, some of the errors might cancel out. For example, if the large 6-year-old females taken on the west coast of Australia in 1957 and 1958 (Fig. 16*b*) represented the fast growing section of that population, and the small 6-year-old females taken on the same coast in 1959, 1960, and 1961 represented the slower growing section of that population, then the mean length of the pooled samples from 1957 to 1961 might be close to the true mean length of 6-year-old females in the original population.

While pooling of samples might improve the reliability of the estimated growth curve to some extent, the curve derived from the commercial catches will always be biassed against those age groups whose length range extends below 35 ft (the minimum legal length). This applies to the males below 5 years of age (Table 10, Fig. 17), and to females below 4 years (Table 10, Fig. 18). For these age groups there may be another source of bias in addition to the selection applied by gunners. From time to time some whaling inspectors have recorded lengths of 35 ft or 36 ft (or even more) for small whales which were in fact below the minimum legal length. If the ages of such whales were determined accurately, they would appear in the growth data as

unusually large young whales. When there have been few individuals in a particular age group (e.g. at 2 years), the mean length of that age group could be greatly distorted by a few instances of measuring bias.

TABLE 10

LENGTHS* OBSERVED AND ESTIMATED IN EACH AGE GROUP

Determined from ear plugs of 2031 male and 1605 female humpback whales taken on the Australian coast

Age (yr)	Males						Females					
	Observed					Estimated Curve	Observed					Estimated Curve
	Number	Range Min. Length	Range Max. Length	Mean Length	Variance		Number	Range Min. Length	Range Max. Length	Mean Length	Variance	
2	14	32	37	34·86	1·49	34·49	6	32	37	34·33	3·87	34·27
3	149	32	40	35·80	1·51	36·12	151	31	43	36·09	2·95	36·29
4	241	33	41	37·07	1·73	37·43	180	35	43	37·97	2·93	37·94
5	297	35	43	38·65	2·70	38·47	214	35	44	39·11	3·40	39·29
6	281	35	43	39·18	2·22	39·30	190	37	47	40·50	3·02	40·39
7	182	36	44	39·83	2·03	39·97	165	37	47	41·19	3·32	41·28
8	127	37	45	40·44	2·68	40·50	116	38	47	42·10	3·05	42·01
9	128	37	45	40·92	3·02	40·92	88	38	47	42·40	3·37	42·60
10	81	37	46	41·44	3·63	41·25	79	41	46	43·46	2·25	43·08
11	74	38	46	41·68	2·05	41·52	78	38	48	43·23	3·63	43·47
12	62	38	46	41·68	1·26	41·74	54	40	48	43·80	3·60	43·80
13	67	35	45	41·78	2·54	41·91	35	40	47	43·69	2·87	44·06
14	34	39	45	42·06	2·72	42·04	38	40	50	43·47	3·72	44·27
15	28	39	45	41·71	2·49	42·15	36	42	47	44·64	1·95	44·44
16	40	39	45	42·52	1·87	42·24	26	40	48	44·19	4·88	44·59
17	34	39	46	42·56	2·56	42·31	19	43	48	45·42	3·26	44·70
18	23	40	46	42·17	2·04	42·36	21	42	49	44·90	3·59	44·80
19	21	39	46	42·67	2·41	42·41	13	40	47	44·38	3·59	44·87
20	16	38	45	41·69	3·76	42·44	9	44	47	46·00	1·50	44·93
						L_∞						L_∞
20+	132	39	47	42·64	2·84	42·58	87	42	50	45·46	3·04	45·21

*Lengths in feet.

For the reasons given above, data from males of less than 6 years and from females of less than 5 years were not included in the calculation of the growth curves. The parameters of the growth curves were estimated for the von Bertalanffy growth equation as given by Beverton and Holt (1957), the fitted curves being shown in Figure 19. The form of these curves is:

$$L_t = L_\infty\,[1 - e^{-k(t-t_0)}].$$

For the males,

$L_\infty = 42{\cdot}58$ ft,
$k = 0{\cdot}226$,
$t_0 = -5{\cdot}348$ years;

and for the females,

$L_\infty = 45{\cdot}21$ ft,
$k = 0{\cdot}205$,
$t_0 = -4{\cdot}936$ years.

The growth curves have been fitted using data from whales ranging from 5 to 19 years of age, and represent the best estimates of growth during these years. Since there are reliable data at certain other points in the life span, the growth curves can be extended to cover most ages.

If the von Bertalanffy curves were extrapolated to age 0 years ($t = 0$), i.e. the time of birth, the mean length of males would then have been 29·87 ft and that of the females 28·78 ft. However, the length of males and females at birth has already been shown to be 14 ft (from measurement of near-term foetuses, which were not subjected to selection or measuring bias).

From the calculated curves the mean length at 1 year of age would be 32·44 ft for males and 31·82 ft for females. The author has examined and measured five small humpback whales identified (from baleen traces and in some cases by the presence of milk in the stomachs) as yearlings, and whose capture was not the result of gunner

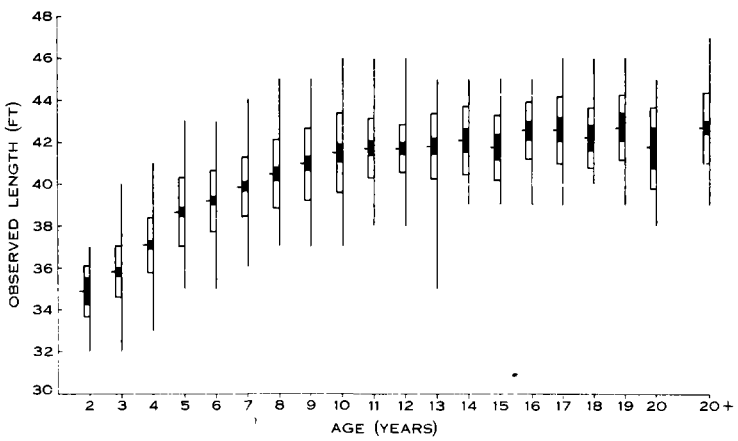


Fig. 17.—Observed lengths within each age group of males. Vertical line shows recorded range; horizontal line gives mean length; black bar extends two standard errors of mean on either side of mean; hollow bar ends one standard deviation on either side of mean. Data from Australian samples aged from ear plugs.

selection. Two of these yearlings, 28 ft 9 in. and 31 ft 4 in. in length were taken under special licence for research purposes. The other three specimens, 29 ft 3 in., 30 ft 0 in., and 30 ft 3 in. in length, were struck by harpoons intended for their mothers, so that these yearlings might be regarded as random samples of 1-year-old whales. The mean length of these five specimens is 29·92 ft, well below the estimates for the mean length of this age group obtained from the calculated growth curves.

Obviously the slope of the growth curves drawn from data from the commercial catches is not sufficiently steep where it represents the early years of growth. The broken lines in Figure 19 represent more closely the growth during these years.

As shown in Table 10, in both sexes the estimated maximum length, L_∞, is very close to the mean length of individuals over 20 years of age. The length L_∞ is then equivalent to the mean length at physical maturity. The value of L_∞ for each sex, being unaffected by changes in the level of selection, should represent very closely the real values for these populations of whales. The mean lengths of males

and females of ages exceeding 20 years in the group IV population did not differ significantly from those in the group V population. There did not appear to be any difference between the two populations under study in respect of rates of growth.

Nishiwaki (1959) gave growth curves (fitted by eye) for humpback whales sampled from catches in the North Pacific Ocean. In his samples the mean length of females at physical maturity was approximately 45·0 ft, while that of the males was close to 43·8 ft. The data do not indicate any real difference in rate of growth of humpback whales in the northern and southern hemispheres.

The largest individual whales of each sex examined by the author were a male of 47 ft, and a female of 51 ft. The latter was not yet physically mature, as the fusion of the posterior vertebral epiphyses had not extended further forwards than the sixth lumbar vertebra, so that this female had not completed its growth.

The oldest humpback whale (based on the examination of ear plugs) examined by the author was 48 years of age (95 ear plug laminations).

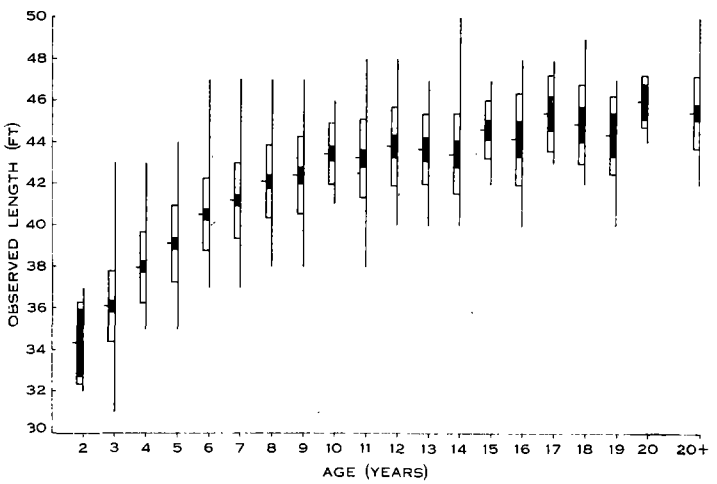


Fig. 18.—Observed lengths within age groups of females sampled at Australian stations. Key as for Figure 17.

IV. History of Exploitation

The group IV population was hunted along the west coast of Australia from 1912 to 1916, from 1925 to 1928, and from 1936 to 1938 (Ruud 1952) and, in the latest cycle, from 1949 to 1963. Insignificant catches were obtained from this population in the Antarctic prior to 1934, but hunting there was intensified from the summer season of 1934–35 to that of 1938–39 (Jonsgård, Ruud, and Øynes 1957).

Ruud indicated that the severely depleted condition of the group IV population in 1938 was caused by the slaughter along the west coast of Australia of 7244 humpback whales from 1936 to 1938. However, the killing of 5429 humpback whales from the same population in the Antarctic from 1934–35 to 1938–39 must also have contributed to the condition of the population in 1938.

From 1935 to 1939 at least 12,673 humpback whales (6804 males and 5869 females) were taken from the group IV population. The catch per unit effort declined towards the end of this period (Ruud 1952) and catching was concentrated upon small whales (see Tables 11 and 12), indicating that the population had been severely depleted.

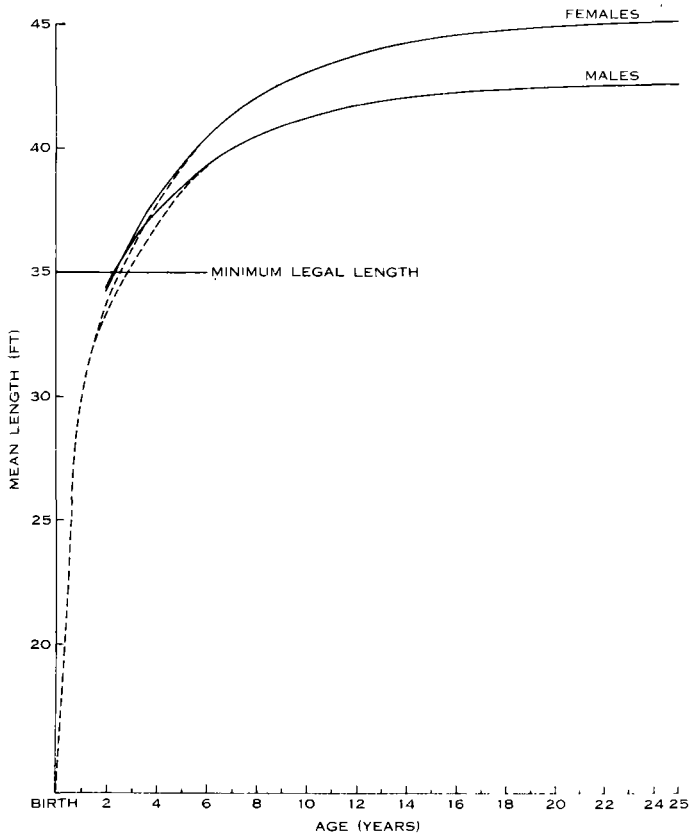


Fig. 19.—Growth curves for group IV and V humpback whales. Solid line estimated from samples of commercial catch; broken line approximate position for natural population.

Individuals of 35 ft in length were highly vulnerable from 1935 to 1939, as shown in Figure 20. Most humpback whales of 35 ft are 3 and 4 years of age (see Section III(*c*)). Therefore, in 1938, humpback whales aged from 3 years and above were greatly reduced in numbers. This means that the year class of 1935, and all earlier year classes, were much reduced by the exploitation of this population from 1935 to 1938. Year classes subsequent to that of 1935 must also have been smaller than year classes in an unfished population, because of the smaller numbers of mature females in the reduced breeding stock.

Humpback whales were fully protected in the Antarctic from 1939 to 1949 except for a temporary relaxation in 1940–41. There was no coastal whaling from Australia during this period.

When commercial operations were re-opened in 1949, the group IV population had apparently recovered in numbers from the depletion induced between 1935 and 1939, but it would still have been deficient in old whales (especially those over 14 years of age) as a result of the operations prior to 1939.

TABLE 11

LENGTH FREQUENCY DISTRIBUTION OF HUMPBACK WHALES TAKEN FROM ANTARCTIC AREA IV, 1934–39

Body Length (ft)	Males						Females					
	1934–35	1935–36	1936–37	1937–38	1938–39	Total Males	1934–35	1935–36	1936–37	1937–38	1938–39	Total Females
24	1					1						
25												
26	1					1						
27	3					3	2		1			3
28	3				1	4	1		2			3
29	2		1		1	4	3			1	1	5
30	6		2	1		9	5		2	1	1	9
31	8		3	1	3	15	2		5	1	3	11
32	18		8	1	1	28	6	1	8	4	7	26
33	18	1	17	2	9	47	9	1	18	1	6	35
34	26	2	22	6	5	61	16		12	4	3	35
35	31	14	43	19	62	169	23	22	37	24	68	174
36	50	17	51	32	30	180	37	32	39	20	33	161
37	46	18	57	22	23	166	26	32	45	23	50	176
38	48	32	48	21	36	185	29	22	43	24	40	158
39	35	34	46	26	7	148	34	34	40	23	21	152
40	73	36	77	45	30	261	55	56	83	53	69	316
41	52	30	60	29	14	185	45	57	45	60	48	255
42	73	22	68	18	11	192	89	50	67	78	59	343
43	47	18	54	18	11	148	66	74	62	78	54	334
44	27	19	44	5	3	98	60	70	63	50	22	265
45	23	9	32	5	6	75	56	92	65	71	54	338
46	15	11	12	2	1	41	51	50	52	36	27	216
47	8	5	14		1	28	37	32	28	32	22	151
48	5	3	3	2		13	33	17	26	15	11	102
49		1	1			2	10	8	12	4		34
50	1					1	10	11	11	8	4	44
51							2	2	5			9
52							2	3	2			7
53							1					1
54												
55												
56												
57	1					1						
Total	621	272	663	255	255	2066	710	666	773	611	603	3363

Catches from this population since 1949 (listed in Table 1) have been limited in various ways. Australian whaling stations have been allotted separate quotas of humpback whales each year by the Australian Government. Catching of humpback

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whales in the Antarctic (south of 40°S.) was limited to 1250 humpback whales each summer from 1949–50 to 1951–52. This quota applied to the whole of the Antarctic region with the exception of the area from 70°W. to 160°W. which was declared a sanctuary. Since the summer season of 1952–53, limitation of the humpback whale

TABLE 12

LENGTH FREQUENCY DISTRIBUTION OF HUMPBACK WHALES TAKEN FROM WEST COAST OF AUSTRALIA, 1936–38

Body Length (ft)	Males				Females			
	1936	1937	1938	Total Males	1936	1937	1938	Total Females
24	2			2				
25	4	1		5		1		1
26								
27	1			1	2	2		4
28	3	4	1	8	2	2		4
29	6	1		7	2	1	1	4
30	20	11	1	32	13	16	3	32
31	31	10	4	45	19	9		28
32	41	11	5	57	30	9	3	42
33	49	14	7	70	35	12	5	52
34	52	5	1	58	26	9	1	36
35	217	221	63	501	129	101	40	270
36	151	189	60	400	84	108	33	225
37	135	178	50	363	78	86	29	193
38	215	187	57	459	82	76	28	186
39	188	162	51	401	54	65	28	147
40	280	360	58	698	72	127	31	230
41	246	125	52	423	49	57	34	140
42	191	258	39	488	47	129	41	217
43	153	140	35	328	60	93	40	193
44	85	109	21	215	40	63	35	138
45	45	50	6	101	43	85	21	149
46	18	34	4	56	32	57	15	104
47	5	9		14	15	38	7	60
48	4	1		5	10	18	6	34
49	1			1	5	5	1	11
50					1	2		3
51					1			1
52					2			2
Total	2143	2080	515	4738	933	1171	402	2506

catch has been affected by setting a limit to the time of taking humpback whales (generally a period of 4 days) instead of a direct limit on the number of humpback whales to be taken. The area south of 40°S. from 70°W. to 160°W. remained a sanctuary until the summer of 1955–56. From the summer of 1954–55, waters south of 40°S. between 0° and 70°W. have also been closed to humpback whaling. In 1958–59, the western boundary of this closed sector was changed to 60°W.

In 1960 the International Whaling Commission proposed to amend the Schedule to the Convention by closing Antarctic area IV (70°E.–130°E.) to humpback whaling for a period of 3 years, and reducing the open season for humpback whaling in Antarctic area V (130°E.–170°W.) from 4 days to 3 days in each of the following three seasons. However, objections lodged by the governments of Japan, Norway, U.S.S.R., and the United Kingdom (most of the countries engaged in pelagic whaling south of 40°S.) rendered these amendments ineffective, so that the regulations for humpback whaling in 1960–61 reverted to a 4-day season for the whole of Antarctic waters (south of 40°S.), with the exception of the area between 0° and 60°W. which remained closed to humpback whaling.

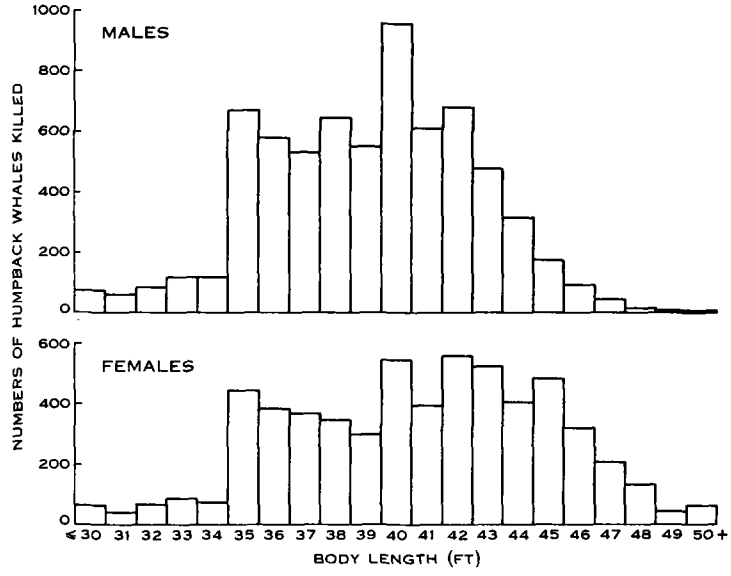


Fig. 20.—Frequency distribution of length in total catch of humpback whales taken from the group IV population, 1935–39.

The group V population was fished only lightly in the years prior to 1950. In the feeding area of this population (130°E.–170°W.), 24 humpback whales were recorded in International Whaling Statistics as killed during the summer of 1938–39, and Omura (1953) referred to 201 humpback whales which were killed in this area during the summer of 1940–41. For some years small catches had been taken in New Zealand (Dawbin 1956); and prior to 1930 a few humpback whales were taken at Twofold Bay on the east coast of Australia (Dakin 1934).

Hunting of the group V population was re-opened in the Antarctic in 1949–50, and on the east coast of Australia in 1952, as shown in Table 2. Catch limits in these localities have been the same as those described above for the corresponding regions of the group IV population.

V. Population Structure

(*a*) *Sex Ratio*

Chittleborough (1958*c*) recorded 51·9% males amongst 1448 humpback whale foetuses taken during mid-pregnancy from Antarctic areas IV and V. At Australian whaling stations, 615 near-term foetuses have been recorded in the catches from 1949 to 1962; 52·2% of these were males. As foetuses are not subject to the sampling bias which is found in most commercial catches, the sex ratio at birth may be taken to be inclined towards males.

The sex ratio within the juvenile and adult portions of the population is less easily determined, because of varying kinds and intensity of selection applied in commercial whaling. Matthews (1938) has shown that females predominate in Antarctic (area II) catches, while males are in excess of females in catches from temperate waters (South Africa). Table 13 shows that this also occurs in catches from the group IV and group V populations of humpback whales.

The cause of the excess of females in Antarctic catches is obscure. There is no evidence of any segregation of the sexes during the summer feeding period.

The reasons for the excess of males in most catches from temperate and tropical regions are less obscure. Some 37% of the mature females give birth each year (Section III(*a*)(iv)), and pregnant females are late in the northward migration (Section II(*d*)(ii)), giving birth soon after reaching temperate waters, so that in subtropical waters at least one-third of the mature females are protected. Catches in warm waters would then be expected to have a preponderance of males.

The area in which chasers from the whaling station near Albany (Western Australia) operate is one of the few in which mature males and females are equally vulnerable, pregnant females being killed when they first reach 35°S. latitude, and before parturition occurs. The relative abundance of mature males and females can be measured by the catch per unit effort within weekly periods throughout the northward migration past this station (Table 7). From these data, the ratio of abundance of mature males to mature females for the whole of the northward migration was 5·17 : 4·71 or 52·3% males. This is in close agreement with the percentage of males at birth.

Table 13 shows that on both the west and east coasts of Australia, the percentage of males in the annual catch tended to decrease in successive years. Budker (1953) showed a similar trend within catches off the coast of Gabon, the percentages of males killed being:

Year	Total Catch	Males (%)
1949	1356	64·6
1950	1404	57·6
1951	1105	49·1
1952	246	41·6

Because of differences in the times of migration of various categories (Section II (*d*)(ii)), the sex ratio within the catches will change as the humpback migratory stream moves past the shore stations. Thus, a change in the sex ratio of the total catch

from one year to another could be caused by the whaling operations having taken place over different periods of the 2 years. However, Chittleborough (1960*a*, Fig. 10)

TABLE 13

PERCENTAGES OF MALES IN CATCHES FROM THE GROUP IV AND V POPULATIONS OF HUMPBACK WHALES

Year	Total Catch	Number of Males	Percentage of Males	Year	Total Catch	Number of Males	Percentage of Males
	West coast of Australia				*Antarctic area IV*		
1935	0	0	—	1935	1331	621	46·7
1936	3076	2143	69·7	1936	938	272	29·0
1937	3251	2080	64·0	1937	1436	663	46·2
1938	917	515	56·2	1938	866	255	29·4
1939	0	0	—	1939	858	255	29·7
Total	7244	4738	65·4	Total	5429	2066	38·1
1949	190	135	71·1	1949	0	0	—
1950	387	250	64·6	1950	779	354	45·4
1951	1217	907	74·5	1951	1112	468	42·1
1952	1182	666	56·3	1952	1127	546	48·4
1953	1297	726	56·0	1953	193	103	53·4
1954	1309	692	52·9	1954	258	133	51·6
1955	1123	580	51·6	1955	28	12	42·9
1956	1119	676	60·4	1956	824	320	38·8
1957	1119	583	52·1	1957	0	0	—
1958	967	509	52·6	1958	0	0	—
1959	700	331	47·3	1959	1413	645	45·6
1960	545	271	49·7	1960	66	28	42·4
1961	578	306	52·9	1961	4	3	
1962	543	304	56·0	1962	56	24	42·9
Total	12,276	6936	56·5	Total	5860	2636	45·0
	East coast of Australia				*Antarctic area V*		
1950	0	0	—	1950	903	441	48·8
1951	0	0	—	1951	162	79	48·8
1952	598	448	74·9	1952	146	51	34·9
1952	700	509	72·7	1953	504	212	42·1
1954	718	511	71·2	1954	0	0	—
1955	720	494	68·6	1955	1097	457	41·7
1956	720	485	67·4	1956	194	91	46·9
1957	721	492	68·2	1957	0	0	—
1958	720	511	71·0	1958	0	0	—
1959	810	543	67·0	1959	885	458	5i·8
1960	810	496	61·2	1960	931	407	43·7
1961	731	448	61·3	1961	293	135	46·1
1962	177	103	58·2	1962	0	0	—
Total	7425	5040	67·9	Total	5115	2331	45·6

showed that when the same (weekly) periods at the same locality are compared, there has been a regular increase in the percentage of females in the catches of recent years.

The decline in the percentage of males in the catch is linked with the rate of exploitation of the population in lower latitudes. Intensive fishing in warm waters reduces the male portion of the population faster than the female portion. This effect is even greater over the range of mature individuals because commercial catches initially contain more immature females than immature males (see Section V(*d*)). Since the stock of mature males is reduced faster than that of the mature females, the percentage of males in the total catch decreases from year to year. This trend can occur only when the greater part of the total catch is taken from lower latitudes (temperate and subtropical waters), rather than from Antarctic waters.

Of the total overall catch of humpback whales from the whole of the group IV population from 1949 to 1962, 52·8% of the 18,136 humpback whales killed were males. This is very close to the percentage of males at birth and the estimate of the percentage of males in the stock of adults passing Albany during the northward migration.

(*b*) *Size Composition*

(i) *Relation between Size Composition of Catch and of Population*

As stressed in Section I (*b*) (i), commercial catches of whales may be far from random samples of the populations from which they were drawn. The size composition of a particular catch depends on the following factors:

(1) Rate of growth of individuals;

(2) Natural mortality;

(3) Time and place of sampling;

(4) Level of selection by gunners;

(5) Effects of previous hunting (fishing mortality).

There is no evidence that either the first or second of these has changed appreciably during recent years, and variations in the time and place of sampling have had only slight effect upon the size composition of catches. Changes in the size composition of the catches have therefore been the result primarily of variations in the level of selection by gunners and the effects of previous fishing mortality.

The level of selection by gunners has not been simply the observation of the minimum legal length of 35 ft. Selection (by size) has varied from one gunner to another, from one whaling station to another, and from one time to another. Selectivity has been influenced greatly by the type of incentive payments made to gunners. Bonuses based upon numbers of whales killed tend to discourage selection, because under those conditions gunners take whatever appears to be safely over 35 ft in length. On the other hand, bonuses based on oil yield or directly upon the length of each whale, lead gunners to look for bigger whales. Chittleborough (1960*b*) has shown that the mean length of pubertal females taken each year on the Australian coast has varied with the degree of selection applied by gunners and has also been influenced by previous selective killing of a diminishing stock.

In the Antarctic, limitation of the pelagic catch by limiting either the period of open season, or the total number of whales to be caught, had resulted in strong

competition between the various expeditions for the highest proportion of the overall catch, so that selection there was at a minimum.

(ii) *Catches from the Group IV Humpback Whale Population*

The size composition of the catches recorded from the group IV population of humpback whales from 1949 to 1962 is shown in Tables 14–17. The majority of these data are from catch returns forwarded to the Bureau of International Whaling Statistics in Sandefjord, Norway. The data for Antarctic catches of 1959 have been adjusted in accordance with the evidence (Chittleborough 1959*b*) of intermingling of the group IV and V populations of humpback whales in the eastern portion of Antarctic area IV during the summer of 1958–59.

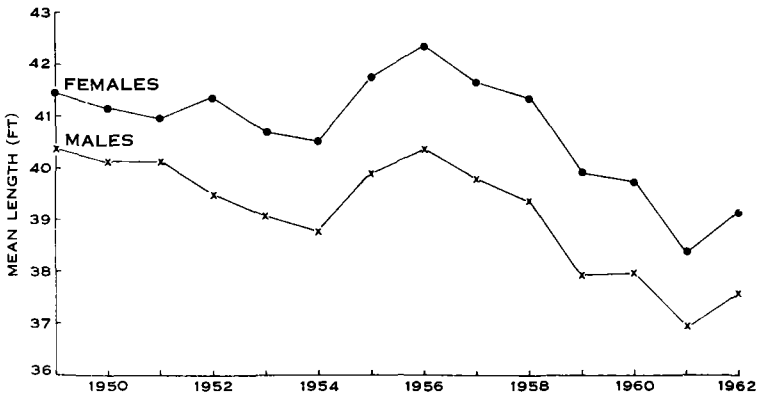


Fig. 21.—Mean lengths of annual catches of male and female humpback whales from the west coast of Australia, 1949–62.

There was little change in selectivity on the west coast of Australia from 1949 to 1954, but the mean lengths of both males and females in the catch declined during this period (Tables 14 and 15, Fig. 21). Mature males were more heavily fished than the mature females, with the result that the mean length of the males decreased more rapidly than that of the females.

Reduction of quotas prior to the 1955 whaling season (Table 1) stimulated more careful selection of large whales. At one station on the west coast the gunners were instructed to shoot, where possible, only those whales that appeared to be 40 ft or more in length, while another station introduced a new bonus system whereby the catchers were paid a bonus for every whale exceeding the average length in the previous season of 39·58 ft.

With the closing of one station on the west coast in 1956 (Table 1) and the concentration of catching power at Carnarvon, the level of selection was raised still higher, and the mean lengths of males and females in the catch rose to maxima in that year (Fig. 21). The increased selection from 1954 to 1956 caused the mean length of the females to rise more than that of the more heavily fished males.

Although attempts were made to maintain a high degree of selection after 1956, large whales became less abundant each year, so that gunners were obliged to accept

TABLE 14

GROUP IV POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the west coast of Australia—Males

Length (ft)	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
30				1		1							1	
31		1												
32		2		1	4					1			2	2
33			5	3	4			2			4	4	3	1
34				5	1		1		4	2	3	3	6	1
35	1	5	17	38	49	46	16	11	13	20	24	14	56	28
36	3	10	38	36	62	72	27	28	28	27	46	27	51	46
37	11	15	64	71	84	87	35	30	40	48	59	54	58	79
38	18	16	81	72	112	127	60	55	77	68	70	62	59	53
39	23	38	133	106	111	113	98	78	98	82	57	50	41	46
40	16	51	167	97	96	84	133	131	102	102	35	25	18	25
41	20	41	167	88	66	61	63	114	69	64	15	18	6	15
42	20	41	108	66	68	51	69	102	71	47	8	7	3	5
43	12	17	72	52	28	23	42	72	38	29	2	5	1	3
44	6	8	37	18	21	18	19	29	27	10	3	2	1	
45	4	4	15	8	16	6	12	18	13	6	3			
46	1	1	3	3	4	3	4	2	3	2	1			
47				1			1	3		1	1			
48								1						
Total	135	250	907	666	726	692	580	676	583	509	331	271	306	304
Mean length (ft)	40·36	40·10	40·11	39·48	39·05	38·77	39·88	40·35	39·78	39·35	37·93	37·97	36·96	37·60

TABLE 15

GROUP IV POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the west coast of Australia—Females

Length (ft)	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
29				1	1		2							
30				1	2									
31				1	2		1							
32	1	1			1	1		1			1	1	1	
33	1		1	1		3	2	1			2	3	6	3
34		1	1						1	1	2	1		1
35	1	4	12	17	36	42	7	6	2	10	26	12	34	17
36	3	9	9	27	33	48	13	11	18	10	30	24	39	19
37	1	8	25	31	41	46	20	7	26	17	22	28	35	42
38	4	7	26	21	58	62	38	13	28	30	42	42	35	43
39	5	10	27	43	51	53	48	33	56	47	35	24	31	27
40	1	16	38	48	47	63	70	58	59	64	55	25	28	21
41	5	12	33	61	53	42	54	37	55	52	46	27	13	26
42	12	21	36	62	55	53	58	48	63	53	30	28	19	12
43	6	15	38	62	52	61	60	53	77	61	24	23	12	6
44	5	9	29	53	57	57	55	68	55	45	16	12	9	10
45	6	11	17	36	27	33	39	43	34	29	19	10	7	7
46	2	9	10	27	29	32	39	26	39	20	10	5	1	3
47	1	2	4	14	17	9	23	20	17	11	4	6	1	
48		2	2	7	8	7	9	10	5	8	5	1	1	
49	1		1	1	1	3	3	7	1			2		1
50			1	2		1	2	1						1
51														
52						1								
Total	55	137	310	516	571	617	543	443	536	458	369	274	272	239
Mean length (ft)	41·43	41·15	40·92	41·35	40·67	40·50	41·72	42·32	41·62	41·33	39·88	39·73	38·35	39·18

smaller whales, with the result that the mean lengths of males and females in the catch progressively declined, as shown in Figure 21.

In 1961 selectivity was changed again by a variation in whaling tactics. At the larger of the two remaining humpback whaling stations on the west coast of Australia (i.e. that at Carnarvon) the bonus system, previously based on the sizes of whales captured, reverted to one based on numbers captured. This stimulated the rate of

TABLE 16

GROUP IV POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the Antarctic — Males

Length (ft)	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
28			2										
29													
30	2	3	2	1						4			
31		1	1				1						
32	2	5	7	1		1				5			
33	4	10	13	5		1				1			
34	8	4	2				1			4			
35	19	11	68	10	11	1	14			74	6		2
36	31	38	46	12	9	1	35			84	3		2
37	34	57	40	14	19	1	53			105	3		2
38	22	40	43	19	24	1	48			116	4		3
39	36	55	63	13	24	1	42			94	6		2
40	58	62	74	9	19	2	58			65	3		8
41	40	60	62	5	8	1	34			47	2		2
42	46	56	52	6	11	1	16			33			3
43	25	33	28	4	3	1	8			8	1		
44	16	15	21	2	3		8			4			
45	8	17	13	1			2			1		1	
46	2		5		1								
47	1	1	3	1	1							1	
48												1	
49			1										
Total	354	468	546	103	133	12*	320	0	0	645*	28	3	24
Mean length (ft)	39·48	39·44	39·00	38·11	38·83		38·78			37·98			

*After adjustment of numbers reported to International Whaling Statistics.

capture of whales, and selection of large individuals was abandoned, so that the mean lengths of catches fell to the lowest level in 13 years (Fig. 21), catches being concentrated upon whales at or very close to the minimum legal length (Tables 14 and 15).

Because of the numbers of small humpback whales very close to the minimum legal length taken in 1961, the Australian companies were reminded prior to the 1962 humpback whaling season that the minimum legal length would be enforced strictly.

The mean length of males and females captured on the west coast in 1962 increased slightly from the values of the previous year (Fig. 21). This was achieved by sparing slightly higher proportions of individuals close to the minimum legal length; in other respects the length frequency distribution of the catches in 1962 was similar to that of 1961 (Tables 14 and 15).

TABLE 17

GROUP IV POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the Antarctic — Females

Length (ft)	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
27			2										
28										1			
29	2	1	1							1			
30	1	1	1		2					3			
31		1	5				1			6			
32	4	5	4		1		2			6			
33	6	9	8	3		1				1	1		
34	3	4	3			1							
35	11	15	52	7	11	1	15			68	6		1
36	13	26	32	3	5	1	43			70	3		2
37	18	28	24	7	11	1	37			55	1		4
38	27	50	29	10	18	1	40			75	1		5
39	38	47	48	8	13	1	46			80	4		2
40	45	48	58	9	18	2	63			91	2		3
41	36	69	52	10	12	1	65			80	2		1
42	62	97	54	13	9	2	60			74	1		8
43	47	79	54	5	8	1	39			52	3		3
44	49	71	43	3	5	1	38			42	7		2
45	32	35	40	4	4	1	24			30	2		
46	15	28	37	3	5	1	23			20			1
47	11	18	18	1			7			7	1		
48	4	10	10	4	2		1			3	3		
49	1	2	2										
50			2		1					3	1	1	
51			2										
Total	425	644	581	90	125	16*	504	0	0	768*	38	1	32
Mean length (ft)	41·15	41·22	40·72	40·26	39·72		40·52			39·67			

* After adjustment of numbers reported to International Whaling Statistics.

(iii) *Catches from the Group V Humpback Whale Population*

The size composition of the catches recorded from the group V population of humpback whales from 1949 to 1962 is shown in Tables 18–24. These records are from catch returns forwarded to the Bureau of International Whaling Statistics, with the exception that the data for Antarctic catches of 1955 (the summer of 1954–55) include the original records from the factory ship *Olympic Challenger*, instead of the amended returns supplied by that expedition to the Bureau of International Whaling Statistics.

The data for Antarctic catches of 1959 have been adjusted in accordance with the evidence of intermingling of the group IV and group V populations in that summer, as already discussed.

The size composition of catches taken on the east coast of Australia reflected changes in selectivity induced mainly by events on the west coast. Although the size composition of the catches on the east coast had not changed appreciably from 1952 to 1954, the slight reduction of quotas on the west coast prior to the 1955 whaling season,

TABLE 18

GROUP V POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the east coast of Australia — Males

Length (ft)	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
30			1		1						1
31	1	1									1
32	1		1		1					3	
33	1		1	2	2	2			2	1	1
34	1	2		1			1		1	2	
35	6	9	18	10	7	5	6	6	7	47	15
36	15	9	13	13	11	14	8	11	12	41	14
37	20	31	18	21	22	20	18	14	26	46	15
38	42	50	59	32	25	46	31	42	46	59	10
39	65	75	75	55	56	57	45	50	63	50	9
40	77	76	89	92	97	94	76	82	78	51	11
41	86	94	78	79	82	88	114	96	84	47	10
42	71	89	78	82	81	96	84	93	66	51	7
43	40	56	47	66	51	40	75	81	62	25	5
44	15	14	19	30	27	23	26	43	31	13	1
45	6	3	11	7	15	3	15	18	9	8	
46	1		3	3	6	4	12	6	5	3	
47				1				1	3	1	
48					1				1		
Total No.	448	509	511	494	485	492	511	543	496	448	100
Mean length (ft)	40·25	40·25	40·17	40·59	40·65	40·38	40·96	41·00	40·47	39·06	38·03

caused more stringent selection of large whales to be applied on the east coast from that year onwards. The mean lengths of both males and females in the catches increased in 1955 and remained high until 1959 (Fig. 22). The mean length of males and females decreased slightly from 1959 to 1960, and in the following years fell drastically (Fig. 22), the mean length of the females taken on the east coast in 1962 being less than that of the females taken on the west coast of Australia in the same year (Tables 19 and 15, respectively).

The small catches taken off Norfolk I. were generally composed of humpback whales larger than those in the catches from other localities within this population (compare Table 20 with Tables 18, 19, and 21–24). This has been due mainly to the

very stringent selection of large whales successfully applied by the small station at Norfolk I., rather than to real differences in the size composition of the whales passing the various sampling points.

In the decline in size composition of catches from the two populations the mean length of the males from the group IV population decreased more rapidly than that of the females, whereas in the group V population the mean length of the

TABLE 19

GROUP V POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the east coast of Australia — Females

Length (ft)	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
31						1	1				
32	1	2	3							3	
33		2	4		1		1	1	1	2	1
34		1			1	1	1		2	4	6
35	5	7	9	7	3	7	1	1	4	38	5
36	5	11	4	3	4	7	3	6	3	21	12
37	11	7	6	12	15	13	5	11	15	28	6
38	6	11	20	13	10	17	14	15	11	32	8
39	15	21	28	21	11	16	12	19	25	33	4
40	14	11	16	27	22	14	18	15	35	23	11
41	20	29	31	22	23	29	22	29	38	24	3
42	22	34	24	27	30	33	30	33	43	25	6
43	21	32	19	27	42	24	26	36	43	12	4
44	14	12	17	23	34	27	22	41	27	7	3
45	10	5	8	22	20	18	26	26	28	18	2
46	1	1	12	9	9	12	15	18	20	5	1
47	4	3	5	9	8	4	7	13	12	3	1
48			1	3	2	4	4	2	3	4	
49		1				1	1		2	1	
50		1				1		1	2		
51				1							
52	1										
Total No.	150	191	207	226	235	229	209	267	314	283	73
Mean length (ft)	41·06	40·66	40·74	41·66	41·85	41·47	42·15	42·22	41·88	39·22	38·64

females decreased far more rapidly than that of the males. These differences resulted from higher fishing mortality in males than in females of the group IV population, and the reverse in the case of the group V population, as discussed in Section VII.

The maintenance of the size composition of catches from the east coast up to 1959, contrasted with the declining sizes of whales taken on the west coast during the same period (Figs. 22 and 21, respectively), is further evidence of the lack of regular exchange between these two populations of humpback whales, as discussed in Section II(*b*).

(*c*) *Age Composition*

Ages were determined from collections of ear plugs and ovaries obtained from catches at Australian Whaling stations. Two laminations in the ear plugs were taken as representing 1 year, as shown by Chittleborough (1959*c*) and later verified by the evidence from two marked whales (Chittleborough 1960*c*, 1962). Age was estimated from the ovaries by dividing the total number of previous ovulations by 1·1 (the average annual rate of ovulation), and adding 5 years for the age at maturity (Chittleborough 1959*c*).

TABLE 20

DISTRIBUTION OF LENGTHS IN CATCHES AT NORFOLK I.

Length (ft)	Males							Females						
	1956	1957	1958	1959	1960	1961	1962	1956	1957	1958	1959	1960	1961	1962
30				1										
31														
32												2		
33			1									1		
34						2								
35	2	2		4		2		4				2	2	
36	4	1	1	4	1	2		1		1	3		4	
37	4	5	1	4	8	6		4	2	1	2	1	4	
38	3	4	2	8	9	8	1	3	2			1	5	
39	6	3	4	13	12	10		3		2	1	6	2	
40	8	14	11	15	15	18		6	2	4	3	7	2	
41	16	15	12	18	17	23	1	4	2	5	3	11	1	
42	17	19	12	13	21	23		5	5	5	4	7	8	
43	15	18	10	3	6	18		5	4	6	7	9	4	
44	11	7	5	4	3	5		4	1	10	12	9	3	
45	3	4	3	3	4	6	1	4	4	10	9	8	4	
46	2					1		6	4	6	11	5	1	
47	1	1	1					4		6	1	4	2	1
48								5	1	1	3	1	2	
49											1			
50													2	
Total catch	92	93	63	90	96	124	3	58	27	57	60	74	46	1
Mean length (ft)	41·31	41·24	41·35	40·75	40·48	40·85		42·09	42·47	43·40	43·47	42·10	41·46	

The sizes of these age samples in relation to the catches are shown in Table 3. Ear plugs were collected only from 1956 onwards. Collections of ovaries were always larger than those of ear plugs obtained from females.

Although the larger collections obtained in recent years may be taken as direct measures of the age composition of the corresponding commercial catches (Chittleborough 1962), the best estimate of the age distribution within the catch is obtained by applying the age–length key derived from the age sample to the length frequency distribution of the commercial catch (as discussed in Section I(*b*)(i)).

For a catch from which the age sample was small or not obtained, the most suitable age–length key should be applied to the length frequency distribution of that catch. Some care is required in the choice of the age–length key most applicable in such instances, because the age–length relation has been shown to vary from one catch to another from the same population as detailed in Section III(*c*). Selection of large whales may take the older whales almost at random, but from each of the younger age groups will take only the largest individuals. When most of the large whales have been removed by prolonged selective killing, only small individuals remain to

TABLE 21

GROUP V POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from New Zealand, 1949–62—Males*

Body Length (ft)	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
34			1	6		2		1	2	1		1		1
35	5	1	6	4	7	14	5	6	6	9	8	11	3	2
36	3	3	7	1	5	7	5	8	9	4	18	32	5	4
37	8	2	3	5	1	5	7	8	13	11	14	26	4	2
38	7	1	7	1	1	5	5	3	5	13	23	26	3	4
39	10	6	5	6	5	10	2	6	9	10	15	20	1	2
40	13	8	7	10	8	12	11	7	14	12	23	23	5	
41	9	11	8	11	3	16	6	12	14	10	24	27	10	2
42	15	7	9	8	8	12	8	7	9	18	24	17	4	1
43	2	9	8	8	12	6	8	9	13	7	9	20	8	3
44	9	2	5	5	6	6	6	4	4	10	16	13	4	1
45	4	2	3	6	3	4	4	5	2	4	5	7	3	
46	2		2		3	2	2		1	1	1	1		1
47	2		1		1	1		3	1	1	1	2		
48					2		2	1		1		1		
49				1										
50				1		1								
Total	89	52	72	73	65	103	71	80	102	112	181	227	50	23
Mean length (ft)	40·47	40·75	40·17	40·51	41·08	39·86	40·56	40·24	39·75	40·11	39·92	39·55	40·38	38·91

* Data from International Whaling Statistics.

be taken from the younger age groups. The few large whales in the catches will then be relatively young (fast growing) individuals which had escaped the catches for a time.

In estimating the age composition of the catches of males, the age–length key from each age sample was applied to the length frequency distribution of the corresponding catch, for each of the annual catches of males from the west coast from 1957 to 1962 (Table 25), and from the east coast in 1957, and from 1959 to 1962 (Table 26). For the catch of males taken on the east coast in 1958, a combined age–length key for all males aged on the east coast from 1957 to 1961 was applied to the length frequency distribution of the 1958 catch.

The size composition of catches of males from the east coast was fairly constant from 1952 to 1960 (Fig. 22) and there was little evidence of change in the age–length relation in collections of ear plugs obtained from 1957 to 1961. Therefore, a single age–length key, prepared from all males aged on the east coast from 1957 to 1961, was applied to the length frequency distribution of the east coast catches of males in each year from 1952 to 1956, to establish the age composition within catches of east coast males of those years.

TABLE 22

GROUP V POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from New Zealand, 1949–62—Females*

Body Length (ft)	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
33				1										
34				3	1	2	1		1					
35		3	2	6	6	6	2	7	8	2	7	6		
36	3		1	6	5	10	5	5	1	10	14	9	2	2
37	3	4	1	1	2	3	4	4	9	7	16	9	4	
38	4		2	3		5	2	5	2	1	8	16	6	1
39	5	1	8	1	2	3	1	6	7	3	10	9	3	3
40	6	2	3	2		7	7	1	4	3	10	12		1
41	7	4	3	2	4	7	1	6	9	6	10	12	1	1
42	5	3	5	7	2	7	7	3	6	5	5	16	3	
43	3	3	5	5	5	7	3	2	7	9	14	7	4	
44	4	2	4	3	3	4	1	8	11	8	13	9	5	
45	9	2	3	2	4	2	3	6	4	7	14	13		
46		2	1	3	3	6	1	6	6	6	8	12	1	
47				1	3	3		1	2	1	5	1		1
48		1		2	2	2	2	2	2	3	1	1	1	
49	2				2	3	1	1	1		2	2		
50			1											
51	1													
Total	52	27	39	48	44	77	41	63	80	71	137	134	30	9
Mean length (ft)	41·58	41·07	41·18	40·10	41·45	40·83	40·51	41·03	41·16	41·42	40·93	41·02	40·60	39·44

* Data from International Whaling Statistics.

Catches of males from the east coast from 1957 to 1961 appeared to be from a stock still containing a greater accumulation of old males than found in catches of the same years from the west coast of Australia (Chittleborough 1962). The lengths of the males taken on the west coast in earlier years (1949–1956) were generally greater than those of more recent years (Table 14). In the earlier years the group IV population probably contained an accumulation of old whales, although because of its previous history of exploitation (Section IV), the group IV population would not have contained, in the 1950's, as great an accumulation of old whales as the group V population.

The size composition of the catches of males from the west coast in the early 1950's was intermediate between the size composition of aged samples of males taken on the west and east coasts from 1957 to 1961 (Fig. 23). The age composition of

TABLE 23

GROUP V POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the Antarctic — Males*

Length (ft)	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
23						3							
24						1							
25	3												
26						5							
27						4							
28						6							
29			1			3							
30	1	1				14					1		
31						8							
32	5			1		22							
33	7	1		3		26					1	1	
34	3			1		14	4			1	4		
35	16	1	6	4		34	2			11	21	3	
36	20	1	3	12		38	6			24	32	5	
37	27	4	3	18		29	8			32	40	9	
38	26	6	3	20		45	17			34	44	25	
39	55	3	1	20		48	20			67	53	27	
40	73	12	8	31		63	18			70	46	19	
41	60	15	10	24		17	6			53	55	9	
42	62	15	4	39		31	4			82	43	11	
43	38	6	3	11		20	3			55	33	4	
44	21	8	4	15		11	2			17	17	14	
45	17	5	5	8		7	1			8	9	4	
46	3			2		4				3	3	3	
47	4	1		1		3				1	3	1	
48				1		1							
49													
50				1							1		
51													
53											1		
Total	441	79	51	212	0	457*	91	0	0	458†	407	135	0
Mean length (ft)	40·01	40·94	39·98	40·26		37·32	38·90			40·28	39·71	39·99	

* From original records of F.F. *Olympic Challenger*.

† Adjusted values.

catches of males from the west coast each year from 1949 to 1956 was estimated by applying to the length frequency distribution of each of these years a pooled age–length key obtained from all males aged on the west and east coasts in the period 1957 to 1961 (Table 25).

The age composition of catches of males at Norfolk I. was determined by applying an age–length key obtained from ear plugs collected there from 1957 to 1961, to the length frequency distribution of each year's catch, with the results shown in Table 27.

TABLE 24

GROUP V POPULATION OF HUMPBACK WHALES

Distribution of lengths within catches from the Antarctic — Females

Length (ft)	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
25						1							
26						3							
27						2							
28	1					3							
29						4							
30	1			1		10							
31	6					3					1		
32	5		1			16					1		
33	6			1		21					1	1	
34	3					19	1				4	2	
35	19	1	5	11		35	2			4	10	1	
36	17	1	2	11		27	8			19	25	2	
37	11	1	4	13		22	13			26	32	7	
38	33	2	4	10		39	12			21	37	17	
39	26	2	2	13		33	13			55	48	19	
40	48	8	3	29		78	15			41	56	18	
41	54	8	7	17		59	11			57	47	12	
42	61	11	11	48		84	5			53	49	17	
43	57	7	13	32		60	10			64	45	16	
44	50	18	12	32		53	5			30	57	12	
45	28	10	15	32		38	5			28	34	8	
46	20	9	8	22		19	1			17	35	6	
47	11	2	4	10		8	2			8	17	10	
48	5	2	3	5		3				2	9	3	
49		1	1	3						2	9	5	
50				2							2	1	
51											5	1	
Total	462	83	95	292	0	640*	103	0	0	427†	524	158	0
Mean length (ft)	41·00	42·99	42·49	42·01		39·79	39·92			41·26	41·56	41·72	

* From original records of F.F. *Olympic Challenger*.

† Adjusted values.

In the case of the females, ovaries were used for assessing the age composition of catches, since the samples of ovaries were far larger than those of ear plugs. An age–length key based on ovarian data does not separate immature and pubertal females (ovary group "O") into age groups: this was done by means of collections of ear plugs from immature and pubertal females.

From the discussion of selectivity in Sections I(*b*)(*i*) and V(*b*), the sequence of recent whaling on the west coast of Australia can be divided into three broad periods.

From 1949 to 1954 selection was at a low level; from 1955 to 1958 selection was high and effective; while from 1959 to 1962 selection was ineffective as the large whales had been removed from the population. An age–length key was prepared from the ovarian data collected on the west coast in each of these periods, and applied to the length frequency distribution of the annual catches within the respective periods, with the results shown in Table 28.

There have also been changes in selection of catch on the east coast of Australia, but not of quite the same magnitude, and though there has been a shift in the sizes and ages of whales taken, this has not resulted in a significant change in the age–length relation. Hence, the age composition of each year's catch of females from the east coast was determined by applying the length frequency distribution of that year's catch to a pooled age–length key containing all the ovarian data collected on that coast from 1952 to 1962, with the results shown in Table 29.

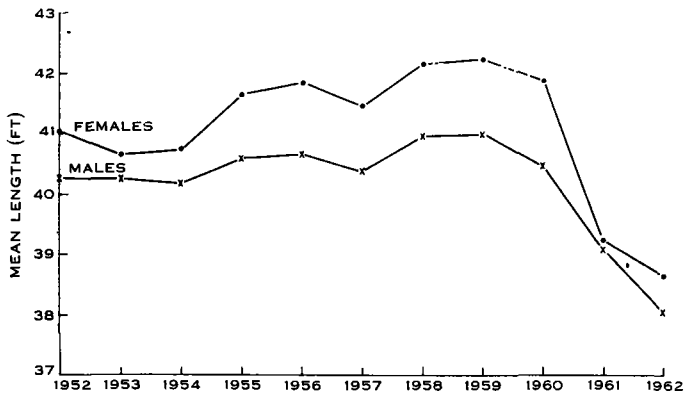


Fig. 22.—Mean lengths of annual catches of male and female humpback whales from the east coast of Australia, 1952–62.

The age composition of catches of females at Norfolk I. was estimated by applying an age–length key obtained from ovarian data collected there from 1956 to 1961, to the length frequency distribution of each year's catch, with the results shown in Table 30.

The age composition of these catches reflect the changes in size composition already discussed. The mean age of the adult males captured from the group IV population, was initially lower, and declined more rapidly, than that of the females (Table 31). The mean age of adults captured from the group V population remained at a relatively high level, falling abruptly in the last 2 years, the mean age of the females falling to a lower level than that of the males.

(d) Physiological Condition

(i) *Immature Fraction*

Because of the application of the minimum legal length, the immature individuals will always be a smaller proportion of the commercial catch than they are of the whole population. Since the mean length at puberty of females is greater than that

of males, i.e. 38 ft 6 in. for females (Chittleborough 1955*b*), and 36 ft 9 in. for males (Chittleborough 1955*a*), commercial catches will contain higher percentages of immature females than of immature males. Nevertheless, the proportions of immature males and females in the catches at a particular locality should remain constant from year to year if the level of selection and the composition of the population do not change. Tables 32 and 33 show that the percentages of immature males

TABLE 25

GROUP IV POPULATION OF HUMPBACK WHALES

Estimated distribution of age in annual catches of males from the west coast of Australia, 1949–62*

Age (yr)	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
2	0	3	3	7	8	6	2	2	3	7	5	4	7	6
3	4	11	40	54	72	70	28	25	27	29	17	50	76	88
4	12	20	81	81	110	118	55	50	67	70	77	54	82	72
5	20	34	129	101	119	123	87	85	125	115	67	67	56	85
6	19	36	131	96	106	106	90	91	81	106	71	37	39	17
7	13	25	92	60	63	61	60	66	77	45	34	18	24	16
8	9	18	66	42	40	37	40	49	45	25	24	13	7	8
9	9	18	65	40	39	34	39	51	39	43	5	8	6	3
10	6	12	41	26	24	21	25	33	26	5	10	5	5	2
11	6	11	37	22	21	17	22	30	17	15	8	2		4
12	5	9	31	19	17	15	18	25	4	12	3	3		
13	5	9	33	21	18	15	20	28	15	17	1		2	
14	3	5	17	10	9	8	11	15	13	4		3		
15	2	4	14	9	8	6	8	12	6					
16	3	5	19	11	11	9	11	17	4	6			1	
17	3	4	17	10	9	7	10	14	3			2	1	
18	2	3	11	7	5	4	6	9						2
19	2	3	10	6	6	4	6	9	4					
20	1	2	8	5	5	4	4	6	6		3			1
20+	11	18	62	39	36	27	38	59	21	10	6	5		
Total catch	135	250	907	666	726	692	580	676	583	509	331	271	306	304

* Using separate ear plug age–length keys of individual samples in each of 1957, 1958, 1959, 1960, 1961, and 1962. For period 1949–56 using combined age–length key; west coast plus east coast, 1956–61.

and females in samples of the catches from the west and east coasts of Australia have not remained constant during the last decade. Percentages of immature whales generally increased from 1951 to 1954, decreased for a time when the level of selection was raised from 1955, then increased as the mature stock decreased in size. The recent increase in the percentage of immature whales captured from the group V population (Table 33) was far more abrupt than the change in catches from the group IV population (Table 32).

(ii) *Pregnant Females*

As discussed by Chittleborough (1958*a*), pregnant individuals constitute a greater proportion of the catch of mature females in the Antarctic (summer months)

than of the catches of mature females from lower latitudes (winter months). This is because females carrying near-term foetuses are later than other females in their northward migration (Section II(*d*)(ii)), and give birth very soon after reaching temperate regions. On the other hand, as most conceptions take place during August, catches in September and October (also from temperate and subtropical regions) will include females in the very early stages of pregnancy. These small embryos are not easy to locate, and so are not always recorded.

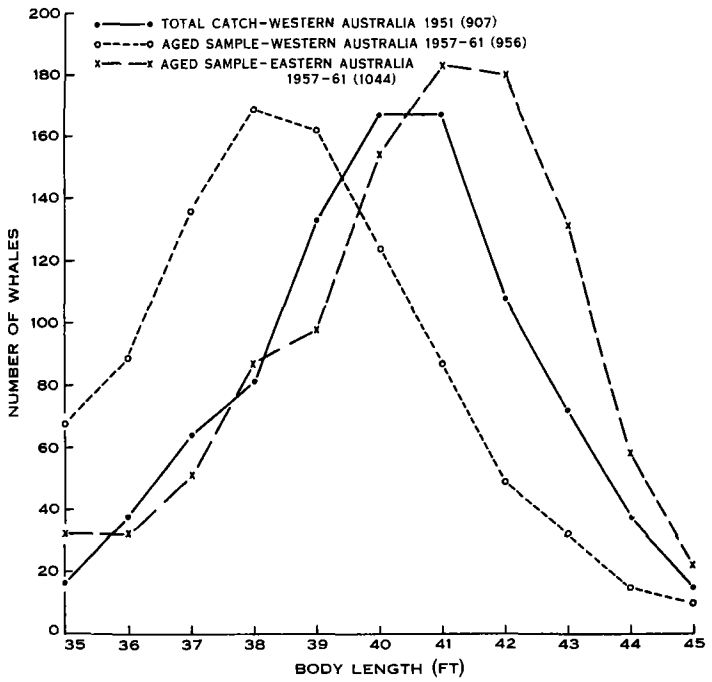


Fig. 23.—Size composition of males in the catch from the west coast of Australia in 1951 compared with size composition of east and west coast samples of males aged by means of ear plugs.

As shown in Section III(*a*)(iv), the average annual birth rate for this species is 0·37, there being 37·2% of the mature females pregnant at one time. No evidence has been found of any variation in the birth rate which might be related to changes in population size brought about by commercial exploitation.

VI. Population Density

(*a*) *Fishing Effort and Catch per Unit Effort*

The abundance of whales at one time or place relative to another can be compared using measurements of catch per unit effort, provided that effort is expressed in terms of a unit which has the same value at all times and places. The unit of effort might be defined as the operation of a vessel, gunner, and crew of standard efficiency or "catching power" in unit area of ocean for unit time. Units of time or area are simple enough, but the catching power is a complex thing, combining the

abilities of the vessel, crew, and gunner, to locate, chase, and kill whales. The catching powers of whaling vessels are variable and have been increased over the years as vessels have increased in size, range, speed, and power; as navigational and whale finding aids have been installed; and as gunners and crews have gained in experience.

While all would agree that the unit of effort should be based upon a vessel (and crew) of standard catching power, as yet no one has succeeded in calibrating all the factors affecting the catching power of vessels, so enabling the catching powers of whaling vessels to be measured in terms of a standard unit.

TABLE 26

GROUP V POPULATION OF HUMPBACK WHALES

Estimated distribution of age in annual catches of males from the east coast of Australia, 1952–62*

Age (yr)	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
2	2	1	1		2	2	0	0	0	5	5
3	16	18	23	19	15	14	12	3	26	67	28
4	28	31	31	25	23	28	20	18	13	72	10
5	45	51	53	41	40	43	38	52	41	44	21
6	56	63	65	55	55	57	52	58	69	46	10
7	42	48	47	42	42	27	42	43	41	47	1
8	35	39	38	36	37	32	39	37	44	28	5
9	34	38	36	36	36	22	40	35	45	32	5
10	24	27	27	29	28	27	30	39	30	7	3
11	21	25	24	25	25	30	27	43	17	6	2
12	21	25	24	25	24	17	27	24	24	21	3
13	20	24	23	26	25	30	27	30	30	10	0
14	10	11	12	13	13	16	14	6	16	6	0
15	11	12	12	12	12	17	14	23	10	6	2
16	12	14	14	16	15	17	18	23	16	5	1
17	11	13	13	15	15	9	17	21	13	8	1
18	8	10	9	11	10	13	14	10	4	8	1
19	7	8	8	9	9	4	12	16	14	1	0
20	5	6	5	6	5	7	6	7	8	3	0
20+	40	45	46	53	54	80	62	55	35	26	2
Total catch	448	509	511	494	485	492	511	543	496	448	100

* Using separate ear plug age–length keys of individual samples in each of 1957, 1959, 1960, 1961, and 1962. For 1958, and period 1952–56, using the combined age–length key of all east coast male samples 1957–61.

The unit of effort used so far in whale research is the "catcher's day's work", introduced by Hjort, Lie, and Ruud (1933). This unit refers only to days when hunting was in progress: days lost by individual catchers due to adverse weather, mechanical failure, etc., should not be included as fishing effort. Hjort, Lie, and Ruud were well aware that the catcher's day's work was not a constant unit of effort, but at that time they considered that the variable factors were of minor importance in relation to changes in the size of the stock.

The importance of some of these variable factors can be demonstrated from data obtained in recent years from whaling operations along Australian coasts.

The catcher's day's work is based on a 24-hr period, a variable portion of which is spent in actual whale hunting. In their earlier years of operations, Australian whaling stations generally had greater daily catching power (of the vessels) than the daily processing capacity (of the factory). Because of this, catching vessels were very often allotted a limited number of humpback whales to be killed in a day. In successive years the average catch per catcher's day's work increased (Fig. 24)

TABLE 27

GROUP V POPULATION OF HUMPBACK WHALES

Estimated distribution of age within catches from Norfolk I. — Males*

Age (yr)	1956	1957	1958	1959	1960	1961	1962
2			1	1			
3	4	3	1	7	4	7	
4	5	4	2	8	7	7	
5	4	3	2	7	7	6	
6	3	4	3	5	5	5	
7	1	1	1	1	1	2	
8	4	5	3	4	6	6	
9	4	4	3	3	4	5	
10	7	8	5	8	9	11	
11	7	8	5	4	5	8	
12	5	5	4	7	7	8	
13	5	6	4	4	6	8	
14	5	6	4	5	6	8	
15	6	5	4	4	5	6	
16	5	4	3	4	3	5	
17	1	2	1	1	1	2	
18	2	3	2	2	2	4	
19	2	2	1	2	3	2	
20	1	1	1	1	1	2	
20+	21	19	13	12	14	22	
Total catch	92	93	63	90	96	124	3

* Applying age–length key from Norfolk I. ear plugs, 1957–61, to length frequency distribution of catches.

as the improved factory capacity and efficiency enabled whales to be processed (and hence killed) more rapidly. If the unit of effort (the catcher day) had been constant, such an increase in the rate of catching might well have been interpreted as the result of an increase in availability of whales.

On the other hand, the use of the catcher day as a unit of effort can mask a decrease in the availability of whales. For example, Table 34 shows that at Tangalooma in 1960 the catch per catcher's day's work was only slightly less than in previous years, but considerably more hours were spent hunting each day in 1960 than in previous years. In other words, a greater effort had to be expended each day in 1960 in order to maintain a daily rate of catching similar to that in previous years.

The number of hours spent in whaling during each catcher day may vary from one station to another (during the same year). For example, throughout the 1959 season the catcher at Byron Bay maintained an average of 8·8 hr of steaming per day, while in the same year, catchers at Carnarvon averaged 12·7 hr of steaming per day. Catchers operating on these populations of humpback whales in Antarctic areas IV and V were presumably steaming (and hunting) for almost the whole of each 24 hr because of the prolonged period of daylight.

TABLE 28

GROUP IV POPULATION OF HUMPBACK WHALES

Estimated distribution of age in annual catches of females from the west coast of Australia, 1949–62*

Age (yr)	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
2	0	0	1	2	3	3	2	2	2	2	2	2	2	2
3	4	11	27	40	58	66	41	26	40	36	45	36	49	41
4	4	12	29	43	63	72	45	29	44	39	49	39	53	45
5	4	12	28	43	61	70	44	28	43	39	48	38	52	44
6	4	13	33	44	54	60	57	42	58	52	50	35	33	31
7	4	12	29	44	47	52	67	54	67	62	37	25	21	22
8	4	9	22	34	37	38	45	37	46	40	26	19	14	14
9	5	11	26	43	41	41	34	29	36	31	20	15	11	13
10	3	7	15	26	23	25	27	24	28	24	13	8	6	5
11	4	8	18	32	30	30	24	21	24	19	13	9	6	4
12	3	7	15	27	24	24	17	15	18	14	14	10	6	3
13	3	6	11	22	20	21	16	16	16	12	8	6	4	2
14	2	4	9	16	14	15	16	15	16	13	5	4	2	1
15	1	3	6	12	11	11	16	16	16	12	4	3	2	0
16	2	6	11	23	21	24	21	20	21	16	9	6	3	2
17	0	1	2	4	4	5	13	12	12	10	4	2	1	3
18	1	2	3	6	5	6	13	13	10	8	4	2	2	1
19	1	0	1	2	2	2	6	6	6	5	1	1	0	1
20	1	1	2	5	5	5	7	6	6	4	2	1	0	1
20+	5	12	22	48	48	47	32	33	27	20	15	13	5	4
Total catch	55	137	310	516	571	617	543	444	536	458	369	274	272	239

* Using separate ovary age–length keys, 1949–54, 1955–58, 1959–61, on length frequency of catches. Ovary group "O" converted to age on ear plug data.

The number of hours per day spent in whaling can vary, during a season at one locality, inversely to changes in density of whales passing that point. For example, at Tangalooma in 1960, from June 6 to 15 there was a mean of 10·35 hunting hours per catcher day. From July 6 to 15 (height of migration past this station) a mean of 7·95 hunting hours per catcher day, and from August 6 to 15 (end of northward migration) a mean of 10·68 hunting hours per catcher day.

The hours spent hunting on a particular day might be reduced because of adverse weather, yet the unit of effort, the catcher's day's work, rates such a day as of equivalent fishing effort as a day when it was possible to stay on the whaling

grounds throughout daylight hours. This effect of weather upon the hours spent whaling might be expected to occur at random, so that it might not be important when comparing rates of catching over long periods of time. Nevertheless, whalers have claimed that adverse weather conditions have been the real cause of an apparent decrease in density of whales from one year to another (Chittleborough 1960*a*).

TABLE 29

GROUP V POPULATION OF HUMPBACK WHALES

Estimated distribution of age in annual catches of females from the east coast of Australia, 1952–62*

Age (yr)	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
2	0	1	1	1	1	1	1	1	1	2	5
3	13	18	21	17	15	18	12	15	20	45	18
4	14	20	22	19	17	20	13	17	22	50	12
5	14	19	22	18	16	20	13	17	21	49	11
6	15	20	23	22	20	21	18	22	30	27	10
7	12	16	16	17	16	16	15	17	24	17	4
8	13	17	17	18	19	19	17	21	27	17	2
9	10	12	11	14	16	14	13	17	20	11	1
10	8	10	10	12	15	12	12	16	17	8	2
11	8	10	9	12	14	12	13	16	18	9	2
12	7	8	8	11	13	11	11	15	16	7	2
13	5	6	6	8	10	8	9	11	12	6	1
14	5	6	5	7	9	7	7	10	10	4	0
15	3	3	4	5	6	5	6	7	8	4	0
16	6	7	7	10	12	10	11	14	15	7	0
17	2	2	4	5	5	5	5	7	7	3	0
18	2	2	2	3	4	3	4	5	5	2	0
19	1	1	2	2	2	2	2	4	3	1	1
20	1	1	2	2	2	3	3	3	4	1	0
20+	11	12	15	23	23	22	24	32	34	13	2
Total catch	150	191	207	226	235	229	209	267	314	283	73

* Applying age–length key for combined ovary samples east coast 1952–61, to length frequency distribution of each year's catch. Ovulation group "O" distributed on ear plug data.

The examples given above show that the catcher day is not a constant unit of time. In an attempt to obtain a more precise unit within which to measure fishing effort, all available ships' logs from Australian whaling companies were examined. Where a log had been kept in detail, it was generally possible to dissect each day's operations into various categories, namely:

(1) Total steaming time; all the time absent from moorings, irrespective of duties.

(2) Steaming time on that day's whaling; this excludes time spent away from moorings when engaged in bunkering, victualling, moving whales moored from the previous day's catch, and other transport duties.

(3) Steaming time hunting (and killing) whales; this excludes time spent steaming out to whaling grounds from the previous night's anchorage, and also

excludes time spent towing whales back to the station (and returning to the whaling grounds). Obviously the hunting time is restricted to daylight hours, whereas (2) may include several hours of darkness.

The "catcher's steaming hour", from category (2), is a more precise measure of whaling effort than the catcher's day's work, as any time at anchor when the factory does not require more whales, is omitted. It also eliminates parts of days lost due to minor repairs, refuelling, adverse weather, etc. Hours spent towing the catch back to the station are included in this unit of effort. Certain vessels can tow fewer whales, and at slower speeds, than others, so that their average catch per steaming hour may be depressed below that of other vessels of equal hunting efficiency but more suited to towing whales.

TABLE 30

GROUP V POPULATION OF HUMPBACK WHALES

Estimated distribution of age within catches from Norfolk I. — Females*

Age (yr)	1956	1957	1958	1959	1960	1961	1962
3	6	2	2	2	6	5	
4	6	2	2	3	6	6	
5	6	2	2	3	6	6	
6	4	3	3	3	5	4	
7	3	1	3	2	6	2	
8	2	1	2	2	4	1	
9	3	2	4	3	4	2	
10	1		2	2	2	1	
11	2	2	3	3	5	2	
12	1	1	2	3	3	1	
13	1		2	2	1	1	
14	1	1	2	1	1	1	
15	2	1	2	3	2	1	
16	2	1	3	3	3	1	
17	1	1	2	2	1	1	
18	1		1	1	1		
19							
20	1		2	3	2	1	
20+	15	7	18	19	16	10	
Total	58	27	57	60	74	46	1

* Applying age–length key from ovaries Norfolk I., 1956–61, to length frequency distribution of catches.

The "catcher's hunting hour", derived from category (3) above, is in theory the most precise measure of whaling effort. However, many ships' logs had not been entered in sufficient detail for this to be extracted for each day's operations, and consequently the catcher's steaming hours had to be taken as measure of effort for vessels operating at Point Cloates, Carnarvon, and Albany.

At Tangalooma and Byron Bay, catchers' hunting hours could be tallied. A catcher's steaming hour at the former station was not equal to a catcher's steaming

hour at other stations, because at Tangalooma one of the whaling vessels was stationed on the whaling grounds each day to act solely as a towing vessel. Thus, although the catching vessels might tow some whales to the station, their steaming time included a much lower proportion of towing time than did the steaming time of catchers at other stations.

The effective length of the catcher day has also been increased by mooring the catchers closer to the whaling grounds, and by the use of spotting aircraft. The increased effort achieved by these means has been calculated in terms of catcher hours (Chittleborough 1962).

TABLE 31

MEAN AGES OF ADULT HUMPBACK WHALES (OVER 5 YEARS OLD) IN CATCHES FROM THE WEST AND EAST COASTS OF AUSTRALIA

Year	Males		Females		Year	Males		Females	
	Number Taken	Mean Age (yr)	Number Taken	Mean Age (yr)		Number Taken	Mean Age (yr)	Number Taken	Mean Age (yr)
	West coast					*East coast*			
1949	99	11·16	43	11·98	1949	—		—	
1950	182	10·82	102	11·52	1950	—		—	
1951	654	10·78	225	11·04	1951	—		—	
1952	423	10·58	388	11·72	1952	357	11·48	109	11·34
1953	417	10·29	386	11·47	1953	408	11·52	133	10·99
1954	375	9·86	406	11·37	1954	403	11·52	141	11·33
1955	408	10·59	411	11·20	1955	409	12·01	171	11·94
1956	514	11·24	359	11·65	1956	405	11·99	186	12·06
1957	361	9·56	407	10·96	1957	405	12·87	170	11·98
1958	288	8·61	342	10·66	1958	441	12·32	170	12·36
1959	165	8·02	225	10·13	1959	470	12·20	217	12·52
1960	96	8·47	159	10·24	1960	416	11·31	250	12·08
1961	85	7·31	116	9·22	1961	260	10·75	137	10·83
1962	53	8·02	107	9·00	1962	36	10·08	27	9·12

In the conversion of aircraft flying hours into equivalent catcher hour units, a rather arbitrary relation was assumed, i.e. 1 aircraft flying hour equals 5 catcher steaming hours. This relation can be calculated where sighting records were made simultaneously from catchers and aircraft operating in the same area at the same time. For example, off Albany in the winter of 1961, two catchers sighted 226 humpback whales in a total of 605 steaming hours. Then 2·68 hours of steaming were required to sight one humpback whale. In the same period, the spotting aircraft sighted 241 humpback whales in 144·6 flying hours, i.e. 0·60 flying hours for each humpback whale sighted. In this instance, 2·68 catcher steaming hours were equivalent to 0·60 aircraft flying hours, or 4·7 catcher steaming hours were equivalent to 1 flying hour.

The relation between the catcher's steaming hour and the aircraft's flying hour would no doubt vary for different aircraft, catchers, personnel, and localities, but

in the case where the ratio could be calculated, the result was close to the value of 5 catcher steaming hours is equivalent to 1 aircraft flying hour, which has been used in calibrating fishing effort.

TABLE 32

GROUP IV POPULATION OF HUMPBACK WHALES

Immature whales in samples of catches from the west coast of Australia

Year	Males				Females			
	Total Catch	Number Examined	Number Immature*	Percentage Immature*	Total Catch	Number Examined	Number Immature and Pubertal	Percentage Immature and Pubertal
1951	907	395	36	9·1	310	90	20	22·2
1952	666	161	35	21·7	516	278	59	21·2
1953	726	111	37	33·3	569	246	93	37·8
1954	692	—	—	—	617	150	44	29·3
1955	580	—	—	—	538	—	—	—
1956	676	—	—	—	443	279	34	12·2
1957	583	488	66	13·5	536	521	134	25·7
1958	509	439	79	18·0	458	438	114	26·0
1959	331	254	88	34·6	369	352	124	35·2
1960	271	208	54	26·0	274	263	120	45·6
1961	306	291	137	47·1	272	263	157	59·7
1962	304	280	142	50·7	239	230	129	56·1

*Testes weights at or less than 4 kg.

TABLE 33

GROUP V POPULATION ON HUMPBACK WHALES

Immature whales in samples of catches from the east coast of Australia

Year	Males				Females			
	Total Catch	Number Examined	Number Immature*	Percentage Immature*	Total Catch	Number Examined	Number Immature	Percentage Immature
1952	448	233	32	13·7	150	102	24	23·5
1953	509	200	25	12·5	191	120	37	30·8
1954	511	298	36	12·1	207	148	49	33·1
1955	494	—	—	—	226	114	24	21·1
1956	485	60	2	3·3	235	139	25	18·0
1957	492	215	13	6·1	229	183	49	26·8
1958	511	205	17	8·3	209	121	29	24·0
1959	543	273	8	2·9	267	205	46	22·4
1960	496	293	22	7·5	314	212	44	20·8
1961	448	446	151	33·9	283	263	143	54·4
1962	100	100	44	44·0	73	73	39	53·4

*Testes weights at or less than 4 kg.

When using the catch per unit effort to compare the abundance of whales from one year to another, it is important that the effort was applied during the same

period of time in those years, because as shown by Chittleborough (1962, Figs. 4, 5, and 12; 1963 Fig. 6; and Figs. 3 and 4 in the present paper), the abundance of whales changes during the season, as the northward and southward migrating streams pass each shore station. The opening date and length of season has fluctuated at each Australian whaling station, but in most cases the stations were operated throughout the greater part of the northward migration. At Carnarvon the relative abundance (catch per unit effort) of humpback whales was measured each year from June 25 to August 26 (this being the only catching period common to every year from 1951 to 1962). At Tangalooma the relative abundance of humpback whales was measured each year from June 10 to August 5.

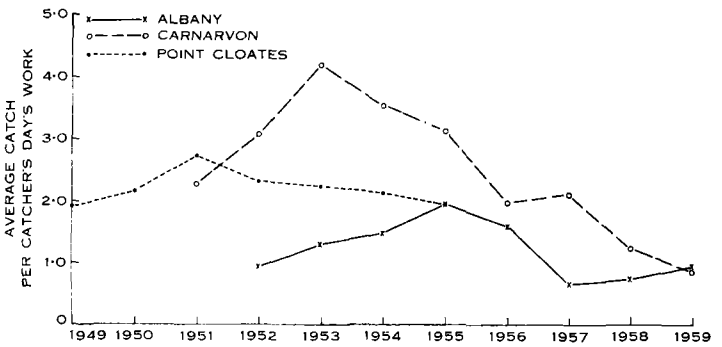


Fig. 24.—Average annual catch (humpback whales) per catcher's day's work at shore stations on the west coast of Australia.

In the measurement of fishing effort, variations in the "catching power" of whaling vessels present more difficulties than the units of time. The Australian whaling industry has employed as wide a range of types of vessels for hunting whales (Table 35), as could be found engaged in whaling in most other countries. Vessels differed very greatly in size, age, speed, manoeuvrability, towing power, and ability to operate successfully in heavy seas. Two small speedy launches, working together as one unit in coastal whaling, and the large steel "Antarctic"-type chaser, were not equivalent units of effort, nor would the relative efficiency of one type to the other, have remained the same under varied operating conditions (such as weather, or configuration of the coastline).

Table 34 shows that similar vessels, operated in the same locality, at the same time, by gunners of similar experience, achieved similar rates of catching. When dissimilar vessels, operating in one locality at the same time, are compared (Fig. 25), their contrasting rates of catching reflect their various efficiencies, during a period when whales were plentiful. However, when the population had been depleted, rates of catching converged to similar low levels, indicating that differences in catching power were of little importance when whales were scarce.

A number of the catchers have operated in each of the past 12 seasons on the Australian coast. This simplifies the analysis of fishing effort, because as pointed out by Hjort, Lie, and Ruud (1933), operations by the same vessels can be compared directly from one season to another. For present purposes, four catchers which

TABLE 34

OPERATIONS OF CATCHERS AT TANGALOOMA DURING PERIOD JUNE 10–AUGUST 5 OF EACH SEASON, 1953–62

Year	Vessel	Total Days Hunting	Total Hours Hunting	Total Humpback Whales Killed	Average Hunting Hours per Day	Average Whales per Catcher's Day's Work	Average Whales per Hunting Hour	Average Hours per Whale
1953	*Kos* I	55	247	171	4·49	3·11	0·69	1·44
1954	*Kos* VII	50	291½	157	5·83	3·14	0·54	1·86
1955	*Kos* II	45	312½	234	6·94	5·20	0·75	1·34
	Kos VII	56	326	263	5·82	4·70	0·81	1·24
	Total	101	638½	497	6·32	4·92	0·78	1·28
1956	*Kos* II	55	367	265	6·67	4·82	0·72	1·38
	Kos VII	55	374	257	6·80	4·67	0·69	1·46
	Total	110	741	522	6·74	4·75	0·70	1·42
1957	*Kos* I	55	387½	270	7·05	4·91	0·70	1·44
	Kos II	55	373½	274	6·79	4·98	0·73	1·36
	Total	110	761	544	6·92	4·95	0·71	1·40
1958	*Kos* I	55	389½	291	7·08	5·29	0·75	1·34
	Kos II	54	398½	300	7·38	5·56	0·75	1·33
	Total	109	788	591	7·23	5·42	0·75	1·33
1959	*Kos* I	57	401½	302	7·04	5·30	0·75	1·33
	Kos II	57	418	305	7·33	5·35	0·73	1·37
	Total	114	819½	607	7·19	5·32	0·74	1·35
1960	*Kos* I	57	532½	270	9·34	4·74	0·51	1·97
	Kos II	57	528½	284	9·27	4·98	0·54	1·86
	Total	114	1061	554	9·31	4·86	0·52	1·92
1961	*Kos* I	56	534¾	119	9·55	2·13	0·22	4·49
	Kos II	57	550½	131	9·66	2·30	0·24	4·20
	Total	113	1085¼	250	9·60	2·21	0·23	4·34
1962	*Looma* II	47	488¾	38	10·40	0·81	0·08	12·86
	Looma III	47	500	30	10·64	0·64	0·06	16·67
	Total	94	988¾	68	10·52	0·72	0·07	14·54

hunted each year on the west coast, and two which hunted each year on the east coast, have been used as standard units of catching power. The steaming or hunting hours of these catchers working in the same localities each year, and over the same period of time (during the northward migration), have been assessed. Adjustments have been made to the effort in those years where the effective hours were increased by the introduction of spotting aircraft or a change of moorings. These adjustments have been made in terms of equivalent steaming or hunting hours by the catchers used as the standard.

TABLE 35

SOME WHALE CATCHING VESSELS USED BY AUSTRALIAN COMPANIES

Vessel	Hull	Length (ft)	Tonnage		Engine
			Gross	Net	
Carnarvon	Steel	160	598	216	Steam
*Tangalooma**	Steel	147	392	294	Steam
Robert Moore	Steel	138	374	155	Steam
Gascoyne	Steel	137	344	123	Steam
Kos I	Steel	125	254	97	Steam
Kos II	Steel	125	254	97	Steam
Kos VII	Steel	125	253	108	Steam
Minilya	Steel	116	248	118	Steam
Cheynes	Steel	112	248	approx. 80	Steam
Haeremai Star	Wood	112	120	78	Twin diesel
Point Cloates	Wood	112	118	80	Twin diesel
Vigilant	Steel	98	101	26	Twin diesel
Norfolk Whaler	Wood	119	217	91	Twin diesel
Byrond I	Wood	109	113	90	Twin diesel
Cascade	Wood	36	Approx. 5 tons (dead weight)		Petrol
Kingston	Wood	36	Approx. 5 tons (dead weight)		Petrol

* Used for towing only.

The unit of effort used for the Australian seasons prior to 1955 was not precisely the same as that from 1955 onwards. Owing to a reduction in quota, a more vigorous management policy made the unit fishing time more effective from 1955. Assuming that the mortality coefficient of 1954–55 was the mean of the 1953–54 and the 1955–56 mortalities, then the effort units in 1954 and earlier years have to be reduced by a factor of 0·7 to equate them with the effort units of 1955 and later years.

From the adjusted effort, in standard units, applied each year by the same catchers operating in the same locality over the same period of time, and the catch of humpback whales taken by these same vessels under those conditions, indices of relative abundance (catch per unit effort) have been calculated for each year (Table 36).

Estimates of the total annual effort on the west coast of Australia were obtained for each winter season by multiplying the adjusted effort of the standard west coast catchers by the ratio of the total west coast catch to the catch by the standard catchers. The Antarctic (area IV) effort was estimated by dividing the catch in each summer

by the mean catch per unit effort of the standard west coast catchers during the two adjacent winters (Table 37). Corresponding estimates of total annual effort applied within the group V population were made using the data from the catchers used as a standard on the east coast of Australia, and the annual catches from the various localities within the group V population (Table 38).

Humpback whale fishing effort in Antarctic areas IV and V had to be estimated in terms of the Australian units, partly because full details of the effort data were not available from these areas, and also because a variety of species was being hunted simultaneously in these southern feeding grounds, making it extremely difficult to separate from the overall Antarctic effort, that portion which had been applied to humpback whales.

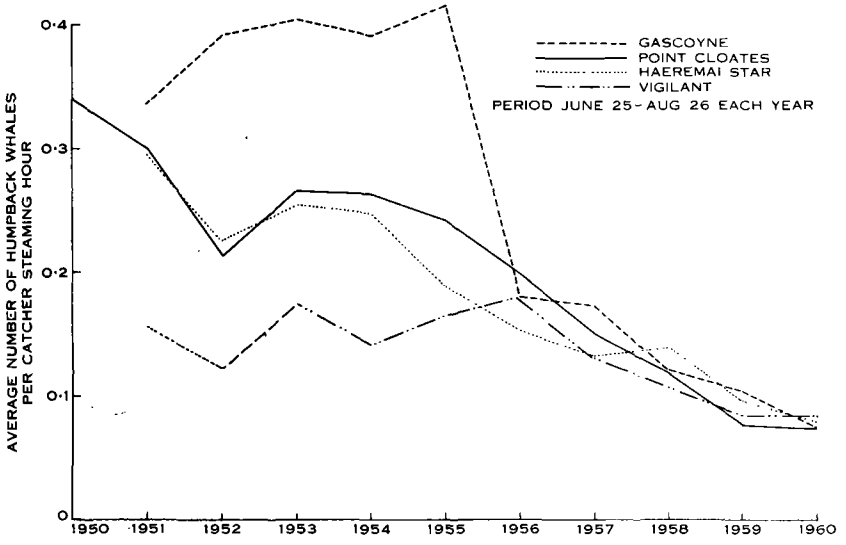


Fig. 25.—Catch per unit effort by four catchers operating on the west coast of Australia during the same period each year.

The total effort expended within a particular population of humpback whales and responsible for the estimated fishing mortality from a particular pair of years (Section VII), was estimated as the mean effort from the temperate regions in the winters of those 2 years, plus the corresponding Antarctic effort in the intervening summer.

(*b*) *Changes in Abundance*

Using the well-documented operations of certain Australian catchers, and after eliminating or adding weighted components for factors which varied the fishing effort in a particular year (where some measure could be made of such factors), the estimated catch per unit effort gives an index of abundance of humpback whales from one season to another (Table 36). The values from the west coast of Australia cannot be compared directly with those from the east coast of Australia as the catching power of the vessels used as standards in the two localities were not the same,

and the unit of effort used on the west coast (catcher's steaming hour) was not the same as that used on the west coast (catcher's hunting hour). These differences cannot be resolved entirely, but the approximate relation would be that 1 standard unit of effort for the west coast was equivalent to 0·5 standard units for the east coast. The indices of abundance (catch per unit effort) are plotted in Figure 26 using this relation.

The two populations appear from Figure 26 to have been initially of similar size. Although there was some decline in numbers soon after post-war whaling began, the abundance of humpback whales in the group IV population continued to be relatively high until 1954, whereas the group V population was relatively abundant until 1959. Since those years the populations have declined in numbers, the group V population decreasing more rapidly than the group IV population.

TABLE 36

ADJUSTED EFFORT, HUMPBACK WHALE CATCH, and CATCH PER UNIT EFFORT, BY CATCHERS ADOPTED AS STANDARD FOR OPERATIONS ON GROUP IV AND V POPULATIONS

Year	Standard Catchers* from Group IV Population			Standard Catchers† from Group V Population		
	Adjusted Effort (steaming hours)	Humpback Whale Catch (number)	Catch per Unit Effort	Adjusted Effort (hunting hours)	Humpback Whale Catch (number)	Catch per Unit Effort
1950	341	162	0·475	—	—	—
1951	995	422	0·424	—	—	—
1952	1568	544	0·347	—	—	—
1953	1465	517	0·353	176	171	0·972
1954	1852	650	0·351	208	157	0·755
1955	2378	580	0·244	638	497	0·779
1956	2631	467	0·178	741	522	0·704
1957	3351	489	0·146	761	544	0·714
1958	2847	350	0·123	788	591	0·750
1959	3015	271	0·090	820	607	0·740
1960	3957	245	0·062	1061	554	0·522
1961	6557	358	0·055	1085	250	0·230
1962	5524	284	0·051	989	68	0·069

*The same four catchers operating on the west coast of Australia from June 25 to August 26 each year.

†Two catchers operating on the east coast of Australia from June 10 to August 5 each year.

In 1962 the group V population was apparently smaller than the group IV population. This difference may have been even greater than indicated by the data in Figure 26, because in 1962 the two catchers previously used as the standard for the east coast data were replaced by two more modern catchers of considerably greater catching power. However, no adjustment was made to the data in order to allow for this change in catching power, because it has been shown above (Fig. 25) that when the abundance of whales has been reduced to a low level, differences in catching power of individual catchers are of minor importance.

Jonsgård, Ruud, and Øynes (1957) claimed that in the Antarctic during the period from 1950 to 1956, the group IV and V populations of humpback whales had increased in abundance relative to the stocks of blue and fin whales. This has little meaning, for if blue and fin whale stocks were declining at faster rates than the humpback whale stocks, the humpback whales could appear to be relatively more abundant than the other species, yet decreasing themselves.

TABLE 37

TOTAL EFFORT IN TERMS OF STANDARD CATCHERS EXPENDED ON THE GROUP IV POPULATION OF HUMPBACK WHALES EACH YEAR FROM 1949 TO 1962

Year	Effort on Males			Effort on Females		
	West Coast Australia	Antarctic Area IV	Total* Effort	West Coast Australia	Antarctic Area IV	Total* Effort
1949	278	745	1147	113	895	1096
1950	526	1040	2372	288	1431	1940
1951	2138	1415	3444	731	1505	2615
1952	1920	294	2282	1487	257	1809
1953	2057	378	2393	1618	355	2043
1954	1972	40	2215	1758	54	2046
1955	2378	1517	4610	2226	2389	4753
1956	3808	0	3901	2501	0	3087
1957	3994	0	4067	3673	0	3700
1958	4140	6028	9939	3727	7178	11,094
1959	3682	368	4398	4106	500	4765
1960	4376	51	5041	4424	17	4720
1961	5604	453	6212	4982	604	5421
1962	5913			4651		

* Catcher steaming hours.

(c) *Changes in Distribution*

As humpback whales have decreased in numbers from year to year, the catches at each Australian shore station have been dispersed over wider areas. This has not been caused by a change in the behaviour of the migrating humpback whales, but because of the lowered density of the whales, forcing the catchers to scour larger areas of ocean in order to locate humpback whales of legal size.

A typical example of the increased dispersion of catches is given in Figures 27 and 28, showing the distribution of the catches by the Carnarvon station in 1951 and 1962, respectively. By 1962 the catch was dispersed farther offshore as well as for a greater distance along the coast than in 1951, increasing accessibility and vulnerability, respectively.

In the 1951 season, the whales were captured within 40 miles of the coast, almost all within Shark Bay. Other whales which passed this latitude outside of Shark Bay were not exposed to hunting at that time, i.e. they were not accessible to

TABLE 38

TOTAL EFFORT IN TERMS OF STANDARD CATCHERS EXPENDED ON THE GROUP V POPULATION OF HUMPBACK WHALES EACH YEAR FROM 1952 TO 1962

Year	Effort on Males					Effort on Females				
	East Coast Australia	Norfolk I.	New Zealand	Antarctic Area V	Total* Effort	East Coast Australia	Norfolk I.	New Zealand	Antarctic Area V	Total* Effort
1952	461		75	218	782	154		49	300	523
1953	524		67	0	702	197		45	0	309
1954	677		136	596	1365	274		102	834	1196
1955	634		91	123	953	290		53	139	564
1956	689	131	114	0	948	334	82	90	0	489
1957	689	130	143	0	938	321	38	113	0	461
1958	681	84	149	615	1628	279	76	95	573	1112
1959	734	122	245	645	1980	361	81	185	830	1645
1960	950	184	435	359	2496	602	142	258	420	1701
1961	1948	539	217	0	2265	1230	200	130	0	1381
1962	1449	43	333			1058	14	129		

*Catcher hunting hours.

the whaling operations of that year. By 1962 the catchers (assisted by spotting aircraft) had extended their operations up to 70 miles west of the whaling station, stretching right across the coastal migration path. The whole of this population was then exposed to hunting.

In 1951, the extreme range of the catch from north to south was less than 60 miles (Fig. 27). A whale swimming at $2\frac{1}{2}$ knots would then take less than 24 hr to pass through the whaling area. Since half of the distance would have been travelled during darkness, some individuals could have passed through the whaling grounds

without having been sighted. Thus vulnerability would have been relatively low within the whaling area occupied in 1951.

In 1962, the extreme range of the catch from north to south extended over 160 miles. A whale travelling at 2½ knots would in that year, take some 64 hr to migrate through the whaling area, so being exposed to hunting on 3 successive days. Vulnerability would then be very high during favourable weather.

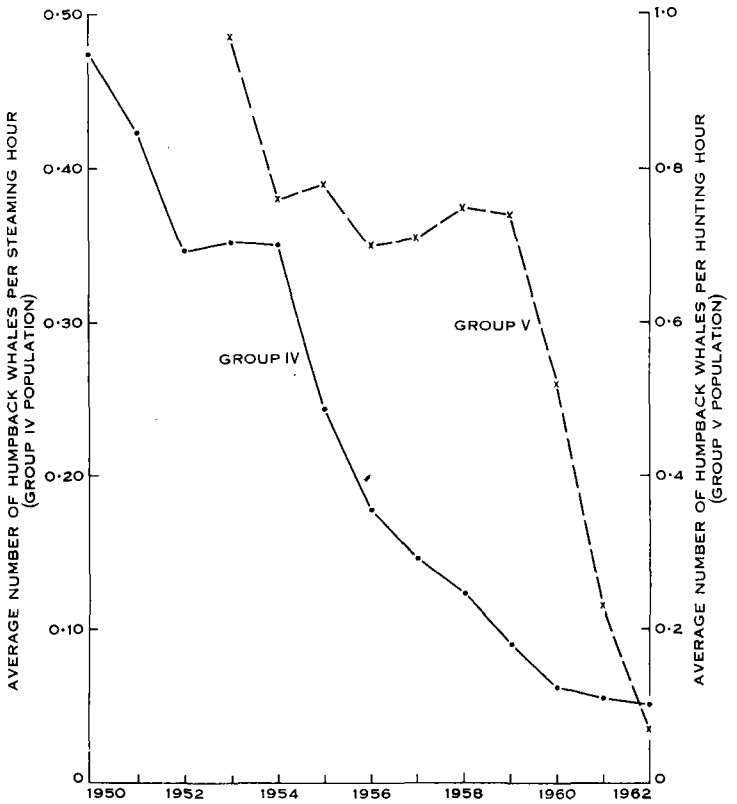


Fig. 26.—Relative abundance (catch per unit effort) of humpback whales in group IV and V populations as measured each winter on the west and east coasts of Australia.

Similar changes in the distribution of the catches have been recorded for the whaling stations at Albany, Tangalooma, Byron Bay, and Norfolk I. (Chittleborough 1962).

VII. Mortality

(*a*) *Instantaneous Total Mortality Coefficients*

Estimates of total mortality have been made from the age composition of Australian catches (Tables 25–30), weighted according to the total effort (Tables 37 and 38) expended in making these catches. The catch in each season from each age group was divided by the value for total effort expended in the corresponding season, so that each of the Tables 25–30 was converted to age composition per unit

of effort. This gives an index of abundance of whales in each age group at that time and locality, with the exception of some of the juvenile age groups which were not fully recruited into the catchable stock.

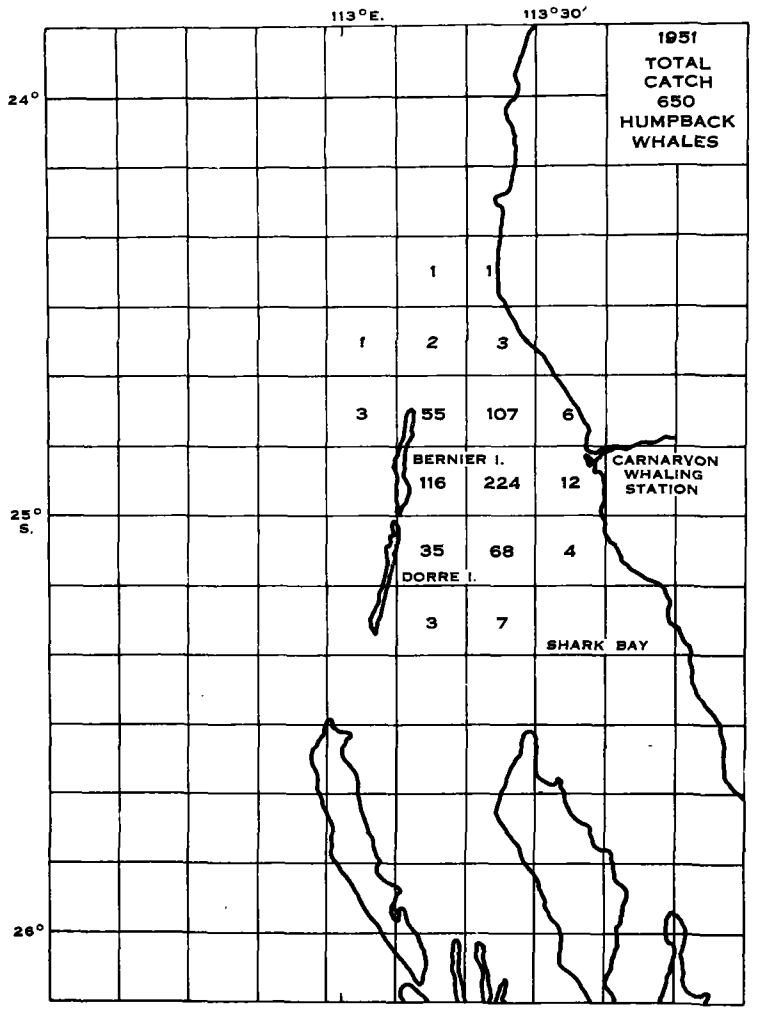


Fig. 27.—Area off Carnarvon whaling station marked in squares, 10×10 nautical miles, showing in each square the number of humpback whales killed in 1951.

Let U_i be the catch per unit of effort at age i in a specified season and locality, and U_{i+1} the catch per unit effort at age $i+1$ in the same locality but one year later. Then:

$$U_{i+1}/U_i = S = e^{-Z},$$

where Z is the total mortality coefficient. The survival rate (S) was calculated for each fully recruited age group in pairs of successive years, separate calculations being made for males and females on both the west and east coasts of Australia. For

the older age groups (those exceeding 15 years of age) the numbers recorded in the catches were so few that the individual estimates of S were unreliable. For these age groups a mean survival rate was calculated by the ratio of the total catch per unit of effort for all age groups from 15 years and over in year $i+1$, to the total catch per unit effort for all age groups from 14 years and over in year i.

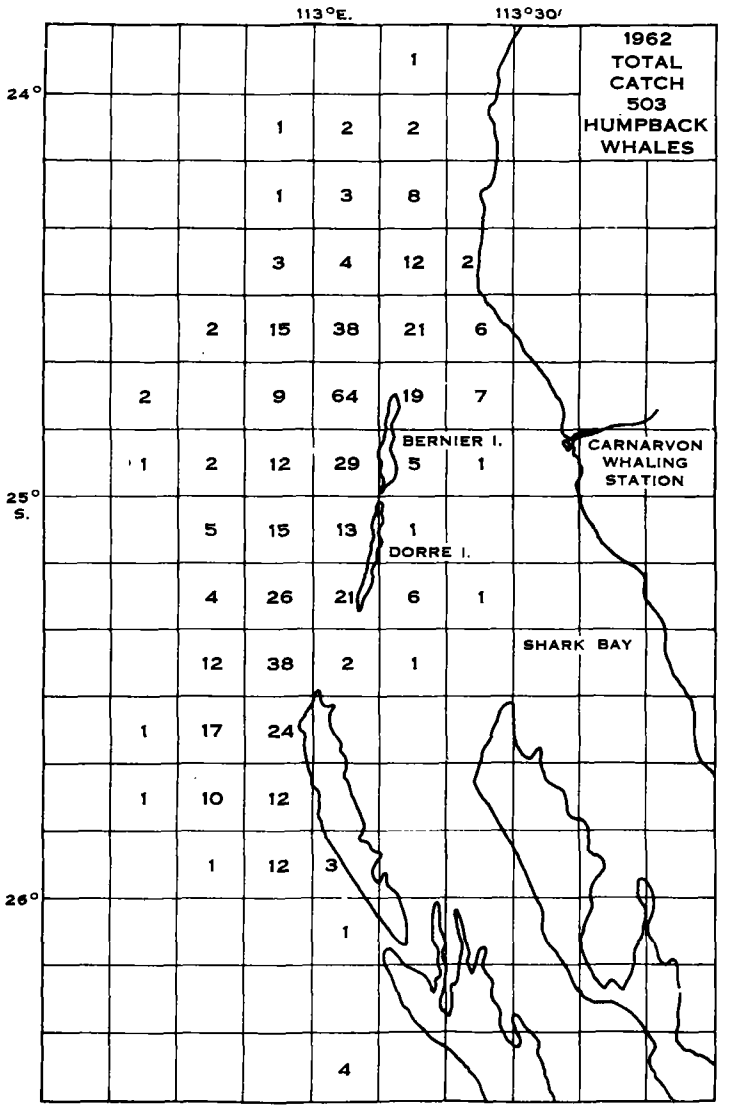


Fig. 28.—Area off Carnarvon whaling station marked in squares 10×10 nautical miles, showing in each square the number of humpback whales killed in 1962.

The instantaneous mortality coefficient (Z) was obtained for each age group from the value of S using the tables prepared by Ricker (1958). This gives a number of estimates of Z for each sex, locality, and pair of years. A mean value of Z for each sex, locality, and pair of years was obtained, weighting the individual estimates

of Z for each age group by the number of whales upon which the estimate was based. Total mortality from 1954 to 1955 was not calculated, owing to the change in the application of effort between these years, as described in Section VI (*a*).

TABLE 39

INSTANTANEOUS MORTALITY COEFFICIENTS (Z) CALCULATED FROM CATCH AT AGE AND EFFORT DATA ON WEST AND EAST COASTS OF AUSTRALIA

Year	1949–50	1950–51	1951–52	1952–53	1953–54	1955–56	1956–57	1957–58	1958–59	1959–60	1960–61	1961–62
						Group IV population						
Males	0·232	0·369	0·600	0·390	0·382	0·425	0·803	0·657	1·091	0·876	0·847	0·900
Females	0·226	0·318	0·315	0·283	0·215	0·360	0·391	0·366	0·803	0·670	0·802	0·539
						Group V population						
Males	—	—	—	0·254	0·441	0·264	0·198	−0·010	0·194	0·476	1·562	1·577
Females	—	—	—	0·325	0·507	0·167	0·233	−0·014	0·139	0·512	1·561	1·753

The mortality coefficients derived from these calculations (Table 39) apply to the adult portion of the relevant stock, since the juvenile age groups in most cases had not been fully recruited.

Table 39 shows that in the group IV population, total mortality was initially about the same in the two sexes, but as whaling progressed, total mortality of males increased to much higher levels than that of females. This is consistent with the earlier changes in the composition of catches of the more heavily fished males (see Section V).

TABLE 40

PROVISIONAL ESTIMATES OF TOTAL MORTALITY COEFFICIENTS FROM NEW ZEALAND CATCHES

Year	1955–56	1956–57	1957–58	1958–59	1959–60	1960–61	1961–62
Males	0·79	0·14	1·02	0·22	0·81	1·60	1·77
Females	0·36	0·16	0·31	0·14	0·09	1·62	2·15
Mean	0·58	0·15	0·67	0·18	0·45	1·61	1·96

On the east coast of Australia (group V population) total mortality rose moderately in 1959–60, then became very high in 1960–61 and 1961–62 (Table 39), even though the catches in these years had not been unusually high (Table 2).

An independent estimate of mortality in 1961–62 can be made from the frequency of sightings of humpback whales off the east coast of Australia during the two winter seasons. At Tangalooma 88·2 humpback whales were sighted per 100 catcher

hunting hours in 1961, and 38·6 per 100 catcher hunting hours in 1962, both values being for the same period (June 12–August 6). These values give a survival rate (S) of 0·44, which is equivalent to a total mortality coefficient (Z) of 0·83. The mortality calculated from the sighting records is lower than the corresponding estimates of mortality from the catch data, but this is to be expected, since the former refers to the whole population (most of the members of which were, in those years of observation, below the minimum legal length), while the latter refer only to the adult (highly exploited) part of it.

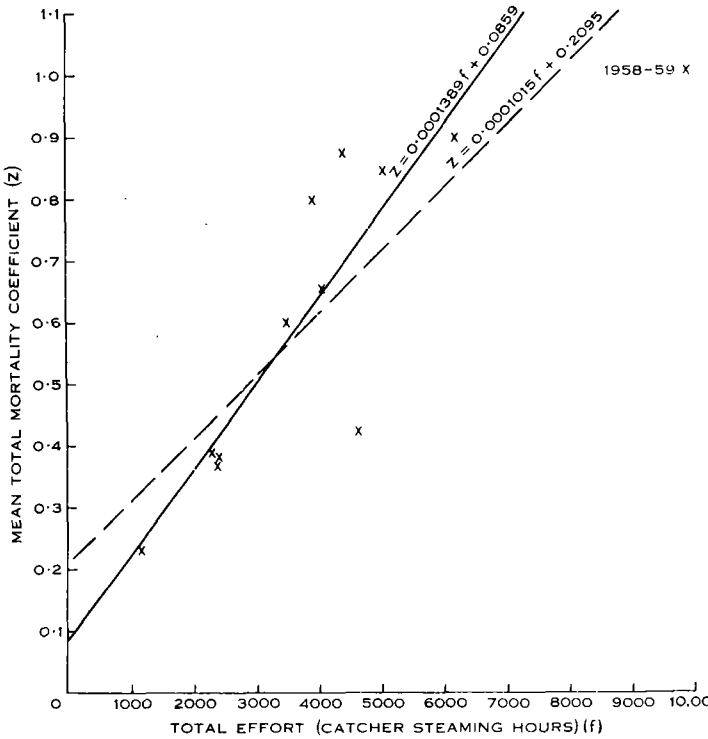


Fig. 29.—Mortality and effort, group IV male humpback whales; broken line regression on all points, solid line regression excluding 1958–59 value.

Further estimates of Z for the group V population can be derived from the catches in Cook Strait, N.Z., making certain assumptions, mainly with regard to effort. Assuming that the growth rate of humpback whales in New Zealand was the same as for Australian specimens, estimates were made of the age composition of New Zealand catches from 1955 to 1962, by applying to the length frequency distribution of males and females killed in New Zealand (records from International Whaling Statistics), the age–length keys derived from the Australian material.

There were no records of measurement of effort expended in taking the New Zealand catches which were made throughout the whole of the northward migration each year, searching being conducted from an elevated position on the shore. The

increase in the annual catch from 1955 to 1960 (Table 2) was due to better searching and improved plant efficiency rather than to an increase in the stock.

The catch per unit effort of each age group was calculated assuming that the total catch per unit effort had been constant from 1955 to 1960 (i.e. the stock did not increase), and that the effort in 1961 was the same as that in 1960. In 1962, two sighting lookouts were operated and approximately half of the sightings were made from the new lookout, so that the effort expended in 1962 was taken to be double that of 1960.

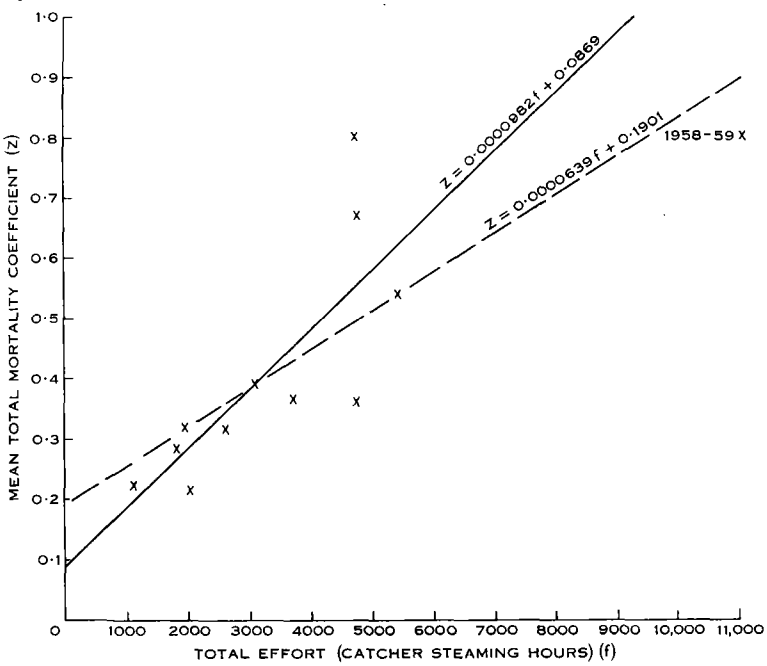


Fig. 30.—Mortality and effort: group IV female humpback whales; broken line regressionon all points, solid line regression excluding 1958–59 value.

Total mortality coefficients were then estimated between pairs of years, using only those age groups which were fully recruited, following the same procedures as for the data from the Australian coasts. The mean values (Table 40) were more variable than the estimates of Z from the data collected on the east coast of Australia but the values derived from the data from both localities rose to similar high levels in 1960–61 and 1961–62.

The results from two widely separated localities (east coast of Australia and New Zealand) show a very sharp rise in total mortality within the group V population from 1960 to 1962. The evidence of at least partial segregation into separate breeding units within this population during the winter (breeding season) suggests that the similar and high mortalities recorded at the same time in different localities were not due entirely to the fishing in those regions, but had a common origin. Recent catches reported from Antarctic area V (included in the total effort recorded in Table 38) have not been sufficiently large to account for these very high mortality coefficients.

There are three possible explanations:

(1) That the group V stock of humpback whales has recently changed its long established migration paths. This hypothesis is contradicted by widely scattered and independent observers throughout the South Pacific islands, on ships, and on the Australian coast, all reporting a great reduction in the number of humpback whales during the winter seasons of 1961 and 1962.

(2) That there was increased natural mortality (of epidemic proportions) due to disease, parasitic infections, or starvation. This also has no supporting evidence, as the few humpback whales captured were in good health, and had a normal thickness of blubber, and gave a normal oil yield.

(3) That substantial catches of humpback whales had recently been taken from this stock in addition to those shown in the available records, in a region where the humpback whales from New Zealand and the east coast of Australia can both be fished simultaneously, i.e. Antarctic area V.

There is some evidence supporting the last hypothesis. Although no humpback whales were reported to have been taken from Antarctic area V in the summer of 1961–62 (Table 2), two marks, previously fired into humpback whales, were recovered from whales killed within Antarctic area V during that summer. The information reported with respect to these marks is shown in the following tabulation:

Mark No.		Release	Recapture
15898	Date	October 12, 1959	December 19, 1961
	Locality	East coast of Australia; 27°S., 153°30′E.	62°21′S., 166°10′E.
	Species	Humpback whale	Sperm whale
	Size	Calf, 2–3 months old with cow	43 ft 8 in. (13·3 m), male
21815	Date	June 2, 1961	February 24, 1962
	Locality	Cook Strait, N.Z.	66°50′S., 162°59′E.
	Species	Humpback whale	Fin whale
	Size	—	65 ft 4 in. (19·9 m), female

There is no likelihood that there could have been any confusion as to the species at the time that these marks were fired into the whales. Some error must have been made with regard to the whales from which the marks were recovered, but whatever the explanation of the obviously erroneous recovery data, the evidence is clear that at least two marked humpback whales were killed in Antarctic area V during the summer of 1961–62. Since marked whales represent only a small fraction of the total catch (in 1959, Australian marks were recovered from 0·9% of the total catch of 2163 humpback whales taken from the group V population), one can infer that a considerable catch (possibly of some hundreds) of humpback whales was taken from Antarctic area V during the summer season of 1961–62.

(*b*) *Natural Mortality and Fishing Mortality Coefficients*

(i) *Group IV Population*

The total mortality coefficient (Z) can be divided into its components, natural mortality (M) and fishing mortality (F), by relating the total mortality to the corres-

ponding fishing effort (f). The total effort was taken as the mean Australian effort in the particular pair of seasons from which the estimate of Z was made, plus the

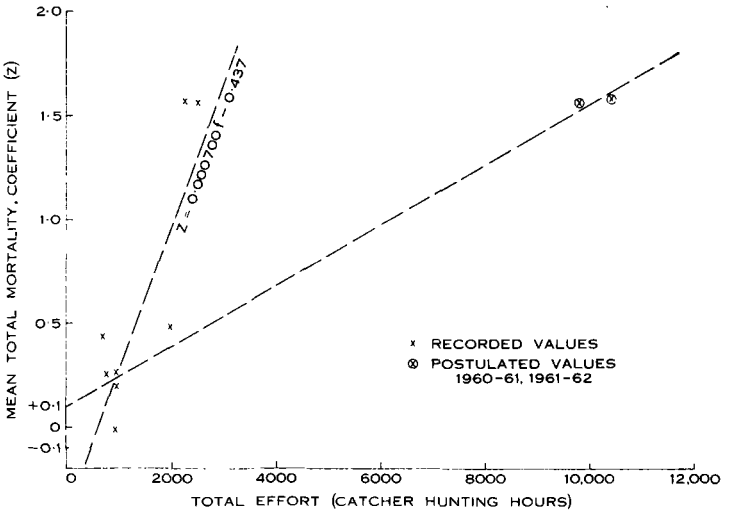


Fig. 31.—Mortality and effort: group V male humpback whales; × recorded values, ⊗ postulated values for 1960–61 and 1961–62.

Antarctic effort in the intervening summer (Table 37). The estimates of total mortality (Z) were plotted against the estimated effort (f) for each sex separately (Figs. 29 and 30).

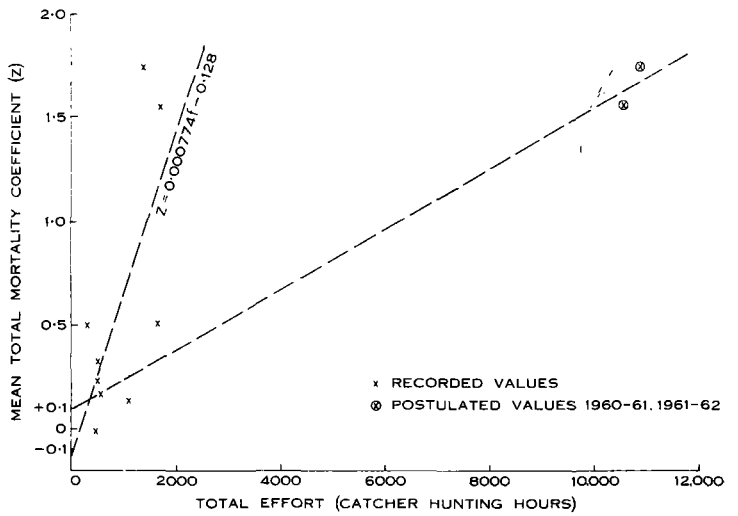


Fig. 32.—Mortality and effort: group V female humpback whales; × recorded values, ⊗ postulated values for 1960–61 and 1961–62.

In each plot the point for 1958–59 was anomalous, the estimated effort being far higher than for any other point, but the total mortality, while high, was not as high as might be expected from the regression. The high effort values derive from very large

Antarctic catches during the summer of 1958–59. If some of these whales did not in fact belong to the group IV population (as indicated by Chittleborough 1959*b*), then the effort as computed would be too high; if 40% of these catches were from outside group IV, then the 1958–59 point would fit closely on the regression line through the other points. For these reasons there appears to be justification in omitting the 1958–59 point from the calculations.

The regressions fitted by least squares, omitting the mortality and effort recorded for 1958–59 gave intercepts on the y axis of 0·086 for males and 0·087 for females (standard error 0·140 and 0·129, respectively). These are estimates of the natural mortality coefficient of adult humpback whales from the group IV population.

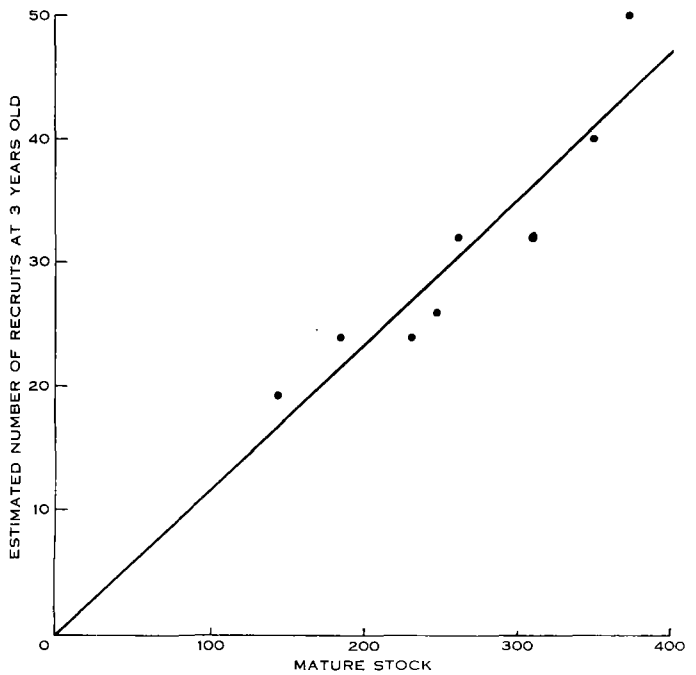


Fig. 33.—Stock–recruitment relationship for group IV humpback whales.

Another approach to the estimation of natural mortality in humpback whales can be made if the age composition has been assessed from a random sample of the virgin stock. This cannot be done in the case of the group IV population because of its previous history of exploitation.

The total mortality in the most recent seasons has ranged from 0·85 to 1·09 for the males and from 0·54 to 0·80 for the females (Table 39). After deducting natural mortality of 0·09, the corresponding fishing mortality coefficients were 0·76–1·00 for males and 0·46–0·71 for females. The difference between males and females is due to the fact that all mature males can be taken by the fishery, while females with calves (35–40% of the total number of mature females) cannot be taken.

(ii) *Group V Population*

The estimates of Z from the data obtained from the east coast of Australia (Table 39) have been plotted against corresponding total effort (Table 38) for each sex separately (Figs. 31 and 32). The regressions fitted by least squares to these points gave intercepts on the y axis of $-0{\cdot}437$ for males and $-0{\cdot}128$ for females. These anomalous values for M were caused by the points for 1960–61 and 1961–62, in which the estimates of effort (based on total reported catch) were far too low in relation to the very high values of Z (the latter being confirmed by independent assessments of mortality from New Zealand catches).

TABLE 41

RECRUITS SURVIVING FROM FEMALES BORN ANNUALLY PER 100 ADULT FEMALES

Female Births (per 100 adult females)	Possible Juvenile Natural Mortality (M)	Survivors to 3 Years of Age	Assumed Natural Mortality in 4th and 5th Years	Recruits, Survivors to 5 Years (maturity)
18·6	0·15	11·9	0·07	10·3
18·6	0·11	13·4	0·07	11·6
18·6	0·07	15·1	0·07	13·1

If the points for the pairs of years 1960–61 and 1961–62 were omitted from the data shown in Figures 31 and 32, significant regression lines could not be fitted to the remaining points as neither total mortality nor effort had changed sufficiently from 1952 to 1959. Then in this case the method of the regression of Z upon f could not be used to separate total mortality into its components (natural and fishing mortality).

Chittleborough (1960*a*) assumed that his estimate of total mortality for adult male humpback whales of the group V population in 1957 and 1958 (based upon samples of ear plugs) was almost unaffected at that time by commercial operations. Then the total mortality coefficient derived from that sample of adult males (0·097) consisted mainly of natural mortality. The estimate of 0·09 for natural mortality for the group IV population should then be regarded as the upper limit for the estimate of M.

If the regression lines of total mortality on total effort for adult males and females in the group V population, are to intercept the y axis at a value of 0·09, approximations can be made for the true positions of the points for 1960–61 and 1961–62 (Figs. 31 and 32). From the difference between the postulated and recorded values of total effort, the additional (unreported) catches in these years can be estimated. On this basis additional mortality within Antarctic area V of some 3700 humpback whales in the summer of 1960–61 and of approximately 1300 humpback whales in 1961–62, would (when added to all other known catches) explain the recent abrupt increase in the total mortality within this stock.

VIII. Recruitment

(*a*) *Stock–Recruitment Relationship*

One approach to the task of estimating recruitment makes use of data on the catch per unit effort from each female age group. The abundance of adult females in each year (from 1949 onwards) on the west coast of Australia has been estimated as the sum of the catches per unit effort of female humpback whales above 5 years of age.

TABLE 42

CATCHABLE STOCK OF GROUP IV HUMPBACK WHALES ESTIMATED FROM CATCH AND FISHING MORTALITY

Year	Australian Catch	Antarctic Catch	Mean Catch	Z	F ($M = 0{\cdot}09$)	Estimated Stock	Australian Catch	Antarctic Catch	Mean Catch	Z	F ($M = 0{\cdot}09$)	Estimated Stock
	Males						*Females*					
1950	250						137					
		468	1047	0·37	0·28	3740		644	868	0·32	0·23	3775
1951	907						310					
		546	1333	0·60	0·51	2615		581	994	0·32	0·23	4320
1952	666						516					
		103	799	0·39	0·30	2665		90	634	0·28	0·19	3335
1953	726						571					
		133	842	0·38	0·29	2905		125	719	0·22	0·13	5530
1954	692						617					
		12	648	0·40	0·31	2095		16	596	0·29	0·20	2980
1955	580						543					
		320	948	0·43	0·34	2790		504	997	0·36	0·27	3690
1956	676						443					
		0	630	0·80	0·71	890		0	488	0·39	0·30	1625
1957	583						536					
		0	546	0·66	0·57	960		0	497	0·37	0·28	1775
1958	509						458					
		645	1065	1·09	1·00	1065		768	1181	0·80	0·71	1665
1959	331						369					
		28	329	0·88	0·79	415		38	360	0·67	0·58	620
1960	271						274					
		3	291	0·85	0·76	385		1	274	0·80	0·71	385
1961	306						272					
		24	329	0·90	0·81	405		32	287	0·54	0·45	635
1962	304						239					

Recruitment to the fishery was taken to occur at 4 years, but since whales were not fully recruited at this age the catches per unit effort of 3-year-old females cannot be used directly, and an indirect method had to be used. This was done for each year class by taking the catches per unit effort at the fully recruited ages, and converting these to actual numbers in the population using the relation that a catch per unit effort of 0·1 is equivalent to a population of 2000 whales (see Section IX (*a*)). The numbers of 3-year-old females was then estimated by adding the known catches of females in the year class, and the estimated deaths by natural mortality (assuming $M = 0{\cdot}1$, but this value is not a critical one).

The estimated number of recruits (3 years old) in each year was then plotted against the number of females in the parent generation, i.e. the number of adult females 4 years earlier (i.e., the pregnant females of 1950 give birth in 1951 and these are the 3-year-old recruits in 1954). The result is shown in Figure 33, giving the relationship R (recruits) $= 0{\cdot}12 \times$ mature stock. Annual recruitment (of 3-year-old whales) as measured by this method is then 12 females per 100 adult females.

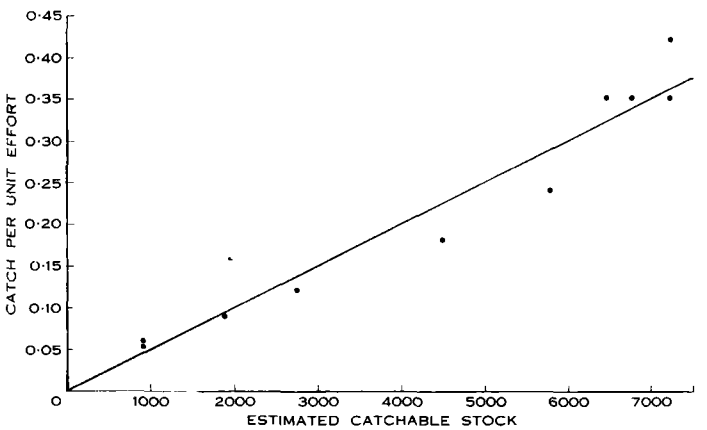


Fig. 34.—Relationship between catch per unit effort and catchable stock size as estimated from catch and fishing mortality; group IV population.

(b) Estimates of Recruitment from Pregnancy Data

A more direct measure of recruitment can be made by applying juvenile mortality to the birth rate, if these values can be determined. In order to measure the latter, attempts have been made to distinguish in the ovaries, corpora albicantia of previous pregnancies from those of ovulations which had not resulted in pregnancy, but as discussed in Section III (*a*)(iv), these attempts have been unsuccessful.

Since there is a seasonal breeding cycle, and the gestation period is almost 12 months long, the proportion of mature females carrying near-term foetuses during the northward migration (when all mature females are equally vulnerable), gives a measure of the birth rate in this population. Using this method with the data from the whaling station at Albany, the average annual birth rate was found to be 0·372 (Section III (*a*)(iv)).

Nishiwaki (1959) used a somewhat similar method to estimate the birth rate of humpback whales in Aleutian waters. He found that approximately 65% of the mature female humpback whales available for catching were pregnant. Since lactating females were not vulnerable, and as equal numbers of lactating and pregnant females could be expected, the composition of the mature female stock feeding in Aleutian waters during the summer should be 65 pregnant : 65 lactating: 35 resting females. This is equivalent to an average annual birth rate of 0·39.

The estimate from the data collected at Albany is more precise than that of Nishiwaki, as the former was based on samples of all categories of mature females,

weighted according to the fishing effort applied throughout the northward migration past that sampling point.

If the birth rate is 0·372 and the sex ratio at birth is 0·5, then 100 mature females will give birth to 18·6 female calves per year. The number of 3-year-old female recruits is therefore: $18 \cdot 6e^{-3M}$ where M is the average natural mortality in the first 3 years. Natural mortality of juveniles has not been measured but it is almost certainly greater than adult natural mortality. A likely range of values for juvenile mortality and the resultant survivors to 3 years of age are shown in Table 41. From the estimate of recruitment at 3 years of age derived from the stock–recruitment relation in the previous section (12 per 100 adults) juvenile mortality would apparently lie in the upper part of the range given in Table 41.

TABLE 43

ESTIMATES OF POPULATION SIZE OF GROUP IV HUMPBACK WHALES BY VARIOUS METHODS

Year	Estimated Catchable Population (from mortality rates)	Catch per Unit Effort	Estimated Catchable Population (from catch per unit effort)	Estimated Catchable Population (DeLury)	Estimated Total Population (sightings)
1930's					10,200
1950		0·47	9400		
1951	7225	0·42	8400		
1952	6450	0·35	7000		
1953	7220	0·35	7000		
1954	6755	0·35	7000		
1955	5775	0·24	4800	9800	
1956	4495	0·18	3600	7800	
1957	2625	0·15	3000	6700	
1958	2730	0·12	2400	5600	
1959	1880	0·09	1800	3700	
1960	905	0·06	1200	2900	
1961	905	0·055	1100	2400	
1962		0·05	1000	1800	

Although some whales are taken by the catchers when 3 years of age, females are not mature until, on the average they are 5 years old. Assuming natural mortality during their fourth and fifth years to be 0·07 (though 0·09 has little effect on the result), recruitment (to maturity) may range from 0·10 to 0·13 (Table 41).

IX. POPULATION SIZE

(a) Group IV Population

A first approximation of population size can be derived from data of sightings of baleen whales in the southern hemisphere in 1933–39. From these records Mackintosh and Brown (1956) estimated a total baleen whale stock of 220,000–340,000, the larger figure being the more likely. Mackintosh (1942) had previously estimated

that 10% of the larger baleen whales in the southern hemisphere were humpbacks so that in the 1930's the southern humpback whale populations may have contained some 22,000–34,000 individuals. These have to be apportioned between the five distinct populations. Following the guide given by Mackintosh (1951), a fair measure of the relative abundance within the populations during the 1930's is as follows:

Group I	Group II	Group III	Group IV	Group V
1	1	2	3	3

Thus, if the group IV population included 30% of the total southern stocks of this species in the 1930's this population contained from 6600 to 10,200 humpback whales, the larger figure being probably the more likely.

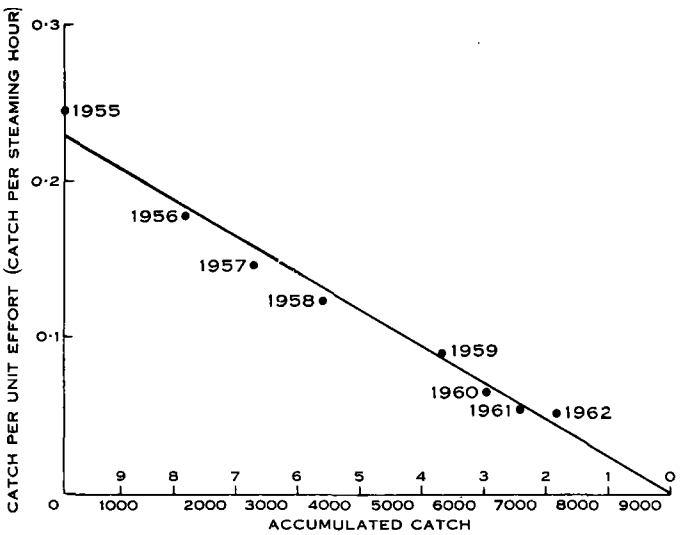


Fig. 35.—DeLury method on group IV population of humpback whales.

The average population size during each recent season can be estimated directly from the catch data and the estimates of fishing mortality (F), as shown in Table 42. The upper limit of M (0·09) has been used; lower values for natural mortality decrease the estimates of stock size only slightly. These estimates refer to catchable stocks of males and females.

The regression of catch per unit effort (best estimate) on total catchable stock is a straight line (Fig. 34) on which a catch per unit effort of 0·1 is equivalent to 2000 humpback whales in the catchable stock. The population sizes estimated from this relation are shown in Table 43.

Another independent estimate of stock size has been obtained from the DeLury (1947) method of plotting catch per unit effort against accumulated catch. This gives a very good relation for the data since 1955 (Fig. 35), with an intercept on the x axis of 9800 $\pm$ 1100, which is an estimate of the catchable stock in 1955. However, this method gives biassed estimates because no allowances have been made for recruitment, natural mortality, the effects of migration, etc. The errors resulting from neglect of these factors leads to an overestimate of the population size.

The various estimates of group IV population size are shown together in Table 43. Unfortunately, the estimate from sightings cannot be compared directly with those by other methods because the period covered by the sighting records does not overlap that to which the other data refer. The history of whaling on this stock (Section IV) is of few catches before 1934, very heavy catches (12,673 in all) from 1934 to 1939, and no whaling from 1939 to 1949. Thus, the stock in 1939 was probably considerably less than the 1950 stock, and the population in 1934 much more than that in 1939 (by an amount less than 12,000 whales). If the population size had been 9400 in 1950, and if over the previous 11 years (when there had been no fishing mortality) the rate of increase $(r-M)$ had been within the range of values given in Section X(*a*), the 1939 population was somewhere in the range of 4000–8000. The 1934 population would then have been in the range of 12,000–16,000. The sighting estimate of 10,000 humpback whales in this population during the period 1933–39 fits well inside this range.

TABLE 44

MEAN CATCHABLE STOCK OF GROUP V HUMPBACK WHALES ESTIMATED FROM CATCH AND FISHING MORTALITY

Period	1952–59	1959–60	1960–61	1961–62
Mean total mortality (Z)	0·224	0·50	1·56	1·67
Fishing mortality (F) ($M = 0·09$)	0·134	0·41	1·47	1·58
Annual catch (C)	1329*	2241*	1456*	595*
			5156†	1895†
Mean population size (C/F)	9920*	5470*	990*	380*
			3510†	1200†

* Total reported catches.

† Assuming additional mortality of 3700 humpback whales in 1960–61 and of 1300 in 1961–62.

The best estimate of the mean catchable stock in 1962 is that it consisted of 1000 whales. In order to determine the number left at the end of 1962, the estimate of mean stock size should be reduced by approximately half the catch taken on the west coast of Australia during the winter season of 1962. Even allowing for some recruitment, the total number of catchable whales remaining in the group IV population at the end of 1962 would not exceed 800.

(*b*) *Group V Population*

The population estimates from sightings (described in the previous section) suggest that the group V humpback whale population contained approximately 10,000 individuals in the period 1935–39. Since there had been little previous exploitation of this population, this estimate is of the size of the population in the virgin state.

Estimates of the size of the catchable stock in recent years, made from fishing mortality coefficients and total catch data (Table 44), suggest that its mean size between 1952 and 1959 was similar to that of the population between 1933 and 1939

as calculated from sightings. There had been little fishing of this population from 1939 to 1950, and the population had apparently remained stabilized.

Since 1959 the population has diminished rapidly. If the total catches were as reported to the Bureau of International Whaling Statistics, the catchable stock remaining at the end of 1962 was less than 200 humpback whales. However, if as suggested in Section VII (*b*), the catches were understated by 3700 humpbacks in 1960–61 and by 1300 in 1961–62, the catchable stock left at the end of 1962 was close to 500 whales.

The method of DeLury was used to obtain independent estimates of the upper limits of population size in recent years. From the regression of catch per unit effort on the accumulated catch from all known records, fitted to the data from 1959, 1960,

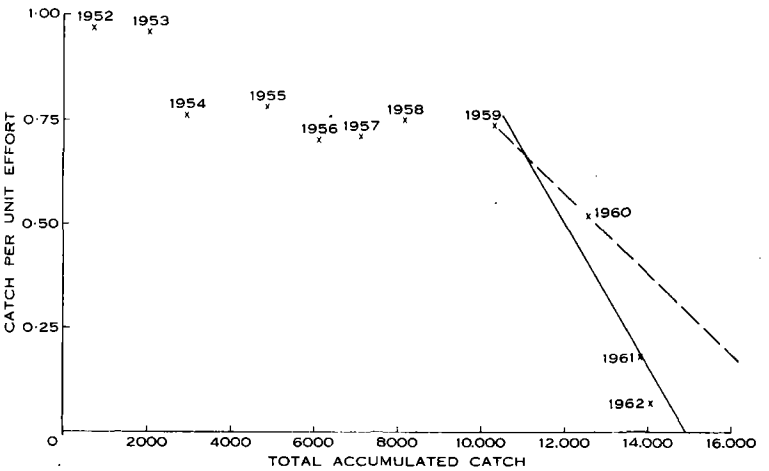


Fig. 36.—Group V population: catch per unit effort and cumulative catch.

1961, and 1962 (Fig. 36), the upper limit of the population size in 1959 would have been 4600 humpback whales. Since the DeLury method must overestimate the population size (especially when used with data such as are available here) this estimate for 1959, being less than the estimate from catch and fishing mortality data (Table 44), is unacceptable.

If in Figure 36 the regression line is taken only through the values for 1959 and 1960, the intercept on the x axis gives an estimate of the population size in 1959 of 7600 humpback whales. This second regression would require that approximately 4900 more humpback whales had been taken in 1961 and 1962: this value is very close to the estimate that 5000 more humpback whales must have been killed in the summers of 1960–61 and 1961–62, to account for the very high mortality coefficients in those years (Section VII (*b*)(ii)).

X. Stock Assessment

(*a*) *Group IV Population*

The net rate of change of the population is the difference between r (the recruitment coefficient) and the sum of F (the fishing mortality coefficient) and M (the

natural mortality coefficient). The population will be in balance, neither increasing nor decreasing if $F = r - M$, and the catch taken is $F \times P = (r-M)P$, where P is the mean population size. Either, or both, M and r will change with population size, M increasing and r decreasing, or M remaining stable and r decreasing, or M increasing and r remaining unchanged as the population increases, and when the population is at its maximum, in the unfished state, $M = r$. The exact relation of M and r is difficult to determine but some reasonable assumptions can be made, and hence the form of the curve $c = (r-M)P$ giving the steady yield determined, and in particular the position and height of the maximum estimated..

For the stock sizes of recent years, r has been estimated (Table 41) as 0·116, and the reasonable limits given as 0·10 and 0·13. The upper limit of M was found to be 0·09 (Section VII (*b*)), the best estimate being 0·07, while the data are also consistent with a value of 0·05.

A range of values of r–M can now be given as follows:

Best estimate	$0{\cdot}116-0{\cdot}07 = 0{\cdot}046,$
High estimate	$0{\cdot}13 \ -0{\cdot}05 = 0{\cdot}08,$
Low estimate	$0{\cdot}10 \ -0{\cdot}09 = 0{\cdot}01.$

The total (catchable) population remaining at the end of 1962 was around 800 whales of which not more than half were adults (Table 32). Taking the mature population as 400 whales, the catches that could be taken from this population without causing a further decline are:

Best estimate	$400 \times 0{\cdot}046 = 18,$
High estimate	$400 \times 0{\cdot}08 \ = 32,$
Low estimate	$400 \times 0{\cdot}01 \ = 4.$

Therefore, some 18 whales could be taken per year, and the stock would maintain itself at the present level. Almost certainly if more than 32 whales were taken the stock would decline.

The size of the stock of humpback whales in the unfished state is not known accurately but before 1949 the catches taken from it were 5800 in 1912–16, 3400 in 1925–28, and 12,800 in 1934–39. Assuming that the stock had recovered to some extent between these periods of whaling, the unfished population was probably between 12,000 and 17,000. In this presumably stable population $r-M=0$, so that as the stock approaches its maximum size there must be a critical reduction in r, or an increase in M, or both.

The maximum sustainable catch therefore probably comes from a stock level of around 10,000 humpback whales, which is about the level in 1949. In this population 85% were mature, so that the maximum sustainable yield is estimated as follows:

Best estimate	$8500 \times 0{\cdot}046 = 391,$
High estimate	$8500 \times 0{\cdot}08 \ = 680,$
Low estimate	$8500 \times 0{\cdot}01 \ = 85.$

The calculation of these permissible catches has been based on data relating to the mature stock, with the assumption that the catch would be taken only from the mature segment of the population. The result would have been much the same if the assumption were made that the catch would be drawn from both mature and immature whales. Catches of immature whales would tend to reduce the net rate of recruitment to the mature part of the stock, and hence the sustainable catch from mature whales. However, allowing for the fact that under this regime, some of the whales that would die from natural causes before reaching maturity are captured, the sustainable catch in numbers would be very slightly increased by fishing both mature and immature segments of the population. On the other hand, the sustainable catch in weight will be slightly less if both mature and immature whales are taken.

If the populations were to be conserved by operating each year on the maximum sustainable yield, the minimum legal length could be abolished. As suggested by Ruud (1954) the application of size limits in whaling may have done more harm than good.

The time taken for the stock to build up to the optimum level can be estimated from the potential net rate of increase, $r-M$. If whaling on the group IV population had been stopped at the end of 1962 there would have been an initial rather rapid increase in the mature stock because of recruitment from the larger mature stocks present in 1958 and 1959 (which now form the dominant immature stock). The mature stock in 1964 would therefore have been about 900 (allowing for some loss, because of natural mortality, of whales now in the stock). These 900 would then increase at a rate of $r-M$, and reach the 8500 level after T years, where

$$e^{(r-M)T} = 8500/900,$$

i.e. $(r-M)T = 2{\cdot}25$. Using the best estimate of $r - M$ ($0{\cdot}046$), $T = 49$ years; using the high estimate of $r-M$ ($0{\cdot}08$), $T = 28$ years.

The length of this delay period is critically dependent upon the level to which the population is reduced before whaling is stopped. If whaling had been stopped in 1959, when the catchable stock was about 1800, then the mature stock after 2 years would have been about 1620, and

$$e^{(r-M)T} = 8500/1620,$$

i.e. $(r-M)T = 1{\cdot}66$, $T = 36$ years (best estimate), or 21 years (high estimate of $r-M$).

Conversely, if whaling continued at the present level, the mature stock would decline at the rate of $F-(r-M)$, which is about $0{\cdot}7$. That is, each year that whaling continued at the present level in terms of fishing mortality rate (the actual numbers taken would decline proportionately to the stock) would increase the delay, until the stock can recover to its optimum level, by at least $0{\cdot}7/0{\cdot}08 = 8{\cdot}8$ years, and probably by $0{\cdot}7/0{\cdot}046 = 15$ years. In terms of catch lost at the optimum level these delays are equivalent to $8{\cdot}8 \times 680 = 5984$ whales, or $15 \times 391 = 5865$ whales. The actual estimate is therefore very little affected by the precise estimate of $r-M$: a

long delay period, due to a low value of $r-M$, corresponds to a lower catch at the optimum stock level. This figure of the net loss of 6000 from the potential catch for each year that operations are continued, may be compared with the actual catch in 1962 of 543 whales.

(b) Group V Population

Pregnancy rates recorded from Cook Strait, N.Z., from 1948 to 1962 were almost identical with those recorded in recent years from Albany (west coast of Australia), so a similar value for recruitment applies to both populations. Natural mortality also appears to be the same in the two populations, so that the range of values for $r-M$ given for the group IV population will be applied to the assessments upon the group V stock.

The total catchable stock remaining at the end of 1962 was close to 500 humpback whales. The mature population, therefore, was about 260 (52% of the 1962 catch were mature). The catches that could be taken from this population without causing a further decline were:

Best estimate	$260 \times 0{\cdot}046 = 12,$
High estimate	$260 \times 0{\cdot}08 = 21,$
Low estimate	$260 \times 0{\cdot}01 = 3.$

Virtually any commercial catches from this population would reduce the stock below the present extremely low level. Hunting of this population in temperate latitudes has now ceased, so that provided these whales are not molested in Antarctic area V, the population may recover at the rate of $P.e^{(r-M)T}$.

The size of the original population was in the region of 10,000 humpback whales, whereas the maximum sustainable catch probably comes from a stock level of about 8500, and if 85% were mature, this means an adult stock of 7225 whales. The maximum sustainable yield would then have been:

Best estimate	$7225 \times 0{\cdot}046 = 332,$
High estimate	$7225 \times 0{\cdot}08 = 578,$
Low estimate	$7225 \times 0{\cdot}01 = 72.$

If there is no further hunting of this population the mature stock size will be increased initially by the recruits from the larger population present in 1958 and 1959. However, the paucity of sightings during the 1962 season suggests that these juveniles had also suffered heavy mortality, so that the mature stock cannot be expected to gain greatly from these recruits. The mature stock in 1964 may be no more than 400 whales. This stock would reach 7225 after T years, so that:

$$e^{(r-M)T} = 7225/400,$$
$$(r-M)T = 2{\cdot}89.$$

If $r-M = 0{\cdot}046$, then $T = 63$ years; if $r-M = 0{\cdot}08$, then $T = 36$ years.

The best estimate of the period of protection necessary for the population to recover to the level required for the maximum sustainable yield is then 65 years, and the most optimistic figure at least 38 years.

As the period needed for full recovery is so great, a whaling station might desire to operate on a smaller scale after a shorter period of protection. An annual catch of say 150 humpback whales would require a mature stock of 3260 whales. If the mature stock size was 400 in 1964, the time taken to reach a level of 3260 adults would be 46 years if $r-M = 0{\cdot}046$ (best estimate) or 19 years if $r-M = 0{\cdot}08$.

XI. Present Status of Fishery

The group IV and V populations of humpback whales are now so depleted that neither will support commercial operations relying solely on this species.

After the failure of the humpback whale fishery in 1962, the whaling stations at Tangalooma, Byron Bay, and Norfolk I., were closed down indefinitely, while the station in Cook Strait, N.Z., has turned to sperm whaling. Thus the group V population of humpback whales was afforded some measure of protection, at least in the northern part of its range.

On the west coast of Australia the station at Albany has depended mainly on sperm whales for several years, although some humpback whales continue to be taken. The station at Carnarvon has entered into other fishing as well as exploring the prospects of sperm whaling, while continuing to hunt humpback whales. In 1963 the Australian Government issued quotas of 450 humpback whales to the station at Carnarvon, and 100 to the station at Albany. Both stations discontinued hunting humpback whales in August owing to scarcity of whales; total catches were 68 humpback whales at Carnarvon, and 19 at Albany.

In July, 1963, the International Whaling Commission passed a resolution that humpback whaling should cease in the southern hemisphere. If this resolution can be put into effect, the group IV and V populations of humpback whales will recover within the range of rates set out above.

XII. Acknowledgments

A large portion of the data and material used in this paper was collected at whaling stations by various members of the Division of Fisheries and Oceanography, CSIRO, as well as by Commonwealth and State whaling inspectors. Australian whaling companies cooperated closely, making facilities available at whaling stations, keeping special records of effort and sightings on catchers and aircraft, giving the author access to ships' logs, and by marking whales when opportunities occurred.

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A mass fish mortality on the Somali Coast

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DURING the period 7th–21st August and 28th August–7th September, 1964, R.R.S. *Discovery* worked in the inshore and offshore waters of the Somali coast, the survey forming part of the National Institute of Oceanography's contribution to the International Indian Ocean Expedition. In the course of the survey dead and moribund fish in large numbers, together with the remains of squid and cuttlefish, were observed concentrated in an inshore area south of Ras Mabber but also dispersed in smaller numbers over a much larger area southwards as far as Ras El Cheil (7° 55'N; 49° 55·0'E) and northwards to Cape Guardafui and into the Gulf of Aden (Fig. 1).

Of the various species sampled or observed Porcupine Fish *Cyclicthys echinatus* (family Diodontidae) were the most abundant and were estimated to comprise at least 75 per cent of the mortality, while the Triggerfish *Odonus niger* and *Abalistes stellaris* (family Balistidae) were the next most common species. A single specimen of *Benthodesmus sp.* was also taken while the following genera were tentatively identified from sightings but were not sampled, *Lutianus sp.* (Snapper) and *Serranus sp.* (Rock Cod). One dead squid was recorded while squid pens and cuttlebone were common in the main area of mortality and also at sta. 5557 (Fig. 1) where, with fish, they were concentrated in a well defined lane. It will be noted that all the fish are representatives of common tropical inshore genera and no commercially important species were encountered. Most of the dead fish were remarkable for their lack of decomposition particularly during the first cruise—indicating the recent origin of the mortality. Decomposed fish tended to occur to the north and in particular at sta. 5557 where the majority of specimens sampled appeared to have been dead for some time. During the second part of the survey more obvious signs of decay were indicated by the detached swimbladders which were taken, along with dead fish, in some of the surface plankton tows.

Large predators were notably absent from the region and few sea birds and no cetacea were seen. Catches of phytoplankton and zooplankton were exceptionally poor in the area south of Ras Mabber and it was only to the north between Cape Guardafui and Socotra and in the vicinity of Ras Hafun that relatively rich plankton occurred. In the latter area swimming crabs were common and were observed on one occasion to be apparently feeding on dead fish.

In considering the cause or causes of the mortality it is significant that the greatest concentration of dead fish coincided with an area of exceptionally cold surface water south of Ras Mabber (Fig. 1). The disposition of the surface isotherms

shows the presence of marked temperature discontinuities in this region and on the line of observations into the coast a drop of some 4°C was recorded between stations 5552 and 5553, a distance of 10 miles, with a minimum temperature of 13·2°C nearer

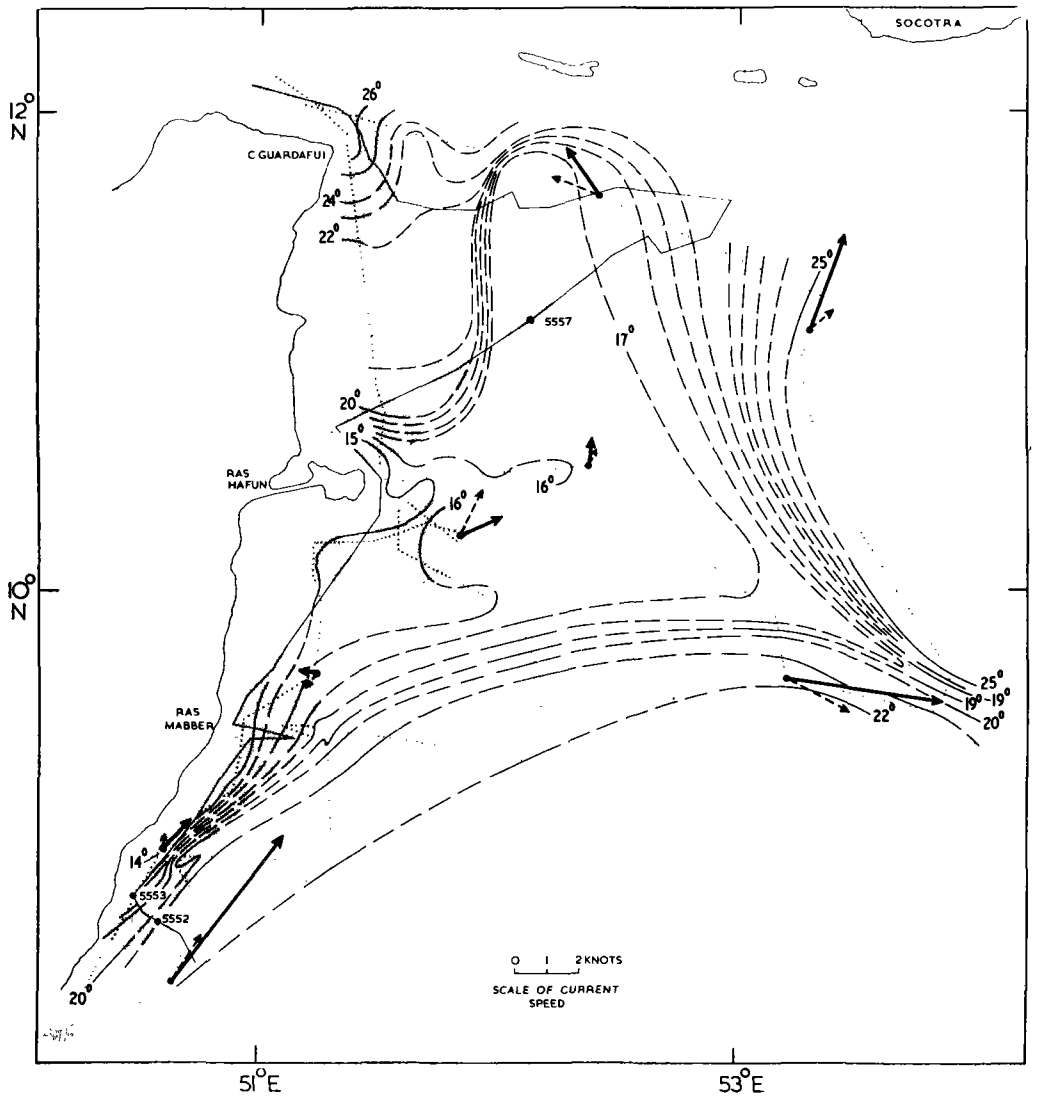


Fig. 1. The chart shows the occurrence of dead fish along the Somali Coast as shaded areas together with surface isotherms (broken line) and current measurements from the second cruise. The length of the current arrows indicate speed; heavy arrows are surface currents, dotted arrows current at 100 m depth. The first cruise track is shown as a thin line and the second as a dotted line.

the coast. Elsewhere dead fish occurred in much warmer surface water but as the surface current measurements show (Fig. 1) these records are consistent with a northerly transport of cold water from the main area of mortality and its gradual warming up. The origin of the cold water is probably due to local upwelling since

temperature sections show an upward slope of the isotherms towards the coast. The dissolved oxygen showed saturation values in excess of 40 per cent near the bottom and 90 per cent at the surface at the inshore stations, and the nutrient content of these surface waters was in general similar to water of the same temperature and salinity taken at some depth further offshore. There was however no evidence of high productivity except in the more northerly warmer older surface water. No water blooms were observed nor was hydrogen sulphide present in any of the hydrological samples.

The mechanism by which the cold water had been upwelled is not at this stage clear. Certainly the conditions prevailing during the survey were not those normally encountered in such typical regions of upwelling as the Peru (GUNTHER 1936) and Benguela Currents (HART and CURRIE 1960) where mass mortalities are well known. Both the prevailing wind during the period of the survey, which was at the time of the S.W. monsoon, and the surface currents were parallel to the coast and there was little offshore transport except in about 8°N where the course of the Somali Current bears eastwards (Fig. 1). This extremely strong current develops and intensifies during the S.W. monsoon and it seems possible that this may be a factor causing the local upwelling since it will be noted that the cold inshore water occurs in the region where the Somali Current starts to diverge from the coast.

It seems likely therefore in the absence of any of the other features normally associated with mass mortalities (BRONGERSMA-SANDERS 1957) that the contributory factor here is the divergence on the coast south of Ras Mabber of upwelled water some 7°C cooler than that normal to the region. If this is so, then it would be of interest to ascertain whether or not a mass mortality is an annual event, since meteorological charts of the Indian Ocean show that the upwelling is a regular seasonal feature. It follows that if fish are killed each year at this time then the recolonisation of the area, when normal conditions return, must be extremely rapid. Only additional, more detailed synoptic observations will clarify this point. As far as the writer is aware this is the first record of a mass mortality on the Somali Coast although it provides a parallel to conditions sometimes encountered on the southern coast of Africa where a sudden drop in temperature can occur in the Agulhas Current (*ibid.* p. 949).

Acknowledgments—The author is grateful to the principal scientist during the cruise, Mr. R. I. CURRIE, for permission to use unpublished data and to Dr. J. C. SWALLOW for making available the provisional current measurements.

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OCEANOGRAPHIC RESEARCH INSTITUTE

Investigational Report No. 11

A Preliminary Report on the Penaeid Prawns of Durban Bay

by

Leonie S. Joubert

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Aerial photograph of Durban Bay, July 1964. *(Photo: Natal Mercury)*

Abstract

In this investigation the taxonomy of seven species of Penaeid prawns, found to date in Durban Bay, is considered. The following species were obtained: *Penaeus japonicus* Bate, *P.latisulcatus* Kishinouye, *P.canaliculatus* Olivier, *P.semisulcatus* de Haan, *P.monodon* Fabricius, *P.indicus* Milne-Edwards and *Metapenaeus monoceros* (Fabricius). Most of these species are found in large numbers in bays and estuaries along the east coast of Southern Africa and it is intended that this report should provide the means whereby any interested person can readily identify the more common inshore Penaeid prawns in this area. A first record of *P.latisulcatus* from South Africa and a new description of *P.canaliculatus* Olivier, previously recorded by Barnard (1950) from Port Edward and Bonza Bay near East London have been included. The authenticity of *P.canaliculatus* has hitherto been regarded as doubtful due to its close resemblance to *P.japonicus* and *P.latisulcatus*, but this species is now considered to be valid.

The paper has been illustrated with diagrams of the species described and provision has been made in Figs. 3 and 4 for locating the various appendages, etc. of the prawn. A key to the sub-families of the family *Penaeidae* has been included as a large number of other species of *Penaeidae* are known to be present in deeper waters off the east coast of southern Africa.

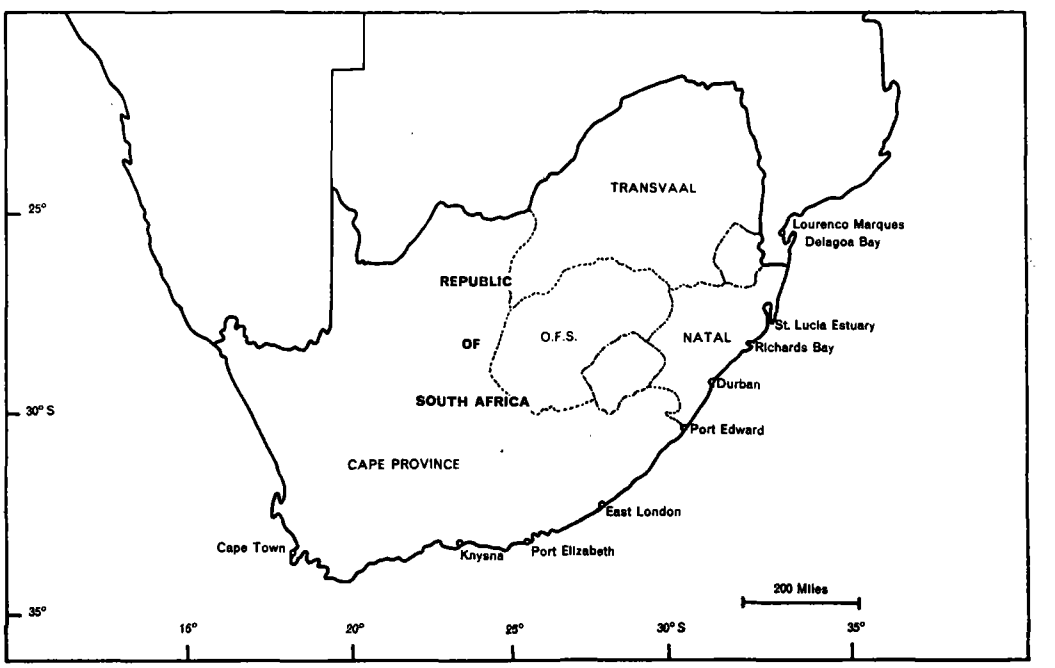


FIG. 1. The Republic of South Africa

Introduction

Although the taxonomy and general biology of the Penaeid prawns has been extensively investigated in many parts of the world, relatively little work has been done on this group in South Africa. In May 1963 a small collection of Penaeid prawns was made in the Durban Bay and provisionally identified with the assistance of the late Dr. K. H. Barnard of the South African Museum. It was then decided that a programme of investigation of the seasonal occurrence and general biology of the Penaeid prawns in the Durban Bay would be undertaken.

Durban Bay is situated adjacent to the city of Durban on the coast of Natal in the Republic of South Africa. The bay is approximately 3½ miles long and 2 miles wide and is landlocked except for a narrow dredged channel which connects it with the sea (Fig. 2). The channel is protected from wave action by two piers to the north and south of the entrance. The Bluff lies along the eastern shore of the bay and the western shore is bordered by the City of Durban. Two small rivers, the Umbilo and Umhlatuzana, drain into an area known as the Sanctuary at the south end of the bay. A series of water samples were collected from the bay and their salinity determined. Water in the area of the Sanctuary was found to have a salinity range of approximately 27.0 - 34.9‰ The salinity increases rapidly as one moves towards the entrance and about ¼ mile from the Sanctuary, a mean salinity of approximately 34.8‰ was obtained. The salinity remains at 34.8 - 35.5‰ throughout the remainder of the bay. The greater part of the bottom of the bay consists of sandy mud and there is relatively little attached aquatic vege-

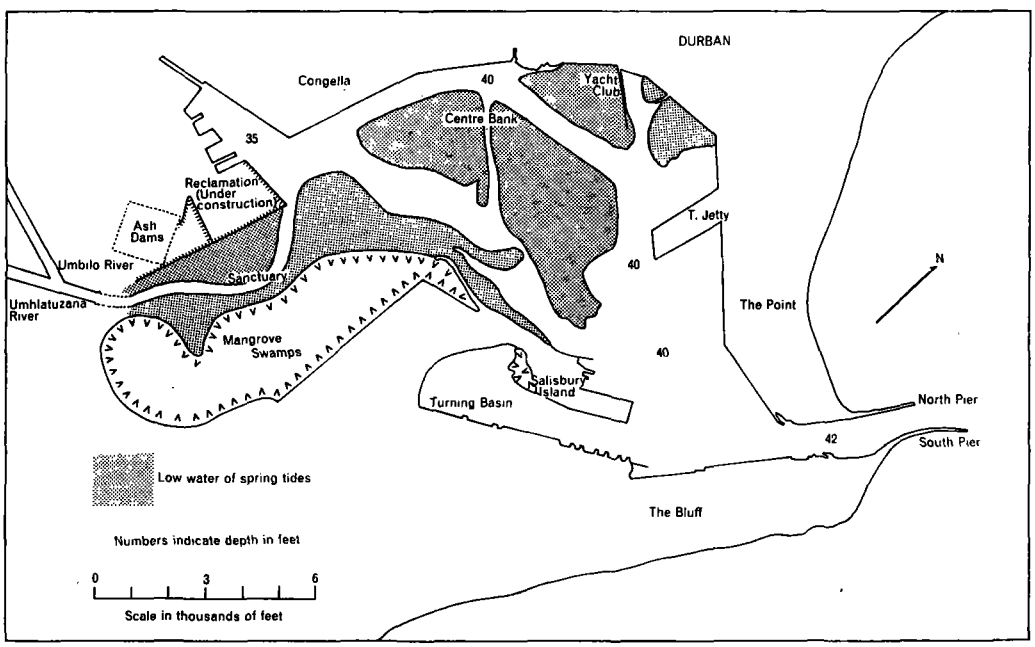
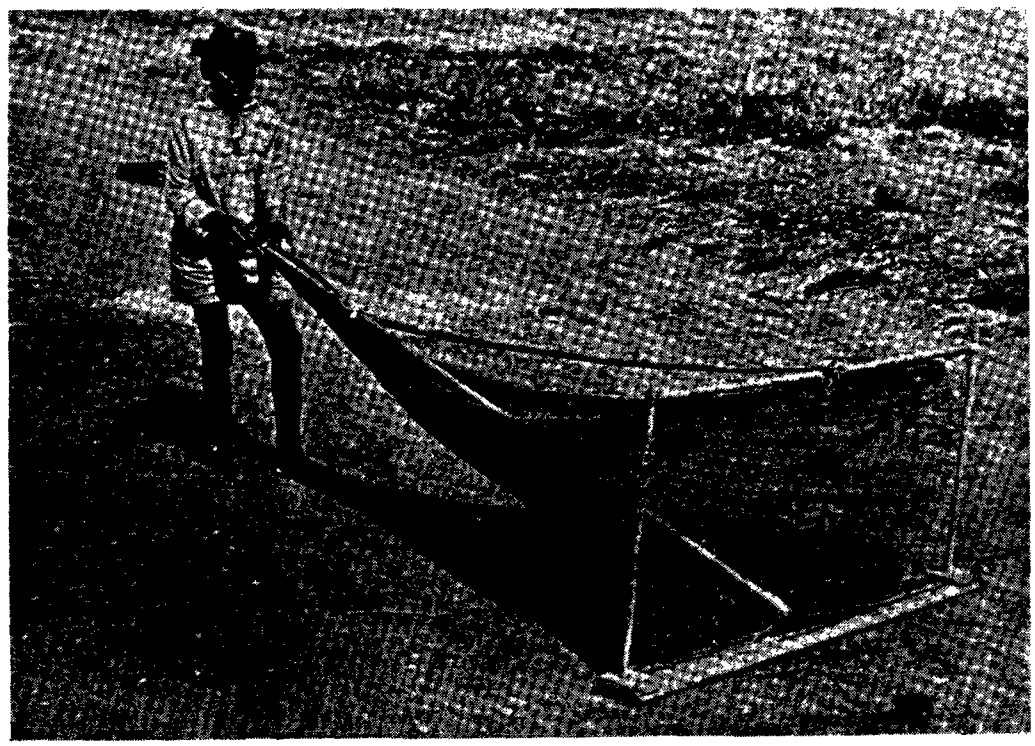


FIG. 2. Durban Bay — modified from the map of the Harbour Engineer, 1964

tation apart from seasonal outbursts of sea lettuce *Ulva lactuca* which appears on the sand banks along the west side of the bay near the Point Yacht Club in varying abundance during the period June-September. Eel grass, *Zostera capensis* may also be found during these months on the centre banks, but is subject to considerable variation in abundance. The year 1963 was extremely favourable for *Zostera* growth but during 1964 there was relatively little growth of *Zostera* in the bay.

Durban Bay is one of the finest natural harbours in the world but due to the policy of reclamation of extensive areas in the south-west region and because of the increasing pollution caused by shipping and the discharge of industrial and other effluent, the bay represents a deteriorating habitat for its natural flora and fauna. It is therefore of considerable interest to record the species of prawns found in the bay at the present time in order to be able to assess what effect these factors may have in the future.

The terms shrimp and prawn are used indiscriminately in South Africa in relation to all species of the *Penaeidea*. For example, *P.japonicus* may be called the Ginger Prawn or the Ginger Shrimp. The use of the terms shrimp and prawn is not confined to the *Penaeidea*, however, and may be used for certain species belonging to other crustacean groups such as the *Caridea*, e.g. *Alpheus crassimanus* the Cracker Shrimp and the *Thallassinidea*, e.g. *Upogebia africana* the Mud Prawn. In general, it is usual to use the term shrimp for a small specimen and prawn for a large specimen. In this paper the term prawn is used to describe all species of *Penaeidea* irrespective of size.



A typical pushnet used by Indian shrimpers in Durban Bay

Method of Sampling

Samples of prawns were obtained from the bay from Indian netters, who net nightly using *push nets*. A push net consists of a net mounted on a frame 4 ft. square. The net is 7 ft. 6 ins. long, the front 2 ft. consisting of $\frac{1}{2}$ in. bar net and the remaining 5 ft. 6 ins. being $\frac{1}{4}$ in. bar netting — these dimensions are in accordance with the regulations laid down in the coastal fisheries ordinance. The net is pushed from the rear by one or two people using a handle attached to the frame (Plate 2). A standard sample of prawns weighing approximately $\frac{1}{2}$ lb. was obtained from the netters every two weeks and was sorted according to species. The number, weight and size range of each species was recorded. In addition, plankton samples which will be examined for the presence of Penaeid larvae entering the bay, were collected at the harbour entrance.

Measurements

The use of total length as a standard measure of the size of a prawn was found to be most unsatisfactory as the tip of the rostrum or telson is often damaged while the prawns struggle in the nets. For this reason, the carapace length has been used as the standard measure of length, rather than total length. Carapace length is defined as the distance between the post-orbital margin and the median-posterior margin of the carapace.

Morphological Features

A number of features such as the pattern of grooves on the carapace, the shape and structure of the rostrum, etc. are used in the generic and specific identification of the *Penaeidae*.

The CARAPACE (Fig. 3) has a number of grooves, carinae (=ridges) and spines which vary sufficiently in the different genera and species, for them to be important features in the identification of prawns.

The ROSTRUM (Fig. 3) may possess dorsal and ventral teeth and although their number is never constant for a species, this feature may be of some value when used in conjunction with the presence or absence of ventral teeth and the shape and length of the rostrum.

The ANTENNULES (Fig. 4) each of which consist of a peduncle made up of three segments terminating in two flagella, are important in the identification of a species. The lengths of the stylocerite (a spine on the lateral margin of the 1st penduncular segment), the prosartema (a foliaceous appendage arising on the inner margin of the 1st peduncular segment) and the two flagella are used relative to the length of the peduncle.

The PETASMA (Figs. 5-11) which consists of a modification of the endopods of the first pair of pleopods of the male to form a channel for the transmission of sperm, is also a feature which differs in relation to species.

The APPENDIX MASCULINA (Figs. 5-11) which is a modification of the distal portion of the endopods of the second pair of pleopods in the male, may vary in shape for different species.

The THELYCUM or seminal receptacle (Figs. 5-11) of the female is situated between the fifth pair of pareiopods and varies in shape in the different species. Species which superficially appear identical may always be separated on the basis of differences in the shape of the thelycum.

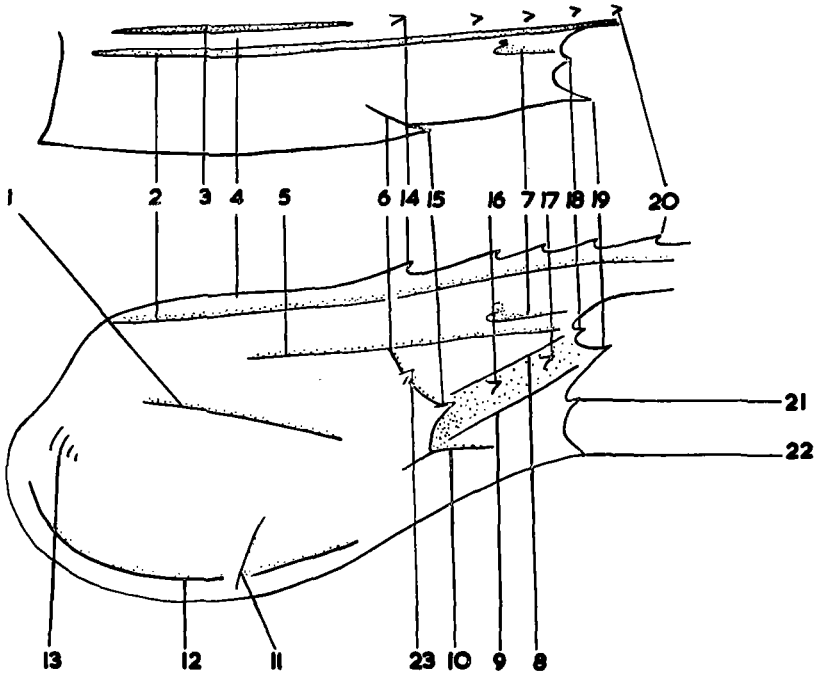


FIG. 3. Diagram of the Carapace of a Penaeid Prawn showing the features used in the classification of the *Penaeidae*

Grooves, carinae and sutures: 1. Branchio-cardiac, 2. Adrostral, 3. Median, 4. Post rostral, 5. Horizontal, 6. Cervical, 7. Gastro-frontal, 8. Gastro-orbital, 9. Gastro-antennal, 10. Sub-hepatic, 11. Vertical, 12. Pterygostomial, 13. Stridulating.

Spines: 14. Epigastric or first rostral tooth, 15. Hepatic, 16. Post-antennal, 17. Post-orbital, 18. Orbital, 19. Antennal, 20. Rostral tooth, 21. Branchiostegal, 22. Pterygostomian.

Taxonomy

A key to the sub-families of the family *Penaeidae* and the genera of the entire sub-family *Penaeinae* is given below. Only two genera, *Penaeus* and *Metapenaeus* of the sub-family *Penaeinae*, comprising seven species, were found in Durban Bay.

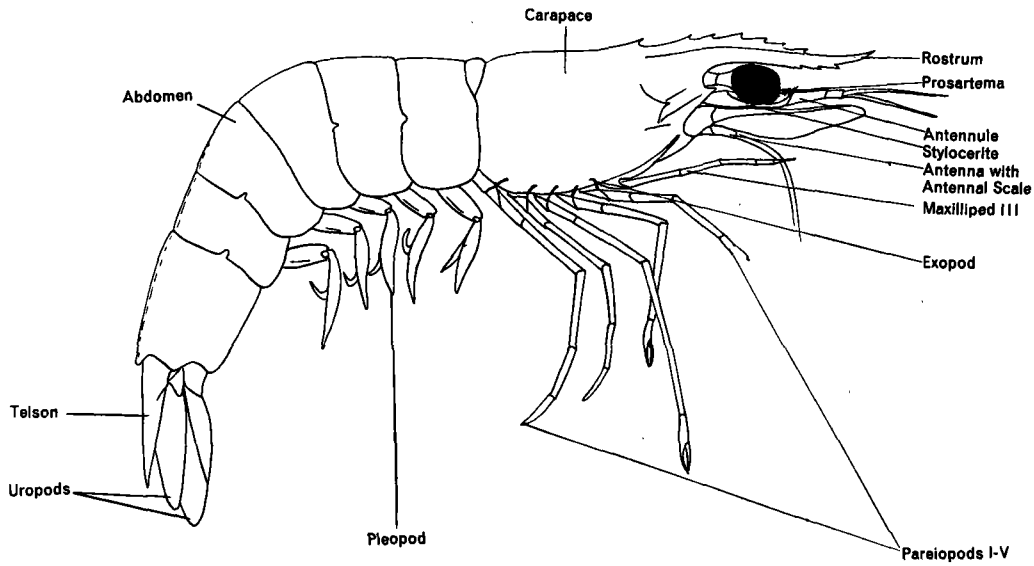


FIG. 4. Diagram of typical Penaeid Prawn

Family *PENAEIDAE* Bate

Penaeidae Bate 1888, Kubo 1949, Dall 1957

Body compressed; rostrum usually well developed, laterally compressed and armed with teeth; antennule with two flagella and a stylocerite; eye well developed; large antennal scale; maxillipeds 2 and 3 pediform with seven segments; pareiopods 1 - 3 chelate gradually increasing in length posteriorly; pareiopods 4 and 5 well developed with a simple dactylus; well developed petasma, appendix masculina, and thelycum; gills numerous with double series of arthrobranchs.

KEY TO THE SUB-FAMILIES OF THE *PENAEIDAE*

1a UPPER ANTENNULAR FLAGELLUM is inserted near posterior border of 3rd antennular segment and is much shorter than lower one; seven pleurobranchs of which all but last are usually rudimentary . . . *Aristaeinae*

1b UPPER ANTENNULAR FLAGELLUM is inserted on the apex of 3rd antennular segment, equal to or sub-equal to lower one; 2-6 pleurobranchs, all fully functional

2a CERVICAL GROOVE reaching to or almost to dorsum; distal portion of appendix masculina made up of two scales . . . . *Solenocerinae*

2b CERVICAL GROOVE reaching not more than two thirds distance between hepatic spine and dorsum; distal portion of appendix masculina is single scale usually thickened.

3a PROSARTEMA present; exopods present on maxillipeds 2 and 3 . . . . . *Penaeinae*

3b PROSARTEMA absent; no exopods present on maxillipeds 2 and 3 . . . . . *Sicyoninae*

Sub-family *PENAEINAE* Burkenroad

Penaeinae Burkenroad 1934, Kubo 1949, Dall 1957

Rostrum well developed, armed dorsally and sometimes ventrally with teeth; post-orbital, post-antennal and supra-hepatic spines absent, other spines may or may not be present; cervical groove does not reach dorsum of carapace. Foliaceaus prosartema present on inner side of basal segment of antennular peduncle; upper antennular flagellum inserted on apex of third segment of peduncle. Second segment of mandibular palp lamellar, usually closing a respiratory canal formed by apposition of antennular peduncles and antennal scale; maxilliped 3 long and pediform, sometimes sexually dimorphic; exopods present on pareiopods 1 - 4 and may or may not be present on pareiopod 5. Telson usually has median dorsal groove and may or may not have lateral spines.

The sub-family contains 16 genera, but as the genera *Xiphopenaeus*, *Artemesia* and *Protrachypene* are restricted to the Atlantic Ocean, they have not been included in this key.

KEY TO THE GENERA OF *PENAEINAE*

1a PETASMA assymmetrical; maxilliped 3 with a basal spine and no epipod; ventral rostral teeth absent . . . . . *Metapenaeopsis* Bouvier

1b PETASMA symmetrical, maxilliped 3 without basal spine; ventral rostral teeth may or may be not present.

2a CARAPACE with longitudinal sutures.

3a FIRST PAREIOPOD without ischial spine; longitudinal sutures of carapace extend more than half length of carapace (except in *P.venusta* — not beyond hepatic spine) . . . . . *Parapeneopsis* Alcock

3b FIRST PAREIOPOD with ischial spine.

4a LONGITUDINAL SUTURES of carapace extend to just above hepatic spine; telson without fixed dorsolateral spines; pareiopod 2 with basal spine; distal portion of appendix masculina quadrate in outline *Trachypeneus* Alcock

4b LONGITUDINAL SUTURES of carapace nearly reaching posterior margin of carapace; telson with pair of fixed dorsolateral spines; pareiopod 2 without basal spine; distal portion of appendix masculina fist-like in appearance . . . . . *Parapenaeus* Smith

2b CARAPACE without longitudinal sutures.

5a EYE strikingly elongated with cornea as wide as stalk; 1st segment of antennular peduncle not exscavated for reception of the cornea; petasmal endopods without longitudinal folds, not united. . . . . *Miyadiella* Kubo

5b EYE typical with cornea much wider than stalk; 1st segment of antennular peduncle excavated for the reception of the cornea; petasmal endopods with well developed longitudinal folds, united.

6a PLEUROBRANCH present on the last throacic segment; epipod present on maxilliped 3; rostrum usually with dorsal and ventral teeth; carapace with gastro-orbital carina.

7a BODY glabrous; incisor process of mandible short, almost right angled . . . . . .

7b BODY densely pubescent; incisor process of mandible elongate and scimitarlike . . . — *Penaeus* Fabricius

7c BODY glabrous except for a row of stiff setae overlying grooves present on carapace and abdomen . . . . . — *Funchalia* Johnson, *Heteropenaeus* de Man

6b PLEUROBRANCH absent on last thoracic segment; no epipod on maxilliped 3; rostrum with dorsal teeth but no ventral teeth; carapace without gastro-orbital carina.

8a BRANCHIOSTEGAL SPINE present; maxillary palp unsegmented . . . . . .

8b BRANCHIOSTEGAL SPINE absent; maxillary palp 2-segmented. — *Penaeopsis* Bate

9a EXOPODS present on pareiopods 1 - 4; 7th thoracic segment with pleurobranch . — *Metapenaeus* Woodmason and Alcock

9b EXOPODS present on pareiopods 1 - 5; 7th thoracic segment without pleurobranch; telson without a pair of fixed spines but with 4 pairs mobile spines; petasma with long stiletto-like terminals — *Macropetasma* Stebbing

9c EXOPODS present on pareiopods 1 - 5; 7th thoracic segment without pleurobranch.

10a TELSON with mobile and fixed dorsolateral spines; pareiopods 2 and 3 without basal and ischial spines . — *Trachypenaeopsis* Burkenroad

10b TELSON without dorsolateral spines; pareiopod 2 has basal and ischial spine; pareiopod 3 with basal spine — *Atypopeneus* Alcock

Genus *PENAEUS* Fabricius

Penaeus Fabricius 1798, Bate 1888, de Man 1911, Bales 1914, Burkenroad 1934, Kubo 1949, Barnard 1950, Dall 1957.
Peneus Alcock 1901.

Carapace and abdomen uniformly glabrous. Carapace without longitudinal or transverse sutures; hepatic and antennal spines pronounced, cervical and antennal carinae always present; orbito-antennal groove always present. Rostrum toothed dorsally and ventrally. Antennular flagella shorter than carapace. Maxilliped 3 sexually dimorphic; basal spines present on pareio-

pods 1 and 2 and exopods always present on 1st 4 pairs of pareiopods and usually present on 5th pair as well. Telson with deep dorso-median groove, no fixed subapical spines, may or may not have lateral movable spines. Petasma with thin median lobes; lateral lobes usually have thickened rounded distal margins. Appendix masculina with ovoid distal segment bearing setae. Thelycum usually has anterior process lying between coxae of 4th pair pareiopods, receptacle lies between coxae of 5th pair pareiopods.

The type species of the genus *Penaeus* is *Penaeus monodon*. The genus contains 28 species of which only 8 species are included in this key. For a complete key to the species of *Penaeus* see Dall 1957 p. 142.

Discussion

The genus *Penaeus* is composed of a large number of species which are morphologically very similar. Six species of *Penaeus* have been found in Durban Bay, viz. *P.japonicus* Bate, *P.latisulcatus* Kishinouye, *P.canaliculatus* Olivier, *P.semisulcatus* de Haan, *P.monodon* Fabricius and *P.indicus* Milne-Edwards. These species fall naturally into three groups:

I. The *P.japonicus* — *P.latisulcatus* — *P.canaliculatus* group characterised by (*a*) the adrostral carina almost reaching the posterior margin of the carapace, (*b*) the presence of a gastro-frontal groove and (*c*) the presence of a sub-hepatic carina.

II. The *P.semisulcatus* — *P.monodon* group characterised by (*a*) the adrostral groove reaching to or slightly beyond the first rostral tooth, (*b*) the absence of a gastro-frontal groove and (*c*) the presence of a sub-hepatic carina.

III. The *P.indicus* group characterised by (*a*) the adrostral groove reaching to the first rostral tooth, (*b*) the absence of a gastro-frontal groove and (*c*) the presence of a sub-hepatic carina.

TABLE 1. MAIN CHARACTERISTICS OF THE GROUPS OF THE GENUS *Penaeus*

	Group I	Group II	Group III
ADROSTRAL CARINA	To posterior margin of carapace	To or just beyond 1st rostral tooth	To 1st rostral tooth
GASTRO-FRONTAL GROOVE	Present	Absent	Absent
SUB-HEPATIC CARINA	Present	Present	Absent

I. *P.japonicus* — *P.latisulcatus* — *P.canaliculatus* are similar, particularly in relation to the size and position of the grooves and ridges on the carapace. *P.canaliculatus* can readily be distinguished from *P.japonicus* and *P.latisulcatus* by the absence of spines on the telson. All three species may be distinguished from each other by the variation in the shape of the thelycum. Kubo (1949), Dall (1957) and Hall (1962) use the width of the postrostral carina as opposed to the width of the adrostral groove as the main feature

distinguishing *P.japonicus* from *P.latisulcatus*. In the specimens examined this feature showed little variation and has therefore been excluded as a means of distinguishing the species.

TABLE 2. **MAIN DIFFERENCES BETWEEN *P.japonicus*, *P.latisulcatus* AND *P.canaliculatus***

	P.japonicus	*P.latisulcatus*	*P.canaliculatus*
POST-ROSTRAL GROOVE	Narrows posteriorly	Does not narrow posteriorly	Narrows posteriorly
HEPATIC CARINA	Ends directly below end of cervical carina	Ends slightly before end of cervical carina	Ends slightly before end of cervical carina
TELSON	Lateral spines short usually only notches where spines inserted are visible	Lateral spines fairly long and easily visible	No lateral spines present
PETASMA	Median lobes with well developed protuberances at apex overhanging lateral lobes	Median lobes with slight protuberances at apex	Median lobes with well developed protuberances at apex overhanging lateral lobes
APPENDIX MASCULINA	Distal portion rectangular in outline; anterior surface and edge bearing setae.	Distal portion triangular in outline; edge fringed with setae anterior surface bearing no setae.	Distal portion triangular in outline; edge fringed with setae, anterior surface bearing no setae.
THELYCUM	Anterior portion slightly shorter than receptacle, has rounded apex; receptacle cylindrical.	Anterior portion shorter than receptacle has bifurcate apex; receptacle composed of two laberal lobes	Anterior portion as long as or longer than receptacle, has rounded apex; receptacle composed of two lateral lobes.
COLOUR	Light fawn with broad red-brown transverse bands	Overall fawn to brown	Light fawn with fairly narrow red-brown transverse bands

The discovery of *P. latisulcatus* Kishinouye (1900) in Durban Bay is a new record for South African waters. Although this species has been found in Durban Bay in fairly large numbers, it has previously been regarded as a colour variation of *P.japonicus*. It has not been possible to obtain Kishinouye's original description of *P.latisulcatus* but comparison of the specimens from Durban Bay with the descriptions of *P.latisulcatus* given by Kubo (1949), Dall (1957) and Hall (1962), has shown them to be synonymous with *P.latisulcatus* Kishinouye. Lanchester (1901) examined two specimens (total length 50.5 mm. and 59 mm.) which he called *P.canaliculatus* Olivier var. These specimens have since caused some confusion as they are identical to *P.latisulcatus*, except that they possess a third median horn on the anterior portion of the thelycum. It has been possible to collect a wide size range of *P.latisulcatus* from Durban Bay and examination of the thelycum of specimens of 63 mm. to 143 mm. in total length has shown that the anterior portion of the thelycum

is primarily trifurcate in the juvenile of *P.latisulcatus* (Fig. 6b). Later the median horn apparently degenerates with a result that the mature thelycum of *P.latisulcatus* is typically bifurcate.

P.canaliculatus Olivier (1811) has been regarded as a doubtful species for some time. Very few specimens have been described and confusion arose after the establishment of *P.japonicus* Bate 1888 and *P.latisulcatus* Kishinouye (1900), as separate species. It was found that many of the specimens which had previously been identified as *P.canaliculatus* were either *P.japonicus* or *P.latisulcatus*, and the authenticity of Olivier's identification became doubtful. Recently a number of specimens were found in Durban Bay which agreed with de Man's description (1911) of *P.canaliculatus* (Olivier) in relation to the absence of spines on the telson and the shape of the thelycum. It has been impossible so far to obtain a copy of Olivier's original description and the specimens have been identified as *P.canaliculatus* according to de Man's description. Barnard (1950) briefly described two specimens from Port Edward, Natal. There are also specimens of *P.canaliculatus* from East London, in the South African Museum.

II. *P.semisulcatus* — *P.monodon* are superficially similar and there has been some confusion with regard to their identification. They are nevertheless readily distinguishable as separate species by the following features:

TABLE 3. **MAIN DIFFERENCES BETWEEN *P.semisulcatus* AND *P.monodon***

	P.semisulcatus	*P.monodon*
ROSTRUM	Extends to tip of antennular peduncle	Extends beyond tip of antennular peduncle
ADROSTRAL CARINA	Extends beyond first rostral tooth	Extends to second rostral tooth
POST-ROSTRAL GROOVE	Present	Absent
SUBHEPATIC CARINA	Inclined anteroventrally	Horizontal
GASTRO-ORBITAL CARINA	Occupies posterior ⅔ of distance between the hepatic spine and post-orbital margin of carapace	Occupies posterior ⅓ of distance between hepatic spine and post-orbital margin of carapace
ANTENNULAR FLAGELLA	Nearly as long as antennular peduncle	Longer than antennular peduncle
PAREIOPOD 5	Exopod present	Exopod absent

III. *P.indicus* is the only species in this group which has been reported from South African waters. The two other species *P.penicillatus* and *P.merquiensis* which may also be included in this group, but which have not been reported from this area, have been included in this key.

KEY TO THE SPECIES OF *PENAEUS*

1a ADROSTRAL GROOVE almost reaching posterior margin of carapace. Well defined sub-hepatic carina and gastro-frontal grooves.

2a TELSON bears no lateral spines; postrostral carina with clear-cut median groove half length of carapace, seminal receptacle of thelycum composed of two lateral lobes, anterior portion as long as or longer than seminal receptacle. . . — *P.canaliculatus* Olivier

2b TELSON bears three pairs lateral spines; post-rostral carina with clear-cut median groove half length of carapace; seminal receptacle of thelycum composed of one or two lobes, anterior portion slightly shorter than seminal receptacle.

3a THELYCUM with single cylindrical receptacle, anterior portion with rounded apex . . . . . .

3b THELYCUM with receptacle composed of two lateral lobes, anterior portion with bifurcate apex . . . . — *P.japonicus* Bate

1b ADROSTRAL GROOVE extending to or just beyond 1st rostral tooth, gastro-frontal groove absent. — *P.latisulcatus* Kishinouye

4a SUBHEPATIC CARINA present.

5a SUBHEPATIC CARINA inclined anteroventrally; gastro-orbital carina occupies posterior $\frac{2}{3}$ distance between hepatic spine and post-orbital margin of carapace; pareiopod 5 bears an exopod; antennular flagellum shorter than peduncle . . . . . — *P.semisulcatus* de Haan

5b SUBHEPATIC CARINA horizontal; gastro-orbital carina occupies posterior $\frac{1}{3}$ distance between hepatic spine and post-orbital margin of carapace; pareiopod 5 bears no exopod; antennular flagellum longer than peduncle . — *P.monodon* Fabricius

4b SUBHEPATIC CARINA absent.

6a GASTRO-ORBITAL CARINA well defined; rostral crest not very high: Maxilliped 3 of male with dactylus .85 - 1.0 times length of propodus . . . . . — *P.indicus* Milne-Edwards

6b GASTRO-ORBITAL CARINA ill defined; rostral crest high.

7a MAXILLIPED 3 of male with dactylus 1.5 - 2.7 times length of propodus . . . . . — **P.penicillatus* Alcock

7b MAXILLIPED 3 of male with dactylus .5 - .6 times length of propodus . . . . . — **P.merquiensis* deMan

*Species not described in this paper

Penaeus japonicus Bate

Penaeus canaliculatus Oliv. var. *japonicus* Bate, 1888, p. 245.
Penaeus canaliculatus (non Olivier) Ortmann, 1890, p. 488; Kishinouye, 1900, pp. 6 and 11; Stebbing, 1914, p. 13.
Peneus canaliculatus (non Olivier) Alcock, 1906, p. 14.
Penaeus japonicus: de Man, 1911; Stebbing 1914, p. 12, 1917, p. 605; Kubo, 1949, pp. 273-278; Barnard 1926, p. 121, 1950, pp. 590-592; Hall, 1962, p. 14.

Common Name GINGER PRAWN

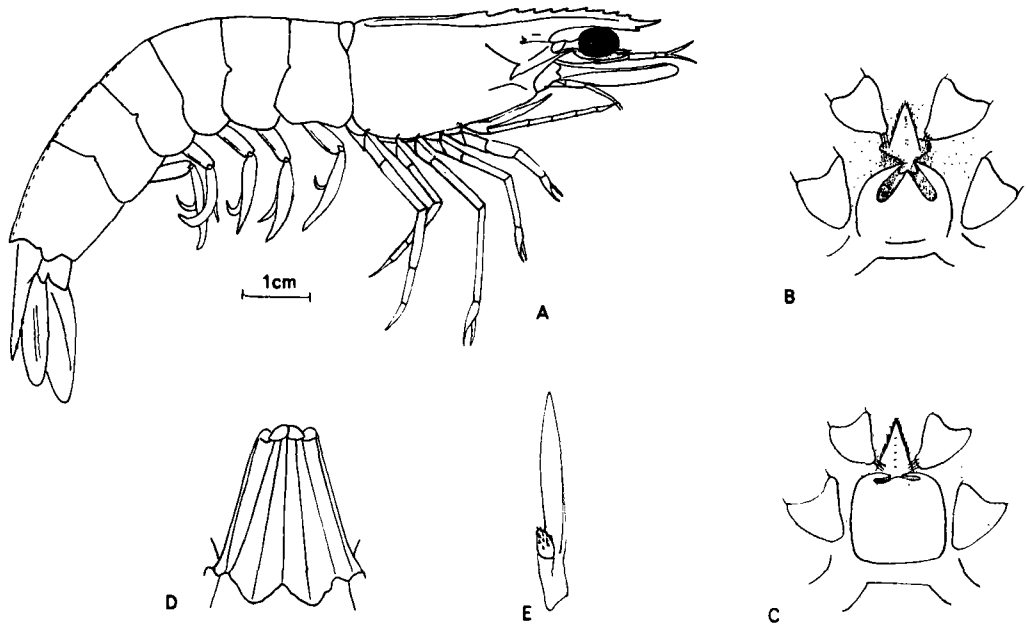


FIG. 5. *Penaeus japonicus* Bate. A, ♀ Cl 29 mm.; B, Thelycum of ♀ Cl 18 mm.; C, Thelycum of ♀ Cl 29 mm.; D, Petasma of ♂ Cl 28 mm.; E, Appendix masculina of ♂ Cl 28 mm.

Study Material

Six Females of carapace length: 16 mm., 18 mm., 26 mm., 27 mm., 29 mm. and 30 mm.

Six Males of carapace length: 17 mm., 24 mm., 25 mm., 26 mm., 27 mm. and 28 mm.

(All specimens from Durban Bay.)

Description

Carapace and abdomen uniformly glabrous. Carapace with well developed orbital, antennal and hepatic spines; gastro-frontal groove relatively deep

and bifurcate; orbito-antennal groove wide anteriorly, narrowing towards hepatic spine; gastro-antennal and gastro-orbital carinae well developed; cervical carina well developed; sub-hepatic carina extends posteriorly ending directly below cervical carina, anteriorly extending almost to anterior margin of carapace; pterygostomian margin rounded bearing no spine (Fig. 5a).

Rostrum armed with 8 - 10 dorsal teeth and one ventral tooth reaching just beyond tip of antennular peduncle; adrostral groove well defined reaching posterior margin of carapace; post-rostral carina reaches posterior margin of carapace; post-rostral groove narrowing posteriorly, is about half length of carapace.

Flagella of antennules short and not more than half length of peduncle; stylocerite extends approximately half length of basal segment of peduncle; prosartema extends almost to distal end of basal segment of peduncle.

Maxilliped 3 almost reaches distal end of basal segment of antennular peduncle and bears an exopod and an epipod, exopod extending about half way along carpus of maxilliped 3; dactylus of maxilliped 3, sexually dimorphic. Exopods present on pareiopods 1 - 5 and pareiopods 1 - 3 bear epipods; basal segment of pareiopods 1 and 2 each bears a spine.

Abdomen dorsally carinated from posterior half of fourth segment to end of sixth segment.

Telson has median groove and bears three pairs lateral spines. In this species notches, where spines inserted, more obvious than spines themselves.

Median lobes of petasma (Fig. 5d) have well developed protuberances at apex.

Distal portion of appendix masculina (Fig. 5e) more or less rectangular in outline with slightly rounded distal margin and fringed with setae which also occur on anterior surface of distal portion.

Anterior portion of thelycum (Fig. 5b and 5c) slightly shorter than receptacle with rounded apex, is more or less triangular in outline; seminal receptacle composed of single cylindrical receptacle.

Penaeus japonicus is a light fawn colour, striped with broad red-brown transverse bands on abdomen and cephalothorax; legs and pleopods tinged with blue; uropods brown, tipped with bands of deep yellow and blue and fringed with crimson setae.

P.japonicus is very abundant in Durban Bay throughout the year and usually makes up the majority of the catch.

Distribution

Two large specimens of *P.japonicus* were collected by Prof. J. L. B. Smith at Knysna (Barnard 1950), and constitute the most southerly limit on the South African coast of any species of the genus *Penaeus*.

P.japonicus has also been recorded from the following localities off the east coast of South Africa: Moçambique (Hilgendorf); off Cape St. Francis, 32 fathoms and off Durban 15 fathoms (Stebbing); Delagoa Bay (Barnard); Richards Bay (Millard and Harrison); St. Lucia Estuary (Day, Millard and Broekhuysen).

Penaeus latisulcatus Kishinouye

Penaeus latisulcatus: Kishinouye, 1900, p. 12; de Man, 1911, pp. 108-11; Kubo, 1949, pp. 278-82; Racek, 1955, pp. 222-3; Dall, 1957, p. 149; Hall, 1962, p. 14.

Penaeus canaliculatus (non Olivier) Lanchester, 1901, p. 571.

Common Name BROWN PRAWN

Study Material

Six Females of carapace length: 15 mm., 16 mm., 19.5 mm., 21 mm., 23.5 mm., 24 mm. and 36 mm.

Six Males of carapace length: 15 mm., 16 mm., 18 mm., 21 mm., 23 mm., and 27 mm.

(All specimens from Durban Bay.)

Description

Carapace and abdomen uniformly glabrous. Carapace with well developed orbital, antennal and hepatic spines; gastro-frontal groove relatively deep and bifurcate; orbito-antennal groove wide anteriorly, narrowing towards hepatic spine; gastro-antennal and gastro-orbital carinae well developed; cervical carina well developed; sub-hepatic carina extends posteriorly ending

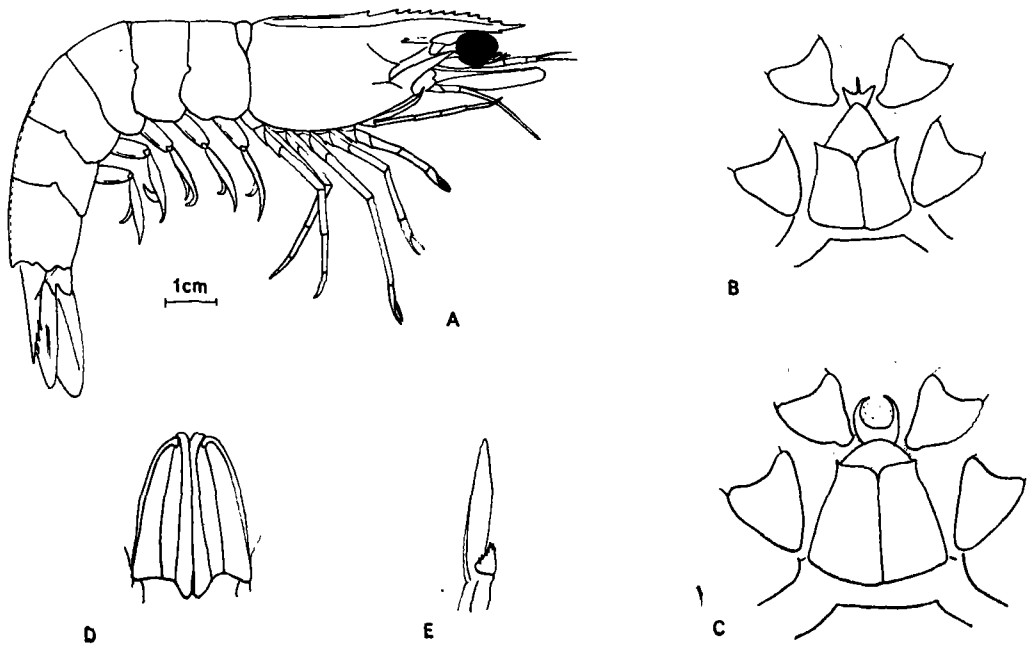


FIG. 6. *Penaeus latisulcatus* Kishinouye. A, ♀ Cl 35.5 mm.; B, Thelycum of ♀ Cl 15 mm.; C, Thelycum of ♀ Cl 35.5 mm.; D, Petasma of ♂ Cl 27 mm.; E, Appendix Masculina of ♂ Cl 27 mm.

before end of cervical carina, anteriorly extending almost to anterior margin of carapace; pterygostomian margin rounded bearing no spine.

Rostrum armed with 10-12 dorsal teeth and 1 ventral tooth, reaching tip of antennular peduncle; adrostral groove well defined, reaching posterior margin of carapace; post-rostral carina reaches posterior margin of carapace; post-rostral groove widens anteriorly and remains uniform width until it ends just before posterior margin of carapace, is about half length of carapace.

Flagella of antennules short and not more than half length of peduncle. Stylocerite extends approximately half length of basal segment of peduncle; prosartema extends almost to distal end of the basal segment of peduncle.

Maxilliped 3 almost reaches distal end of basal segment of antennular peduncle and bears an exopod and epipod, exopod extending about halfway along carpus of maxilliped 3; dactylus of maxilliped 3 sexually dimorphic. Exopods present on pareiopods 1 - 5 and pareiopods 1 - 3 bear epipods; basal segments of pareiopods 1 and 2 each bears a spine.

Abdomen dorsally carinated from posterior half of fourth segment to end of sixth segment.

Telson has median groove and bears three pairs of lateral spines which are fairly long and easily visible.

Median lobes of petasma (Fig. 5d) have only very slight protuberances at apex.

Distal portion of appendix masculine (Fig. 5c) more or less triangular in outline with rounded distal margin and fringed with setae, anterior surface bearing no setae.

Apex of anterior portion of thelycum (Fig. 5b and 5c) bifurcate; seminal receptacle composed of two lateral lobes.

Penaeus latisulcatus is fawn to brown in colour; with blue tinged pareiopods and pleopods; telson tipped with bands of blue and red and fringed with crimson setae.

P.latisulcatus is fairly abundant in Durban Bay throughout the year and appears to live in close association with *P.japonicus*.

Distribution

This species has not been recorded from any other part of the east coast of Southern Africa to date.

Penaeus canaliculatus Olivier

Penaeus canaliculatus Olivier, 1811, p. 660; de Man, 1911, p. 106; Barnard, 1950, p. 590.

Common Name STRIPED PRAWN

Study Material

Six Females of carapace length: 14 mm., 15 mm., 16 mm., 24 mm., 29 mm. and 33 mm.

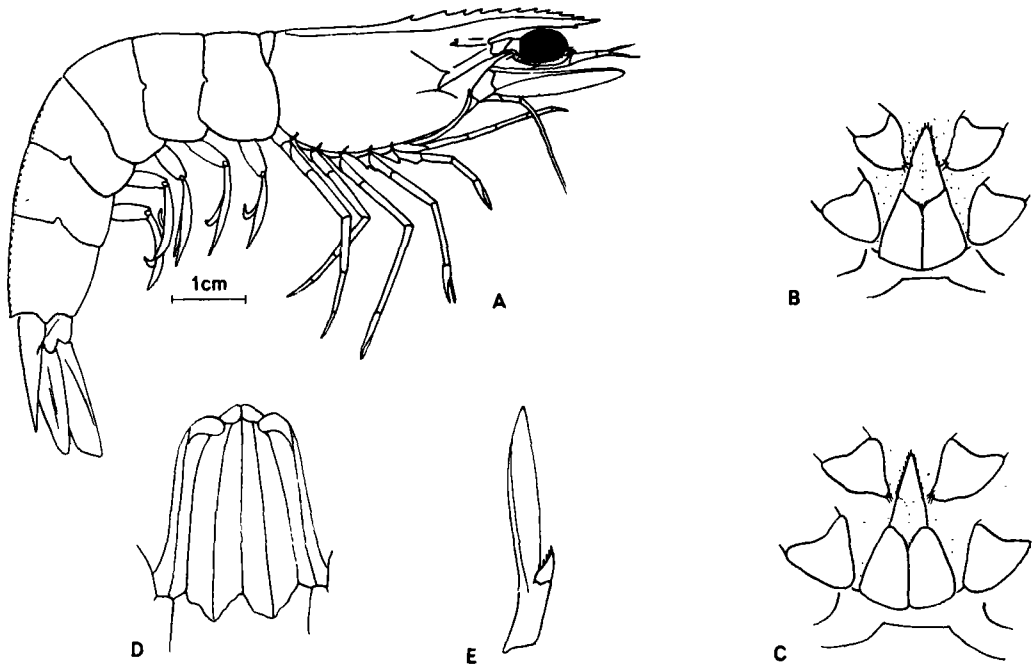


FIG. 7. *Penaeus canaliculatus* (Olivier). A, ♀ Cl 29 mm.; B, Thelycum of ♀ Cl 29 mm.; C, Thelycum of ♀ Cl 33 mm.; D, Petasma of ♂ Cl 29 mm.; E, Appendix Masculina of ♂ Cl 29 mm.

Six Males of carapace length: 15 mm., 15 mm., 16 mm., 17 mm., 17 mm. and 29 mm.
(All specimens from Durban Bay except for one female of carapace length (Cl) 33 mm. and one male of Cl 29 mm., which were collected at Bonza Bay, East London by the South African Museum.)

Description

Carapace and abdomen uniformly glabrous. Carapace with well developed orbital, antennal and hepatic spines; gastro-frontal groove relatively deep and bifurcate; orbito-antennal groove wide anteriorly, narrowing towards hepatic spine; gastro-antennal and gastro-orbital carinae well developed; cervical carina well developed; sub-hepatic carina extends posteriorly terminating before end of cervical carina, anteriorly extending almost to anterior margin of the carapace; pterygostomian margin rounded and bearing no spine (Fig. 7a).

Rostrum armed with 10-11 dorsal teeth and 1 ventral tooth, reaching to tip of antennular peduncle; adrostral groove well defined reaching posterior margin of carapace; post-rostral carina reaches posterior margin of carapace; post-rostral groove narrowing slightly posteriorly, is about half length of carapace.

Flagella of antennules short and not more than half length of peduncle; stylocerite extends approximately half length of basal segment of peduncle; prosartema extends almost to distal end of basal segment of peduncle.

Maxilliped 3 almost reaches distal end of basal segment of antennular peduncle and bears an exopod and an epipod, exopod extending about halfway along carpus of maxilliped 3; dactylus of maxilliped 3 is sexually dimorphic. Exopods present on pareiopods 1-5, pareiopods 1-3 bear epipods; basal segment of pareiopods 1-2 each bears a spine.

Abdomen dorsally carinated from posterior half of fourth segment to end of sixth segment.

Telson has a median groove and bears no lateral spines.

Median lobes of petasma (Fig. 7d) with well developed protuberances at apex similar to *Penaeus japonicus*.

Distal portion of appendix masculina (Fig. 7e) more or less triangular in outline with rounded distal margin fringed with setae, anterior surface bearing no setae.

Anterior portion of thelycum (Fig. 7b and 7c) as long as or longer than receptacle, with rounded apex; seminal receptacle composed of two lateral lobes.

Penaeus canaliculatus and *P.japonicus* are identical in colouring except that the transverse bands are slightly narrower in *P.canaliculatus*.

P.canaliculatus is found in small numbers in Durban Bay and appears to live in close association with *P.japonicus* and *P.latisulcatus*.

Distribution

This species has been recorded from only two other localities off the east coast of Southern Africa. Two specimens (both females) were collected off Port Edward (Barnard 1950) and a further two specimens (a male and a female) were collected at Bonza Bay, East London in 1962 by the South African Museum.

Penaeus semisulcatus de Haan

Penaeus semisulcatus de Haan, 1850, p. 191; de Man, 1911, pp. 97-100; Stebbing, 1917, p. 441; Calman, 1925, p. 12; Holthius, 1949, p. 1056; Barnard, 1950, p. 588; Kubo, 1956; Dall, 1957 pp. 154-157; Hall, 1962, p. 15.

Penaeus ashiaka Kishinouye, 1900, pp. 7-14; Rathbun, 1902, p. 38; Nobili, 1903, p. 2.

Peneus monodon (non Fabricius) Alcock, 1906, p. 8.

Penaeus monodon (non Fabricius) Bate 1888, p. 250; Kubo, 1949, pp. 291-6; Hall, 1956.

Common Name GREEN PRAWN

Study Material

Six Females of carapace length: 14 mm., 18 mm., 20.5 mm., 26 mm., 30 mm. and 33 mm.

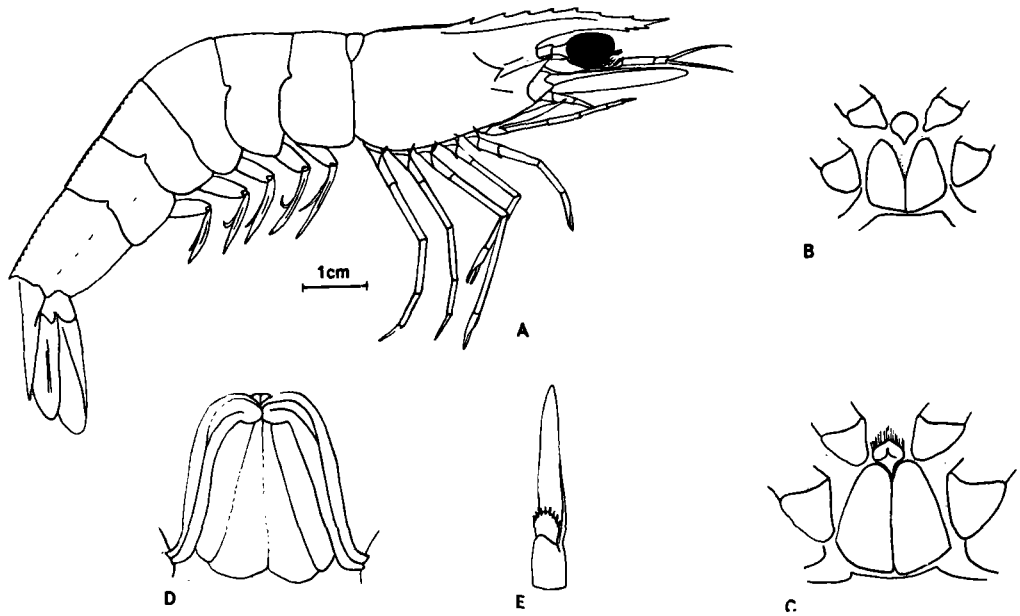


FIG. 8. *Penaeus semisulcatus* de Haan. A, ♀ Cl 26 mm.; B, Thelycum of ♀ Cl 20.5 mm.; C, Thelycum of ♀ Cl 26 mm.; D, Petasma of ♂ Cl 27 mm.; E, Appendix Masculina of ♂ Cl 27 mm.

Six Males of carapace length: 11 mm., 14.5 mm., 15 mm., 16 mm., 19 mm. and 27 mm.

(All specimens from Durban Bay.)

Description

Carapace and abdomen uniformly glabrous. Carapace with well developed antennal and hepatic spines but with no orbital spine; gastro-frontal groove absent; orbito-antennal groove shallow, narrowing slightly towards hepatic spine; gastro-antennal carina well developed reaching from antennal spine to below hepatic spine; gastro-orbital carina occupies posterior two-thirds of distance between post orbital margin of carapace and hepatic spine; cervical carina well developed; sub-hepatic carina relatively short and inclined at an angle of approximately 20° to horizontal; pterygostomian margin rounded bearing no spine (Fig. 8a).

Rostrum slightly curved and armed with 7-8 dorsal and 2-4 ventral teeth (usually 7 above and 3 below), reaching tip of antennular peduncle; adrostral carina well defined extending to just beyond first rostral tooth; post rostral carina almost reaches posterior margin of carapace; post rostral groove shallow and only about one-third length of carapace.

Flagella of antennules more than half length of peduncle; stylocerite extends just half length of basal segment of peduncle; prosartema reaches distal end of basal segment of peduncle.

Maxilliped 3 reaches distal end of basal segment of anteular peduncle and bears an exopod and an epipod, exopod reaching to proximal end of

carpus of maxilliped 3; dactylus of maxilliped 3 sexually dimorphic. Exopods present on pareiopods 1-5; pareiopods 1-3 bear epipods; basal segment of pareiopods 1 and 2 each bears a spine; pareiopod 1 also bears an ischial spine.

Abdomen dorsally carinated from anterior portion of fourth segment of end of sixth segment.

Telson has median groove and bears no lateral spines.

Petasma (Fig. 8c) with two large lateral lobes entirely overhanging distal portion of median lobes.

Distal portion of appendix masculina (Fig. 8d) very similar to that of *Penaeus japonicus* but is broader and the margin only is fringed with setae.

Anterior plate of thelycum (Fig. 8b) small and knoblike; seminal receptacle composed of two lateral lobes.

P.semisulcatus is a pale brown-green colour with darker brown-green transverse bands; pleopods are green, fringed with crimson setae; uropods are tipped with green-blue and fringed with crimson setae.

P.semisulcatus is found in large numbers at times in Durban Bay. It is interesting to note that during the winter months (June to August) when there is a good growth of eel grass (*Zostera capensis*), on the centre banks in the bay, large numbers of *P.semisulcatus* are found living in it. Prolific growth of eel grass does not occur every winter, however, and during the years that there is little or no eel grass, very few specimens of *P.semisulcatus* are found in the bay.

Distribution

P.semisulcatus has also been recorded from the following localities off the east coast of South Africa: Off Durban 38 fathoms (Calman); St. Lucia Estuary and off Zululand Coast, 26 fathoms (Barnard); Richards Bay (Millard and Harrison); St. Lucia Estuary (Day, Millard and Broekhuysen); Delagoa Bay (de Freitas).

Penaeus monodon Fabricius

Penaeus monodon Fabricius, 1798, p. 408; Holthius, 1949, pp. 1051-7; Barnard, 1926, p. 121; 1950, p. 584; Kubo, 1956; Dall, 1957, p. 152; Hall, 1962, p. 15; de Freitas, 1963, p. 4.

Penaeus carinatus Dana, 1852, p. 602; de Man, 1911, p. 101; Racek, 1955, p. 215.

Peneus semisulcatus (non de Haan) Alcock, 1906, p. 10.

Penaeus caeruleus Stebbing, 1905, p. 77; Racek, 1955, p. 217.

Penaeus bubulus Kubo 1949, p. 296; Hall, 1956.

Common Name TIGER PRAWN

Study Material

Six Females of carapace length: 12 mm., 16.5 mm., 26 mm., 31 mm., 40 mm. and 44 mm.

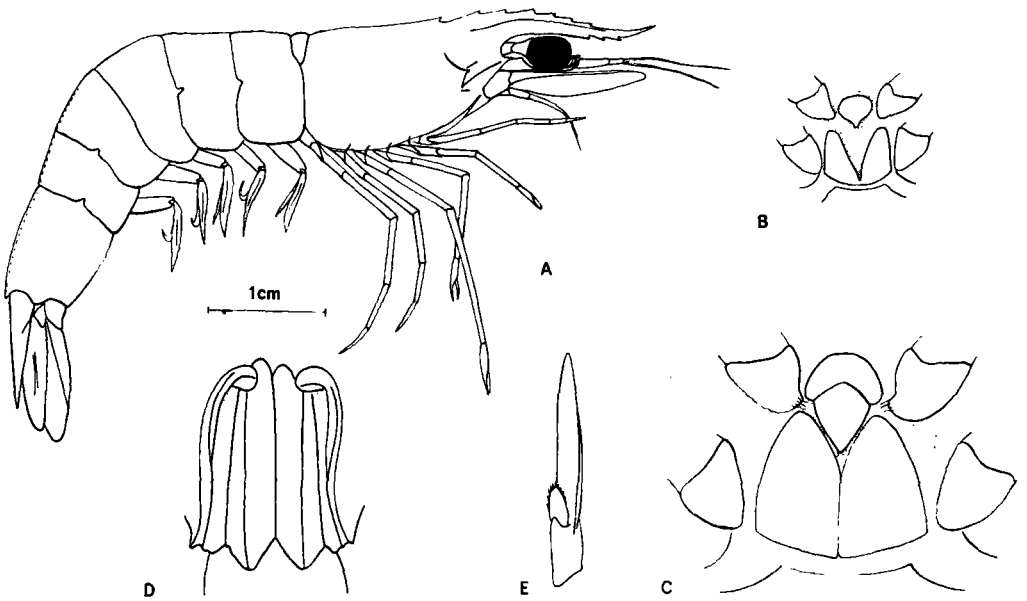


FIG. 9. *Penaeus monodon* Fabricius. A, ♀ Cl 16.5 mm.; B, Thelycum of ♀ Cl 16.5 mm.; C, Thelycum of ♀ Cl 40 mm.; D, Petasma of ♂ Cl 39 mm.; E, Appendix Masculina of ♂ Cl 39 mm.

Six Males of carapace length: 12.5 mm., 22 mm., 25 mm., 30 mm., 34 mm. and 39 mm.

(All specimens from Durban Bay.)

Description

Carapace and abdomen uniformly glabrous; carapace with well developed antennal and hepatic spines but with no orbital spine; gastro-frontal groove absent; orbito-antennal groove shallow, narrowing slightly towards hepatic spine; gastro-antennal carina well developed reaching from antennal spine to below hepatic spine; gastro-orbital carina occupies posterior one-third of distance between post orbital margin of carapace and hepatic spine; cervical carina well developed; sub-hepatic carina very short and lies horizontally; pterygostomian margin rounded, bearing no spine (Fig. 9a).

Rostrum with double curve and armed with 6-8 dorsal teeth and 2-4 ventral teeth (usually 7 above and 3 below), reaching beyond tip of antennular peduncle; adrostral carina well defined extending to 2nd rostral tooth; post-rostral carina almost reaches posterior margin of carapace; post-rostral groove virtually absent.

Flagella of antennules longer than antenullar peduncle; stylocerite extends nearly half length of basal segment of peduncle; prosartema reaches distal end of basal segment of peduncle.

Maxilliped 3 reaches distal end of basal segment of antennular peduncle and bears an endopod and an epipod, exopod reaching to proximal end of carpus of maxilliped 3; dactylus of maxilliped 3 is sexually dimorphic. Exopods present on pareiopods 1-4 but there is no exopod present on pareio-

pod 5; pareiopods 1-3 bear epipods; basal segment of pareiopods 1 and 2 each bears a basial spine; pareiopod 1 also bears an ischial spine.

Abdomen dorsally carinated from anterior portion of 4th segment to posterior end of 6th segment.

Telson has median groove and bears no dorso-lateral spines.

Petasma (Fig. 9d) with one median lobe slightly higher than other, two lateral lobes slightly overhang distal portions of median lobes.

Distal portion of appendix masculina (Fig. 9e) rectangular in shape and twice as long as broad, margin fringed with setae.

Anterior portion of thelycum (Fig. 9b and c) small and knoblike; seminal receptacle composed of two lateral lobes.

P.monodon is a blue-fawn colour with darker, blue-brown transverse bands; uropods and pleopods tipped with crimson setae.

Very few specimens of *P.monodon* were found in Durban Bay. The largest specimen found until recently was a female with a carapace length of 16.5 mm., but in January 1964 a number of very large specimens of *P.monodon* (the largest having carapace length of 44 mm.) were netted from an enclosed area of the bay which is in the process of being reclaimed. These specimens were probably trapped in the basin when reclamation first started approximately six months previously, preventing them from migrating out to sea to breed at maturity.

Distribution

P.monodon has been recorded from the following localities along the east coast of South Africa: Natal (Krauss); Zwartkops River Mouth and Nahoon River (Stebbing); Buffalo River, Port St. Johns, Umgeni Lagoon and Delagoa Bay (S. Afr. Mus.); off Durban 27-40 fathoms (Gilchrist); Richards Bay (Millard and Harrison); St. Lucia Estuary (Day, Millard and Broekhuysen); Delagoa Bay (de Freitas).

Penaeus indicus Milne-Edwards

Penaeus indicus Milne-Edwards, 1837; de Man, 1911; Kubo, 1949, p. 311; Barnard, 1950, p. 588; Racek, 1955, p. 220; Hall, 1962, p. 16; de Freitas, 1963, p. 3.
Penaeus indicus var. *longirostris* de Man, p. 511.
Peneus indicus Alcock, 1906, p. 12.
Penaeus semisulcatus (non de Haan) Stebbing, 1914, p. 69.
?Penaeus durbani Stebbing 1917, p. 442.

Common Name WHITE PRAWN

Study Material

Six Females of carapace length: 16 mm., 17 mm., 20 mm., 25 mm., 31 mm. and 38 mm.

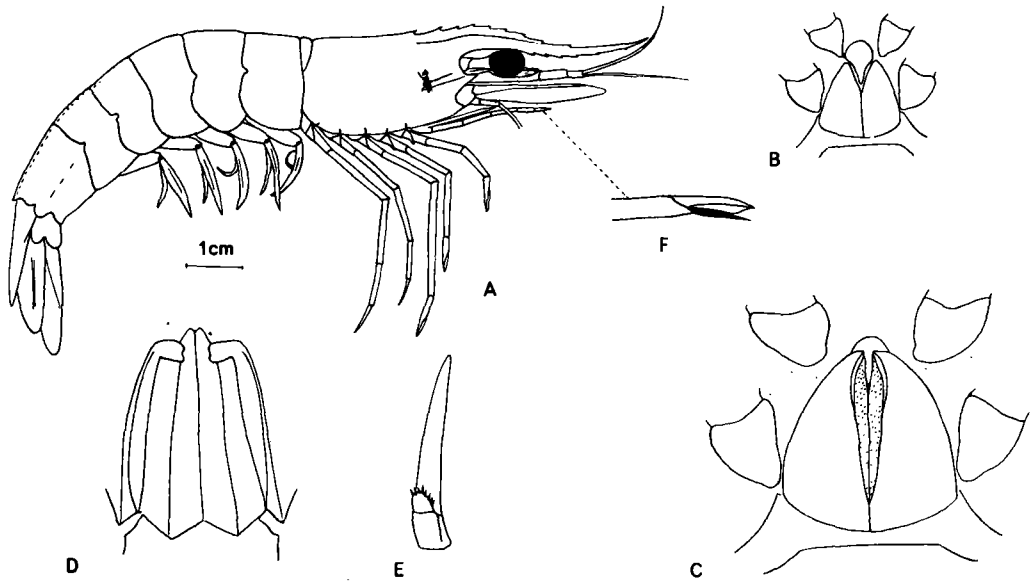


FIG. 10. *Penaeus indicus* Milne-Edwards. A, ♀ Cl 27 mm.; B, Thelycum of ♀ Cl 17 mm.; C, Thelycum of ♀ Cl 31 mm.; D, Petasma of ♂ Cl 26 mm.; E, Appendix Masculina of ♂ Cl 26 mm.; F, Tip of maxilliped 3 of ♂ (enlarged).

Six Males of carapace length: 15 mm., 16 mm., 22 mm., 26 mm., 30 mm. and 31 mm.

(All specimens from Durban Bay.)

Description

Carapace and abdomen uniformly glabrous. Carapace with well developed hepatic and antennal spines but with no orbital spine; gastro-frontal groove absent; orbito-antennal groove quite deep and not very wide; gastro-antennal carina well developed; gastro-orbital carina occupies posterior two-thirds of distance between post-orbital margin of carapace and hepatic spine; cervical carina short; no sub-hepatic carina present; pterygostomian margin rounded bearing no spine (Fig. 10a).

Rostrum with distinct double curve and armed with 7-9 dorsal and 4-5 ventral teeth, reaching far beyond tip of antennular peduncle; adrostral carina well defined extending to first rostral tooth; post-rostral carina extends to within one-fifth of carapace length from posterior margin of carapace; post-rostral groove very shallow.

Flagella of antennule nearly $1\frac{1}{2}$ times length of antennular peduncle; stylocerite extends about $\frac{1}{3}$ length of basal segment of peduncle; prosartema reaches distal end of basal segment of peduncle.

Maxilliped 3 reaches distal end of basal segment of antennular peduncle and bears an exopod and an epipod, exopod reaching to proximal end of the carpus of maxilliped 3; dactylus of maxilliped 3 sexually dimorphic (Fig. 9f). Exopods present on pareiopods 1-5; pareiopods 1-3 bear epipods; basal segment of pareiopods 1 and 2 bears a basal spine; pareiopod 1 also bears an ischial spine.

Abdomen dorsally carinated from anterior portion of third segment to posterior portion of sixth segment.

Telson has median groove and bears no lateral spines.

Median lobes of petasma (Fig. 10d) with rounded tips which are longer than lateral lobes, lateral lobes slightly overlap median lobes.

The distal portion of appendix masculina (Fig. 10e) deltoid in shape and margin fringed with setae.

Anterior portion of thelycum (Fig. 10a and b) small and knoblike with a point like the radicle of a seed growing down between the two lateral lobes which make up seminal receptacle. In specimens with a carapace length greater than 27 mm. lateral lobes of seminal receptacle tend to curl back down midline, revealing small tubercles covering inner surfaces of lateral lobes.

Penaeus indicus is white, lightly speckled with brown; tips of pleopods and uropods are yellow.

Penaeus indicus is not common in Durban Bay. Fairly large numbers were found in the Sanctuary but very few specimens were found in the open areas of the bay. Recently a number of very large specimens of *P.indicus* were netted in the enclosed area of the bay which is being reclaimed, as was the case in *P.monodon.*

Distribution

P.indicus has also been recorded from the following localities off the east coast of South Africa: Quelimane (Hilgendorf); Umgeni Lagoon (Stebbing); off Tugela River, 24 fathoms, Zwartkops River mouth, Buffalo River, Port St. Johns and Delagoa Bay (S. Afr. Mus.); St. Lucia Estuary (Fisheries Survey, 1940); Richards Bay (Millard and Harrison); St. Lucia Estuary (Day, Millard and Broekhuysen); Delagoa Bay (de Freitas).

Genus *METAPENAEUS* Wood-Mason and Alcock

Metapenaeus Wood-Mason and Alcock, 1891.
Metapeneus Alcock 1906.
Penaeopsis de Man, 1911; Schmitt, 1926.

Carapace and abdomen usually partly pubescent. Carapace without longitudinal or transverse sutures; well developed hepatic and antennal spines; hepatic carina ill-defined behind level of hepatic spine but well defined in front; orbito-antennal groove present; pterygostomian angle blunt. Antennular flagella shorter than carapace; pereiopods 1-3 bear basal spines; exopods present on pareiopods 1-4; ischium and merus of pareiopod 5 is often modified in adult male. Telson with deep dorsomedian groove, with no fixed subapical spines but usually with movable dorsolateral spines which may be microscopic and very numerous. Petasma tubular with thickened median lobes and even thicker lateral lobes which form disto-lateral spout-like projections each with a dorsal lobule produced posteriorly into an expanded plate-like projection; median lobes have a dorsal lobule produced into a thin recurved hood-like structure; appendix masculina has no setae

on the distal segment. Thelycum is composed of an anterior median plate and two posterior lateral plates. Pleurobranchiae are present on segments 3-7 of the thorax.

Discussion

Metapenaeus monoceros is the best known species of the genus *Metapenaeus* in South Africa. A second species, *M.stebbingi* has been recorded from Delagoa Bay (Barnard 1950) but appears to be extremely rare. A third species, *M.affinis*, has been recorded by Stebbing (1914) but its identification is uncertain.

KEY TO THE SOUTH AFRICAN SPECIES OF *METAPENAEUS*

1a	Carapace has large pubescent areas; 1st rostral tooth directly above hepatic spine; petasma with distomedian projections rounded	*Metapenaeus monoceros* (Fabricius)
1b	Carapace glabrous with small pubescent areas along cervical carina and below first rostral tooth; 1st rostral tooth in front of hepatic spine. Petasma with distomedian projections long and spoutlike (see Barnard 1950)	*Metapenaeus stebbingi* Nobili

Metapenaeus monoceros Fabricius

Penaeus monoceros Fabricius, 1798, p. 409.
Metapeneus monoceros Alcock, 1906, p. 18.
Metapenaeus monoceros Barnard 1950, p. 597; Hall, 1958, p. 537; de Freitas, 1963, p. 5.
Penaeopsis spinulicauda Stebbing, 1914, p. 17, 1917, p. 444.
Penaeopsis monoceros Stebbing, 1914, p. 70; Calman, 1925, p. 12.
Not
Penaeopsis monoceros de Man, 1911.
Metapenaeus monoceros Kubo, 1949, pp. 329-333; Dall, 1957, pp. 184-187.

Common Names

SPECKLED PRAWN (Durban Bay).
GINGER PRAWN (St. Lucia and Richards Bay).

Study Material

Six Females with carapace length: 12 mm., 22 mm., 25 mm., 27 mm., 28 mm. and 29.5 mm.

Six Males with carapace length: 11 mm., 19 mm., 20 mm., 21 mm., 23 mm. and 25 mm.

Description

Carapace and abdomen irregularly pubescent. Carapace with well developed antennal, orbital and hepatic spines; no gastro-frontal groove or gastro-orbital carina; gastro-antennal carina ill-defined, slight depression of cara-

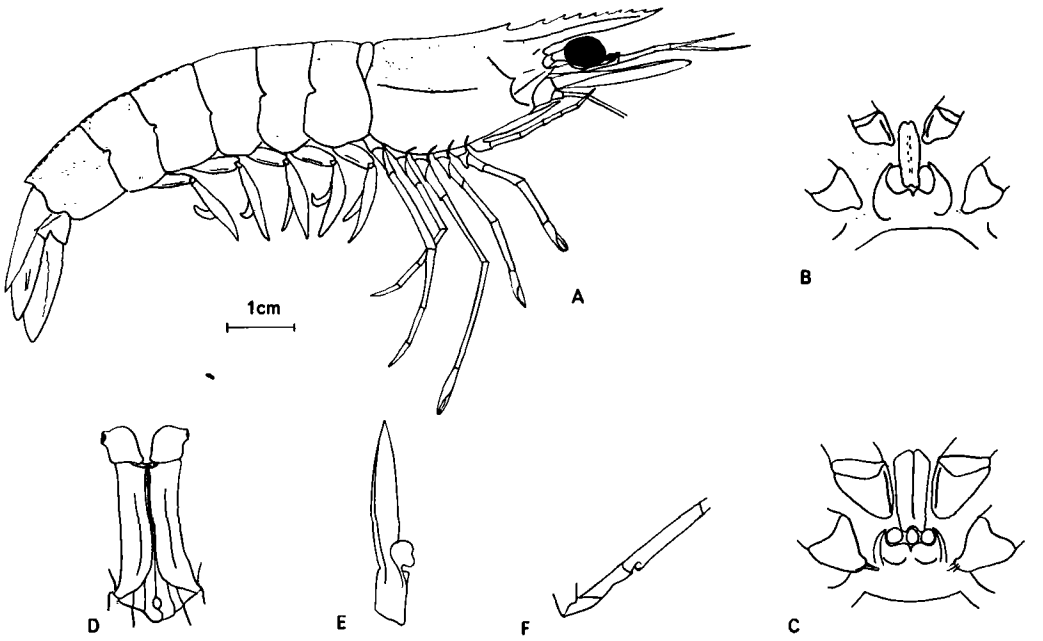


FIG. 11. *Metapenaeus monoceros* (Fabricius). A, ♀ Cl 25 mm.; B, Thelycum of ♀ Cl 18 mm.; C, Thelycum of ♀ Cl 29.5 mm.; D, Petasma of ♂ Cl 20 mm.; E, Appendix Masculina of ♂ Cl 20 mm.; F, Forepart of Pareiopod 5 of ♂ (enlarged).

pace forms orbito-antennal groove; cervical carina well developed and almost straight; sub-hepatic carina descends vertically for a short distance and then curves anteriorly ending before pterygostomian margin which is rounded (Fig. 11a).

Rostrum straight with tip slightly uptilted bearing 9-10 dorsal teeth and no ventral teeth, it extends to tip of antennular peduncle. Adrostral carina well defined ending at base of second rostral tooth; post-rostral carina not very well defined and extends to posterior margin of carapace; post-rostral groove absent.

Flagella of antennules just over half length of antennular peduncle; stylocerite extends half length of basal segment of peduncle; prosartema almost reaches distal end of basal segment of peduncle.

Maxilliped 3 reaches to end of stylocerite of antennule and bears an exopod but no epipod. Exopods present on pareiopods 1-4 and pareiopods 1-3 bear epipods and a spine on each basal segment; pareiopod 1 bears ischial spine. Pareiopod 5 of adult male has a keel on posterior margin of ischium, with a spine on the merus, curving outwards and downwards (Fig. 10f).

Abdomen dorsally carinated from beginning of 4th segment to end of 6th segment; traces of dorsal carina present on segment 2 and 3.

Telson has a median dorsal groove and bears no lateral spines.

Disto-median projections of petasma (Fig. 10d) extend beyond tip of lateral lobes and are rounded, whole length of lateral lobe is doubled over on each side meeting at mid-line to form an almost completely enclosed channel. Petasma greatly thickened.

Distal portion of appendix masculina (Fig. 10e) rounded and attached to endopod of second pleopod by means of stalk.

Thelycum (Fig. 11b and c) has elevated postero-lateral plate and an anterior median lobe which is elevated and grooved along its mid-line; coxopod of pareiopod 4 has a sharp vertical ridge.

M.monoceros is white, covered with speckles of dark brown pigment.

M.monoceros is fairly common in Durban Bay being found in largest numbers in the Sanctuary.

Distribution

M.monoceros has also been recorded from the following localities off the east coast of South Africa: Quelimane (Hilgendorf); Delagoa Bay and off Tugela River 12-14 fathoms (Stebbing); off Umvoti River, 38 fathoms (Calman); Delagoa Bay, Zululand Coast, Umgeni Lagoon, Umkomaas, Port St. Johns and Cape Henderson (S. Afr. Mus.); Richards Bay (Millard and Harrison); St. Lucia Estuary (Day, Millard and Broekhuysen); Delagoa Bay (de Freitas).

Summary

A survey of the Penaeid prawns in Durban Bay was carried out during the period May 1963 to August 1964. Seven species, belonging to two genera of the family *Penaeidae* were recorded from the bay; they include the following species: the Ginger Prawn *Penaeus japonicus* Bate, the Brown Prawn *P.latisulcatus* Kishinouye, the Striped Prawn *P.canaliculatus* Olivier, the Green Prawn *P.semisulcatus* de Haan, the Tiger Prawn *P.monodon* Fabricius, the White Prawn *P.indicus* Milne-Edwards, and the Speckled Prawn *Metapenaeus monoceros* (Fabricius). *P.latisulcatus* is a new record for South African waters.

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B R E V I O R A

Museum of Comparative Zoology

CAMBRIDGE, MASS. JULY 15, 1965 NUMBER 226

THE LARVAL FORM OF THE HETEROMI (PISCES)

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The distinctive order Heteromi (Lypomi, Halosauriformes, or Notacanthiformes) includes about 25 species arrayed among about eight genera within the three families Notacanthidae, Halosauridae, and Lipogenyidae. All appear to be bottom fishes which, as adults, live between a few hundred and about 3500 meters. The placement of the order, which has been divided into two by many authors (Gill, 1889; Goode and Bean, 1896:129, 162; Berg, 1940:453; and Lagler, Bardach and Miller, 1962:40), within the teleostean hierarchy has been problematical. The most penetrating study of possible relationships is that of Marshall (1962) who emphasized the unity of the order, and allied it with the true eels or Apodes, chiefly on the basis of significant resemblances in swimbladder structure. The group was also recognized as a distinct order allied to the true eels within their superorder Elopomorpha by Greenwood, Rosen, Weitzman and Myers (1965) — a treatment in which I wholly concur.

The reproductive biology of the group has been a complete enigma. Neither eggs nor larvae have been reported, although Marshall (1962) and Greenwood *et al.* (1965) suggested that if the Heteromi shared common ancestry with the apodal fishes, a leptocephalus-like young should be expected. Similar speculation was included in the review of reproduction in the group provided by Mead, Bertelsen and Cohen (1964:583). It is thus most gratifying to report here on a single, relatively large leptocephalus taken during the midwater trawling program of the International Indian Ocean Expedition. It is broken and badly damaged, but has the typical shape and transparency of a relatively large eel leptocephalus and head structure unmistakably that of a halosaur, probably of the genus *Aldrovandia*. This metamorphosing young was taken as follows:

R/V *Anton Bruun,* Cruise VI, Sta. 351D, APB label 7354; 29 June 1964; Southern Indian Ocean between 31°45′S, 65°08′E and 32°26′S, 65°05′E; 0359 to 1507 hrs.; 10-foot Isaacs-Kidd trawl equipped with Foxton Trousers (Foxton, 1963) set to trip at 350 m; maximum depth of haul 1786 m; probable depth of capture below 125 m; depth of bottom 4480 m. MCZ catalog number 43994.

The body of this specimen which lacks the terminal part is 263 mm long and is composed of 250 somites. It lacks much of its skin, and the anal and the ventral fins are either undeveloped or were lost during capture. The flanks are densely stippled with fine black pigment. The head is similarly but more darkly colored. Along the ventral profile are series of black spots, each continuous with its mate across the ventral midline and connected with the adjacent spots mid-ventrally by a fine line of dense pigment. These spots probably occur throughout the length of the fish, but both skin and pigment are missing in many areas (Fig. 1). Within or surmounting each ventral spot, at least anteriorly, is a pore which may be the precursor of the series of ventral luminous organs seen in *Aldrovandia rostrata* (Günther, 1887, pl. 59, fig. A). Spots and pores occur on every fourth or fifth somite, a relationship similar to that between light organs and rows of scales in certain species. Prior to preservation, the body was nearly as transparent as that of most eel leptocephali. The pectoral fin, which is set close behind the gill opening, is formed of twelve rays. The dorsal fin, badly damaged but including at least eight rays, is short-based and situated relatively far forward compared to that of other halosaurs, suggesting a substantial relative shortening of the post-dorsal part of the body with growth. The anus cannot be found.

The head (Fig. 1) is about as broad as deep and terminates anterior to the gape in a prolonged fleshy snout. The gill openings are broad and continue anteriorly to near the symphysis of the lower jaw. Branchiostegal membranes are free from each other and from the isthmus. The gill membrane is thin and fragile. None of the osteological peculiarities noted by Marshall (1962:253) can be ascertained. Gill rakers are present and lath-like, are about as long as the opposite filaments, and number 4 + 1 + 14 on the first arch.

Jaws are poorly developed and bear teeth only at the tip of the mandible. Upper jaw bones are similar in structure to adult *Aldrovandia,* i.e. a somewhat flattened maxillary bone that abuts anteriorly on the end of the premaxillary which, with its

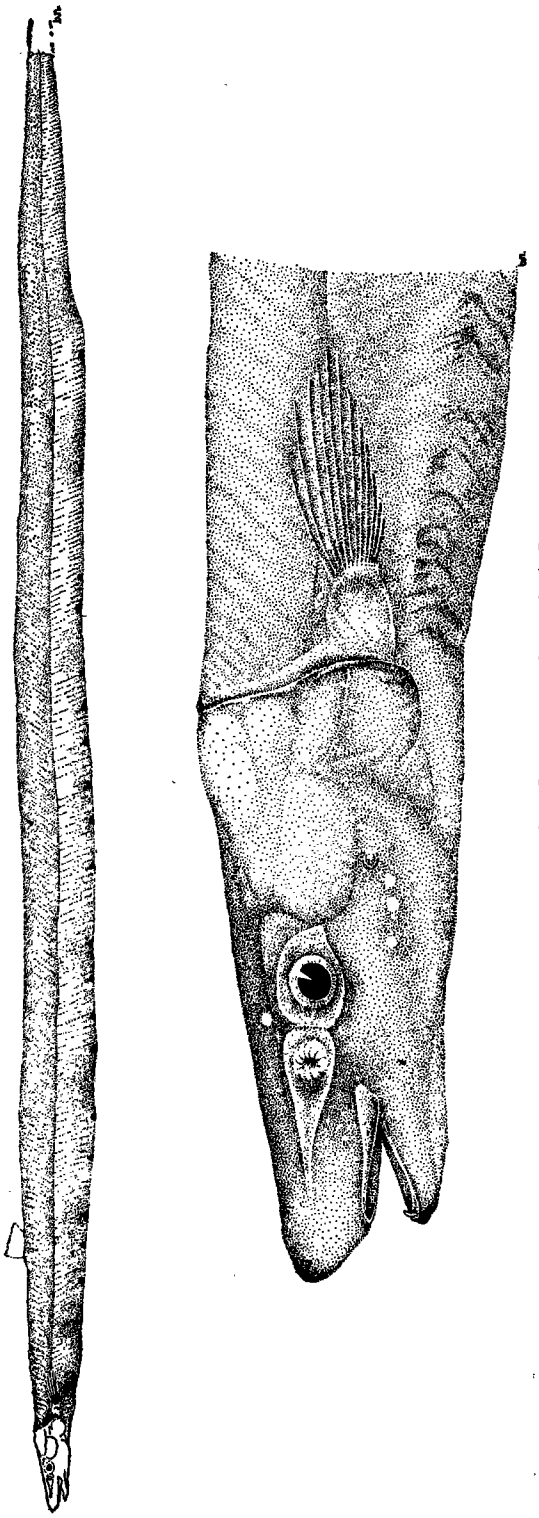


Figure 1. Metamorphosing leptocephalus of *Aldrovandia* sp.

opposite partner, courses transversely across the gape. Pores, presumably sensory, occur on the cheek (Fig. 1) and another pair is situated on the top of the head above the anterior edge of the orbit.

The capture of a specimen, small but of adult appearance, which has been identified provisionally as *Halosaurus nigerrimus* Alcock, 1899, indicates that halosaurs can complete their metamorphosis in midwater. This fish, 185 mm long, was also caught in the more southern latitudes of the Indian Ocean, as follows:

R/V *Anton Bruun,* Cr. VI, Sta. 349B, APB label 7332; 26 June 1964; 26°24′S, 65°02′E to 26°44′S, 65°05′E; 0830 to 1425 hrs.; 10-foot Isaacs-Kidd trawl equipped with Foxton Trousers set to trip at 350 m; maximum depth of haul 1470 m; probable depth of capture below 125 m; depth of bottom 4571 m. MCZ catalog number 43993.

These specimens thus clearly show that heteromous fishes have leptocephalus young so strikingly similar to those of the true eel that a close relationship between the two orders must be recognized, and that the young of at least some of these benthic fishes are pelagic. Thus either a spawning migration of the adults must occur or, less likely, buoyant eggs spawned on the bottom must rise through a water column of substantial height.

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CRUISE OF R.R.S. DISCOVERY IN THE INDIAN OCEAN

By R. S. BAILEY, *British Ornithologist with expedition.*

During 1964 The Royal Research Ship Discovery was working in the Indian Ocean to complete her part in the International Indian Ocean Expedition. A brief summary of the ornithological work during 1963 was published in the Ibis in January 1964. (Ibis, 106: no. 1.) The work was divided into three cruises, the first two of which were surveys along 58° east and 68° east meridians as far south as 20° south. The last was a survey of the Somali Current. The routine work included current measuring and the analysis of seawater to determine its salinity, temperature and the oxygen, nitrate and phosphate contents. Quantitative net hauls were made down to one thousand metres and the density of chlorophyll present in the plant plankton was measured in the surface layers.

I attempted to estimate bird numbers by counting for at least an hour four times a day. Many factors make it difficult to compare these counts, but they probably give a good indication of the changes in density over the ocean. It is extremely difficult to sample the food available to seabirds directly, but an attempt was made using a surface plankton net towed at five knots. The catches taken with this net give some idea of how productive the sea is and, when they have been analysed, it may be possible to determine some of the ecological factors which affect the distribution of seabirds.

Our first destination after leaving Aden at the beginning of March, the tail end of the N.E. Monsoon, was the Kuria Muria Islands. In July 1963, at the height of the S.W. Monsoon season we had spent several weeks in the upwelling area off the Arabian coast and many species of birds were concentrated around these islands, suggesting that they are an important breeding station. Unfortunately conditions in July were too rough to attempt landing, but in March this year we were able to land on Hasikiya, the westernmost island. Hasikiya was the most desolate island I have ever encountered. Only one species of land plant was found growing, and rats were apparently the only mammals. Only one true land bird was seen—a Peregrine which probably subsisted on the rats. The island was deserted by most of the seabirds seen in the surrounding seas during the south-west monsoon and only the Blue-faced Booby was nesting. It had just begun laying and, while several thousand birds were seen, only about fifty nest scrapes contained eggs. The only other seabirds on the island were a few Socotra Cormorants, which suggests that the huge numbers of this species that I saw in Kuria Muria Bay in 1963 were migrants from the Persian Gulf.

Our visit to the Arabian coast showed the profound effect of the seasonal changes on the bird community. The seas off Arabia in March were warm and few birds were seen. Only Jouanin's Petrels and Blue-faced Boobies were common, but a few Red-billed Tropic-birds, Lesser Black-backed Gulls and phalaropes were also seen. Upwelling was no longer progressing, so the water was poor in plankton and fish and, as a result, was presumably unable to support the huge populations of birds. Even Arabian Sea resident species, such as the Persian Shearwater, the Socotra Cormorant, the Brown-winged Tern and Hemprich's Gull had disappeared, perhaps to find upwelling areas in other parts of the Arabian Sea.

It was not to find boobies that I had visited the island, however. I wanted to search for evidence of breeding petrels, especially Jouanin's

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Petrel and the Persian Shearwater. The only signs of suitable nest sites were shallow burrows and crevices in the steep-sided gullies which serve as water courses at certain times of year. Some of these burrows contained small piles of feathers and bones which may provide evidence of the species which nest on the island, when they have been identified. Conclusive evidence, however, must wait until an expedition can visit the island during the breeding season.

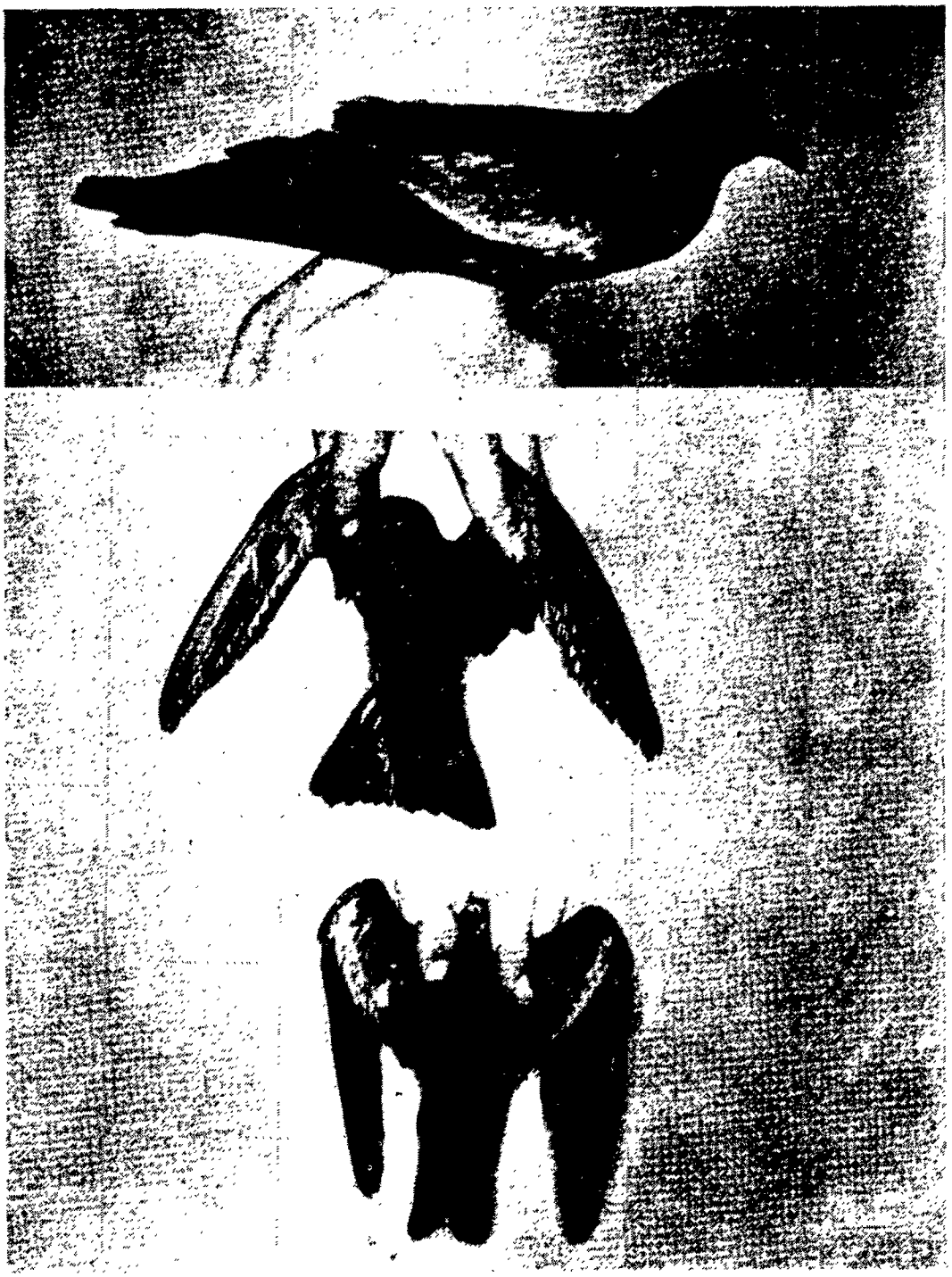
The first longitudinal survey was carried out in March and April. The main aim was to study the system of equatorial currents before the beginning of the south-west monsoon. At the boundaries of these currents with the counter-current there is a tendency for the water layers to mix bringing nutrient salts to the surface. This results in an increase in productivity and consequently one might expect to find seabirds there in large numbers.

The distribution of oceanic birds was so patchy that it is difficult to make generalisations at this stage. None of the species were evenly spread along the transects, and both the Arabian Sea and the zone between 8° south and 13° south seemed especially unfavourable. This may be connected with the greater distance from breeding colonies, but I believe that the productivity of the sea is more important. The richest areas were those just south of the equator and again south of 15° south. This suggests that the boundaries between the equatorial currents may be richer than the surrounding seas. When the biological material has been worked up it will be possible to analyse this more thoroughly.

On our way south Wedge-tailed Shearwaters increased suddenly at 4° south at a convergence marked by a drop in sea temperature and the presence of Sargassum weed. Two species of all-black storm-petrels were seen. A Swinhoe's Storm-petrel came aboard at 7° north, but the other species remains a mystery. It was probably Matsudaira's Storm-petrel and was commoner than the smaller Swinhoe's Storm-petrel. In March both species were rare in the equatorial region. They probably spread along the rich boundaries of the equatorial currents from the Pacific Ocean during their non-breeding season.

The commonest bird at sea, however, was the Sooty Tern, and flocks of fifty to a hundred were seen almost everywhere. Along 58° east it was concentrated in three zones: 10-12° north, 5° north and 17-20° south, whereas in 68° east it was less common and more scattered. Sometimes flocks of Sooty Terns were accompanied by Frigate-birds, but these are difficult to identify at any distance. White-tailed Tropic-birds and Blue-faced Boobies were also occasionally seen at sea but no obvious concentrations were recorded. The other tropical seabirds, such as noddies, Audubon's Shearwaters, White and Brown-winged Terns, were very rarely recorded more than fifty miles from their breeding islands. By April a few Wilson's Storm-petrels and Great Skuas had reached the area south of the equator.

On leaving Cochin in mid May we made for the Arabian coast to begin the second longitudinal survey. In the Arabian Sea at the beginning of the S.W. Monsoon a gradual build-up in numbers had begun to take place. Upwelling had just started close to the Arabian coast and small numbers of Persian Shearwaters, Hemprich's Gulls and Crested Terns were seen around the Kuria Muria Islands, as well as small numbers of Pale-footed Shearwaters and Wilson's Storm-petrels from the south. Jouanin's Petrels and Red-billed Tropic-birds had also begun to concentrate near the coast.

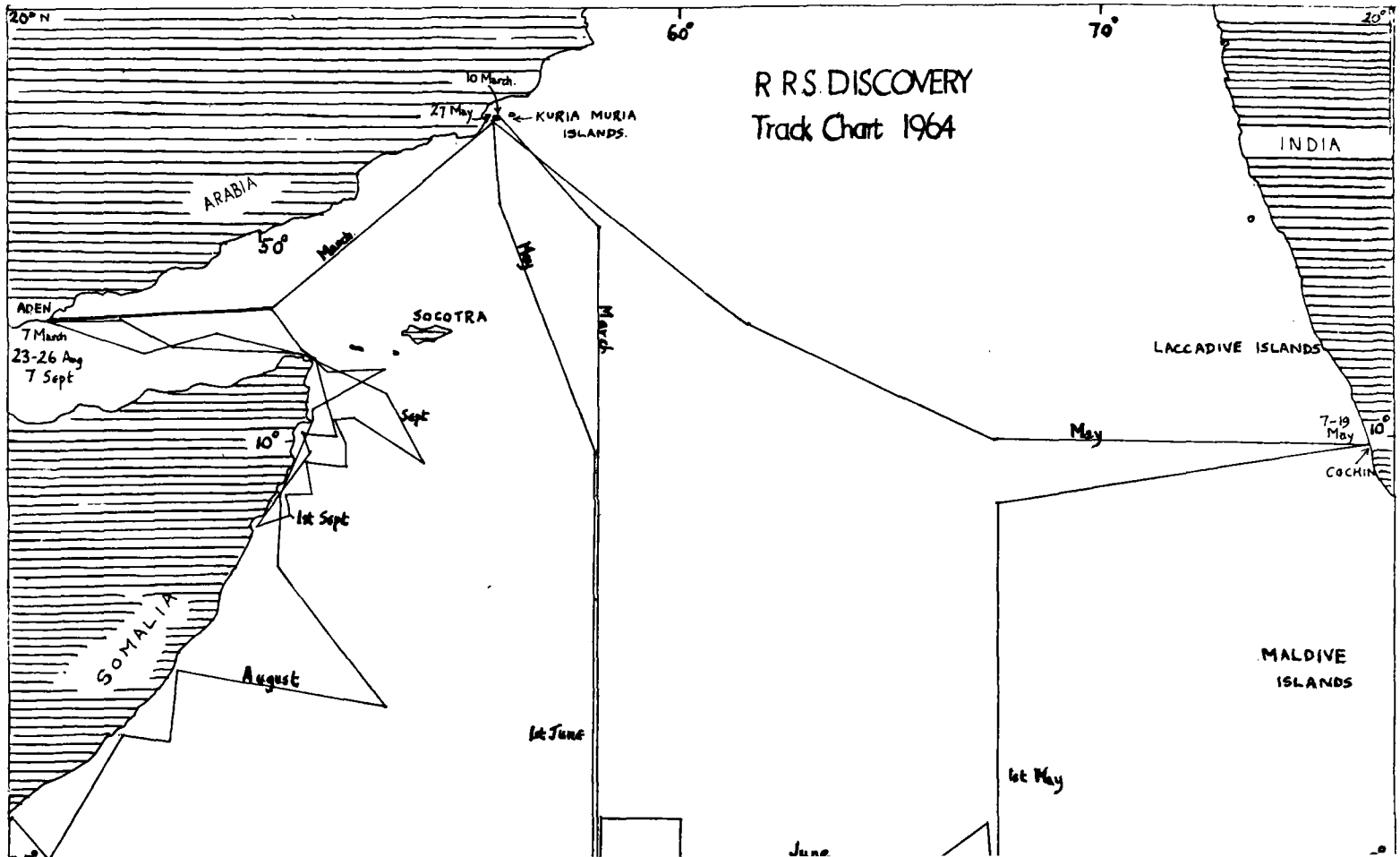


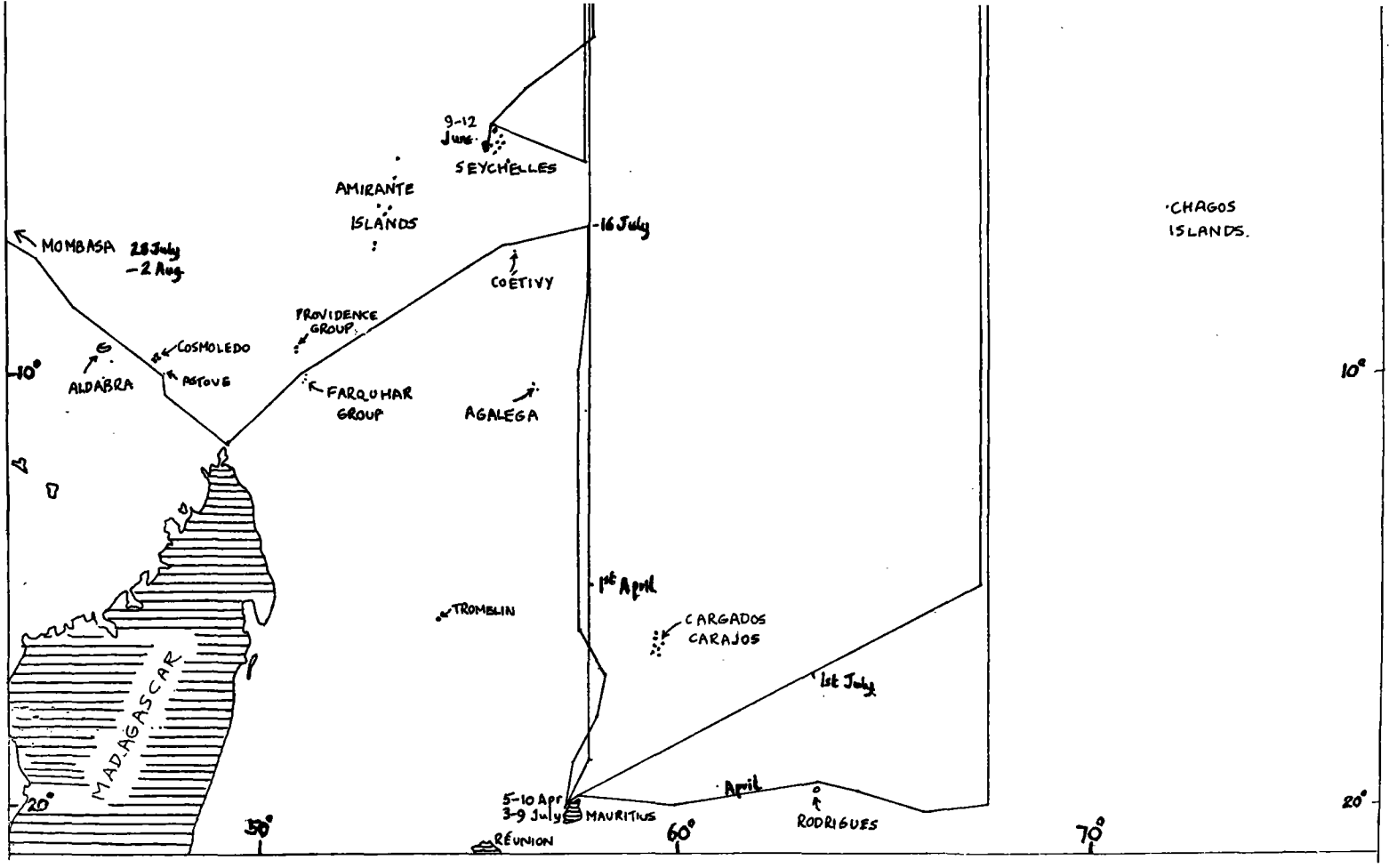
SWINHOE'S STORM-PETREL

Indian Ocean

Photo: R. S. Bailey.

Fifty-four


R R S DISCOVERY
Track Chart 1964
20° N
60°
70°
20° N
10° N
10 March.
27 May
KURIA MURIA ISLANDS.
ARABIA
50°
March
May
INDIA
ADEN
7 March
23-26 Aug
7 Sept
SOCOTRA
March
LACCADIVE ISLANDS
Sept
10°
May
7-19 May
10°
COCHIN
1st Sept
SOMALIA
August
MALDIVE ISLANDS
1st June
1st May
June


9-12 June
SEYCHELLES
AMIRANTE ISLANDS
MOMBASA 28 July – 2 Aug
16 July
COETIVY
CHAGOS ISLANDS.
PROVIDENCE GROUP
COSMOLEDO
ASTOVE
ALDABRA
FARQUHAR GROUP
AGALEGA
10°
1st April
TROMELIN
CARGADOS CARAJOS
1st July
MADAGASCAR
April
5-10 Apr
3-9 July
MAURITIUS
RODRIGUES
RÉUNION
20°
50°
60°
70°

In the Arabian Sea and to the south of the Laccadives, Pale-footed Shearwaters and White-faced Storm petrels were seen moving north-west. By the end of May numbers of White-faced and Black-bellied Storm-petrels had appeared in the central Arabian Sea, but I was unable to confirm any records of White-bellied Storm-petrels. All I saw clearly had the black belly stripe. Few other birds were seen but Jouanin's Petrels extended south to the equator in small numbers.

The second longitudinal survey gave me the opportunity to record changes in distribution which had occurred since the onset of the monsoon. The most obvious difference was the presence of Southern hemisphere migrants but there had been some changes in the distribution of resident species. There was some evidence that Wedge-tailed Shearwaters had spread north into the Arabian Sea. By June, the larger all-black storm-petrels had become much commoner in the area of calms on the equator. During both surveys they were concentrated in this zone. It is not easy to suggest why it should become more common in the south-west monsoon if one assumes that it breeds in the Pacific Ocean at this time of year. The birds in the Indian Ocean must belong to a non-breeding population unless they breed in the northern winter in an undiscovered area.

Blue-faced Boobies and White-tailed Tropic-birds were again seen scattered at sea, but the only concentration of note was of the latter around Mauritius in July. A few Red-tailed Tropic-birds were also seen south of 15° south. Frigate-birds had shown a tendency to spread north but, with the exception of Sooty Terns, the distribution of most tropical species showed no significant changes. By late May Sooty Terns had disappeared from the central Arabian Sea and were not seen north of 8° north. They had presumably moved south towards their breeding islands. In July large numbers were seen moving south-east after heavy winds in the area between Mauritius and the Seychelles. It is quite certain that their movements are extremely complex and are probably associated with differences in breeding season in different parts of the ocean.

Few of the antarctic migrants were seen south of the Arabian Sea. Only during their migration are they seen in the equatorial zone. In June, for instance, small parties of Wilson's and Black-bellied Storm-petrels were seen feeding close to the equator, where the more productive areas may serve as transit feeding grounds. A few other southern hemisphere migrants reach the tropics in small numbers. On several occasions I saw black and white gad-fly petrels. Some may have been Trinidade Petrels, but others were almost certainly Soft-plumaged Petrels, recognised by their dark underwing. Prions were also widespread between 13° and 20° south. Finally, I recorded a probable Giant Petrel off north Madagascar in July.

We had intended to land on one of the islands to the north of Madagascar, but this proved impossible owing to rough seas. While passing close to Farquar atoll, Astove and Cosmoledo, I was able to record the species moving to and from the islands. Off Farquhar, Sooty Terns were extremely common with small numbers of Common Noddies, Crested Terns and Red-footed Boobies. Off Astove few birds were seen, suggesting that there are no important breeding colonies there at that time of year. At dusk while passing Cosmoledo, large numbers of Sooty Terns and Red-footed Boobies were seen moving towards the islands.

In August we made two short trips to the Somali coast south of Cape Gardafui. The strong monsoon winds create a fast-moving current running up the African coast and, as the water moves north, its course gradually veers away from the coastline. Water upwells to fill the gap and, from

about 8° north to Cape Gardafui, there is a huge wedge of cold water which is rich in nutrient salts. As in other upwelling areas I expected to find large concentrations of birds but, compared with the Arabian coast upwelling area, there were remarkably few.

The warm Somali current further south was also poor for birds. Near the coast a few Jouanin's Petrels, Wilson's Storm-petrels and Little Terns were seen while, further out in the Arabian Sea, Sooty Terns and Black-bellied Storm-petrels appeared, with small numbers of Wedge-tailed Shearwaters and the larger all-black storm petrels. As soon as we entered the area of cold water there was a small but marked increase in numbers and the species composition changed completely. Persian Shearwaters, Wilson's Storm-petrels and Red-billed Tropic-birds became widespread, but very few other birds were seen. Another sudden change occurred passing from the cold water into the hot Gulf of Aden water. Dolphins played round the ship's bows and Wilson's Storm-petrels and Jouanin's Petrels became common.

It is very difficult to suggest why this upwelling area should be so poor in birds. A clue is given, however, by the fact that the cold water was extremely rich in plant plankton but only moderately rich in the planktonic animals which graze it. This suggests that large communities of fish, upon which birds can feed, had not had time to develop. This may happen when the water has drifted further east off Socotra. As our survey had to be restricted to the centre of the upwelling, centred on Ras Hafun and Ras Mabber, it was impossible to investigate this possibility.

In addition to my census work I was also interested in the food of seabirds. Of the seventeen which landed on board, some regurgitated their stomach contents which usually consist of remains of flying fish or squid. Among those which definitely feed on squid are Jouanin's Petrel, Pale-footed and Wedge-tailed Shearwater, all three species of of booby, Greater Frigate-bird and Sooty Tern—all the common oceanic birds of the tropical Indian Ocean, in fact. The species of squid most frequently found is thought to come to the surface only at night. This is one more piece of evidence that many species of seabirds feed at night.

During the coming year, I shall be writing up this work at the Edward Grey Institute of Field Ornithology. I hope to reach some conclusions about the environmental factors which restrict the distribution of different species of seabirds; the plankton changes markedly from place to place in quantity and type, and I hope to find relationships between these changes and bird distribution.

I owe my thanks to a large number of people for their help and advice. When reading up the background to Indian Ocean ornithology I found the sea reports of the R.N.B.W.S. most helpful. The 1964 cruise was run by the National Institute of Oceanography, to whom I am most grateful for such an opportunity to study oceanic birds. I have also had a great deal of help from the officers and crew of the Discovery and my grant has very kindly been given by the Nuffield Foundation.

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国際インド洋調査に於て日本船が行なった植物色素，光合成調査の結果概要

国際インド洋調査植物色素・光合成国内作業グループ

Summary Report on Photosynthesis and Chlorophyll in the Eastern Indian Ocean observed by Japanese Ships during IIOE

Prepared by

National Working Group on Photosynthesis-Chlorophyll of IIOE

Japanese participation in the observations on the photosynthetic rate and chlorophyll content of the phytoplankton as an item of IIOE was made as follows (Figs. 1, 2): (ref. to this bulletin No. 11, p. 82)

Ship	Period	Participating scientist
Kagoshima Maru	Dec. 1963 - Jan. 1964	Takuro Endo
Koyo Maru	Dec. 1962 - Jan. 1963	Kaoru Takesue
〃 〃	Dec. 1963 - Jan. 1964	〃 〃
Umitaka Maru	Dec. 1962 - Jan. 1963	Yatsuka Saijo
〃 〃	Dec. 1963 - Jan. 1964	Ichitaro Sakamoto
Oshoro Maru	Dec. 1963	Teruyoshi Kawamura

Photosynthetic rate as estimated by tank method was generally low except the region of upwelling, *e. g.*, southeast of Java Islands (Figs. 3, 4). In the west of 100°E the photosynthetic rate near the surface was 0.2-0.4 mgC/m³/hr to the north of 5°S, while it was 0.1 mg C/m³/hr to the south of 5°S. In the east of 100°E it was larger than 0.4 mg C/m³/hr to the south of 10°S, while it was 0.1-0.3 mgC/m³/hr to the south of 100°E.

The depth of maximum photosynthetic activity (estimated by tank exp.) was found at 25 m in the north on 78°E line, while it was at 50 m or 75 m in the south. The depth of maximum photosynthetic activity was always deeper than the depth of maximum production estimated by *in situ* experiments.

Daily primary production estimated by *in situ* experiments was generally 0.1-0.2 gC/m²/day (Figs. 5, 6). Comparatively high values, 0.3-0.7 gC/m²/day, were obtained to the southeast of Java Islands. Daily primary production on 94°E line was generally higher in 1963-64 than in 1962-63 (Figs. 5, 6).

Chlorophyll *a* content was generally very poor, being about 0.1 mg/m³ in the north and less than 0.05 mg/m³ in the south at the surface to the west of 100°E, and about 0.05 mg/m³ at the surface to the east of 100°E (Figs. 7, 8). The depth of maximum chlorophyll was often observed in the lower part of the euphotic zone (50-125 m). The depth of maximum chlorophyll was 50-75 m in the equatorial region, and 100-125 m in the south. These depths corresponded to the upper limit of the thermocline. The chlorophyll distributed in these depths were those which had lost their photosynthetic ability as suggested by the results of the tank experiments. (Y. Saijo)

国際インド洋調査に於て，日本船は第1次（1962年12月－1963年1月），第2次（1963年12月－1964年1月）の2回，インド洋東半部の海域で調査を分担した（本会報11号82頁参照）(Figs. 1, 2)。この中植物色素並びに光合成（基礎生産）に関する調査結果について概説する。参加船並びに植物色素，光合成研究担当の乗船科学者は次のとおりである。

かごしま丸　第2次航海　（遠藤　拓郎）
耕洋丸　第1,2次航海　（武居　薫）
海鷹丸　第1次航海　（西条　八束）
同　第2次航海　（坂本市太郎）
おしよろ丸　第2次航海　（川村　輝良）

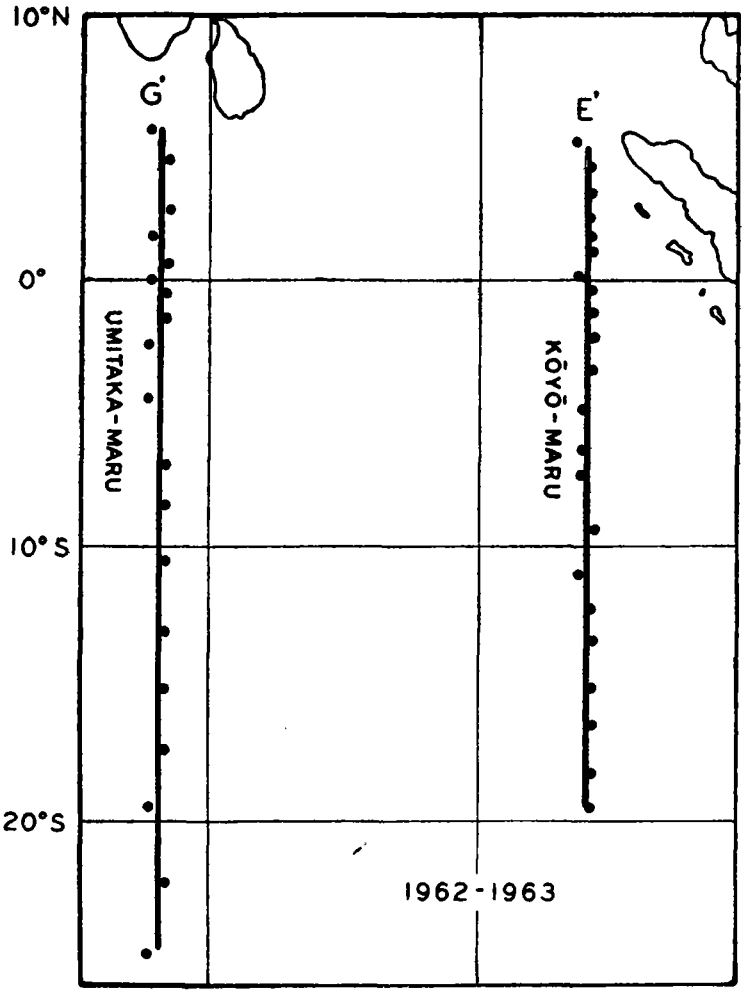


Fig. 1. Track and stations of Japanese ships in IIOE, Dec. 1962-Jan. 1963.

測 定 方 法

1) 採水：午前9.00—11.00の間に Van Dorn 採水器（12*l*）により0，10，25，50，75，100，125，150，200m各層より採水。

2) 光合成量測定：主としてタンク法により，可能な測点でのみ *in situ* 法を実施した。培養瓶は明暗ともに Tyston（商品名）250*ml* 試薬瓶を用い，^{14}Cは第一化学薬品株式会社製 $Na_2{}^{14}CO_3$ 溶液10μc/m*l* をアンプルにいれて用意した。その activity は Jitts (C. S. I. R. O. Australia) に検定して貰った。

タンク法では各瓶に試水を移し（100m又は125mの深さまで），^{14}Cを加え，Incubator（30W reflector 付螢光灯6本を透明底壁下面より照射，水槽内照度約12,000 lux，水槽内温度は表面海水を循環して同温度に保つ）中に，4時間おき，Millipore filter HA type (24mm径）で濾過，3% NaCl 溶液並びに 0.001 N HCl の3% NaCl 溶液で洗滌後，デシケーター中に保存して持帰る。帰航後2πガスフローカウンターを用いて資料の放射能を測定した。光合成量は全炭酸を90mg CO /*l* と仮定し，明瓶の計数値から暗瓶の計数値を差しひいて求めた。

In situ 法は，100m又は125mまでの各層から採った試水を瓶に入れ，^{14}C を加えて，瓶を再び採水した層に吊した。吊下露出時間は正中時から日没までであ

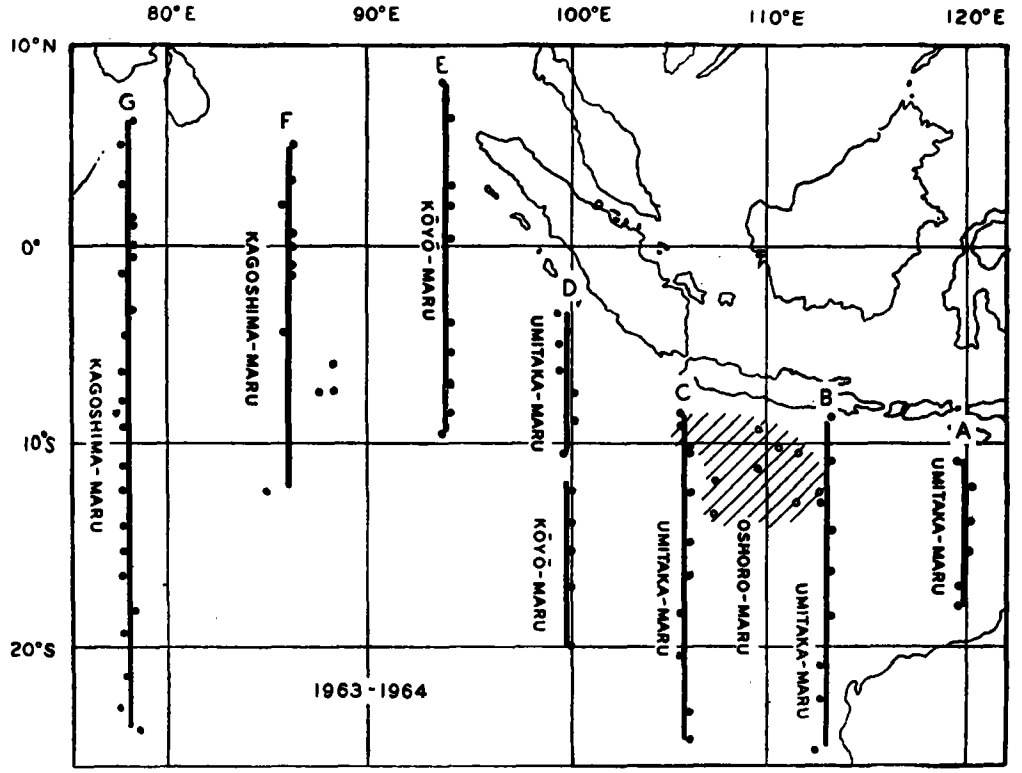


Fig. 2. Track and stations of Japanese ships in IIOE, Dec. 1963-Jan. 1964.

る。日没後引き上げ，タンク法と同じ要領で資料を処理した。

3) 植物色素量の測定：通常 200 m までの各層から採水した各6－8 *l* の試水を Millipore fillter HA type (47mm径) を用いて濾過し，濾紙を水蒸気に30秒さらした後，デシケーター中に入れ，乾燥，冷暗所に保存して持ちかえった。帰航後フィルター資料を92%アセトンに溶かし，sonification (10KC) を 5－10分間行なった後，冷蔵庫に24時間放置，10,000G 以上で10分遠心分離，上澄液を Hitachi 或は Shimadzu の分光光度計により，light path 5 cm のミクロセルを使用して，750，665，645，630，510，480 mμ の各 optical density を測定，Richards and Thompson の式を用いてクロロフィル量を算出した。なお各波長の測定値より 750mμ の測定値を差引いて濁りの補正を行なった。

調査結果の概要

1) タンク法による光合成量 (Figs. 3, 4)：今回の調査水域全般にわたって，湧昇流のあるジャヴァ島南東水域を除くと，光合成量は概して低かった。表層付近の光合成率をみると100°E以西では，5°S以北の水域に於て0.2—0.4mgC/m³/hr を示して比較的高く，それより南方では0.1 g に低下する。これに対し 100°E以東に於ては，10°S以北で0.4 mg 以上の高い値を示し，それ以南では0.1—0.3 mgC/m³/hr 程度になる。

78°E線において光合成能力の最大値を示す層が，北の方で25m層に見出され，南へ下るにつれて50m層あるいは75m層と次第に深くなり，これらの層が *in situ* 法で最大値が示される層よりはるかに深い層であることは注目に値する。このような傾向は，106°E，113°E各線においては，50m層あるいは75m層の最大値として見出されたが，他の線では必ずしも明らかでなかった。なお78°E線上で赤道付近にかなり高い光合成能力 (0.6—1.0mgC/m³/hr) が見出された。

2) *In situ* 法による光合成量 (基礎生産量) (Figs. 5, 6)：*In situ* 法による半日の測定値を2倍して求めた1日の生産量は，調査水域全般にわたって0.1—0.2 gC/m²/day 程度であったが，ジャヴァ島南東水域で

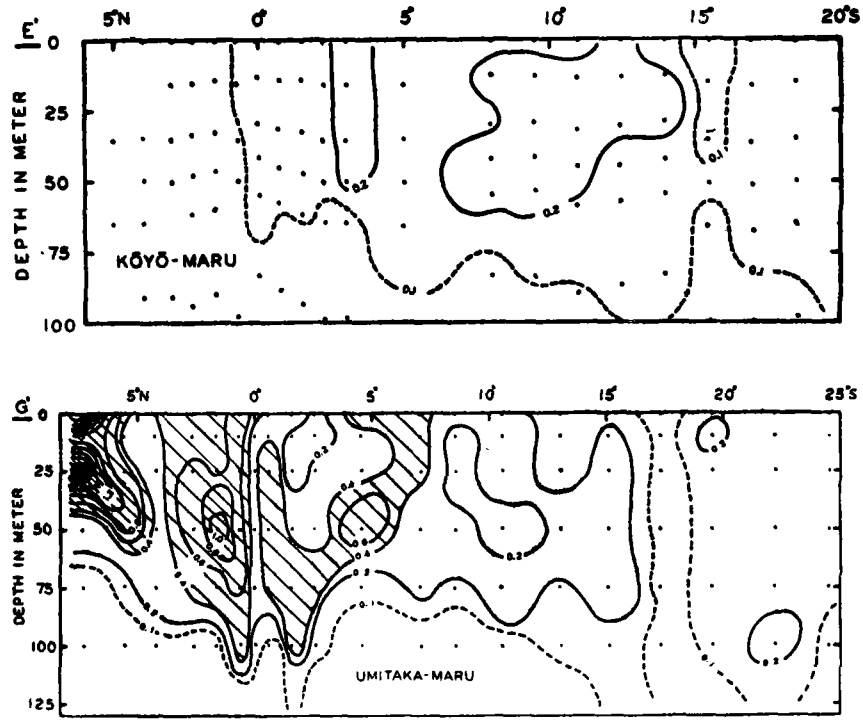


Fig. 3. Rate of photosynthesis measured by the tank experiments on the cruises in Dec. 1962-Jan. 1963. (mgC/m³/hr)

は0.3—0.7gC/m²/day という高い値が得られた。なお94°E線における第1次，第2次の2回の測定結果を比較すると，全般的に第2次の方が値が大きい傾向が認められる。

3) 植物色素 (Figs. 7, 8)：クロロフィル量は沿岸に近い一部の水域を除き，きわめて小さかった。とくに表層水においては，100°E以西の水域では，北部で0.1mg/m³前後，南部で0.05mg/m³以下，100°E以東の水域で一般に0.05mg/m³であった。それより深い層においてもクロロフィル量はせいぜい0.2—0.3mg/m³程度にすぎなかった。

特に興味あることは，クロロフィル量の最大値を示す層が生産層 (euphotic zone) の下部の50—125m層に多く見出されることである。大体の傾向として赤道付近では最大値が50—70m層に，それより南になると100—125m層に見出される。これらのクロロフィルの大部分がすでに光合成能力を失ったものであることは，タンク法の測定結果から明らかである。

(西条八束記)

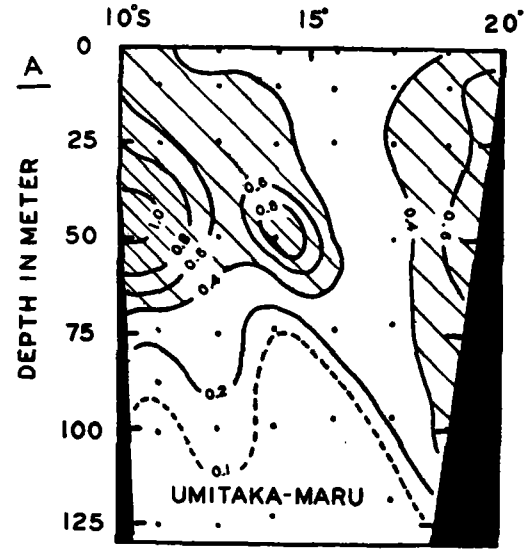


Fig. 4. Rate of photosynthesis measured by the tank experiments on the cruises in Dec. 1963-Jan. 1964. (mgC/m³/hr)

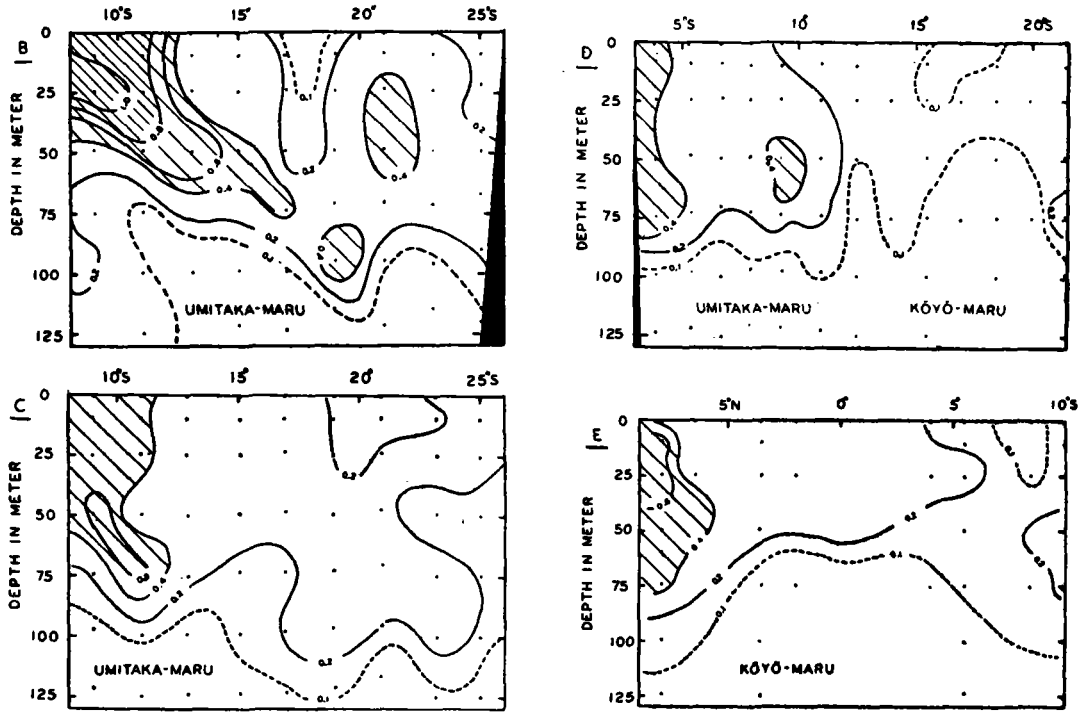


Fig. 4. (continued)

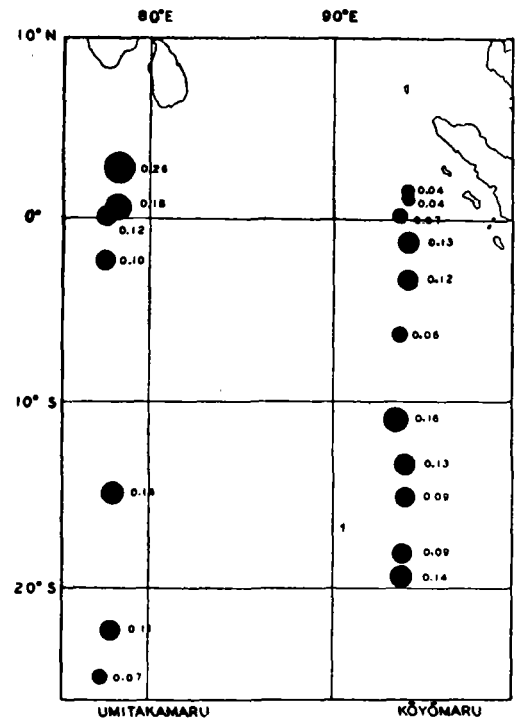


Fig. 5. Primary production estimtaed by the *in situ* experiments on the cruises in Dec. 1962-Jan. 1963. (gC/m²/day)

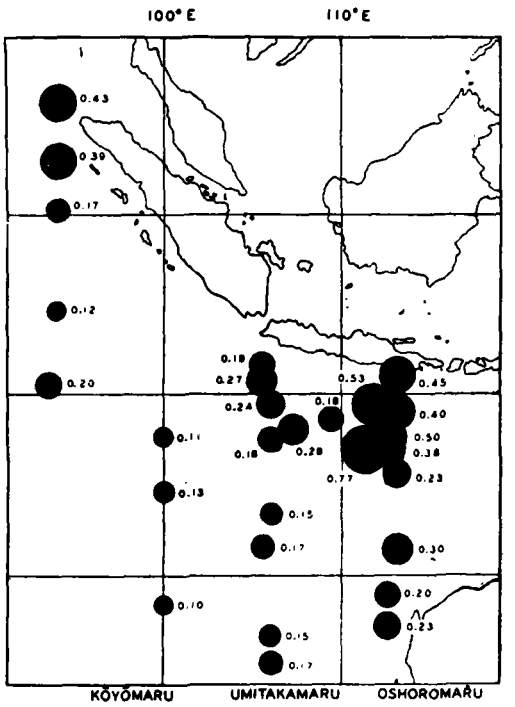


Fig. 6. Primary production estimated by the *in situ* experiments on the cruises in Dec. 1963-Jan. 1964. (gC/m³/day)

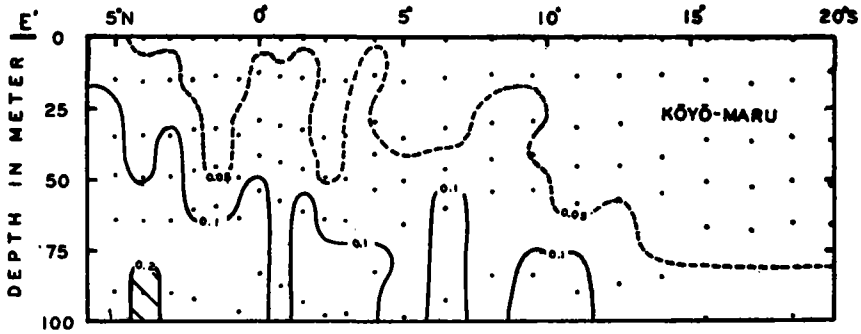


Fig. 7. Chlorophyll *a* content on the cruises in Dec. 1962–Jan. 1963 (mg/m³). Data from the "Umitaka Maru" were discarded for their incorrectness due to the delay of air transportation of dried filters from Colombo to Japan.

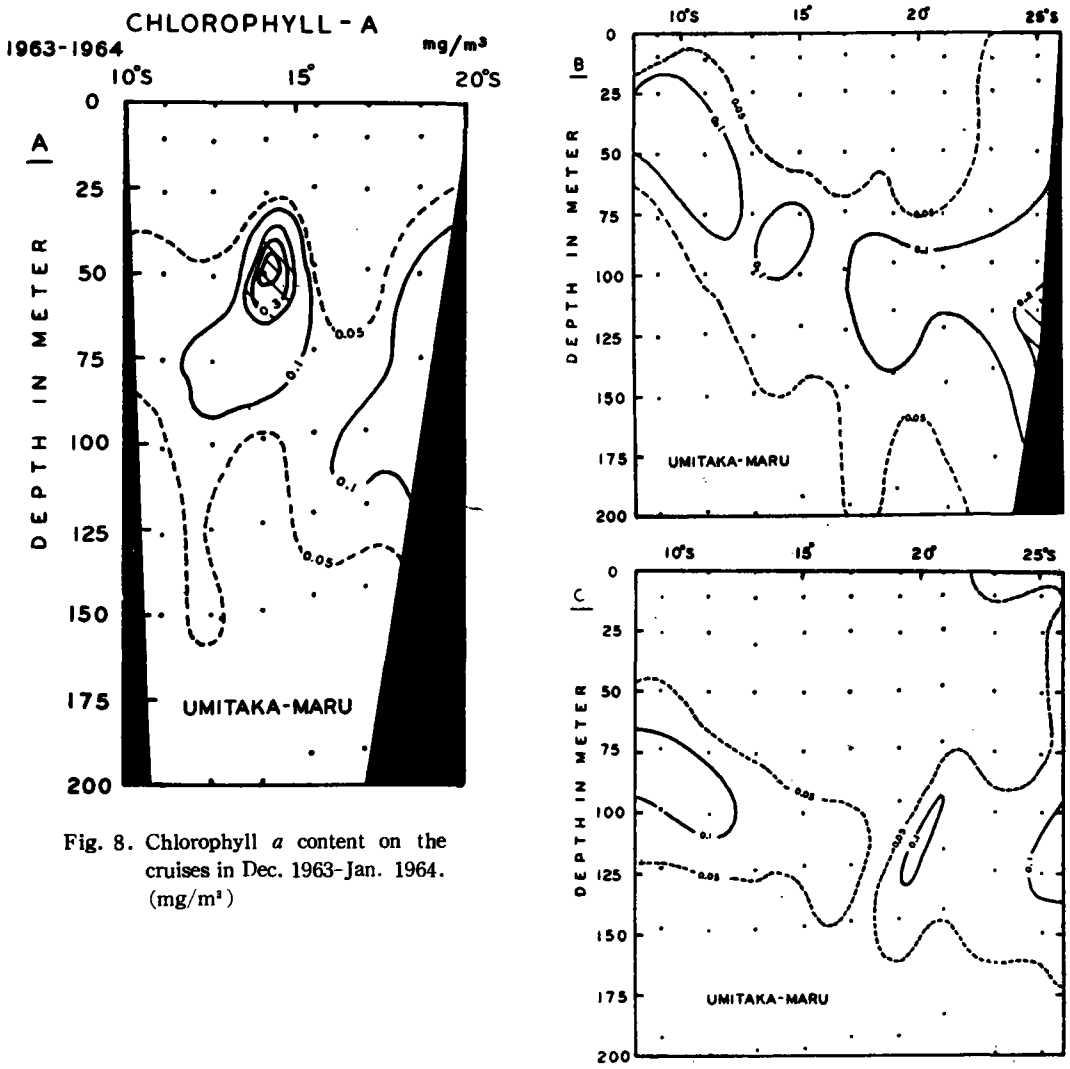


Fig. 8. Chlorophyll *a* content on the cruises in Dec. 1963–Jan. 1964. (mg/m³)

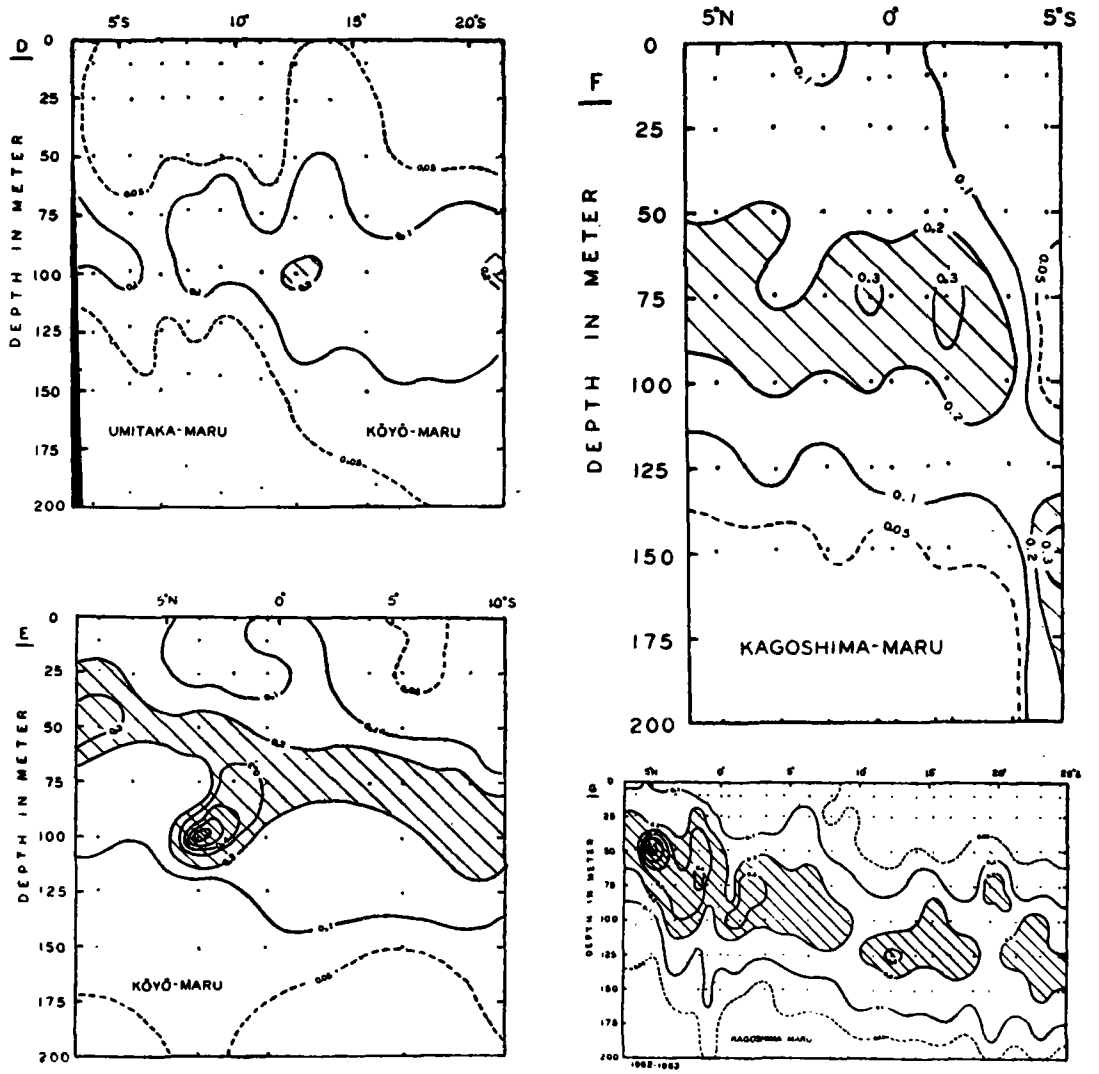


Fig. 8. (continued)

C. R. Acad. Sc. Paris, t. 261, p. 2245-2248 (13 septembre 1965). Groupe 11.

OCÉANOGRAPHIE BIOLOGIQUE. — *Phytoplancton et productivité primaire dans une baie de Nossi-Bé (Madagascar)*. Note de M. Alain Sournia, présentée par M. Théodore Monod.

Le phytoplancton d'une baie tropicale est étudié ici en relation avec les facteurs hydrologiques et sous les aspects suivants : composition taxonomique, pigments photosynthétiques et productivité primaire. Le cycle annuel est très accidenté, du fait de la proximité des côtes. L'intérêt est attiré sur les variations nycthémérales. Une comparaison est établie entre les mesures de productivité par l'oxygène et par le carbone 14.

De février 1963 à juillet 1964, une étude du phytoplancton et de la productivité primaire, en relation avec les facteurs hydrologiques, a été effectuée dans la baie d'Ambanoro, à Nossi-Bé. Ces recherches constituant les premières en date sur ce sujet et dans cette région, nous en donnons ici les résultats préliminaires.

Le climat annuel (latitude : 13° Sud) consiste essentiellement en l'alternance de deux saisons, l'une chaude et pluvieuse (été austral) d'octobre à avril, l'autre fraîche et sèche (hiver austral) de mai à septembre. L'hydrologie annuelle reproduit cette succession avec un certain décalage : eaux chaudes et dessalées de décembre à mai, eaux fraîches et à forte salinité de juin à novembre. Ces phénomènes sont représentés sur le diagramme T-S (*fig.* 1), qui montre aussi que températures et salinités n'évoluent pas simultanément dans le cours de l'année : ainsi, lors du passage de la saison sèche à la saison des pluies (décembre), la température atteint rapidement une valeur élevée alors que la salinité n'a encore que très peu diminué. A noter également sur ce diagramme l'instabilité des valeurs estivales en comparaison de l'homogénéité des valeurs hivernales. Enfin, l'écart thermique annuel des eaux n'excède pas 5°C, comme il est d'usage en milieu tropical, alors que le dessalement en saison des pluies peut dépasser la dilution de 10 % d'eau douce. Aussi peut-on sans doute attribuer à la pluviosité le rôle essentiel dans les variations annuelles du milieu, sans perdre de vue toutefois que deux ordres de phénomènes se trouvent juxtaposés : d'une part, modifications thermiques, d'autre part, modifications de salinité par apports d'eaux douces — et donc d'éléments nutritifs — d'origine atmosphérique.

Examinons maintenant le cycle annuel du phytoplancton sous ses divers aspects : composition taxonomique (prélèvements au filet, comptages par la méthode d'Utermöhl), pigments photosynthétiques (méthode de Richards et Thompson, formules de Parsons et Strickland), enfin, productivité primaire (méthode au carbone 14 de Steemann Nielsen).

Le microplancton végétal et le nanoplancton se distinguent nettement l'un de l'autre par leurs caractères biologiques et taxonomiques : le premier est essentiellement constitué de Diatomées, richement diversifié, et sujet

à d'importantes fluctuations annuelles allant de l'extinction quasi totale à de brusques floraisons de *Rhizosolenia alata* Brightw., *Guinardia flaccida* (Castr.) Per. et *Chætoceros* spp. La cyanophycée planctonique *Trichodesmium* donne lieu en saison des pluies à de véritables phénomènes d'« eaux rouges ». Le nanoplancton d'autre part, ainsi que l'ultraplancton, principalement composé de Péridiniens et divers Flagellés, montre plus de constance et, à défaut de microplancton, constitue à certaines époques de l'année l'essentiel de la biomasse phytoplanctonique.

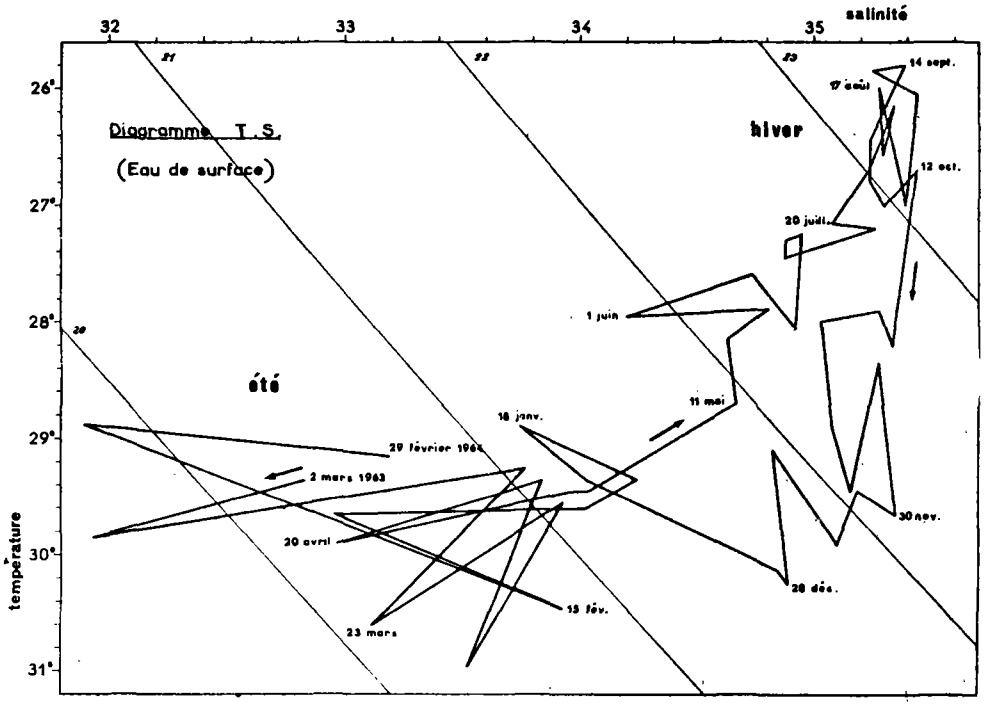


Fig. 1. — Variations annuelles de la température et de la salinité (mesures hebdomadaires). Chaque point représente la moyenne entre deux mesures effectuées le même jour, l'une à marée haute, l'autre à marée basse.

L'analyse des pigments chlorophylliens (*fig.* 2) révèle une alternance de deux saisons calquée sur le cycle hydrologique. De septembre à décembre, c'est-à-dire notablement décalée par rapport à l'hiver hydrologique, s'étend une période hivernale au cours de laquelle s'observent les valeurs annuelles minimales. La seconde période, également décalée par rapport à l'été hydrologique, va de janvier à août; les concentrations rencontrées sont plus élevées mais aussi plus irrégulières, ce dernier point étant à rapprocher de l'instabilité des salinités pendant cette partie de l'année. Les variations saisonnières de la productivité (*fig.* 2), quoique peu marquées, reproduisent cependant dans leurs grandes lignes celles des teneurs en pigments : la période hivernale est peu accentuée, mais les valeurs

annuelles maximales, comme pour les pigments, se situent entre janvier et août.

Production primaire et concentration en pigments montrent l'une et l'autre des valeurs moyennes élevées, relativement fortes pour une zone tropicale, mais justifiables par la situation tout à fait littorale du secteur étudié. La relation productivité / biomasse, telle que déterminée par le rapport : productivité *in situ* par unité de chlorophylle *a*, prend la valeur moyenne annuelle de 7,6 mg de carbone par heure et par milligramme de

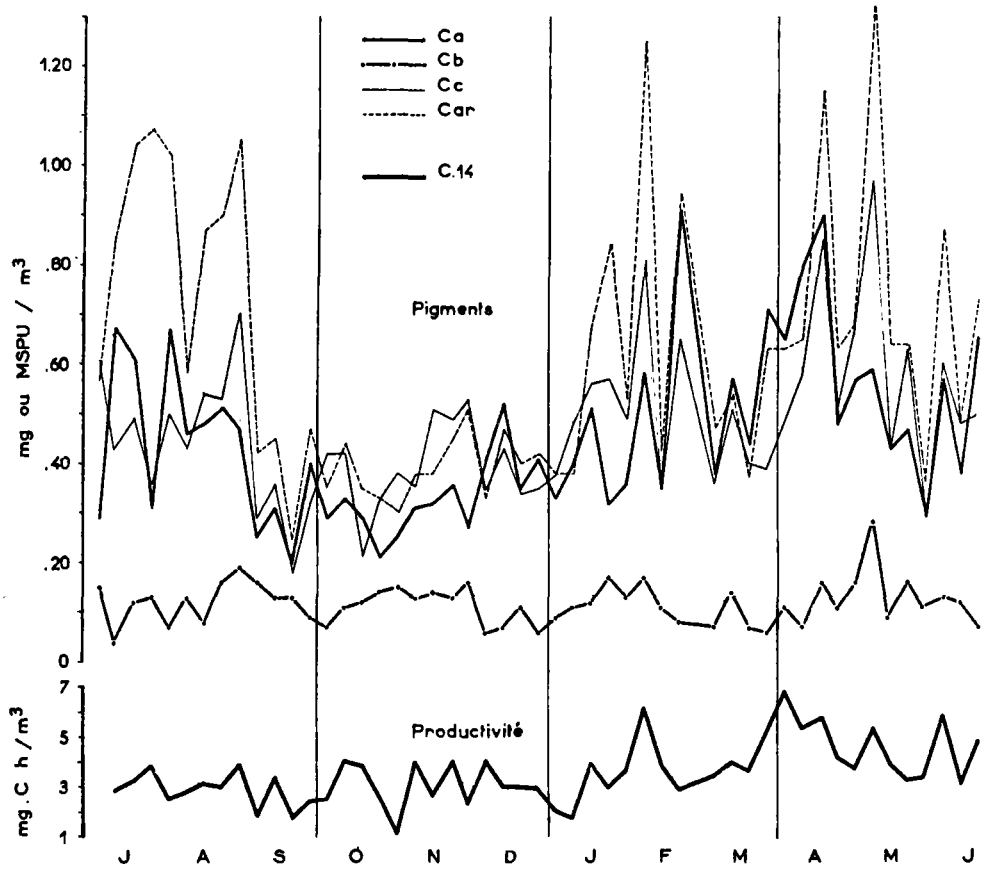


Fig. 2. — Variations annuelles des teneurs en pigments (chlorophylles *a*, *b* et *c*, caroténoïdes) et de la productivité nette apparente (mesures *in situ* entre 7 et 11 heures locales, à 1 m de profondeur).

chlorophylle *a*, taux comparable aux estimations des divers auteurs. Quant à la productivité globale annuelle, elle atteint d'après nos mesures 15 g de carbone par mètre cube et par an pour la couche superficielle.

Comme le montre la figure 2, le cycle annuel est accidenté d'importantes variations secondaires. En effet, le domaine littoral est étroitement soumis aux facteurs physiques tels que : pluies, marées et courants de marée, turbidité, etc., dont l'effet est ici ressenti plus rapidement et plus profon-

dément qu'en domaine pélagique. C'est dans le but d'évaluer l'importance de ces variations à court terme que nous avons effectué, tout au long du cycle annuel, plusieurs études du cycle nycthéméral, sous la forme de prélèvements à intervalles réguliers pendant 30 à 40 h. En voici les premières conclusions :

Dans sa composition taxonomique, le phytoplancton est soumis à une périodicité de 24 h apparemment liée au cycle de l'éclairement solaire; ainsi les Péridiniens nanoplanctoniques montrent-ils une multiplication intense en début de matinée. Une seconde périodicité, imposée par la marée, soit de 12 h environ, doit être invoquée concurremment à la première pour rendre compte des variations dans l'abondance des divers groupes systématiques.

L'intensité de l'activité photosynthétique n'est pas répartie de façon régulière de part et d'autre de la méridienne : en effet, la productivité est souvent plus élevée l'après-midi que le matin. D'autre part, la diminution relative de la photosynthèse survenant aux environs de midi dans les eaux superficielles n'a pu que dans quelques cas être mise en parallèle avec une plus faible densité du plancton de surface. Aussi s'agit-il généralement d'une inhibition sous un éclairement défavorable.

Au cours de ces cycles diurnes, nous avons simultanément mesuré la production primaire de deux façons : d'une part, par la méthode du carbone 14 (en subdivisant la journée solaire en quatre périodes d'exposition *in situ* de 3 h chacune), d'autre part par la mesure des variations du taux d'oxygène dissous *in situ* (celui-ci rapporté au pourcentage de saturation). Il est alors possible de comparer, pour une même journée, la quantité de carbone consommé et la quantité d'oxygène dégagé. Une corrélation satisfaisante a été trouvée entre les deux méthodes : si les deux quantités sont exprimées en molécules-gramme, on en déduit un quotient apparent de la photosynthèse généralement voisin de 2. Le quotient théorique est, comme on sait, égal à l'unité. Aussi conclut-on, sans préjuger des valeurs absolues, que l'estimation fournie par la méthode du carbone 14 est deux fois plus faible que celle obtenue par les mesures d'oxygène *in situ*.

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SOME FEATURES OF ORGANIC PHOSPHORUS DISTRIBUTION IN THE SOUTH-EAST INDIAN AND SOUTH-WEST PACIFIC OCEANS

By D. J. ROCHFORD*

[*Manuscript received July* 17, 1963]

Summary

Concentrations of organic phosphorus significantly different from zero (0·10–0·38 μg-atom/l) have been found at most depths in a series of stations in the south-east Indian and south-west Pacific Oceans. For three meridional sections of the central and west Pacific and east Indian Oceans mean concentrations of organic phosphorus in the 0–200 m layer were found to be maximal (0·20–0·38 μg-atom/l) along the southern boundary of the South Equatorial Current, along the Equatorial Divergence, and within the boundary of the Counter Current and North Equatorial Current. South of 30° S. to about 40° S. another maximum was found which could not be associated with marked current movements. Pronounced maxima were also found in the vertical profiles of organic phosphorus. These sometimes occurred at the same depth as major hydrological core layers. The most consistent agreement in depth was found between the Antarctic intermediate salinity minimum and an intermediate depth organic phosphorus maximum around 1000 m. At 41% of stations examined these two layers were found at the same depth. At several locations the depths of the maxima in organic phosphorus varied in the same direction and at the same rate as the major hydrological layers during one year's observations.

I. INTRODUCTION

Although much earlier work had been carried out on the amounts of organic phosphorus (difference between the total phosphorus and inorganic phosphate values) in surface and near surface waters (Kalle 1935; Redfield, Smith, and Ketchum 1937; Harvey 1948; Armstrong and Harvey 1950; Hansen and Robinson 1953) Ketchum, Corwin, and Keen (1955) were the first to determine concentrations of organic phosphorus to depths of 1000 m and more. Their results indicated that, whilst 95% of surface waters of the equatorial Atlantic contained significant amounts of organic phosphorus, waters deeper than 1000 m contained no measurable amounts of organic phosphorus. However, in 1957–58 R.V. *Crawford* found appreciable quantities of organic phosphorus at most depths of the Atlanic Ocean (Fuglister 1957; Metcalf 1960). Also later Strickland and Austin (1960) detected organic phosphorus at concentrations of 1 μg-atom/l or more at depths of about 1000 m around 50° N. in the eastern Pacific.

In 1961 and 1962 organic phosphorus values of south-east Indian and south-west Pacific Ocean waters were determined to at least 2000 m during cruises of H.M.A.S. *Diamantina* and H.M.A.S. *Gascoyne*. These results also show appreciable amounts of organic phosphorus at most depths. This paper examines the general features of organic phosphorus distribution based upon *Diamantina* and *Gascoyne* results and draws attention to the connection between vertical maxima of organic phosphorus and circulation of subsurface water masses.

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II. Material and Methods

The inorganic and total phosphorus values used to calculate organic phosphorus are in course of publication (C.S.I.R.O. Aust. 1962*b*, 1962*c*, 1963, *et seq.*).

Organic phosphorus was determined at sea as follows: 100-ml samples of seawater were drawn from the Nansen bottles into 150-ml Pyrex conical flasks,

TABLE 1
DETERMINATION OF THE SALT ERROR FACTOR
The figures given are the values for absorbance

	Amounts of P as KH_2PO_4 Added (μg/l)							Mean
	20	40	50	60	70	80	100	
Series 1, 3.xi.61								
Distilled water								
Reading	0·070	0·130	—	0·187	—	0·242	0·297	
Blank*	0·008	0·008	—	0·008	—	0·005	0·005	
Corrected reading	0·062	0·122	—	0·179	—	0·237	0·292	
Seawater								
Reading	0·078	0·132	—	0·180	—	0·229	0·269	
Blank†	0·025	0·025	—	0·025	—	0·022	0·022	
Corrected reading	0·053	0·107	—	0·155	—	0·207	0·248	
Factor	**1·17**	**1·14**	—	**1·15**	—	**1·14**	**1·14**	**1·15**
Series 2, 6.xi.61								
Distilled water								
Reading	0·068	—	0·158	—	0·219	—	0·294	
Blank*	0·007	—	0·007	—	0·007	—	0·007	
Corrected reading	0·061	—	0·151	—	0·212	—	0·287	
Seawater								
Reading	0·082	—	0·158	—	0·210	—	0·280	
Blank†	0·030	—	0·029	—	0·028	—	0·027	
Corrected reading	0·052	—	0·129	—	0·182	—	0·253	
Factor	**1·15**	—	**1·14**	—	**1·13**	—	**1·13**	**1·14**
Series 3, 10.xi.61								
Distilled water								
Reading	0·069	—	0·156	—	—	—	—	
Blank*	0·007	—	0·007	—	—	—	—	
Corrected reading	0·062	—	0·149	—	—	—	—	
3·5% NaCl								
Reading	0·072	—	0·149	—	—	—	—	
Blank†	0·018	—	0·018	—	—	—	—	
Corrected reading	0·054	—	0·131	—	—	—	—	
Factor	**1·15**	—	**1·14**	—	—	—	—	**1·15**

* Reagent blank.
† Blank for P in reagents and in seawater or NaCl solution.

0·2 ml of 72% perchloric acid added and digestion at 200–250°C carried out immediately on a sand tray. After evaporation of water, heating was continued until fuming of the salt residue commenced. The samples were then allowed to cool and 100 ml of distilled water and 2 drops of 2% phenolphthalein added. If the solution was

alkaline, perchloric acid was added until a slight acidity persisted. The flasks were allowed to stand 24 hr to dissolve the salts. Phosphate was then determined by the usual method (C.S.I.R.O. Aust. 1962*a*). The SCOR-UNESCO intercalibration tests at Honolulu in September 1961 (Ketchum 1961) showed that the salt error correction

TABLE 2
COMPARISON OF TOTAL PHOSPHORUS DETERMINATIONS

Depth (m)	Mean of 4 Samples (μg-atom/l)		Mean Difference (μg-atom/l)
	C.S.I.R.O.	Woods Hole	
42	0·42	0·42	0
173	0·46	0·46	0
353	1·35	1·30	0·05
535	2·64	2·49	0·15
812	3·02	3·01	0·01

factor of 1·10 as previously used by C.S.I.R.O. (Rochford 1960) was low. This salt error correction was redetermined in November 1961 and a value of 1·15 was found (Table 1). This correction has been applied to the data of this paper. Table 2 shows the results of a comparison of total phosphorus values by the method of this paper

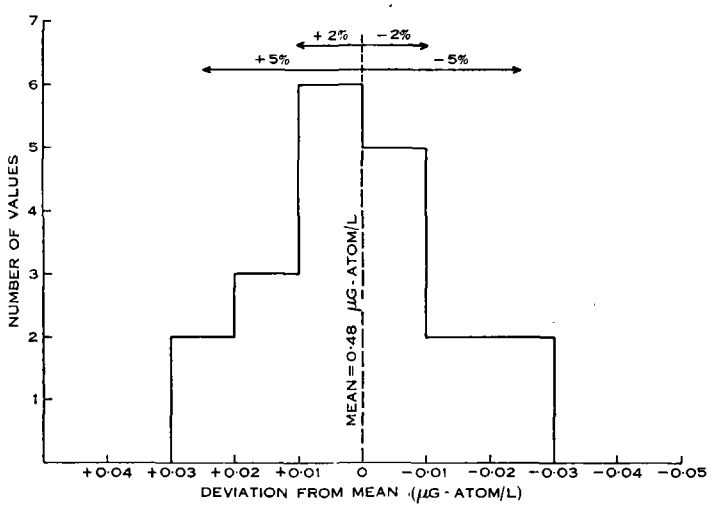


Fig. 1.—Deviations about the mean of 20 replicate inorganic phosphate analyses of a sample of seawater with a mean concentration of 0·48 μg-atom/l.

with those by the modified Harvey autoclave method used at the Woods Hole Oceanographic Institution, e.g. by Ketchum. The comparison samples were collected at a station between Oahu and Hawaii from R.S. *Vityaz* during a SCOR-UNESCO intercalibration cruise in September 1961. At this station both methods gave very

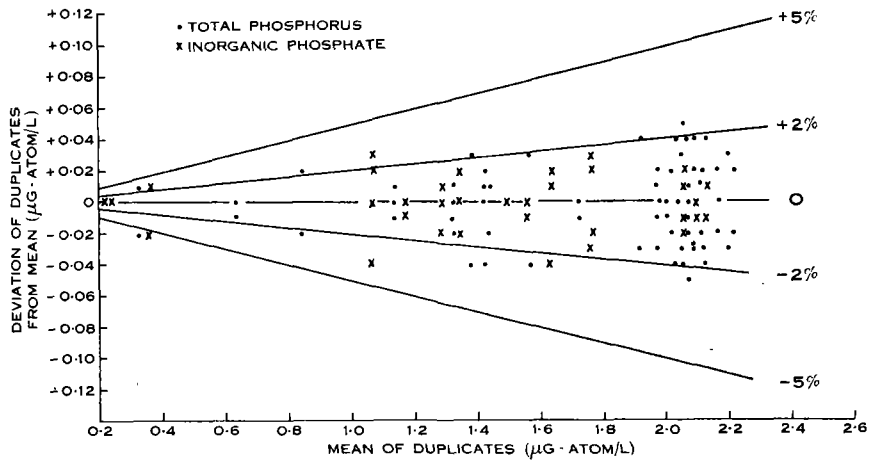


Fig. 2.—Deviations about the mean of analyses of duplicate samples from the same Nansen bottle for inorganic phosphate and total phosphorus.

TABLE 3

REPLICATE PHOSPHATE DETERMINATIONS

Seawater was filtered through an H.A. Millipore filter. Organic phosphorus is the difference between total and inorganic values

Sample No.	Inorganic Phosphate P (μg/l)	Total Phosphorus (μg/l)	Organic Phosphorus (μg/l)	Sample No.	Inorganic Phosphate P (μg/l)	Total Phosphorus (μg/l)	Organic Phosphorus (μg/l)
1	18		9	21	20		6
2		27		22		26	
3	18		8	23	19		7
4		26		24		26	
5	19		7	25	20		6
6		26		26		26	
7	18		8	27	19		7
8		26		28		26	
9	19		6	29	18		8
10		25		30		26	
11	20		7	31	20		8
12		27		32		28	
13	20		6	33	19		—
14		26		34		—	
15	20		7	35	19		7
16		27		36		26	
17	19		6	37	20		8
18		25		38		28	
19	19		6	39	20		7
20		25		40		27	

much the same values of total phosphorus. The inorganic phosphate determination had a standard deviation of 5% (0·025 μg-atom/l) of the mean for 20 replicate determinations at a mean phosphate value of 0·48 μg-atom/l (Fig. 1). At a higher

TABLE 4
PRECISION OF PHOSPHATE DETERMINATIONS

Series	Determination	Mean (μg-atom/l)	S.D. (% of mean)	S.D. (μg-atom/l)
1	inorganic P	0·48	7	0·030
2	inorganic P	0·60	4	0·025
3	inorganic P	2·00	3	0·040
4	total P	0·85	4	0·034
5	total P	2·00	2	0·040
6	organic P (series 4 and 2)	0·23	8·2	0·018

phosphate range (1·90–2·30 μg-atom/l) a series of duplicate values of inorganic phosphate and total phosphorus had a standard deviation of less than 2% (0·04 μg-atom/l) of the mean of each duplicate series (Fig. 2). Table 3 gives the results of a

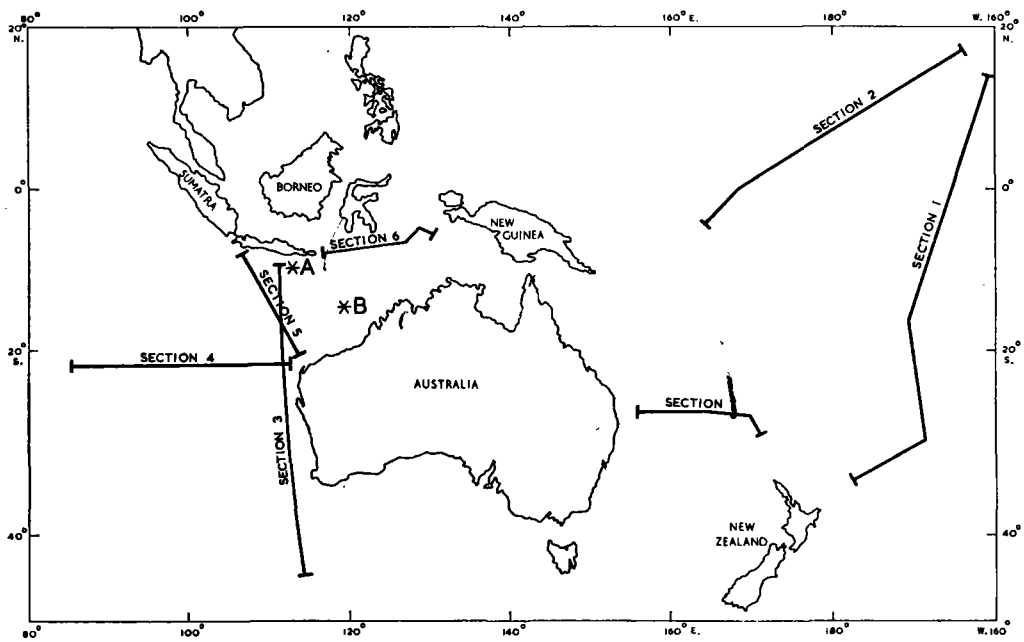


Fig. 3.—Chart of the positions of the comparison stations (A and B) and sections 1–7.

replicate series of organic phosphorus determinations of the same seawater. The standard deviations of the inorganic phosphate, total phosphorus, and organic phosphorus values of Table 3 are given along with other estimates of phosphate precision (Figs. 1 and 2) in Table 4. Use of the formula $(\sigma_1^2+\sigma_2^2)^{\frac{1}{2}}$ where σ_1 is the

standard deviation of the total phosphorus determination (series 4) and σ_2 that of the inorganic (series 2, Table 4) results in a standard deviation of 17% or 0·04 μg-atom/l for their differences. The observed standard deviation was much less (series 6, Table 4). It is considered probable that the standard deviation of organic phosphorus lies

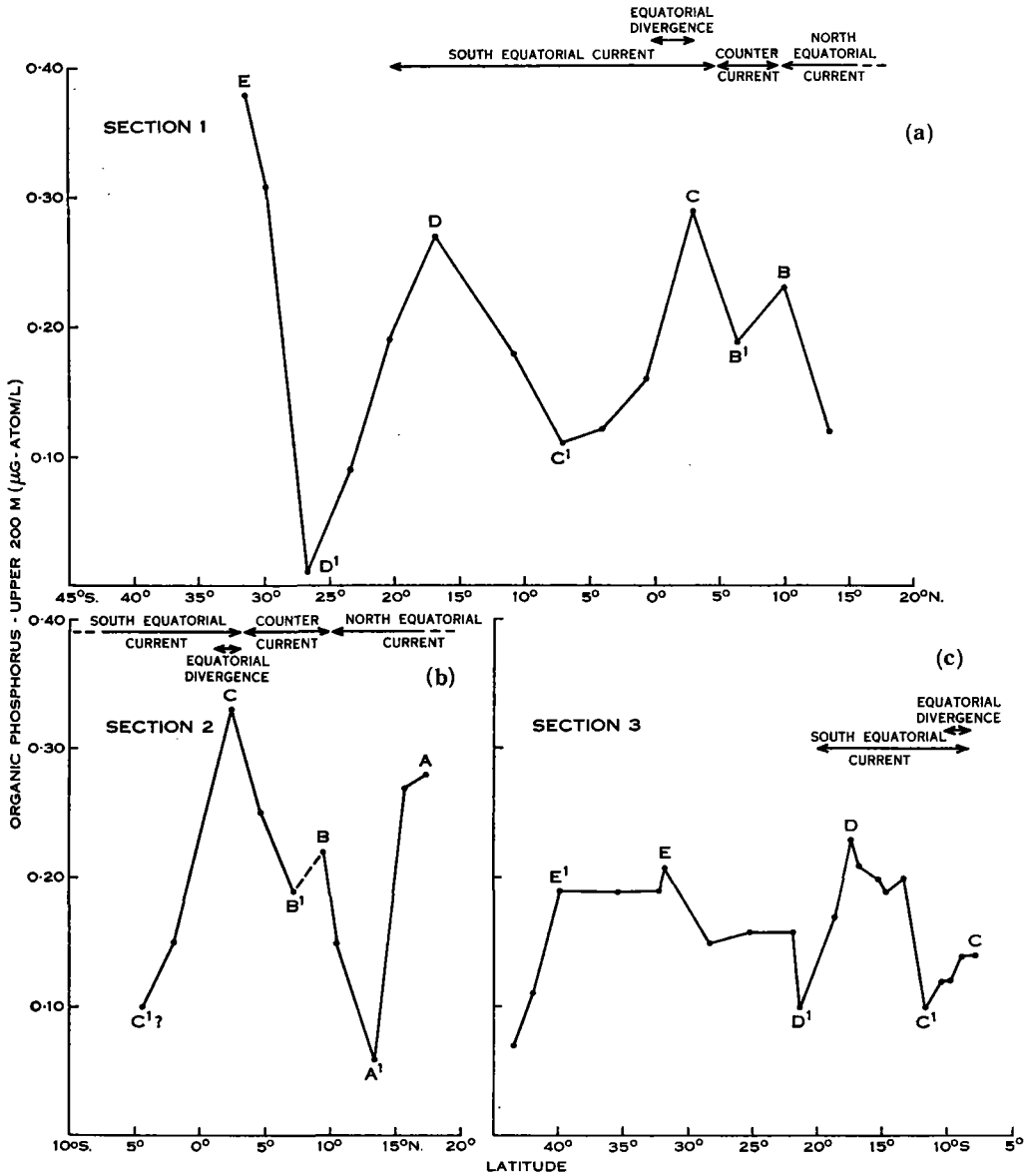


Fig. 4.—Mean concentration of organic phosphorus in the upper 200 m. (*a*) section 1; (*b*) section 2; (*c*) section 3 (Fig. 3).

between these values. It is proposed to use a standard deviation of 12% or 0·03 μg-atom/l at a mean organic phosphorus value of 0·23 μg-atom/l. Values of organic phosphorus greater than three such standard deviations (0·09 μg-atom/l) will be considered significantly different from zero.

III. Meridional Distribution

In the mid Pacific (section 1, Fig. 3) the mean concentration of organic phosphorus within the upper 200 m varied greatly with latitude (Fig. 4(*a*)). Regions of high concentration (0·23–0·38 μg-atom/l) were found at B, C, D, and E (Fig. 4(*a*)) and of low concentration (0·01–0·19 μg-atom/l) at B^1, C^1, and D^1.

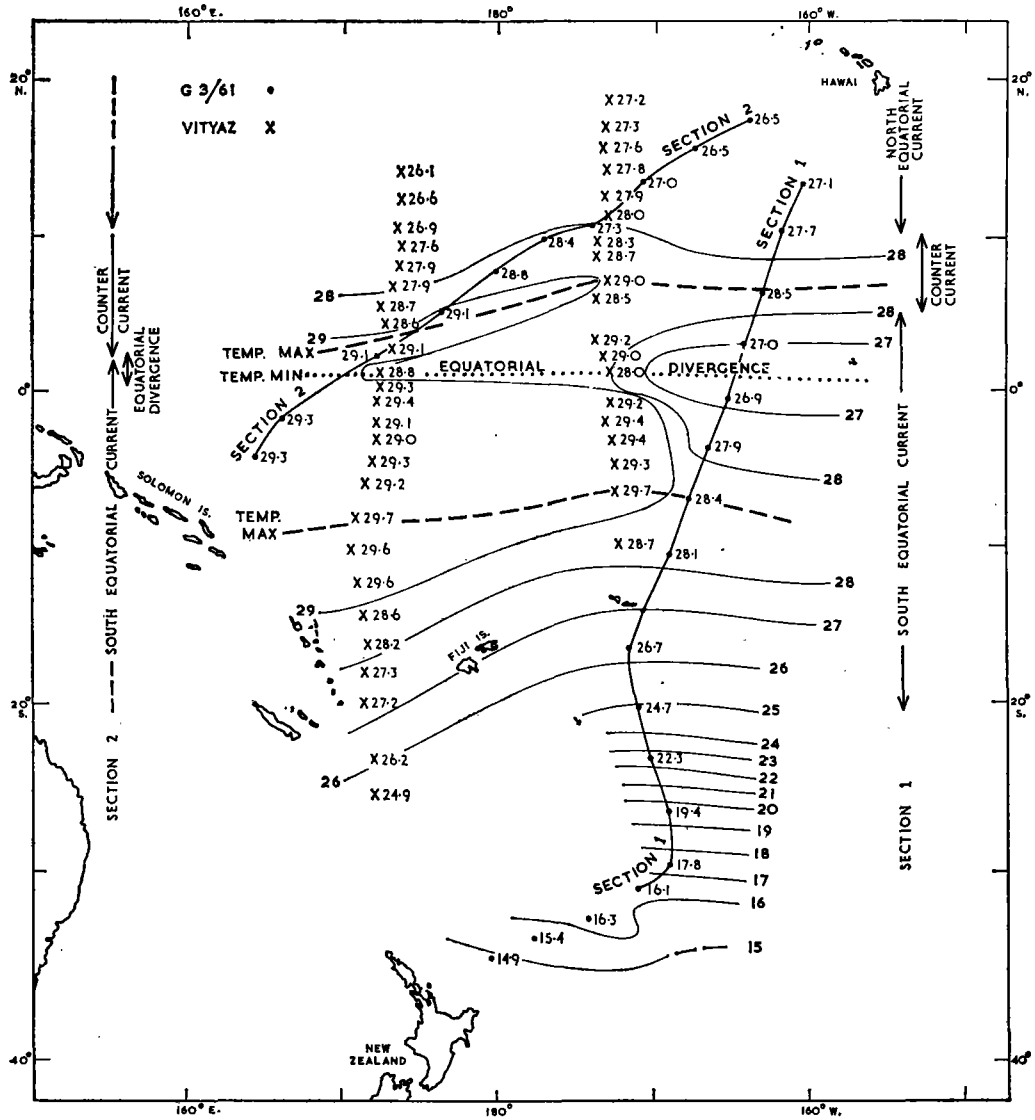


Fig. 5.—Surface temperatures and equatorial currents of the western Pacific Ocean. •, *Gascoyne*, August to October 1961; ×, *Vityaz*, October 1957 to February 1958.

In the west Pacific (section 2, Fig. 3) a region of high concentration (0·33 μg-atom/l) was found at C (Fig. 4(*b*)) in about the same latitude as region C of section 1 (Fig. 4(*b*)). Another region of high concentration (0·28 μg-atom/l) was found at A

(Fig. 4(*b*)). Secondary regions of high and low concentration at B and B^1 of section 2 (Fig. 4(*b*)) also occurred along section 1 at about the same latitudes (B, B^1, Fig. 4(*a*)). The region of low concentration at C^1 (Fig. 4(*a*)) had its northern limit at C^1 along section 2 (Fig. 4(*b*)).

In the south-east Indian Ocean the meridional variation in the mean concentration of organic phosphorus in the upper 200 m was much less than in sections 1 and 2 of the Pacific Ocean (Fig. 4(*c*)). A region of high concentration (0·23 μg-atom/l)

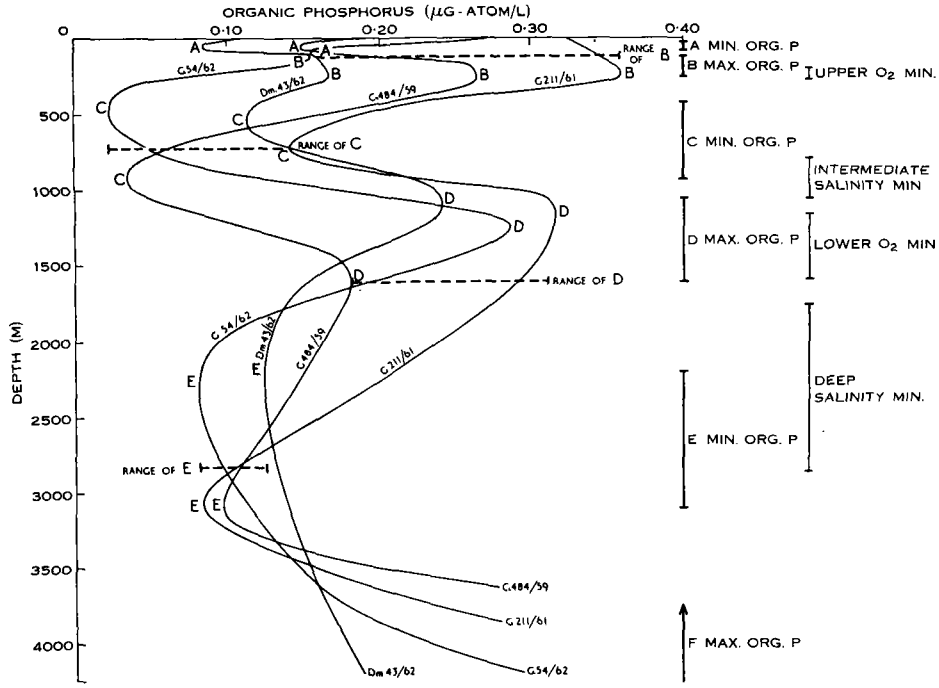


Fig. 6.—Smoothed vertical profiles of organic phosphorus at the following positions:

Ocean	Vessel	Station	Position	
Atlantic	*Crawford*	484/59	0° 14′ S.	20° 17′ W.
Pacific	*Gascoyne*	211/61	2° 20′ N.	172° 10′ E.
Indian	*Diamantina*	43/62	31° 54′ S.	112° E.
Pacific	*Gascoyne*	54/62	34° 01′ S.	153° 05′ E.

at D (Fig. 4(*c*)) corresponds in latitude with region D of section 1 (Fig. 4(*a*)). The broad region of comparatively high values (0·19–0·21 μg-atom/l) at E–E^1 (Fig. 4(*c*)) had a northern limit at the same latitude as E of section 1 (Fig. 4(*a*)). The region of low concentration at D^1 (Fig. 4(*c*)) occurred further north than in section 1 (D^1, Fig. 4(*a*)).

From surface temperatures, zones of maximum and minimum temperatures have been distinguished along sections 1 and 2 (Fig. 5). These zones in conjunction

with salinity have been used to identify the meridional position of the South Equatorial Current, Equatorial Divergence, Counter Current, and North Equatorial Current. Along section 3 the position of the South Equatorial Current and Divergence along its northern boundary have been taken from Rochford (1962).

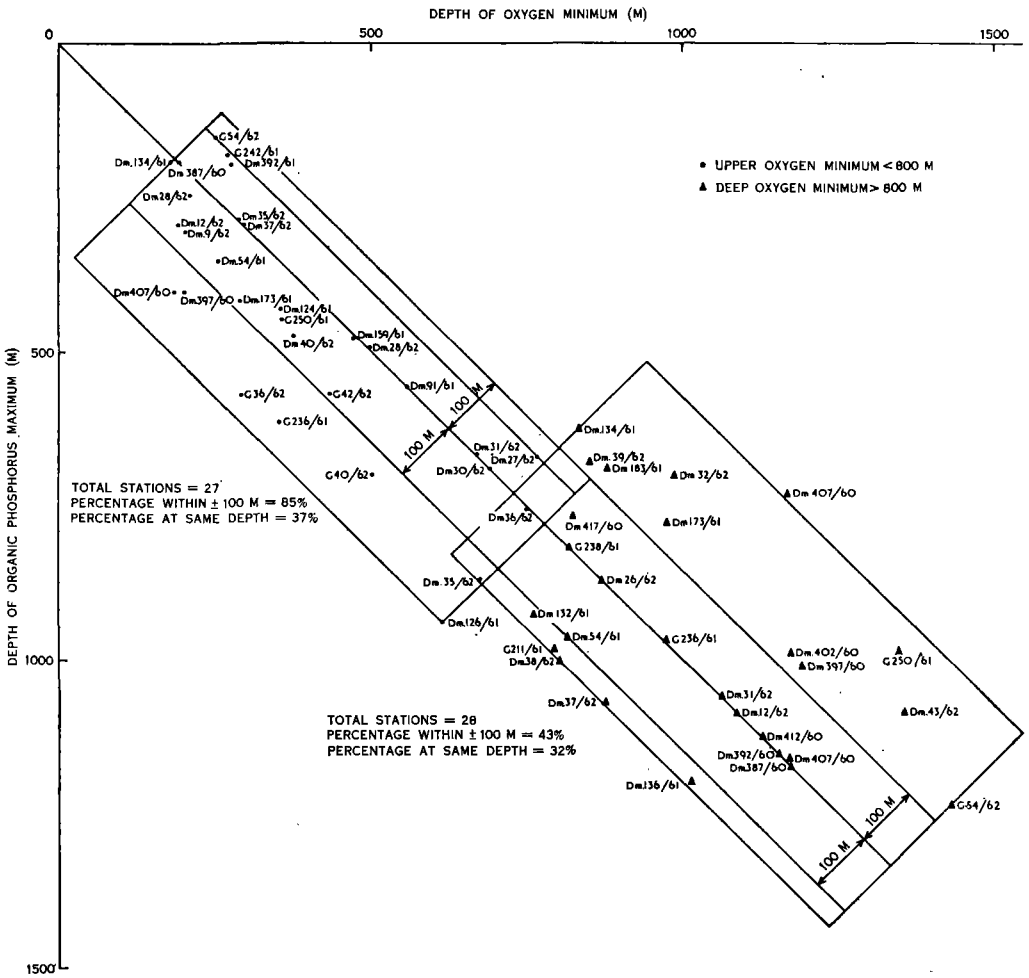


Fig. 7.—Relation between depths of upper and lower oxygen minima and organic phosphorus maxima B and D (Fig. 6) at stations of the south-east Indian and south-west Pacific Oceans (Fig. 3).

Along sections 1 and 3 the high concentration of organic phosphorus at D (Figs. 4(*a*) and 4(*c*)) occurred at the southern boundary of the South Equatorial Current. Along sections 1 and 2, and to a lesser extent along 3, the Equatorial Divergence is marked by the region of high organic phosphorus concentration at C (Figs. 4(*a*) and 4(*c*)). The slight increase in organic phosphorus concentration at B along sections 1 and 2 (Figs. 4(*a*) and 4(*b*)) occurred at the boundary of the Counter Current and North Equatorial Current. The region E–E^1, section 3 (Fig. 4(*c*)) was bounded to the north by the cyclonic eddy west of Fremantle (Wyrtki 1962*a*) and to

the south by the subtropical, subantarctic transition zone (Rochford 1962). It was situated therefore within a region of vertical mixing. Region E of section 1 (Fig. 4(*a*)) could mark the northern boundary of a similar region of vertical mixing in the south-west Pacific.

IV. Vertical Distribution

Figure 6 shows the vertical distribution of organic phosphorus at four widely separated stations in the Atlantic, Pacific, and Indian Oceans. At these stations

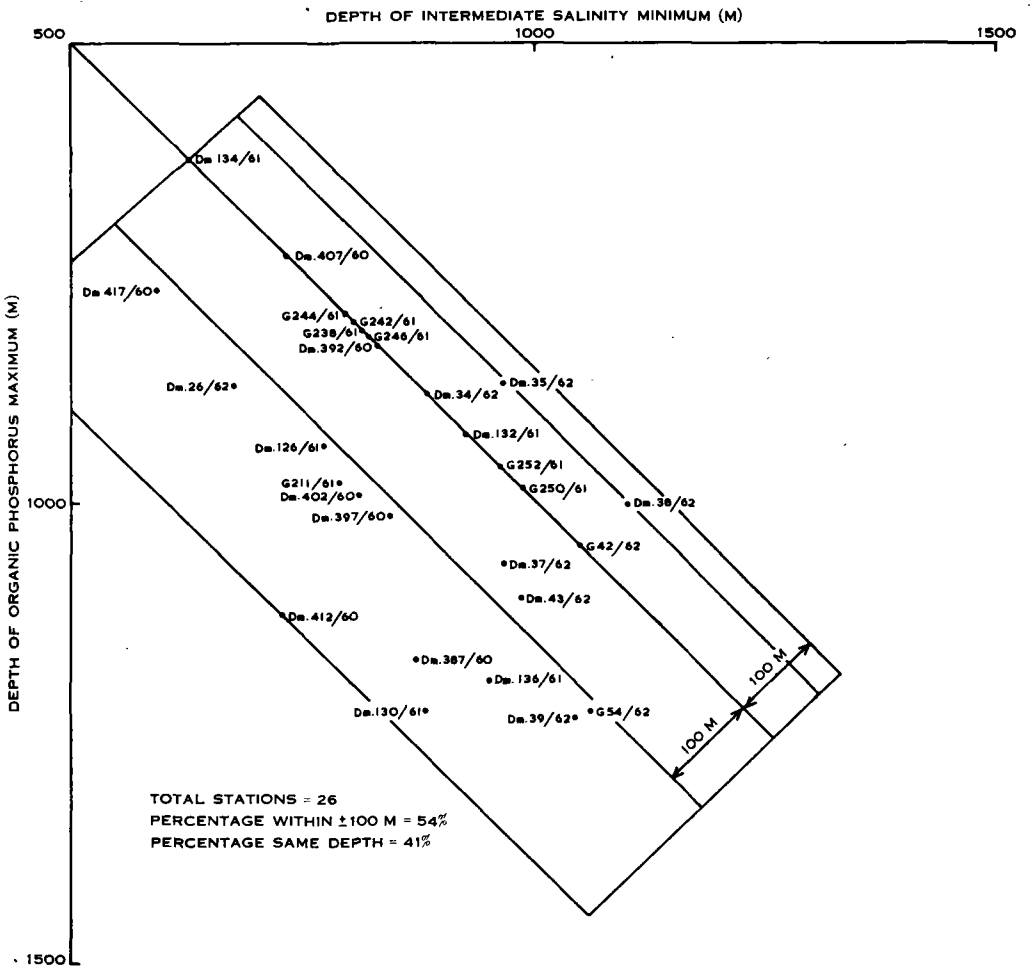


Fig. 8.—Relation between depths of intermediate salinity minimum and organic phosphorus maximum D (Fig. 6) at stations of the region (Fig. 3).

organic phosphorus did not increase or decrease uniformly with depth but passed through depth strata of high and low values. The values of organic phosphorus within these strata (A, B, C, D, and E, Fig. 6) varied more from station to station near the surface (A, Fig. 6) than at depths (E, Fig. 6). However, the depth range of these strata was much less near the surface (A, Fig. 6) than at depths (E, Fig. 6). The close correspondence in depth range of the upper and lower oxygen minima and of

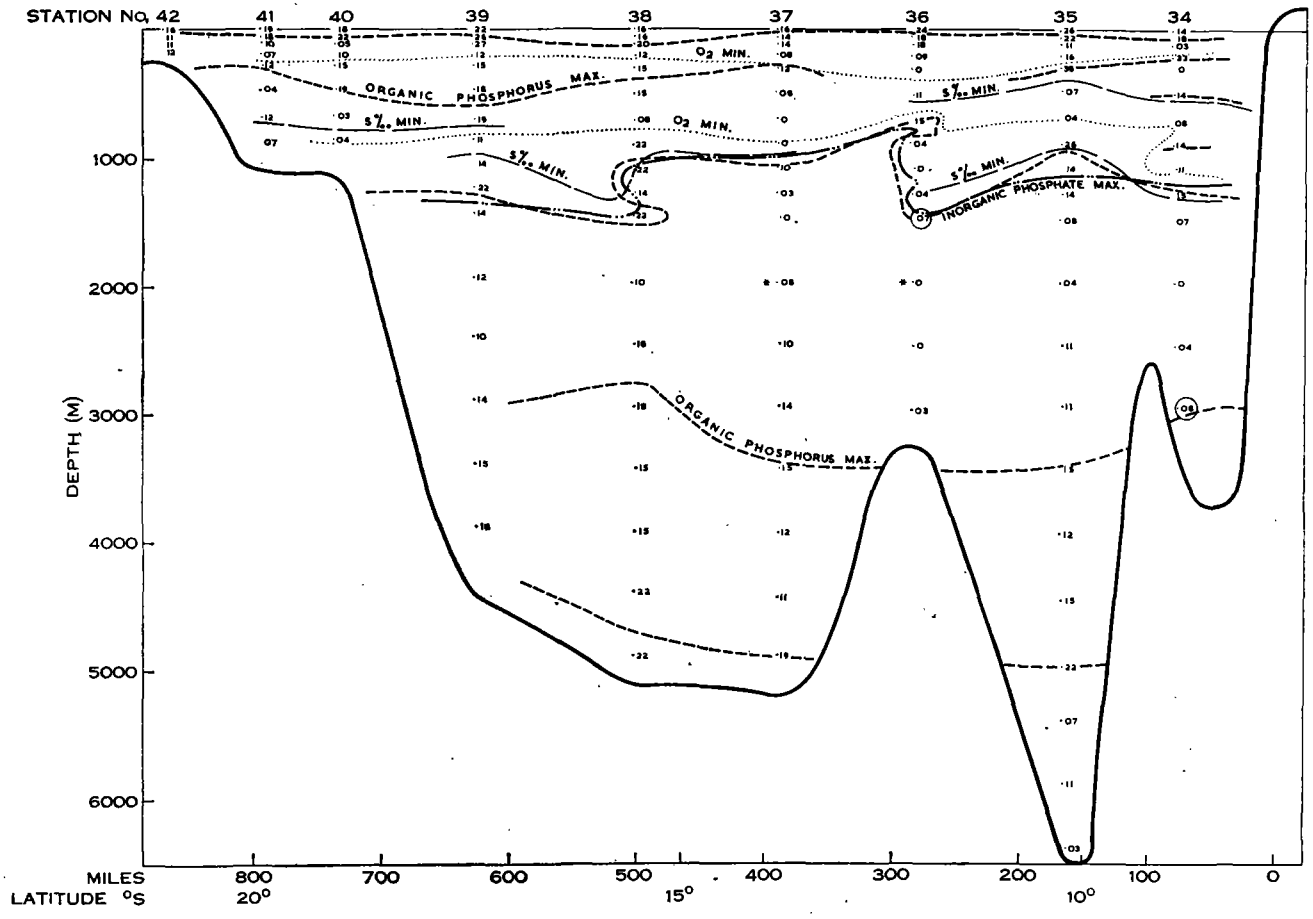


Fig. 9.—The distribution to the bottom of organic phosphorus (μg-atom/l) along section 5 (Fig. 3) from Sunda Strait to North-West Cape, Australia, in March 1962 (Cruise Dm1/62). Circled value cannot be regarded as significant. $S‰$ = salinity.

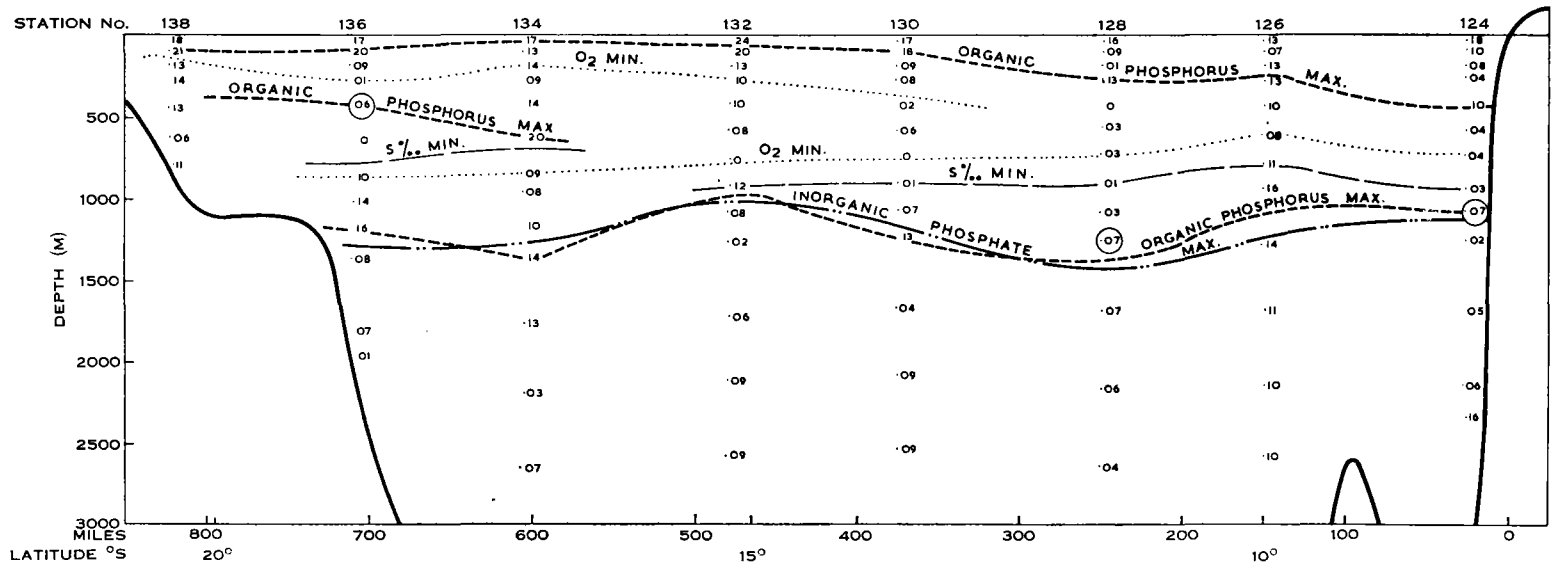


Fig. 10.—The distribution to 3000 m of organic phosphorus (μg-atom/l) along section 5 (Fig. 3) from Sunda Strait to North-West Cape, Australia, in June 1961, Cruise Dm2/61. Circled values cannot be regarded as significant. $S‰$ = salinity.

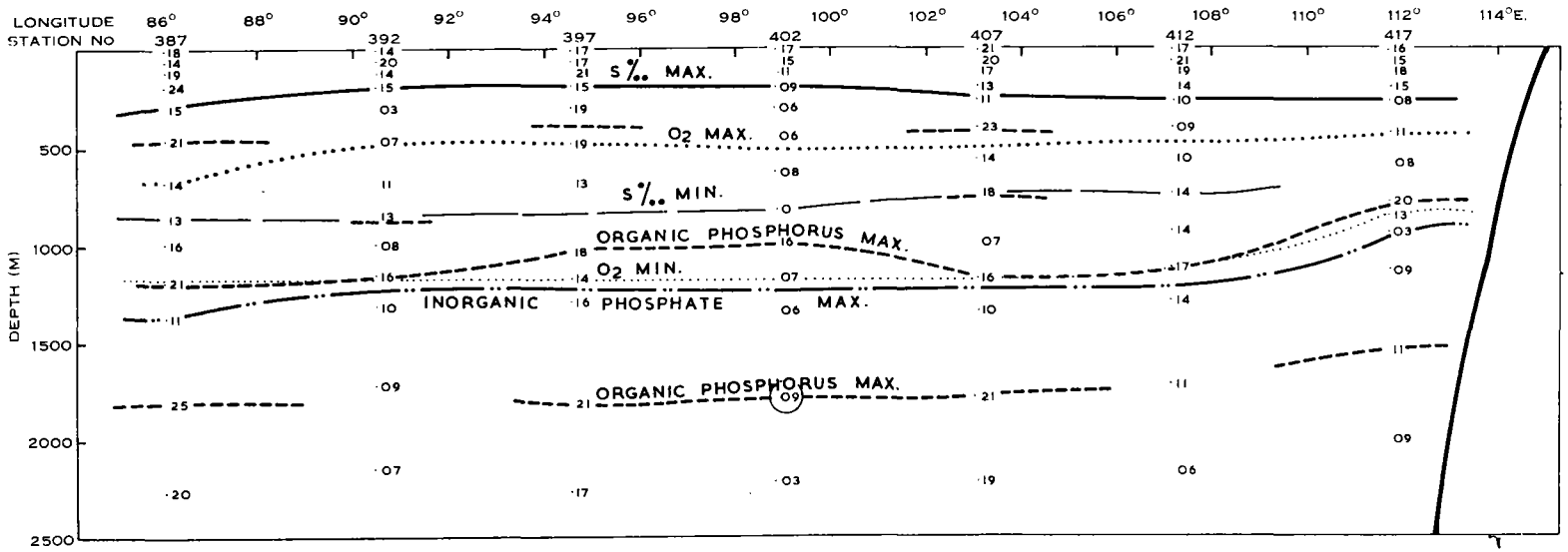


Fig. 11.—The distribution to 2500 m of organic phosphorus (μg-atom/l) along section 4 (Fig. 3) from Onslow to 86° E. in October 1960, Cruise Dm3/60. $S‰$ = salinity.

organic phosphorus maxima B and D (Fig. 6) at these four stations suggested that hydrological structure determined the depth of organic phosphorus maxima. However, the available evidence indicates (Fig. 7) that only 37% of stations of the region (Fig. 3) had an upper organic phosphorus maximum at the same depth as the upper oxygen minimum and only 32% had a lower organic phosphorus maximum at the same depth as the lower oxygen minimum. Better agreement in depth was found

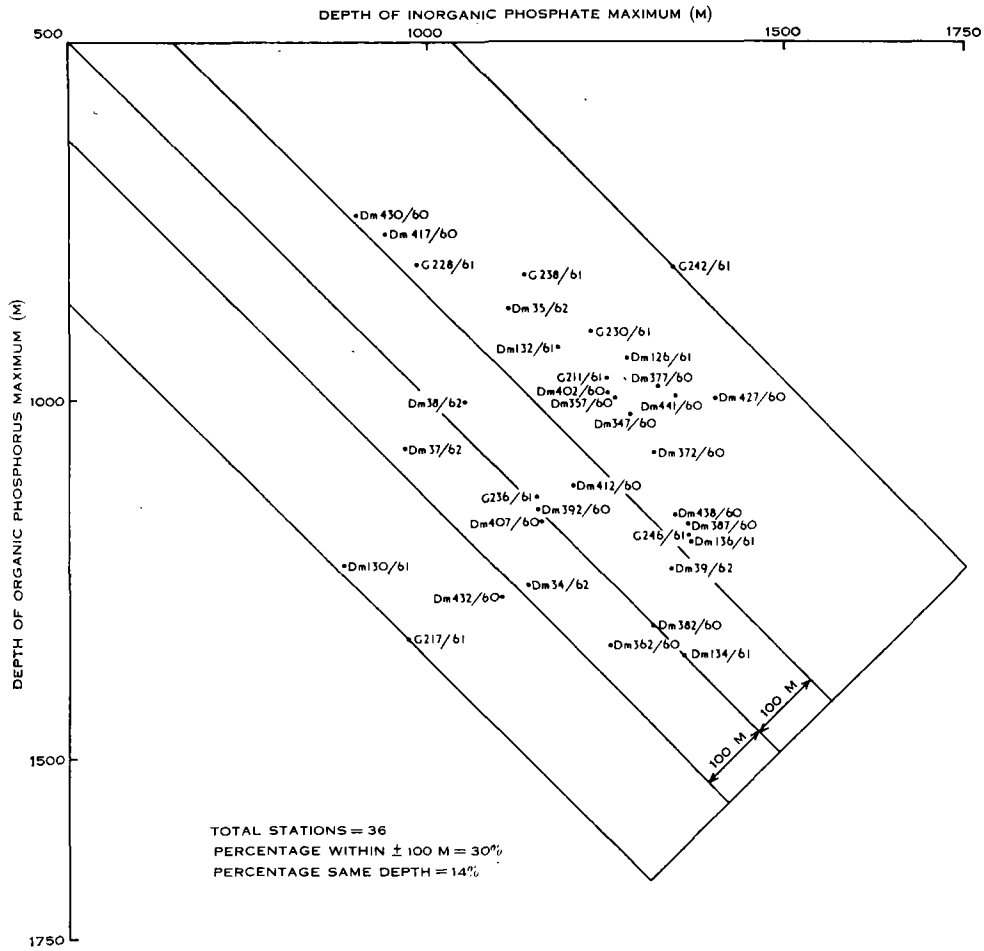


Fig. 12.—Relation between depth of intermediate phosphate maximum and organic phosphorus maximum D (Fig. 6) at stations of the region (Fig. 13).

between the lower organic phosphorus maximum and the intermediate salinity minimum where at 41% of stations these layers had the same depth (Fig. 8). Along section 5 in March 1962 the depth of these two layers coincided at most stations (Fig. 9) but in June 1961 (Fig. 10) the organic phosphorus maximum was found along this section at much the same depth although the intermediate salinity minimum was absent or lying well above. However, on both these occasions and in October 1960, along section 4, the lower organic phosphorus maximum was found at much the same depth as the inorganic phosphate maximum (Figs. 9, 10, and 11). A more extensive examination of this relation however (Fig. 12) showed that these two layers coincided

in depth at only 14% of a total of 36 stations. Along section 6 (Fig. 13) the major inorganic phosphate maximum, at 1500–2000 m, in general was found between organic phosphorus maxima.

At position A (Fig. 3) the intermediate organic phosphorus maximum (AA^1A^2, Fig. 14), the upper organic phosphorus maximum (B^1B^2, Fig. 14) and the near surface maximum (CC^1C^2, Fig. 14) increased in value and ascended towards the surface at

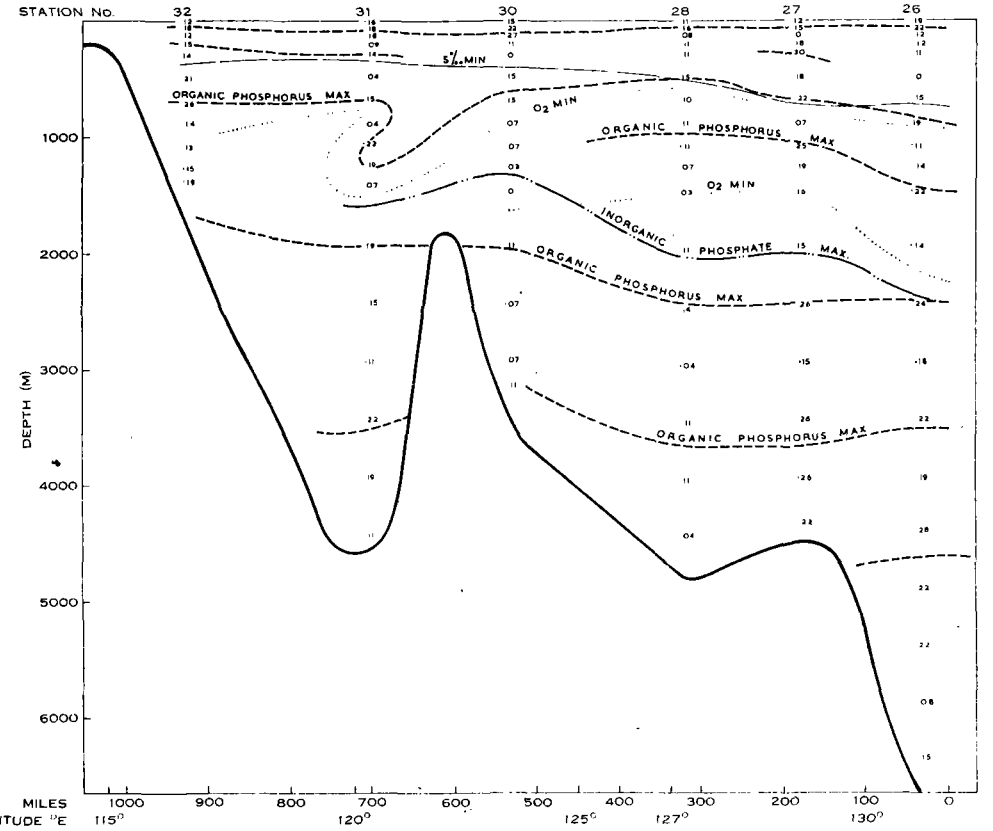


Fig. 13.—The distribution to the bottom of organic phosphorus (μg-atom/l) along section 6 (Fig. 3) from the eastern Arafura to the Flores Sea in March 1962 (Cruise Dm1/62). $S‰$ = salinity.

an average rate of 6×10^{-4} cm/sec during the period between the north-west Monsoon in February and the south-east Trades in August. During this same period all major hydrological core layers ascended at this same rate, which is very similar to the value of 5×10^{-4} cm/sec calculated by Wyrtki (1962*b*) for the rate of upwelling in this region. The highest values of organic phosphorus within these maxima were found in August during the period of greatest upwelling (Wyrtki 1962*b*). At position B (Fig. 3) downward displacement of the major hydrological core layers between February and August was accompanied by a corresponding downward displacement of the organic phosphorus maxima (BB^1B^2 and AA^1A^2, Fig. 15). Again, however, the values of these organic phosphorus maxima increased from February to August (Fig. 15).

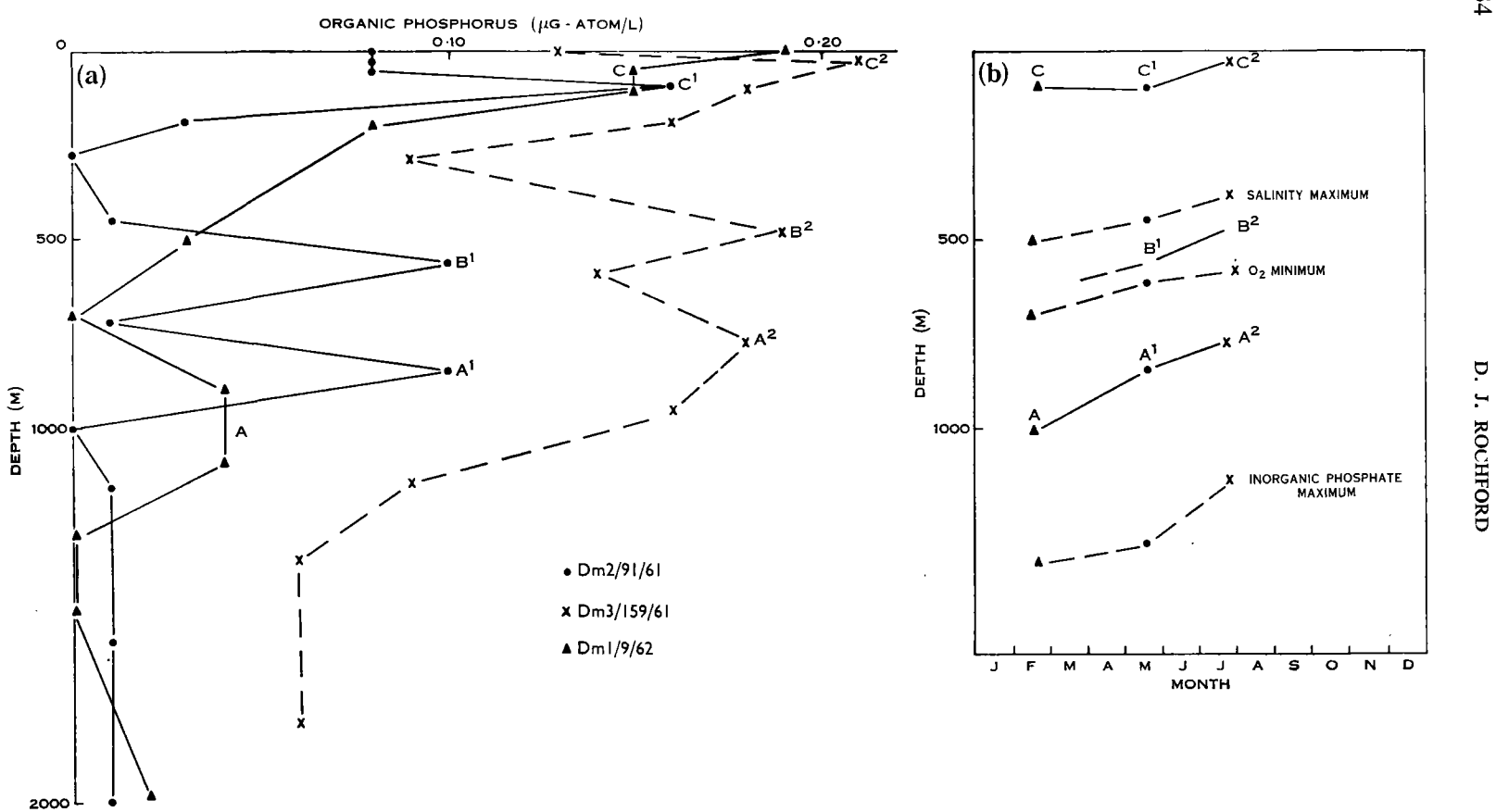


Fig. 14.—(*a*) Vertical profiles of organic phosphorus (μg-atom/l) at stations on position A (Fig. 3): AA^1A^2, B^1B^2, CC^1C^2. Maxima plotted in (*b*). (*b*) Monthly changes in depth of organic phosphorus maxima in relation to hydrological structure. Station coding as in (*a*).

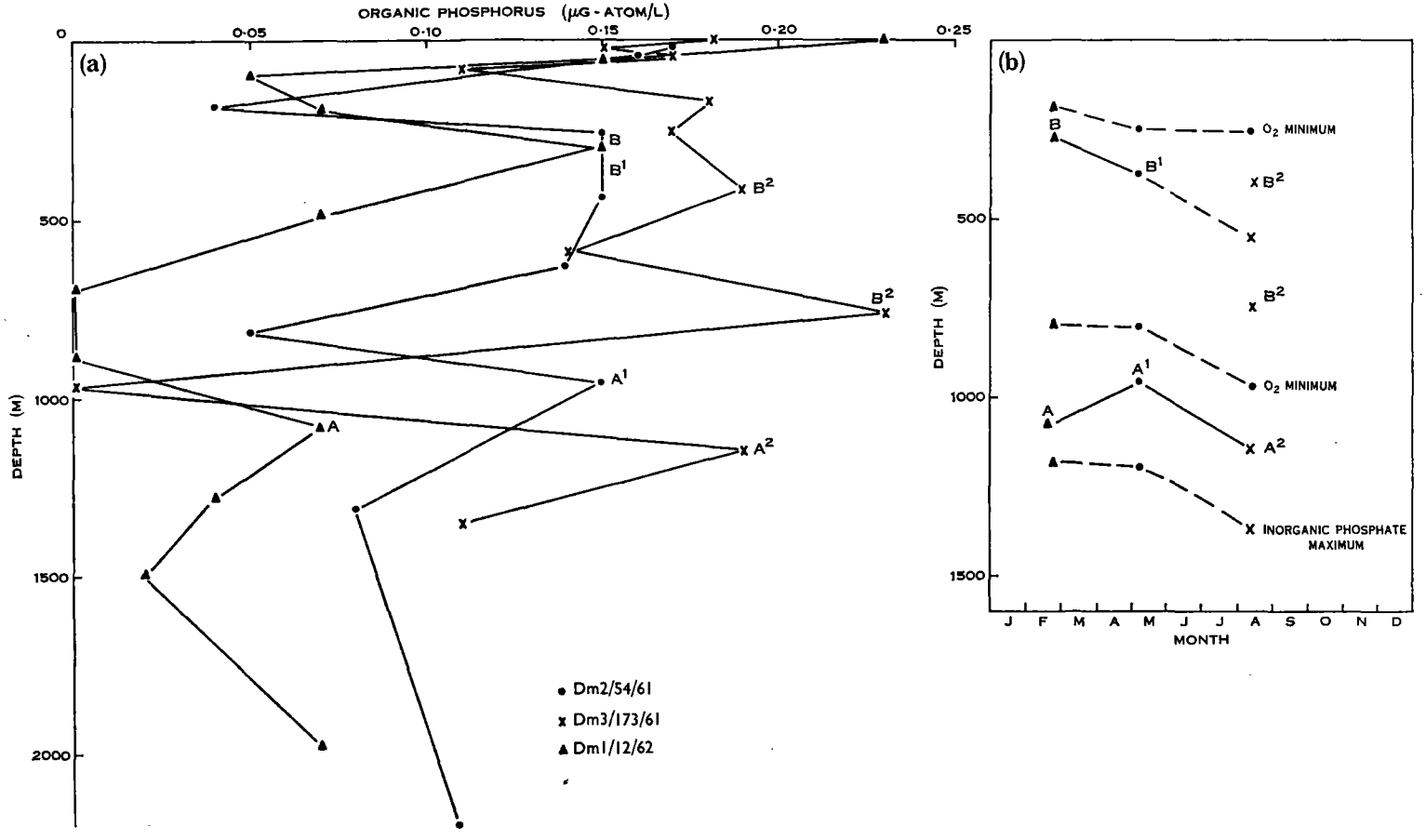


Fig. 15.—(*a*) Vertical profiles of organic phosphorus (μg-atom/l) at stations on position B (Fig. 3): AA^1A^2, BB^1B^2. Maxima plotted in (*b*). (*b*) Monthly changes in depth of organic phosphorus maxima in relation to hydrological structure. Station coding as in (*a*).

V. Particulate Content of Organic Phosphorus Maxima

During cruise Dm1/62 of H.M.A.S. *Diamantina* total phosphorus determinations were carried out on both filtered (Millipore type H.A.) and unfiltered seawater at several stations between Java and north-west Australia. The results show the following (Fig. 16):

(1) From 1500 to 4000 m at Station Dm1/33/62 there was no significant difference between the total phosphorus of filtered and unfiltered seawater and only below 3000 m could any significance be ascribed to the organic phosphorus values. However, at 4320 m there was an organic phosphorus maximum which consisted of about 40% particulate and 60% dissolved organic phosphorus. The concentration of particulate organic was 0·09 μg-atom/l which is below the limit of significance (Section II).

(2) At Station Dm1/36/62 the total phosphorus values of filtered and unfiltered seawater were the same in the upper 300 m. From 300 to 700 m, however, these two values progressively diverged, so that the organic phosphorus maximum at 700 m was formed entirely of particulate organic phosphorus at a concentration of 0·12 μg-atom/l.

(3) At Station Dm1/40/62 as at Dm1/36/62, the total phosphorus values of filtered and unfiltered seawater were the same in the upper 300 m. The organic phosphorus maximum between 300 and 500 m consisted entirely of dissolved organic phosphorus at 300 m but of about 70% particulate at 490 m. The concentration of this particulate organic phosphorus was 0·13 μg-atom/l.

At these three stations, therefore, the organic phosphorus maxima consisted of between 40 and 100% particulate organic phosphorus. It must be noted that the concentrations of particulate organic phosphorus involved (0·09–0·13 μg-atom/l) were close to the limit of analytical significance. More evidence is required before a general conclusion can be drawn that particulate organic phosphorus forms the largest part of the organic phosphorus maxima. This would be in conformity with the results of Jerlov (1959), who found a particle maximum within the core of the intermediate salinity minimum at 150° W. in the Pacific Ocean and attributed this to an accumulation of particles within a zone of strong eddy diffusivity. This also could be the explanation for the close conformity in the depth of the intermediate organic phosphorus maximum and the core of the Antarctic intermediate salinity minimum (Section IV).

VI. Conclusions

In the south-east Indian and the south-west Pacific Oceans the difference between the total phosphorus and inorganic phosphate, the so-called organic phosphorus, is significantly greater than zero at most depths and stations sampled. Meridionally the organic phosphorus in the upper 200 m has maximum values near the boundaries or upwelling regions of the equatorial currents of the Pacific and Indian Oceans and between 30–40° S. in the latter. Vertical profiles of organic phosphorus are dominated by a series of organic phosphorus maxima, which sometimes coincide in depth with major hydrological layers. The most consistent relation was found between the depth of an intermediate depth organic phosphorus maximum and the intermediate

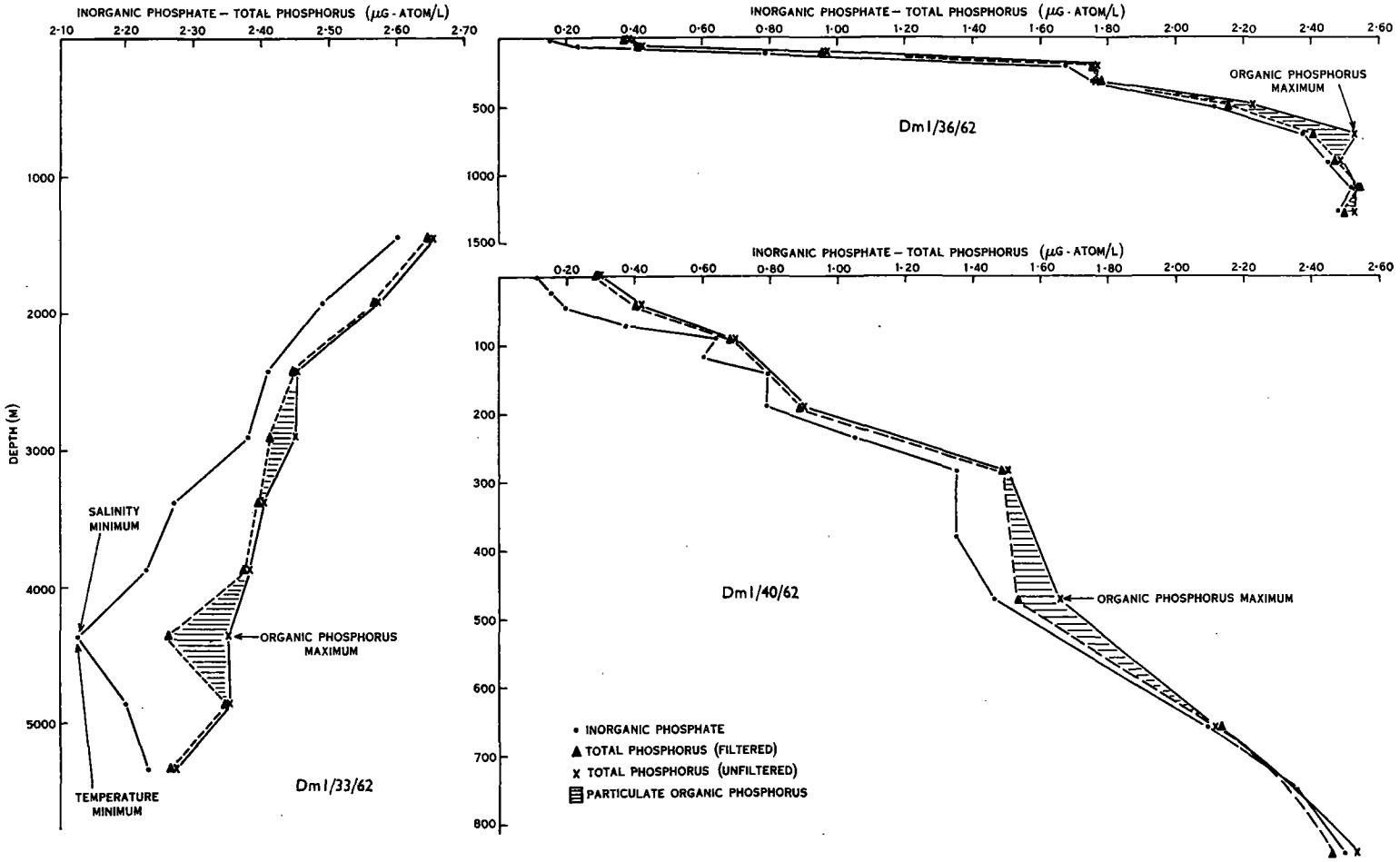


Fig. 16.—Vertical profiles of inorganic phosphate, total phosphorus of filtered seawater, and total phosphorus of unfiltered seawater at *Diamantina* stations.

salinity minimum. These organic phosphorus maxima were found to vary in depth with the upward and downward displacement of hydrological layers during a 6–7 months period. Filtration of seawater at three stations has shown that between 40 and 100% of the organic phosphorus in these organic phosphorus maxima was in the particulate form. However the concentrations of particulate organic phosphorus (0·09–0·13 μg-atom/l) were very close to the experimental error and no great significance can be attached to these results.

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SOME OBSERVATIONS ON SILICATE AND OXYGEN IN THE INDIAN OCEAN

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During the Monsoon Expedition to the Indian Ocean in 1960 analyses were made for silicate at ten stations, along with oxygen and other hydrographic observations. The location of the stations is shown in Fig. 1 and the date are given in the tables. In Fig. 2 the distribution of both silicate and oxygen is plotted for comparison. The temperature distribution is not included, to avoid complication, but may be inferred from the oxygen curves.

As is true elsewhere, the slope of the curve for silicate distribution follows that for oxygen and for temperature, being related to the depth of the thermocline and the oxygen minimum. The silicate maximum is very much greater than that in the Atlantic but somewhat less than that in the Pacific, another indication of the relation of the Indian to the Pacific. No intermediate maximum of silicate was found, a phenomenon occasionally encountered in the Pacific, but only in certain sections.

The oxygen curves for eight of the stations are plotted simultaneously in Fig. 3 (those for Stations IV-16 and 19 are closely similar to that for IV-12). The depth of the oxygen minimum shows a north-south trend and it is curious to observe that at all but the most north erly station (III-15) the oxygen concentration is nearly the same at a depth of about 700 meters. This may have a relation to the Antarctic Intermediate Water Mass, although it is not the present purpose to discuss hydrography and circulation. Oxygen in the deep water shows a progressive decrease from south to north, consistent with the presumed direction of motion.

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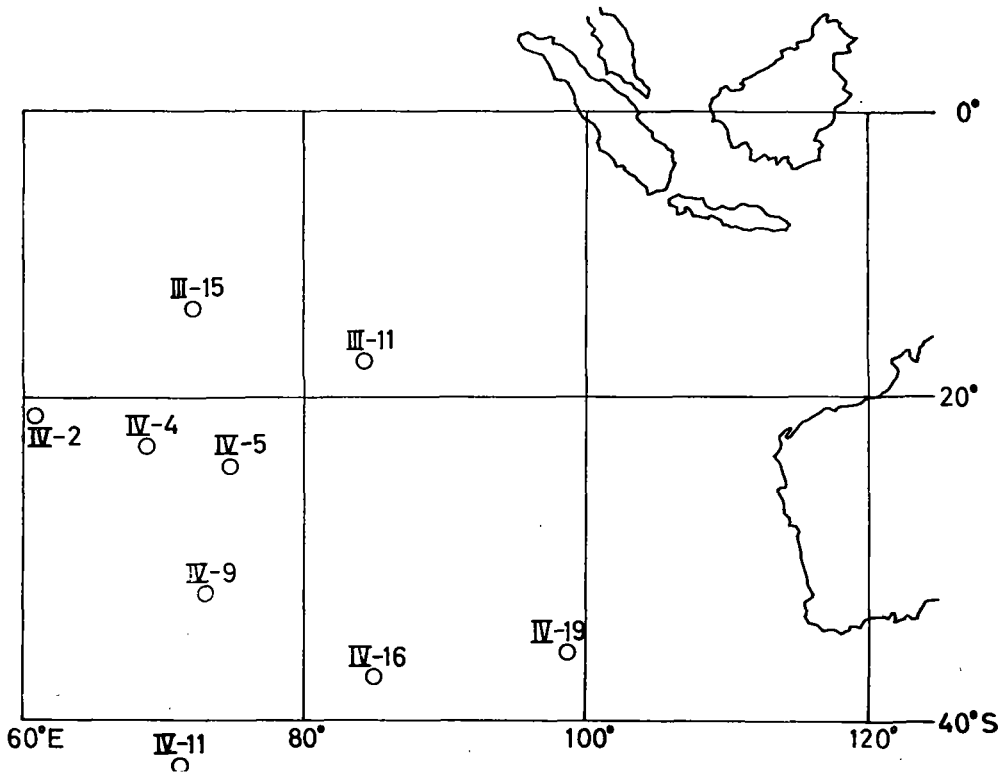


Figure 1. Location of stations.

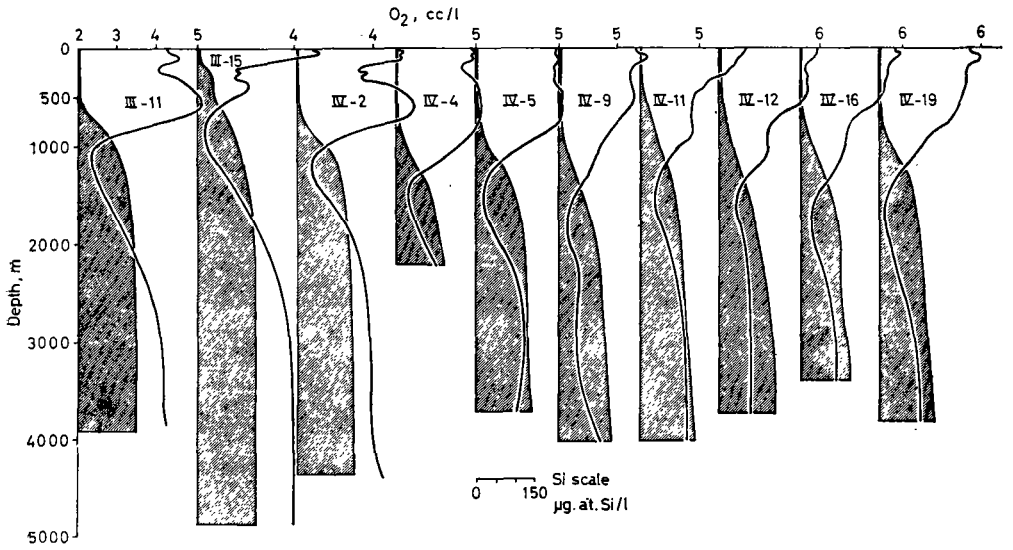


Figure 2. Vertical distribution of silicate and oxygen. Scale for silicate (solid black) is shown at the bottom in milligram atoms of Si per liter. Scale for oxygen at the top in cc per liter.

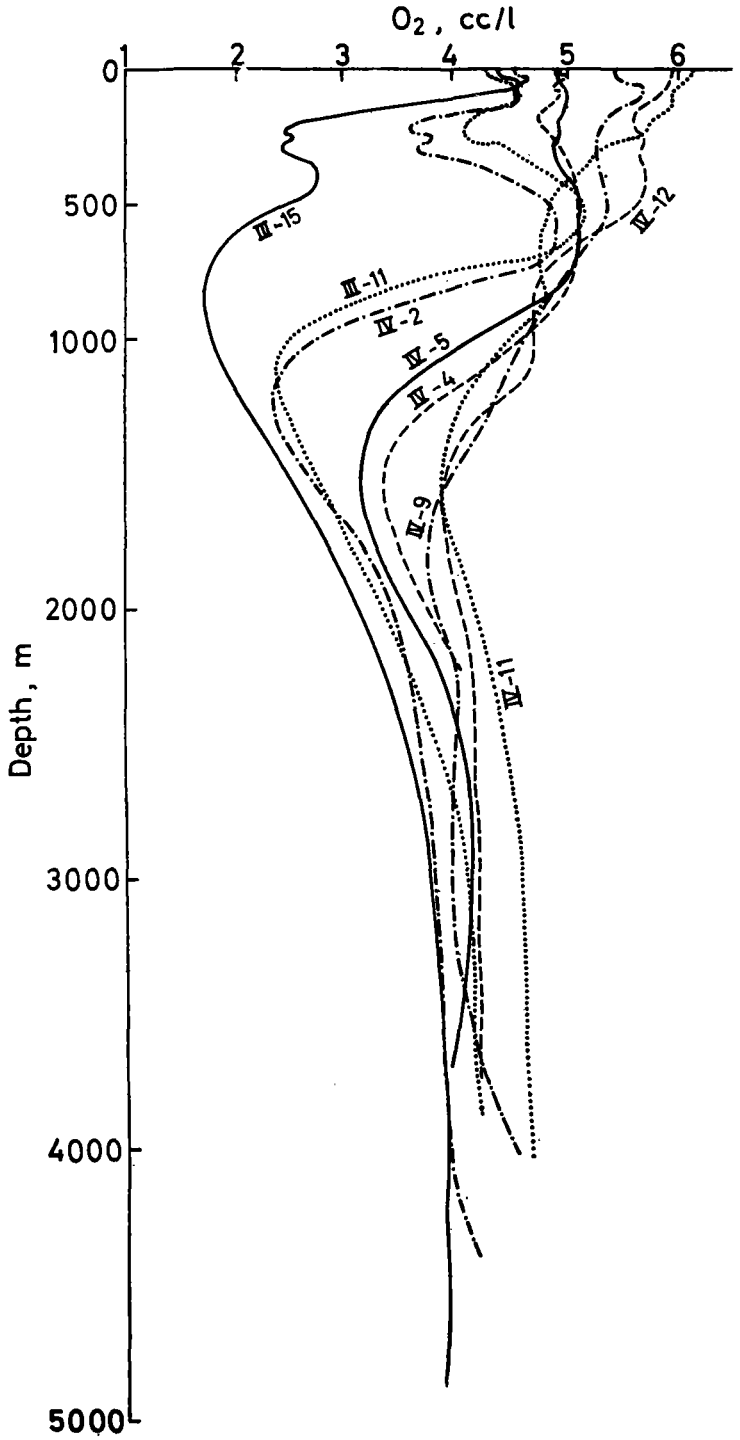


Figure. 3. Vertical distribution of oxygen at eight stations.

Station III–11. 18°53′S ; 88°02′E. Nov. 27, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	25.6	5.5	4.20
9	25.5	6	4.21
27	25.5	5.5	4.24
45	24.8	6	4.29
69	23.6	5.5	4.47
87	22.5	5	4.50
108	22.1	6	4.59
128	21.7	6	4.67
168	21.1	5	4.58
205	19.4	7	3.83
243	18.5	7	4.16
281	16.9	7	4.24
357	14.5	7	4.62
431	12.3	7	4.93
495	11.1	7.5	5.15
593	9.5	9.5	5.13
690	7.8	19	4.55
786	6.4	53	3.30
881	6.0	76	2.45
977	5.6	93	2.20
1166	4.9	102	2.41
1456	4.0	112	2.62
1936	3.1	125	3.19
2413	2.5	125	3.56
2894	2.2	135	3.80
3380	2.0	145	3.89
3868	1.9	147	4.07
4457	1.9	147	—

Station III–15. 13°S; 75°E. Dec. 1, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	26.39	4.5	4.32
10	26.41	4.5	4.44
40	24.20	4.5	4.68
55	22.92	4.5	4.74
76	21.85	6	4.41
101	20.85	8	3.86
126	19.33	12	3.61
152	16.32	27	2.35
176	14.88	30	2.38
200	13.86	33	2.60
230	12.42	37	2.46
259	11.46	40	2.29
288	10.95	40	2.38
322	10.77	35	2.71
361	10.10	33	2.81
405	9.37	36	2.86
458	8.70	45	2.59
562	7.88	60	1.95
655	7.12	73	1.74
746	6.50	86	1.67
955	5.65	95	1.88
1150	4.77	105	2.02
1376	4.01	108	2.38
1647	3.24	118	2.73
2009	2.51	126	3.15
2479	1.95	138	3.60
3020	1.61	138	3.83
3581	1.38	142	3.90
4155	1.35	148	3.94
4880	1.43	148	3.97

Station IV–2. 20°19′S; 58°08′E. Dec. 12, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	26.04	4	4.32
34	25.08	4	4.67
63	24.54	4	4.62
97	23.90	4.5	4.66
131	22.57	5	4.42
163	20.79	8.5	3.61
195	19.70	10.5	3.38
227	18.98	8.5	3.87
259	17.49	13	3.39
290	16.54	12	3.71
326	15.26	13	3.79
371	13.98	13	3.76
439	12.71	8	4.89
507	11.56	9	4.85
599	10.14	8	5.06
695	8.92	13	4.81
789	7.32	32	4.10
808	7.30	33	3.92
902	6.18	52	3.05
997	5.70	73	2.53
1091	5.16	90	2.38
1186	4.63	100	2.20
1250	4.36	104	2.28
1419	3.75	104	2.77
1605	3.24	108	2.96
1888	2.54	120	3.28
2216	2.09	128	3.59
2721	1.83	133	3.75
3241	1.70	139	3.82
3748	1.57	142	3.91
4251	1.23	142	4.24

Station IV–4. 25°01′S ; 69°34′E. Dec. 14, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	23.94	4	4.77
10	23.71	4	4.74
24	23.52	4.5	4.98
43	21.86	4.5	4.73
67	21.08	4.5	4.93
96	20.81	4	5.01
125	20.24	4	4.78
152	19.70	5	4.69
190	18.42	4.5	4.76
237	17.11	4.5	4.89
282	15.37	5	4.93
327	14.11	5.5	5.03
395	13.20	6	—
463	12.42	6	5.07
550	11.66	6.5	5.12
639	10.72	7.5	5.10
816	8.49	11	4.85
1080	4.95	42	4.06
1353	3.62	78	3.31
1728	2.72	94	3.56
2218	1.92	124	3.92

Station IV–5. 24°30′S; 73°50′E. Dec. 15, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	23.96	4.5	4.85
30	22.56	4.5	4.93
50	21.22	5	4.90
76	20.64	4.5	5.05
101	20.20	4	5.09
126	19.80	4	5.11
152	19.30	4	5.01
177	18.66	4	4.86
202	17.87	4.5	4.85
226	17.16	4.5	4.91
250	16.16	4	4.96
279	15.25	4.5	4.85
308	14.34	4.5	4.92
342	13.47	5	5.08
376	12.84	5.5	5.06
414	12.32	6.5	5.15
470	11.83	6.5	5.10
510	11.43	6	5.26
569	10.92	6.5	5.06
667	9.92	6.5	5.17
764	8.84	9	5.07
862	7.42	21	4.62
959	5.71	37	4.22
1056	4.58	58	3.74
1249	3.81	82	3.20
1541	3.19	106	3.11
2029	2.38	120	3.47
2528	1.86	120	3.98
3028	1.56	129	4.25
3555	1.44	138	4.18
3657	1.45	138	4.14

Station IV–9. 33°21′S ; 72°41′E. Dec. 18, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	18.92	3.5	5.36
10	18.32	3.5	5.32
21	18.22	3.5	5.32
51	16.22	3.5	5.68
91	14.58	4	5.55
131	13.91	4	5.44
171	13.42	5.5	5.26
210	12.98	5.5	5.22
249	12.69	5.5	5.24
288	12.46	7	5.21
327	12.20	7	5.28
365	12.00	7	5.34
403	11.75	7	5.34
442	11.68	7	5.39
489	11.36	7	5.43
537	11.10	7	5.33
632	10.30	7.5	5.20
732	9.12	14	4.90
827	7.79	22	4.72
1015	5.26	34	4.55
1202	3.85	45	4.39
1481	3.07	70	3.93
1784	2.64	82	3.78
2130	2.22	97	4.06
2497	1.92	108	3.99
2964	1.66	123	4.02
3441	1.38	133	4.20
3959	1.14	133	4.50

Station IV–11. 42°07′S; 70°41′E. Dec. 21, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	10.88	4	6.22
11	10.89	4	6.15
46	10.56	4	6.26
56	10.53	4	6.18
76	9.81	4	6.08
96	9.76	5	5.99
121	9.08	5	6.02
152	8.90	6	5.95
192	—	8	5.76
232	8.68	9	5.79
272	8.40	10.5	5.45
311	8.12	12	5.26
350	7.62	15	5.29
400	7.54	17	4.91
448	6.98	22	4.87
520	5.84	29	4.95
594	5.42	31	4.78
667	4.72	39	4.87
707	4.28	40	4.90
808	3.83	40	4.94
908	3.58	55	4.53
1005	3.32	62	4.37
1102	3.04	65	4.23
1199	2.92	73	4.13
1390	2.78	82	3.90
1679	2.56	83	4.09
1972	2.40	90	4.25
2462	2.06	100	4.48
2961	1.65	110	4.60
3465	1.08	134	4.63
3970	0.86	141	4.71
4054	0.90	142	4.73

Station IV–12. 39°49′S ; 75°03′E. Dec. 23, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	13.67	3	6.04
39	13.40	3	6.02
78	12.58	6.5	5.82
116	12.17	7	5.69
154	11.78	7	5.62
192	11.46	7	5.67
230	11.37	7.5	5.78
267	11.28	7.5	5.76
303	11.06	7.5	5.79
338	11.03	—	5.88
374	10.97	7	5.88
410	10.93	7.5	5.86
448	10.88	8	5.82
485	10.77	8	5.80
522	10.39	8.5	5.64
607	9.28	11.5	5.10
704	7.82	19	4.79
804	6.60	27	4.72
901	5.47	33	4.78
998	4.59	40	4.77
1095	3.94	45	4.71
1191	3.52	55	4.43
1384	3.04	76	4.09
1678	2.69	84	3.99
1969	2.46	97	4.17
2472	1.96	138	4.23
2974	1.62	138	4.18
3481	1.32	143	4.29
3681	1.34	145	4.32

Station IV–16. 37°50′S; 84°45′E. Dec. 25, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	14.78	3	5.84
10	14.77	3	5.84
40	14.46	3	5.94
55	13.01	4	6.09
75	12.24	5.5	6.00
111	12.04	6	5.69
151	11.86	6	5.80
192	11.78	6	5.81
232	11.75	6	5.84
273	11.64	6	5.83
313	11.58	6	5.72
353	11.56	6.5	5.60
391	11.32	7	5.61
429	11.10	7	5.63
468	10.90	7.5	5.60
505	10.72	8	5.55
543	10.38	8.5	5.57
581	10.03	8	5.52
615	9.70	10	5.12
661	9.26	14	5.01
730	8.42	15	4.86
799	7.54	20	4.74
891	6.34	28	4.72
984	5.16	41	4.75
1168	3.78	50	4.45
1351	3.19	71	3.83
1730	2.68	96	4.25
2214	2.29	96	4.41
2700	1.78	113	4.56
3188	1.31	133	4.62

Station IV–19. 36°19′S ; 98°40′E. Dec. 29, 1960

Depth *m*	Temp. °C	Silicate *μg* at. Si/*l*	Oxygen cc/*l*
0	15.40	4	5.68
25	15.40	4	5.71
50	13.80	4	6.09
75	13.12	4.5	5.91
126	12.60	4.5	5.66
202	11.70	5.5	5.71
277	11.26	6	5.70
352	10.84	6.5	5.67
427	10.34	7	5.57
500	9.96	8	5.53
572	9.62	8	5.46
643	9.15	8.5	5.37
715	8.52	11	5.15
788	7.71	17	4.90
861	6.64	29	4.67
935	5.66	31	4.58
987	5.31	38	4.50
1034	4.64	47	4.44
1087	4.34	50	4.28
1181	3.89	66	4.02
1276	3.44	66	4.01
1369	3.34	88	3.66
1463	3.08	88	3.74
1653	2.77	89	3.74
1945	2.52	100	3.86
2433	2.13	109	4.23
2813	1.70	118	4.44
3137	1.40	132	4.56
3496	1.15	140	4.60
3657	1.06	142	4.66
3805	1.02	142	4.63

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СТРОНЦИЙ-90 в ПОВЕРХНОСТНЫХ ВОДАХ ИНДИЙСКОГО ОКЕАНА в 1960—1961 гг.

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Географическое распределение Sr^{90} на поверхности Мирового океана обладает, по-видимому, рядом особенностей по сравнению с распределением его на поверхности суши. Помимо причин, определяемых расположением очагов загрязнения и атмосферной циркуляцией, в этом должны проявиться процессы циркуляции вод Мирового океана. Для того, чтобы оценить роль этих процессов, требуется охватить исследованиями значительные площади каждого океана. Кроме того, известно, что воды океана подвержены перемешиванию, имеющему сезонный ход, в результате чего происходит обновление вод поверхностного слоя. При таких обстоятельствах особую ценность представляют результаты повторных, многократных наблюдений.

В 33-м рейсе э/с «Витязь» были продолжены работы по исследованию содержания Sr^{90} в водах Индийского океана, начатые в 31-м рейсе. Сбор образцов стронция океанской воды производился из проб воды объемом 120—160 *л* путем осаждения карбонатов в присутствии NH_4Cl. На 100 *л* воды добавлялось 600 *г* NH_4Cl и 1200 *г* Na_2CO_3. Для определения Sr^{90} в карбонатных осадках применялась схема анализа, исключающая необходимость отделения Sr от Ca: Y^{90} — продукт распада Sr^{90} — выделялся непосредственно из смеси стронция и кальция, подвергнутой радиохимической очистке. Выход Sr определялся при помощи пламенной фотометрии[1]. Это значительно упростило химическую стадию определений, по сравнению с методами, использующими для разделения Sr от Ca соли ЭДТА и крепкую азотную кислоту. Ход анализа представлен схематично в табл. 1. В условиях серийного анализа, как это имело место в настоящей работе, описанная методика обеспечила выход иттрия на мишень около 50%.

Счет активности Y^{90} производился на 4 π-счетной установке с эффективностью счета около 80% и фоном около 1 импульса в минуту [3]. Радиохимическая чистота мишени контролировалась по скорости спада радиоактивности.

Для того, чтобы оценить надежность результатов, полученных при помощи новой методики, определяли Y^{90} в ряде проб по нескольку раз после соответствующего периода накопления. Воспроизводимость результатов иллюстрируется табл. 2.

Как видно по данным табл. 2, случается, что разброс результатов, полученных для одной и той же пробы, выходит за пределы статистической ошибки счета Y^{90}. Очевидно, в ходе определения Y^{90} имеют

[1] Концентрация природного стронция в водах Индийского океана принята равной 8,7±0,5 *мг/л* [6].

Схема анализа Таблица 1

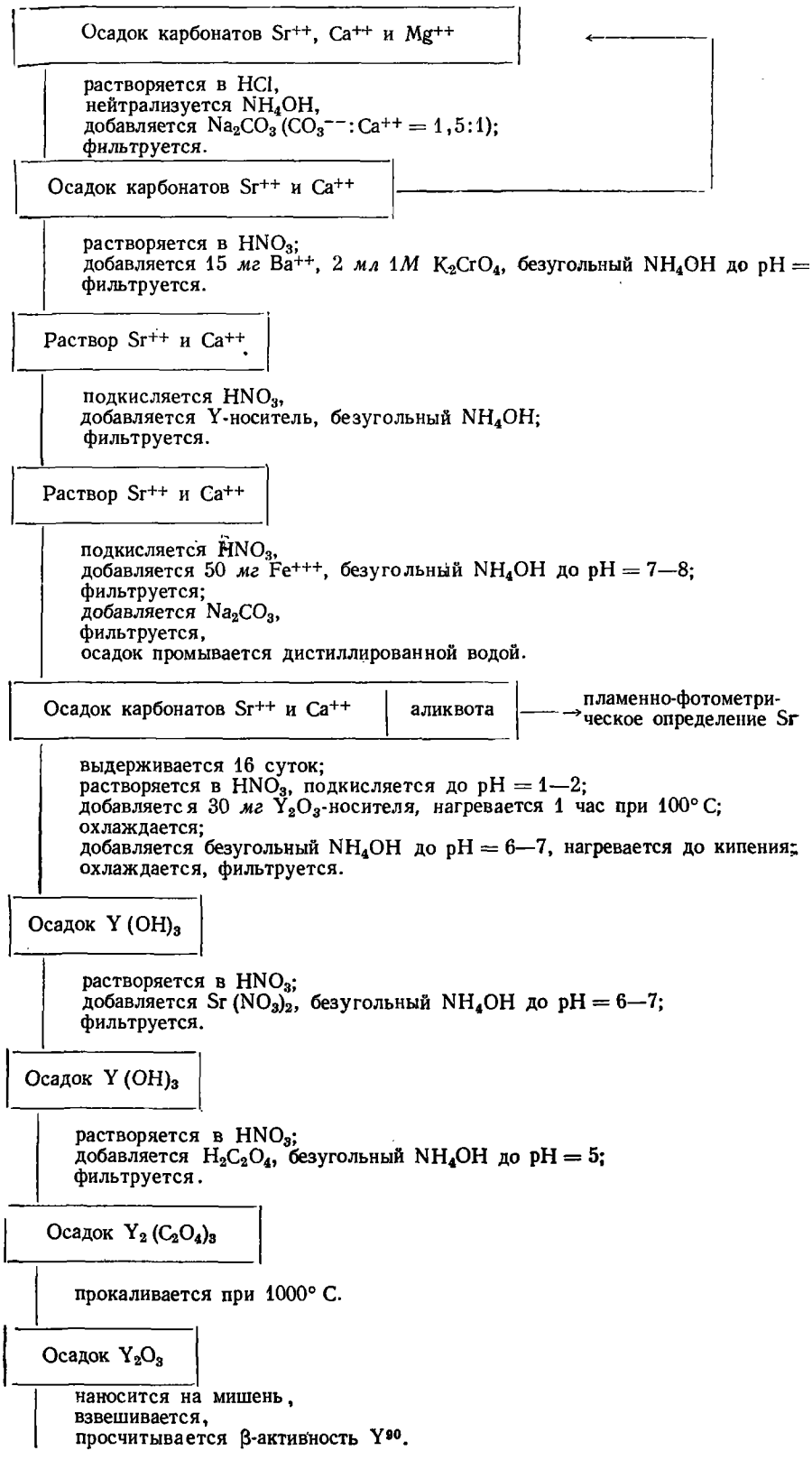
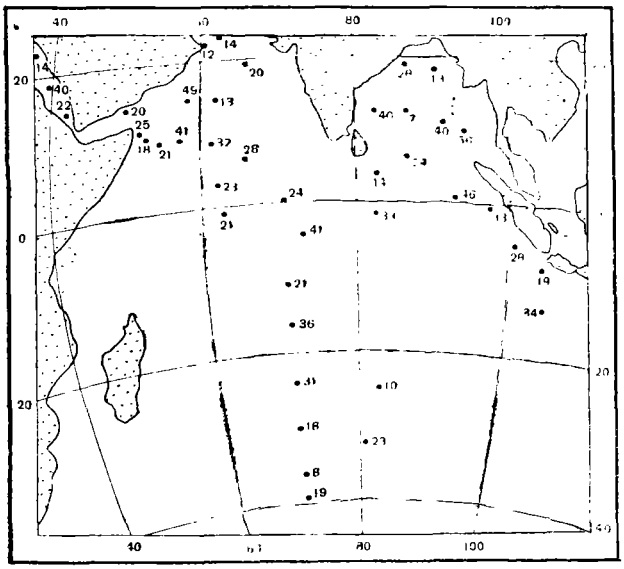


Таблица 2

Результаты повторного определения Y^{90} в одних и тех же пробах Sr^{90}

Индекс пробы	Счет Y^{90}, *имп/мин/мишень*	Выход Y	Активность Y^{90}, *имп/мин*/проба		Относительное отклонение результатов, %
			отдельные определения	среднее значение	
Ст.—	2,5±0,3 6,6±0,7	0,26 0,57	9,6±1,2 11,6±1,2	10,6	9
Ст. 4781	3,4±0,2 4,2±0,3	0,66 0,47	5,2±0,3 8,9±0,6	7,0	27
Ст. 4790	3,4±0,5 6,1±0,6	0,40 0,69	8,5±1,2 8,8±0,9	8,7	2
Ст. 4796	3,7±0,4 2,4±0,5 2,5±0,3	0,70 0,32 0,41	5,4±0,6 7,5±1,5 6,1±0,7	6,3	14 19 3
Ст. 4807	3,1±0,4 4,0±0,6	0,43 0,70	7,2±0,9 5,7±0,9	6,4	12
Ст. 4811	3,5±0,4 4,7±0,5	0,42 0,66	8,1±0,5 7,1±0,8	7,6	7
Ст. 4974	14,3±1,4 15,5±1,2	0,33 0,47	43,3±4,2 32,0±2,6	37,6	15

место какие-то случайные погрешности. Наиболее вероятная ошибка, возникающая за счет них, равна, по данным табл. 2, 10%. Эта величина учтена при оценке суммарной ошибки результатов измерений.



Распределение Sr^{90} на поверхности Индийского океана в октябре 1960 г.—марте 1961 г. (распады в минуту на 100 *л*)

Результаты определения Sr^{90} в пробах поверхностных вод Индийского океана приведены в табл. 3. Поправки к значениям активности включают в себя статистическую ошибку счета активности и погрешности определения выходов стронция и иттрия. Данные таблицы нанесены на карту (рисунок).

Таблица 3

Концентрация Sr^{90} в поверхностных водах Индийского океана в 1960—61 гг.

№ станций э/с «Витязь»	Координаты		Дата	Активность Sr^{90}, расп/мин на 100 л
	широта	долгота		
			1960 г.	
4780	22°21′ с.	37°22′ в.	13.X	14± 2
—	18°31′ »	39°10′ »	14.X	40± 8
4781	14°05′ »	42°20′ »	15.X	22± 5
4790	14°44′ »	50°02′ »	25.X	20± 5
4795	11°11′ »	52°13′ »	28.X	25± 8
4796	10°19′ »	53°14′ »	29.X	18± 5
4797	9°23′ »	54°56′ »	31.X	21± 4
4800	9°33′ »	57°08′ »	1.XI	41±10
4803	15°23′ »	58°25′ »	3.XI	49±10
4807	22°23′ »	59°53′ »	5.XI	12± 2
4811	22°49′ »	62°03′ »	8.XI	14± 2
4816	15°03′ »	62°09′ »	10.XI	13± 2
4820	8°40′ »	61°54′ »	13.XI	32± 5
4829	3°25′ »	62°06′ »	15.XI	23± 5
4840	00°55′ ю.	62°33′ »	17.XI	21± 5
4848	6°59′ с.	65°57′ »	21.XI	28± 4
4854	19°15′ »	65°56′ »	26.XI	20± 5
4874	00°00′ »	70°52′ »	12.XII	24± 5
4877	3°56′ ю.	73°10′ »	14.XII	41± 9
4882	10°40′ »	70°59′ »	18.XII	21± 7
4885	16°42′ »	70°58′ »	20.XII	36± 7
4888	24°04′ »	71°17′ »	22.XII	31± 8
4890	30°00′ »	71°22′ »	24.XII	18± 9
4892	36°06′ «	71°18′ »	26.XII	8± 3
4893	39°24′ »	71°19′ »	27.XII	19± 4
4895	31°50′ »	80°35′ »	29.XII	23± 6
4898	24°44′ »	83°03′ »	31.XII	10± 5
			1961 г.	
4911	1°57′ ю.	83°03′ »	10.I	33± 5
4921	4°22′ с.	83°05′ »	24.I	14± 4
4926	13°17′ »	83°03′ »	28.I	40± 9
4933	18°58′ »	87°00′ »	31.I	28± 6
4936	13°37′ »	86°53′ »	2.II	7± 3
4940	6°52′ »	87°02′ »	5.II	24± 4
4955	11°04′ »	92°02′ »	14.II	40± 6
4962	18°03′ »	90°54′ »	28.II	13± 3
4974	9°14′ »	93°40′ »	6.III	56±11
4984	00°56′ с.	92°35′ »	10.III	45± 9
4990	01°00′ ю.	96°56′ »	13.III	33± 6
5001	5°17′ »	100°37′ »	17.III	28± 5
5006	13°40′ »	104°49′ »	20.III	34± 9
5020	8°10′ »	104°39′ »	22.III	19± 3

Началу сбора проб предшествовало относительное затишье в испытании ядерного и термоядерного оружия. Последний атомный взрыв был произведен в Сахаре более чем за 6 месяцев до сбора первой пробы — 1.IV— 1960 г.[2]. К моменту второго взрыва, произведенного там же 27.XII — 1960 г.[3], был закончен сбор проб в западной части Индийского океана, до меридиана 80° в. д. (см. рисунок). Следовательно, по крайней мере первая половина результатов настоящего исследования свободна от влияния отдельных взрывов и поэтому отражает, очевидно, закономерности глобального загрязнения вод Индийского океана.

[2] «Правда» от 2.IX—1960 г.
[3] «Правда» от 31.XII—1960 г.

Известно, что распределение продуктов ядерных взрывов в атмосфере обнаруживает определенные закономерности, связанные с особенностями меридиональной циркуляции воздушных масс. В средних широтах обоих полушарий концентрация радиоактивных аэрозолей в приземном слое атмосферы максимальная; при этом уровень концентрации в южном полушарии ниже, чем в северном. В районе экватора наблюдается минимальная загрязненность воздуха [5]. Соответственно обнаруживается зональность в распределении радиоактивных продуктов и на поверхности суши [4]. Однако вследствие сдвига зон с наиболее благоприятными условиями для выпадения радиоактивных осадков широтный эффект здесь несколько сглажен.

Наблюдения за радиоактивностью атмосферы над Индийским океаном показали, что в период, предшествовавший нашим исследованиям, распределение радиоактивных аэрозолей над поверхностью океана было аналогичным распределению их над поверхностью суши. В обоих полушариях проступают характерные максимумы концентрации, а в районе экватора — глубокий минимум [1]. Что касается распределения Sr^{90} на поверхности океана, то, как видно по данным табл. 3 и рисунка, в 1960—1961 гг. здесь не обнаруживается какой-либо четкой зависимости концентрации Sr^{90} от географической широты в пределах исследованной области от 20° с. ш. до 40° ю. ш. Во всех районах собственно Индийского океана значения активности флуктуируют приблизительно около одной и той же величины, равной в среднем 25 распадам в минуту на 100 *л*.

Наиболее примечательным результатом является отсутствие понижения концентрации Sr^{90} в экваториальных водах. Это, естественно, можно рассматривать как следствие обмена вод экваториальной области Индийского океана с водами других его районов. Возможна, однако, и вторая причина: известно, что сумма годовых атмосферных осадков в приэкваториальных зонах океанов является наивысшей [2], поэтому низкое содержание радиоактивных аэрозолей над экватором может компенсироваться более интенсивным вымыванием их из атмосферы. Оценка роли обоих факторов требует дополнительных исследований.

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HIGH NITROGEN FIXATION RATES IN THE SARGASSO SEA AND THE ARABIAN SEA[1]

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ABSTRACT

Nitrogen fixation rates have been measured in the Sargasso Sea and the Arabian Sea using the N^{15} method. Heavy enrichments in N^{15} were found in a number of experiments in which the blue-green alga, *Trichodesmium*, was used for the experimental material.

INTRODUCTION

In a previous communication (Dugdale, Menzel, and Ryther 1961), we reported the results of an experiment in which low nitrogen fixation rates associated with the blue-green alga, *Trichodesmium*, were measured using the N^{15} method. We have recently obtained confirmation of large-scale nitrogen fixation in the Sargasso Sea, where the original experiment was carried out, and in the Arabian Sea.

METHODS

The N^{15} method for detecting nitrogen fixation has been adapted by Neess et al. (1962) to the measurement of fixation rates in aquatic communities. The following procedure is carried out after placing water containing the desired organisms in a 1-liter flask having a standard taper joint at the neck and into which a specially designed gas flushing unit is fitted: 1) Atmospheric N_2 (as well as other gases) is flushed from the water with a mixture of 80% He and 20% O_2 at a pressure of 0.8 atm; 2) 0.2 atm N_2 enriched to 95% N^{15} is added to the flask and equilibrated with the aqueous phase by shaking; 3) the sample is incubated in the flask under the conditions selected for the experiment; 4) the particulate fraction is captured on a glass filter (Hurlburt 984H) and converted to molecular nitrogen by a Dumas combustion (Dugdale and Barsdate 1964); 5) the N^{15}/N^{14} ratio of the resulting N_2 is determined with a mass spectrometer, the ratio converted to atom per cent N^{15}, and the enrichment over the normal atom per cent N^{15} of the organic material calculated.

Isotope ratios were measured with either a Consolidated-Nier 21-201 magnetic mass spectrometer or with a Bendix 17-210 time-of-flight mass spectrometer. The atom per cent N^{15} values in Table 2 that have two significant figures to the right of the decimal point were obtained with the time-of-flight spectrometer. All other measurements were made with the magnetic spectrometer. The atom per cent excess N^{15} associated with each flask has been calculated by subtracting the control (normal atom per cent N^{15} of *Trichodesmium*) or by subtracting the average of the five Bermuda controls (0.349) given in Table 1.

RESULTS

Results for the Sargasso Sea nitrogen fixation experiments conducted at Bermuda are given in Table 1. Material for these experiments was collected about 4 km from Bermuda by towing a No. 8 or No. 20 plankton net at the surface. Upon return to the laboratory, individual colonies of

[1] Contribution No. 3 from the Institute of Marine Science and No. 1510 from the Woods Hole Oceanographic Institution. This research was supported by National Science Foundation Grant GB-24 and by the United States Biological Program of the International Indian Ocean Expedition. We wish to thank Dr. F. A. Richards, Department of Oceanography, University of Washington, for the Consolidated-Nier mass spectrometer used in these studies.

TABLE 1. *Sargasso Sea fixation results*

Date	Sample	Light	Length of incubation (hr)	Atom % N^{15}	Atom % N^{15} excess
4 Sept 1962	Control	—	—	0.348	—
	Flask 1	Artificial light	13	0.350	0.002
11 Sept 1962	Control	—	—	0.348	—
	Flask 1	Artificial light	18	0.349	0.001
	Flask 2	Artificial light	24	0.356	0.008
20 Sept 1962	Control	—	—	0.350	—
	Flask 1	Direct sunlight	8	0.518	0.169
	Flask 2	Direct sunlight	8	0.566	0.217
1 Oct 1962	Flask 1	Dark	24	0.353	0.004
	Flask 2	Artificial light	24	0.358	0.009
12 Oct 1962	Control	—	—	0.350	—
	Flask 1	50% of incident light	4.5	0.399	0.049
	Flask 2	80% of incident light	4.5	0.377	0.027
	Flask 3	100% of incident light	4.5	0.384	0.034
19 Oct 1962	Control	—	—	0.351	—
	Flask 1	5 hr direct sunlight, 15 hr artificial light	20	0.559	0.208
	Flask 2	5 hr direct sunlight, 15 hr artificial light	20	0.447	0.096

Trichodesmium were separated from the other plankton and placed in fixation flasks containing Millipore®[2] (0.45 μ)-filtered surface seawater. After treatment with N_2^{15}, the flasks were incubated for various lengths of time either in artificial light (16,000 lux) at 20C or in a seawater-cooled box exposed to direct sunlight. The box was fitted with neutral density filters for the 12 October 1962 experiment.

In some experiments (20 September 1962, 19 October 1962), the rate of fixation was about 20 times the highest rate reported in the earlier communication (Dugdale et al. 1961). In the remainder, fixation was low or undetectable. The highest rates observed here are comparable to fixation rates observed in lakes during periods of nitrogen-fixing blooms (Dugdale and Dugdale 1962). The 19 October 1962 experiment, in which 1 μg-at. NH_4^+-N/liter was added to flask 2, suggests that NH_4^+-N inhibits fixation. That a certain degree of variability occurs within a given experiment may be seen in the 20 September 1962 results, in which like treated flasks showed a difference in rate of fixation. Some of the experimental conditions that may affect fixation will be discussed later.

The results of nitrogen fixation measurements made during Cruise 4A of the U.S. Biological Ship for the International Indian Ocean Expedition, the *RV Anton Bruun*, are summarized in Table 2. The majority of the stations is located in the northern Arabian Sea; Stations 174 and 176 lie farther south along the coast of Saudi Arabia. The enrichments in N^{15} observed are similar to those shown in Table 1, the value for the 4-hr experiment on Station 188, 4.65 atom per cent excess, being the highest measured in the sea to date.

Colonies of *Trichodesmium* were used for experimental material in all the experiments except at Station 183, where a large quantity of *Rhizosolenia* was collected from the surface, and at Station 194, where a heavy bloom of *Noctiluca* occurred. Two distinct forms of *Trichodesmium* were observed in the No. 20 mesh nets normally towed for 10 min or less at 1, 10, 20, 30, and 40 m, one occurring as green bundles of filaments and the other as larger brown spherical clumps of filaments corresponding to the form we have worked with in the

[2] Registered trademark, Millipore Filter Corporation, Bedford, Massachusetts.

TABLE 2. *Indian Ocean fixation results*

Date	Station	Latitude	Longitude	Length of incubation (hr)	Atom % N^{15}	Atom % N^{15} excess
17 Oct 1963	174	16°27′ N	54°40′ E	32	0.719	0.370
18 Oct 1963	176	16°28′ N	57°09′ E	5.5	0.387	0.038
28 Oct 1963	183	23°42′ N	66°21′ E	9	0.366	0.017
29 Oct 1963	184	22°34′ N	65°50′ E	7	1.024	0.675
31 Oct 1963	188	23°21′ N	64°52′ E	4	5.00	4.65
1 Nov 1963	190	24°47′ N	61°39′ E			
	Flask *a*	10 colonies		5	0.81	0.46
	Flask *b*	Numerous colonies		5	0.47	0.12
1 Nov 1963	191	23°57′ N	60°58′ E	10	0.352	0.003
1 Nov 1963	192	23°08′ N	60°36′ E	30	0.902	0.553
3 Nov 1963	194	22°22′ N	60°06′ E	28	0.354	0.005
3 Nov 1963	195	21°32′ N	60°40′ E	38	0.354	0.005

Sargasso Sea. At six stations, the former type was observed at virtually all the depths mentioned above; the latter appeared and became abundant in the collections at Stations 191, 192, 193, and 195, all in northwestern Arabian Sea near the Gulf of Oman.

When the negative results with *Rhizosolenia* (Station 183) and *Noctiluca* (Station 194) are removed from consideration, it becomes clear that high enrichments occurred in a large proportion of the *Trichodesmium* experiments, that is, in five out of eight possibilities. Cloudiness, suggesting the presence of bacteria, developed quickly in the incubation flasks from Stations 191 and 195, a possible explanation for the failure to observe nitrogen fixation at these stations, which showed heavy concentrations of the brown form of *Trichodesmium*. Strong fixation occurred in experiments using the brown form exclusively (Station 192) and in those using the "green bundles" form (Station 190).

DISCUSSION

The variability observed in these measurements (*see* below) precludes certain levels of speculation regarding the significance of these data. However, we consider it a virtual certainty that the large-scale blooms of *Trichodesmium* reported from tropical oceanic regions are indeed nitrogen-fixing blooms analogous to those observed in lakes associated with several species of *Anabaena* by Dugdale and Dugdale (1962) and by Goering (1962).

Certain reservations must be made; for example, our experiments do not prove that *Trichodesmium* is itself able to fix nitrogen. However, this is unimportant from the point of view of the ecologist, since the ability to fix nitrogen has been clearly shown to lie with the *Trichodesmium* colonies (that is, the alga and any associated bacteria or fungi).

Up to this point we have not been concerned with the species composition of the experimental material beyond noting obvious macroscopic differences. Three species, *T. erythraeum* Ehrenb., *T. hildebrantii* Gom., and *T. thiebautii* Gom., are reported for the Indian Ocean by Desikachary (1959), and McLeod, Curby, and Bobblis (1962) suggested that two or more species may have been present in their collections at Bermuda.

The data obtained so far have been characterized by a disturbing lack of consistency, that is, experiments at Bermuda separated by only a few days give highly divergent results, and the same is true for the cruise data. We suspect that a large portion of this discrepancy may lie in the experimental method. Now that we have obtained N^{15} enrichments of a high order, replication and suitable experimental design should yield insight into the problem. McLeod et al. (1962) report a twentyfold variation in the rate of photosynthesis from cells of a given collection of *Trichodesmium*. In some collections, cells were present that

would not photosynthesize, and other cells would do so only after a period of adaptation to light. Therefore, some of the variability from day to day and within any single experiment may be the result of differences in the physiological condition of the colonies. Menzel (1962) has also shown an autoinhibition of photosynthesis by *Trichodesmium* at Bermuda; at Station 190 flask *a* contained only 10 colonies and fixed nitrogen at double the rate of flask *b*, that contained numerous colonies. The organisms may also be sensitive to other features of the technique such as the length of sparging and composition of the sparging gas.

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The distribution of dissolved organic carbon in the Western Indian Ocean*

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Abstract—The concentration of dissolved organic carbon between 0 and 2000 m depth was measured along a section from 20°S to 20°N in the Western Indian Ocean. No apparent correlation existed between primary production and the level of dissolved carbon in the euphotic zone. Deep water masses were characterized by temperature-salinity relationships and by the concentration of carbon. Calculations for the mixing of these water masses of differing origin on the basis of salinity, corresponded with similar calculations based on carbon. Assuming 90% conversion of total particulate organic matter to carbon dioxide by grazing organisms a minimum of 260 years is required to produce the amount of organic carbon present in the Arabian Sea. The conclusion is reached that carbon in solution and in particulate form in the ocean is extremely stable and subject to limited change by biological action.

INTRODUCTION

THE CYCLE of organic matter at the surface of the oceans involves the synthesis of carbon-containing compounds by micro-organisms and the return to the environment of these compounds by respiration, excretion, and decomposition. The organic compounds may dissolve and subsequently be utilized by heterotrophic organisms, or may be impounded as a refractory residual which may be indefinitely lost to the biochemical cycle. The differential decomposition of organic matter is selective and must ultimately induce changes in the relative abundance of particular compounds (SKOPINSTEV, 1959).

Although data on the distribution of dissolved organic carbon are limited to only nine studies, several of which are limited to single stations (reviewed by DUURSMA, 1961) it is obvious that concentrations in deep water may be as high as those recorded from the surface, and that there is a remarkable similarity in concentration over the oceans as a whole. The concentration of carbon in deep water depends upon the past history of the water mass, on the settling of organic particulate matter from the surface and its dissolution, and on factors enhancing or retarding decomposition by bacterial activity. On the other hand, concentrations in the euphotic layers where organic matter is synthesized, are commonly thought to be dependent largely upon the rate of biological production and upon the mechanisms controlling organic decomposition. If this is the case, one may ask why the amount of dissolved organic carbon (D.O.C.), which ranges from 0·5 to 3·0 mgC/L in the surface waters of the open sea does not vary more. Since seasonally primary production may vary by two

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orders of magnitude, what determines the upper and lower limits of concentration of D.O.C., and how, if at all, does surface production control the concentration of carbon in the deep sea ?

OBSERVATIONS AND METHODS

The present study of the distribution of dissolved organic carbon in the western Indian Ocean is based on data collected during the fourth cruise of the *Anton Bruun* in October–November, 1963. The general distribution and factors controlling the concentration of D.O.C. in the deep water are analyzed and the relation between plant production and D.O.C. examined in surface waters.

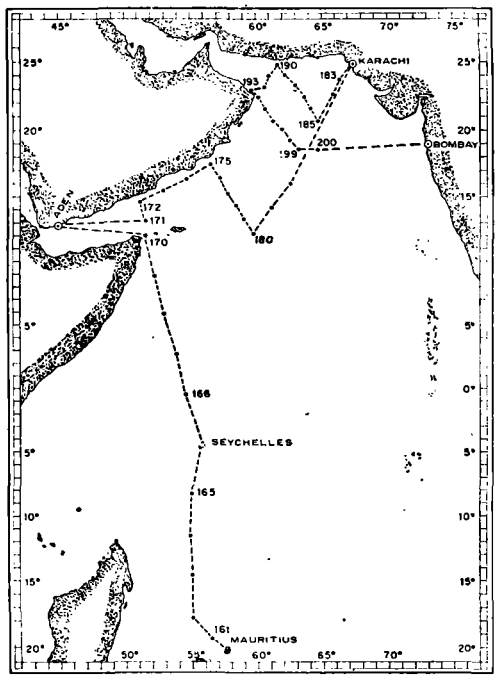


Fig. 1. Track of the *Anton Bruun* (Cruise 4A) showing station locations.

Dissolved and particulate carbon were measured by wet and high temperature dry combustion respectively, and the carbon dioxide evolved measured by infra-red absorption (MENZEL and VACCARO, 1964). Primary production was measured by the carbon–14 method of STEEMANN NIELSEN (1952) using a simulated *in situ* incubator cooled with running surface sea water. Salinity was determined with an inductance salinometer. The data on which this study is based and ancillary data will be deposited with the National Oceanographic Data Center, Washington, D.C.

RESULTS

The distribution of carbon in deep water

The location of stations occupied in this study are shown in Fig. 1. In Fig. 2 typical T–S diagrams for the water masses of the Indian Ocean (DEFANT, 1961)

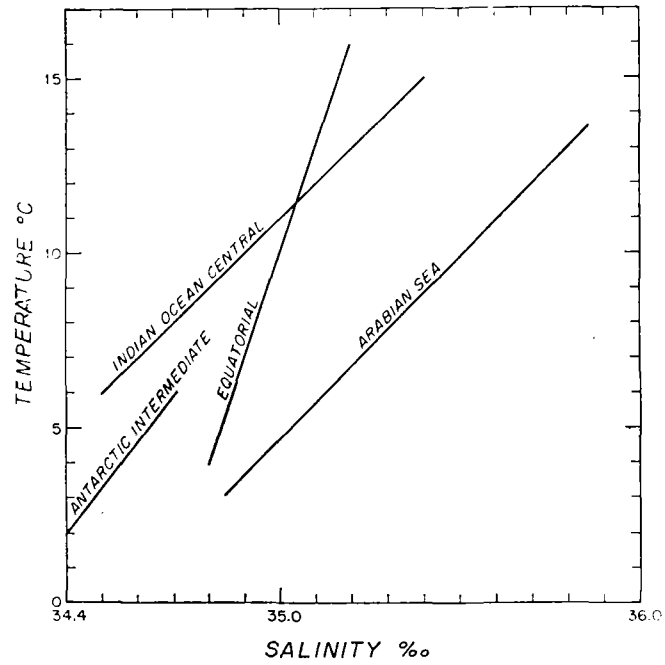


Fig. 2. T–S diagrams of water masses occurring in the Western Indian Ocean. Indian Ocean Central, Equatorial and Antarctic Intermediate Water from Defant (1961). Arabian Sea Water from data of *Anton Bruun* Station 184.

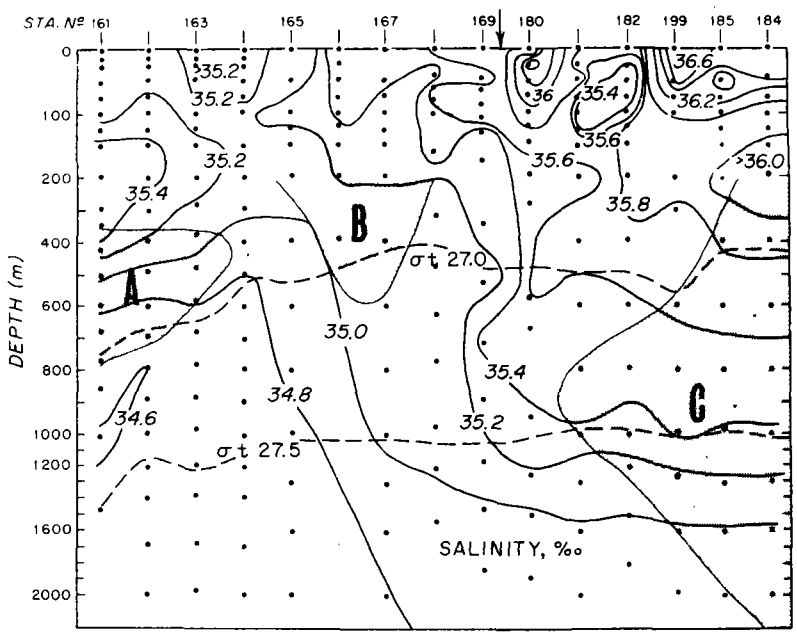


Fig. 3. Salinity profile of the Western Indian Ocean (*Anton Bruun* Stations 161–169 and 180–184) showing the location of unattenuated Indian Ocean Central (A), Equatorial (B) and Arabian Sea Water (C) and the depth of σ_t 27·0 and 27·5.

are illustrated along with an idealized diagram from Sta. 184 (Arabian Sea) at the northern limit of the section. At individual stations isolated depths were compared to these diagrams and the regions where " unadulterated " water occured below 200 m delineated (Fig. 3). A small residue of Antarctic Intermediate Water was apparent at Stations 161–162 ($S = 34{\cdot}6‰$) but the entire water column at all other stations may be characterized as consisting of Indian Ocean Central Water (Stas. 161–163; A) Equatorial Water (Stas. 166–167; B), and Arabian Sea Water (Stas. 181–184; C), or mixtures of the same. It is likely that the bulk of the water in the Arabian Sea is of Red Sea origin but since there is no basis for suggesting the presence of undiluted Red Sea water the designation Arabian Sea Water was chosen and defines the northern boundary limit.

The mixing influences of these three water masses (below 200 m) may be diagramatically illustrated by increasing salinity between the southern and northern limits (Fig. 3). Along σ_t surface 27·0 there are varying mixtures of all three masses while along σ_t 27·5 the influence of Equatorial Water is not felt and it is likely that mixtures of Arabian Sea Water and Indian Ocean Central Water alone control the T–S relationships. This is not surprising since CLOWES and DEACON (1935) have detected water of " Red Sea " origin at depths of 1200 m as far as 30°S.

The distribution of D.O.C. is correlated with salinity, decreasing in the south-to-north direction at depths below 200 m implying that organic carbon may have the characteristic of a conservative property. The three masses may be characterized as follows : Indian Ocean Central Water, 1·5–2·0 mgC/L; Equatorial Water, 0·6–0·8 mgC/L; and Arabian Sea Water, 0·2–0·4 mgC/L. If the concentration of D.O.C. is in fact conservative, one would expect that dilution effects measured by changing D.O.C. should correspond to those indicated by salinity. In order to test this contention, two σ_t surfaces (27·0 and 27·5) were selected and the assumption made that all mixing along these surfaces occurs only in a horizontal direction.

The dilution effects of two opposing water masses with parameters X_1 and X_2 were calculated according to the formula :

$$D = \left(\frac{X_2 - x_0}{X_2 - X_1}\right) 100$$

where D is percent of the given water mass with parameter X_1 and x_0 is the observed parameter at an intermediate station. The mixing effects calculated in this way from salinity and carbon are shown graphically in Fig. 5a and 5b. Considering the cumulative errors induced by necessary extrapolations between values to obtain the salinity and carbon concentration at a given σ_t level, the agreement is by and large rather remarkable.

As stated above three water masses were evident along σ_t 27·0 and in Fig. 5a the Equatorial Water has been selected as a reference point. At Stas. 166 and 167 100% of the water was of equatorial origin while at station 161 100% of the water was of Indian Ocean Central origin. Similarly, at Stas. 184 and 185 100% of the water was of Arabian Sea origin. Along σ_t 27·5 only two water masses were apparent and the reference point (100%) indicates the location of Arabian Sea Water. Examination of Fig. 2 will show at what point the σ_t surfaces enter unadulaterated water as characterized by T–S relationships.

The distribution of carbon in surface waters

In order to eliminate possible local influences in normal salinity and D.O.C. structures, the above discussion has been limited to depths below 200 m. Anomalies in salinity structure even in surface waters, however, also reflect corresponding anomalies in the concentration of D.O.C. (Figs. 3 and 4). The most marked deviations in both parameters are evidenced at 100–200 m at Stas. 184 and 185, at the surface at Sta. 199, and at 10–100 m at Stas. 180 and 181.

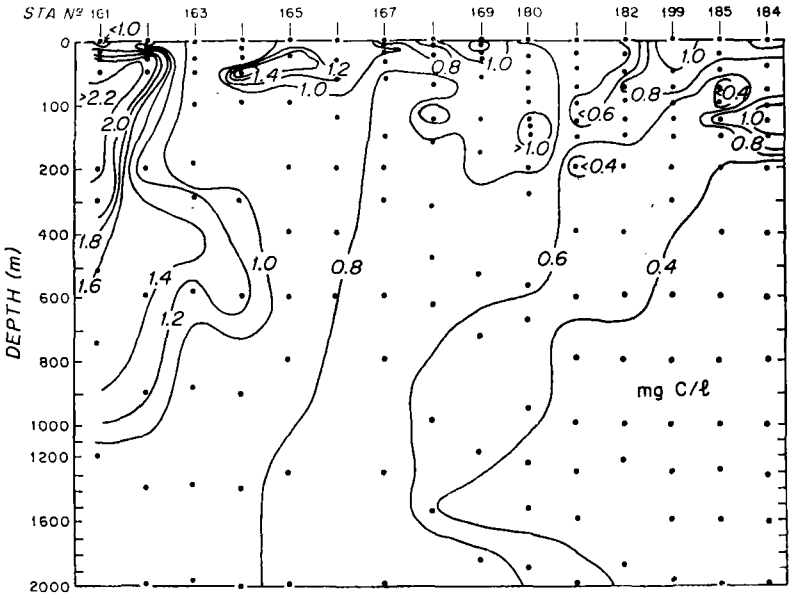


Fig. 4. Dissolved organic carbon profile of the Western Indian Ocean.

The conclusion drawn from these data is that variations in the concentration of D.O.C. at all depths sampled in the Indian Ocean are controlled by hydrodynamic features which are reflected by salinity distribution. If this is so, it would suggest that carbon in solution is not rapidly influenced by biological activity. This conclusion necessitates the assumption that the level of D.O.C. in the surface of the oceans is not directly related to primary production. Evidence to support this contention is presented in Table 1. While the average amount of carbon in the euphotic zone varied only by a factor of two the corresponding rate of primary production integrated over the euphotic zone varied by over two orders of magnitude, with no obvious systematic correlation with D.O.C.

The vertical distribution of particulate and dissolved organic carbon at Stas. 196 and 198 demonstrate an essentially constant relationship from the surface to the bottom of the Arabian Sea with higher values occurring at the surface (Table 2). These two fractions occur in an average ratio of approximately 1 : 10 over the entire water column.

Table 1. The relation between primary production and dissolved organic carbon in the euphotic zone of the western Indian Ocean

Station	*Primary production* gC/m²/day	*D.O.C.* (Av. mg/L)	*Station*	*Primary production* gC/m²/day	*D.O.C.* (Av. mg/L)
161	0·04	1·76	181	1·06	0·65
162	0·15	1·76	199	1·09	0·88
169	0·28	1·23	187	1·40	0·68
180	0·46	0·85	196	1·62	0·73
164	0·49	1·20	190	1·65	0·68
168	0·56	0·86	193	1·69	0·59
182	0·60	0·68	197	1·80	0·84
165	0·70	1·20	198	1·81	0·98
167	0·71	0·86	188	1·82	0·78
185	0·73	0·60	189	2·04	0·62
184	0·86	0·82	186	2·05	0·89
166	0·97	1·01	191	2·28	0·56
163	0·97	0·82	195	5·28	0·81
			194	6·82	0·51

Table 2. The vertical distribution of particulate and dissolved organic carbon in the Arabian Sea

	Station 196			*Station* 198	
Depth (m)	*Part. C* (g/m³)	*D.O.C.* (g/m³)	*Depth* (m)	*Part. C* (g/m³)	*D.O.C.* (g/m³)
1	0·157	1·00	1	0·057	1·48
6	0·166	1·10	13	0·068	—
12	0·155	0·92	20	0·073	—
19	0·204	0·96	26	0·079	—
29	0·114	1·04	30	0·064	0·90
39	0·086	0·74	40	0·084	0·76
50	0·040	0·74	50	0·048	1·04
75	0·025	0·84	75	0·040	0·72
100	0·026	0·76	100	0·041	0·72
150	0·016	0·82	150	0·043	—
200	0·018	0·78	200	0·026	—
250	0·035	0·50	397	0·021	0·22
300	0·027	0·46	596	0·022	0·46
400	0·017	0·64	795	0·030	0·54
500	0·043	—	916	0·051	0·54
600	0·054	0·60	1201	—	0·36
800	0·021	0·20	1492	0·040	0·20
1000	0·031	0·36	1892	0·031	0·48
1300	0·049	0·28	2291	—	0·30
1600	0·026	0·36	2690	0·032	0·36
2000	0·035	0·34	3090	—	0·36
2400	0·045	0·36	3390	0·037	—
2800	0·053	0·34			
3200	0·030	0·36			
Total (gC/m²)	123	1275		118	1353

DISCUSSION

An integration of the amount of carbon occurring at any one time in the Arabian Sea indicates a total concentration of approximately 120 g particulate and 1300 g dissolved organic carbon under a square meter of surface (Table 2). Assuming that

100% of the surface production is reflected either in the particulate or dissolved fraction, and further assuming a mean annual production of 50 gC/m²/year (RYTHER, 1959), the preceeding calculations would indicate an accumulation of 2–3 years of particulate and 26 years of dissolved carbon in the water column.

Obviously the assumption that 100% of the organic matter synthesized at the surface remains as organic carbon cannot be granted. Considerable fractions of the annual plant production are consumed by zooplankton. This fraction may approach 100% in the Sargasso Sea (MENZEL and RYTHER, 1961). If approximately 10%

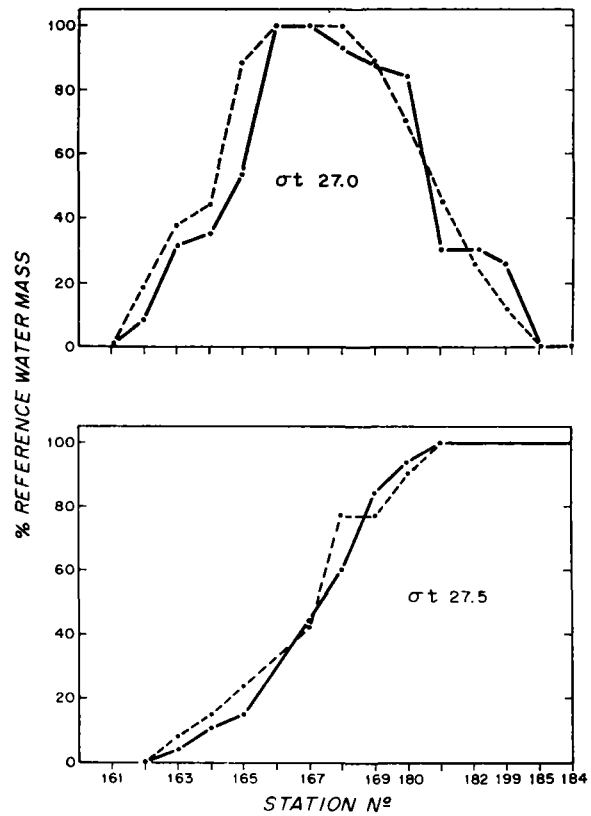


Fig. 5. Water mass dilution calculations based on salinity (solid lines) and dissolved organic carbon (dashed lines) at specified σt levels in the Western Indian Ocean. See text for explanation.

of the phytoplankton eaten are converted to organic matter and the remaining 90% respired as carbon dioxide, a single step in the food chain would increase the time required to produce 1300 g of dissolved carbon to 260 years. Additional corrections would have to be allowed for the conversion of primary to secondary consumers, and for respiration by bacteria at any stage in these conversions. Thus dissolved organic matter in sea water must be the result of an extremely long process of accumulation. Considering the oceans as a whole this phenomenon may be even more marked since values for D.O.C. in the deep water of the Atlantic and Pacific Oceans are from 2 to 10 times higher than in the deep water of the Arabian Sea (reviewed by

DUURSMA, 1961). Furthermore, present indications are that the annual rate of primary production in the Atlantic and Pacific are considerably lower than that in the Arabian sea.

On the basis of particulate carbon only, integrated values in the Tasman Sea of 400 g/m² indicate an excess of 10–20 times the annual production (DAL PONT and NEWELL, 1963) while values of 3–6 kg dry suspended matter from the Indian Ocean (LISITSIN, 1960), indicate an accumulation of 30–60 years (assuming 50% carbon). One explanation for relatively high D.O.C. concentrations in deep water may be that particles falling through a water column dissolve and continually increase the level of presumably unstable D.O.C. until an equilibrium is reached between decomposition and accumulation. This has been suggested and the hypothesis advanced that " old " water, being exposed to detrital rain for a longer period, contains more dissolved organic carbon than " young " water (DUURSMA, 1961). That such a critical equilibrium could be maintained over a long period of time seems rather unrealistic, since, in the data presented earlier, carbon appears to maintain its integrity as well as does salinity. It seems more likely that D.O.C. occurring in deep water is the result of production at the time the water occupied a surface location, and that the great bulk of particulate matter entering subsurface waters is in fact insoluble. If this is so the bacterial decomposition of unstable and soluble carbon compounds would be principally a surface phenomenon (RILEY, 1951). If subject to heterotrophic decomposition below the surface, each particle may be attacked by bacteria and the bulk of the carbon converted directly to carbon dioxide without ever appearing in solution as organic matter. Evidence for this contention is supplied by the fact that maxima and minima of particulate matter have been shown to correspond to the stratification of water masses in vertical section suggesting that particles remain in suspension for considerable lengths of time (JERLOV, 1959; DAL PONT and NEWELL, 1963). These particles may be derived from plankton production at the source of origin of the water, or may sink from the surface and stratify in density gradients. In addition, bottom sediments contain largely insoluble forms of carbon (VALLENTYNE, 1960). The presence of quantities of photosynthetic pigments in deep water and bottom sediments in the Indian Ocean (KUTYURIN and LISITSIN, 1961) does not contradict this supposition since these pigments are water insoluble and stable in the dark at low temperature.

One may also question the apparant lack of correlation between primary production and D.O.C. since excretion and decomposition are integral parts of the photosynthetic cycle. DUURSMA (1963) has indeed shown seasonal cycles in D.O.C. which correspond to seasonal cycles of primary production in the north-eastern Atlantic. DUURSMA further estimated the annual increment of D.O.C. in surface waters and obtained a value (52 gC/m²/year) markedly similar to gross production in the same general area (STEELE, 1958). As he states, it is difficult to accept the implication that all carbon produced could eventually appear as dissolved matter, with nothing decomposed or consumed and respired by zooplankton or bacteria. In order for DUURSMA's (1963) calculations to be meaningful, however, one must grant the assumption that the parcel of surface water studied was not enriched or diluted with respect to D.O.C. horizontally and/or vertically with other water masses. It is likely, however, that the rate with which organic matter is recycled in tropical environments is very rapid due to high temperature and higher levels of bacterial

activity. In temperate waters (such as DUURSMA studied) the rate of this reaction may be considerably slower and the relation between production and accumulation of by-products would as a result be more obvious.

It has been shown (FOGG, 1958; HELLEBUST, in prep.) that significant quantities (2–80%) of photosynthesized carbon may be excreted as extracellular products and some D.O.C. must originate from this source. It is conceivable, however, that in nature the bulk of these compounds are unstable and easily attacked, entering solution only briefly before being oxidized to the inorganic phase. Thus the small amount of dissolved carbon which remains as a residual is essentially refractory and may be decomposed only by long term processes (SKOPINTSEV, 1959). This hypothesis is supported by the fact that D.O.C. may be used to characterize sub-surface and deep water masses and that there appears to be no direct correlation between primary production and dissolved carbon in these data.

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On the production, composition, and distribution of organic matter in the Western Arabian Sea*

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INTRODUCTION

DURING the period September–November, 1963, the R.V. *Anton Bruun* worked in the Western Arabian Sea, between Karachi and the Gulf of Aden, as a part of the U.S. Program in Biology, International Indian Ocean Expedition (IIOE). Similar cruises by other ships have been or will be made in the same area during the IIOE. Not until the results of these several surveys are compiled and compared can there be hope of understanding the complex circulation of the Arabian Sea on a seasonal basis and in relation to the reversing monsoon wind system.

The following account will describe conditions in a limited area and at just one time of year, the calm interval in autumn between the Southwest and Northeast Monsoons. Its purpose is to illustrate the unusual physical and chemical environment in the Arabian Sea and the extraordinary levels of primary productivity which result. A second objective is to present new data relating to the authors' interests in the relationship between living and dead organic matter in the ocean, a study which was facilitated by the extreme range of biological productivity which was observed in the Arabian Sea and the waters immediately to its south.

Cruise 4A of the *Anton Bruun* departed Mauritius on September 25, 1963, and occupied 10 stations (161–170) between Mauritius and Cape Guardafui, Somalia, before reaching the Arabian Sea. Data from these 10 stations are included in the results to be discussed herein. In the Arabian Sea itself, 30 stations were occupied which together comprised a NE section along the central axis of the sea parallel to the Arabian coast, three sections from the central basin into and normal to the Arabian coast, and short sections across the Gulf of Oman and the Gulf of Aden (Fig. 1).

At all of the 40 stations referred to above Nansen bottle casts were made, usually to the bottom but in some cases to only 2000 m, and the following variables were measured : temperature, salinity, dissolved oxygen, phosphate, nitrite, nitrate, silicate, dissolved and particulate iron, and dissolved organic carbon. Also at each station samples were taken with a large-volume plastic sampler from 5–8 depths within the euphotic zone for subsequent determination of particulate carbon, nitrogen, and phosphorus, phytoplankton pigments, and carbon assimilation by the C^{14} technique. Samples for the latter were taken from the depths to which

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100, 50, 25, 10 and 1 per cent of the incident light penetrated. The uptake of C^{14} was measured for 24 hr on deck in incubators fitted with neutral density screens, thereby exposing the samples to the same fraction of incident sunlight to which they had been subjected *in situ*. In a second series of samples C^{14}-uptake was measured for 4 hr under artificial illumination of approximately 1000 foot candles.

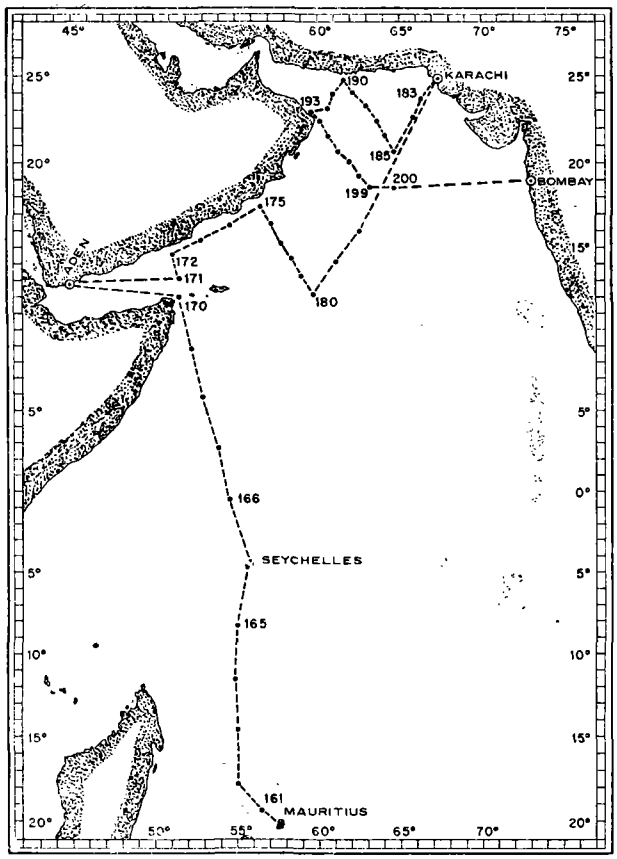


Fig. 1. Track of *Anton Bruun* Cruise 4A showing station positions.

All data from the cruise will be available from the National Oceanographic Data Center, Washington, D.C. The present discussion will be limited to consideration of certain aspects of the temperature, phosphate, oxygen, chlorophyll-*a*, primary productivity, and particulate organic carbon‡. The concentration and distribution of dissolved organic carbon has been described elsewhere (MENZEL, 1964).

NUTRIENTS AND PRODUCTIVITY

The physical structure and chemical characteristics of the surface layers of the Arabian Sea may be illustrated by means of a profile showing the distribution of

‡References to methods used :
Phosphate (MURPHY and RILEY 1962); chlorophyll-*a* (RICHARDS with THOMPSON, 1952 and CREITZ and RICHARDS, 1955, substituting Whatman GF/C glass filters for Millipore® filters); primary productivity (STEEMANN NIELSEN, 1952) with minor modifications; particulate carbon (MENZEL and VACCARO, 1964); oxygen (Winkler titration with biniodate standardization).

properties along a line consisting of five stations in the central basin roughly 100 miles apart and extending in a SW–NE line towards Karachi. For contrast, a similar profile is shown for the North Atlantic (Sargasso Sea) as constructed from five stations occupied by R.V. *Chain* in February, 1962, along the 65°E meridian between 34° and 26°N (Fig. 2). By this it is not meant to be implied that the Sargasso Sea represents some kind of " standard " or " normal " ocean, but the differences between the two regions will serve to emphasize the features of the Arabian Sea which are especially pertinent to the following discussion.

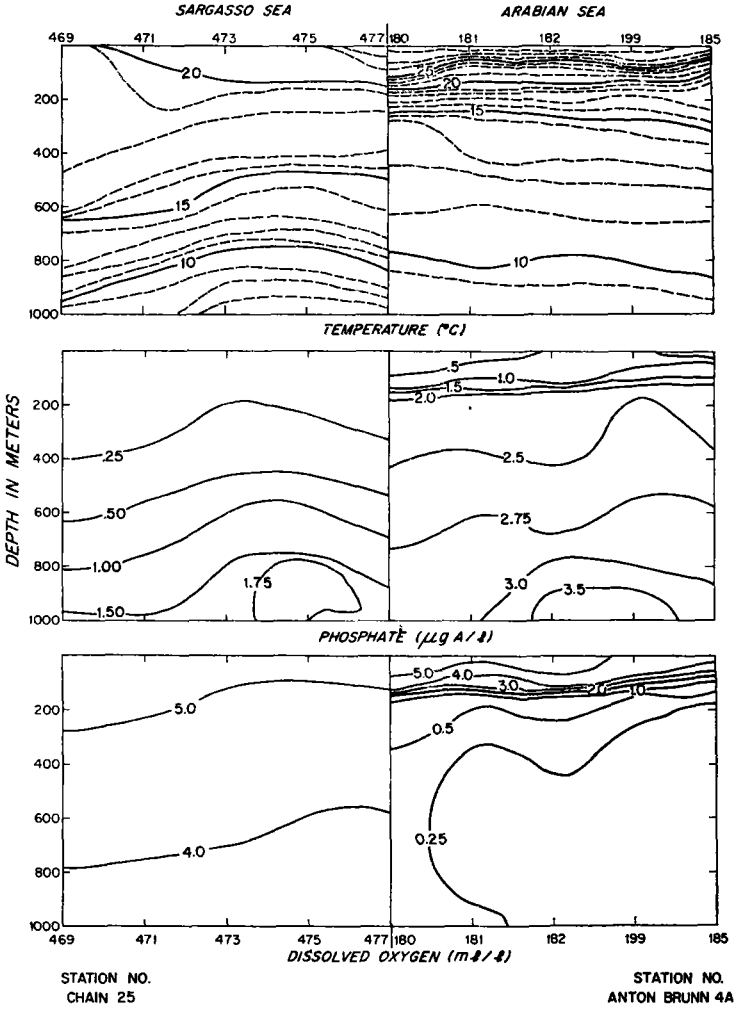


Fig. 2. Vertical distribution of temperature, phosphate, and dissolved oxygen for five stations each in the Sargasso Sea and Arabian Sea (see text for time and position of Sargasso Sea stations).

The Sargasso Sea is characterized by relatively weak thermal stratification in the region of the permanent thermocline, which extends approximately from 600 to 900 m. At the latitudes illustrated there are seasonal changes in the surface waters with the development of a summer thermocline in the upper 100 m. The

Arabian Sea, on the other hand, is permanently and strongly stratified near the surface with a gradient of 10–15°C in the upper 200 m. There is nothing comparable to the deep permanent thermocline of the North Atlantic.

Nutrient levels in the Arabian Sea increase sharply with depth beginning very near the surface, and fertile waters lie close to if not within the limits of the euphotic layer (50–100 m in the Central Arabian Sea). A comparable nutrient gradient in the Sargasso Sea is seen only within the deep, permanent thermocline, so that the euphotic zone in that region is underlaid by several hundreds of meters of impoverished water. In addition to this difference, the general level of nutrients in the Arabian Sea are appreciably higher than in the North Atlantic. Phosphate concentrations within the upper 200 m of the Arabian Sea exceed those found at any depth in the Sargasso Sea. Phosphate is used here merely as an index of nutrients in general. Nitrate and silicate, which were measured, and undoubtedly other non-conservative nutrient elements are distributed much the same as is inorganic phosphorus. For example the nitrate maximum at Stn. 182 (Arabian Sea) was 56·2 μgA/l as compared to 29·0 μgA/l at *Chain* Stn. 473 (Sargasso Sea). Roughly speaking, it could be said that nutrient concentrations in the Arabian Sea are about twice those in the North Atlantic.

Clearly these two factors, the high levels of nutrients and their proximity to the surface, set the stage for high biological productivity in the Arabian Sea. Any vertical pertubation, whether it be wind-induced upwelling, divergence at current boundaries, Langmuir-type circulation, internal waves, or simple wind mixing, that can break down, disrupt or shift upwards even slightly the barrier of thermal stratification will turn the potential productivity to reality. Just as clearly, it is the monsoons which provide the energy required for these dynamic processes. It is not within the scope of this paper to describe or illustrate the various ways in which these forces may operate in the Arabian Sea. Many if not all of those named above are probably important at different times and places. In all likelihood they are highly localized and irregular in both time and space. One of the most obvious characteristics of the plankton production in the Arabian Sea during the cruise of the *Anton Bruun* was its patchy distribution. Commonly, the ship would drift, while on station, through areas of extremely dense plankton blooms which might vary in size from a hundred yards or less to several miles in diameter, but which were often sharply delineated by extremely clear and unproductive water. To describe in general terms the productivity of such a region is clearly a problem.

The vertical distribution of dissolved oxygen further reflects the productivity of the Arabian Sea (Fig. 2). In contrast to the Sargasso Sea, where high levels of oxygen prevail to depths of 1000 m or more, the oxygen concentration in the Arabian Sea drops sharply immediately below the euphotic zone, in mirror image of the nutrient distribution. Concentrations below 1 ml/l were found as shallow as 100–200 m and only trace amounts were occasionally measured within the 500–1000-meter depth interval. No anoxic water was found either during Cruise 4A or earlier the same year (January 1963) when the *Anton Bruun* first arrived in the Indian Ocean and made the Arabian Sea crossing between Aden and Bombay. Scientists on the Soviet Vessel *Vityaz* did, however, report anoxic sulfide-containing water at mid-depths in the Arabian Sea during the fall of 1960 (IVANENKOV and ROZANOV, 1961).

The inverse relationship between high surface nutrient and productivity levels and low concentrations of dissolved oxygen in the underlying waters is a common aspect of fertile marine areas. Presumably, it results from the sinking of organic matter produced at the surface and its subsequent decomposition and oxidation below the euphotic zone. Most frequently this combination occurs in the upwelling regions along the west coasts of continents as in West Africa (HART and CURRIE, 1960), Peru (GUNTHER, 1936), and California (SVERDRUP and FLEMING, 1941). It is perhaps less common as far offshore as the central Arabian Sea and suggests that vertical turbulence with concomitant high productivity occurs throughout the entire region.

Probably the most wide-spread and predictable example of high productivity in the Arabian Sea is that associated with upwelling along the Somali and Arabian coasts. Even here, however, the factors causing the upwelling are complex and undoubtedly vary seasonally as well as locally. During the Southwest Monsoon

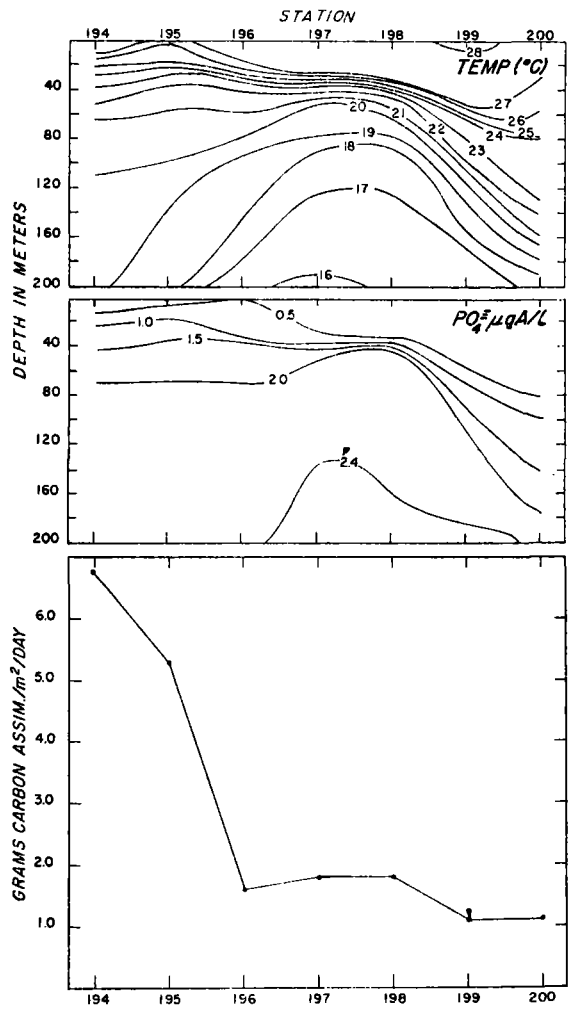


Fig. 3. Vertical distribution to 200 m of temperature and phosphate and integrated primary productivity along section formed by Stn. 194–200 (See, Fig. 1).

the strong and persistent winds which blow offshore or parallel to the coast may directly transport surface waters offshore with a resulting vertical replacement of deep, nutrient-laden water. These conditions were encountered by *Discovery* during the summer of 1963. In the preliminary report of that cruise (IIOE RRS. *Discovery* Cruise 1, the Royal Society, London; December 1963) profiles from offshore into the coast of Arabia showed a marked shoreward uptilting of isotherms and phosphate isopleths, the 18° isotherm in one case rising from 200 m at the offshore end of the section to the surface at the shoreward end.

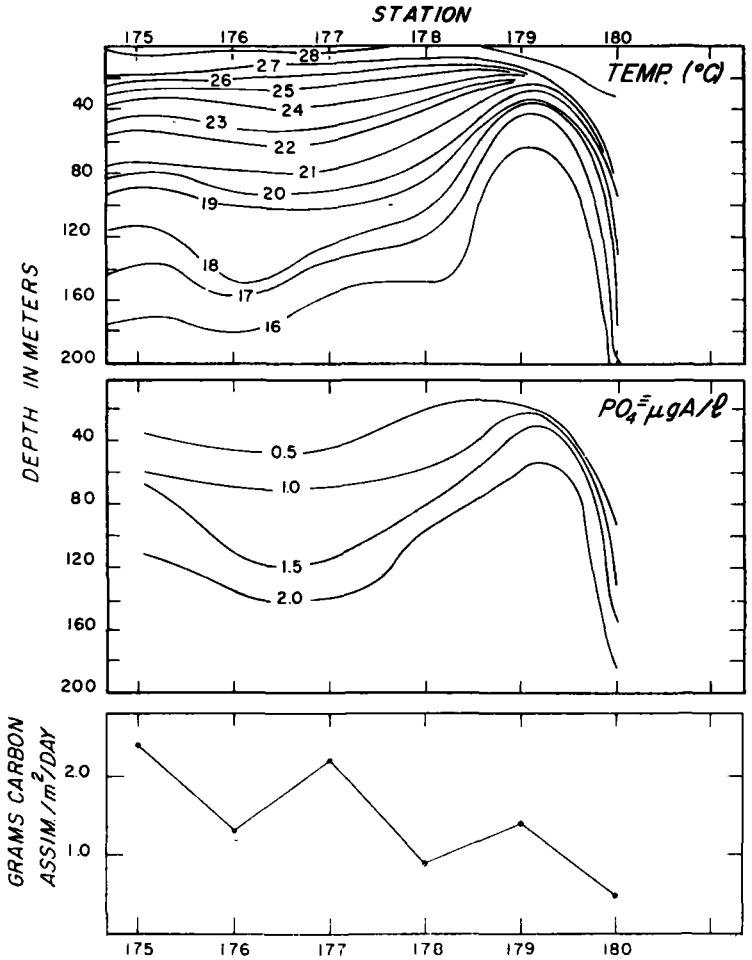


Fig. 4. Vertical distribution to 200 m of temperature and phosphate and integrated primary productivity along section formed by Stn. 175–180 (See Fig. 1).

In the same report the surface currents were described as a " predominantly north-eastward flow close to the coast." It cannot be certain whether these water movements were local phenomena produced *in situ* by the monsoon winds or whether they were part of a much broader surface circulation, perhaps involving the entire Arabian Sea. If the latter, the associated upwelling could be considered as geostrophic in nature rather than directly wind driven.

During October–November, on the other hand, the above question did not arise. This was the period between the Southwest and Northeast monsoons : the wind was calm and the sea, flat. What little breeze did develop usually blew from the north or east. There could be no possibility of the surface water being wind driven offshore from the Arabian coast under these circumstances. Yet strong surface currents could be detected by the ship's drift, northeasterly in direction at a distance of 100–200 mi offshore and southwesterly close along the Arabian coast from the Gulf of Oman to the Gulf of Aden. The " doming " of the isopleths at a distance of about 200 mi offshore could be intepreted as a divergence produced at the front between two opposing currents, though other explanations are possible.

Upwelling (using the term in its general sense) was unquestionably associated with these currents, as illustrated by the distribution of both temperature and phosphate along the two sections described by Stns. 194–200 and 175–180 respectively (Figs. 3 and 4). Off the Gulf of Oman (Stns. 194 and 195) rates of production were 5·7 and 6·4 g carbon/m²/day, values which are, to the authors' knowledge, higher than ever before reported for the ocean. While these rates were extraordinary and represent " bloom " conditions, the mean production rate for all 40 stations was 1·5 and for the 30 Arabian Sea stations 1·8 g carbon/m²/day, a level which is an order of magnitude greater than that of the oceans as a whole.

PRODUCTIVITY IN RELATION TO ORGANIC MATTER

Figure 5 shows the relationship between carbon assimilation (measured at 1000 foot candles) and particulate carbon at each of the five depths sampled within the euphotic zone and for all 40 stations occupied on Cruise 4A. The filled circles show the regression of carbon assimilation on total particulate organic carbon. The open circles represent the regression on particulate carbon associated with phytoplankton, or " living carbon," as it will be referred to henceforth. The latter has been calculated by multiplying values for chlorophyll-*a* by 35, the relationship between carbon and chlorophyll in healthy growing cultures of phytoplankton found at this laboratory (MENZEL, unpublished data). Actually, this is a minimal value, since ratios of 35–70 : 1 were measured in the algal cultures, this range being essentially in agreement with those reported by HARRIS and RILEY (1956), MCALLISTER *et al.* (1964) and others. Higher ratios (*ca.* 50 : 1) were also found from the regression of chlorophyll on particulate carbon in the North Atlantic (MENZEL and RYTHER, 1964). The use of the minimal ratio is based on the authors' hypothesis, advanced in the above mentioned publication, that higher ratios measured both in cultures and natural populations reflect the presence of dead cells or detritus as the case may be. The filled and open triangles are plots of carbon assimilation against total and living particulate carbon respectively for the very high values which, to enable them to be shown on the graph, have had both variables divided by ten.

The relationship between carbon assimilation and total particulate carbon is obviously non-linear and highly scattered suggesting the presence of large and variable quantities of dead or detrital carbon in the particulate matter. The open circles show rather less scatter and better linearity indicating that chlorophyll is probably a better index of living, photosynthetically-active carbon. The very high values (triangles) are particularly interesting in that the chlorophyll-based (living)

and the total particulate carbon values for the most part agree well with each other indicating that, when very large concentrations of particulate carbon were present, as in a dense plankton bloom, it was mostly in the form of healthy, living organisms.

Much of the scatter seen in Fig. 5 in the relationship between photosynthesis and living carbon can be reduced if values are used for carbon assimilation under natural illumination and if carbon assimilation, living carbon, and total particulate carbon each are integrated over the entire euphotic zone. This is shown in Fig. 6 for all 40 stations. In this figure the values for chlorophyll (used to calculate living

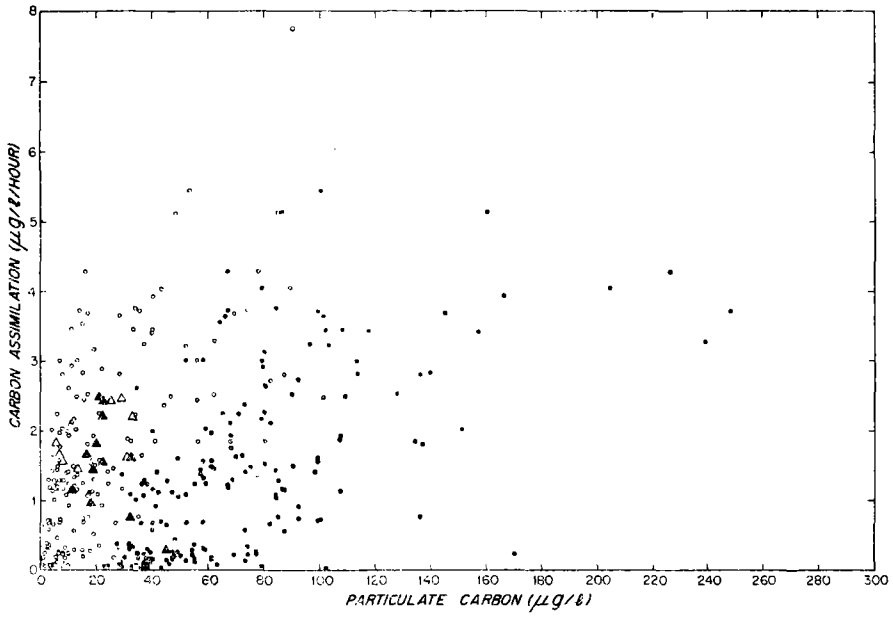


Fig. 5. The regression of carbon assimilation (at 1000 foot candles) on living carbon (open circles and triangles) and on total particulate carbon (filled circles and triangles) for all depths sampled at all Cruise 4A stations. (see text for further explanation).

carbon) have been adjusted by correcting for the amount of phaeophytin in the samples, using the method of YENTSCH and MENZEL (1963). This correction was applied only for values of chlorophyll above 0·1 g/m², since the change at lower concentrations was not great enough to be significant.

Again the total carbon values show no sign of a linear relationship to productivity, but now the regression of carbon assimilation on living carbon is clearly linear and the fit, with a few exceptions, is surprisingly good enough, in fact, to inspire some confidence that the estimation of living carbon by this means may be quite reasonable.

It follows that the difference between living and total carbon is equivalent to detrital carbon and these values have been plotted serially for each station in Fig. 7. The irregularity of the curves in this figure merely reflect the fact that the ship passed in and out of areas containing variable amounts of organic matter and may recall what was said earlier concerning the patchy distribution of life in the Arabian Sea. What is evident from this figure is that the living phytoplankton represents no more

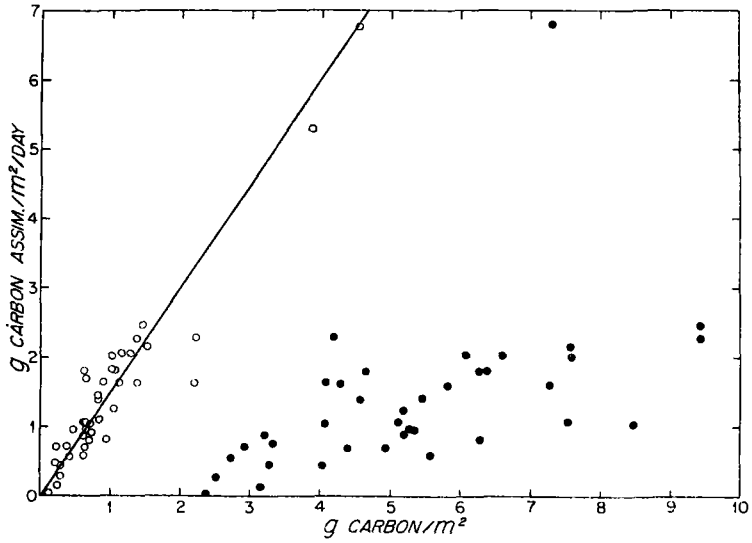


Fig. 6. The regression of carbon assimilation (natural light) on living carbon (open circles) and total particulate carbon (filled circles) for all Cruise 4A stations (see Fig. 1). Values are integrated for entire euphotic zone. Broken line is least squares fit for open circles.

than 10–20 per cent of the total organic matter, though the two appear to increase and decrease in phase. The exceptions to this were the few stations where phytoplankton blooms were encountered (e.g. Stns. 194, 195). There the integrated living carbon for the whole euphotic zone accounted for 60 per cent of the total carbon, while at individual depths near or at the surface virtually all the carbon was represented by living organisms (Fig. 5).

It should perhaps be reiterated here that the living carbon fraction may have been underestimated by taking the minimal carbon : chlorophyll ratio (35 : 1)

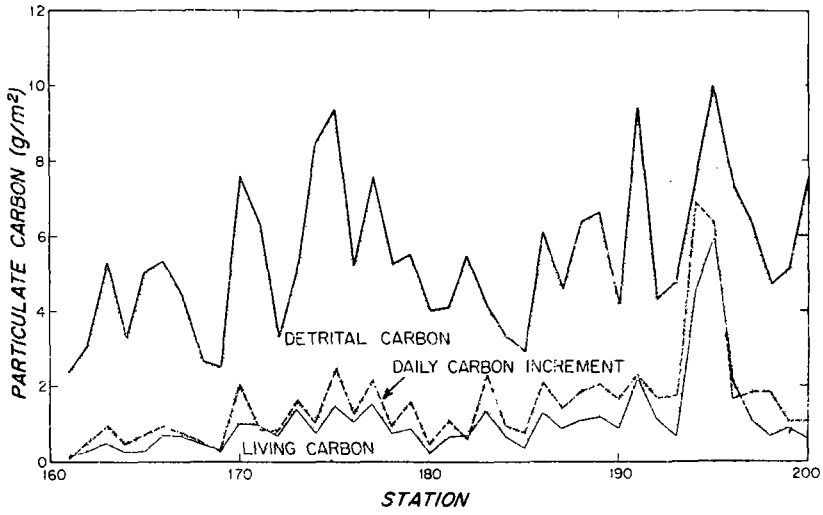


Fig. 7. Total and living carbon and daily carbon production for all Cruise 4A stations (see Fig. 1) shown in serial order.

which we found in laboratory cultures. As we pointed out earlier, however, there is some justification for thinking that higher ratios in cultures may be due to the presence there of dead cells, which would be no different from the detritus we are attempting to measure in nature (MENZEL and RYTHER, 1964). A small increase (e.g. 50 : 1) would not significantly affect the relative proportion of living and dead material. The implications of this relationship with respect to such matters as the food available to zooplankton are worth some consideration.

The broken line in Fig. 7 shows the daily rate of primary productivity plotted in the same units. In view of the uncertainties in the calculation of the living carbon fraction, minor differences are probably not significant. It is obvious, however, that the standing crop of living organisms represents on the average approximately one day of primary production while the turnover rate of total carbon ranges from about a week to 10 days. This is perhaps not surprising in the tropics. It does illustrate not only the rapid turnover of organic matter but also the potential biological instability of such an area. If conditions are otherwise favourable for the existence of animal populations and the primary production is in the form of a food which the animals can utilize, enhanced productivity of these higher forms of life will be favored. If, on the other hand, animal populations are not present in adequate numbers or are otherwise unable to consume the primary production, and if an appreciable fraction of it sinks below the euphotic zone, its subsequent oxidation could easily lead to the anaerobiosis discussed above and its attendant threat to the animal life. Mass mortalities will, of course, accentuate the problem and tend to make it self-perpetuating, not only indirectly by contributing still more oxygen demand to the system but also in removing the trophic levels capable of utilizing the primary organic production.

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HIGH SALINITY IN SEA WATER

Highest Salinity in the World Ocean?

DURING the International Geophysical Year the R.V. *Atlantis*, passing through the Red Sea (Cruise 242), found an anomalously high temperature in the deep water opposite Jeddah. This was reported by Neumann and Densmore[1] in an unpublished manuscript of the Woods Hole Oceanographic Institution. On its way to join the International Indian Ocean Expedition the new R.V. *Atlantis II* carried out a series of hydrographic stations along the length of the Red Sea. Purposely, the ship

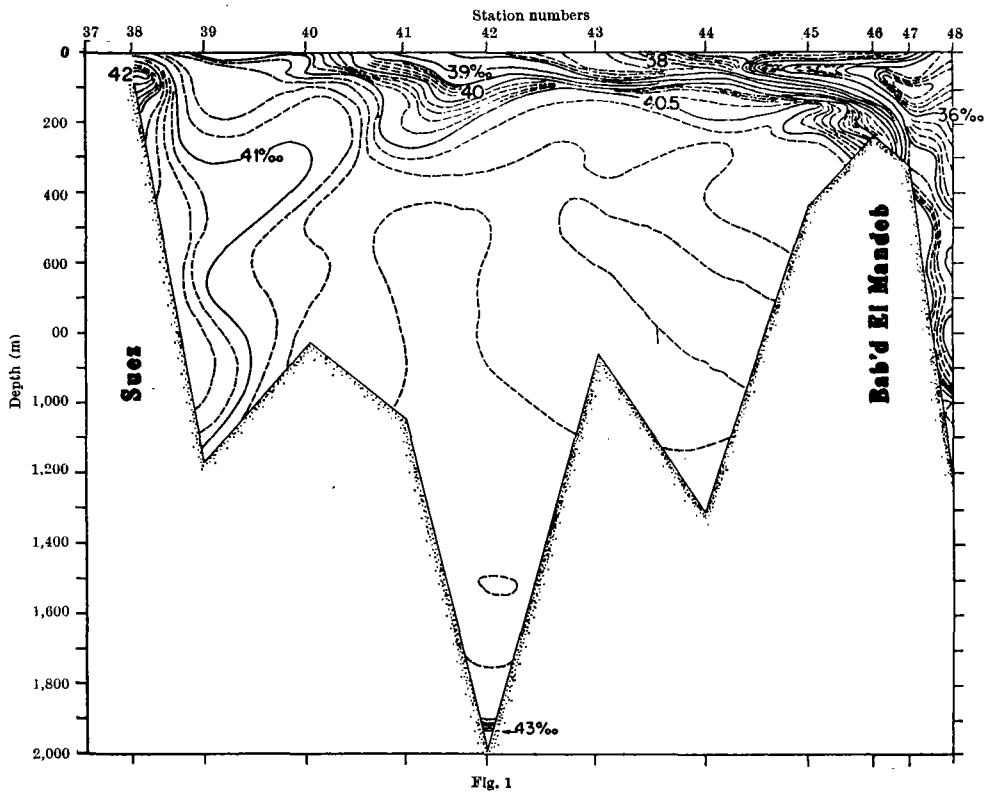


Fig. 1

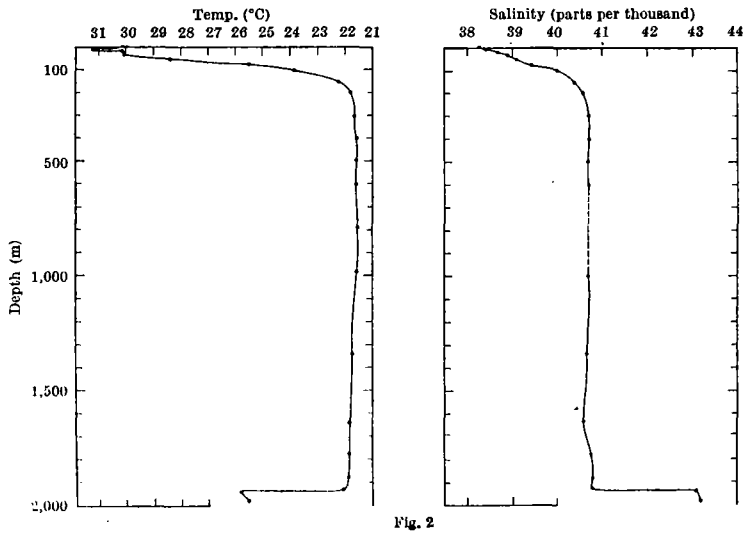


Fig. 2

stopped at the position where Neumann and Densmore[1] found this high temperature. At 21° 21·5′ N., 38° 04·5′ E., Station 42–*Atlantis II*, samples of high-temperature, high-salinity water were obtained close to the bottom.

Fig. 1 gives the profile of salinity distribution from the Gulf of Suez to the Straits of Bab'd El Mandeb as determined from the R.V. *Atlantis II* during July 1963. At Station 42 in the deepest part of the section, 1,931–1,978 m., the water was found to be 25·76°, 3·5° warmer than the rather homothermal water above it. Its salinity was 43·18 parts per thousand, 2·4 parts greater than the surroundings immediately over this band of anomalous water (approximately 50 m thick). Fig. 2 gives the vertical distribution of temperature and salinity for Station 42.

(More recently the British R.R.S. *Discovery* has sampled even deeper depths, 2,400 m, in the neighbouring area and has found clear indications of mixtures of normal Red Sea water and the hot salty water from Station 42.)

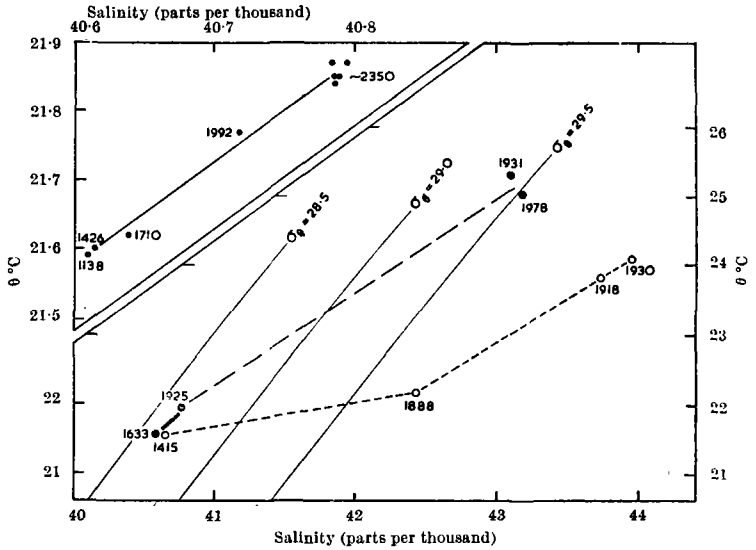


Fig. 1. Potential temperature/salinity diagram for hydrographic stations in the Red Sea. Upper left: ●, *Discovery* 5247; 21° 07′ N., 38° 10′ E.; March 1, 1964; lower right: ○, *Albatross* 254; 21° 10′ N., 38° 09′ E.; May 3, 1948; ●, *Atlantis II* 42; 21° 21′ N., 38° 05′ E.; August 1, 1963; ——, *Discovery* 5247. The figures by the points are depths in metres. The potential density lines are approximate, being extrapolated from Knudsen's formula

Cruise 8 of R.V. *Atlantis II* was sponsored by grant *NSF–GP*821 from the U.S. National Science Foundation.

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(*Reprinted from Nature, Vol.* 205, *No.* 4967, *pp.* 165–166, *January* 9, 1965)

Hot Salty Water at the Bottom of the Red Sea

WATER at a temperature of more than 44° C and salinity exceeding 270 parts per thousand (close to saturation) has been found by the R.R.S. *Discovery* in a small depression below 2,000 m depth in the Red Sea near 21° 17′ N., 38° 02′ E. Three previous expeditions[1–3] have reported abnormal water in this neighbourhood, but nothing so extreme.

This unusual water was found at *Discovery* station 5580, on September 11, 1964, on the way back from the Indian Ocean, in attempting to re-occupy the *Atlantis II* station 42 (ref. 3). The deep parts of the Red Sea are very irregular, with depth changes of several hundred metres frequently occurring within a few miles. There may be many small isolated basins, though not all of them contain abnormal water.

In order to find the most likely place for sampling, a dan buoy was anchored and a sounding survey made relative to it, within about 5 miles radius (Fig. 1). This revealed two small depressions; one of them, about 1·5 miles across and 200 m deeper than its immediate surroundings, was chosen. Water samples were collected from it, using a pinger as a guide in putting the deepest bottle close to the bottom. Two casts were made, the first one consisting of 12 bottles spread over 400 m of depth range. The temperatures observed were normal for Red Sea deep water (about 22° C) down to 200 m off the bottom, followed by a sharp increase to well over 40° C in the lowest 150 m. The second cast was arranged to provide more detail in the transition zone and to collect larger samples of the abnormal deep water. Above 35° C we could use only 60° C unprotected thermometers of low pressure-sensitivity since all other available thermometers, protected and unprotected, were off scale.

Temperatures within the hot water were obtained from the unprotected thermometers by applying a pressure correction appropriate to the sampling depth. The latter could be determined by extrapolation from known shallower sampling depths, combined with evidence from the pinger reflexions and the known depth of water.

The vertical profiles of temperature and salinity are shown in Fig. 2. The 'salinities' were measured on a conductivity bridge, after dilution where necessary. The highest salinities required dilution to about one-eighth concentration by weight to bring them on scale. The depths, and hence temperatures, marked † are less certain (± 15 m, ± 0·2° C) due to greater wire angle and unknown effect of sea floor slope.

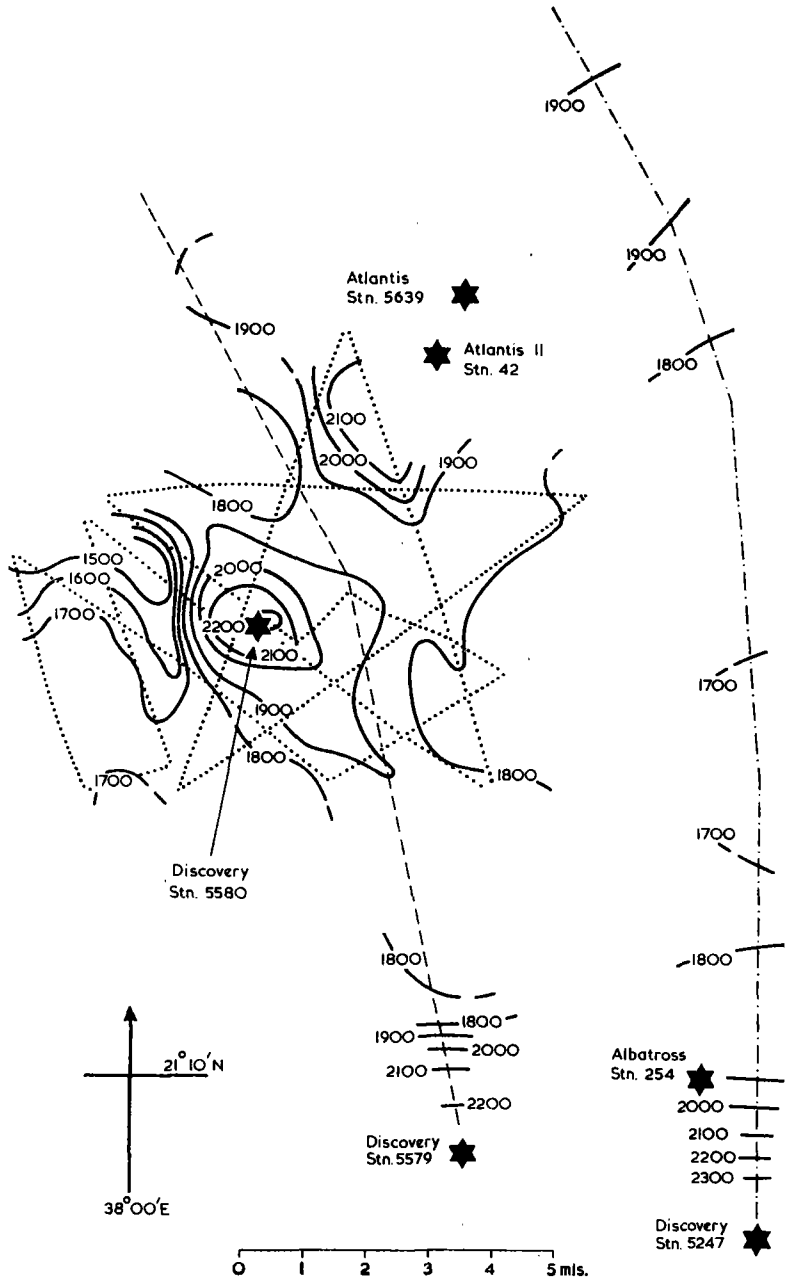


Fig. 1. Bathymetry and station positions where unusually hot salty water has been found. Contours are in metres, corrected according to Matthews's table for Area 51 (ref. 5). —·—·—, R.R.S. *Discovery* sounding track, Mar. 1, 1964; — — — — , sounding track, Sept. 11, 1964; . . . . . , sounding track, Sept. 11, 1964, with positions determined by radar from an anchored buoy

The bathymetric contours of Fig. 1, based only on *Discovery* soundings, suggest that the *Atlantis* stations may well have been in a different small basin, and indeed they show a different sill depth and temperature–salinity curve from *Discovery* station 5580. The position of the

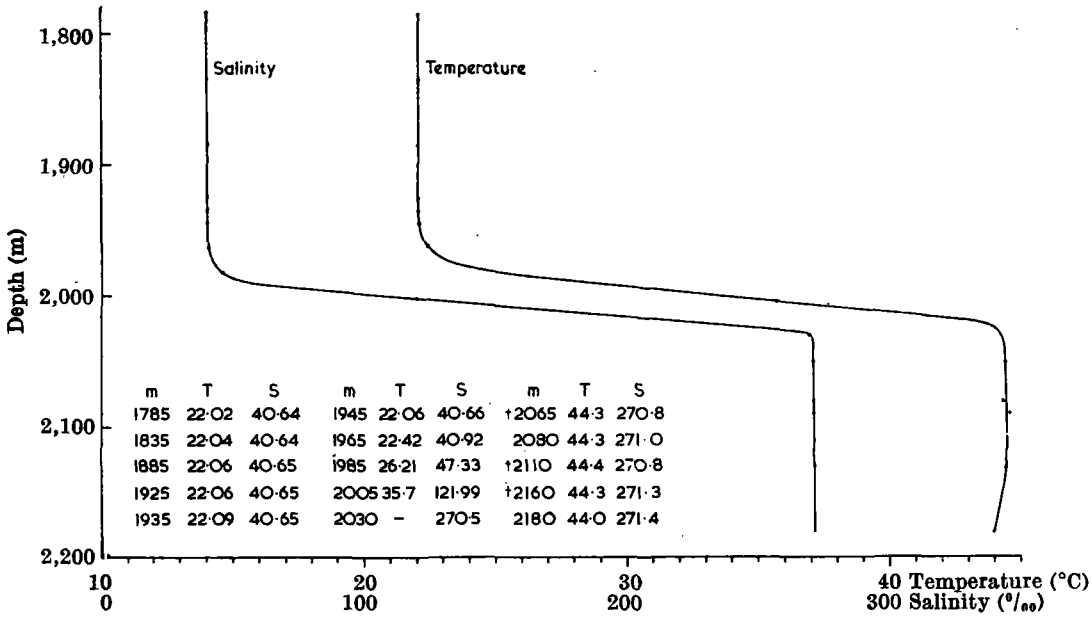


Fig. 2. Provisional values of temperature and salinity for *Discovery* station 5580

Albatross station 254, shown in Fig. 1, seems inconsistent with the *Discovery* positions, since at *Discovery* station 5247 only a trace of the abnormal water was found[4].

Preliminary estimates of sulphate, magnesium and calcium, and of the chlorinity : conductivity ratio, suggest that this water is not just concentrated sea-water. Further chemical work is proceeding at the University of Liverpool and at the National Institute of Oceanography.

Speculating on the origin of the abnormal water, it seems unlikely that it can have been formed by evaporation in a shallow sea, as suggested by Charnock[4] for the previously reported abnormal water. More probably it may be due to solution of salt deposits exposed on the sea floor.

The increased density of the concentrated solution would inhibit convection through the transition layer due to heating from the interior of the Earth, and would permit some increase of temperature. The observed temperature gradient in the transition region (nearly $0{\cdot}5°$ C m^{-1}) is such that the heat loss upwards, with no more than molecular conduction, must be approximately 6 microcalories per square centimetre per second, comparable to the heat flow found coming through the sea floor itself in regions of high tectonic activity, such as the central part of the Red Sea.

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Carbon Dioxide in Surface Waters

In order to elucidate the role of atmosphere–ocean interaction in the geochemical cycle of carbon, the Scripps Institution of Oceanography has been measuring the concentration of carbon dioxide in surface ocean waters and in the adjacent atmosphere as part of a world-wide survey initiated during the International Geophysical Year. The results of the first two expeditions are reported by Keeling *et al.*[1]. This work is continuing under the direction of the senior author.

The measurements of concentration of carbon dioxide

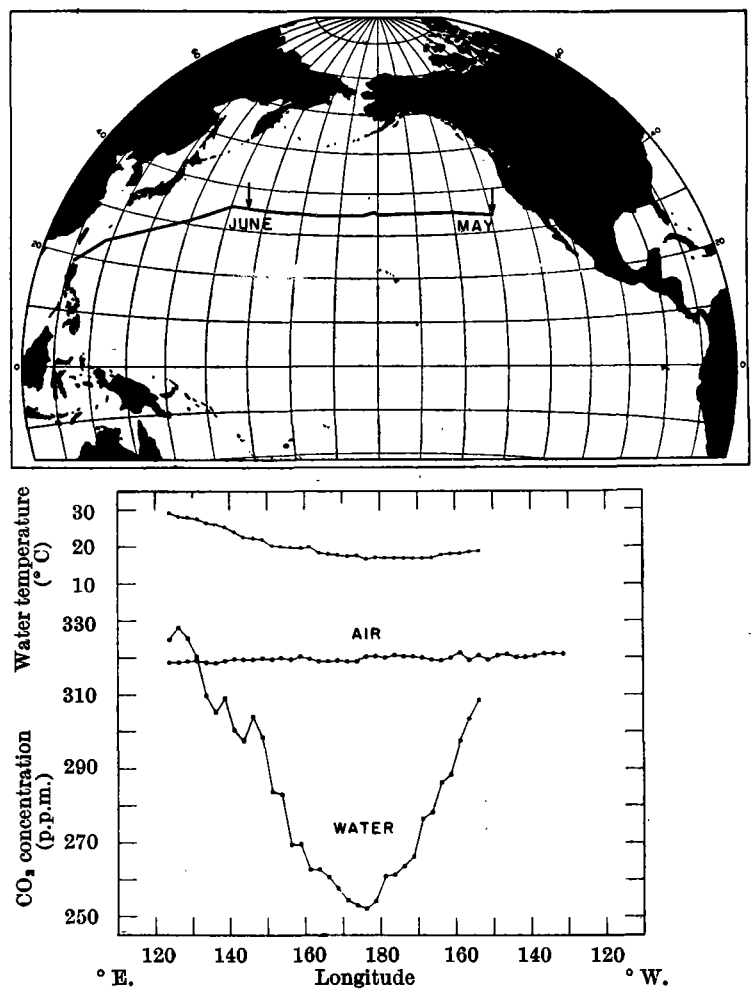


Fig. 1. Top, track of R.V. *Argo*, May 18–June 9, 1962. Bottom, concentration of carbon dioxide near the ocean surface, in the atmosphere and in ocean water, and surface ocean water temperature, as a function of longitude. Points represent averages of all results for each 2·5° of longitude and are plotted in the centre of the respective intervals

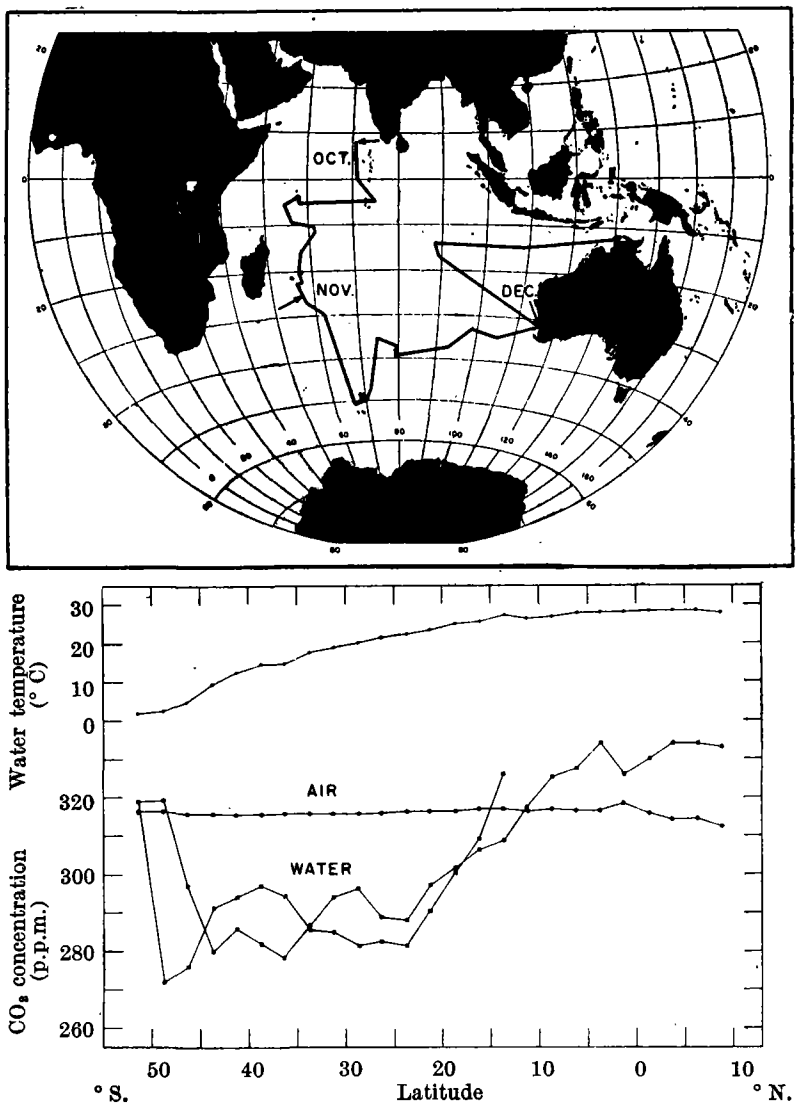


Fig. 2. Top, track of R.V. *Argo*, October 6–December 21, 1962. Bottom, results as in Fig. 1. Points represent averages of all results for each 2·5° latitude interval

reported here were made with an infra-red gas analyser, described by Smith[2], aboard the R.V. *Argo* on the *Lusiad* Expedition, during May 18, 1962–August 14, 1963. The carbon dioxide gas in the surface water was determined by recording the concentration of carbon dioxide in a continuously circulating, closed volume of air equilibrated with a constantly renewed supply of ocean water. The carbon dioxide in atmospheric air was determined in a stream of air first sucked through polyethylene tubing from intakes located on the foremast and aft on the '*A*' frame, then pumped into the analyser and vented[1]. The sampling sequence yielded two 5-min average atmospheric and one 15-min average ocean water measurement every 30 min.

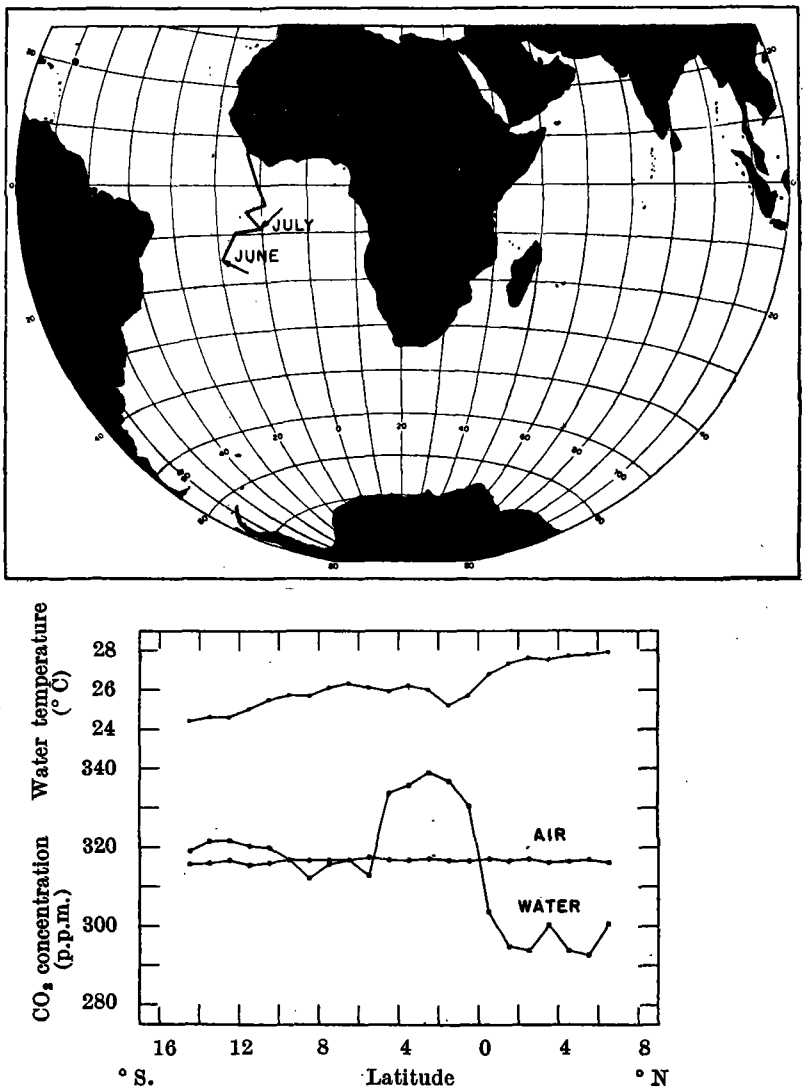


Fig. 3. Top, track of R.V. *Argo*, June 28–July 7, 1963. Bottom, results as in Fig. 1. Points represent averages of all data for each 1° latitude interval

Measurements of carbon dioxide in ocean water were made whenever the ship was under-way and during some of the periods when the ship was occupying stations. Measurements of atmospheric carbon dioxide were carried out during the entire time the ship was at sea except for short periods needed for equipment calibration. A total of 11,313 atmospheric and 4,874 ocean water measurements, representing all the 1962 data and 10 days of 1963 data (June 28–July 7), have been fully processed. The concentration (mixing ratio) of carbon dioxide is reported in parts per million by volume of dry air (p.p.m.). Positive or negative departures of the concentrations of ocean water carbon dioxide from equilibrium with the atmo-

sphere at the time of measurement are referred to as supersaturation or undersaturation.

Marked undersaturation occurred in the Pacific Ocean during the spring of 1962 between 152° W. and 122° E. near 35° N. with the lowest concentration, 68 p.p.m. below saturation, at 175° E. (Fig. 1). In the Indian Ocean, slight supersaturation occurred along the entire length of the equatorial track between 45° E. and 95° E. on four equatorial crossings (5° N. to 5° S.) made in connexion with a sub-surface current investigation[3] during the period of the summer monsoon. A subsequent survey from 7° N. to 52° S. made during the southern spring indicates a slight supersaturation north, and moderate undersaturation south, of 15° S. except for approximate saturation near the island of Kerguelen (49° S., 70° E.) (Fig. 2). On an Atlantic equatorial crossing in July 1963 supersaturation was clearly evident although less marked than in the eastern Pacific[1] (Fig. 3).

Concentrations of atmospheric carbon dioxide ranged from 313 p.p.m. to 322 p.p.m. For the appropriate season and latitude most of the results agreed within 1 p.p.m. with results reported by Bolin and Keeling[4].

This work was supported by grant *G*19168 from the U.S. National Science Foundation. A complete report of the *Lusiad* Expedition is being prepared for future publication.

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INORGANIC NUTRIENT ANIONS IN DEEP OCEAN WATERS

By Dr. TSAIHWA J. CHOW and ARNOLD W. MANTYLA
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PHOSPHATE, silicate and nitrate in the oceans are considered to be nutrients for marine life growth. Their presence in the euphotic zone sustains biological activities and, in turn, their concentrations in deep waters are regulated by the regeneration processes. Numerous papers on this subject have been published and summarized in various review articles[1–6]. However, most of the literature deals with the shallow coastal waters and seldom extends its coverage to the pelagic regions or below the minimum oxygen zone.

During the past several years, the Scripps Institution of Oceanography has carried out various deep-sea expeditions: the *STEP*-I Expedition (1960) to the Peru Current of the Pacific between the equator and the Tropic of Capricorn; the *Lusiad* Expedition (1962–63) to the equatorial Indian Ocean; and the *Dodo* Expedition (1964) to the Somali Current region of the Indian Ocean. During parts of these expeditions, deep hydrographic stations were occupied, and the chemical properties of the deep waters were analysed. The north Atlantic data cited here were those of the transatlantic cruise of the R.R.S. *Discovery II* during the International Geophysical Year (1957). The oceanographic properties of these expeditions have been made available in the form of preliminary data reports[7,8].

The purpose of this article is to give a brief description of the inorganic nutrient salts in the deep waters which were covered by the aforementioned expeditions.

Except for the upwelling areas such as the Peruvian coasts, the silicate concentration of sea-water above the thermocline was uniform and usually less than 10 microgram-atom/litre. Below the thermocline, the silicate content increased rapidly with increasing depth. The Peruvian waters showed a silicate concentration of 140 μg-at/l. at the 2,000-m depth; in the 2,000–6,000-m layer, the silicate content increased only slightly to a value of 160 μg-at/l. The same pattern of silicate distribution was also observed in the equatorial Indian Ocean waters with

a concentration of 90 μg-at/l. at the 2,000-m level, and about 110 μg-at/l. in the 2,000–6,000-m deep waters. The highest silicate content of the North Atlantic deep waters was about 60 μg-at/l. which was much lower than that of the Pacific and Indian Oceans. The silicate vertical profiles did not show any anomaly in the minimum oxygen zone. The minimum oxygen zone normally occurs at the 800–1,000-m depth in the open ocean.

Along the Peruvian coastal region, surface water phosphate content as high as 2 μg-at/l. was detected. Beyond the upwelling region, a uniformly low phosphate concentration was present in the mixed layer. The phosphate content increased with increasing depth; and in the minimum oxygen zone, it reached the average maximum value of 2·7 and 3·0 μg-at/l. for the Indian and Pacific Oceans, respectively. Then the phosphate concentration of sea-water began to decrease toward the bottom. For the water column between 2,000 and 6,000 m, the average phosphate content was about 2·5 μg-at/l. for the Pacific and 2·4 μg-at/l. for the Indian Ocean. The North Atlantic phosphate data showed a large degree of scattering, and its maximum concentration was about 2·0 μg-at/l. at the intermediate depth. The Atlantic water between 2,000 and 6,000 m showed an average phosphate concentration of about 1·6 μg-at/l.

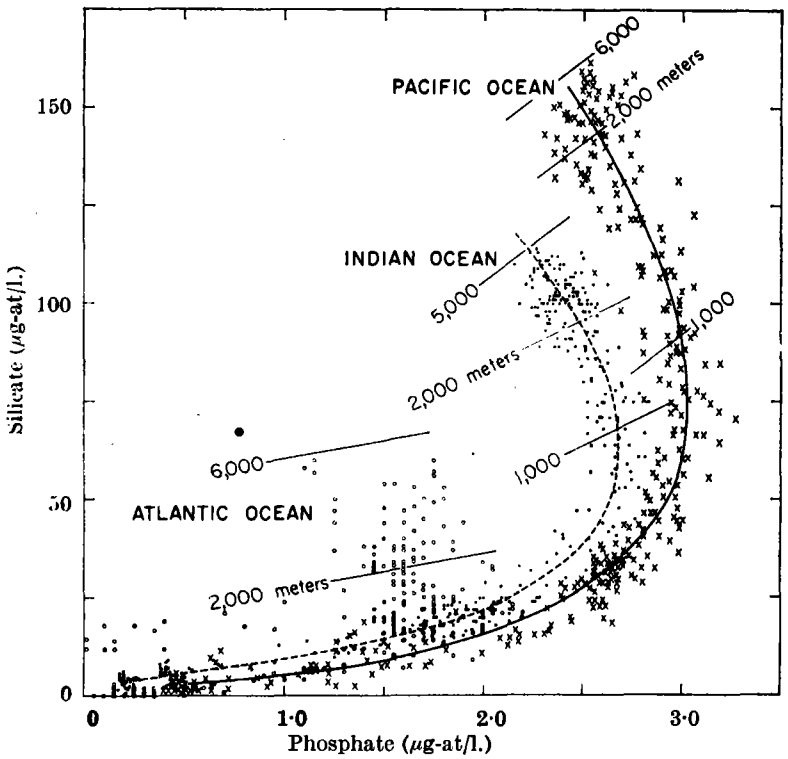


Fig. 1. Relationship between silicate and phosphate in the Pacific, Indian and Atlantic Ocean waters

Owing to the complex analytical procedure, the nitrate determination is often difficult to perform at sea; therefore, only limited data on the nitrate distribution in the oceans are available. When coastal upwelling or river run-off was prominent, high nitrate concentration was found in the surface waters[7,9]. However, the nitrate content was often depleted in the surface waters of the Pacific Ocean. Below the euphotic zone, the nitrate content increased sharply to 30 μg-at/l. and reached its maximum concentration of about 45 μg-at/l. in the minimum oxygen zone, and then attained an average of 40 μg-at/l. in the 2,000–6,000-m deep waters. The average nitrate concentration for North Atlantic deep water was 20 μg-at/l., which was only half the Pacific value. The nitrate content of the Indian Ocean was reported earlier[1] as being less than that of the Pacific waters. No significant nitrate data of the Indian Ocean deep waters have been reported in recent years.

The correlations among the phosphate–silicate–nitrate distribution in the ocean waters were also examined. In order to obtain consistent results, the nutrient atom ratios were based on the data which were obtained by analysing equal portions of the same water samples. The relationship between phosphate and silicate for the three major oceans is shown in Fig. 1. The atom ratio of these two chemicals was usually less than 10 in the surface waters of all three oceans except for few scattered Atlantic surface samples.

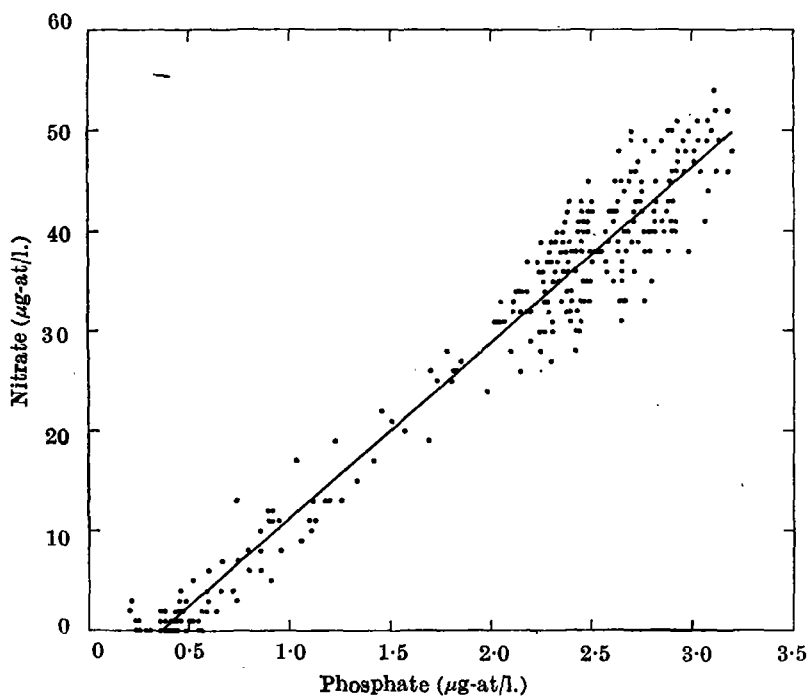


Fig. 2. Relationship between nitrate and phosphate in the Pacific Ocean waters

Below the surface-layer, the silicate-to-phosphate ratios are characteristic for the various waters and significantly different from each other. For the Pacific and Indian Oceans, the silicate-to-phosphate ratio increased with increasing depth to a ratio of about 25 in the minimum oxygen zone. With the increasing silicate and decreasing phosphate contents in the 2,000–6,000-m region, the silicate-to-phosphate ratio increased exponentially to about 55–65 for the Pacific deep waters while that of the Indian Ocean deep waters was calculated to be about 40–50. For the Atlantic waters, the silicate versus phosphate plot showed much dispersion, and its atom ratio ranged from 20 to 40 for the deep waters.

Stefansson and Richards[9], in their investigation of nutrient distribution off the Washington and Oregon coasts, stated that "the silicate-to-phosphate ratio is variable, although at silicate concentrations of less than 55 μg-at/l. its mean value is approximately 22 : 1". This estimation is in agreement with the upper layer of the Pacific water as shown in Fig. 1 of this article. Based on the Pacific deep water (1,700 m) data given by Stefansson and Richards (R/V *Brown Bear* Cruise 299, Station 25), the silicate-to-phosphate ratio was computed to be 56—a value approaching that given in this article. In previous work on Atlantic water, the silicate-to-phosphate atom ratio was given as 13–16 for the intermediate waters[10,11].

The relationship between the phosphate and nitrate contents of the Pacific waters is given in Fig. 2. It shows a linear correlation, and the data have been fitted by the least square method. The equation of the linear line is expressed in atoms as:

$$N = [(17{\cdot}5 \pm 4{\cdot}0)\ P] - 6{\cdot}5$$

The linear line did not pass through the point of origin indicating an excess phosphate in respect to nitrate in the ocean. The slope of the line represented the interaction of these two elements in the ocean. If the nitrate and phosphate were assimilated or regenerated according to this ratio, then the excess phosphate in the ocean would be 0·37 μg-at/l. Stefansson and Richards[9] gave the linear equation as $N = 15{\cdot}82\ P - 9{\cdot}95$ for the Washington and Oregon coastal waters. The difference between these two sets of equations was within the analytical error. It should be mentioned here that the maximum depth of the Washington and Oregon coastal region is about 2,000 m; therefore, it was not possible to include the deeper waters, which were usually high in nitrate-to-phosphate ratio, in the least-square computation of Stefansson and Richards. Owing to limited nitrate data available, the nitrate-to-phosphate ratio of the Indian Ocean deep waters was estimated to be approximately 15 : 1.

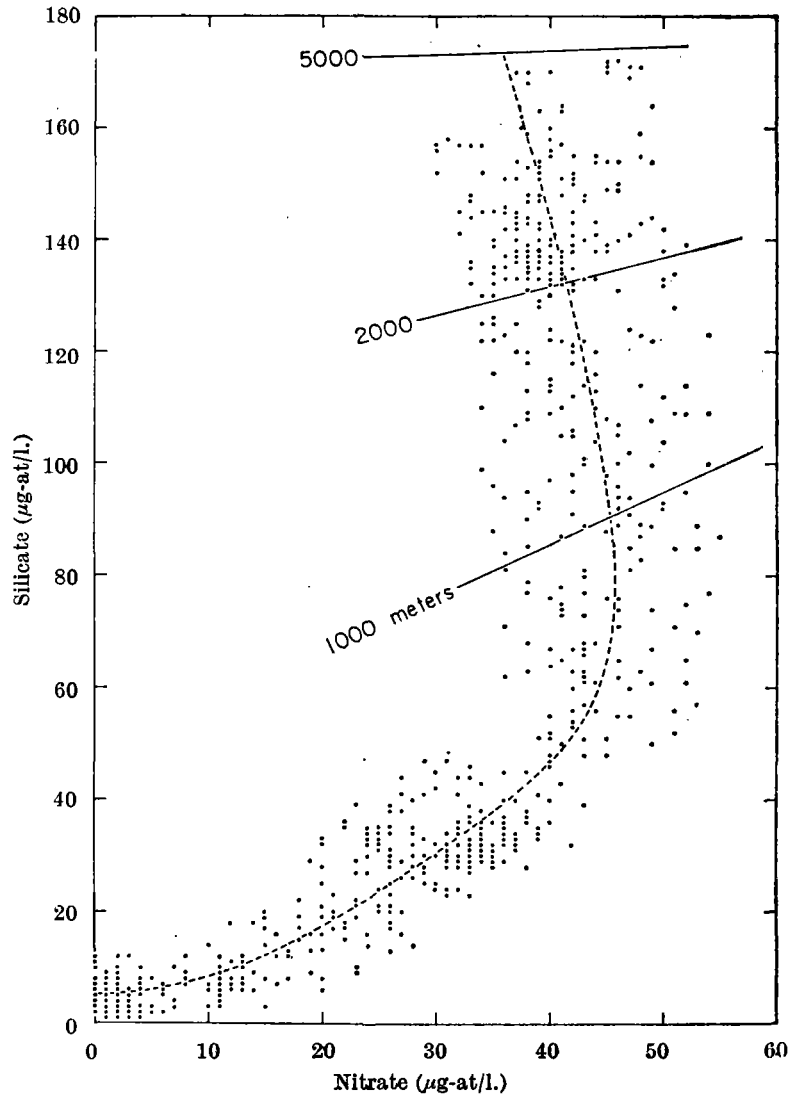


Fig. 3. Relationship between silicate and nitrate in the Pacific Ocean waters

The silicate-to-nitrate correlation of the Pacific waters is shown in Fig. 3. Since the silicate and nitrate contents of the surface waters were low, the individual Si/N ratios showed much scattering. However, it was demonstrated that these two elements were increasing in equal proportion with depth until the minimum oxygen zone was reached. Owing to the progressive increasing silicate and decreasing nitrate in the waters below the minimum oxygen zone, the silicate-to-nitrate ratio increased to about 3–5 for the Pacific deep waters. For the Atlantic waters, the silicate-to-nitrate ratio was computed from Richards's data[10] as approaching 2 as the limit. Since the nitrate data were limited in the Indian Ocean deep waters, the silicate-to-nitrate ratio was only roughly estimated as 3 : 1.

Table 1. RANGES OF PHOSPHATE–SILICATE–NITRATE ATOM RATIOS IN WATERS BETWEEN 2,000 AND 6,000 M

	Silicate / Phosphate	Silicate / Nitrate	Nitrate / Phosphate
S.E. Pacific Ocean	55–65	3–5	13–19
Equatorial Indian Ocean	40–50	3*	15*
N. Atlantic Ocean	20–40	1–2	12–16

* Estimated average values.

In summary, the ranges of the phosphate–silicate–nitrate atom ratios for the deep waters between 2,000 and 6,000 m are given in Table 1. The nutrients showed the same pattern of distribution in the three major oceans, varying only in magnitude of concentration. When the atom ratios were computed, the values showed significant characteristics for each ocean.

The oceanographic expeditions conducted by the Scripps Institution of Oceanography were sponsored by the U.S. National Science Foundation and the Office of Naval Research. The hydrographic surveys of the *STEP*-I and the *Dodo* Expeditions were under the leadership of Prof. W. S. Wooster, and that of the *Lusiad* Expedition was under Prof. John A. Knauss.

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Chemical Composition of the Hot Salty Water at the Bottom of the Red Sea

In a recent communication Swallow and Crease[1] directed attention to the existence of a basin about 200 m deep at the bottom of the Red Sea near 21° 17′ N., 38° 02′ E., filled with highly saline water at a temperature of more than 44° C. The present communication gives a brief preliminary account of the chemical composition of this water.

Table 1 shows the variation of temperature, salinity (from conductivity) and chlorinity with depth. The temperatures and depths are revised values supplied to us by Swallow and differ slightly from the provisional values given in the reference cited[1]. In particular the temperature of the hot water after revision is about 0·4° C higher.

The constancy of the chlorinity of the water within about 150 m of the bottom suggested that this water would be uniform in composition and this proved to be the case. The average ionic ratios relative to chlorinity were found to be as follows (the corresponding ratios for ocean waters are given in brackets): sodium, 0·5980 (0·5556); potassium, 0·0139 (0·0205); calcium, 0·0303 (0·0213); magnesium, 0·0052 (0·0668); sulphate, 0·0048 (0·1400); bromine, $0{\cdot}79 \times 10^{-3}$ ($3{\cdot}48 \times 10^{-3}$); manganese $3{\cdot}2 \times 10^{-4}$ (about $2{\cdot}5 \times 10^{-6}$). These ratios suggest that this water cannot have been formed by evaporation in a shallow sea as suggested by Charnock[3], or by the dissolution of salt deposits in Red Sea bottom water. The similarity of the ionic ratios to those of oil field and other deep-well brines is quite striking, in particular the

Table 1

Corrected depth (m)	Temperature (° C)	Salinity (parts per thousand) by conductivity	Chlorinity (parts per thousand)
1,795	22·02	40·64	
1,845	22·05	40·64	
1,895	22·05	40·65	
1,925	22·06	40·65	22·54
1,945	22·06	40·66	
1,970	22·41	40·92	22·68
1,995	26·20	47·33†	26·34
2,010	36·11	121·99†	69·24
2,045	—	270·5†	155·1
2,055	44·8	270·8†	155·4
2,095	44·8	270·8†	155·5
2,140	44·9	271·3*†	155·4
2,195	44·4	271·4†	155·4

* Salinity determined gravimetrically[2] 254·9; density ($d_{4}^{18\cdot5}$) 1·1989.

† Owing to departures of ionic ratios from those of normal sea waters these values do not represent true salinities.

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low SO_4/Cl ratio, and this suggests that this water has a connate origin, that is, it has been expelled from sediments by geothermal heating.

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The chemical composition of the hot salty water from the bottom of the Red Sea

P. G. BREWER,* J. P. RILEY* and F. CULKIN†

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Abstract—Samples of a hot salty water discovered in a deep basin in the Red Sea have been analysed for dissolved gases and major and minor constitutents. It is shown that this water is different in composition from ordinary sea water and some possible explanations of its composition are discussed.

IN A recent note SWALLOW and CREASE (1965) have described the discovery of a basin 200 m deep filled with highly saline water at a temperature of *ca.* 44·8°C at the bottom of the Red Sea‡. Preliminary chemical analyses by the present authors (BREWER, RILEY and CULKIN, 1965) showed that this water had a different composition from ordinary sea water. The purpose of the present paper is to record more complete chemical data on this most unusual water which may enable others to draw conclusions about its origin.

Two water bottle casts were made on 11 September 1964 at this station. The first, which consisted of 12 N.I.O. bottles, covered the bottom 400 m of the water column and showed that the temperature was normal to within 200 m of the bottom. However, in the next 50 m an increase of over 20°C was found ; beneath this region the temperature remained constant at *ca.* 45°C to the bottom. The second cast was made to cover the transition zone in more detail and to provide large samples of the abnormal water. These large samples were collected at distances of 25 m and 30 m from the bottom using N.I.O. 5 l. polypropylene sampling bottles. The smaller samples were stored in 8 oz glass bottles with polyethylene closures. After collection all samples were analysed on board for salinity (by inductively-coupled salinometer), dissolved oxygen, nitrate, silicate and phosphate. The bulk samples were transferred to 5 high density polyethylene bottles for analysis at the National Institute of Oceanography and at the University of Liverpool.

ANALYSIS OF THE DISSOLVED SOLIDS

Analyses of the water samples for major and minor components were made using the methods detailed in Table 1. The results obtained at the N.I.O. for the major ions are shown in Table 2. The average analysis of the high salinity samples agreed well, for most components, with the results of analyses made by ion exchange methods at Liverpool (M. TONGUDAI unpublished) on a bulk sample from 2155 m. The results of analyses for minor components are given in Table 3.

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‡*Discovery* Station 5580, 11th September 1964, 21° 17′ N., 38° 02′ E. Total water depth 2219 m.

Table 1. Methods of analysis used for samples

Component	*Method used*	*Reference*
Salinity	Gravimetric	MORRIS and RILEY (1964)
Chlorinity	Potentiometric titration	HERMANN (1951)
Sodium and Potassium	Ion exchange for total cations: deduct figures for K, Mg, Ca, Sr to obtain Na by difference.	CULKIN (unpublished)
	Potassium gravimetrically as KB $(C_6H_5)_4$	CULKIN (unpublished)
Magnesium	EDTA titration at pH10 using EBT as indicator, figures for Ca and Sr deducted	CULKIN (unpublished)
Calcium	EDTA titration at pH13 using calcein as indicator	PATE and ROBINSON (1958)
Strontium	Direct flame photometry	CULKIN (unpublished)
Sulphate	Gravimetric as $BaSO_4$	BATHER and RILEY (1954)
Bromide	Oxidation to bromate with ClO^-, excess oxidizing agent reduced with formate. Iodine liberated by treatment with I^- and H^+ and titrated with $S_2O_3^{2-}$	HASLAM and MOSES (1950) MORRIS and RILEY (unpublished)
Fluoride	Photometric with lanthanum alizarin complexone	GREENHALGH and RILEY (1961)
Boron	Photometric with curcumin	GREENHALGH and RILEY (1962)
Lithium	Ion exchange separation, flame photometry	RILEY and TONGUDAI (1964)
Iodide	Catalytic action on reaction between Ce^{4+} and As^{3+}	BARKLEY and THOMPSON (1960)
Manganese	Coprecipitation with $Fe(OH)_3$, photometric as $KMnO_4$. Chemical yield checked by tracer method; chloride removed, photometric as $KMnO_4$.	P. G. BREWER (unpublished)
Copper	Photometric with 2,2′-diquinolyl	RILEY and SINHASENI (1958)
Ferric iron	Photometric with bathophenanthroline	LEWIS and GOLDBERG (1954)
Ferrous iron	Photometric with 2,2′-dipyridyl	COOPER (1948)
Zinc	Anion exchange separation, photometric with dithizone	J. MURPHY (unpublished)
Total carbon dioxide	Sample acidified, CO_2 stripped from it with air, absorbed and weighed	——— ———
Silicate	Photometric as molybdenum blue	MULLIN and RILEY (1955)
Nitrate	Reduction to nitrite and photometric determination	MORRIS and RILEY (1963)

COMPOSITION OF THE DISSOLVED GAS

A considerable amount of gas was liberated from the very saline waters shortly after they had been brought to the surface and caused them to effervesce slightly. Since it was thought that the composition of this gas might provide a clue to the origin of the water, it was decided to collect a sample of it. In the absence of conventional gas sampling apparatus, a 500 ml Squibbs type funnel was connected to the sampling cock of the water bottle, and water was allowed to flow up into the funnel until it overflowed. The well greased tap of the funnel was then closed and its ground-glass stopper was inserted tightly, care being taken not to trap air underneath it. The stopper was well waxed and wired down and the funnel was stored on its side to prevent loss or ingress of air. Within a few hours the evolution of gas was complete and later examination showed that 25 ml of gas at S.T.P. had been liberated per litre of water. This gas had presumably been retained by the water by hydrostatic

Table 2. Dissolved oxygen and major component analyses of Red Sea deep water

Corrected depth (m)	*Temp.* °C	O_2 ml/l	$Cl‰$	*Ratios to chlorinity (by weight)*							
				Na^+	K^+	Ca^{2+}	Mg^{2+}	$Sr^{2+} \times 10^3$	SO_4^{2-}	$Br^- \times 10^3$	$Mn^{2+} \times 10^4$
1925	22·06	2·25	22·542	0·5537	0·0206	0·0209	0·0675	0·38	0·1420	3·43	1·51
1970	22·41	—	22·681	0·5552	0·0205	0·0208	0·0669	0·34	0·1409	3·43	—
2010	36·11	—	69·244	0·5914	0·0149	0·0289	0·0176	0·30	0·0368	1·32	3·47
2055	44·8	0·15	155·39	0·5979	0·0138	0·0303	0·0052	0·30	0·0048	0·80	3·15
2095	44·8	0·14	155·47	0·5979	0·0139	0·0304	0·0051	0·30	0·0049	0·80	3·42
2105	—	0·14	155·08	0·5974	0·0139	0·0304	0·0051	0·30	0·0047	0·78	3·48
2140	44·9	0·16	155·42	0·5978	0·0139	0·0303	0·0053	0·29	0·0048	0·78	3·42
2145	—	0·15	155·13	0·5980	0·0139	0·0303	0·0052	0·29	0·0048	0·79	3·22
2155*	—	—	154·28	—	—	—	—	—	—	—	—
Standard Sea Water	—	—	19·374	0·5556	0·0205	0·0213	0·0668	0·41	0·1400	3·48	$\sim 2 \times 10^{-3}$

*Bulk sample, gravimetric salinity = 254·94 Densities, $d_{22.5°}^{22.5°} = 1·19888$; $d_{45°}^{45°} = 1·19569$

Table 3. Minor components in average sea water and bulk sample of highly saline Red Sea water taken from 2140 m (μg/kg)

Component	*Boron*	*Copper*	*Fluorine*	*Iodine*†	*Iron (III)**	*Iron (II)*	*Lithium*	*Zinc*
Red Sea water	7,800	14	51·2	30 ± 1·7	220	n.d.	262	~1,000
Average sea water	4,600	~5	1,400	~60	< 20	0·0	190	< 5

Component	*Total Carbon dioxide*	*Nitrate-Nitrogen*	*Silicate-silicon*
Red Sea water	6,500	10	5,500
Average sea water	90,000	180‡	2,600‡

n.d. = not detected, *passing 0·5 μ filter, †iodide, ‡in water at 1945 m at this station.

pressure while it was *in situ*. When the samples were brought to the surface its very low solubility in the highly saline water caused it to be evolved.

An AEI MS10 mass spectrometer was used for analysis of the gas. The separating funnel containing the sample was inverted and sealed to a vacuum line. The gas over the water sample was dried by passage through a cold trap and pumped into a glass bulb of small volume fitted with a stopcock and ball and socket joint. The bulb was connected to the mass spectrometer and the mass spectrum was plotted. The volume ratio of nitrogen/argon in the sample was found to be 100/1·21, which should be compared with a ratio of 100/1·19 in air and 100/2·59 in the dissolved gas in sea water (chlorinity 20·0‰ at 22°) saturated with air. This suggests that the gas might have had its origin in air. The presence of ^{4}He, which might have originated from radio-active decay of uranium, was specifically sought but it could not be detected.

The total carbon dioxide content of the sample (6·7 mg/l) was unusually low for a natural water.

DISCUSSION

The detailed discussion of the origin of the hot high salinity water demands a more expert knowledge of geology of the Red Sea area and of the geochemistry of natural waters than is possessed by the authors. Attention will therefore be drawn only to three possible modes of origin for it and to chemical evidence supporting one of them. It will be left to others, better qualified, to relate the hydrology to the geology of the rift valley which constitutes the bed of the Red Sea.

These possible modes of origin of the saline water are as follows :

(i) The water might have been concentrated by evaporation in the very hot shallow coastal regions and flowed down as a density current to the basin in which it is found. Against this hypothesis must be set the fact that waters of such high salinity are not known to occur in the marginal areas of the Red Sea, and if they did exist, it is improbable that they would be able to traverse *ca.* 100 km of uneven sea floor without being diluted by turbulent mixing. An even more telling point against this hypothesis is the fact that the water has an ionic composition quite

different from that of sea water (see Table 2), or of any water which might be formed as a residual mother liquor in the formation of an evaporite deposit.

(ii) That the water had resulted from the action of sea water on a bed of halite underlying the floor of the basin. Calculations show that to attain a chlorinity of 155·2‰ 227·02 g of sodium chloride would have to be dissolved in 0·77298 kg of sea water (Cl = 22·67‰). However, the ionic composition of the saline water is quite different from that which would be formed by the dissolution of halite in sea water in such amounts as to give a chlorinity of 155‰, even if allowance is made for the dissolution of gypsum and dolomite or limestone which usually overlie salt beds (see Table 4). In particular attention should be drawn to the following facts : (a) the concentration of bromine in the water (0·13 g/kg) is about twice that expected from the dissolution of halite in sea water; halite itself normally contains only traces of bromine, (b) the concentration of potassium (*ca.* 2·1 g/kg) is *ca.* 5 times as great as that in the hypothetical water; halite usually contains very little potassium since the latter only crystallizes at a late stage in the marine evaporite series (BORCHERT, 1964), (c) the concentration of sulphate is only *ca.* $\frac{1}{4}$ of that of the hypothetical water, (d) the content of calcium is *ca.* ten times that of the hypothetical water; this extra calcium cannot have arisen from the solution of either calcium carbonate or calcium sulphate since the concentrations of both total carbon dioxide and sulphate are low.

Table 4. *Ionic compositions* (g/kg) *of saline water and of hypothetical water of chlorinity* 155·2 g/kg *assuming sea water of chlorinity* 22·67‰ *has dissolved sodium chloride.*

	Salinity	Cl^-	SO_4^{2-}	$Br^- \times 10^3$	$F^- \times 10^3$	Na^+	K^+	Mg^{2+}	Ca^{2+}	$B \times 10^3$
Saline water	254·9	155·2	0·749	0·123	0·0160	92·77	2·15	0·81	4·70	0·008
Hypothetical water	258·7	155·2	2·455	0·060	0·0012	99·05	0·351	1·172	0·370	0·004

(iii) There remains the attractive possibility that the water is connate (i.e. that it originates from interstitial water of old sediments or from water of crystallization of evaporite sequences, from which it is removed by geothermal heating, and emerges as a hot spring). Such a possibility is attractive, particularly for a region such as the Red Sea floor which has a very high heat flux. This effect might provide an explanation of the high temperature of the saline water. A search through the analyses for sub-surface waters of all types collected by WHITE, HEM and WARING (1963), showed that the only waters which resembled the Red Sea sample in either salinity or chemical composition were those of oil field brines and other deep well brines. A number of analyses from this collection which closely resemble that of the Red Sea water are shown as ionic ratios in Table 5 together with the corresponding ratios for the latter. It is apparent that there is sufficient agreement between the ratios to suggest that the highly saline water is a connate water of this type. However, there are a few points of difference which may perhaps not be significant since these brines display a considerable variation in ionic ratios presumably related to the nature of their source rocks. In particular, the Ca/Na ratio is less than one third of any of those of the published analyses. The total carbon dioxide content of the Red Sea water is unusually low for a natural water. The Li/Na and I/Cl ratios are several orders of magnitude

Table 5. Comparison of Red Sea saline water with oil well and other deep well brines

		Brines		
Ratios by weight	1	2	3	4
Ca/Na	0·051	0·14	0·26	0·17
Mg/Ca	0·17	0·12	0·23	0·27
K/Na	0·023	0·014	0·018	0·012
Li/Na	0·000005	0·00030	—	—
HCO_3/Cl	0·00004	0·00090	0·00038	0·0077
SO_4/Cl	0·0048	0·0012	0·0035	0·00000
F/Cl	0·00011	0·00001	—	—
Br/Cl	0·0079	0·0032	0·0046	0·0059
I/Cl	0·0000002	0·00015	0·00013	0·00003
B/Cl	0·00005	0·000076	—	—
Total solids (g/kg)	254·9	200·0	217·0	25·7
SiO_2 (mg/l)	11	16	—	6

1. Red Sea highly saline water.
2. West Bay Plaquemines Parish Louisiana U.S.A. from silty Miocene sandstone near salt dome. Analysis by H. C. WHITE (cited by WHITE, HEM and WARING, 1963, Table 13, analysis also showed 30 mg Mn/l; 51 mg Fe/l; 180 mg Sr/l; 0·4 mg Cu/l; 5 mg Zn/l.)
3. Polasna-Krasnokamsk NW of Molotov City U.S.S.R. from carboniferous limestone containing $CaSO_4$ and NaCl (KUZNETSOV and NOVIKOV, 1943; KUZNETSOV, 1943).
4. Paintsville, Johnson County, Kentucky, U.S.A. brine from Permian Sandstone (HAUSER, 1953).

less than any of those in the collected analyses. The comparatively high manganese and zinc contents of the sample (50 and *ca.* 1 mg/kg respectively) are unusual for a natural water, but somewhat similar concentrations were found in the Louisiana oil field brine (analysis 2 Table 5). It thus seems probable that the water is connate water, a similar conclusion has been reached by C. NEUMANN (personal communication to Dr. J. C. SWALLOW; NEUMANN and CHAVE, 1965).

The high concentration of dissolved gas contained in the sample and the similarity of its N/Ar ratio to that of air depleted in oxygen, rather than to that of the dissolved air in sea water is interesting. However, there are too few published analyses of dissolved gases from connate waters for any conclusions to be drawn.

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Part III

Physical oceanography

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A Study of Microseisms in South Africa

J. Darbyshire

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Summary

Microseisms have been recorded at Hermanus near Cape Town since 1961 October, using an N.I.O. two-component horizontal seismograph. Wave records have also been taken by means of a ship-borne wave recorder aboard R.S. *Africana II*. The spectra of waves and microseisms due to a storm in 1962 April are compared and there is a two to one frequency relationship as would be expected from the wave interference theory of microseism generation. Estimates were made of the direction of approach of the microseisms, assuming various models and allowing for the effect of refraction. The evidence on the whole suggests that the microseisms consist of a mixture of Rayleigh and Love waves coming from the same range of directions.

1. Introduction

Since 1961 October, a two-component horizontal seismograph of the type described by Tucker (1958), and Darbyshire and Hinde (1961) has been installed at the Magnetic Observatory, Hermanus, Cape Province, about seventy-five miles south-east of Cape Town. Records have been taken regularly for fifteen minutes, eight times a day. Microseism activity was very low, less than 3μm until the onset of the winter in 1962 April. One storm in this month gave very interesting results and these form the subject of the present paper. It was fortunate that sea waves were also being systematically recorded at this time by means of an N.I.O. ship-borne wave recorder on board the Division of Sea Fisheries research ship *Africana II*.

2. Description of the situation

Figure 1 shows sketches of the weather situation for April 9, 10, 11, 12, 13 and 14, at 12^h GMT, extracted from the weather charts issued by the South African Weather Bureau. A storm approaches from WSW of Cape Town and moves round the Cape, being approximately south of it at 1962 April 11 12^h and it then moves up along the coast. On the 13th, another storm appears and for a time two storms are effective. The positions of wave recording for 1962 April 10 22^h, 1962 April 11 22^h, 1962 April 12 11^h and 1962 April 15 00^h are shown by crosses on the most appropriate weather chart.

The wave records were frequency analysed by using the N.I.O. wave analyser (Barber & others, 1946). The microseism records for 1962 April 10 11^h, 1962 April 11 02^h, 1962 April 11 11^h, 1962 April 12 17^h and 1962 April 14 11^h, were digitized and analysed by the DEUCE computer. The power frequency spectra

are shown in Figure 2, the frequency interval being 0·007 s^{-1} for the waves and also for the microseisms the frequencies of which have been halved to facilitate direct comparison. The ordinates on the microseism spectra represent the sum of the energies of the two components. As will be seen below, the positions of wave recording were outside the wave interference areas but the agreement between the two sets of spectra is very striking and gives good evidence for Longuet-Higgins' theory of wave interference (1950).

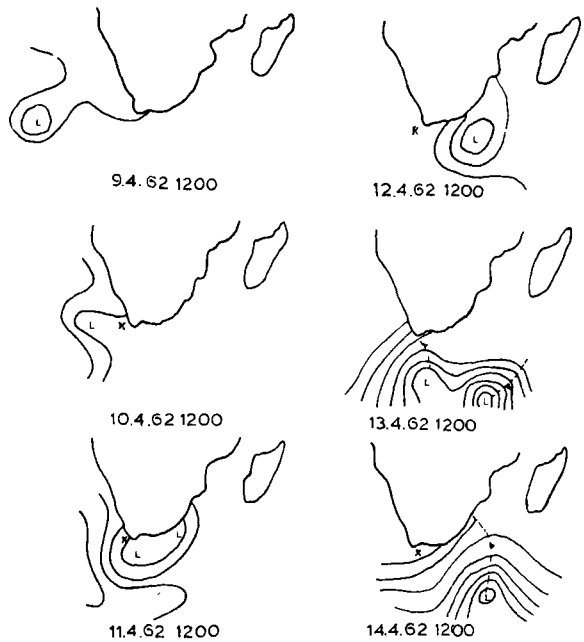


FIG. 1.—Position of storms, 1962 April 9 to 14.

As no vertical seismograph was available, it was not possible to determine from the horizontal seismographs whether the microseisms consisted of Rayleigh waves only or a mixture of Rayleigh and Love waves but a knowledge of the positions of wave interference would greatly help in this regard. Accordingly wave frequency and directional spectra were predicted from the weather charts by a method developed by J. Darbyshire (1961) for the North Atlantic and adapted by M. Darbyshire (1962) for South African waters. This method predicts the wave energies contained in wave period bands 5–7, 8–10, 11–13, 14–16, 17–19 s and direction classes 0°–45° and so on over a set of 300-mile side squares shown in Figure 3. This method indicated that there were bands of wave energy moving in opposite directions within the squares shown shaded. The square 23 applies to 1962 April 10 12^h, 44 to 1962 April 11 12^h, 36 to 1962 April 12 12^h and 57 to 1962 April 14 12^h. The energy values are shown in Table 1 and are compared with the sum of the variances of the two microseism records at that time.

There is some resemblance between the trends of the two sets of figures, both showing a marked decrease at 1962 April 12, but the waves show a marked rise between the 10th and 11th whereas the microseisms only show a slight increase. The great increase in wave activity on the 14th is not shown by the microseisms

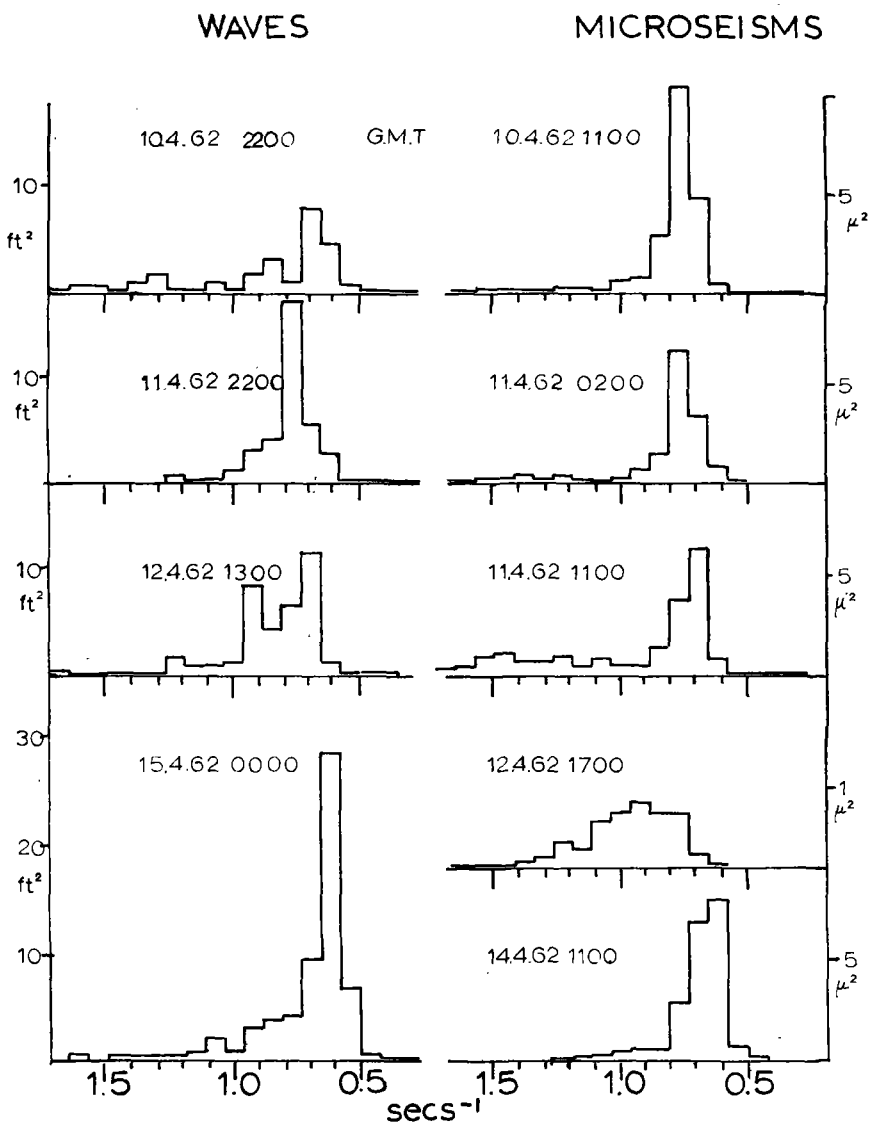


FIG. 2.—Frequency spectra of waves and microseisms, 1962 April 10 to 15.

but this can be explained to some extent by the wave interference area being further away from the recording station. The predicted wave amplitudes are not unreasonable but the periods are too short. It is possible that a given wind speed generates waves of higher period in these waters where there is a permanent swell than it would in the North Atlantic (see Phillips 1961). As the time for the waves to travel is only about twenty-four hours, however, errors in period leading to errors in group velocity will not greatly affect the placing of the wave interference areas. In this work no allowance has been made for coastal reflection but the waves were only coming head-on towards the coast in one of the examples, that of 1962 April 11 and the effect was probably slight apart from this.

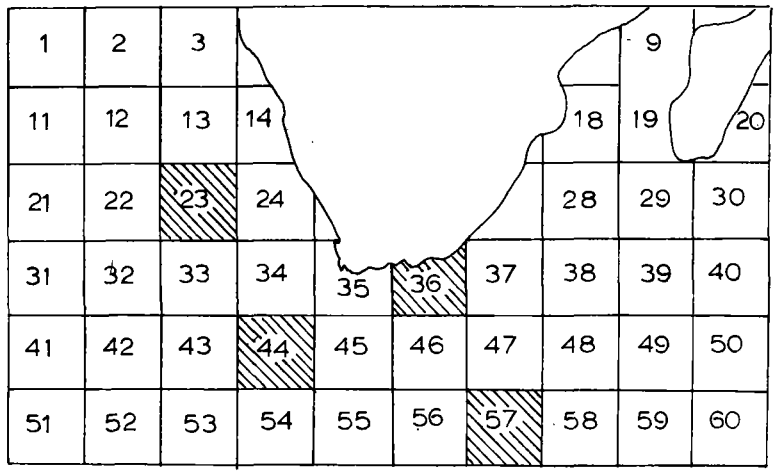


FIG. 3.—Diagram of 300-mile square-grid system showing areas of wave interference.

Table 1

Comparison of predicted wave energies and microseism variances

Date, time and location	Period band (s)	a_1^2 energy*	Direction	a_2^2 energy*	Direction	$a_1^2a_2^2$	Total $a_1^2a_2^2$	Total σ^2 for microseism (μm^2)
10.4.62	5–7	2·4	NE	1·1	SW	2·65		
1200	8–10	5·6	NE	2·2	SW	12·30	15·5	4·58
square 23	11–13	1·2	NE	0·44	SW	0·50		
11.4.62	5–7	1·5	SE	3·2	NW	4·8		
1200	8–10	3·5	SE	7·6	NW	26·5	34·8	5·07
square 44	11–13	0·8	SE	4·4	NW	3·5		
12.4.62	5–7	2·5	W	0·75	E	1·9		
1200	8–10	5·8	W	1·5	E	8·7	10·6	1·34
square 36	11–13	4·0	W	0				
14.4.62	5–7	2·5	SE	5·6	NW	14·0		
1200	8–10	5·8	SE	11·2	NW	64·5	122·5	5·05
square 57	11–13	4·0	SE	11·0	NW	44·0		
	14–16	0		1·6	NW	0		

* Unit of energy is $ft^{2/3}$ s.

3. Determination of direction of approach of microseisms

Various models have been suggested for the nature of microseisms approaching a given station. In the simplest case of all, the waves consist entirely of Rayleigh waves coming from a single direction. This would lead to a correlation coefficient of unity between the two horizontal component records which is seldom obtained. The next case is that of a mixture of Rayleigh and Love waves coming from a single direction. This was considered by Darbyshire (1954). A more complicated case was considered by Iyer (1959) who took the Rayleigh waves to come from one direction but the Love waves to be isotropic. These models are clearly idealistic

as the Rayleigh waves will only rarely come from one direction and Longuet-Higgins has considered the general case of both Rayleigh and Love waves coming from a range of directions. The analysis however, in the case of two horizontal components, even when this spreading is taken into account, gives the same value of the mean angle of approach as that of the angle in the simple case, and values of R^2/L^2, the Rayleigh to Love wave activity ratio, are not very different. The various models will be considered in order. The analysis is based on the maximum value of the correlation between two records (or the coherence) and the variances. These were worked out by computer and are given in Table 2.

Table 2

Variance and correlation coefficients of microseism records

Date	Time	Direction	Variance σ^2	Total variance EW+NS	Correlation coefficient
10.4.62	1100	EW	1·435	4·580	−0·183
		NS	3·145		
11.4.62	0200	EW	1.995	4·020	−0·284
		NS	2·025		
11.4.62	1100	EW	1·726	5·069	0·03
		NS	3·343		
12.4.62	1700	EW	0·606	1·338	−0·148
		NS	0·732		
14.4.62	1100	EW	1·725	5·053	−0·246
		NS	3·328		

(1) *Mixture of Rayleigh and Love waves coming from the same direction.*

Let $R(t)$ represent the Rayleigh wave motion and $L(t)$ the Love wave motion.

$R(t)^2$ is the Rayleigh wave activity and $L(t)^2$, the Love wave activity, x movement taken to be positive in W to E direction, $\bar{x}^2$ variance of EW component, y movement taken to be positive in S to N direction a $\bar{y}^2$ variance of NS component, θ measured from the positive x axis,

$$x = R(t)\cos\theta - L(t)\sin\theta, \qquad y = R(t)\sin\theta + L(t)\cos\theta$$

$$\bar{x}^2 = R(t)^2\cos^2\theta + L(t)^2\sin^2\theta, \qquad \bar{y}^2 = R(t)^2\sin^2\theta + L(t)^2\cos^2\theta$$

$$r_{xy} = \{R(t)^2 - L(t)^2\}\cos\theta\sin\theta = \tfrac{1}{2}\{R(t)^2 - L(t)^2\}\sin 2\theta$$

and

$$\bar{x}^2 - \bar{y}^2 = \{R(t)^2 - L(t)^2\}\cos 2\theta$$

so

$$\sin 2\theta = \frac{2r_{xy}}{R(t)^2 - L(t)^2}$$

$$\cos 2\theta = \frac{\bar{x}^2 - \bar{y}^2}{R(t)^2 - L(t^2)}$$

and so

$$\tan 2\theta = \frac{2r_{xy}\bar{x}\bar{y}}{\bar{x}^2-\bar{y}^2}.$$

The expressions for both $\sin 2\theta$ and $\cos 2\theta$ involve $\{R(t)^2-L(t)^2\}$ which can be positive or negative and so there is no restriction on the signs of these and

$$2\theta = n\pi + A$$

where

$$A = \tan^{-1}\frac{2r_{xy}\bar{x}\bar{y}}{\bar{x}^2-\bar{y}^2}$$

$$R(t)^2+L(t)^2 = \bar{x}^2+\bar{y}^2 \text{ and } R(t)^2-L(t)^2 = 2r_{xy}/\sin 2\theta$$

whence $R(t)/L(t)$ can be determined.

(2) *Rayleigh waves from one direction, Love waves isotropic.*

The analysis is similar but we assume initially that the Love waves come at an angle ϕ,

then

$$r_{xy} = \tfrac{1}{2}\frac{R(t)^2\sin 2\theta - L(t)^2\sin 2\phi}{\bar{x}\bar{y}}$$

and $\bar{x}^2-\bar{y}^2 = R(t)^2\cos 2\theta - L(t)^2\cos 2\phi$.

If all values of ϕ are equally probable, we can replace $\frac{1}{2}\sin 2\phi$ by

$$\tfrac{1}{2}\int_0^{2\pi} k\sin 2\phi\, d\phi = 0.$$

Then

$$r_{xy} = \frac{\frac{1}{2}R(t)^2\sin 2\theta}{\bar{x}\bar{y}}$$

$$\text{and } \bar{x}^2-\bar{y}^2 = R(t)^2\cos 2\theta$$

and once again

$$\tan 2\theta = \frac{2r_{xy}\bar{x}\bar{y}}{\bar{x}^2-\bar{y}^2}.$$

There is a difference between this case and case (1), however, as now $R(t)^2$ is always positive and the sign of $\sin 2\theta$ is determined by that of r_{xy} and that of $\cos 2\theta$ by that of $\bar{x}^2-\bar{y}^2$ and so we can only accept the solutions of $2\theta = n\pi + A$ which give the right sign to $\cos 2\theta$ and $\sin 2\theta$. $R(t)/L(t)$ can be found in a similar manner to case (1).

(3), (4) and (5). *Cases taking into account a finite range of directions.*

This has been discussed by Longuet-Higgins (1962). In general we have:

$$x = \textstyle\sum_n R_n\cos\theta_n\cos(6nt+\alpha n) - \sum_m L_m\sin\theta m\cos(6mt+\alpha m)$$
$$y = \textstyle\sum_n R_n\sin\theta_n\cos(6nt+\alpha n) + \sum_m L_m\cos\theta m\cos(6mt+\alpha m);$$

if the αs are uniformly distributed, it can be shown that for a small interval $d\sigma d\theta$

$$\sum_{d\sigma d\theta}\tfrac{1}{2}R_n^2 = F(\sigma,\theta)d\sigma d\theta$$
$$\sum_{d\sigma d\theta}\tfrac{1}{2}L_n^2 = G(\sigma,\theta)d\sigma d\theta.$$

Then

$$\bar{x}^2 = \int_0^{2\pi} \cos^2\theta F d\theta + \int_0^{2\pi} \sin^2\theta G d\theta$$

$$\bar{y}^2 = \int_0^{2\pi} \sin^2\theta F d\theta + \int_0^{2\pi} \cos^2\theta G d\theta$$

$$\bar{x}\bar{y} = \Gamma xy\bar{x}\bar{y} = \int_0^{2\pi} \cos\theta \sin\theta F d\theta - \int_0^{2\pi} \cos\theta \sin\theta G d\theta.$$

It is more tractable analytically to assume a rectangular distribution of directions, and assuming the Rayleigh and Love waves have the same mean direction, thus

$$F = R^2 \text{ for } \alpha-\beta < \theta < \alpha+\beta$$

and is o outside these limits.

$$G = L^2 \text{ for } \alpha-\gamma < \theta < \alpha+\gamma.$$

Thus

$$\bar{x}^2 = \tfrac{1}{2}\beta \int_{\alpha-\beta}^{\alpha+\beta} R^2\cos^2\theta d\theta + \tfrac{1}{2}\gamma \int_{\alpha-\gamma}^{\alpha+\gamma} L^2\sin^2\theta d\theta$$

$$\bar{y}^2 = \tfrac{1}{2}\beta \int_{\alpha-\beta}^{\alpha+\beta} R^2\sin^2\theta d\theta + \tfrac{1}{2}\gamma \int_{\alpha-\gamma}^{\alpha+\gamma} L^2\cos^2\theta d\theta$$

$$\bar{x}\bar{y} = \tfrac{1}{2}\beta \int_{\alpha-\beta}^{\alpha+\beta} R^2\cos\theta \sin\theta d\theta - \tfrac{1}{2}\gamma \int_{\alpha-\beta}^{\alpha+\beta} L^2\cos\theta \sin\theta d\theta;$$

on integrating

$$\bar{x}^2 = \tfrac{1}{2}(R^2+L^2) + \frac{R^2}{4\beta}\sin 2\beta \cos 2\alpha - \frac{L^2}{4\gamma}\sin 2\gamma \cos 2\alpha$$

$$\bar{y}^2 = \tfrac{1}{2}(R^2+L^2) - \frac{R^2}{4\beta}\sin 2\beta \cos 2\alpha + \frac{L^2}{4\gamma}\sin 2\gamma \cos 2\alpha$$

$$\bar{x}\bar{y} = \frac{R^2}{4\beta}\sin 2\beta \sin 2\alpha - \frac{L^2}{4\gamma}\sin 2\gamma \sin 2\alpha$$

$$= \sin 2\alpha\left(\frac{R^2}{4\beta}\sin 2\beta - \frac{L^2}{4\gamma}\sin 2\gamma\right).$$

Then $\bar{x}^2+\bar{y}^2 = R^2+L^2$

$$\sin 2\alpha = \frac{2\bar{x}\bar{y}}{\left(\frac{R^2}{2\beta}\sin 2\beta - \frac{L^2}{2\gamma}<\sin 2\gamma\right)}$$

$$\cos 2\alpha = \frac{\bar{x}^2-\bar{y}^2}{\left(\frac{R^2}{2\beta}\sin 2\beta - \frac{L^2}{2\gamma}\sin 2\gamma\right)}$$

and

$$\tan 2\alpha = \frac{2\bar{x}\bar{y}}{\bar{x}^2-\bar{y}^2}.rxy$$

which is the same equation as in the simple case. Three particular cases are of interest.

(3) *No Love waves present.*

Then

$$\cos 2\alpha = \frac{\bar{x}^2-\bar{y}^2}{R^2}\left(\frac{2\beta}{\sin 2\beta}\right)$$

$$\sin 2\alpha = \frac{2\bar{x}\bar{y}}{R^2}\left(\frac{2\beta}{\sin 2\beta}\right)$$

and again if $2\beta < 90°$ the signs of $\cos 2\alpha$ and $\sin 2\alpha$ are determined by that of $(\bar{x}^2-\bar{y}^2)$ and $\bar{x}\bar{y}$ and we have the same restrictions as in case (2). 2β can be calculated.

(4) *Rayleigh and Love waves from the same range of directions.*

Then

$$\cos 2\alpha = \frac{\bar{x}^2-\bar{y}^2}{(R^2-L^2)}\cdot\frac{2\beta}{\sin 2\beta}, \qquad \sin 2\alpha = \frac{2\bar{x}\bar{y}}{(R^2-L^2)}\cdot\frac{2\beta}{\sin 2\beta}$$

as the denominator can be positive or negative, there is no restriction on the sign of $\cos 2\alpha$ and $\sin 2\alpha$ and all the roots of $2\alpha = n\pi+A$ are admissible.

Now

$$R^2+L^2 = \bar{x}^2+\bar{y}^2, \qquad R^2-L^2 = \frac{2\bar{x}\bar{y}}{\sin 2\alpha}\cdot\frac{2\beta}{\sin 2\beta}$$

so the only difference between these equations and the corresponding ones for case (1) is the factor $2\beta/\sin 2\beta$ which is near unity for moderate values of β and so the value of R/L will not be greatly changed.

(5) *Love waves isotropic, $\gamma = \pi$.*

$$\cos 2\alpha = \frac{(\bar{x}^2-\bar{y}^2)}{R^2}\cdot\frac{2\beta}{\sin 2\beta}, \qquad \sin 2\alpha = \frac{\bar{x}\bar{y}}{R^2}\cdot\frac{2\beta}{\sin 2\beta}$$

which gives the same result as in case (3); again for $\beta < 90°$ as R^2 is always positive, there is the same restriction as in cases (2) and (3). The expression for R/L will again only be affected by the factor $2\beta/\sin 2\beta$.

Table 3 gives values of α (or θ) and the maximum possible value of β observed from Figure 4 which allows for the effect of refraction and those calculated according to these models, values of β being calculated for case (4) and in cases (5) and (6), given the observed value.

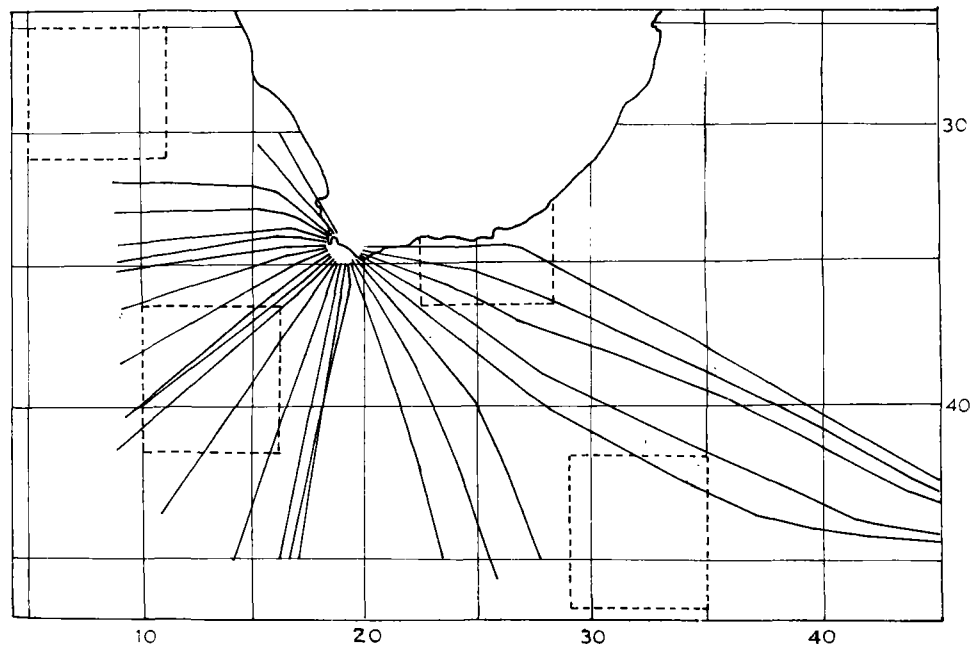


FIG. 4.—Refraction diagram for 6-sec microseisms.

Table 3

Observed and computed values of α and β

Example	Date Time	α observed	β observed	Model 1 α	Model 1 R/L	Model 2 α	Model 2 R/L	Model 3 α	Model 3 β	Model 4 α	Model 4 R/L	Model 5 α	Model 5 R/L
a	10.4.62 1100	135°	5°	102°	1·50	102°	0·82	102°	61½°	102°	1·50	102°	0·82
b	11.4.62 1100	220°	30°	178°	0·71	267°	0·70	267°	65°	178°	0·70	267°	0·71
c	12.4.62 1700	340°	20°	299°	1·20	299°	0·46	299°	76°	299°	1·21	299°	0·48
d	14.4.62 1100	320°	10°	288°	1·41	288°	0·78	288°	61°	288°	1·41	288°	0·78

The analysis was repeated by using a narrow band of frequencies, which included about the ten highest harmonics on the spectrum. The correlation coefficients and the variances could be worked out from the Fourier coefficients, for if:

$$x = \sum_{n=i}^{n=j} A_{xn} \cos nwt + \sum_{n=i}^{n=j} B_{xn} \sin nwt$$

$$y = \sum_{n=i}^{n=j} A_{yn} \cos nwt + \sum_{n=i}^{n=j} B_{yn} \sin nwt$$

$$2\bar{x}\bar{y} = \sum_{i}^{j} A_{xn}A_{yn} + \sum_{i}^{j} B_{xn}B_{yn}$$

$$2\bar{x}^2 = \sum_{i}^{j} (A_{xn}^2 + B_{xn}^2)$$

$$2\bar{y}^2 = \sum_{i}^{j} (A_{yn}^2 + B_{yn}^2),$$

iw and *jw* being the limits of the frequency band. The results are shown in Table 4.

Table 4

Observed and computed values of α and β

Example	Period range secs	α	β	Model 1 α	Model 1 R/L	Model 2 α	Model 2 R/L	Model 3 α	Model 3 β	Model 4 α	Model 4 R/L	Model 5 α	Model 5 R/L
a	6·4–7·2	135°	5°	102°	2·50	102°	1·64	102°	40°	102°	2·50	102°	1·64
b	6·7–7·7	220°	30°	188°	0·67	278°	0·80	278°	57°	188°	0·60	278°	0·93
c	5·4–6·5	340°	20°	327°	1·41	327°	0·70	327°	66°	327°	1·48	327°	0·77
d	7·1–8·2	320°	10°	300°	1·83	300°	1·08	300°	54°	300°	1·84	300°	1·09

The computed angles α are too small by 30° to 40° in the case of Table 3. The agreement, using a narrow frequency band is better, the computed angles now being between 13° and 32° too small. Of the various models used, (1) and (2) can be discarded as being unrealistic. Model (3) gives much too high values of β and it seems therefore unlikely that the waves consist only of Rayleigh waves. Model (4) on the whole gives better values of α than (5) and so gives a more accurate representation than any other model.

4. Refraction of microseisms

Figure 4 shows a refraction diagram for 6 s microseisms. It is based on the same assumptions as the diagrams prepared for Bermuda, (Darbyshire 1955), the British Isles (Darbyshire & Darbyshire 1957), and the western North Atlantic (Iyer, Lambert & Hinde 1958). The same procedure is followed as in the last named reference, the waves being assumed to travel outwards from the recording station and using the reciprocity principle to find divergence and convergence areas. The velocity of distortional waves in the sea bed was assumed as before to be 2·8 km/s. The depths east of Cape Agulhas are based on recent soundings taken by the S.A.S. *Natal* and R.S. *Africana II*, in connexion with the International Indian Ocean Expedition. Fewer soundings are available for the portion to the west and this part may not be so reliable.

5. Conclusions

Microseisms and waves recorded near Cape Town show a two-to-one frequency relationship which supports Longuet-Higgins's theory of microseism generation. Estimates of the direction of approach, taking into account the effect of refraction give some indication that the microseisms consist of a mixture of Love and Rayleigh waves coming from the same range of directions.

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WAVE OBSERVATIONS IN SOUTH AFRICAN WATERS*

J. Darbyshire and Mollie Darbyshire

ABSTRACT

Instrumental measurements of sea waves have been made off the coast of South Africa since January 1962. A ship-borne wave recorder is fitted in the Research Ship "Africana II" and is in regular use when the ship is at sea. The area normally covered lies between 31° and 38°S, and 15° and 22°E but in addition two longer cruises have been made to Marion Island. Records, of 15 minutes duration, are usually taken four times a day, and are in the form of a continuous trace of water level against time. The maximum wave height has been read from each record and values of mean and dominant wave periods have been calculated. The wave direction is estimated visually. The frequency distribution of these variables is summarised in tables and graphs. More detailed knowledge is given by the wave spectrum, which shows the wave energy plotted against its frequency. Examples obtained by means of harmonic analysis, illustrating the wave patterns developed by two different storms, are shown and discussed.

INTRODUCTION

Regular measurements of sea waves have been made by the Division of Sea Fisheries Research Ship "Africana II" since January 1962, using a ship-borne wave recorder. The general theory of wave generation and the method of measuring waves from a ship at sea have been described previously in this journal[3]. It is proposed to examine here the data which have so far been collected and to present the results available to date.

The area covered by the ship in its normal cruises is shown in Fig. 1. Two long cruises have also been made to Marion Island and these will be dealt with separately. The wave record appears as a continous trace of water level against time. Records of 15 minutes duration are usually taken four times a day while the ship is at sea. An example of a portion of a wave record is shown in Fig. 2. 458 such records have been made in the normal cruise area between January 1962 and March 1963. The number of observations in each one degree square is shown in Fig. 1. Unfortunately these are not well distributed through the year but are biased towards the summer months as shown in Table I. All available observations have nevertheless been used to make the total as large as possible. When the ship is moving the time scale is distorted and the records are only useful for measuring wave heights. However, 318 completely useable records were made when the ship was stationary and the number of these in each month is also shown in Table 1.

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MAXIMUM WAVE HEIGHT

The height from crest to trough of the highest wave on the record is known as the maximum wave height or H_{MAX}. In the wave record in Fig. 2. this is 24 feet. The maximum height has been measured for each record and the percentage of values falling in each 1 foot class is plotted in Fig. 3. The highest wave recorded was 30 feet and the modal value was 10 feet. The curve shown represents

$$y = 7{\cdot}6\exp - (\log 0{\cdot}1x)^2 / 0{\cdot}45$$

where x is the maximum wave height and y is the percentage frequency. This is a log normal curve and the constants have been chosen, both to give a reasonable fit to the observed data, and to satisfy the condition

$$\int_0^\infty y.dy = 100$$

The scatter of the points is due to the observed data being rather few but the curve

TABLE I—The number of wave observations in each month.

		No. of observations	*No. of observations with ship stationary*
1962	January	61	46
	February	39	34
	March	41	28
	April	55	29
	August	41	28
	September	41	27
	October	57	42
1963	January	58	43
	February	40	22
	March	25	19
	Total	458	318

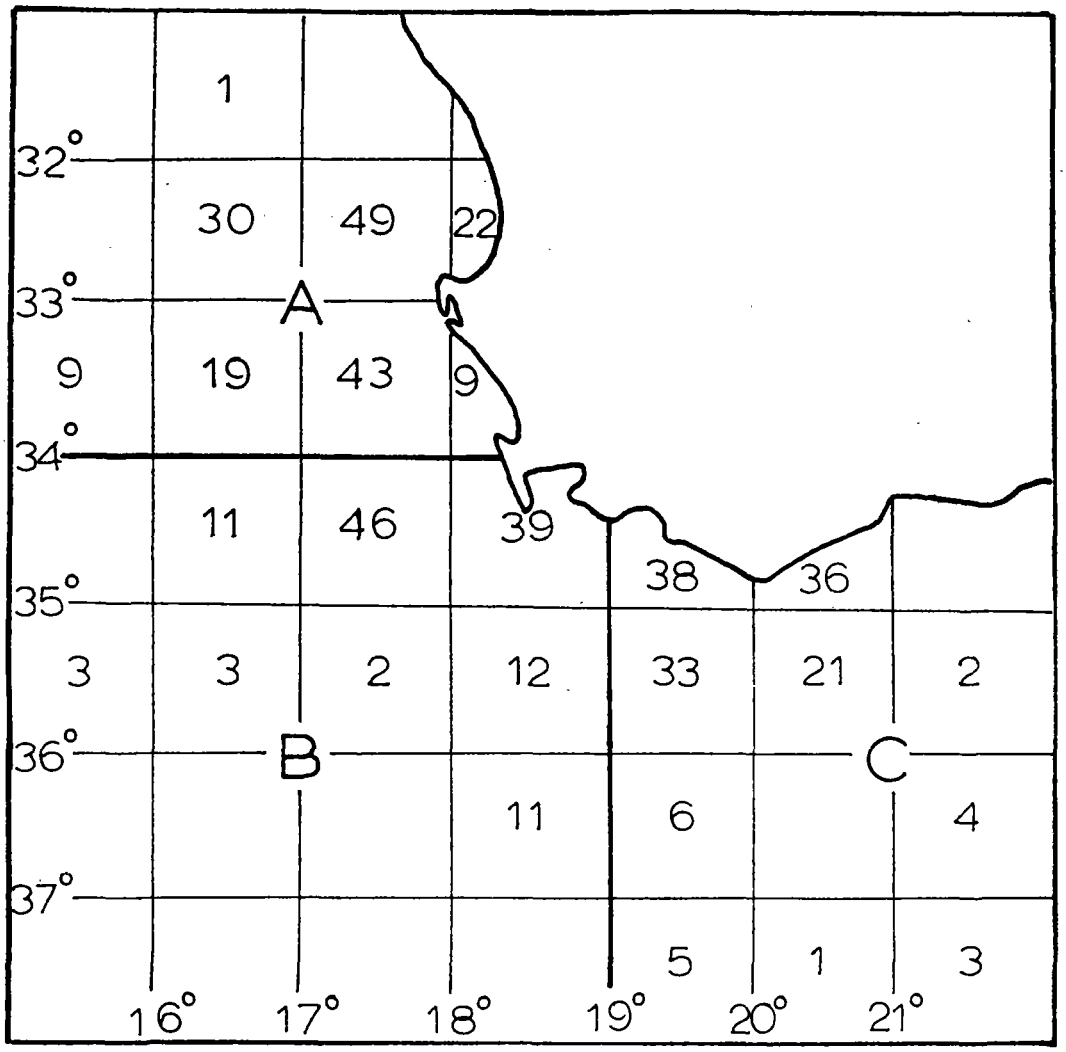


Fig. 1. The normal cruise area showing the number of observations in each one degree square.

gives a useful indication of the probability of the occurrence of any given wave height.

WAVE PERIOD

The wave period is a more difficult quantity to define and measure. In a simple wave pattern, the period is the length of time between the passage of two crests or two troughs, but the wave patterns we are studying tend to be rather complicated and a precise period difficult to determine. Two unsubjective measures of period which can easily be obtained have been suggested by Tucker[5]. These are the zero-crossing period and the crest period. An approximate mean water level is drawn on the wave record and a zero-crossing is then a point where the wave trace, moving in an upward direction, crosses this level, while a crest is a water level maximum. Zero-crossings and crests are indicated in Fig. 2.

If L is the length of record
N_z is the number of zero-crossings
and N_c is the number of crests.
then the zero-crossing period $T_z = L/N_z$
and the crest period $T_c = L/N_c$

Most wave records consist of a mixture of sea and swell: that is, the waves generated by the local wind and those generated by distant storms. If the wave pattern is built up from a number of different periodicities, the spectrum is rather broad, and T_z will

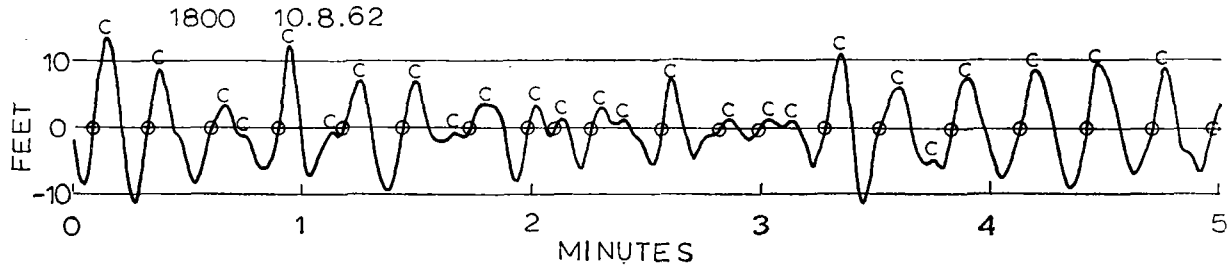


Fig. 2. A five-minute portion of a wave record. Wave crests are marked C and zero-crossings O.

be a good deal bigger than T_c. If, however, the period range in the spectrum is small, T_z and T_c will be almost equal. The ratio T_c/T_z gives a measure of the spectral band width. The mathematical theory for this has been discussed by Cartwright and Longuet-Higgins.[1]

T_z and T_c have been calculated for all records taken while the ship was stationary. The ratio T_c/T_z is generally about $\frac{3}{4}$. The percentage in each $\frac{1}{2}$ second class has been plotted in Fig. 4(a). The values of T_c lie quite close to the log-normal curve

$$y = 28/2 \exp - (\log x/7)^2 /0{\cdot}08$$

while the values of T_z fit the curve

$$y = 23/2 \exp - (\log x/10)^2 /0{\cdot}06$$

reasonably well. The maxima are quite widely separated, showing that we are dealing with quite broad band spectra in most cases.

The relationship of wave height to wave period is also interesting. In Table II the distribution of maximum wave height against zero-crossing period, expressed as a percentage, has been shown for the areas A, B and C marked in Fig. 1. There is no significant difference in the height distribution for the three areas but the periods seem to be a little lower in area C than in A or B.

WAVE DIRECTION

The dominant wave direction is estimated visually by one of the ship's officers at the time of recording. Table III shows the frequency distribution in eight direction classes for each of the three areas. South-west and south are the most common wave directions in all areas. Very few waves come from the north, and in area A, very few from the east or south-east. This is to be expected since most waves are generated by storms moving from west to east in the depression belt usually located to the south of the African continent.

TABLE II—Distribution of maximum wave height and zero-crossing period expressed as a percentage.

Height in feet	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*Total*
0– 5	2		1	1	1	1	2	1		9
5–10		1	8	6	5	6	1			27
10–15		2	6	8	12	6	2		2	38
15–20			2	2	6	1	3			14
20–25				1	2	2	1	2		8
25–30				1		1	1		1	4
Total	2	3	17	19	26	17	10	3	3	100

Height in feet	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*Total*
0– 5						1			1
5–10	1	3	6	5	6	4	3		28
10–15	1	4	5	11	9	10	5	2	47
15–20		1	4	3	4	1	4	4	21
20–25					1	1	1		3
Total	2	8	15	19	20	17	13	6	100

Height in feet	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*Total*
0– 5	1		1	1	1				4
5–10			5	12	14	9	3		43
10–15		1	3	2	10	11	2	1	30
15–20			2	2	2	2	4	3	15
20–25				4	1	2			7
25–30						1			1
Total	1	1	11	21	28	25	9	4	100

Area A...143 observations
Period in seconds
Area B...80 observations
Period in seconds
Area C...95 observations
Period in seconds

TABLE III—Frequency distribution of wave direction expressed as a percentage.

Area	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*
A	5	1	1	4	37	36	12	4
B	1		12	22	21	36	6	2
C		1	19	9	23	35	10	3
Total	2		10	11	28	36	10	3

CRUISES TO MARION ISLAND

The data from these two cruises in June and July 1962 and April 1963 is presented separately from the main area. There were a total of 143 wave observations, 54 of them with the ship stationary. The maximum wave height against the percentage frequency in each 1 foot class is also shown in Fig. 3. Marion Island is in latitude 47°S and so during much of the time the ship was actually in the storm belt. The waves are generally higher than in the coastal region, 38 feet was the highest recorded and the modal value was about 15 feet. The period distribution is shown in Fig. 4 (b). Here the range covered is similar to that in the coastal region except that T_c tends to be slightly higher so that the separation between the maxima of T_z and T_c is less. The waves generated by storms in these latitudes travel to the coast of South Africa so that the longer waves in both regions would tend to be similar. Height would be reduced after the waves leave the generating area because the total energy is spread over a wider area. T_c which depends more on the local wind would usually be higher in more southerly latitudes.

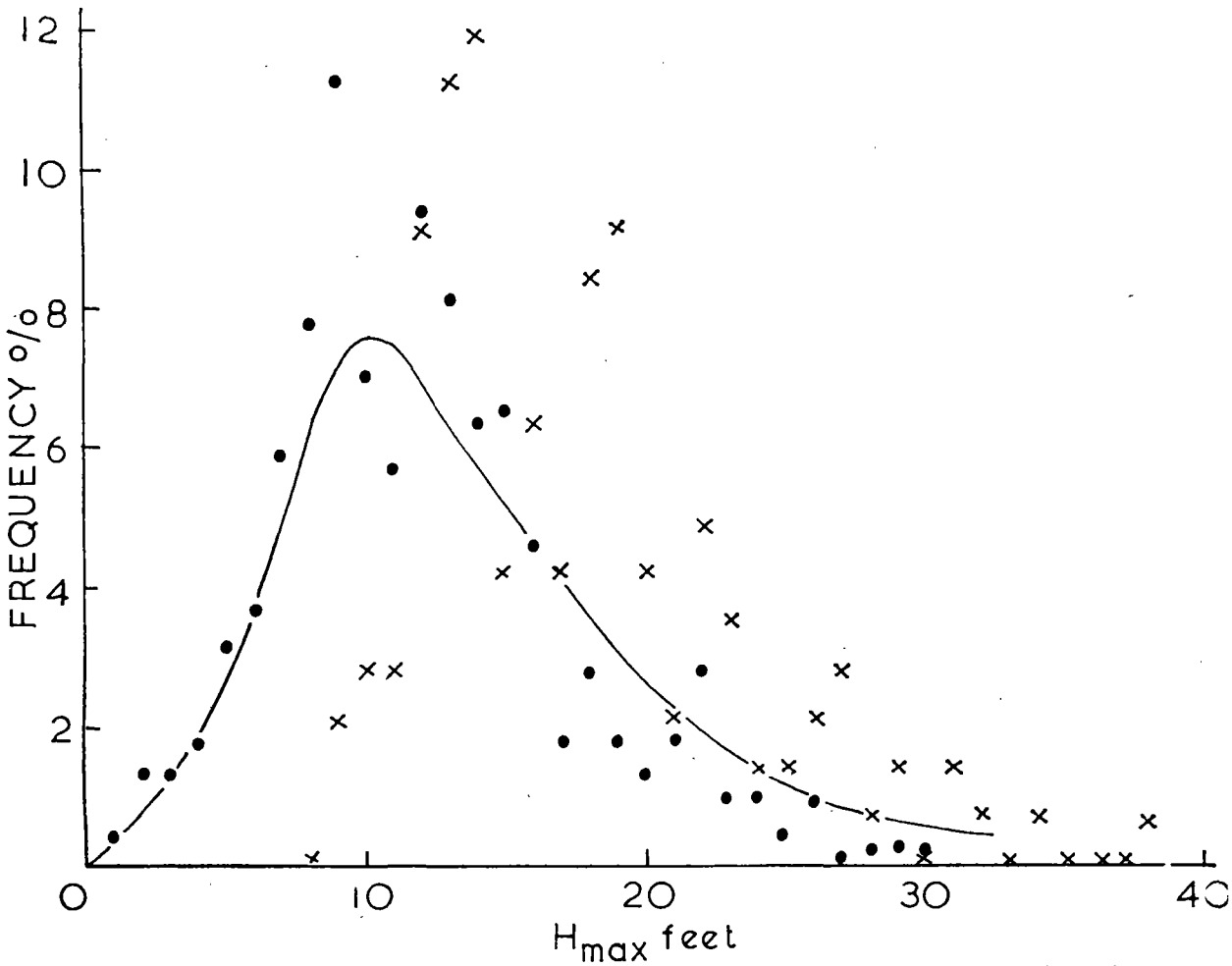


Fig. 3. The frequency distribution of maximum wave height. The circles show data from the normal cruise area and the crosses data from the Marion Island cruises.

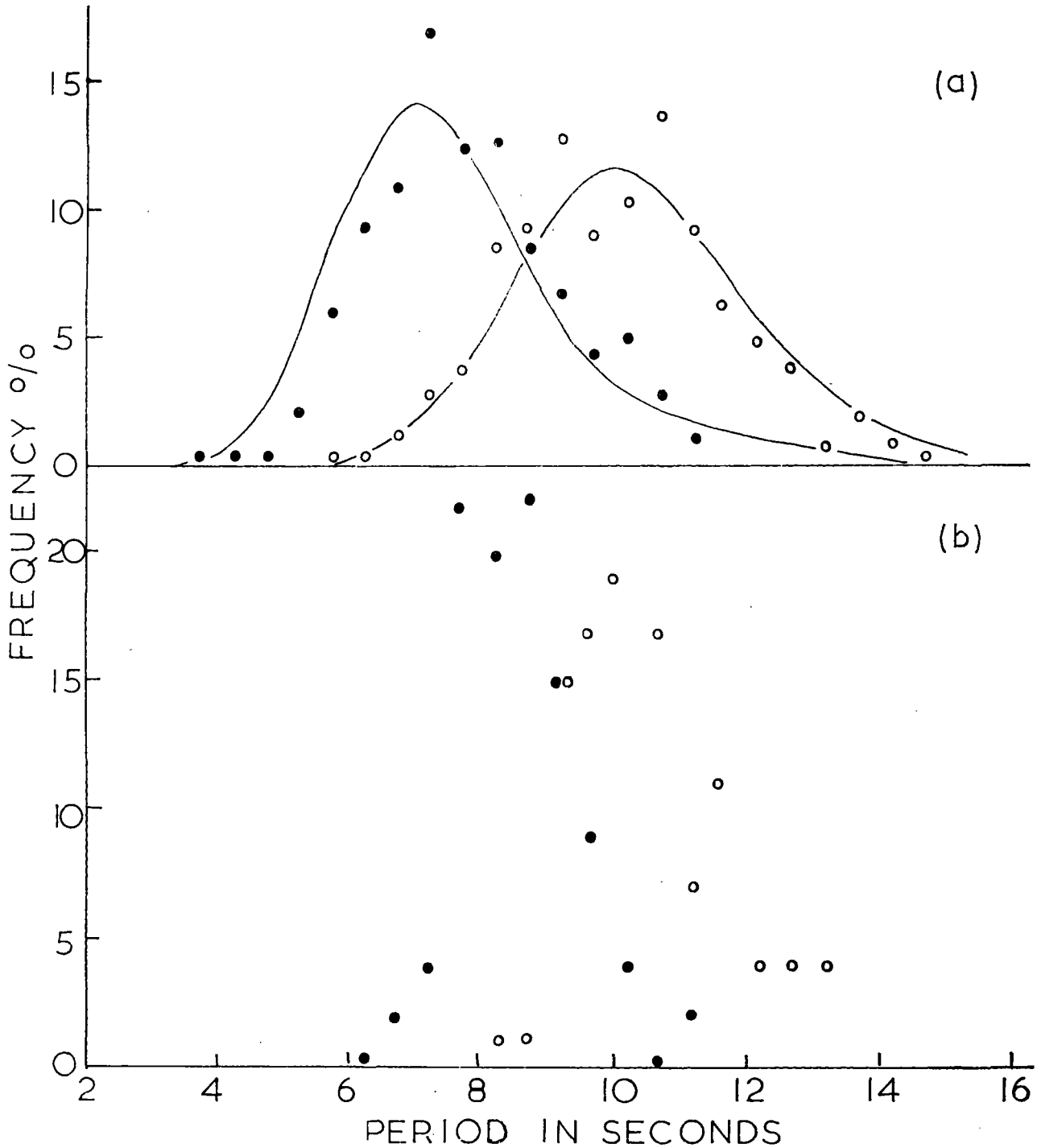


Fig. 4. The frequency distribution of wave period (a) for normal cruise area, (b) for Marion Island cruises. The closed circles give the crest period and the open circles the zero crossing period.

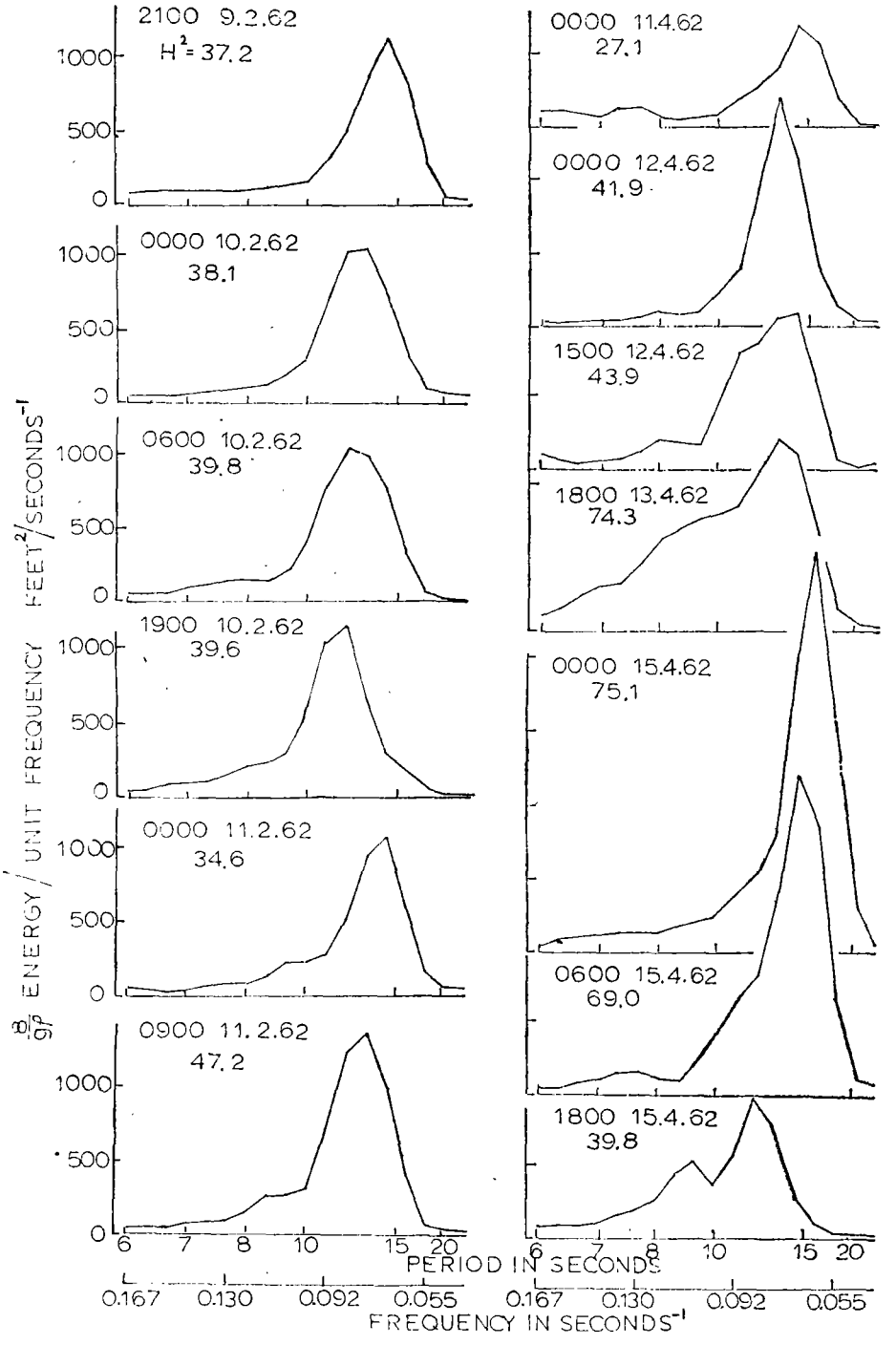


Fig. 5. Some examples of wave energy spectra.

WAVE ENERGY SPECTRUM

Only a few records have so far been analysed to give the wave energy spectrum. An optical analogue method was used and the spectra obtained were divided into equal frequency bands of 0·0075 seconds^{-1}. In Fig. 5. the energy in each of these bands is plotted against the frequency. The period scale is also indicated. The total energy in the spectrum is equal to $1/8g\rho H^2$ where H is the equivalent height, the height of a simple sine wave having the same total energy. An empirical relationship

$$H_{MAX} = 2{\cdot}40\ H$$

exists between the maximum and equivalent wave heights.[2] The value of H^2 for each spectrum is indicated in the diagram.

The waves whose spectra are shown here were generated by two storms in February and April 1962. Both storms moved from west to east, but the one in April came closer to the coast of South Africa. All the spectra are simple in shape with a clear maximum. The period of maximum energy, T_f, varies from 12 to 16 seconds. corresponding to values of T_z of 10 to 12 seconds. This ratio is in agreement with an empirical relationship between T_f and T_z found from data in the North Atlantic Ocean and around the coasts of Britain[4].

These two sets of spectra would appear to be fairly typical but more records need to be analysed before any definite conclusions about the spectrum both inside and outside the generating area can be reached.

CONCLUSIONS

The graphs and tables presented here provide a summary of the wave conditions experienced so far. They give a fairly good indication of the most common and the most extreme conditions to be expected although there is insufficient data at the moment to attempt a seasonal classification. The Marion Island cruises indicate that the wave height increases as one goes further south but that the period remains roughly the same. Examples of storm spectra show that most of the energy at these times is contained in the band from 10 to 16 seconds.

ACKNOWLEDGMENTS

The authors wish to thank the Director of the National Institute of Oceanography, Surrey, England, for the loan of the ship-borne wave recorder, also the Director of the Division of Sea Fisheries, Cape Town, and the Captain and Ship's Officers of the "Africana II" for their co-operation. Acknowledgment is made of funds provided by C.S.I.R. towards this research.

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The International Indian Ocean Expedition

PROGRESS IN METEOROLOGY

By C. S. Ramage
(Scientific Director for Meteorology, International Indian Ocean Expedition)

The two-year meteorological observing effort of the International Indian Ocean Expedition (IIOE) is now two-thirds over and most of the special measurement programmes have been completed. Thus the plans outlined in my article which appeared in the April 1963 issue of *The Marine Observer* have been largely fulfilled and investigators are now concentrating on assimilating and using the wealth of novel data at their disposal.

Of fundamental importance has been the continued and increasing help from merchant ships. On an average day the International Meteorological Centre in Bombay receives 200 weather reports by radio from ships in the Indian Ocean. A further 100 are added subsequently by mail. Many oceanographic vessels make radiation measurements and upper air soundings.

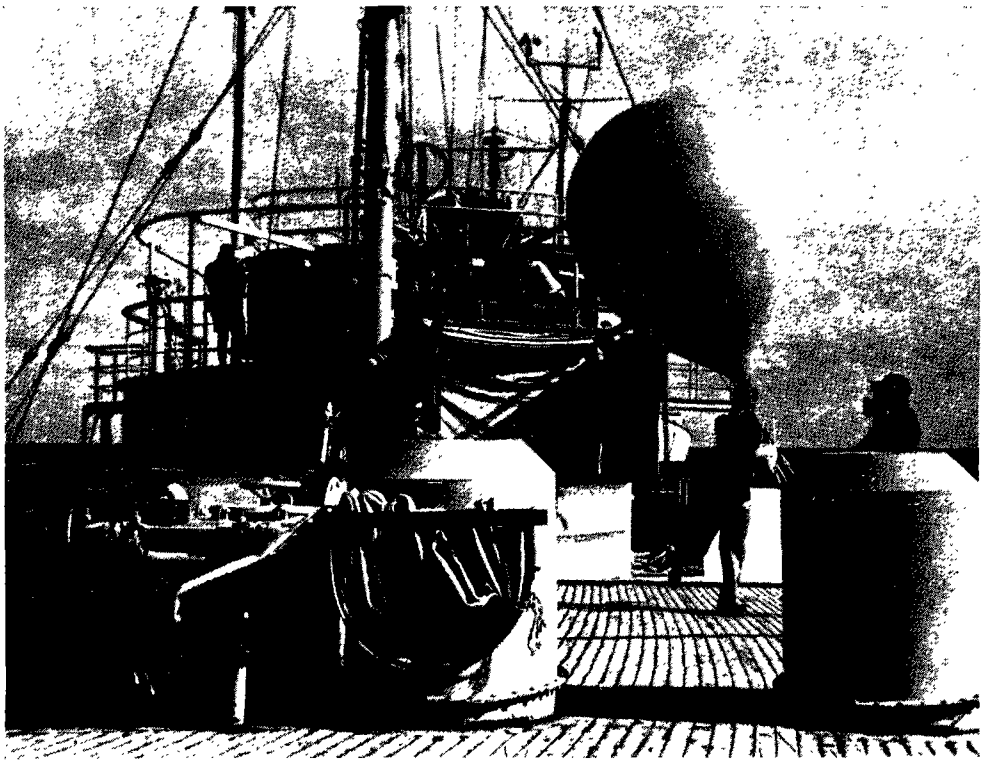
Research Aircraft

Five aircraft of the U.S. Weather Bureau and the Woods Hole Oceanographic Institution flew extensive scientific missions from their base in Bombay during May, June and July 1963, probing equatorial circulation systems and the Arabian Sea and Bay of Bengal monsoons. On 22nd May one of the DC-6 aircraft made the first aerial eye penetration of a north Indian Ocean tropical cyclone; on the 24th maximum winds of 104 kt. and an eye sea-level pressure of 947 mb. were recorded by the aircraft.

Three of the research planes returned for six weeks during February and March of this year. This time, besides equatorial flights, they ranged into the southern hemisphere, made many sorties in support of the University of Washington's air-sea interaction study and measured the intensity and extent of the western Indian sea-breeze. During the two visits, 124 scientific missions, totalling 830 hours were flown.

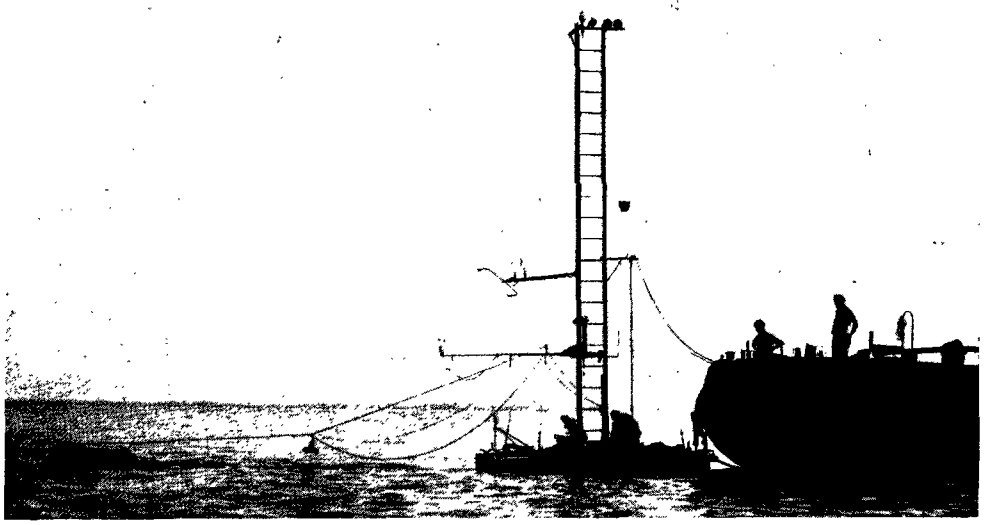
Air-Sea Interaction

In a project timed to coincide with return of the research aircraft to India, meteorologists from the University of Washington shipped a specially instrumented buoy (MENTOR) to Bombay and then with the Dutch tug *Oceaan* acting as tender made, and automatically recorded, continuous measurements of wind, temperature and humidity between 50 and 200 miles west of Bombay. While the fine structure of air-sea interaction was thus being recorded, MENTOR was being 'boxed' by the



A daily event on the U.S. research vessel *Anton Bruun*—release of a balloon-borne radiosonde. At other times during the day smaller balloons are tracked by theodolite to determine upper winds. The *Anton Bruun*, primarily designed for research into marine biology, has voyaged more extensively over the Indian Ocean than any other IIOE ship.

Photo by Woods Hole Oceanographic Institution.



research aircraft flying between 1,500 and 14,000 feet collecting data from which the total energy entering and leaving the 80 × 100 × 3 mile box could be evaluated.

Weather Satellites

As part of a grant from the U.S. National Science Foundation to the U.S. Meteorology programme of the expedition, a complete automatic picture taking ground equipment (APT) for weather satellites was installed at the International Meteorological Centre in December 1963. A few days later, the new satellite TIROS 8 was suitably instructed and pictures were received from it as it passed over the station. Immediate cloud information is thus available in Bombay from the North Indian Ocean and adjoining countries. In addition, intensive regular photography by TIROS 7 and TIROS 8 significantly contributes to research.

Meteorological Rockets

During 1964 meteorological rockets are being fired synoptically from Indian Ocean stations in a combined IIOE-International Quiet Sun Year (IQSY) programme. Australia, India, Italy, Pakistan and the United States are participating. The rocket probes will provide wind data, and occasionally temperature, pressure and density information between 20 and 45 miles above the earth.

Data Processing

The IBM 1620 computer installed at the International Meteorological Centre is now rapidly checking expedition data for accuracy and has begun computing ocean/atmosphere heat exchanges using punch card records of ship's weather observations. Data are also being microfilmed and back-plotted on a master synoptic chart file. Progress has been so rapid that specific plans are now being formulated for preparation and publication of detailed IIOE meteorological atlases.

Research

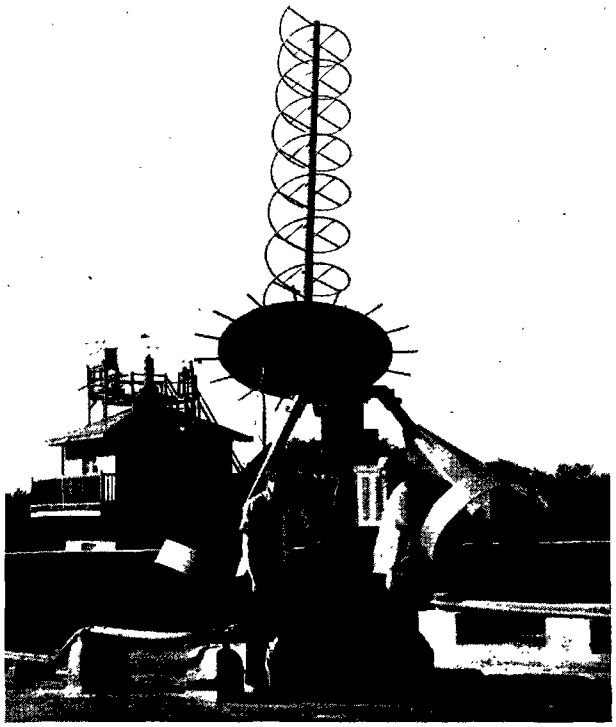
In August 1963 investigators reported preliminary research results at a seminar in Bombay. The proceedings have appeared in pre-published form. Studies have so far largely concentrated on monsoon circulations, upper air climatology, air-sea exchange, sea breezes, and tropical cyclones. Two investigations now in hand illustrate the wealth and variety of data that diligent effort can provide.

INDIAN SEA BREEZE: The sea breeze of the mountain-rimmed coast of western India is among the world's most intense, extending a hundred miles or more inland and to seaward and two miles in depth. During early March the research aircraft flew multi-level day and night missions perpendicular to the coast and traversing *Oceaan* (the Netherlands Research Ship) whose officers were making frequent pilot balloon ascents. Besides continuous onboard electronic and photographic records, observers on the aircraft noted the drift of smoke and the edge of the Bombay 'smog'; autographic records at coastal and inland stations pinpointed wind, temperature and humidity changes and a special programme of one-hourly wind observations by merchant ships provided information on circulation variations along the coast.

Opposite page (lower photograph):
The University of Washington's MENTOR buoy being assembled in Bombay harbour. A movable instrumented boom measures wind, temperature and humidity up and down the 30-ft. mast. Similar reference measurements are made from the fixed boom, on the end of which can be seen a sonic anemometer.

Watertight wells in the buoy's pontoons contain electronic equipment. When measurements begin at sea, stability is ensured by filling the cylindrical keel with water and lowering it to a position vertically below the mast. The buoy floats freely 1,000 feet upwind of and attached by electric cables to the tug tender which houses recording equipment.

Photo by U.S. Information Service.



A satellite automatic picture taking (APT) antenna installed at the International Meteorological Centre. The antenna, driven by Selsyn motors remote-controlled from the receiving console, tracks the satellite as it orbits from horizon to horizon.

Photo by U.S. Information Service.

DOLDRUMS: A study of doldrum weather over the eastern Indian Ocean is focussing attention on the meteorological events of 5th February 1964. On that day numerous merchant ships traversing the Singapore–Colombo, Singapore–South Africa, Singapore–Fremantle and Fremantle–Aden routes made weather reports. Surface and upper air observations were made at Gan, Diego Garcia and Cocos and at continental coast stations. Two research aircraft flew from Gan to Cocos. One RAF transport aircraft made excellent time-lapse films of clouds between Gan and Singapore and another, equally valuable 35 mm. stereo cloud photographs between Singapore and Gan. The Gan radarscope was photographed for rain echoes while TIROS 7 and 8 recorded clouds over the whole region in a sequence of orbits.

New observing techniques and intensive application of older, well-tried methods are delineating the weather of the Indian Ocean in unprecedented detail. A relatively few scientists, powerfully aided by the computer, are now engaged in the challenging and exciting task of understanding and explaining.

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SALINITY MAXIMA IN THE UPPER 1000 METRES OF THE NORTH INDIAN OCEAN

By D. J. ROCHFORD*

[*Manuscript received January* 6, 1964]

Summary

The comprehensive hydrological data from cruise 31 of R.S. *Vityaz* in the north Indian Ocean have been used to identify all salinity maxima of the upper 1000 m. On the basis of density differences these salinity maxima have been grouped into five water masses. Three of these have been named according to their assumed origin; Red Sea, Persian Gulf, and Arabian Sea. The other two can not as yet be assigned origins, although one is confined largely to the northern part of the Arabian Sea and the other to the equatorial region of the Indian Ocean. Paths of flow of these water masses to the south and east have been established from salinity charts. Submarine topography in the Madagascar–Seychelles and Maldive–Chagos regions provides an explanation for the diversion and separation of the flow paths of these water masses.

I. INTRODUCTION

The extensive hydrological data obtained by R.S. *Vityaz* during cruise 31 in the Indian Ocean have been used by Ivanov-Frantskevich (1961) to identify and plot the limits of Indian Central water, Arabian Sea Water, and Red Sea water. Mokiyevskaya (1961) described the oxygen and nutrient characteristics of these high salinity water masses. However, in examining the hydrological structure of the upper 500 m of the south-east Indian Ocean, it was found necessary to make a more detailed study of the characteristics and distribution of north Indian Ocean high salinity water masses in order to decide the origin of the salinity maxima of the former region.

The data from cruise 31 of R.S. *Vityaz* are not extensive enough in space or depth to show all the features of the distribution of these salinity maxima, but as a guide to the planning of future cruises it was thought useful to publish the results of this study to show:

(1) The deficiencies in our present knowledge of the number and general distribution of such maxima;

(2) The degree of complexity in the salinity–temperature relations of north Indian Ocean waters;

(3) The need for more closely spaced and more carefully chosen sampling depths to allow the fullest interpretation of the water mass structure of these waters.

II. MATERIAL AND METHOD

The data from cruise 31 of R.S. *Vityaz* were obtained from World Data Centre B. The data from cruise 2 of R.S. *Ob* have been published (Arctic and Antarctic Research Institute, Leningrad, 1959). The distribution of stations used by six ships in the

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north Indian Ocean is given in Figure 1. The following steps were followed for the identification of the high salinity water masses of the north Indian Ocean:

(1) For each station a salinity–temperature diagram was drawn (e.g. Fig. 2) using a scale of 2 cm for each 1°C and 0·10‰ salinity.

(2) From these diagrams the salinity–temperature values of all salinity maxima (Fig. 2) of the upper 1000 m were determined. A salinity maximum is defined as that point on a salinity–temperature curve which has a salinity value greater than the value

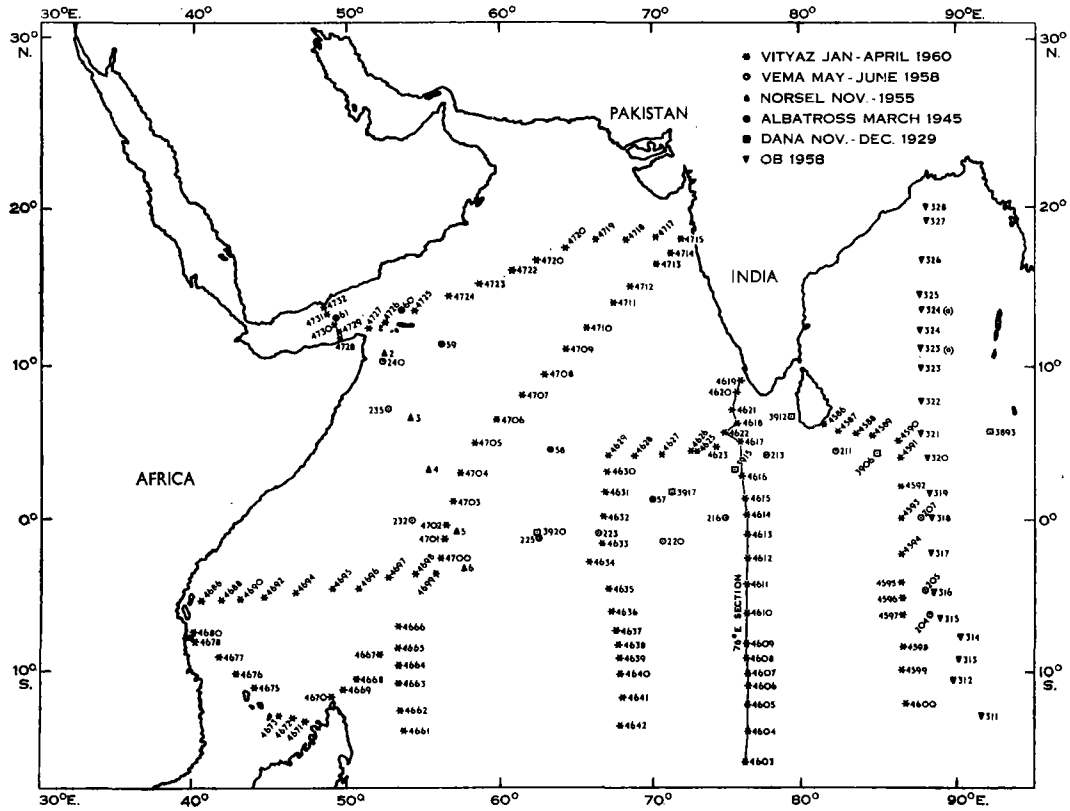


Fig. 1.—Chart of the stations used.

obtained by the mixing of the waters above and below it on the curve. On an individual curve maxima sometimes coincide with observed values (e.g. *A*, *B*, and *D*, Fig. 2) but in other cases they fall between observed values and their properties must be determined from a smooth free-hand curve (e.g. *C*, Fig. 2). Generally, however, by comparing salinity–temperature curves from adjacent stations, the shapes of these fitted curves can be kept consistent.

(3) The salinity–temperature values of these salinity maxima were plotted on a salinity–temperature diagram of the same scale as Figure 2, and each salinity

maximum is identified by its station number. Appropriate σ_t curves were drawn (Fig. 3).

(4) These salinity maximum values were then grouped into water mass assemblages centred around a σ_t surface (*A* and *B*, Fig. 3) or crossing the least number of σ_t surfaces (*C*, *D*, and *E*, Fig. 3).

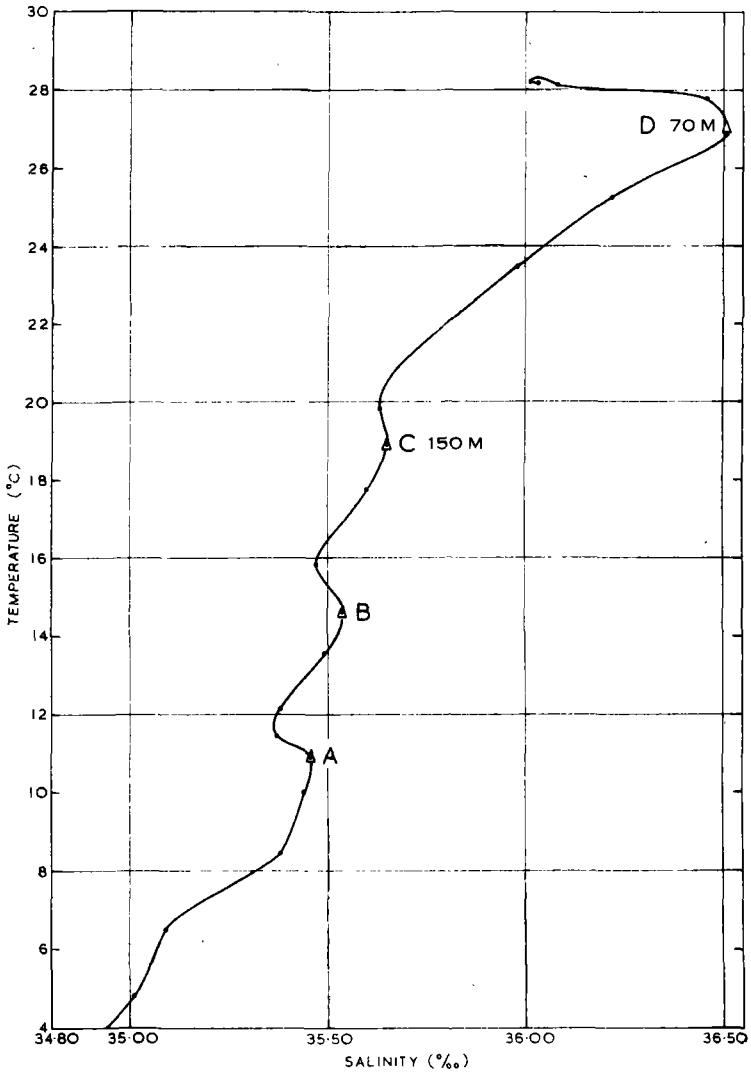


Fig. 2.—Temperature–salinity diagram for *Vityaz* station 4710 showing the characteristics of salinity maxima *A*, *B*, *C*, and *D*.

(5) On the same diagram salinity–temperature characteristics of the oxygen minima of the region were entered (Fig. 3). These oxygen minima generally form only in waters of poor advection (Wyrtki 1962) and therefore should not, as a rule, be found within the mixing envelope of any high salinity water mass assemblages.

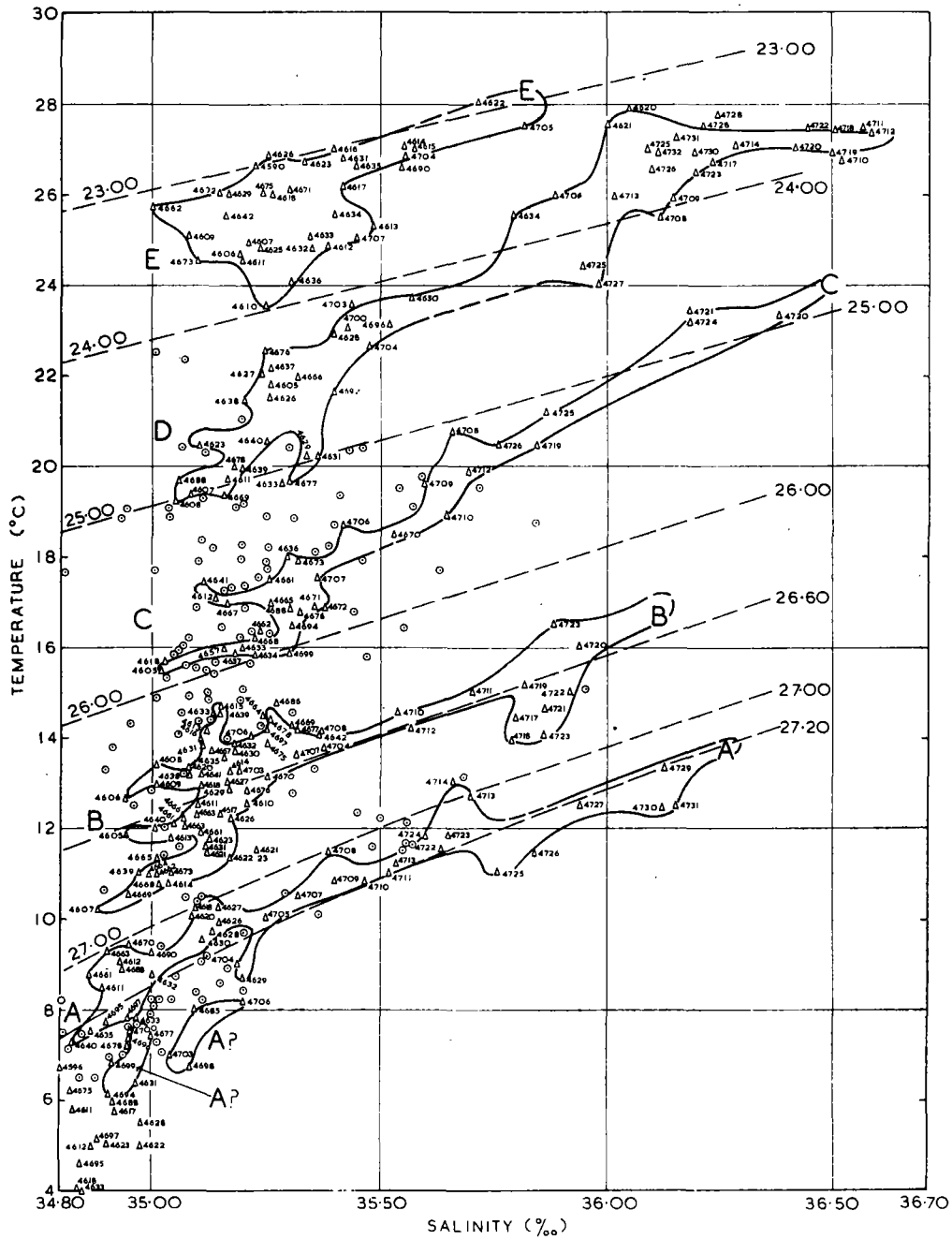


Fig. 3.—Salinity–temperature characteristics of all salinity maxima of the upper 1000 m for the Arabian Sea and north Indian Ocean. Each maximum has been identified by its station number and grouped into water mass assemblages *A*, *B*, *C*, *D*, and *E*. The salinity–temperature characteristics of oxygen minima have been plotted on the same diagram (⊙).

If this does happen it is generally possible to adjust the temperature–salinity limits of the envelope to conform to this requirement.

(6) For each water mass, charts (e.g. Fig. 4) were then prepared showing the distribution of salinity (read from Fig. 3) and its depth (from original data records).

Salinities were determined on *Vityaz* cruise 31 by the Knudsen titration and are probably accurate to about ±0·02‰. For this reason, salinity maxima cannot be

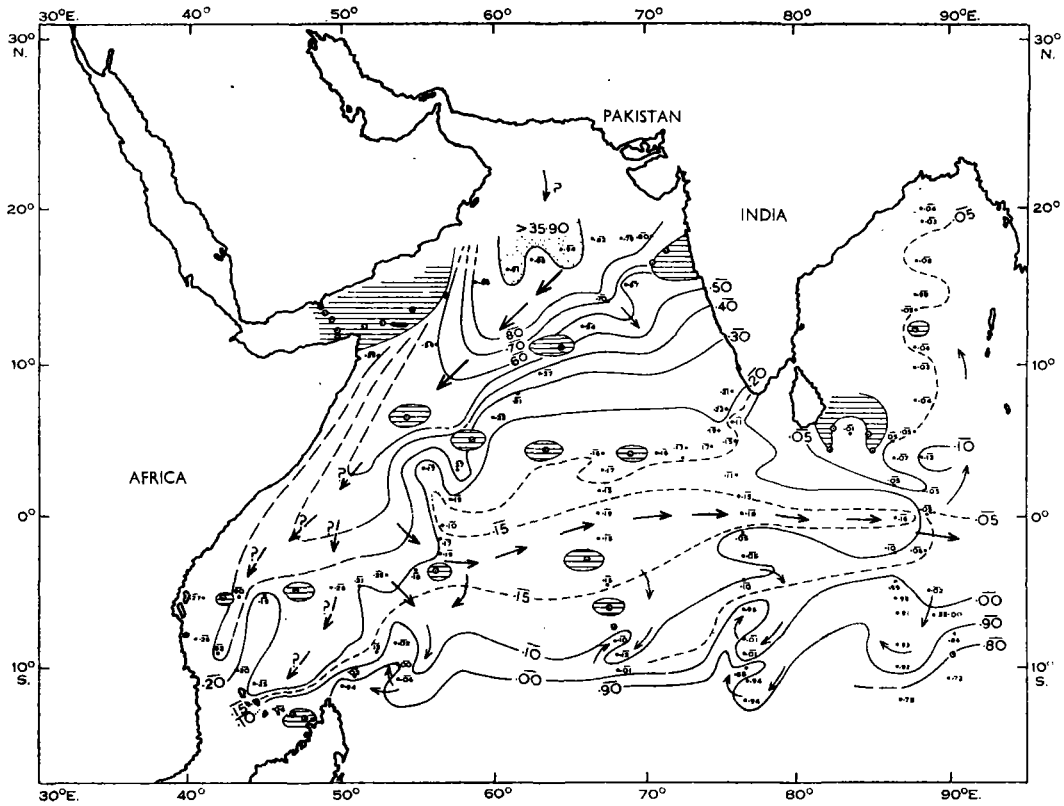


Fig. 4.—Chart of the distribution of salinity within the core of salinity maximum *B*. In all charts of the distribution of salinity, salinities of 35·00‰ or more are quoted as barred values less 35·00. Salinities of 34·00–34·99‰ are quoted as values less 34·00. Salinities greater than 35·99‰ are quoted in full. Arrows show the major directions of drift from the source region. Cross rulings show the extent of stations, marked ⊙ at which salinity maximum *B* was not found.

considered significant unless their salinity is 0·04‰, or more, greater than the value at their temperature on the line connecting adjoining minima. The significance that can be attached to the depth calculated for a particular salinity maximum is also affected by the accuracy of the salinity determination. A maximum on the salinity–temperature curve will be displaced towards higher or lower temperatures, and hence towards greater or lesser depths, if opposing values (within the above accuracy limits) of salinity be used to define the maximum. In general terms it is difficult to

assess the magnitude of this error of depth, since it is influenced by the shape of the individual salinity–temperature curves and by the depth separation of the points forming the curve. However, it is thought not to exceed 100 m between 500–1000 m and to be less than 50 m between 0–500 m.

Inorganic phosphate distribution within the core of the various salinity maxima (e.g. Fig. 5 for salinity maximum *B*) was sometimes used to aid the correct contouring of salinity and to verify paths of distribution within the salinity pattern. Some isolated

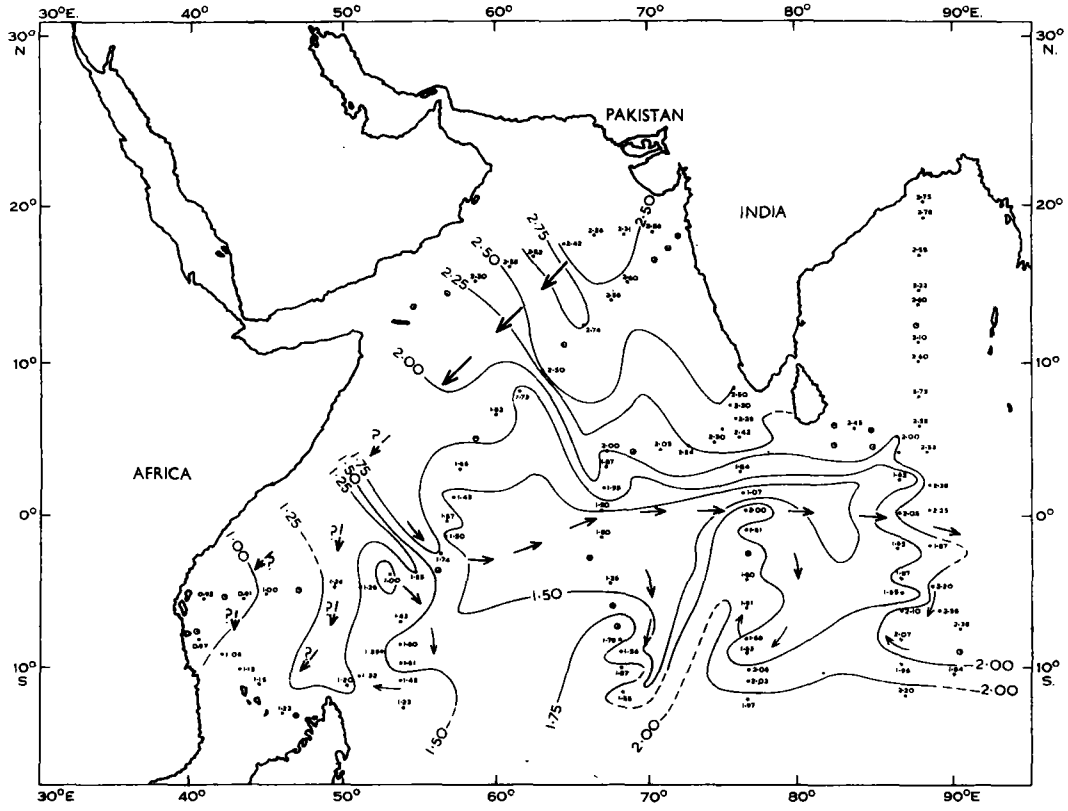


Fig. 5.—Chart of the inorganic phosphate distribution within the core of salinity maximum *B*. Arrows show the major directions of drift from Figure 4.

stations within the major flow paths of these salinity maxima do not show in their temperature–salinity relation evidence of a particular maximum. An example of this is the group of stations to the south of India within the eastern drift of water mass *D* (Fig. 6). Whilst the absence of this water mass at these stations could be caused by localized strong mixing or diversion by counter drift, it is possible, and sometimes very probable, that this absence is the result of lack of sampling at the depth of this water mass. For example at station 4614 (Fig. 7) within the above group of stations, the shape of the temperature–salinity curve between 90 and 110 m, and hence the presence or absence of salinity maximum *D*, can not be decided from the data

available. However, at all such stations the water mass has had to be considered absent. Future cruises are needed with sampling depths chosen so that the true shape of the temperature–salinity curve and hence the presence or absence of any water mass can be determined.

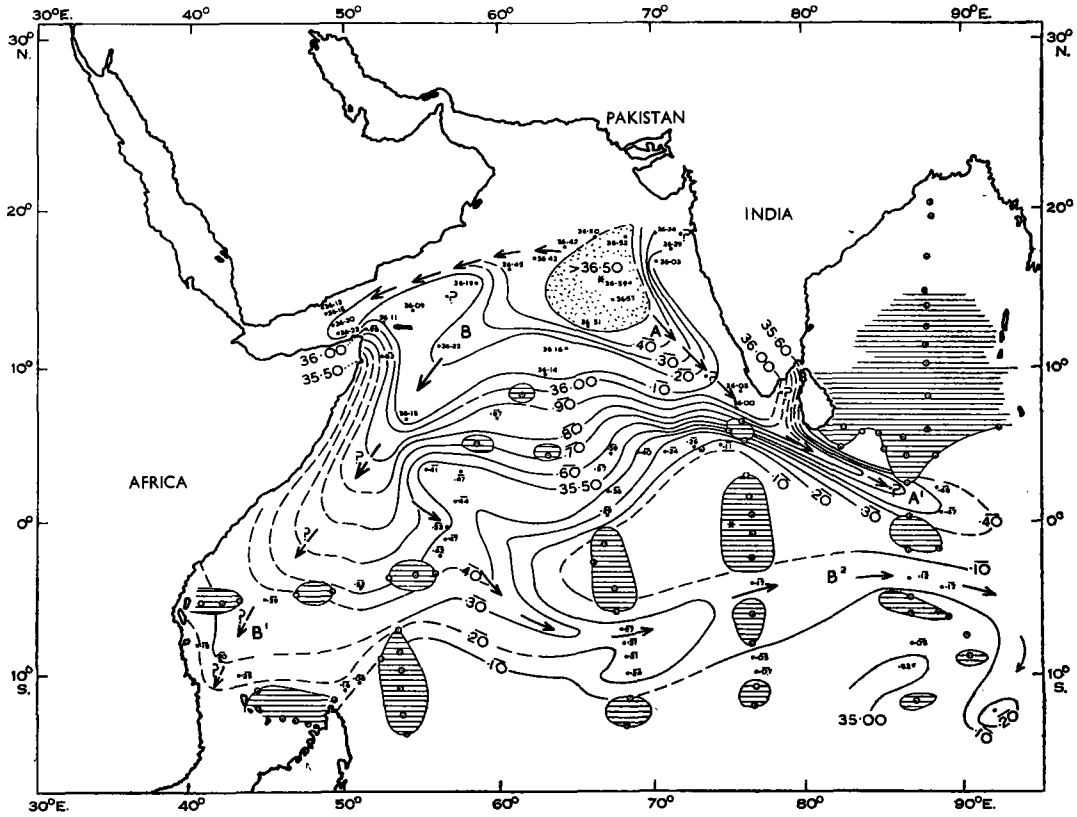


Fig. 6.—Chart of the distribution of salinity within the core of salinity maximum *D*. Salinity and other coding as in Figure 4. A–A^1 Major drift path during south-west monsoon. B–B^1–B^2 Major drift paths during north-east monsoon.

III. Salinity Maxima of the North Indian Ocean

Five salinity maxima were identified in the Arabian Sea and north Indian Ocean (*A–E*, Fig. 3).

(*a*) *Salinity Maximum A*

The highest salinity values were found in the Gulf of Aden (Fig. 8) and clearly identify the Red Sea as the origin of this salinity maximum. The salinity distribution of this water mass shows that it spreads from the Gulf of Aden eastwards towards India and southwards towards Madagascar and the African coast to at least 10° S.

The relatively high salinity of this water mass in the east Indian Ocean can be maintained only by persistent spreading from the west side but no indication of the routes of such spreading can be found in the salinity countours.

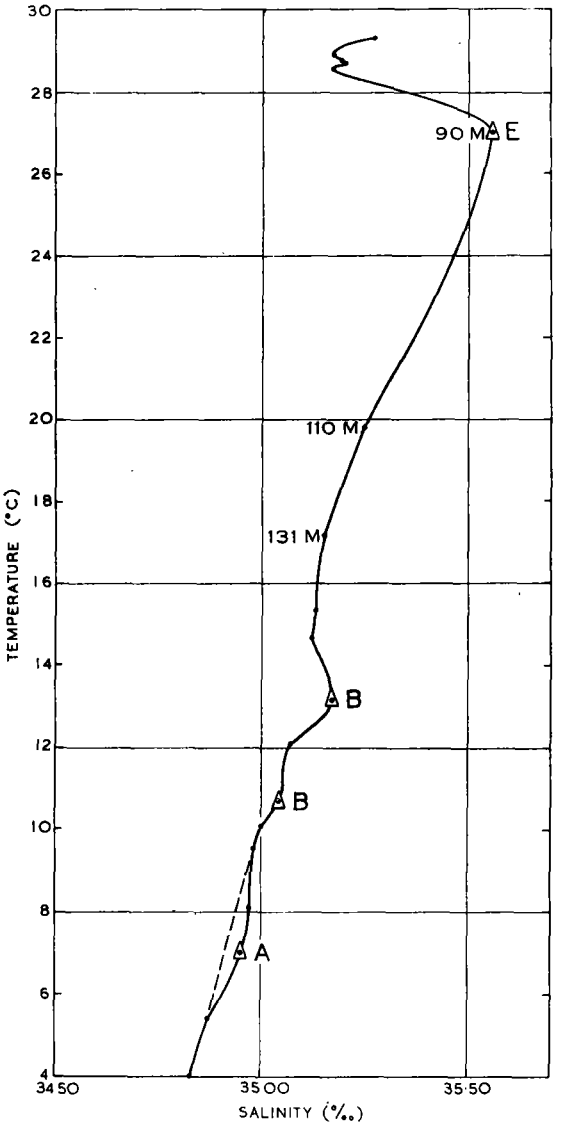


Fig. 7.—Temperature–salinity diagram for *Vityaz* station 4614 showing the characteristics of salinity maxima, *A*, *B*, and *E*.

The Red Sea water mass entered the Arabian Sea at about 800 m (Fig. 9) and spread south at about the same level. Generally this water mass shallowed to 500–600 m as it spread eastwards. Along its southern limit of distribution in the

central and eastern parts of the Indian Ocean this water mass was found as deep as 800–900 m. The sudden and somewhat anomalous deepening of this water mass at 0–5° N. around 60° E. (Fig. 9) was caused by depths greater than 900 m at stations 4703, 4705, and 4706. However, at both stations 4703 and 4705 two salinity maxima within the density range of water mass *A* were found at depths of 600–1052 m. At station 4706 only one salinity maximum identifiable as water mass *A* was found at 970 m. The depths in Figure 9 show the deepest occurrence of water mass *A* in the above region around 60° E. where it is thought deep mixing was greatly increased.

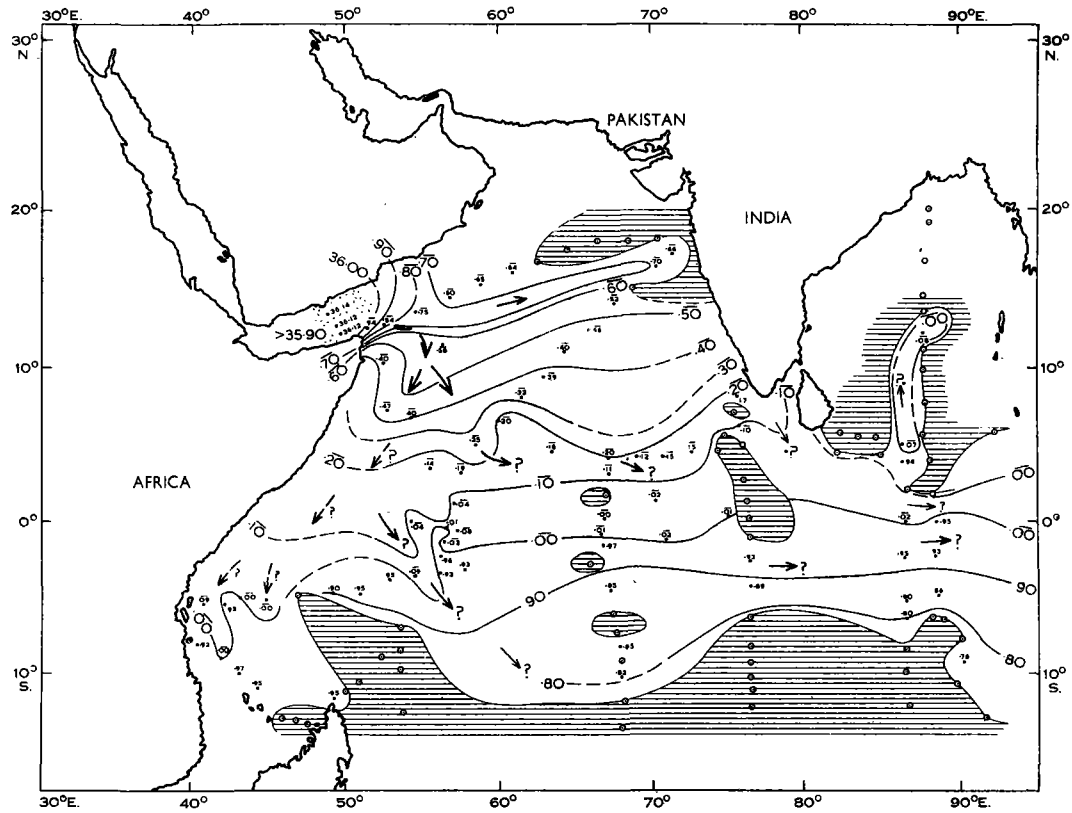


Fig. 8.—Chart of the distribution of salinity within the core of salinity maximum *A*. Salinity and other coding as in Figure 4. Arrows show major directions of drift from the source region.

(*b*) *Salinity Maximum B*

Since the highest salinity values in this group (Fig. 3) were found at depth in the central, north Arabian Sea (Fig. 4), and these high salinity waters were absent around the Gulf of Aden, the Persian Gulf is considered the origin of salinity maximum *B*. The comparatively high salinities along the Somali coast to at least 10° S. must be maintained by a spreading of these Persian Gulf waters in that direction. Centred around the equator, from 55°–90° E. at least, was a region of relatively high salinity

waters; the eastward penetration of these Persian Gulf waters is thought to be principally through this region. Southward from this region salinities decreased, probably because of strong mixing with lower salinity waters along the frontal region at about 10° S. (Ivanov-Frantskevich 1961). This Persian Gulf water spreads into the Bay of Bengal but the data are not sufficient to show by which route this occurs. This Persian Gulf water was found at depths of about 300 m in the north Arabian Sea but elsewhere along its paths of spread (to the south-west and to the east along

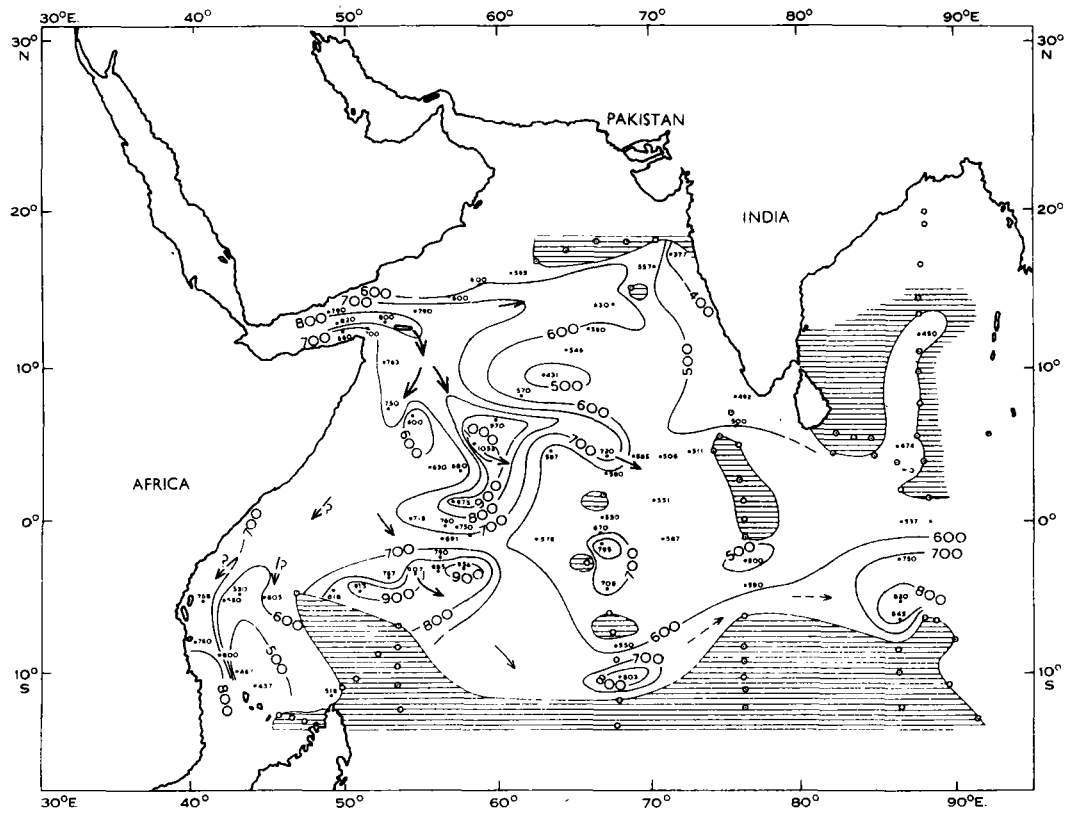


Fig. 9.—Depth of the core of salinity maximum *A*. Arrows from Figure 8.

the equator) its average depth was around 200 m (Fig. 10). In the Bay of Bengal and south of the equator it was found at depths of 300–400 m. In the north Arabian Sea the inorganic phosphate value of this Persian Gulf water was about 2·50 μg-atom/l and this value was maintained throughout the eastern part of the Arabian Sea (Fig. 5). Along its principal paths of spread to the south-west and to the east, phosphate values were much lower (1·00–1·50 μg-atom/l). Very high phosphate values (greater than 3·00 μg-atom/l) were found at the depth of these Persian Gulf waters in the Bay of Bengal.

(c) *Salinity Maximum C*

Near its apparent source region in the Arabian Sea this salinity maximum possessed salinity–temperature characteristics which clearly separated it from the salinity maxima *B* and *D* adjoining it on the curve (Figs. 2 and 11). Its distribution was very limited in extent (Fig. 12) compared with that of *B* and *D* (Figs. 4 and 6) being found only at depths of 100–200 m (Fig. 13). The available salinity data suggest that this high salinity water drifts south in the central part of the Arabian Sea until it meets

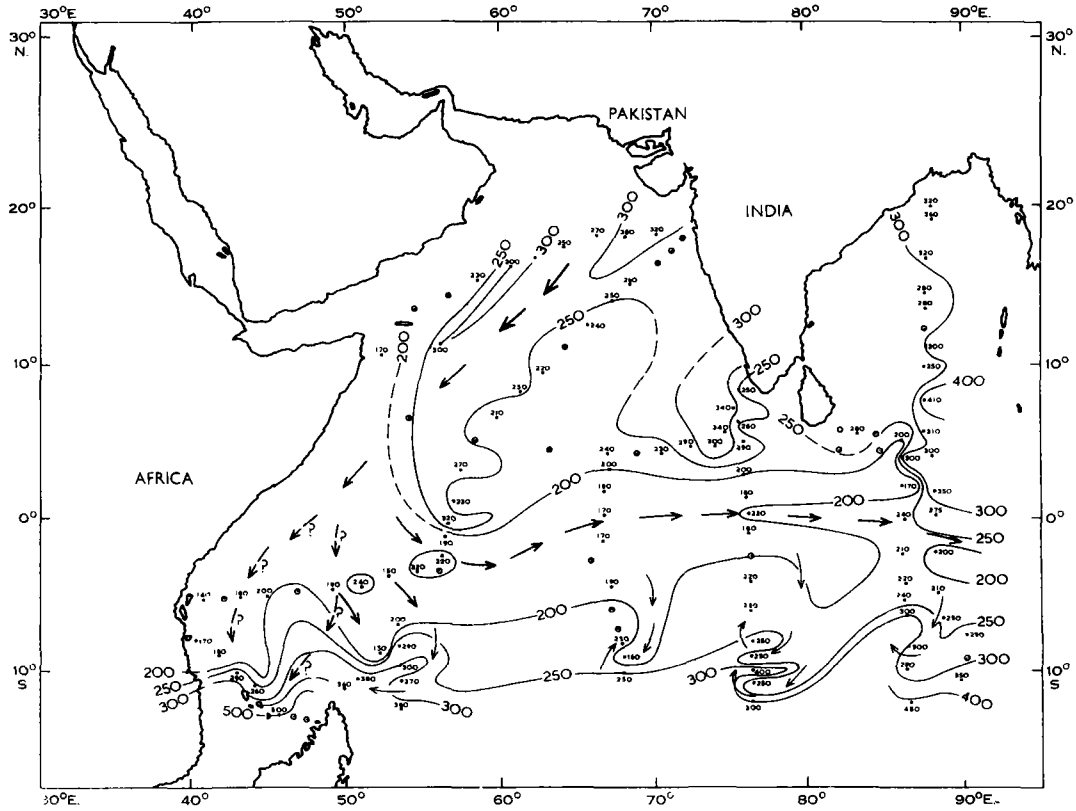


Fig. 10.—Depth of the core of salinity maximum *B*. Arrows from Figure 4.

the zonal currents around the equator. Within these zonal currents it either loses its identity by mixing or is spread as isolated patches of water usually towards the west. The origin of this high salinity water cannot be decided although it must be in the north Arabian Sea or from the surface of the Persian Gulf.

(d) *Salinity Maximum D*

This maximum was found at the surface of the central Arabian Sea (Fig. 14) where its highest salinities were recorded (Fig. 6). This water has therefore been called Arabian Sea high salinity water. Because of its shallow depth (Fig. 14) this water is subject to seasonal changes in distribution, caused by monsoonal reversal of

surface currents. The general distribution of salinity within the core of this Arabian Sea high salinity water (Fig. 6) is thought to be governed by the north-east monsoon circulation pattern. This causes a movement of the water mass, to the west in the north Arabian Sea, to the south-east in the region west of 60° E. and to the east

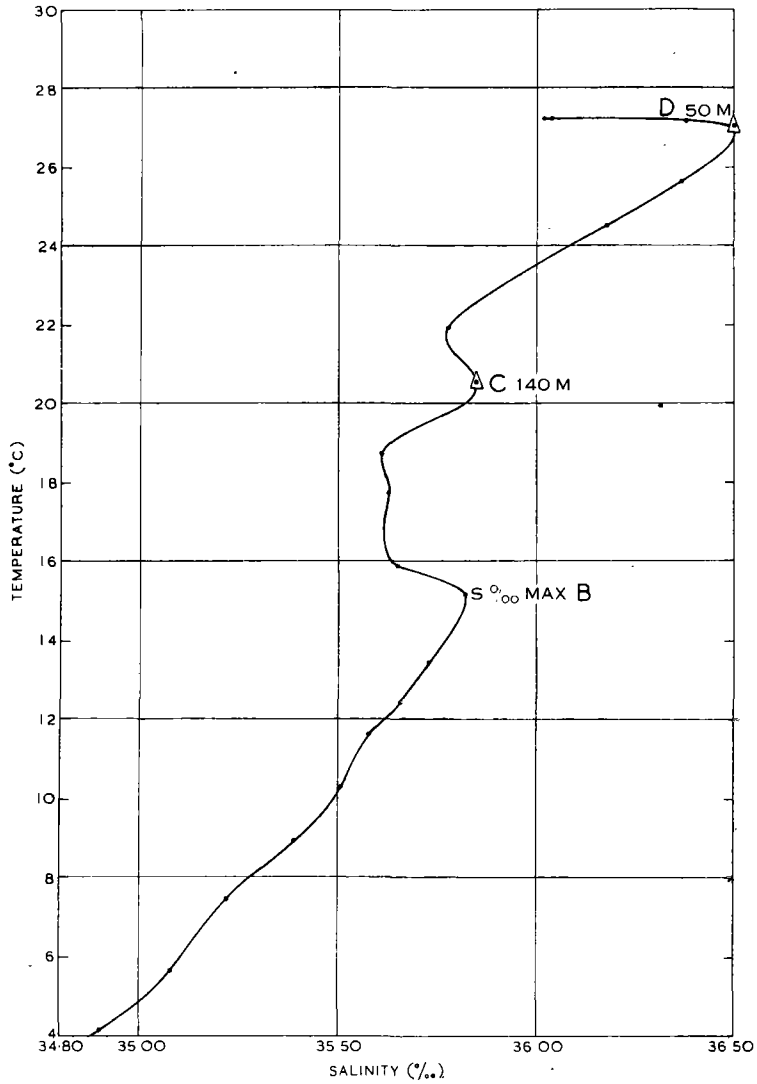


Fig. 11.—Temperature-salinity diagram for *Vityaz* station 4719 showing the clear separation of salinity maximum *C* from salinity maxima *B* and *D*.

around 5° S. (B–B^1–B^2, Fig. 6). However, the distribution of this high salinity water southward past Ceylon (A–A^1, Fig. 6) is thought to be part of the south-west monsoon pattern. In general the depth at which this water occurred increased from north to south and from west to east (Fig. 14).

(e) *Salinity Maximum E*

This high salinity water was found throughout the equatorial region of the Indian Ocean from about 10° S. to 10° N. (Fig. 15). It did not occur in the Arabian Sea or in the Bay of Bengal. High salinities (greater than 35·50‰) were found at *V*, *W*, and *X Y* (Fig. 15) close to the equator and at *Z* (Fig. 15) in the south Arabian Sea. The depth of this salinity maximum varied from 0–110 m (Fig. 16), with depths greater than 75 m predominating in the south, north, and east.

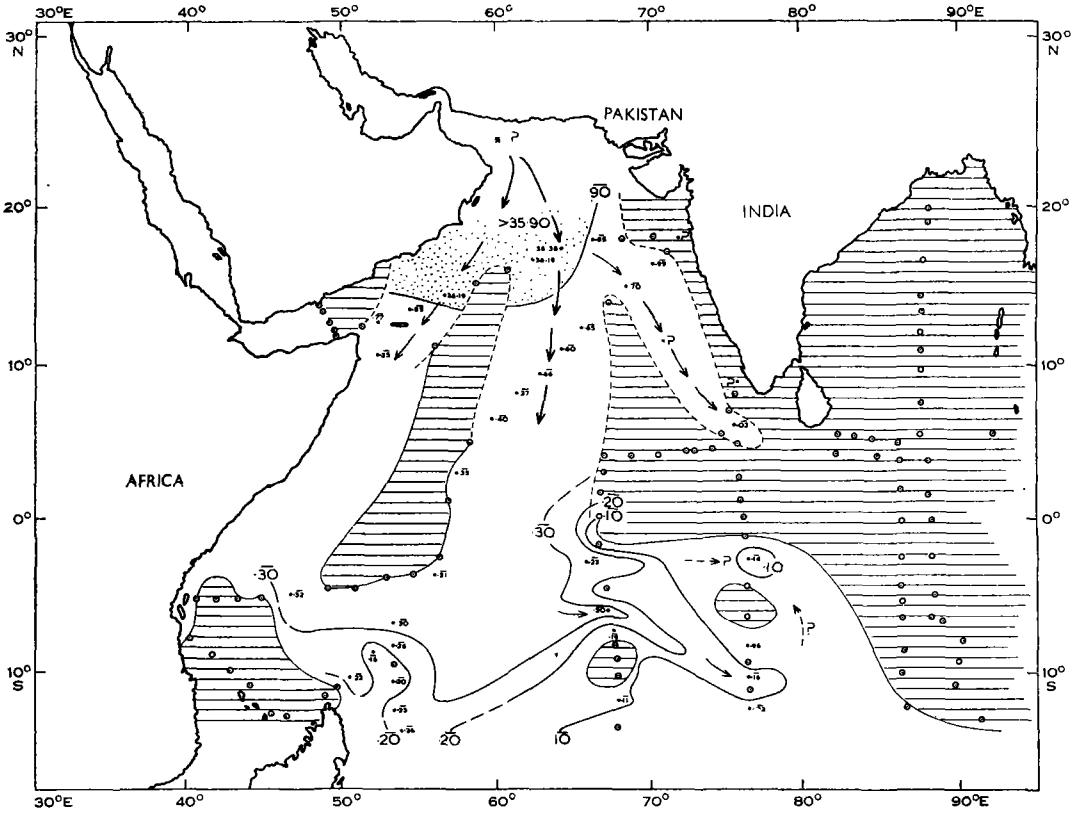


Fig. 12.—Chart of the distribution of salinity within the core of salinity maximum *C*. Salinity and other coding as in Figure 4.

IV. Vertical Distribution of Salinity Maxima

Vityaz stations along the 76° E. meridian (Fig. 1) have been used to prepare a representative trans-equatorial section of salinity and of the vertical relations of the salinity maxima (Fig. 17) in the upper 900 m. South of 13° S. only one salinity maximum was found between 100–250 m. This maximum which comprises only the upper part of the Indian Central Water of Sverdrup *et al.* (1942) is considered continuous with the south-east Indian high salinity water (Rochford 1961). North of 13° S., however, a complex salinity pattern was found. This pattern was caused by variations in the depth and geographic positions of the various high salinity waters of northern

origin (Fig. 3). Very weakly developed salinity maxima thought to be of Red Sea origin (*A*, Fig. 3) were found only between 2° and 4° S. at depths of 500–600 m, and at 500 m at stations 4618 and 4620 near South India. Since these waters are found as far east as the 110° meridian (Rochford 1961) considerable eastward transport must occur through this section at other times. Ovchinnikov (1961) using the "differential method" found that all flow along the 76° E. section at 500 m was directed to the east, in the same direction as deduced above from salinity distribution (Fig. 18).

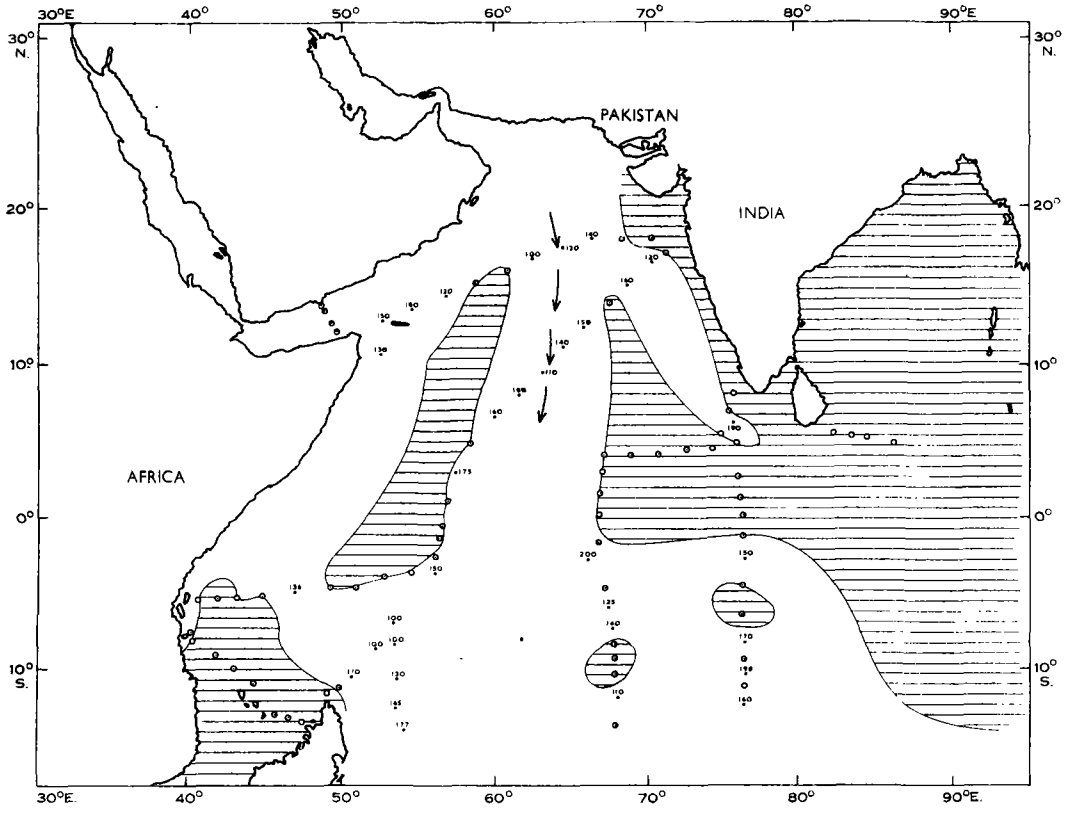


Fig. 13.—Depth of the core of salinity maximum *C*.

High salinity waters of the Persian Gulf (*B*, Figs. 3 and 17) were found at 200–300 m at all stations north of 12° S. except for station 4617 at 5° N. South of this station the phosphate content of these Persian Gulf waters was less than 2·00 μg-atom/l whilst north it was much greater than 2·00 μg-atom/l (Fig. 17). South of 5° N. the highest salinity of these waters was found at station 4615 near the equator. This is believed (Section III) to be the centre of eastward movement of these Persian Gulf waters. Ovchinnikov (1961) found from direct measurements that waters at 200 m were moving to the east in a zone from 2° S. to 3° N. centred around station 4615 (Fig. 19); this is in good agreement with the deductions from salinity distribution.

Ovchinnikov (1961) also found eastward movement from 5° S. to 12° S., the southern position agreeing with the southern limit of Persian Gulf waters, deduced from salinity values (Fig. 17).

Between 100 and 200 m isolated patches of high salinity waters *C* and *D* (Fig. 17) from the Arabian Sea (Section III) were found; south of India the very high salinities (greater than 36·00‰) of waters from the Arabian Sea (*D*, Fig. 3) were thought to be caused by the previous south-west monsoon circulation (Section III). The very low

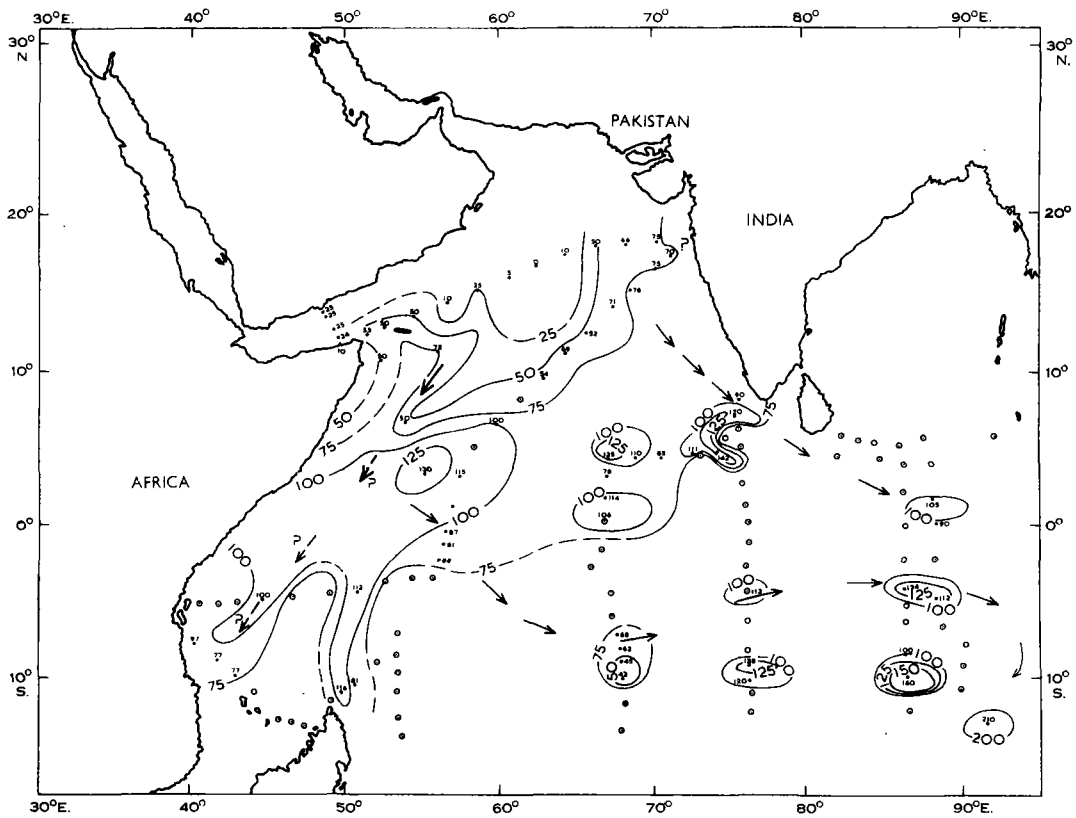


Fig. 14.—Depth of the core of salinity maximum *D*. Arrows from Figure 6.

salinity waters around 8° S. and 6° N., within the 100–200 m stratum (Fig. 17) must be part of a discrete horizontal circulation bounded by the high salinity water masses *B*, *C*, *D* and *E*.

Since the lowest salinities of the Indian Ocean, north of 20° S., at depths of 100–200 m are found in the eastern part (Sverdrup *et al.* 1942) it is probable that these low salinity waters originate in this region and are flowing west. This would agree with observed currents at 15 m (Fig. 20) but not with those at 200 m (Fig. 19). Further

consideration will be given to the origin and circulation of these low salinity waters in a separate paper (Rochford, unpublished data).

High salinity waters, *E* (Fig. 3), were found at 50–100 m at all stations from 11° S. to 6° N. (Fig. 17). These waters form the subsurface salinity maximum with a σ_t of about 23·30 as observed by Jerlov (1953). A section at 88° *E.* (Jerlov 1953) shows these waters to have high salinities (greater than 35·50‰) around the equator, in about the same position as a high salinity belt of water mass *E* along the 76° E.

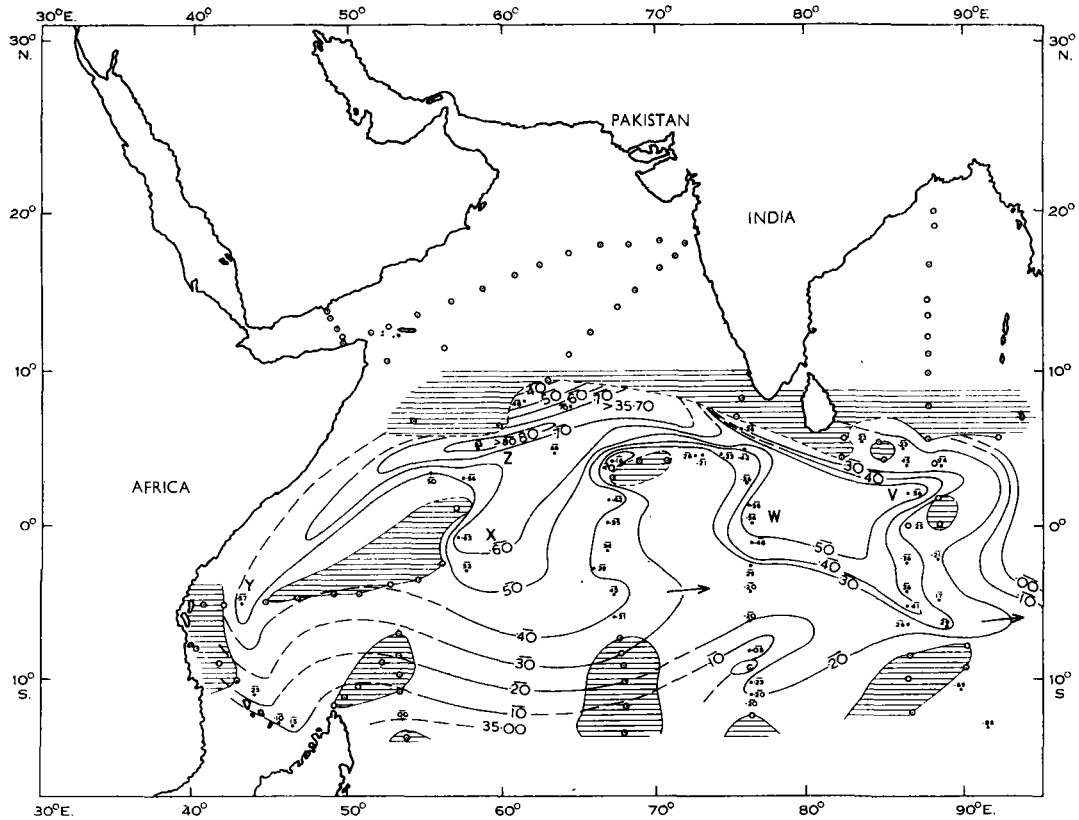


Fig. 15.—Chart of the distribution of salinity within the core of salinity maximum *E*. Salinity and other coding as in Figure 4.

section of *Vityaz* near the equator (Fig. 19). Along this latter section the boundaries of this high salinity water mass *E* coincided to some extent with those of the counter current (Fig. 19). Presumably the counter current carries these high salinity waters to the east along the equator.

Moving south from the equator, water mass *E* mixed with low salinity waters (less than 34·50‰) of the south-equatorial current above the upper salinity minimum (Fig. 17). This mixing decreased the salinity of *E* which then increased again when *E* mixed with the south-east Indian high salinity water around 12° S. at the southern

boundary of the South-Equatorial current. Spreading north from the equator *E* increased in salinity by mixing with Arabian Sea waters (*D*, Fig. 17).

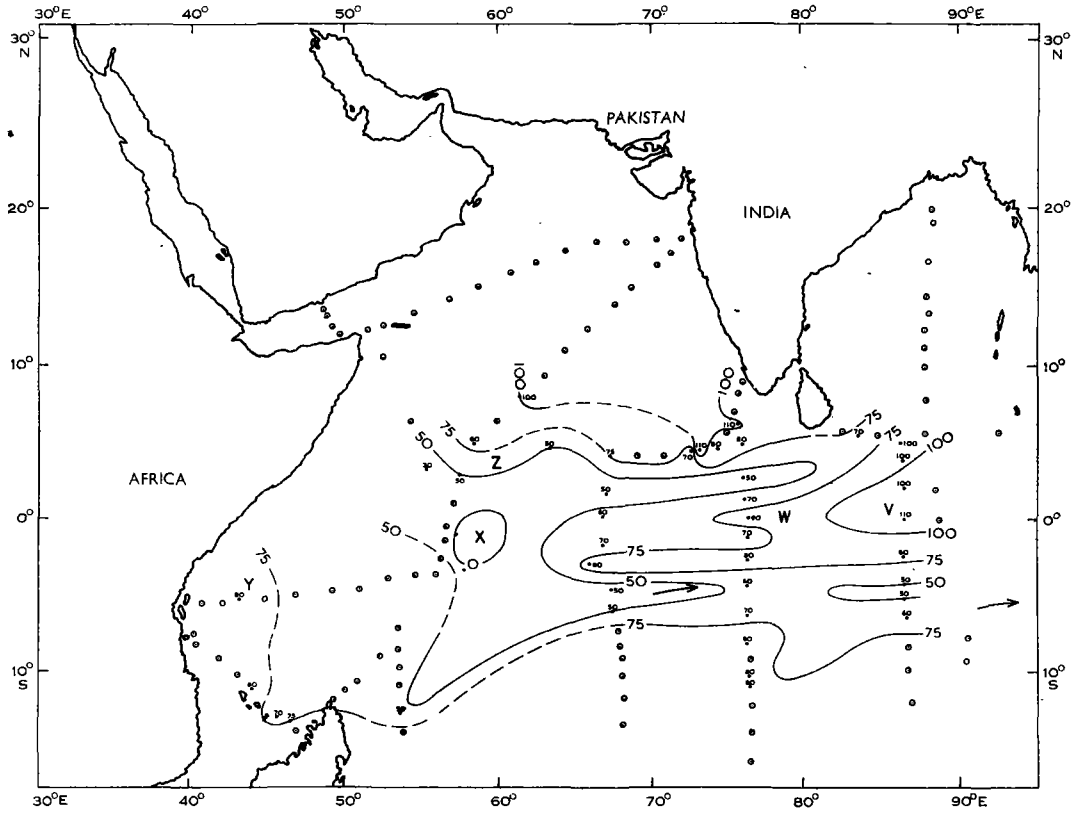


Fig. 16.—Depth of the core of salinity maximum *E*.

V. Effect of Submarine Topography on the Equatorial Distribution of High Salinity Waters

In the west central Indian Ocean the zonal flow above 1000 m is somewhat restricted by the Madagascar–Seychelles–Nazareth Bank array of islands and shallow banks (Fig. 21).

Soon after leaving their source regions the Red Sea, Persian Gulf, and Arabian Sea high salinity waters separated into a south-westerly and an easterly flow path in the vicinity of the equator (e.g. A^1 and A^2, Fig. 21) caused probably by the obstruction of the Madagascar–Seychelles group of islands and shallow banks (Fig. 21). The south-west flow of Persian Gulf and Arabian Sea waters divided west of the Seychelles into two paths (e.g. B^2 and B^3, Fig. 21), the separation of which cannot be related to features of the submarine topography. Moreover, the direction of flow along these paths, based upon salinity distribution, was in opposition to direct measurements of flow at 200 m (Fig. 19).

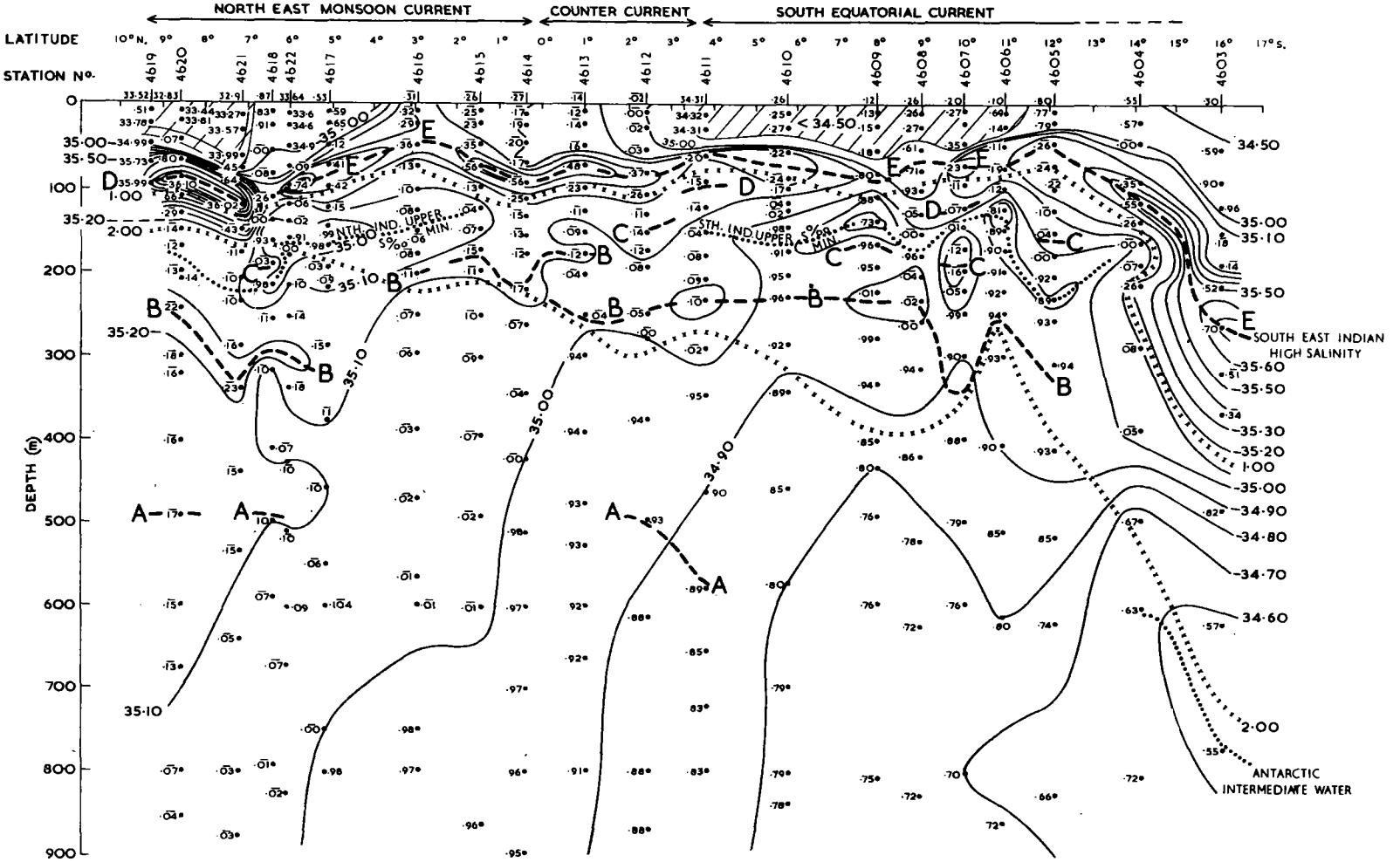


Fig. 17.—Salinity distribution along a 76° E. section showing the depths of the salinity maximum and minimum layers. Salinity coding as in Figure 4; × × × × depth of 1·00 and 2·00 μg-atom/l phosphate isolines. Salinity maxima of Figure 3 identified by letters but other minima and maxima given full names. Surface currents from Ovchinnikov (1961).

In the central equatorial regions of the Indian Ocean the Maldive–Chagos Islands confine the easterly movement of high salinity waters, in the upper 1000 m, to three main passages (Fig. 22):

Passage 1. Between South India and the Maldive Islands the passage is some 170 miles wide and between 2500 and 3000 m deep.

Passage 2. Between the Maldive Islands and the Chagos Islands the passage is some 240 miles wide and between 3500 and 4000 m deep.

Passage 3. South of the Chagos Islands there is an uninterrupted passage between 4000 and 5000 m deep.

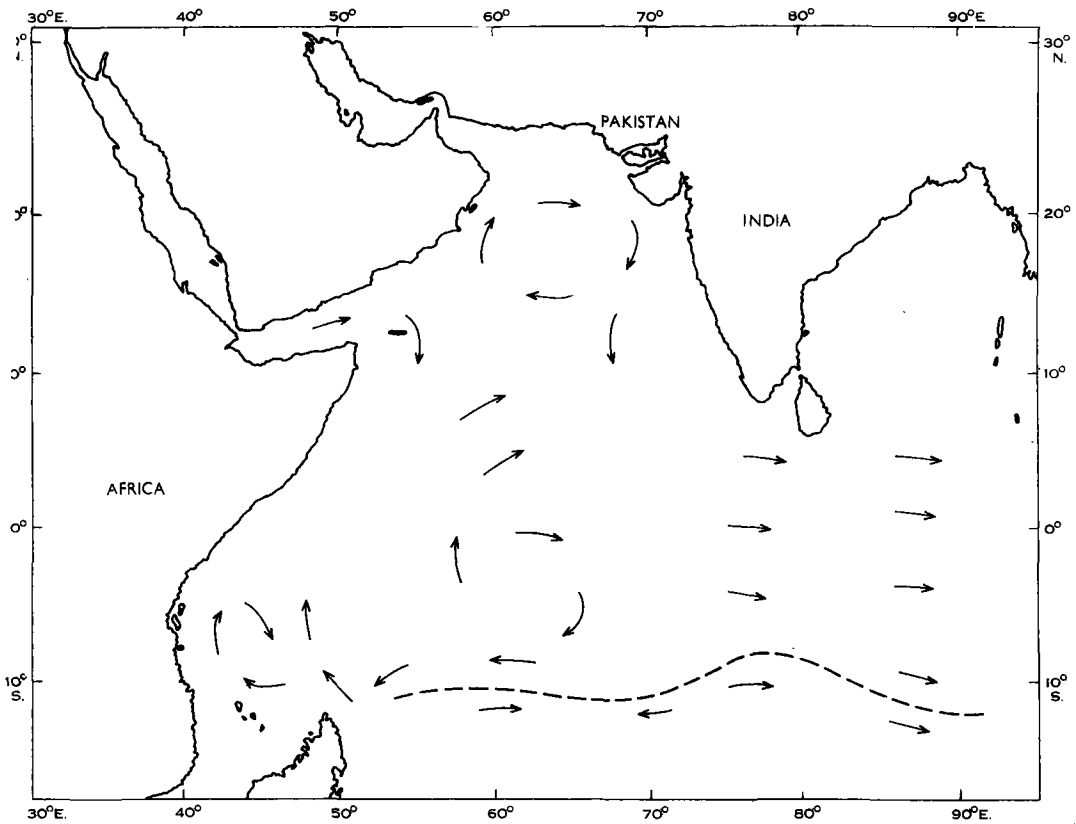


Fig. 18.—Chart from Ovchinnikov (1961) showing the direction of water movement at 500 m during cruise 31 of R.S. *Vityaz*.

The evidence of Sections III and IV indicates that during the north-east monsoon at least the most clearly defined easterly path of Red Sea water (*A*, Fig. 22) occurred within Passage 2 at depths of about 500 m. Persian Gulf water (*B*, Fig. 22) as evidenced by the peak in salinity near the equator (Fig. 4) also moved eastwards, predominantly through the northern part of this passage at depths of about 200 m. The westward movement of waters through the centre of Passage 2 (Fig. 22) at this same depth is

probably responsible for the diversion of another minor flow path of Persian Gulf waters to the south of this passage (B^1, Fig. 22). The Chagos Islands spread some of these waters further to the south (B^2, Fig. 22) and divert the major flow of supposed Arabian Sea waters eastwards into Passage 3 (*C*, Fig. 22) at depths of about 200 m.

The flow paths of Arabian Sea waters (*D*, Fig. 22) through these passages at depths of 100–125 m cannot be decided from salinity distribution (Fig. 6) and current measurements at 15 m (Fig. 20) but are probably more complicated in direction than those of the deeper waters. The Maldive–Chagos Islands therefore channel the

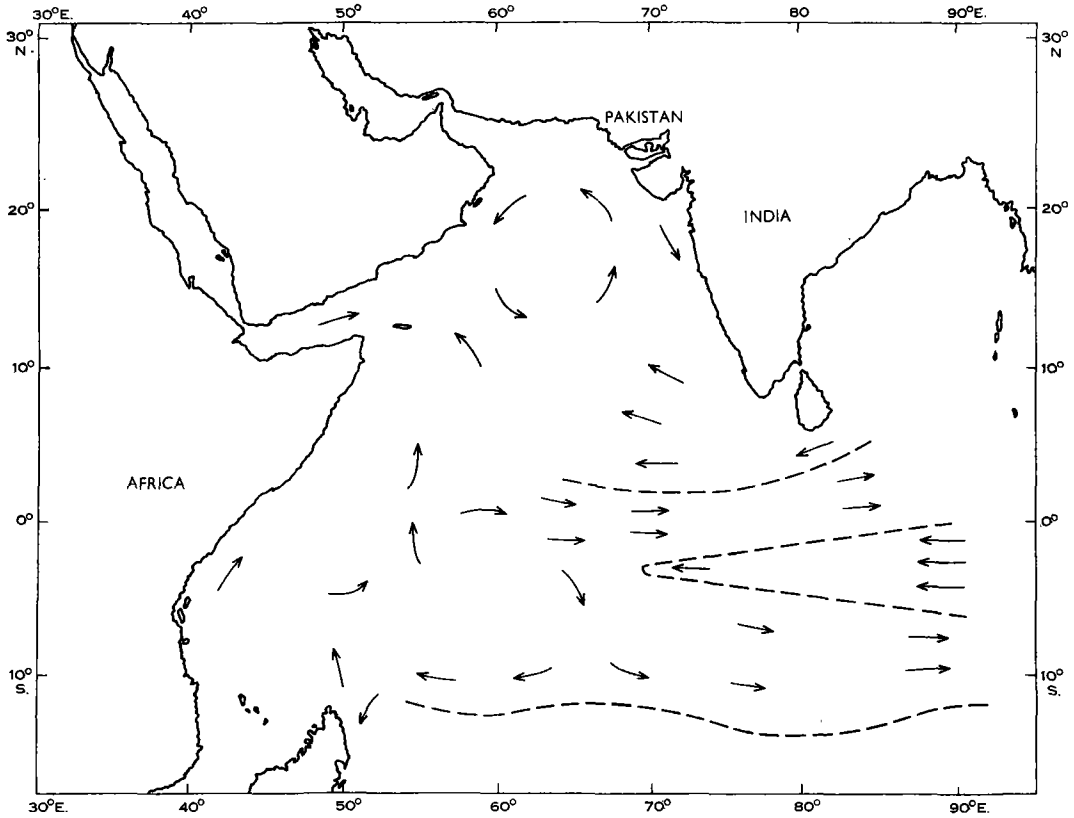


Fig. 19.—Chart from Ovchinnikov (1961) showing the direction of water movement at 200 m during cruise 31 of R.S. *Vityaz*.

easterly flow of these high salinity waters into relatively restricted passages which could be used for the monitoring of seasonal changes in the eastward transport volume of such waters.

The bifurcation of flow of Red Sea water to the east, accentuated, if not entirely caused by the Maldive–Chagos Island barrier (Fig. 22) continues as far east as 105° E. (Fig. 23) where it has been observed in the intermediate circulation (Rochford 1961). Persian Gulf waters, on the other hand, constrained into a single major flow

path during passage south of the Maldive Islands (Fig. 22) continue to flow east along a single path as far as north-west Australia (Fig. 23) (Rochford, unpublished data). Similarly, Arabian Sea waters, diverted south of the Chagos Islands (Fig. 22) flow to the east along a single major path which always lies south of 5° S. and continues into the region off north-west Australia (Fig. 23).

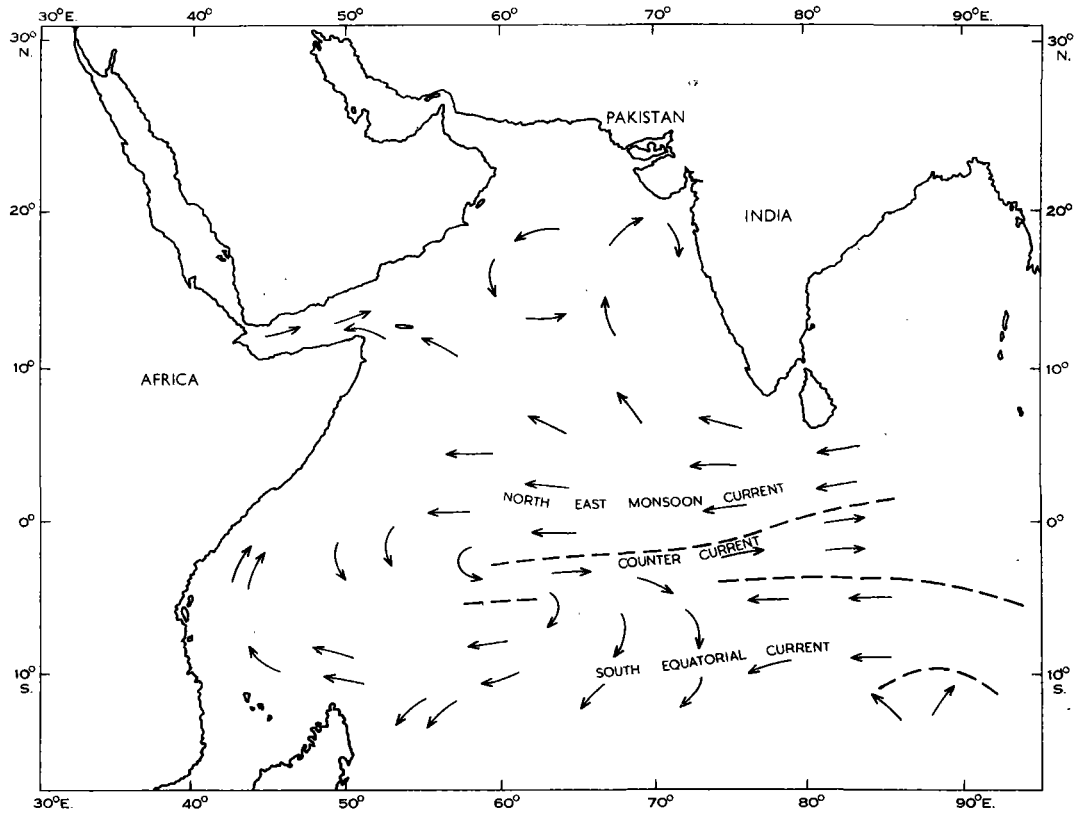


Fig. 20.—Chart from Ovchinnikov (1961) showing the direction of water movement at 15 m during cruise 31 of R.S. *Vityaz*.

VI. Conclusions

From salinity–temperature characteristics five high salinity water masses have been identified in the upper 1000 m of the north Indian Ocean during the period of the north-east monsoon (Fig. 3). The general distribution of these water masses has been found to agree with the direct measurements of currents as made by a differential method (Ovchinnikov 1961) for which current measurements were taken at 15, 50, 100, 200, 300, 500 and 700 m at some 140 deep stations of the North Indian Ocean. Red Sea high salinity water at depths of 500–1200 m occurs along a path extending south-west to Madagascar at least, and along another path to the south-east extending south of the Maldive Islands to south-west Australia (Fig. 23). Persian Gulf high

salinity water spreads along two major paths at depths of 200–500 m one of which carries this water to the west of Madagascar and the other along the equator to about 90° E. and south-east to the Timor Sea (Fig. 23). Arabian Sea high salinity water spreads south-west to the Seychelles where it divides into two paths, one to the west of Madagascar and the other to the east at about 5° S., passing south of the Chagos Islands at depths of 60–100 m. This water is found to the north-west of Australia at

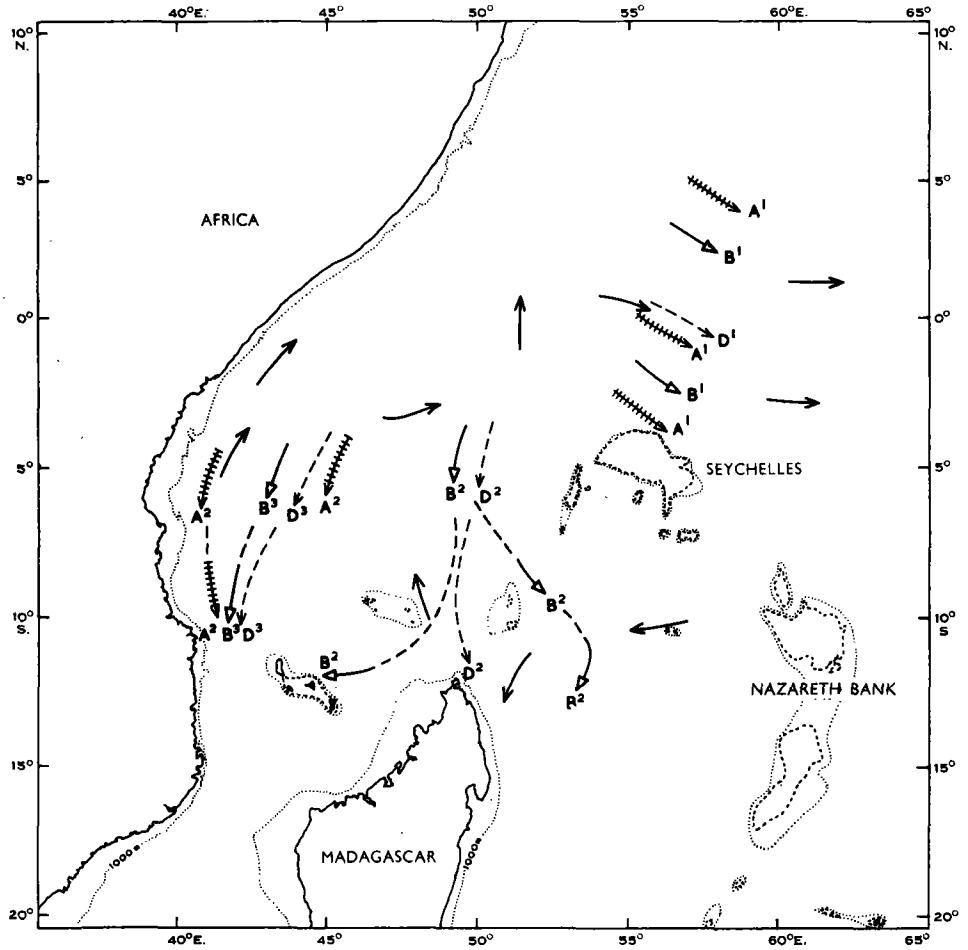


Fig. 21.—The major flow paths of high salinity waters, based upon salinity distribution, in relation to submarine topography of the west central Indian Ocean. The black arrows, from Ovchinnikov (1961), show the measured direction of flow at 200 m.

depths of 200–250 m (Fig. 23). Persian Gulf water, and to a much less extent Red Sea high salinity waters are found in the centre of the Bay of Bengal at depths of 300–400 m and 400–500 m respectively (Fig. 23). A fourth high salinity water is thought to originate in the northern part of the Arabian Sea or Persian Gulf but at lower temperatures than the Arabian Sea high salinity water proper. This water occurs throughout the Arabian Sea to the equator but not east of about 80° E. (Fig. 23).

The fifth high salinity water mass was found only between 10° N. and 10° S. within the equatorial region and is thought to be spreading east within the counter current

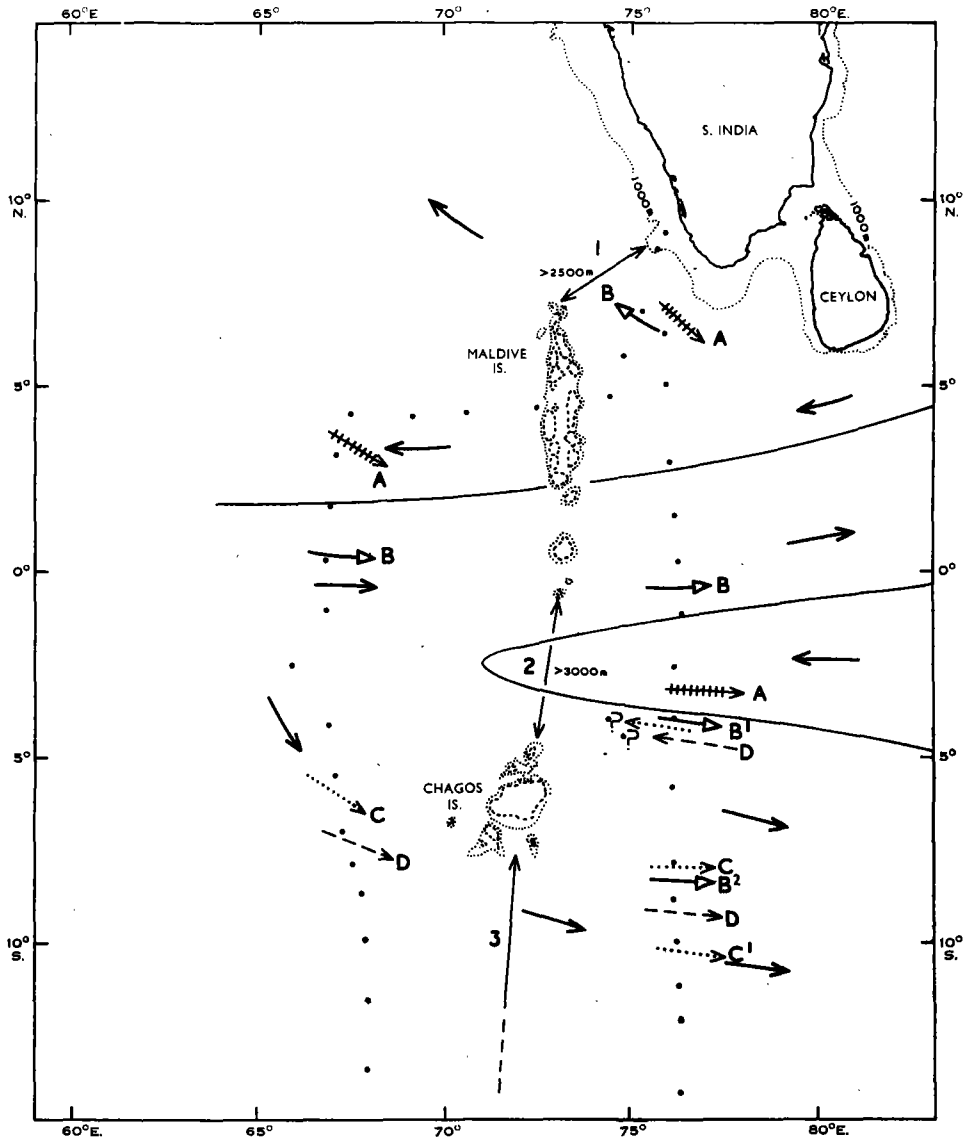


Fig. 22.—The major flow paths of high salinity waters, from salinity distribution, in relation to submarine topography of the central equatorial Indian Ocean. Black arrows and continuous black lines show the direction and boundaries of current flow at 200 m as measured by Ovchinnikov (1961).

(Fig. 23). The submarine topography of the Madagascar–Seychelles and Maldive–Chagos Islands provides an explanation for the diversion and separation of the flow paths of these water masses.

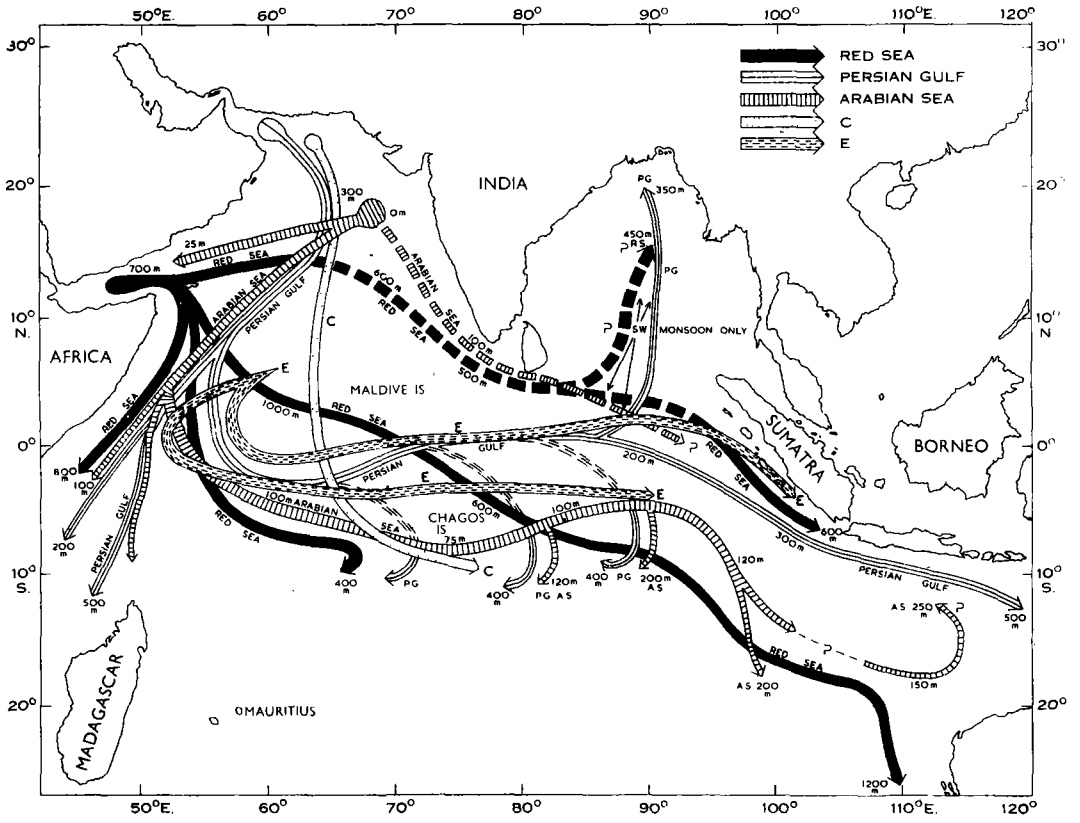


Fig. 23.—The major flow paths of high salinity water masses of the north Indian Ocean. Numbers along these paths show the depth at that point.

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HYDROLOGY OF THE INDIAN OCEAN

III. WATER MASSES OF THE UPPER 500 METRES OF THE SOUTH-EAST INDIAN OCEAN

By D. J. ROCHFORD*

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Summary

The following seven water masses have been identified, and their distribution traced during several seasons of the year: Red Sea mass, with the same distribution and properties in 1962 as the north-west Indian Intermediate described in 1959–60; Persian Gulf mass, which is confined to the region south of Indonesia and is limited in extent of easterly flow by the opposing flow of Banda Intermediate water; upper salinity minimum mass, entering via Lombok Strait and moving zonally in the direction of the prevailing surface currents, a secondary movement of this water mass towards north-west Australia is limited by the northern boundary of a south-east Indian high salinity water mass. This latter water mass occurs as three separate core layers north of 22–23° S. The deep core layer mixes with waters of the oxygen maximum below it, the mid-depth core layer mixes with Persian Gulf and upper salinity minimum water masses, and the upper core layer mixes with the Arabian Sea water mass. The latter water mass spreads eastwards to about 120° E. and southwards to north-west Australia, in conformity with surface currents. A sixth water mass enters with the counter-current and is found as a salinity maximum within the thermocline to about 20° S. A seventh water mass characterized by a salinity maximum around temperatures of 28–29°C has a limited distribution and an unknown origin. Both of these water masses move in the direction of surface currents.

I. INTRODUCTION

General features of the intermediate water mass structure and circulation (Rochford 1961) and of the major hydrological zones within the upper 50 m (Rochford 1962) of the south-east Indian Ocean have been established from hydrological data of H.M.A.S. *Diamantina*. Within the upper 500 m of this region, however, it was suspected that a number of high salinity water masses of probable north Indian Ocean origin were contributing to its rather complicated water mass structure. The characteristics and origins of the high salinity water masses of the north Indian Ocean and their paths of entry into the east Indian Ocean have now been established (Rochford 1964). The analysis of the water mass structure and circulation of the upper 500 m of the south-east Indian Ocean in this paper shows to what extent these high salinity waters penetrate into the south-east Indian Ocean and what seasonal changes in the positions of their paths of movement occur in this region.

II. MATERIAL AND METHODS

The Australian data used are in CSIRO Aust. (1963, 1964*a*, 1964*b*). The data for *Vityaz* cruise 31 were obtained from World Data Centre B, Moscow.

Figures 1 and 2 show the location of the stations used. The salinity–temperature values of all salinity maxima or minima have been read from smoothed salinity–

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temperature diagrams (e.g. Fig. 3) for each station. The Australian salinity measurements were made with an inductively coupled salinometer (Brown and Hamon 1961) and have a precision of $\pm 0{\cdot}005‰$. The Russian salinity measurements were made by Knudsen titration and therefore have a precision of about $\pm 0{\cdot}01‰$. When using

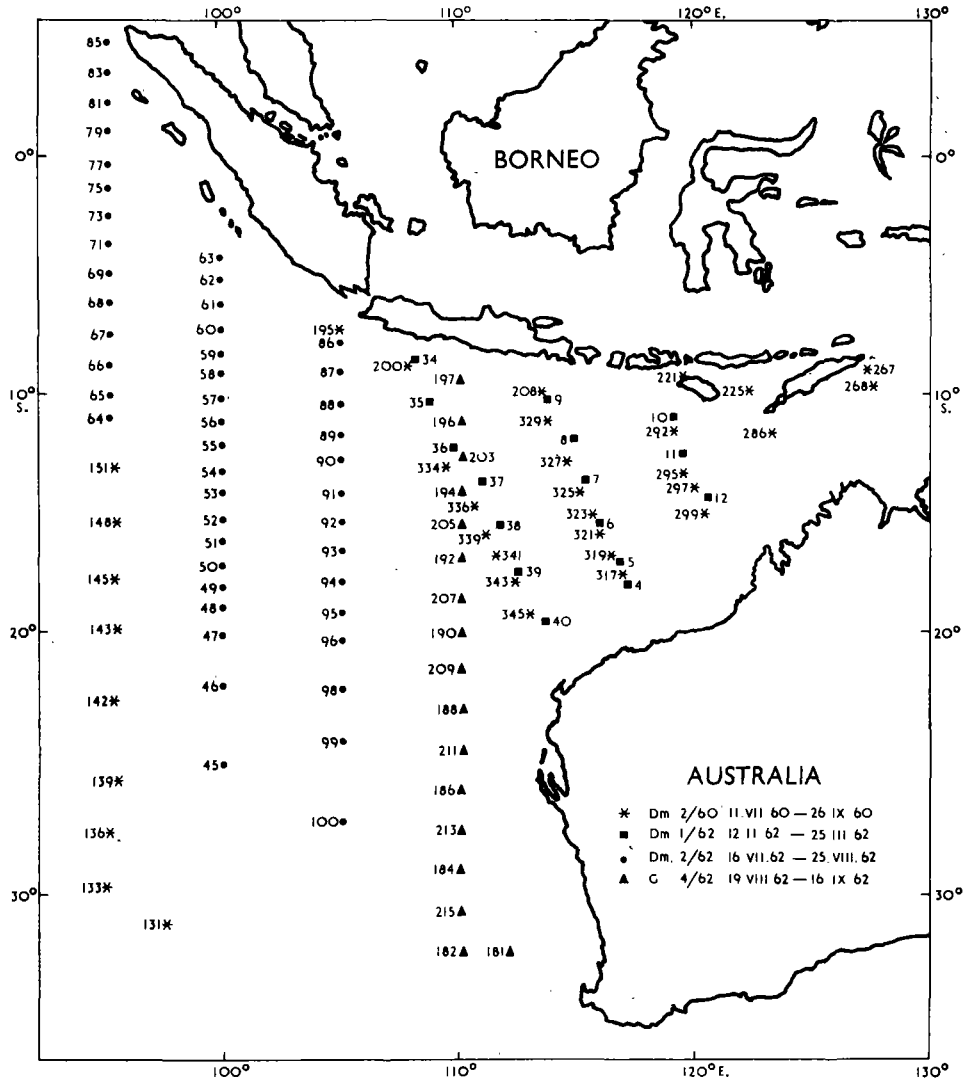


Fig. 1.—Location of stations.

Australian data, differences of $0{\cdot}01‰$ were taken as definitive in locating a salinity maximum on a salinity–temperature curve. The corresponding value for Russian data was $0{\cdot}02‰$. These maxima and minima have been plotted on a general salinity–temperature diagram (e.g. Figs. 4 and 5) and grouped into water mass assemblages using previously described characteristics (Rochford 1964) whenever possible to identify high salinity waters from the north Indian Ocean (*A*, *B*, *D* and *E*, Fig. 4).

However, the northward spreading of high salinity waters from the south (B^1 in Fig. 4) and the southward movement of high salinity waters from the north, gives rise to mixtures of waters whose water mass origin sometimes cannot be decided from their salinity–temperature characteristics (e.g. values in circles and triangles Figs. 4 and 5). The circled values in Figure 4 for example have salinity–temperature characteristics of water mass D but are some 0·2–0·4 μg-atom/l lower in inorganic phosphate than D at the same density (Fig. 6). Similarly the values in triangles in Figure 4 should be considered part of water mass assemblage E but are some 0·4–0·5 μg-atom/l lower in inorganic phosphate at similar densities (Fig. 6). These differences in inorganic phosphate are of sufficient magnitude to justify the classification of circled values as water mass B^1 and of the values in triangles as water mass F (Fig. 6).

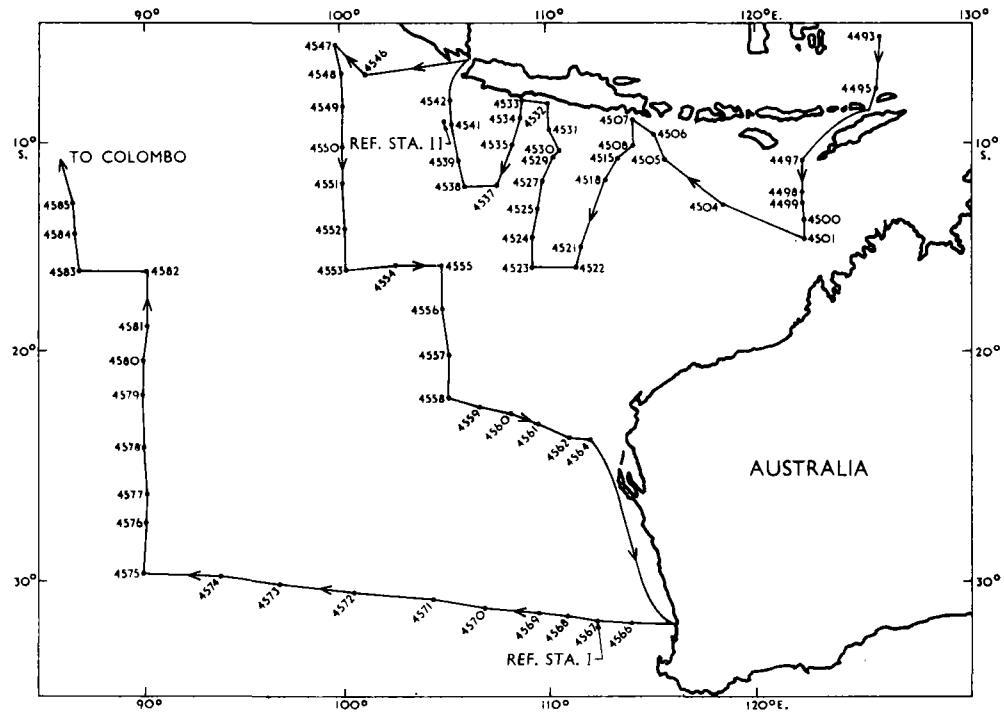


Fig. 2.—Location of *Vityaz* stations in October–December 1959.

III. The Distribution of Water Masses During the South-East Trade Season

Diamantina cruises 2/60 and 2/62 and *Gascoyne* cruise 4/62 (Fig. 1) provided data for a study of the water mass distribution during this season. The following water masses have been identified and the distribution of their core layers followed in this region. In ascending order of depth these are:

Red Sea (*A* in Fig. 4).—This water mass has the same salinity–temperature characteristics as the north-west Intermediate (Fig. 4) of unknown origin previously found in this region (Rochford 1961). Its general distribution based on recent data (Fig. 7) also agrees well with that of the north-west Indian Intermediate from 1959–60 data (Rochford 1961, Fig. 9). The north-west Indian Intermediate water mass can

now be identified as Red Sea in origin. The depth of this Red Sea water has been shown (Rochford 1961, Fig. 8) to increase from about 700 m in the north to about 1300 m in the south.

Persian Gulf (*B* in Fig. 4).—This water mass entering from the north-west with salinities around 35·10‰ (Fig. 8) at depths of 150–200 m (Fig. 9) spreads to the south-east, terminating at *Z* (Fig. 8) with salinities around 34·80‰ and depths of 400 m (Fig. 9), and at *V* (Fig. 8) with salinities around 34·65‰ and depths of 500 m (Fig. 9). During the south-east trades this water mass was not found south of 15° S.

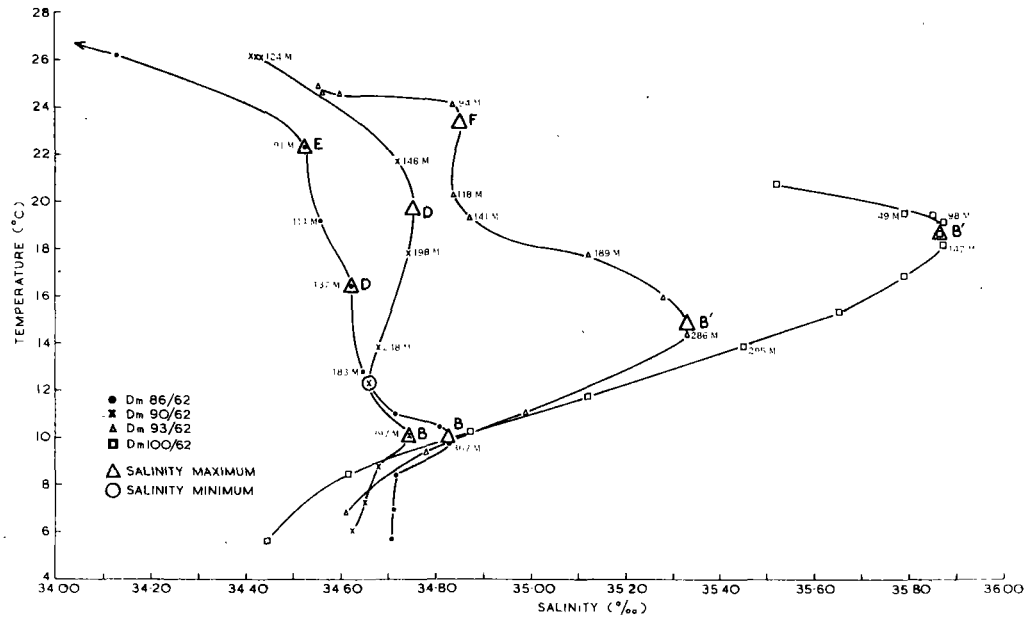


Fig. 3.—Temperature–salinity diagram *Diamantina* stations 86, 90, 93, and 100/62. Numbers give depth of observation. Letters indicate water mass (Section II of text).

South-east Indian high salinity (B^1 in Fig. 4).—During its movement northward beyond *XY* (Fig. 10) this water mass mixed principally with three kinds of water. The salinity–temperature (Fig. 4) and the density–inorganic phosphate relations (Fig. 6) show these to be: (1) the oxygen maximum layer of density 26·80–26·90 σ_t (2 in Fig. 6); (2) Persian Gulf or the salinity minimum water mass or both around a density of 26·30 σ_t (3 in Fig. 6); and (3) Arabian Sea of density 24·90–25·40 σ_t (4 in Fig. 6). Mixing with the oxygen maximum occurred along a path extending north-west (Fig. 10) at depths of 250–300 m (Fig. 11). Mixing with Persian Gulf or salinity minimum waters or both occurred mainly in the north-east (Fig. 12) at depths of 200–250 m (Fig. 13). Mixing with Arabian Sea waters occurred along the whole extent of a frontal region north of *XY* (Fig. 14) at about 20° S. and as far north as 12–15° S. within one region centred around 115° E. and another around 100° E. (Fig. 14) at depths of 125–150 m (Fig. 15).

Upper salinity minimum (σ_t 26·30, Fig. 4).—Lowest salinities within the core layer of this water mass were found in the Banda and Flores Seas and off the southern

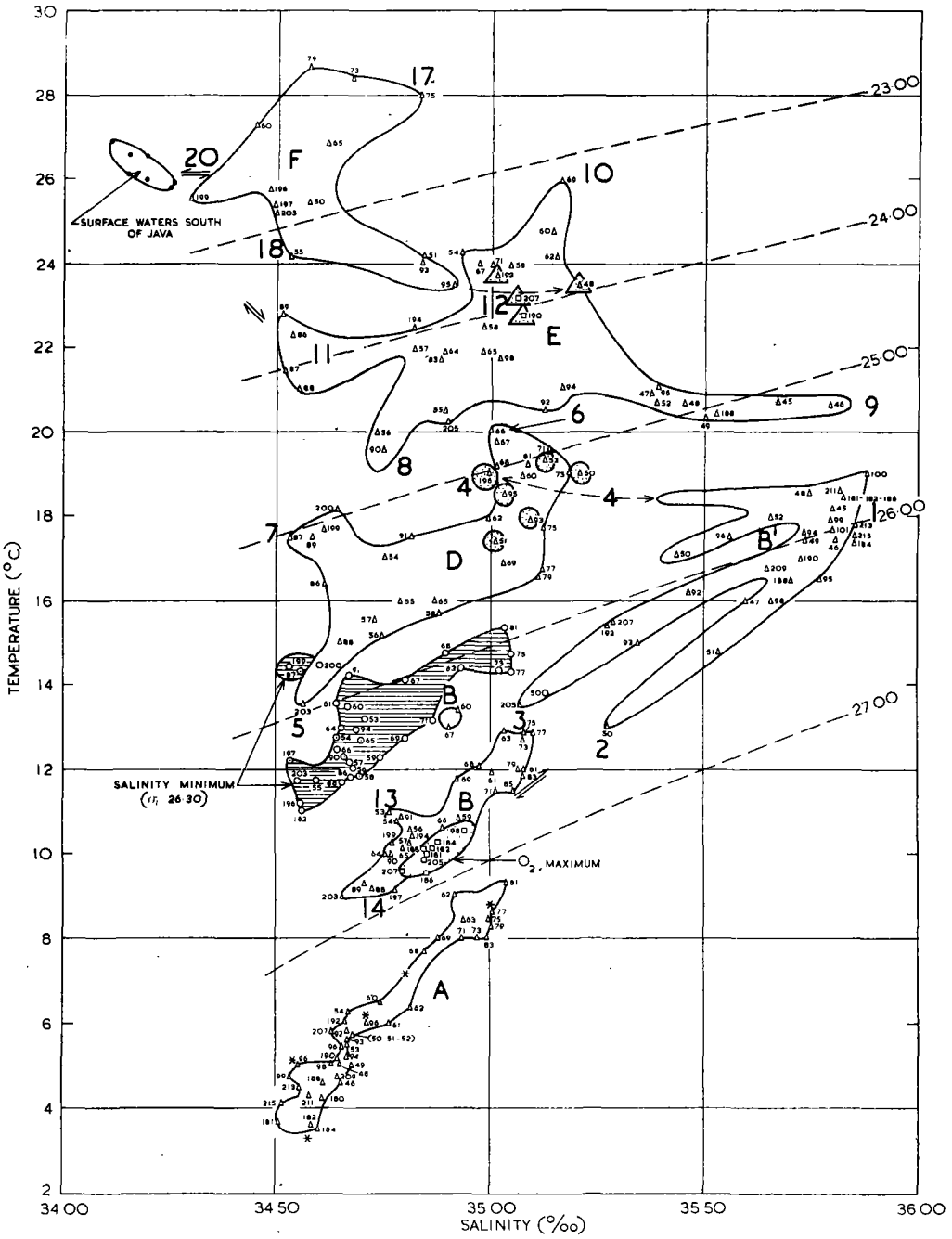


Fig. 4.—Water mass grouping of salinity maxima and minima observed in temperature–salinity relations of cruises Dm2/62 and G4/62 (Fig. 1). Letters identify water masses (Section II of text). Large numbers indicate specific limits of identification of water masses. Maxima in circles and triangles grouped according to Figure 6. * Values of north-west Indian intermediate water mass (Rochford 1961).

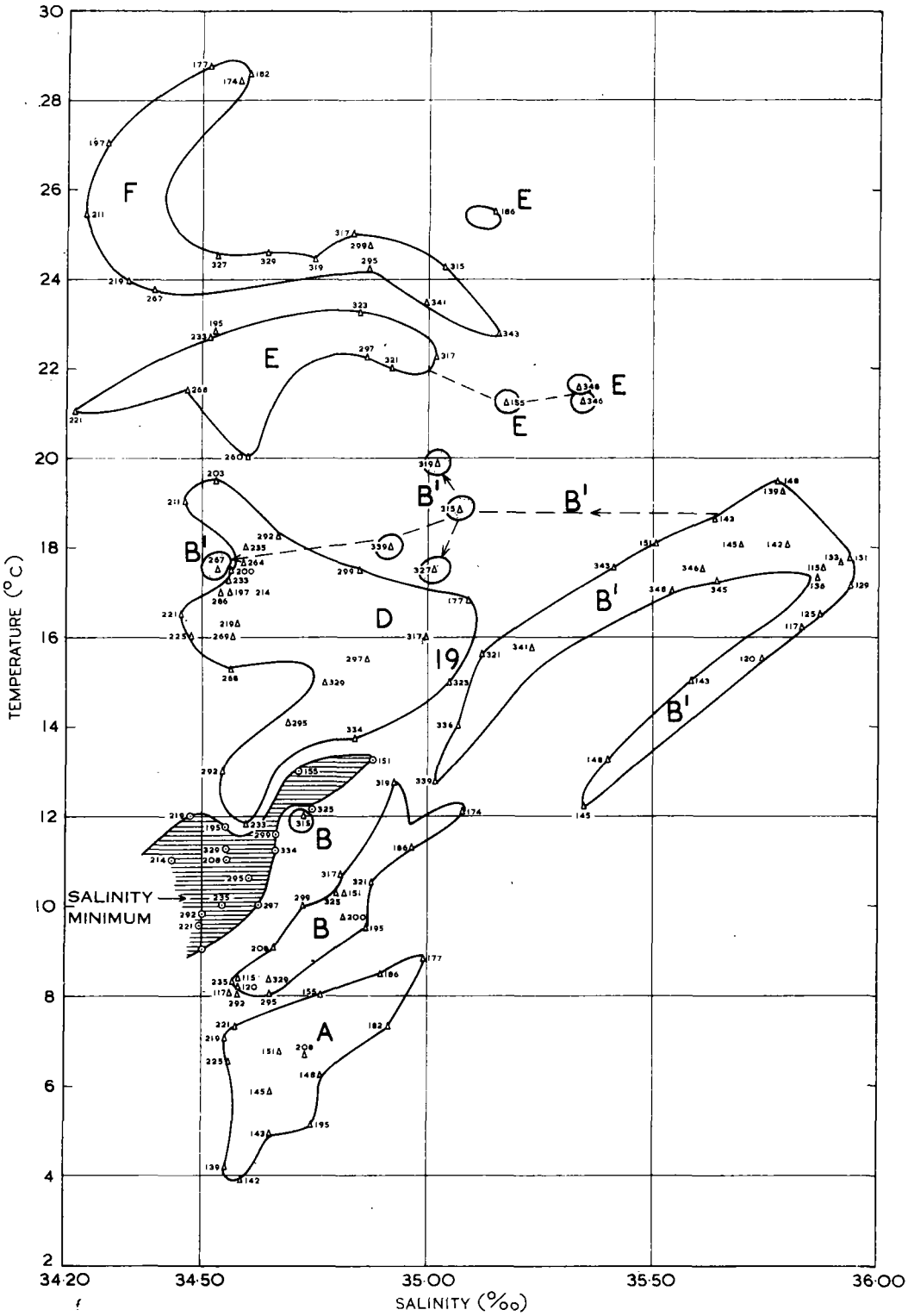


Fig. 5.—Groupings as for Figure 4 using data of *Diamantina* cruise 2/60 (Fig. 1).

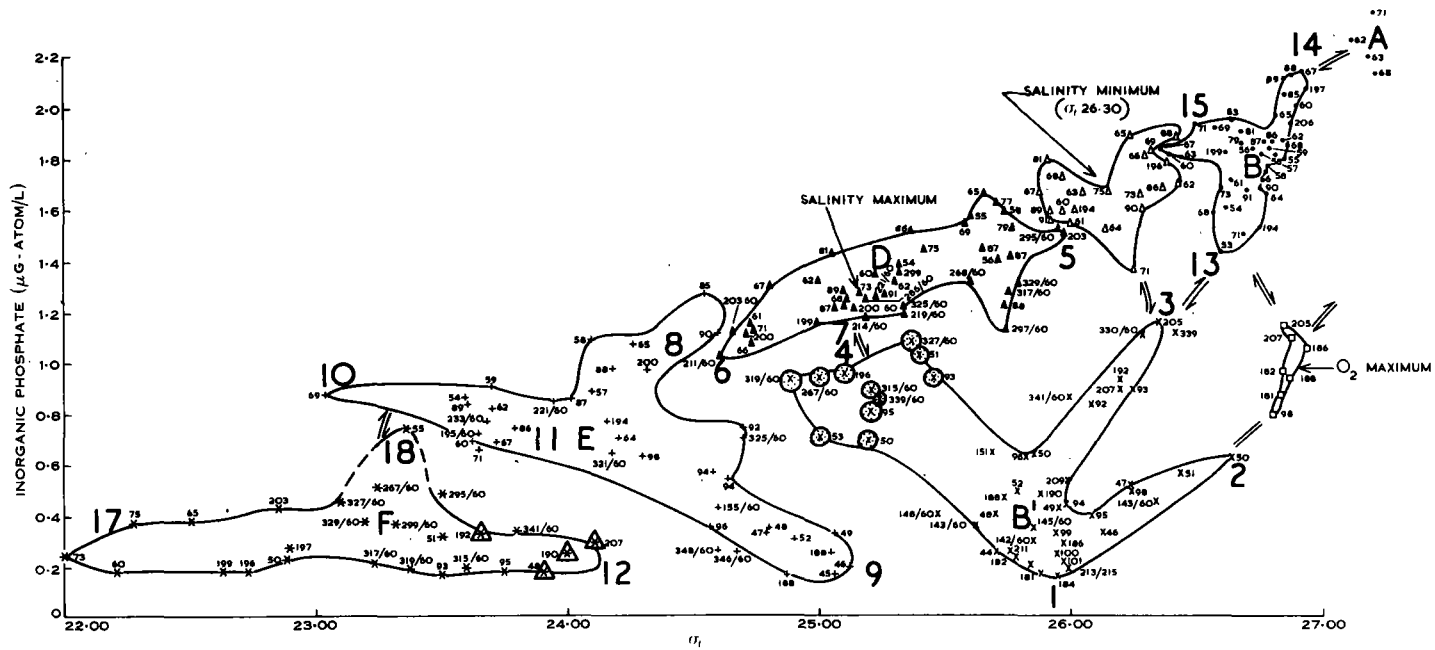


Fig. 6.—The density (σ_t)–inorganic phosphate relations of all salinity maxima and minima of Figure 4 and of selected maxima and minima of Figure 5. Water mass groupings based upon temperature–salinity (Fig. 4) except for values within circles and triangles which have been grouped by their position on Figure 6. Numbers refer to corresponding locations on Figure 4. Letters indicate water masses.

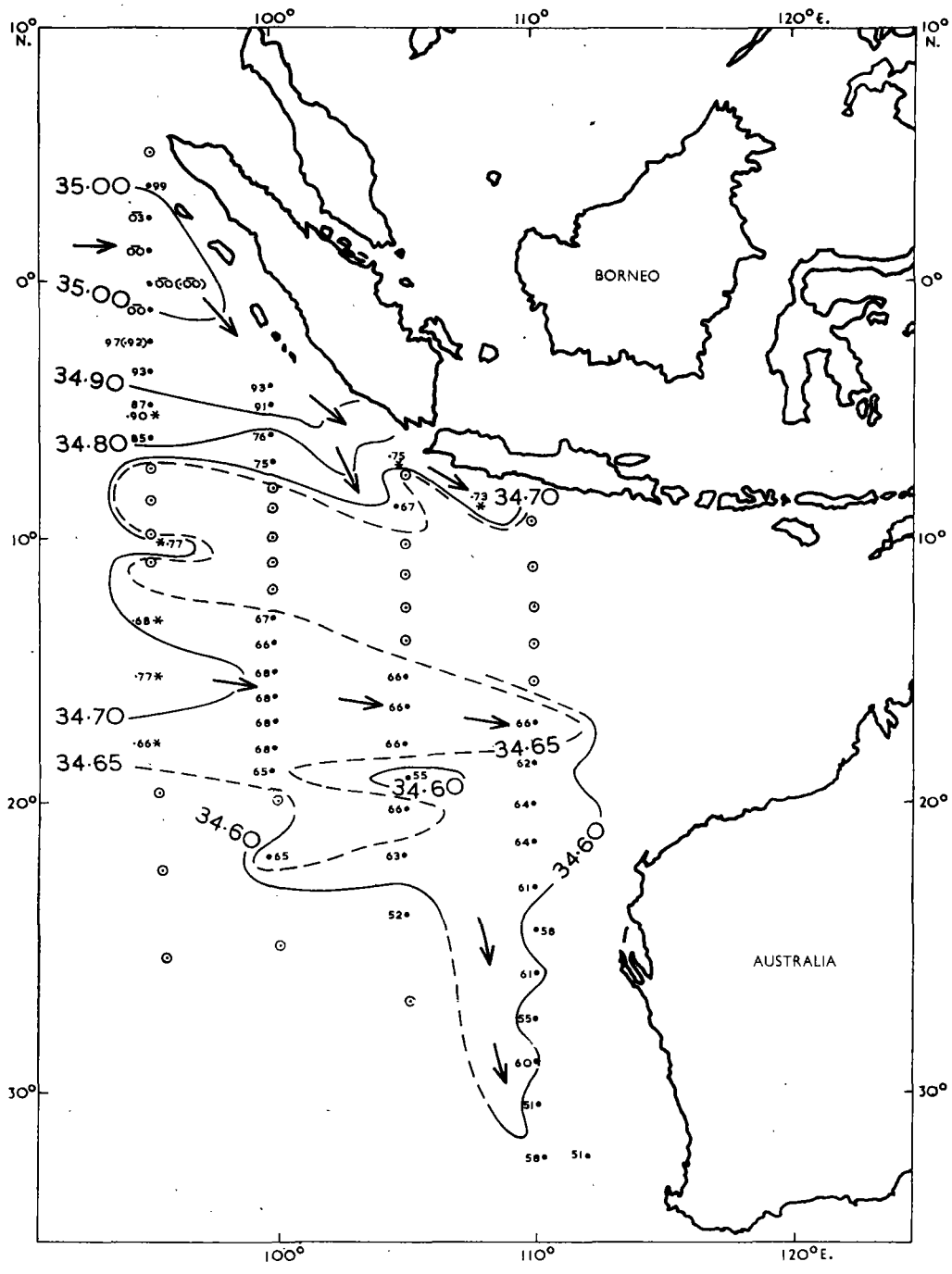


Fig. 7.—Distribution of the salinity of water mass *A* within the period July–September (1960–1962). Salinities should be prefixed by 35 (barred value), and by 34 (non-barred value) to obtain the correct value. ⊙, stations without evidence of water mass *A* in the temperature–salinity relation.

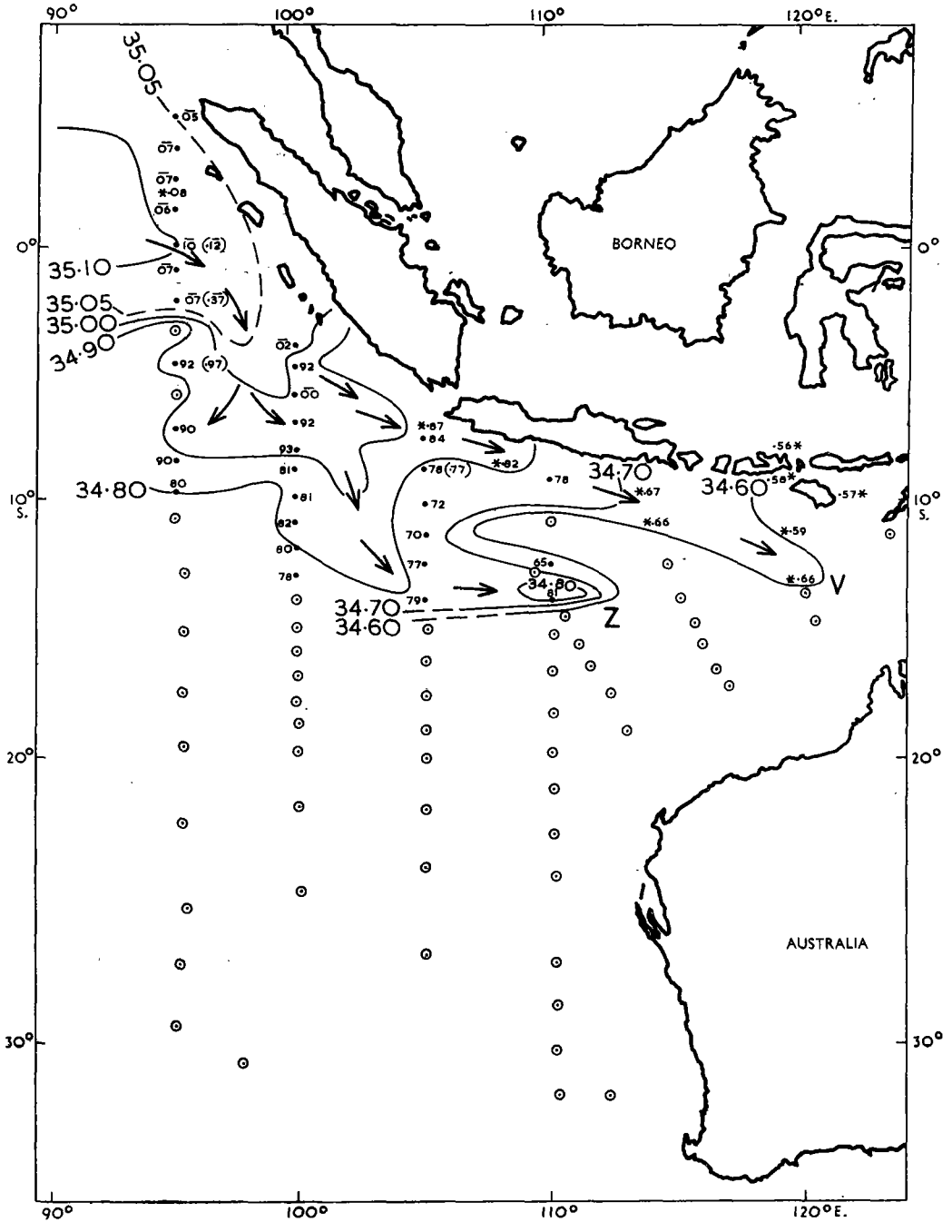


Fig. 8.—Distribution of the salinity of water mass *B* during July–September (1960–1962). For salinity coding see Figure 7. * 1960 stations.

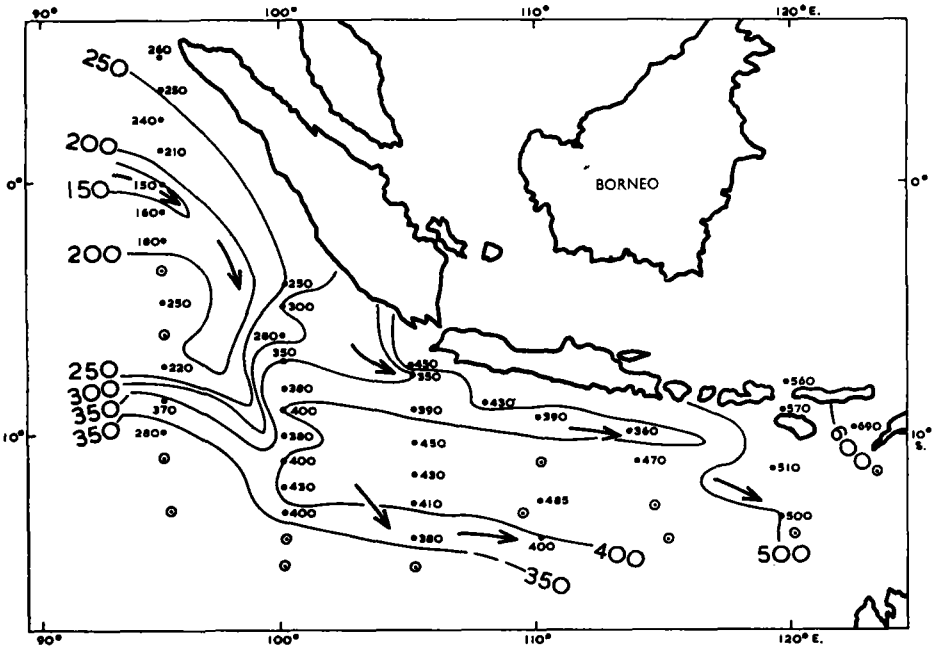


Fig. 9.—Depth (m) of water mass *B* during July–September. Arrows as in Figure 8.

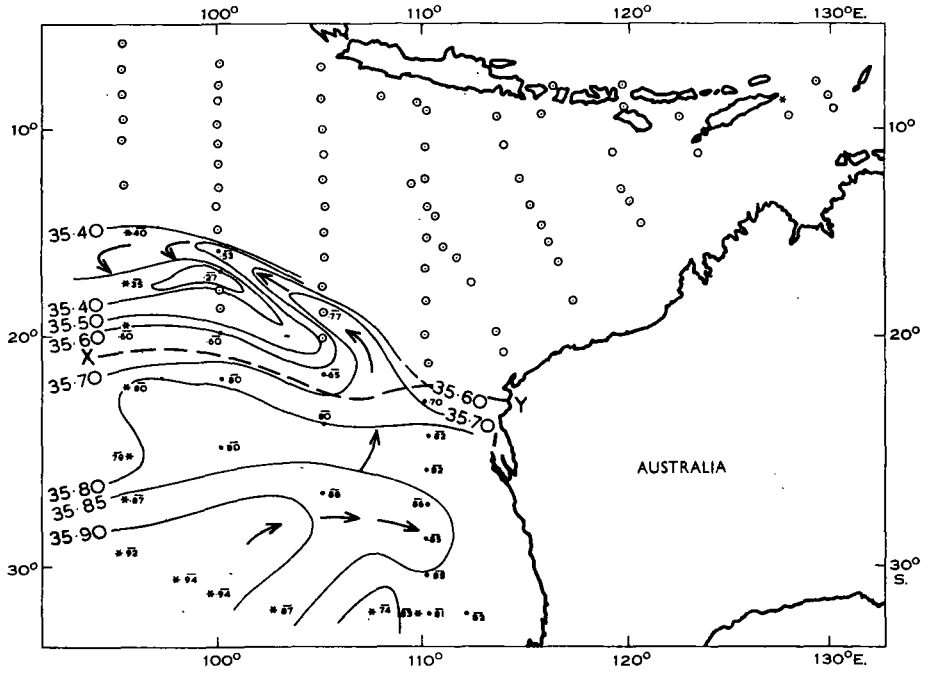


Fig. 10.—Salinity distribution within the core of water mass B^1 (Fig. 4) and north of *XY* within the core of mixtures of B^1 and the oxygen maximum only (2 in Fig. 4). For salinity coding see Figure 7.

coasts of Timor, Soembawa, and Java (Fig. 16). Salinity distribution indicated (Fig. 16) that this water mass spread westward in the region of about 10° S. to at least 95° E. In the region of lowest salinities in the Flores Sea at about 120° E. (Fig. 16) the depth of this water mass was about 300 m (Fig. 17). Along its path of westward movement and along its southern boundary, its depth varied between 250 and 300 m (Fig. 17), but to the north its depth shallowed to within 150 m of the surface. Its origin seems to be at depths of about 300 m within the Banda and Flores Seas. These two seas are connected with the Indian Ocean by the Bali-Lombok Strait which has a sill depth of 300 m (Bruun and Kiilerich 1957) and this strait is presumably the path

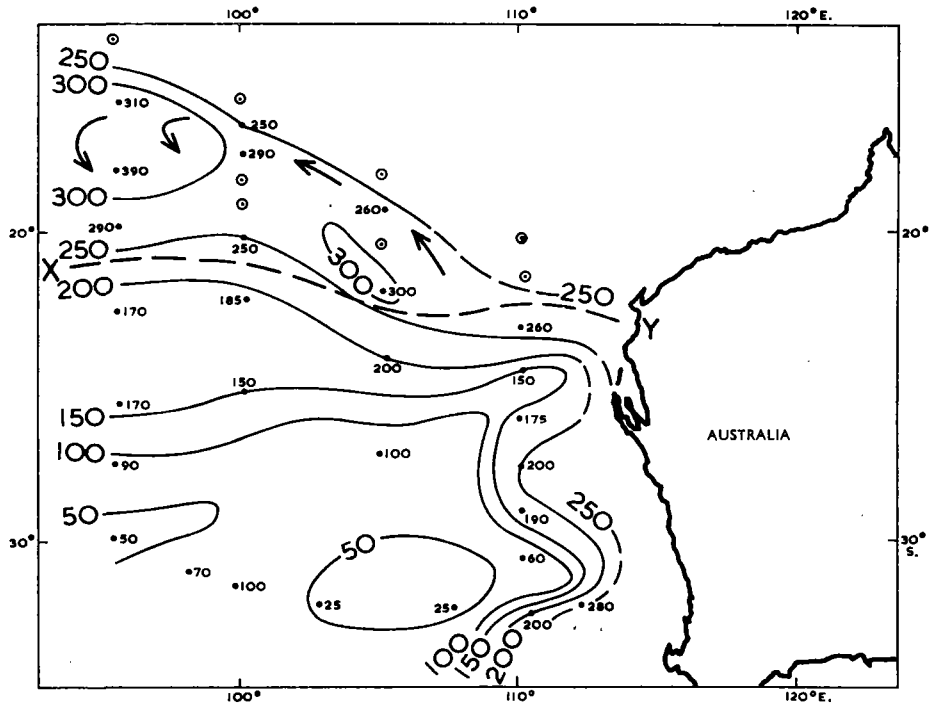


Fig. 11.—Depth (m) of water mass B^1 and of its mixtures with the oxygen maximum (2 in Fig. 4) north of XY. Arrows as in Figure 10.

of entry of this water mass into the east Indian Ocean. The properties of this water mass are very similar to those of the southern salinity minimum of Wyrtki (1961) for this region.

Arabian Sea (*D* in Fig. 4).—This water mass entered the region at about 2° S. along the 95° E. meridian (Fig. 18). Its salinity decreased by mixing with: (1) water mass *E* lying south of its entry (6 in Figs. 4, 6, and 18); (2) near surface waters of low salinity south of Java (7 in Figs. 4, 6, and 18); (3) waters of the upper salinity minimum (5 in Figs. 4, 6, and 18). However, off the north-west coast of Australia its salinity increased by mixing with high salinity waters from the south-east Indian Ocean (19 in Figs. 5 and 18). This water mass entered the region at a depth of 125 m (Fig. 19), mixed with *E* and the waters south of Java at about the same depth, but deepened to

200–250 m as it mixed with waters of the upper salinity minimum and the high salinity waters from the south-east Indian Ocean (Fig. 14).

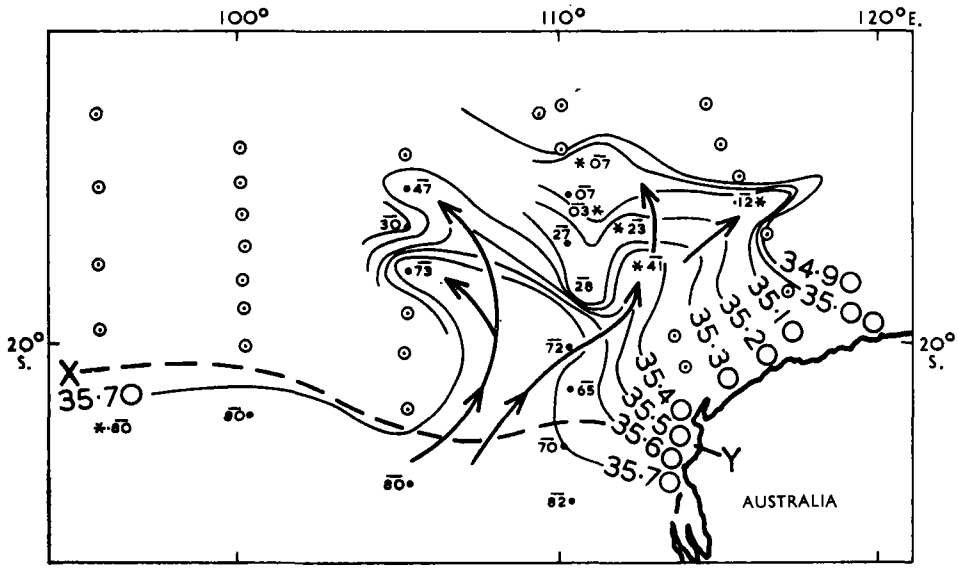


Fig. 12.—Salinity distribution within the core of mixtures of water mass B^1 (Fig. 4) and Persian Gulf waters (3 in Fig. 4). For salinity coding see Figure 7.

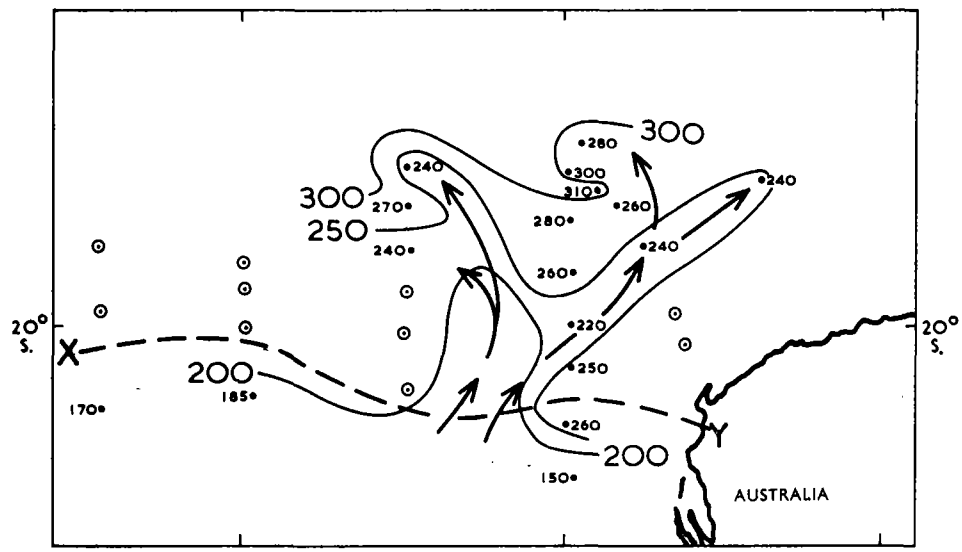


Fig. 13.—Depth (m) of mixtures of water mass B^1 and Persian Gulf waters (3 in Fig. 4). Arrows as in Figure 12.

Salinity maximum E (counter-current, *E* in Fig. 4).—After entering the region at 10 (Fig. 20) this water mass decreased in salinity by mixing with: (1) low salinity surface waters south of Java (11 in Figs. 4, 6, and 20); (2) low salinity waters (5 in Fig. 18) to the south along the region 8 (Figs. 4, 6, and 20). As this water mass moved

farther to the south, however, its salinity increased by mixing with high salinity surface waters south of 20° S. (9 in Figs. 4, 6, and 20). During its mixing with (1), the depth of this water mass varied between 100–120 m (Fig. 21). Mixing with (2), however, caused this water mass to deepen to about 150 m (Fig. 21). At its southern limit of identification this water mass was found at depths of 75–100 m (Fig. 21). It has the same properties as the subtropical lower water of Wyrtki (1961), who considered its origin was in the Arabian Sea. More recent evidence (Rochford 1964) does not agree with this.

Salinity maximum F (Fig. 4).—This water mass, with a salinity at its point of entry (17 in Fig. 22) 0·35‰ less, but with a temperature some 3°C greater, than those of *E* (Fig. 3), was not found in the north Indian Ocean during the north-east monsoon (Rochford 1964). In the south-east Indian Ocean it was found at isolated groups of stations between 2 and 20° S. (Fig. 22). The salinity of this water mass decreased by mixing with low salinity surface waters south of Java (20 in Figs. 4 and 22). This diluted water spread to the south and mixed with waters of the counter-current *E* (Fig. 4) at 12 (Figs. 4 and 22). This water mass was found at depths of 50–130 m (Fig. 23) with maximum depths towards the south-east.

Low salinity surface waters move south-east from the Bay of Bengal during the south-east trades into the region west of Sumatra and eastwards along the coast of Java. At about 10° S. the westward south-equatorial current of low salinity (Rochford 1962) commences. The distribution of salinity of this water mass *F* (Fig. 22) could, with few exceptions, be fitted into such a circulation pattern if its source region were situated north of the equator, but not if its source were to the north-east of Indonesia or the Pacific Ocean.

IV. Vertical Distribution of Water Masses Along the 105° E. Meridian

Some features of the mixing pattern observed in Figures 4 and 6 become clearer when the vertical distribution of water masses based upon salinity–temperature relations (Fig. 3) along a typical north–south section is considered (Fig. 24). For example, the mixing between water mass B^1 and the oxygen maximum (Region 2 of Figs. 4 and 6) is seen to occur between 20–22° S. as the result of the downward displacement of B^1 by the surface frontal barrier at 23–24° S. (Fig. 24). Mixing between B^1 and Persian Gulf waters (Region 3 of Figs. 4 and 6) occurs between 15° and 17° S. presumably because of turbulence developed along the subsurface front at 14–15° S. separating water masses of the north from those of the south. Direct mixing between B^1 and *D* (Region 4 of Figs. 4 and 6) does not occur along 105° E. and along the salinity maximum at 170 m (Station 95, Fig. 24) although a mixture of B^1 and *D* is also mixing with the overlaying water mass *E* at Station 94 (Fig. 24). High salinity water masses (*B* and *D*, Fig. 4) of the north Indian Ocean and the low salinity water mass (S‰ minimum Fig. 4) from north of Java were not found south of the front at 14–15° S. (Fig. 24). This front corresponds to that of Ivanov-Frantskevich (1961) at 10–12° S. for the central and western Indian Ocean. Ivanov-Frantskevich (1961) claims that Antarctic Intermediate water ascends to the surface in this frontal zone eastward of 90° E. No evidence of this can be found in the 105° E. section (Fig. 24).

Waters of the counter-current *E* (Fig. 4) were found north of the 14–15° S. front with a much lower salinity than south of it (Fig. 24). The main entry of *E* occurred to the

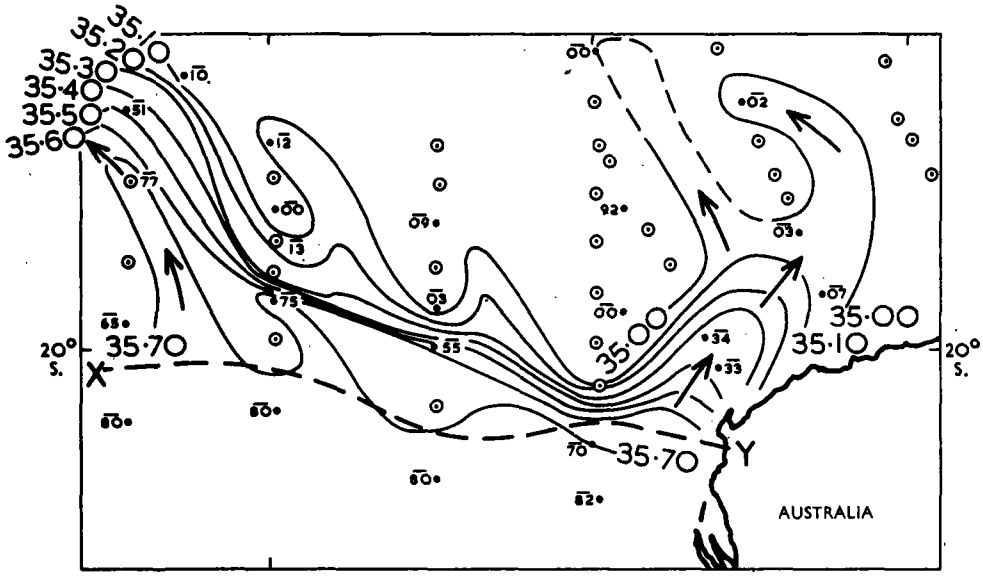


Fig. 14.—Salinity distribution within the core of mixtures of water mass B^1 (Fig. 4) and Arabian Sea waters (4 in Fig. 4). For salinity coding see Figure 7.

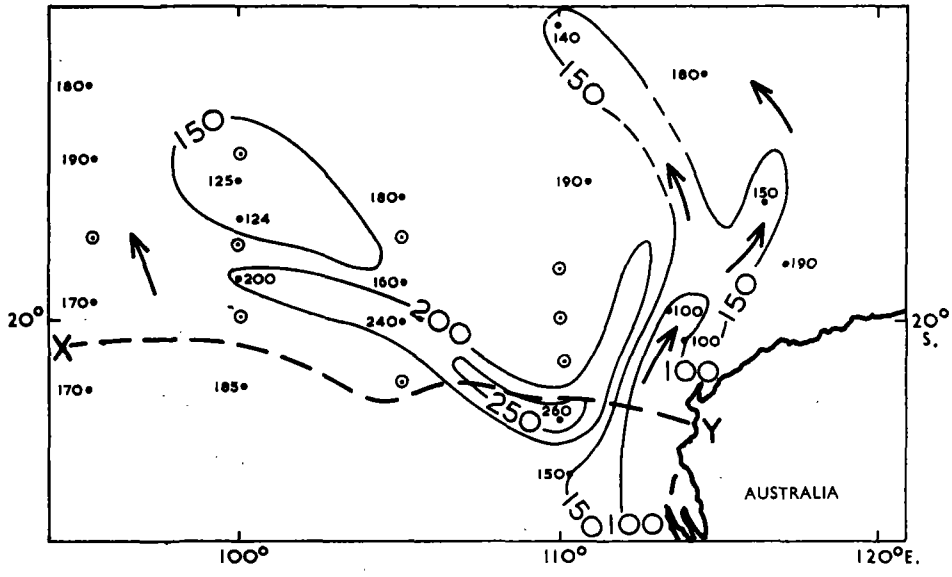


Fig. 15.—Depth (m) of mixtures of water mass B^1 and Arabian Sea waters (4 in Fig. 4). Arrows as in Figure 14.

north of this front (Fig. 24) so that the higher salinities of *E* south of the front must be caused by mixing with B^1 (Fig. 24).

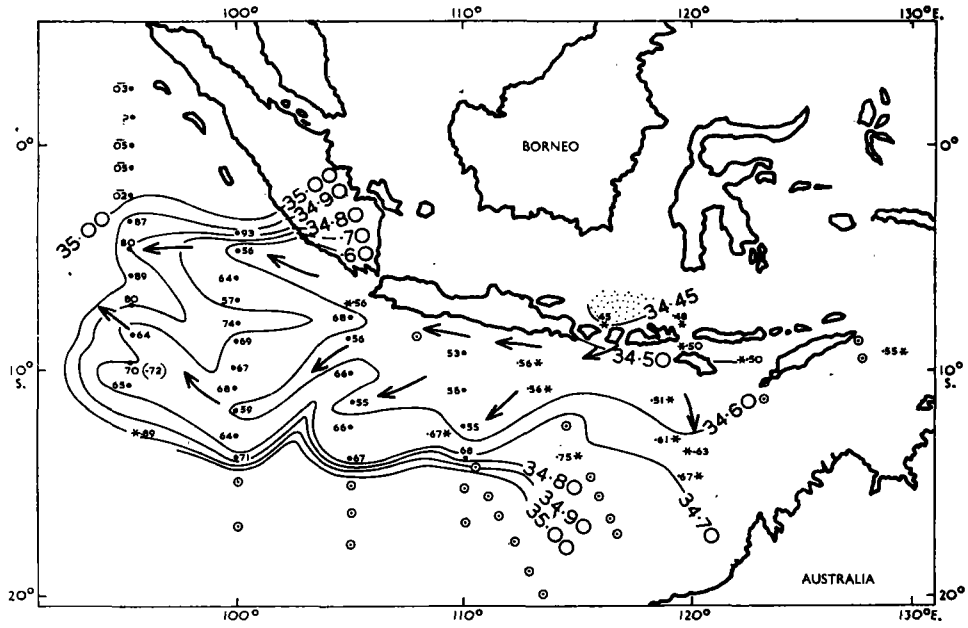


Fig. 16.—Salinity distribution within the core of the salinity minimum around σ_t 26·30 (Fig. 4). For salinity coding see Figure 7.

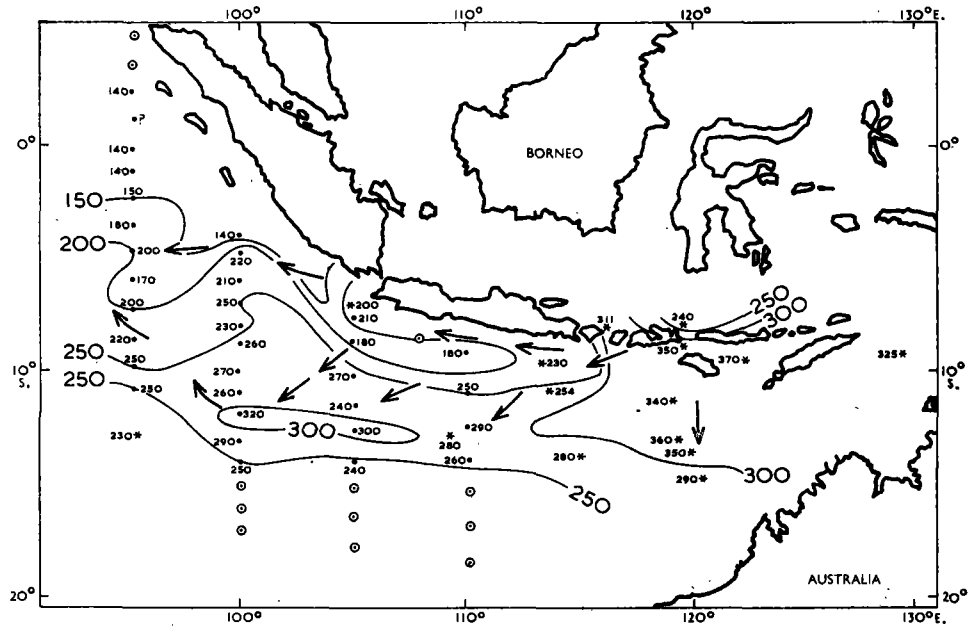


Fig. 17.—Depths (m) of the salinity minimum (Fig. 16). Arrows as in Figure 16.

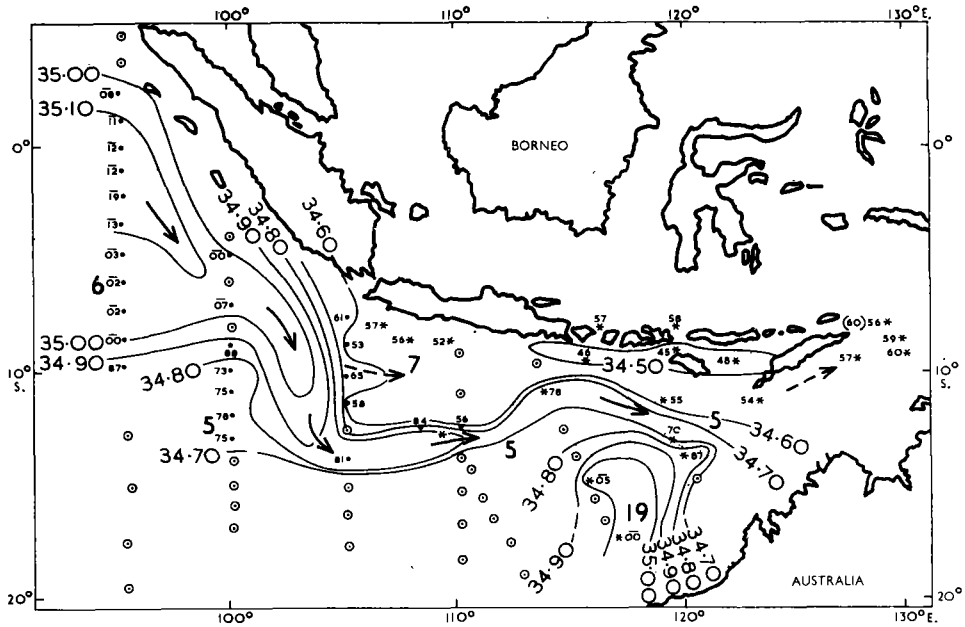


Fig. 18.—Salinity distribution within the core of Arabian Sea waters (*D* in Fig. 4). Numbers refer to water mass limits of Figure 4. For salinity coding see Figure 7.

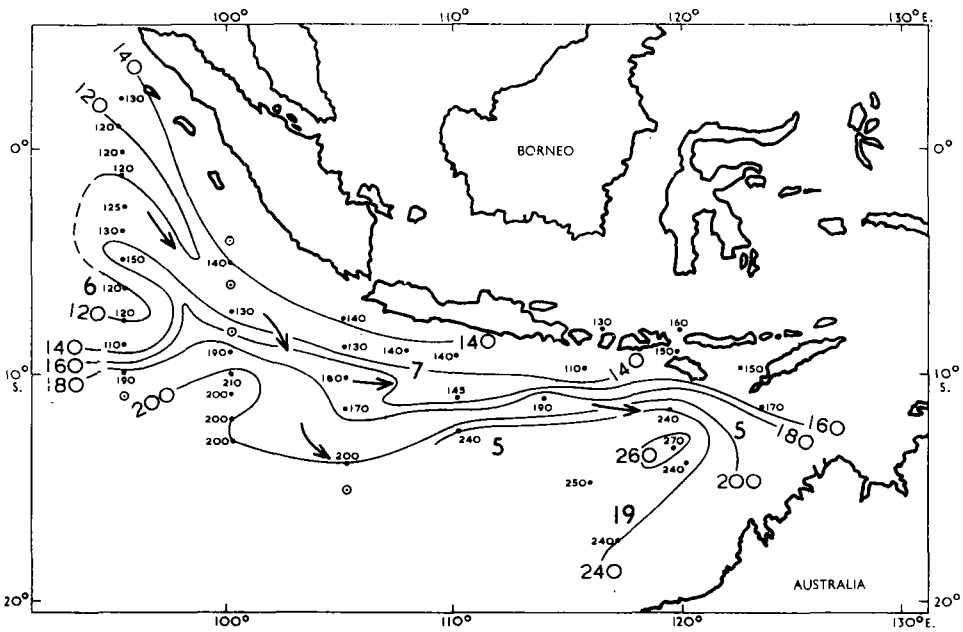


Fig. 19.—Depth (m) of the Arabian Sea waters (*D* in Fig. 4). Arrows and numbers as in Figure 18.

It could be argued that since water masses *E* and *F* are found close to the surface (Figs. 21 and 23) they could be formed by local processes rather than transport from an external source. Thus surface or near surface high salinity waters from south of the front at 23–24° S. (Fig. 24) would be progressively diluted by increased precipitation (Wyrtki 1961) as they moved towards the north. Mixing within the upper 100–125 m could form a temperature–salinity relation of the type shown in Figure 3. However, the inorganic phosphate (Fig. 25) and oxygen (Fig. 26) along the 105° E.

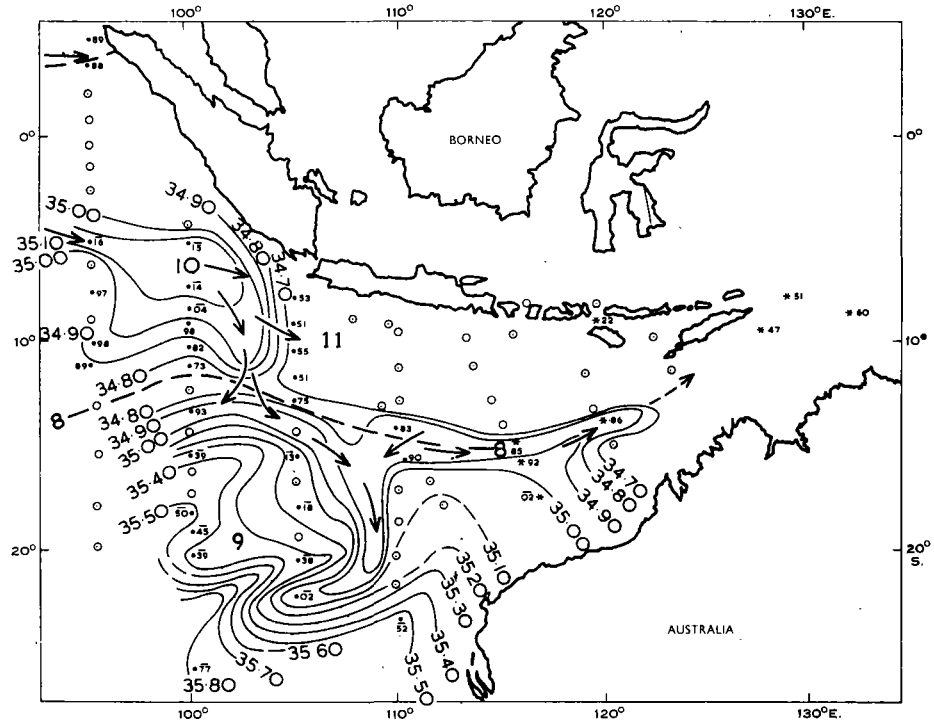


Fig. 20.—Salinity distribution within the core of water mass *E* (Fig. 4). Numbers refer to water mass limits of Figure 4. For salinity coding see Figure 7.

section show that water masses *E* and *F* are low in oxygen (less than 4·00 ml/l) and high in phosphate (greater than 0·40 μg-atom/l). These properties cannot be reconciled with a surface formation of these water masses within the south-east Indian Ocean, and their sources must be external to the region.

V. Seasonal Changes in Distribution of Water Masses

On cruise 31 R.S. *Vityaz* occupied a sufficient number of stations in the south-east Indian Ocean to trace the distribution of the water masses of Section III during October–December 1959, i.e. during the transition period from south-east to north-west monsoon (Fig. 2).

In January–March 1962 H.M.A.S. *Diamantina* occupied stations throughout the region to the north-west of Australia (Fig. 1) during the north-west monsoon.

These have been used to determine the eastern limits of the water masses of Section III during this period. On the assumption that the distribution observed in these different years and in July–September 1962 (Section III) is representative of average conditions, comparison is made in this section of the seasonal changes in position of the major distribution paths with selected isohalines of the water masses within the upper 500 m of the south-east Indian Ocean.

Persian Gulf.—This water mass was found along two major paths in October–December (Fig. 27) as previously established for July–September (Section III) but in January–March the station network was sufficient only to establish the northern division of flow as a permanent year-round feature. Along this northern path, the position of the 34·65‰ isohaline indicated that maximum flow to the east occurred in October–December.

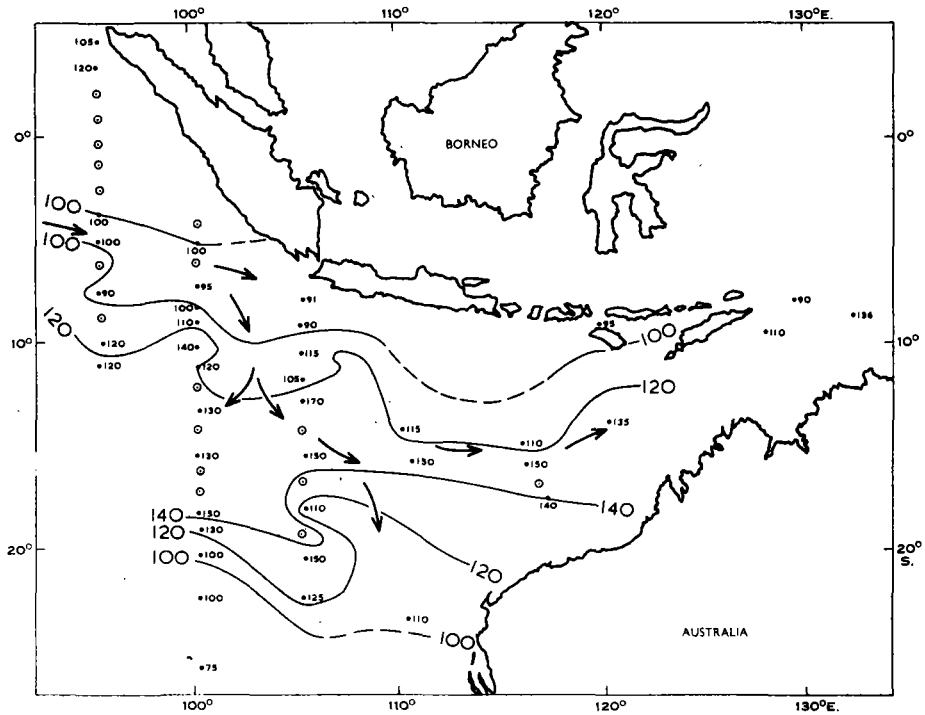


Fig. 21.—Depth (m) of water mass *E* (Fig. 4). Arrows and numbers as in Figure 20.

South-east Indian high salinity.—Seasonal changes in position of the northern limits of mixtures of this water mass and the oxygen maximum (2 in Fig. 4) could not be examined because of lack of stations south of 20° S. on *Diamantina* cruise 1/62. The northern limit of mixtures of this water mass and Persian Gulf water (3 in Fig. 4) was based upon the position of the 34·90‰ isohaline (Fig. 28) which lies within the frontal zone at 15° S. (Fig. 24) separating water mass B^1 from those of the north Indian Ocean. The change in position of this isohaline indicates that the greatest penetration of water mass B^1 into the region north-west of Australia occurs in October–December, when the greatest eastward flow of Persian Gulf waters also occurs (Fig.

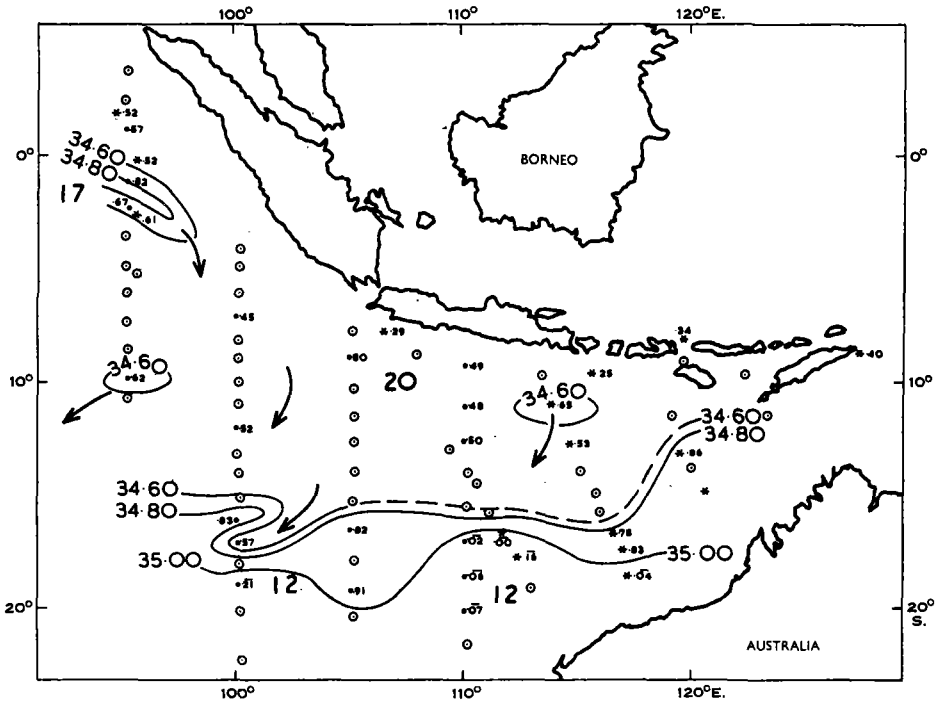


Fig. 22.—Salinity distribution within the core of water mass *F* (Fig. 4). Numbers refer to water mass limits of Figure 4. For salinity coding see Figure 7.

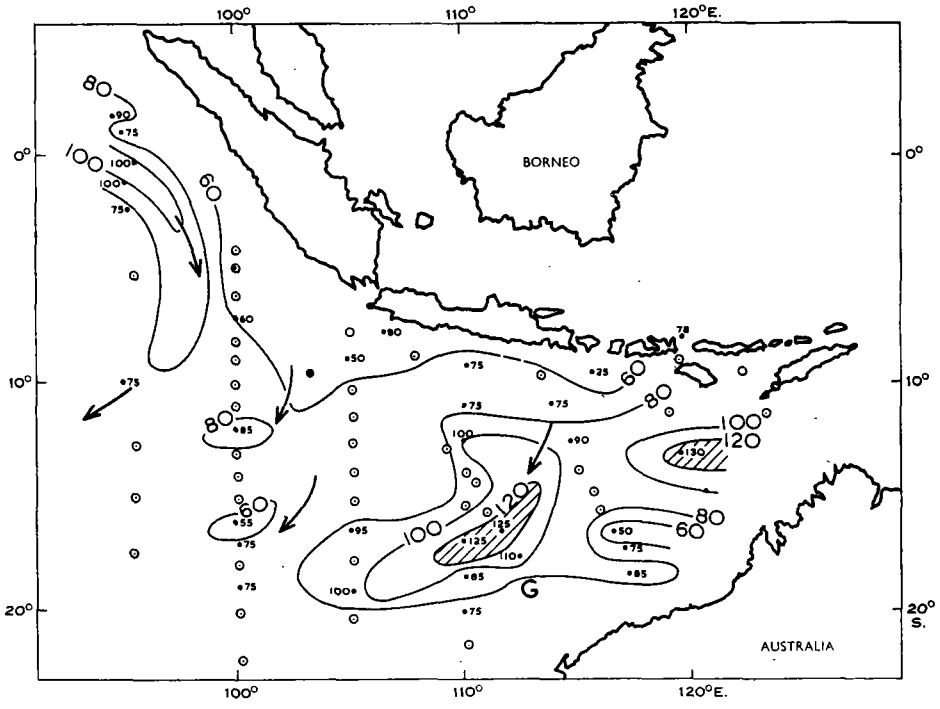


Fig. 23.—Depth (m) of water mass *F* (Fig. 4). Arrows and numbers as in Figure 22.

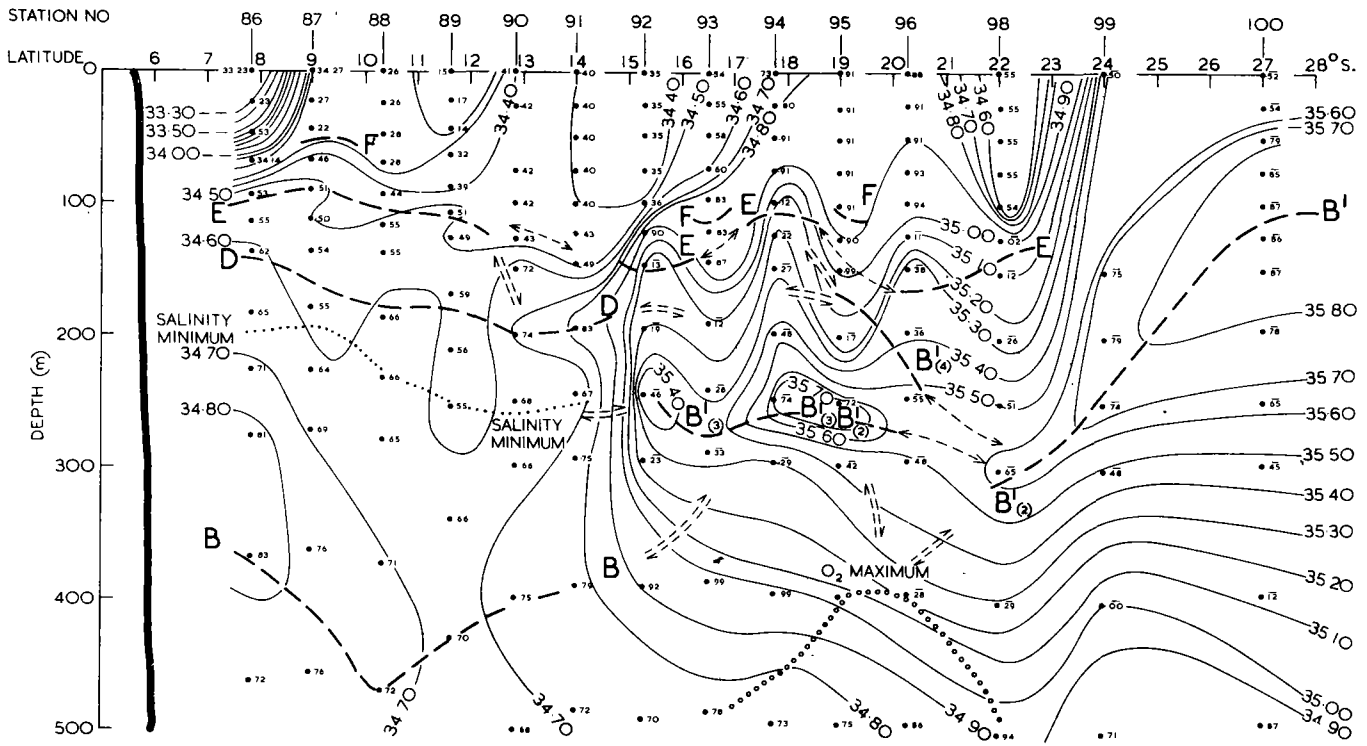


Fig. 24.—Salinity distribution to 500 m along the 105° E. meridian of the south-east Indian Ocean. For salinity coding see Figure 7. The depths of the core layers of the various water masses are given by the heavy dashed lines (maxima) and heavy dotted lines (minima) with the name of the water mass shown by its code letter (Fig. 4). Numbers refer to various mixtures of B^1 (Fig. 6).

27). The northern limit of mixtures of water mass B^1 and Arabian Sea waters (4 in Fig. 4) was based upon the position of the 35·10‰ isohaline. The position of this isohaline could be fixed on the eastern side only during January–March (Fig. 29) and on the western side only in October–December so that the extent of its seasonal change in position for the entire region cannot be established. Along the 105° E. meridian, however, the northern limit of this isohaline was much further north in October–December than in July–September (Fig. 29).

Salinity minimum (σ_t 26·30).—The southern limit of this water mass was defined by the position of the 34·70‰ isohaline. This isohaline formed the northern limit of the frontal zone at 15° S. (Fig. 24). The seasonal changes in position of this isohaline (Fig. 30) indicated that the greatest westward penetration occurred in July–September and the greatest penetration southward along the north-west coast of Australia in January–March. The relative stability of position of the isohaline in the centre of the region (* in Fig. 30) suggests that the volume transport of this water mass remains constant but its direction of flow is varied during the year.

Arabian Sea.—The 34·90‰ isohaline was chosen as the southern limit of this water mass. This isohaline lies within the frontal zone at 15° S. (Fig. 24). Changes in position of this isohaline (Fig. 31) indicated that this water mass moved eastwards to the greatest extent in January–March and receded westwards until October–December before eastward movement again occurred. The northern boundary of mixtures of water mass B^1 and Arabian Sea water along the 105° E. meridian (Fig. 29) varied in position according to the extent of eastward penetration of Arabian Sea water (Fig. 31).

Water mass E (counter-current).—The 34·80‰ isohaline on the northern side of the minimum (8 in Fig. 20) was chosen as the invading boundary of this water mass. This restriction was applied since salinity values south of this minimum are formed by the mixing of these minimum salinity waters and water mass B^1 and are more representative of B^1 than *E*. No data west of 105° E. were available in January–March and none within 200 miles of Sumatra in October–December. It has been assumed, however, that since water mass *E* occurred east of 105° E. during these periods there must have been a flow from the west at the same time (arrows in Fig. 32). The changes in position of the 34·80‰ isohaline indicated that this water mass penetrated further to the east in October–March than in July–September (Fig. 32).

Water mass F.—Invading from the north-west, this water mass first decreases in salinity to form a region of minimum salinities (Fig. 22) and then increases its salinity by mixing with waters of higher salinity from the south. The 34·70‰ isohaline to the north of this salinity minimum was chosen as the invading boundary of this water mass. Changes in position of this isohaline (Fig. 33) indicated a progressive movement of this water mass to the east during the north-west monsoon (November–March). A rate of flow of 5–10 miles per day (0·2–0·4 knots) would cause this displacement within the maximum period (July–March) or minimum period (September–January) respectively. These values compare with a maximum velocity of 31 cm/sec (0·6 knot) for the eastwardly flowing Java current computed from the dynamic topography by Soeriaatmadja (1957).

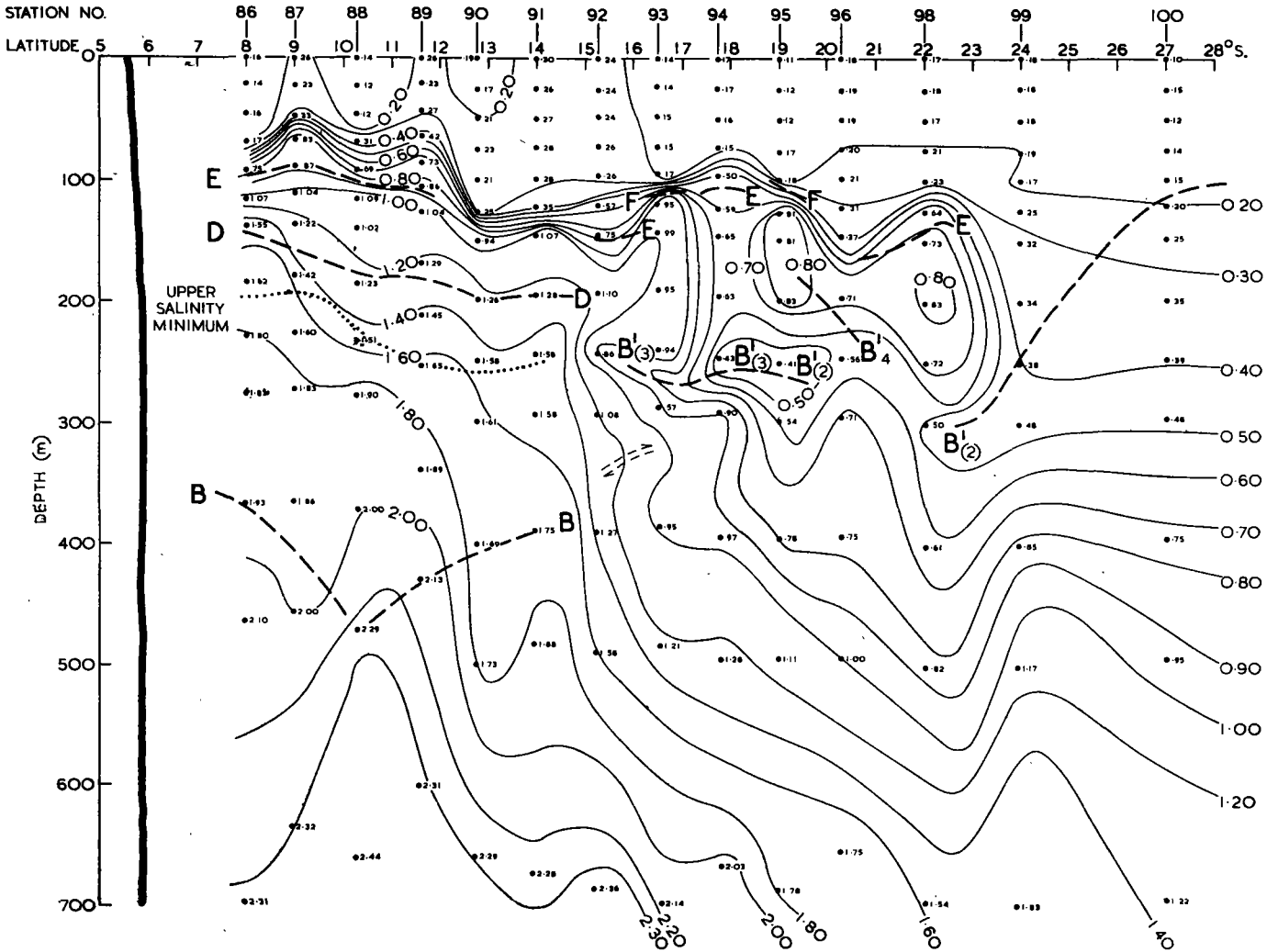


Fig. 25.—Inorganic phosphate distribution to 500 m along the 105° E. meridian. Depths of the core layers and coding of the various water masses as in Figure 24.

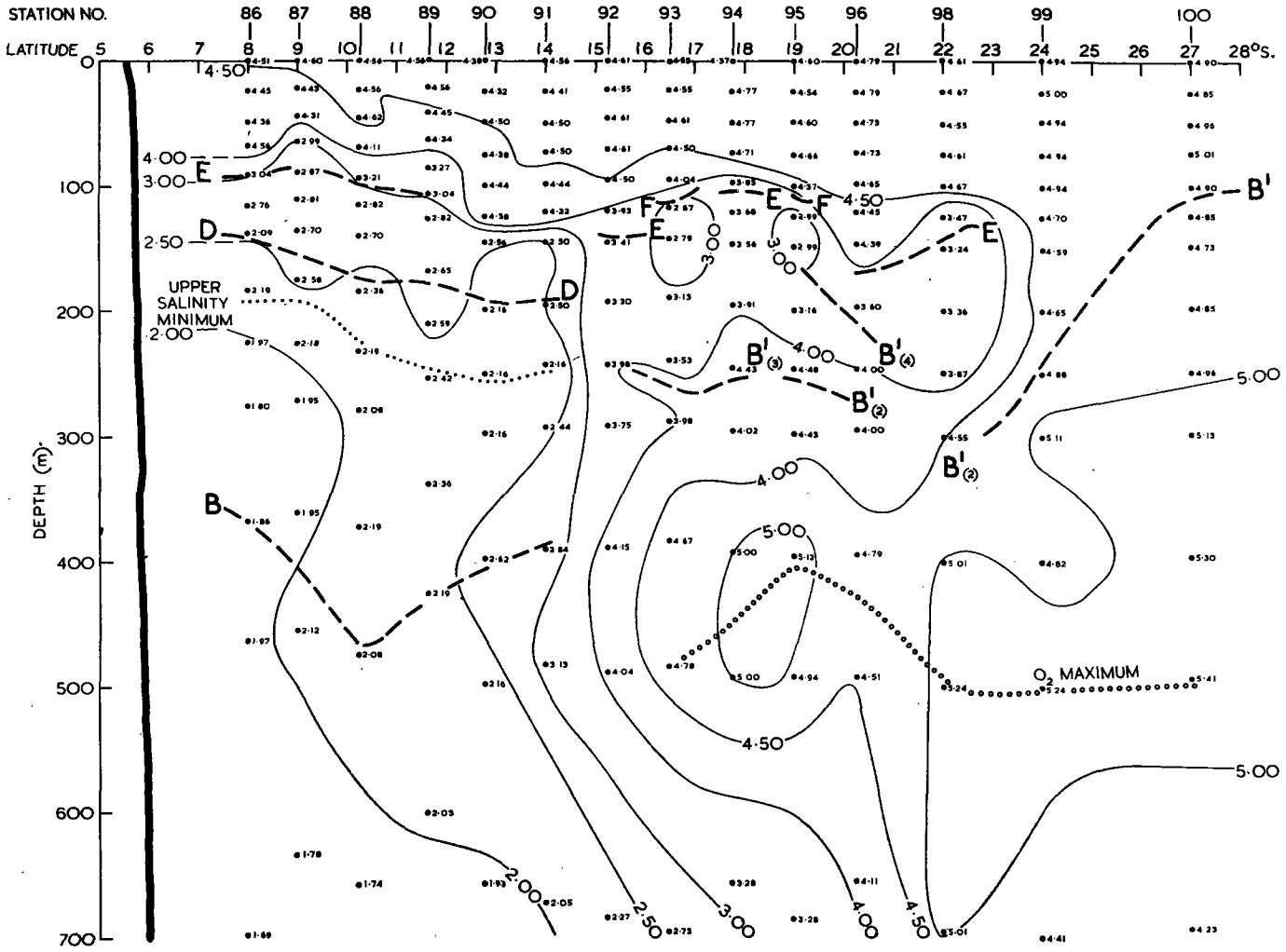


Fig. 26.—Oxygen distribution to 500 m along the 105° E. meridian. Depths of the core layers and coding of the various water masses as in Figure 24.

VI. Factors Controlling the Flow of Water Masses

The meridional boundary of water mass *F* oscillated about a mean position in November from an extreme western position in August to an extreme eastern position in March (Fig. 34). The changes in meridional position of the other water masses above 250 m generally followed this timetable, but at 500 m water mass *B* was found

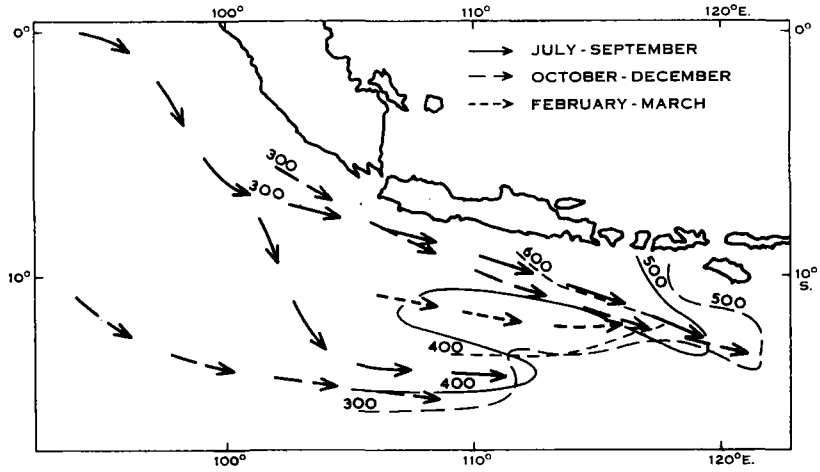


Fig. 27.—The position and average depth of the 34·65‰ isohaline of water mass *B* (Fig. 4) during July–September 1962, October–December 1959, and February–March 1962.

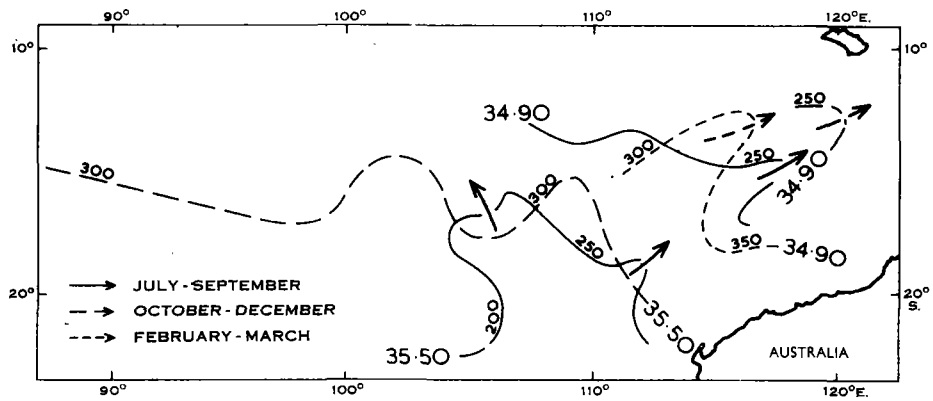


Fig. 28.—The position and average depth of the 35·50‰ and 34·90‰ isohalines of mixtures of water mass B^1 and Persian Gulf waters (3 in Fig. 4) during July–September 1962, and October–December 1959, and of the 34·90‰ isohaline only during February–March 1962.

at an extreme western position in March and at an extreme eastern position in November. To a depth of at least 250 m, therefore, the westwardly recession of these water masses occurs during the period of strong winds from the south-east and could be caused by increase in zonal circulation. This possibility has been examined by comparing the mean rate of westwardly recession of these water masses between August

and March, with the vertical distribution of geostrophic velocity to the west (Wyrtki 1962) for the same region during October (Fig. 34). The extent of agreement in shape and magnitude of these two curves, especially when it is considered that the water mass curve is an average for six months and the geostrophic curve is based upon one

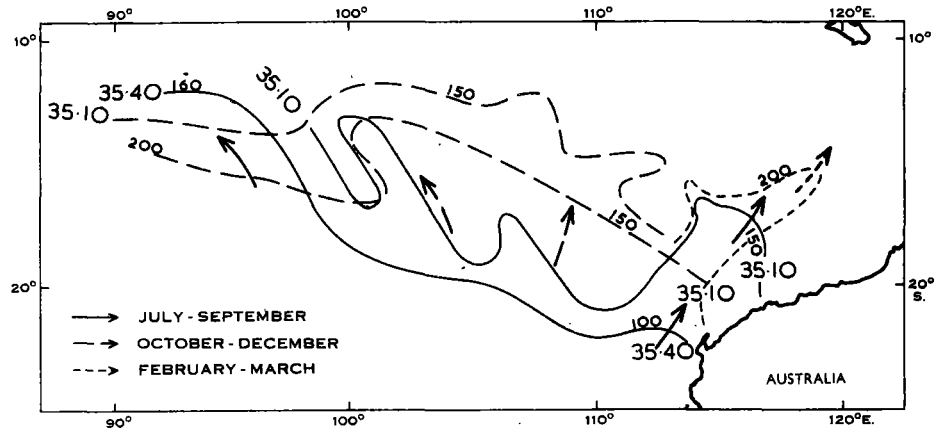


Fig. 29.—The position and average depth of the 35·40‰ and 35·10‰ isohalines of mixtures of water mass B^1 and Arabian Sea waters (4 in Fig. 4) during July–September 1962, and October–December 1959, and of the 35·10‰ isohaline only during February–March 1962.

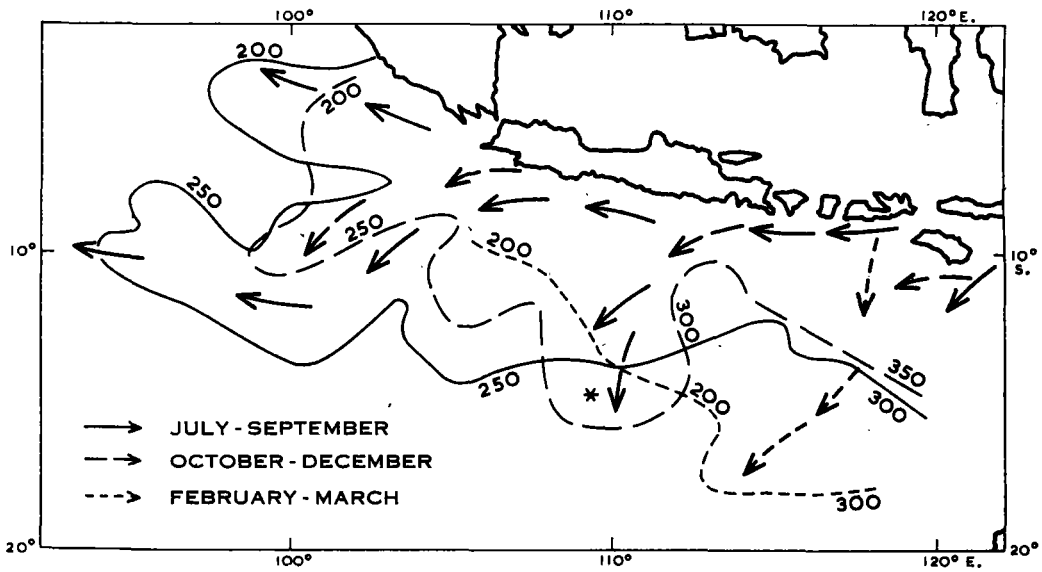


Fig. 30.—The position and average depth of the 34·70‰ isohaline of the salinity minimum around σ_t 26·30 (Fig. 4) during July–September 1962, October–December 1959, and February–March 1962.

month only, indicates that westward movement of the waters of the upper 250 m causes the recession of these water masses. Below 250 m, however, water mass *B* moves eastwards in opposition to the surface circulation during March–November (Fig. 34). During November–March this water mass recedes westwards at an average

rate of 0·75 miles per day. The Banda Intermediate water mass flows into the Indian Ocean at depths of 800 m (Rochford 1961) during November–March (Wyrtki 1957).

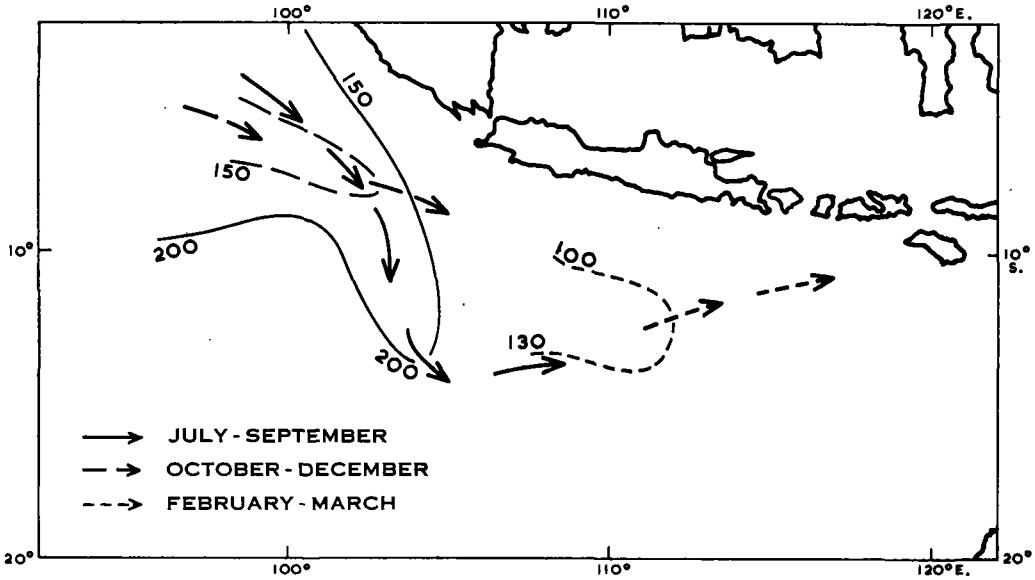


Fig. 31.—The position and average depth of the 34·90‰ isohaline of water mass *D* (Fig. 4) during July–September 1962, October–December 1959, and February–March 1962.

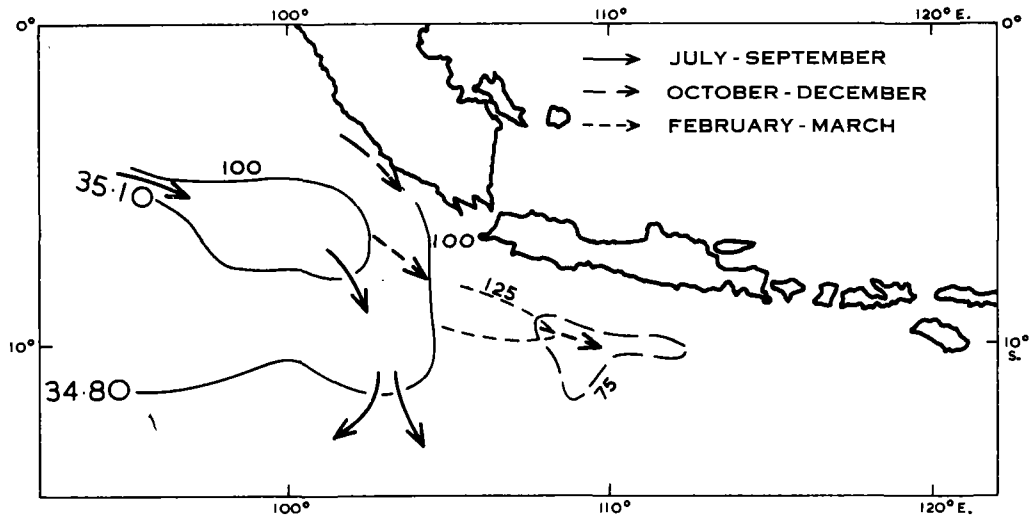


Fig. 32.—The position and average depth of the 35·10‰ and 34·80‰ isohalines of water mass *E* (Fig. 4) during July–September 1962, and of the 34·80‰ isohaline only during October–December 1959, and February–March 1962.

Patches of this water mass have been found drifting west (at depths of 450–550 m) at a rate of 1·4 miles per day (Rochford 1963) which is very similar to the rate of *B*.

It is thought therefore that the westwardly recession of *B* is governed by intermediate, and not by surface, circulation.

The extent of meridional movement of water masses off north-west Australia (Fig. 35) increased with depth to a maximum around 250 m (Fig. 35). All these movements therefore cannot be governed by the local surface circulation. The timetable of movement also changes with depth around 200 m (Fig. 35). Above 200 m movements to the south occurred in August–March whilst below 200 m it occurred in March–November. Above 200 m the direction of movement of water mass B^1 (4 in Fig. 4) agreed with that of surface currents and is presumably, therefore, governed by them. Below 200 m, however, the direction of movement is in opposition to surface currents. At these depths the greatest southward penetration of the upper salinity minimum occurs in November–March when the escape of this water mass to the west

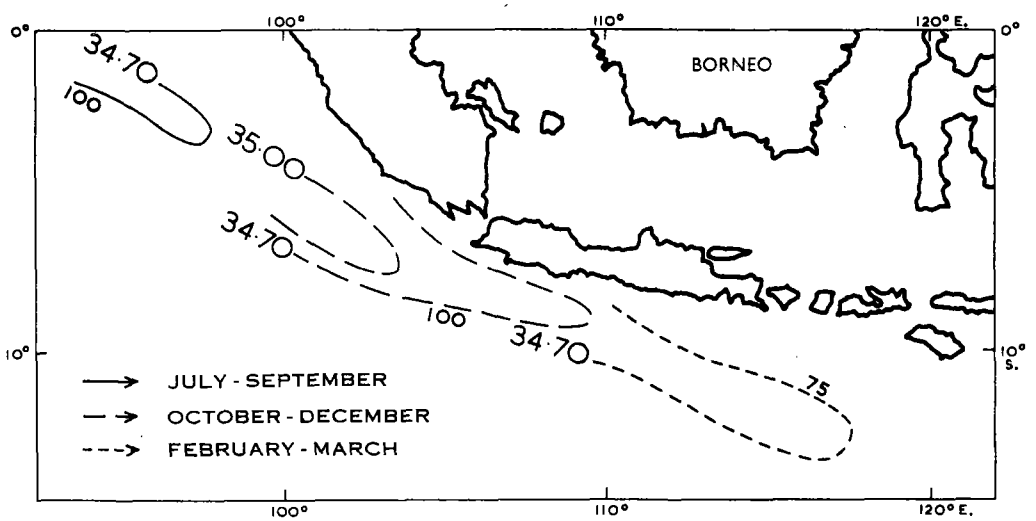


Fig. 33.—The position and average depth of the 34·70‰ isohaline of water mass *F* (Fig. 4) during July–September 1962, October–December 1959, and February–March 1962.

is blocked by eastward flow of north Indian Ocean water masses (Figs. 34 and 35). This year-round movement of this water mass from its source region indicates that its transport into the east Indian Ocean must persist throughout the year. Water mass B^1 (3 in Fig. 4) above the upper salinity minimum follows the same timetable, but has a greater range of movement (Fig. 35). It is unlikely, therefore, that seasonal changes in the northward flow of water mass B^1 could be governed by changes in the position of the upper salinity minimum. It is more probable that the northward flow of water mass B^1, to the north-west of Australia, is governed by factors of a seasonal nature near its source region, off south-west Australia (Rochford 1962) and that movement of B^1 controls the direction of flow of the upper salinity minimum.

VII. Conclusions

Four water masses of the north Indian Ocean have been identified within the south-east Indian Ocean:

Red Sea.—This water mass has the same temperature–salinity characteristics as the earlier north-west Indian Intermediate (Rochford 1961) and had the same distribution in July–September 1962 as in July–November 1959–60 (Rochford 1961). It is now considered the source of this earlier intermediate water mass.

Persian Gulf.—This water mass is found north of 15° S. only and its major flow is to the east within several hundred miles of Indonesia. Its depth along this flow path deepens from 150–500 m.

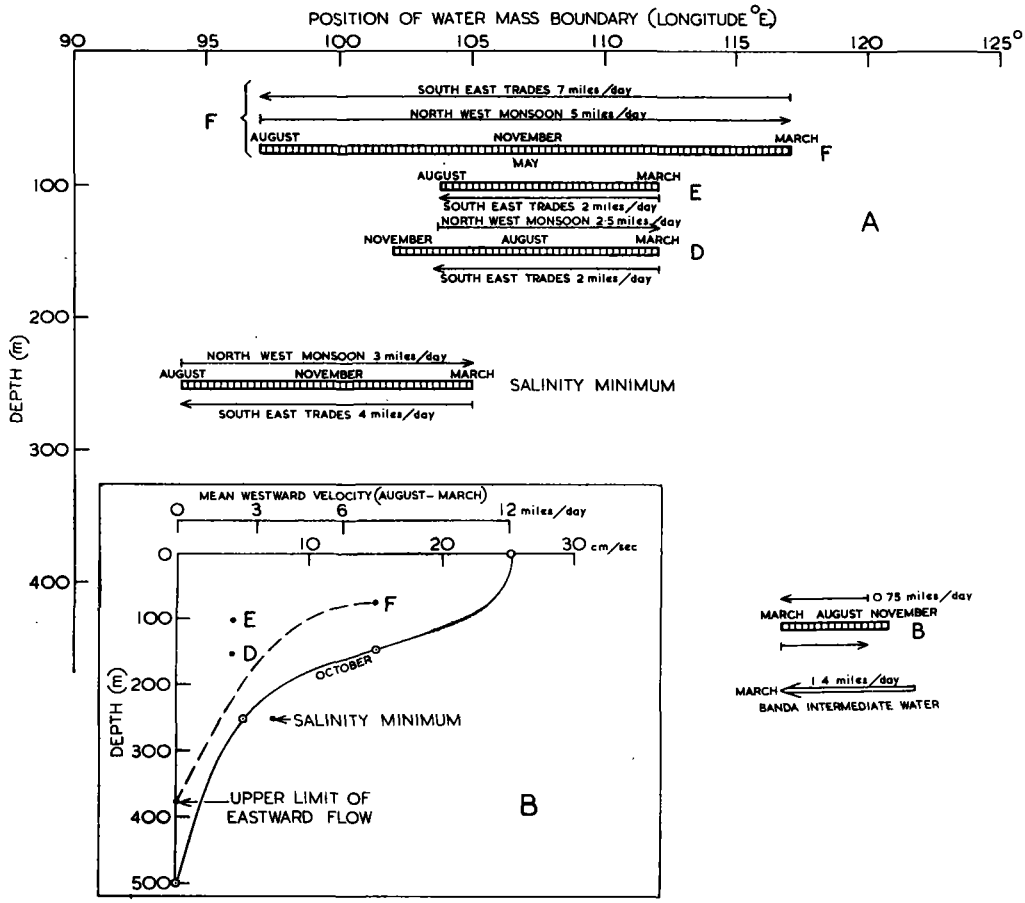


Fig. 34.—(*A*) The longitude of the meridional water mass boundaries on the three cruises and average velocities of eastward and westward flow. The velocity of westward flow of the Banda intermediate water mass is shown for comparison. (*B*) The vertical distribution of westward flow of water masses (●––●) compared with that of the geostrophic velocities (○—○) (Wyrtki 1962).

Arabian Sea.—This water mass is found north of a boundary from 10° S. and 95° E. to 20° S. and 115° E. and flows predominantly to the east at depths increasing from 150 m to 250 m in the downstream direction. It mixes in the north with low-salinity, near-surface water south of Java and in the south-east with high salinity water of the south-east Indian high salinity water mass.

Water mass E (counter-current).—This water mass enters the region to the south-west of Sumatra and flows to the east and south-east at depths of 100–150 m.

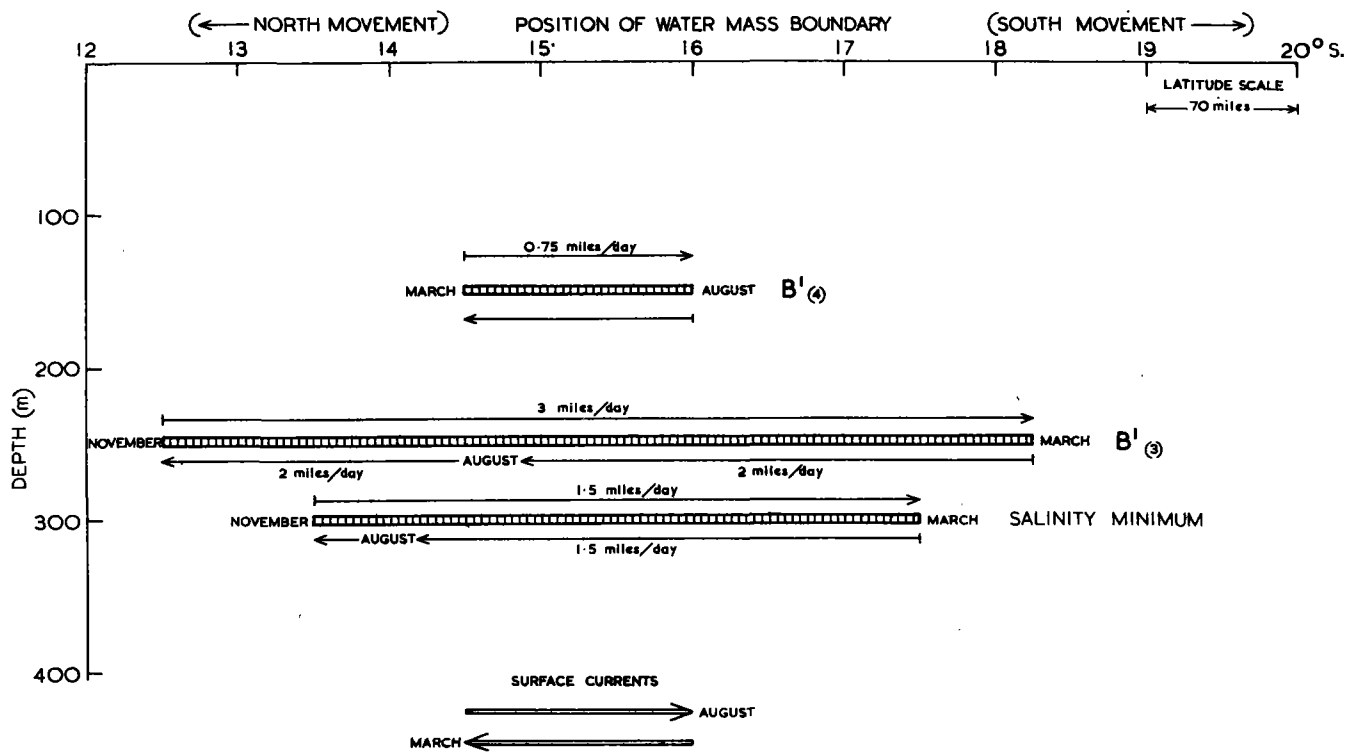


Fig. 35.—The latitude of the zonal water mass boundaries on the three cruises and average velocities of northward and southward flow. Meridional direction of surface currents shown for comparison.

It mixes with low-salinity, near-surface water south of Java and in the south-east with high-salinity water of the south-east Indian high-salinity water mass. Mixtures of this latter type are found as far south as 22° S.

Two other water masses, as yet unnamed, have been found in the south-east Indian Ocean.

Upper salinity minimum.—From the region of the Lombok Strait this water mass spreads at about 300 m, westwards in August–September and towards north-west Australia in February–March. Its southern limit was found at about 15° S. at a depth of 250 m.

Water mass F.—This water mass enters the region west of Sumatra at depths of 75–100 m. It is widely distributed in the region north of about 15° S. but its salinity distribution does not show its direction of movement eastwards. Its southern limit is similar to that of *E* some 25–50 m below it.

One major water mass from the south Indian Ocean has been found and has been named the *south-east Indian high salinity water mass.* This is found within only one core layer south of about 20° S. but north of this latitude it is found in several core layers according to its mode of mixing. The deepest mixing occurs between it and the oxygen maximum at depths of 250–300 m in the vicinity of 15° S. Mid-depth mixing occurs between it and the Persian Gulf, and upper salinity minimum water masses to the south of Java around 15° S. at depths of about 300 m. Shallow depth mixing occurs between it and the Arabian Sea water mass around 12–15° S. along the 95° and 115° E. meridians at depths of about 150 m.

Seasonal changes in the distribution of these water masses have been found. Movements to the east and west within the upper 300 m are controlled by surface currents. Below 300 m, however, such movements follow those of the Banda Intermediate water mass at 500–800 m. The extent of southern penetration of these water masses towards north-west Australia is governed by surface circulation to a depth of 200 m, but by the extent of northward movement of south-east Indian high salinity water at depths below 200 m.

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Survey of Trawl Grounds off the North-West Coast of Australia with Special Reference to Hydrographical Conditions on the Grounds

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Survey of Trawl Grounds off the North-West Coast of Australia with Special Reference to Hydrographical Conditions on the Grounds

Kiyoshi MASUDA, Shigekatsu NAKANE, Shoji SAITO and Takeji FUJII

Abstract

1. Exploratory trawlings were carried out off the north-west coast of Australia two successive summers, December 1962 and December 1963~January 1964, on the ocassions of training cruises of the "Oshoro Maru" of Hokkaido University. Full data may be referred to "Data Record of Oceanographic Observations and Exploratory Fishing" No. 8, No. 9.

2. Off Legendre Island a shallow bottom extends northward, and the area around this bank has been known as a trawling ground called by fishermen "Nose of Long-nosed genie". Horizontal isotherms and isohalines at the bottom strongly curved towards the northern direction at this region, indicating that water of high temperature and high salinity extended from the coastal region to the offshore region. Such an area has been known to be a good trawling ground in general.

3. Off Cape Thouin there was an intrusion of low temperature and low salinity offshore water into the coast in the direction from ENE to WSW. Exploratory trawlings made in the areas around this water and apart from this water indicated that the area off Cape Thouin was also a good trawling ground at this season.

4. The current was measured with a current meter (Toho Dentan CM-2) off Port Walcott. Tidal current was directed mostly to 150° during flood tide, and mostly to 285° during ebb tide, with the maximum velocity of 0.6 m/sec. recorded during the ebb tide.

5. Off the north-west coast of Australia "Kuchimidai" (*Lethrinus ornatus* CUVIER & VALENCIENNES) was most abundant among the trawl caught fish, occupying 16.4% in weight of total catch including all fish in the net, on the average of all stations. The catch of this species off this coast has been reported more than 40% in the Fisheries Statistics which was based on the catch of commercially important fish stored on the ships. In the present samples the mean body length (fork length) of this species was 28.26 cm in female and 29.95 cm in male. Ratio of number for female to male was 1:0.67. The deeper the grounds shifted, the larger the size of fish.

6. A larger catch of "Chikodai" (*Argyrops spinifer* FORSKAL), "Akadai" (*Lutjanus janthinuropterus* BLEEKER) and "Nagadai" (*Scolopsis temporalis* CUVIER & VALENCIENNES) was obtained in the grounds on the east side of the

warm water extrusion (ref. to 2) and on the contrary, the catch of "Himedai" (*Nemipterus peronii* CUVIER & VALENCIENNES), "Yokosujifuedai" (*Lutjanus vitta* QUOY & GAIMARD) and "Sennendai" (*Lutjanus scbae* CUVIER & VALENCIENNES) was increased on the offshore of this area.

7. The catch of "Chikodai", "Akadai" "Hata" (Epinephelinae), "Hiraaji" (*Caranx malabaricus* BLOCH & SCHNEIDER), "Nagadai" was apparently decreased at night as compared with the day light catch.

緒 言

トロール船の海外進出にともない，オーストラリヤ北西岸は，アフリカ，ニュージーランドと共に遠洋トロール漁場として脚光を浴びた。最盛期だった 1960 年には，稼動トロール船 7 隻を数え，約 3,700 トンの水揚高があった。しかし現在では，アフリカ漁場が，更に大型化されたトロール船によって開発が促進されつつあるのに反し，オーストラリヤ北西岸漁場は，あまり顧みられない状態である。

筆者等は本学練習船おしよろ丸（1,180 トン，船尾トロール型）に依り，1962 年 12 月および 1963 年 12 月～1964 年 1 月に亘り，この海域に於てトロール実習を行ない，海洋観測並びに漁業試験を実施した。その資料をもとにして漁場の検討をしたので，概況ではあるがその結果を報告する。尚，この論文の整理に当って種々御教示を頂いた北海道大学水産学部遠洋漁業学教室，上野元一助教授，資料整理に際して協力して頂いた漁業科専攻科，吉田雄司君に対し，心から感謝する次第である。

資料および方法

Fig. 1 は 1962 年 12 月 14 日より 19 日迄の間実施した海洋観測点および操業地点を示す。操業

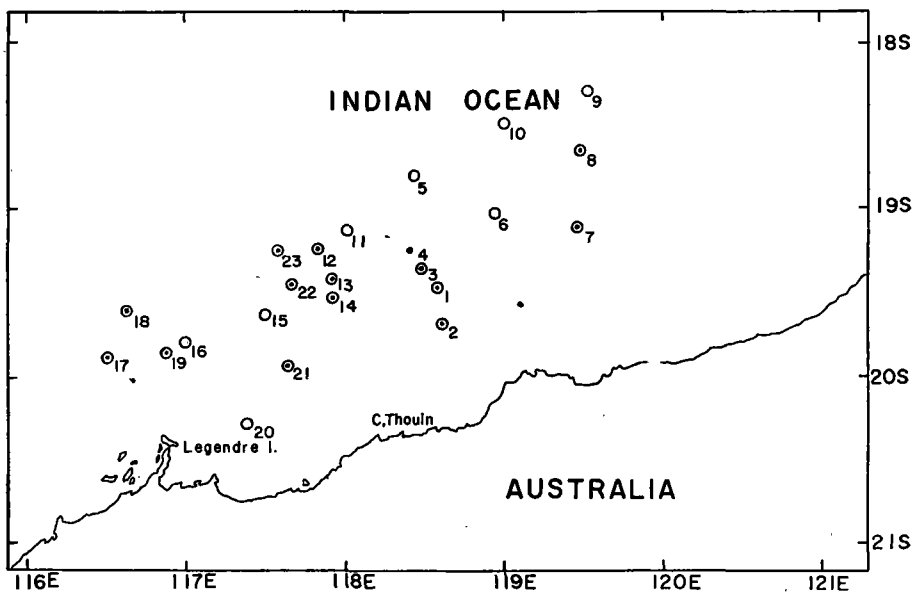


Fig. 1. Location of the hydrographic stations and the trawl fishing positions occupied by the "Oshoro Maru" in Dec. 1962
⊙: Hydrographic and trawl fishing position
○: Hydrographic station ●: Trawl fishing position

地点の選定に当ってはこの海域全般の傾向を摑む意味で広範囲に亘り，特に水深に依る魚種の変化に留意した。トロール網はトワイン製，Head Rope 長さ 37.1 m (122 尺) を使用した。海洋調査は，表面，10 m，20 m，30 m，50 m，75 m，100 m 層を標準層として海底附近迄行ない，温度，塩分を測定した。採泥，B.T. (Bathy Thermograph) を用いての測温も行なった。生物調査は主としてクチミダイを対称にして，体長，体重，生殖巣状態，耳石採集，胃内容物等の調査を併せて行った。

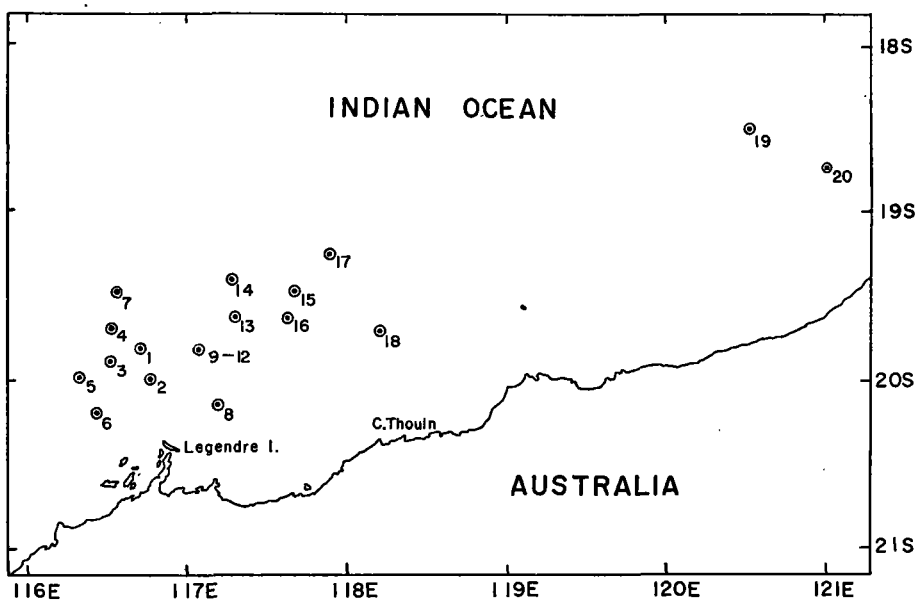


Fig. 2. Locations of the hydrographic stations and trawl fishing positions occupied by the "Oshoro Maru" in Jan. 1964 from Dec. 1963

Fig. 2 は 1963 年 12 月 28 日より 1964 年 1 月 6 日迄の間実施した海洋観測点および操業地点を示す。操業地点は 1962 年 12 月の調査資料を参考にして，Legendre 島 (20°21′S 116°50′E) 沖合に存在する北方へ強く張出した暖水塊周辺の調査に重点を置き，この附近の漁場形成，解明のための資料蒐集に努力した。また，St. 9 に於て船内使用時の 12 時，18 時，00 時，06 時に操業し，同一地点での時刻に依る漁獲高および魚種組成の変化について考察した。トロール網はクレモナ製，Head Rope 長さ 43.3 m (143 尺) を使用し，各操業地点での海洋調査，漁業試験は 1962 年にならった。St. 8 で投錨仮泊中，電気流速計 (東邦電探製，CM-2 型) を用いて，1963 年 12 月 31 日 10 時より 45 時間連続潮汐流の毎時の流向，流速を観測した。

結果および考察

水深および海底地形

Fig. 3 は海図をもとに，音測結果を添加した等深線図である。等深線は海岸線とほぼ平行に走っている。116°40′E で 50 m，60 m 等深線が北方に伸び Bank を形成し，この 60 m 線の西側が通称『天狗の鼻』と呼ばれているところである。この Bank はこの南方に存在する半島と共に海潮流に大きな影響を与えている。118°35′E～119°00′E にも Bank があり，その他は概して平坦である。

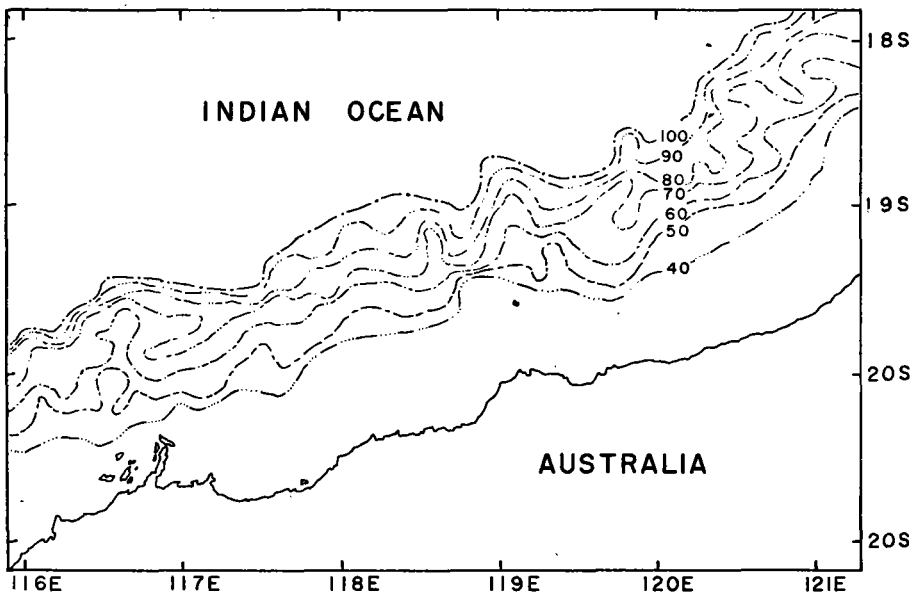


Fig. 3. Depth contours

潮汐流

Fig. 4 は St. 8 (20°08′S 117°12′E) で観測した流速の時間経過に対する変化を示し，Fig. 5 は流速と流向の関係を示したものである。Port Walcott (20°39′S, 117°13′E) の潮汐と比較すると，Port Walcott の高潮時，低潮時の前後 50 分以内に転流し，漲潮時にはほぼ 150°，落潮時にはほぼ 285° に流れる場合が多い。この海域では大体 SE～NW に流れるが，落潮流は漲潮流の反方位より約 45° 西寄りである。流速の最高値は落潮時に 0.6 m/sec を記録した。

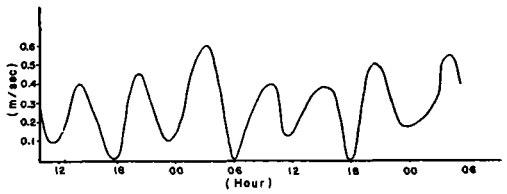


Fig. 4. The relation between time and rate in tidal current

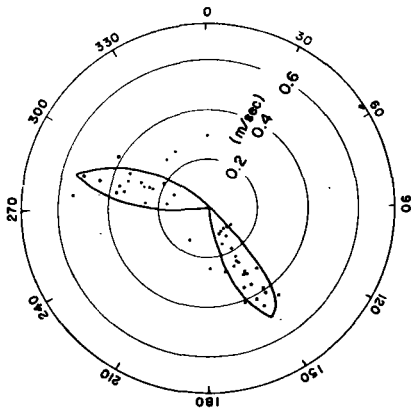


Fig. 5. Direction and rate of tidal current

海 況

Fig. 6 は 1962 年 12 月の 10 m 層の温度，塩分の分布を示す。温度分布についてみると，28.0°C の水塊が広範囲に，沖合より沿岸に楔状に入り込んでいる。この 28.0°C の暖水塊の突込みは顕著で，Fig. 10 (A) はその拡がりの状態を示している。St. 5, 11, 12 で 27°C 台の水塊に 28.0°C の水帯が楔状に割込んでいるのを見ることが出来る。Fig. 7 は 1963 年 12 月～1964 年 1 月の 10 m 層の温度，塩分の分布を示す。温度分布についてみると東端にある 28.5°C の等温線は西方に移行するに従って逓減している。この状態は 1962 年に東方に存在した温水塊が発達して西方に伸びたものと推定

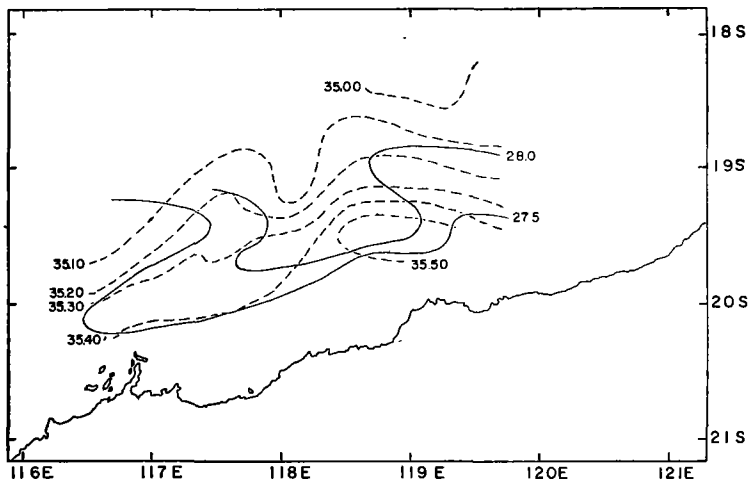


Fig. 6. Horizontal distribution of temperature (°C) and salinity (‰) at the 10 m level in Dec. 1962

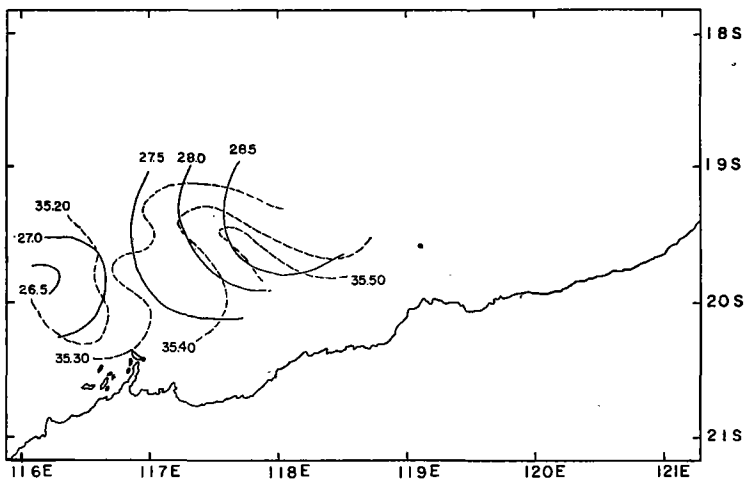


Fig. 7. Horizontal distribution of temperature (°C) and salinity (‰) at the 10 m level in Jan. 1964 from Dec. 1963

される。塩分については 35.50‰ の高鹹水塊が St. 15 を中心にして，沿岸より沖合に向かって NW に張出して居り，反対に 35.20‰ の低鹹水塊が St. 6 を中心にして SSE に突込んでいる。St. 8, 9 は両水塊の間に位している。上述の現象より 1962 年，1963 年とも，表層附近においては東方よりの暖水塊の消長が大きくこの海況に影響していると思われる。

海底附近の温度分布については両年共 Legendre 島沖合に沿岸より沖合に向う顕著な温水塊の張出しが認められる。それは 1962 年に N，1963 年は NW にそれぞれ張り出している。また，Cape Thouin (20°21′S, 118°12′E) 沖には沖合冷水塊が，ENE より沿岸に向け突込んでいるが，これは左程顕著でなく，しかも 1963 年には観測点の主体を西方に移したため再確認出来なかった。他の区域の等温線はほぼ陸岸に平行して分布している (Fig. 8, Fig. 9)。塩分についてみると，1962 年に於

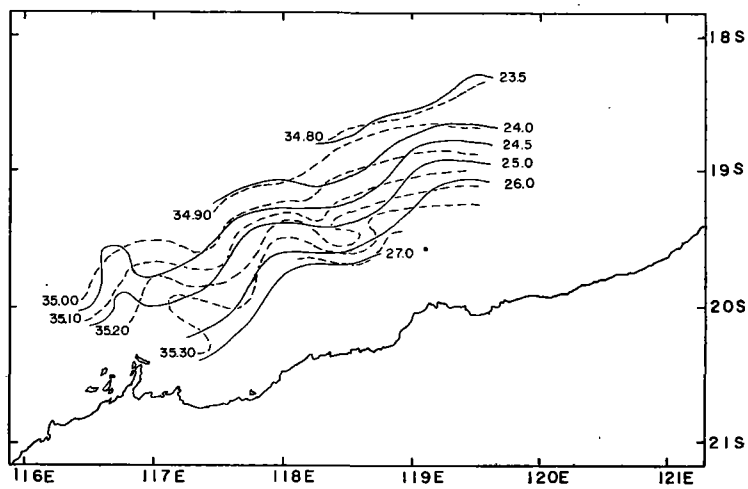


Fig. 8. Horizontal distribution of temperature (°C) and salinity (‰) at the sea bottom in Dec. 1962

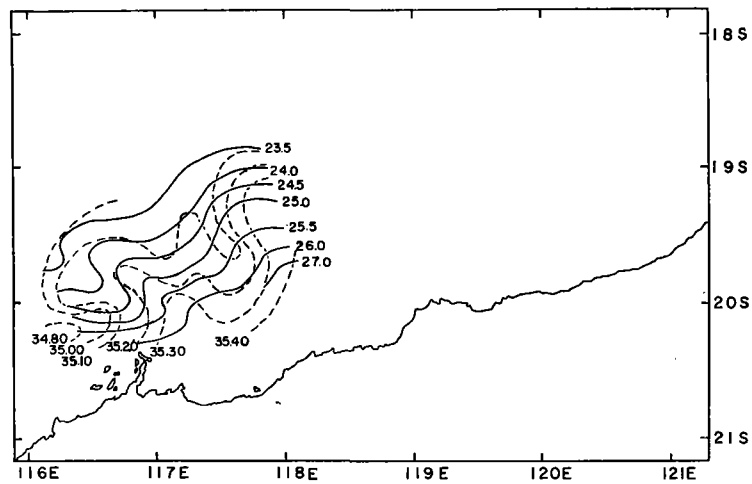


Fig. 9. Horizontal distribution of temperature (°C) and salinity (‰) at the sea bottom in Jan. 1964 from Dec. 1963

ては St. 15 に沖合よりの低鹹水があり，これを挟んで沿岸よりの高鹹水の張出しが見られる。St. 1 附近は局部的に複雑な様相を呈している (Fig. 10 (B))。その他の区域では，平担で，第温線と類似した傾向を示している。1963 年では St. 6 に 34.81‰ の非常に低鹹な水塊が存在して，35.40‰ の沿岸性の高鹹水塊に西から東へ割り込んでいる。このため高鹹水は強く NW に張出した形となっている。その張出しの東側は沖合性低鹹水と沿岸性高鹹水とが交互に存在し複雑な分布をしているが，1962 年と比較すると，表層の場合と同様なことが推定される。即ち東方水塊が西方に伸びて来ていると云うことである。

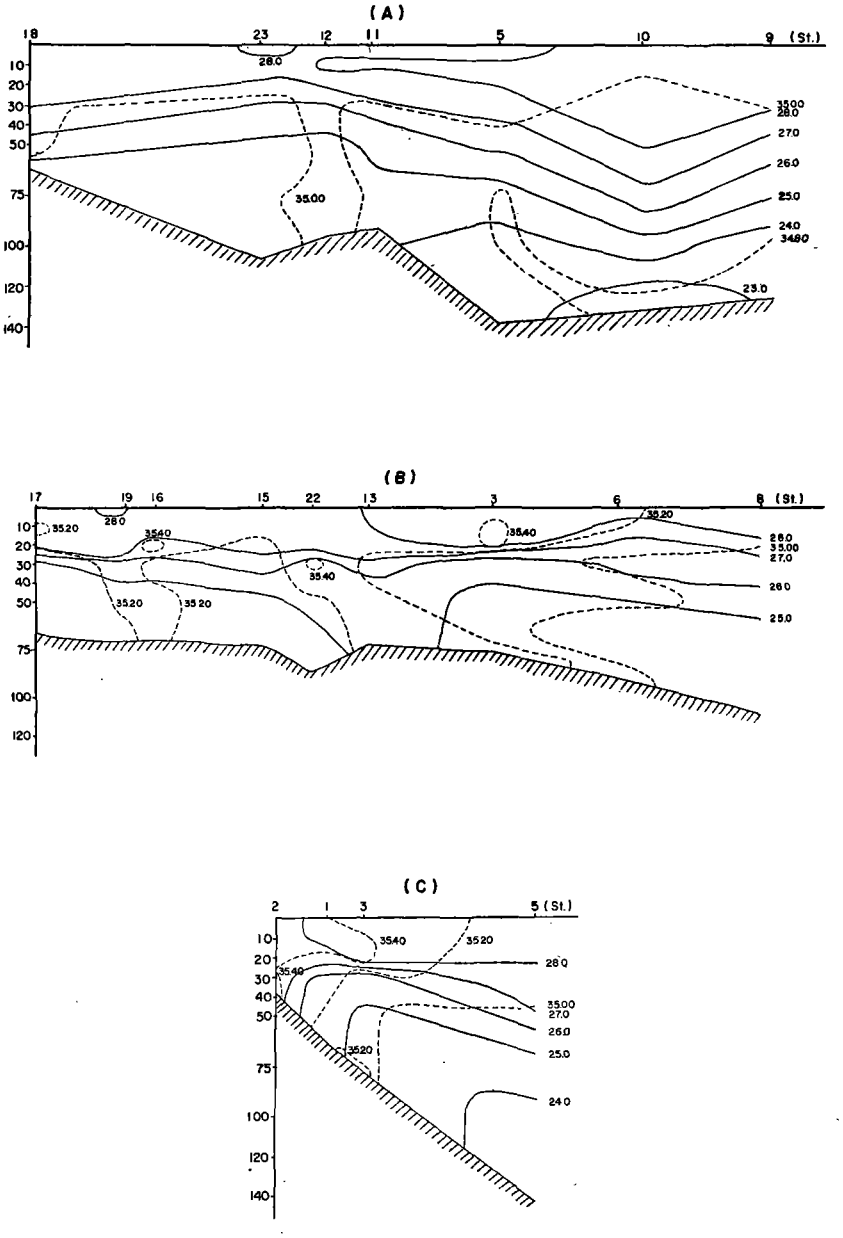


Fig. 10. Vertical distribution of temperature (°C) and salinity (‰) in longitudinal and latitudinal sections in Dec. 1962

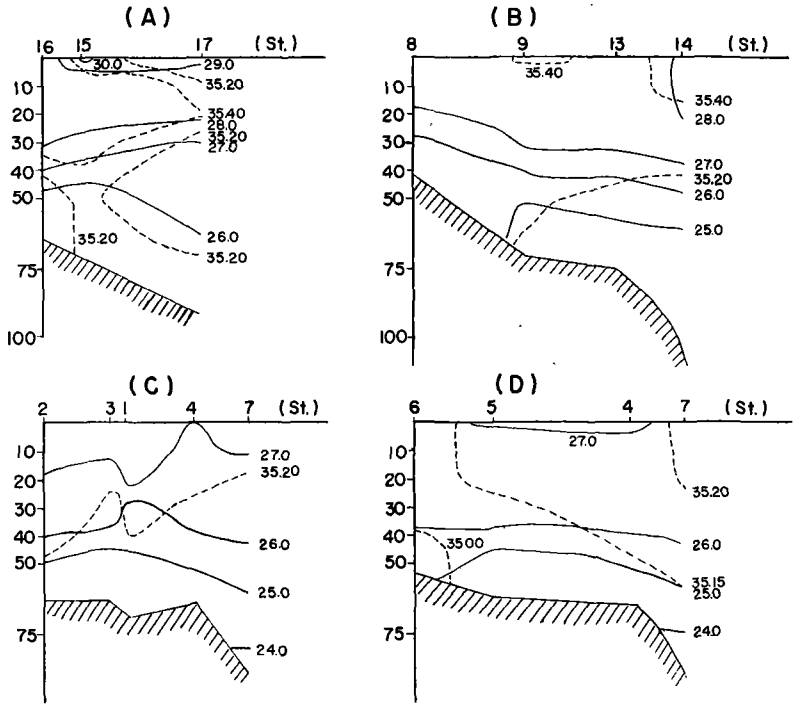


Fig. 11. Vertical distribution of temperature (°C) and salinity (‰) in longitudinal sections in Jan. 1964 from Dec. 1963

Fig. 12 はこの海域一般に見られる B.T. の記録である。温度変化の傾向は，表面より 20～30 m の深さ迄等しい温度で，それより深くなると急激な温度低下を示し，海底より 20～30 m 附近から再び変化せず海底に達している。この海域の 12 月では太陽が頂点近くにあり，その照射は強烈で，このため表面下 20 m ～30 m 間の水帯は急速に暖められて対流を起し，この間の水帯の温度は均一となる。鉛直断面についてみると一般に等温線の分布状態は，表面と海底附近では疎で，中央部は密になっている。塩分についてみると，35.00‰ の水塊が St. 9 ～St. 11, St. 23～St. 18 に存在し，St. 9, 10 の海底附近にある 34.80‰ の低鹹水帯は St. 5 において 75 m 近く迄上昇しているが，これは海底の地形の影響に依るものであろう (Fig. 10 (A))。沿岸寄りも大体同型である (Fig. 10 (B))。即ち 35.20‰ の水塊が St. 8～St. 13, St. 22～St. 16, St. 19～St. 17 と各個に存在している。

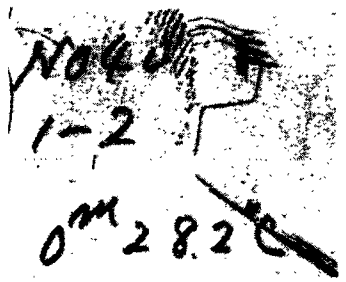


Fig. 12. Record of bathy thermograph

漁 況

Legendre 島沖に顕著に現われる高温，高鹹水塊の沿岸より沖合北方への張出しと，Cape Thouin 沖で ENE より WSW に向う低温，低鹹水塊の沿岸水塊への突込みが漁場形成に当って，意義は大きいと考えられる。

1962 年の St. 1, 2, 3, 4 についてみると St. 1, 2, 3 ではカワハギ，ウミヒゴイ，カノコウオ，その他雑魚合計 1 時間当り漁獲量（以下漁獲量は 1 時間当りの重量で示す）は 100 kg 以下であった

のに対し，St. 4 ではクチミダイ，アカダイ，ヨコスジフエダイ，チコダイ等の有用魚が多く漁獲量は 720 kg である。これは St. 4 が他の 3 地点に比して，低温，低鹹な沖合水域に属しているためと考えられる。St. 2 では底水温 27.47°C, 底塩分 35.41‰ と，操業地点 15 点の中で最高の温度，塩分を示したが，漁獲量は 15 kg と最低である。一般に高温，高鹹水域では有用魚種が少なくて雑魚が多く，特に海綿類，サンゴ類の底棲生物が非常に多い。また有用魚は小型である。そしてこれらの小型魚の胃内容物は，底棲生物に附着している稚ガニ，小エビ，サンゴ片などが多く見られた。水深の漁獲におよぼす変化については，海岸線にほぼ平行している等深線と，同じくほぼ平行している等温線との間で二次的に影響があるが魚種については明かでない。魚種に依り相違はあるが温度は 24.0°C ～25.5°C, 塩分は 35.00‰～35.20‰ で漁獲が多い，しかしクチミダイは 35.00‰ 以下に多い様である。

1963 年の St. 8, 1, 4 は張出し温水塊の中心線に位し，St. 9, 7 は東側に，St. 1, 2, 3, 5, 6 は西側にある。これ等諸地点間を比較検討してみると，St. 8 は沿岸水域に属しヒメダイ，ハタが少し漁獲されたのみで，海綿類は 1.392 kg である。St. 1 は甲イカ，ヒラアジが多く，クチミダイ，アカダイは少くなかった。St. 4 はアカダイ，エソが多い。東側の St. 7 はメイチ，センネンダイが多く，沖合水域にもかかわらず大型の海綿類が 1,605 kg もあった。St. 9 はアカダイ，クチミダイ，チコダイ，ハタが多く漁獲量は 808 kg で，海綿類も 346 kg と少なく好漁場である。これは沖合よりの 25.0°C, 35.20‰の水塊の影響と思はれる。(Fig. 11 (B))。St. 2, 3, 5, 6 については，何れも張出し温水塊の西側であるとは云え，St. 2, 3 は張出しの西縁に在り，殊に St. 3 は St. 1 との間に断層が現はれている程であり，(Fig. 11 (C)), St. 5, 6 とはその水域を異にしている。特に St. 6 は 34.8‰ と非常に低鹹である (Fig. 9)。漁獲についてはクチミダイが非常に多く，その外，ヒメフエダイ，ヒメダイ，センネンダイ，ヒラアジ，アカメが目立って多かった。これは非常に低鹹な水塊が西方より東に向って来て，その前面に魚群が溜ったものと考えられる。St. 5 はクチミダイ，アカダイが多かったが，漁獲量は 574 kg と St. 6 の 1344 kg の半分も獲れない。St. 2, 3 は共にアカダイ，ヒメダイ，クチミダイ，ハタが多く，魚種も漁獲量も同一である。温水塊中央部，東側，西側の平均漁獲量は各々 378 kg, 693 kg, 778 kg で中央部は西側の約 1/2 である。しかし，この張出し温水塊周辺は好漁場を形成している。St. 9, 10, 11, 12 では同一地点を起点に曳網を行ない，各回の漁獲についてみると St. 9, 11 は共に曳網針路が 70° で時間的には 12 時と 00 時なので，両者間で比較してみると，チコダイ，アカダイ，ハタ，コロダイ，ヒラアジ，ナガダイ，アオバダイは昼間の漁獲が夜間より多く，クチミダイ，ヒメダイ，センネンダイ，ヨコスジフエダイ，エソは殆んど変化がみられず，甲イカは夜間が多かった。総漁獲量では 808 kg, 429 kg と夜間は昼間の約 1/2 である。St. 10, 12 については 177°, 25° で曳網したので比較には無理があるが，チコダイ，アカダイ，クチミダイ，ハタ，ナガダイは朝網が晩網より漁獲が多く，特にクチミダイは約 3 倍である。総漁獲量は約 2 倍である。St. 14, 13 はアカダイ，クチミダイ，ヒラアジ，サメ等は沖合側の St. 14 が多く，St. 17 はチコダイ，アカダイ，ヨコスジフエダイが多く好漁場である。St. 19 も 539 kg の漁獲がありクチミダイ，コロダイが多かったが，St. 20 は漁獲皆無で海綿類，サンゴ類，その他の底棲生物が 2.600 kg も乗網した。

魚種別の漁獲状況および生物調査

1. クチミダイ

この海域での主要魚種である。広範囲に分布しているが，底水温 24°C～26°C で漁獲され，27°C 以上になると見られない。また，塩分については 34.8‰～35.3‰ で多いが，概して低鹹水塊に多い。1963 年の St. 2, 3, 5, 6, 9, 12 は 100 kg 以上漁獲された地点であるが，何れも沖合に張り出して

いる温水塊周辺である。1,518 尾の平均体長は 28.65 cm で雌雄別平均体長は 28.20 cm, 29.95 cm で雄が大きい。雌雄比は 1:0.67 で雌が多い。深みのものは浅いところのものより大型であり，又大きさの差が少なく，全体的に型が揃っている (Fig. 13)。1959 年～1961 年の水産庁漁獲統計によると，クチミダイは総漁獲の 45.4%, 42.6%, 46.8% であるが，本船の統計では 14.6% である。これは水産庁の統計が有用魚種に対する比であり，本船の統計が漁獲されたすべての魚類との比であるためと考えられる。

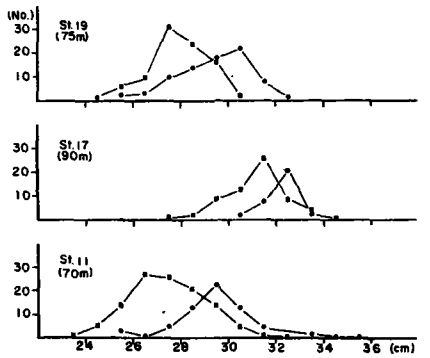


Fig. 13. Frequency distribution of fork length of "Kuchimidai"
■: Female ●: Male
( ): Depth of sea bottom

2. チコダイ

この海域では全般的に漁獲量が少なく，1963 年には総漁獲量の 2.1%である。温度，塩分との関係についてみると，23.5°C～25.5°C で 26°C 以上になると漁獲されず，塩分は 35.10‰～35.30‰ で 35.40‰ の高鹹水域ではみられない。体長は 21～33 cm の範囲で 24～29 cm の中型群が多く，深みのものは浅い所のものより大きい (Fig. 14)。

3. ヨコスジフエダイ

1963 年の St. 17, 3, 7, 11 でそれぞれ 30 kg 以上漁獲されている。温度との関係についてみると，分布範囲が広く 27°C 以上に於ても漁獲されているが，その割合に総漁獲量の 3.3%と絶対量は多くない。体長は 22～34 cm で水深の深い所のものが浅い所のものより大きい一般的傾向を持っているが (Fig. 15), St. 9, 10, 11, 12 の同一地点操業を行なった時の体長組成をみると，St. 10, 11, 12 の間で相違のあることを認めた。即ち，体長が St. 10 では 22～28 cm で主群は 23 cm, St. 11 では 22～32 cm で主群は 25 cm

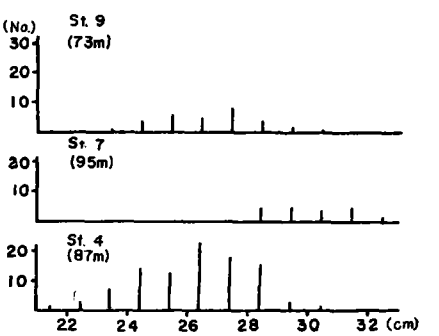


Fig. 14. Frequency distribution of fork length of "Chikodai"
( ): Depth of sea bottom

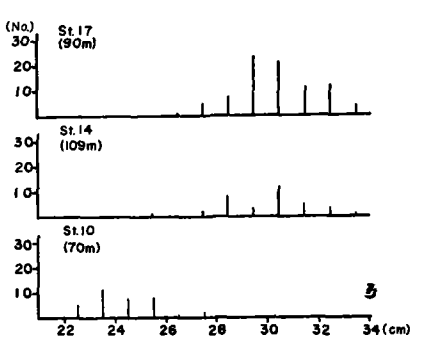


Fig. 15. Frequency distribution of fork length of "Yokosujifuedai"
( ): Depth of sea bottom

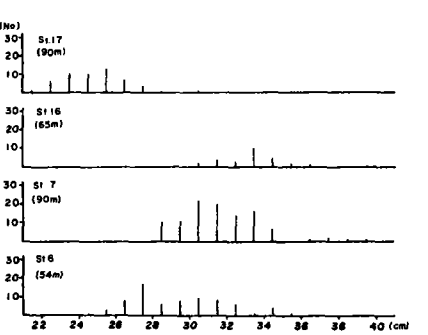


Fig. 16. Frequency distribution of fork length of "Himefuedai"
( ): Depth of sea bottom

であり，St. 12 では 24～31 cm で主群は 27 cm である。このことは夕方は小型群が少量漁獲され，真夜中には，大，中，小の混成群が相当量漁獲され，朝方は大型魚を混じえた中型魚が漁獲されることになる。

4．ヒメフエダイ

温度，塩分についてみると，23.80°C～27.16°C, 34.81‰～35.43‰と他の魚種にみられない広範囲に亘って漁獲されている。棲息環境に対する適応範囲が広いので特徴は明らかでないが，総漁獲量の 3.3% と絶対量は少ない。体長組成は 21～40 cm で組成分布範囲が広く，水深の変化に依る体長組成の変化傾向は全然無いが，水域毎にある程度の分布範囲を有する。Fig. 16 に示す様に St. 7, 17 は共に水深 90 m であるが，St. 7 の体長組成が 28～40 cm で主群が 30～34 cm であるのに対して St. 17 では 21～31 cm で主群は 23～26 cm と対称的である。St. 15, 17, 18 は中型，小型群で組成され，St. 3, 6, 7, 9, 16 は中型，大型群からなっている。Fig. 8 で 35.10‰ の等塩分線が St. 16 のところで NW から錐状に SE に突き出しているが，この NE 側が小型，中型群で W 側が中型，大型群であることから，両者は異った種類とも考えられる。480 尾の平均体長は 29.48 cm であるが，St. 9 と St. 5 では 33.44 cm と 19.31 cm で非常に大きな差がある。主群は 31～32 cm である。雌雄比は 60:57 でほぼ同数で，平均体重は 769.2 g, 821.0 g と雄の方が重い。

5．ヒメダイ

総漁獲量の 6.4%を占めクチミダイ，アカダイに次いで多く，特に Legendre 島沖合の張出し温水塊の西側では平均 80 kg の漁獲をみた。また，St. 19 に於いても 95 kg の漁獲があり，分布は相当広いと考えられる。しかし，水深 90 m 以上になると漁獲は減少する。体長組成は 15～45 cm と大小の差が非常に大きい，主群は 23～26 cm で 30 cm 以上のものは少数である。水域によりまとまった体長組成を示しているが，St. 2 は例外で 24～45 cm と範囲が広い。水深の深い処のものは浅い処のものより大きいという一般的傾向は，余りはっきりしないが多少認められる。雌雄比は 41:55 で雄が多く，平均体重は 264.3 g, 309.1 g と雄の方が重い (Fig. 17)。

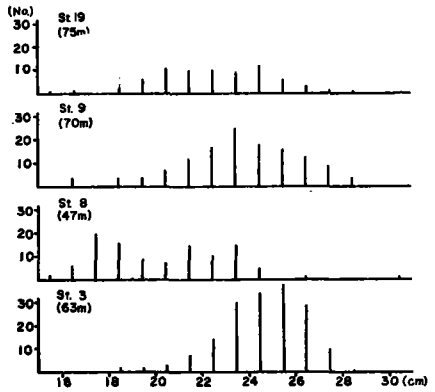


Fig. 17. Frequency distribution of fork length of "Himedai"
( ): Depth of sea bottom

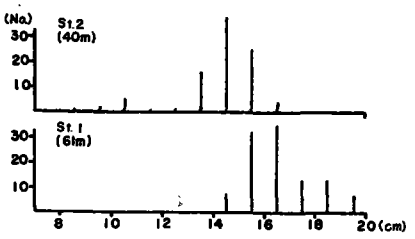


Fig. 18. Frequency distribution of fork length of "Shimaaji"
( ): Depth of sea bottom

6．シマアジ

水温 27.48°C, 塩分 35.41‰ の高温，高鹹な沿岸水塊でも漁獲され，体長組成は 8～20 cm で，主群は 14～17 cm である。水深の深い処のものは浅い処のものより大きい (Fig. 18)。

要 約

1. Legendre 島沖合に顕著な高温，高鹹水塊が SE から NW 方向に張り出し，その周辺が好漁場を形成している。

2. Cape Thouin 沖合に ENE から WSW 方向に沖合水塊の突込みがあり，その周辺が漁場となっている。

3. 潮流は Port Walcott の漲潮時におおよそ 150° 方向，落潮時に 285° 方向に流れる。流速は最高 0.6 m/sec である。

4. クチミダイはこの海域での主要魚種で，平均体長は 28.65 cm で雌雄比は1:0.67と雌が多く雄は雌より大型である。

5. Legendre 島沖合に張り出した温水塊の東側にはアオバダイ，チコダイ，アカダイ，ナガダイ，西側ではヒメダイ，ヨコスジフェダイ，沖側にメイチダイ，センネンダイが多い。

6. チコダイ，アカダイ，ハタ，ヒラアジ，ナガダイ，アオバダイは夜間漁獲が少ない。

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electronic computer aids research on Indian Ocean expedition

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1. Introduction

Before the turn of the century the *Valdivia*, a converted German steamship, rounded the Cape of Good Hope one day in the Fall of 1898 to carry out an extensive geophysical survey over the Indian Ocean on the German Deep Sea Expedition. During the ensuing year she traversed the Indian Ocean many times, collecting oceanographic samples, probing the depths and making detailed meteorological observations. After 1899 and until the beginning of the International Indian Ocean Expedition no other significant multi-disciplinary investigation had been made in this region. The general plans for the U. S. Program in meteorology on the International Indian Ocean Expedition (IIOE) were described by Ramage (1962). Since October 1962 newsletters covering the activities and programs have been published by Dr. C. S. Ramage, IIOE, Scientific Director for Meteorology at Colaba Observatory, Bombay 5, India.

In the early days, many months and even years in some cases were required to collect, assemble and analyze data from expedition ship reports like those of the *Valdivia* and from adjacent land stations. Long distance communication networks had not been developed to provide rapid data transmission over so vast a region as the Indian Ocean. Today the situation has changed considerably: heavily instrumented research aircraft [3] cover thousands of air miles, automatically photographing clouds and recording observations at frequent intervals; several oceanographic vessels equipped with modern laboratories and instruments simultaneously probe and sample large oceanic regions, recording most of their data automatically; and continental centers, island stations, aircraft and ships transmit large quantities of data daily through high speed communications networks to collection centers. Thus, modern scientific expeditions are assured of accurate and timely information covering extensive areas under investigation. However, even the most efficient and well staffed scientific expeditions are hard pressed to keep up with data collection and processing, not to mention performing research, in the field as data are received. The need for electronic computers to assist researchers and process data as they are received is greater than ever before.

In recent years engineering improvements and reductions in size and cost of computers have made possible their inclusion in the budgets of large scale field projects and expeditions, if not in a plan for field equipment, then certainly at the earliest practicable date. At the International Meteorological Centre (IMC), established by the Indian Meteorology Department at Bombay, India, to coordinate and direct the Indian Ocean Expedition meteorological program, a medium scale electronic computer and auxiliary machine equipment were installed in January 1964. The establishment of the computer at IMC was made possible through a United Nations Special Fund grant and currently is supported by a United Nations Special Fund Mission.

The activities at IMC include, in addition to a computer facility, extensive data collection and analysis programs to support the research being actively pursued by all staff members. Map analyses have been performed twice daily since January 1963 for several levels from the surface to 100 mb, covering the IIOE region shown in Fig. 1. The data coverage on this chart is typical of that found on most days after late data has been plotted. Synoptic surface and upper air data are being plotted on semi-transparent master charts from which sepia and blue line ozalid copies can be reproduced. Late data are back-plotted from manuscripts, micro-film and hard copy teletype on the master charts as soon as possible. Nearly all meteorological data received at IMC for the IIOE region are micro-filmed. At the University of Hawaii, TIROS photographic composites, are being made covering those periods that one or more TIROS satellites were over the IIOE regions.

[1] Mr. Suryanarayana is a senior scientist in the Indian Meteorology Department, currently assigned to the computer section at the International Meteorological Centre.

[2] Lt. Col. Miller is on a 3-year assignment to the National Science Foundation and the International Indian Ocean Expedition.

[3] The Woods Hole Oceanographic Institution and Weather Bureau Research Flight Facility aircraft flew weather missions in support of the IIOE meteorological program over the Indian Ocean, Bay of Bengal and Arabian Sea from May to July 1963 and February to March 1964. Reconnaissance missions were flown from 500 ft to 40,000 ft to obtain detailed meteorological data at frequent intervals on magnetic tape film, and from personal observations.

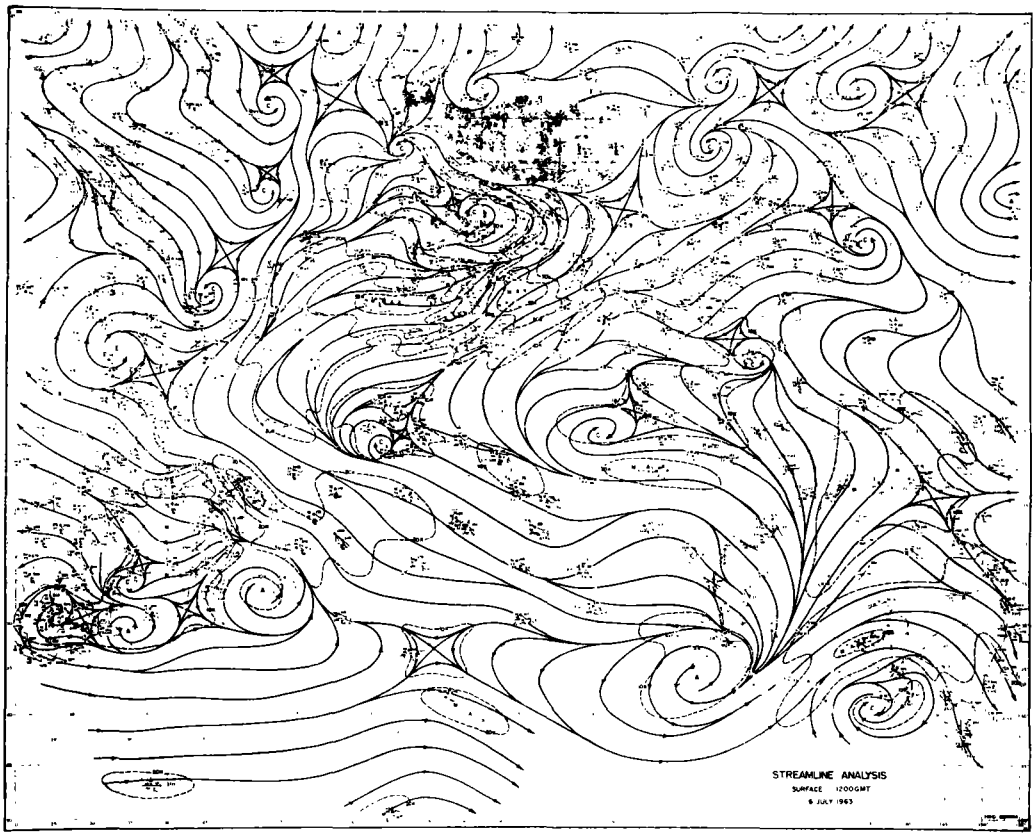


FIG. 1. Plotted low level chart for 6 July 1963 on the IIOE base map. This chart is typical of the data coverage after all late data are received and plotted at IMC. Winds for 3000 ft are usually plotted for land stations on the low level chart. The wind shafts and arrows for upper air data stand out on this chart.

TIROS Automatic Picture Transmission (APT) equipment was put into operation at IMC in January 1963.

The computer at IMC is an IBM 1620 card system with a capability of reading 250 punched cards per minute, or punching 125 cards per minute. The configuration of this system includes a 60,000 digit core memory and automatic floating point arithmetic circuitry. A console typewriter is used for optional input/output data transmission into the computer. Fig. 2 shows part of the computer room at IMC, Colaba Observatory.

This computer is serving as a research tool by being applied to compute various derived meteorological parameters which when analyzed will aid in developing an understanding of the seasonal monsoon circulations. It is also being used to process data. Radiosonde and upper wind reports, surface ship and selected island surface observations are being punched on cards. These data are thoroughly checked for accuracy and validity by 1620 computer programs developed at IMC. Climatological summaries of meteorological data and air-sea energy exchange computations are being made by the computer. Derived data as well as checked original observations covering the entire IIOE period (1963–1965) are to be made available in the form of punched cards, tabulated forms, microfilm and atlases.

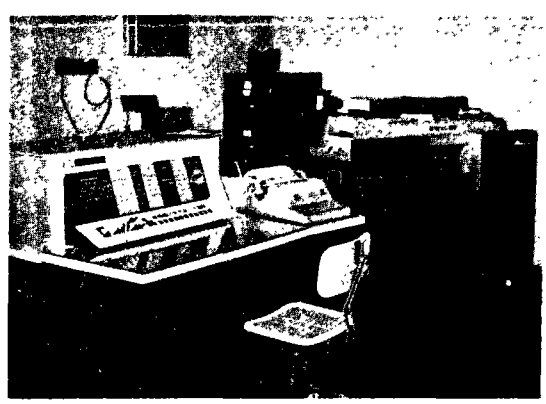


FIG. 2. Part of the computer room at IMC. An additional 40,000 digit core memory unit is placed to the left of the 1620 Consol and is not shown. The combined card read/punch unit is shown to the right.

2. Processing upper air data

A 1620 program was developed to process and check radiosonde observations received at IMC from approximately 150 stations in the IIOE region. Fig. 1 shows the distribution of these upper-air stations over the IIOE region. The computer program is divided into 3 sections: the first section meshes mandatory and significant level data which have been punched on cards in the same format as received, i.e., mandatory levels followed by significant levels; the second section decodes the data and computes heights at each level by the hydrostatic formula, recomputes relative humidities and checks for valid temperatures and lapse rates. This part of the program was developed to check radiosonde reports in a manner similar to that used at the Climatic Center, Asheville, N. C. The third section makes natural log interpolations of meteorological parameters at 50-mb intervals and punches them out in a format similar to that now used for Northern Hemisphere radiosonde data at Asheville.

Upper winds are being punched on cards from approximately 150 pibal, rawin and rabal stations. These data are also being checked by the computer for validity and unusual shear conditions. For each upper-air observation checked, an error list is typed out on the 1620 typewriter. All data will be checked against the error lists by technicians and correction cards punched wherever possible.

3. Air-sea energy exchange computations

Each month 6000 to 8000 ship reports are received at IMC from the Indian Ocean, Bay of Bengal and Arabian Sea. (Seas around Indonesia included.) These data are extremely important in providing low level data coverage over the vast oceanic area which includes only a few island stations and makes up the central region of investigation. Fig. 1 displays a typical distribution of ship reports plotted on the surface chart at IMC for 6 July 1963. Detailed checking of all ship reports punched on cards is accomplished with the aid of a computer program. Originally this program was presented to IMC by the U. S. Bureau of Commercial Fisheries, U. S. Department of Interior. The program was modified at IMC to fit data checking and computational requirements for the IIOE region.

Individual ship reports are punched on cards in the format used in synoptic broadcasts. This procedure is followed to minimize punching time and errors. Punched ship data covering a period of one month, or any other desired interval, are sorted into 5° latitude and longitude blocks and finally sorted into 10° longitudinal strips, all in ascending order. This sorting is quickly accomplished by an automatic sorting machine. Each set of sorted data from all sources is then processed for errors by the computer. Many of the meteorological parameters are checked against climatological mean values. Those values which fall outside of acceptable ranges of the mean are rechecked and error messages are typed. All other values are retained for later computation. Error messages serve to indicate which ship observations should be checked further. Wherever possible, errors are corrected before the final computational run is made.

Air-sea energy exchange computations are made using the meteorological data averaged over 5° square areas. These computations are carried out to obtain rates of heat transport through the air-sea interface in cal cm^{-2} per day according to the expression:

$$Q_{st} = Q_s - Q_b - Q_r - Q_e - Q_h.$$

Where, Q_{st} represents total rate of heat transport. Incoming and outgoing radiation at the surface of the sea are represented by Q_s, Q_b and Q_r. Heat exchange due to evaporation or condensation is computed according to a form of Sverdrup's evaporation equation as described by Tabata (1958) and Roden (1959). Sensible heat exchange computations are carried out using the Bowen ratio method. Finally, averaged meteorological parameters and heat budget computations are punched on cards. A computer program has been developed to arrange these data for printing in grid form so that analyses can be made directly on the grids.

4. Computer derived analytical aids

The map analyses together with daily discussion periods provide the continuity and background necessary to understand the basic flow patterns and also provide guide lines along which research is being conducted at IMC. However, many interesting questions concerning variations in the weather and flow patterns of the monsoon circulations cannot be answered through conventional analyses alone. Therefore, several derived meteorological parameters are computed with the aid of 1620 computer programs; the results are plotted on graphs or auxiliary charts.

For example, two programs to compute horizontal velocity divergence and vorticity have been put into operation. One method applies finite differences using directions and speeds extracted from streamline analyses. The other method is based on the more objective Bellamy approach whereby observed wind data from sets of three stations are used. At present these computations are being made over India and adjacent regions south of 25N where there is adequate data coverage. Another program computes horizontal particle trajectories at specified levels from the flow directions and speeds obtained in the daily streamline analyses.

Programs have been, or are being developed to investigate thermal fields. As described in Section 3, heat budget computations at the air-sea interface are being made over the IIOE oceanic regions. In addition, radiosonde data punched on cards and computer checked will provide the input to a program now being developed to compute static stability. Several statistical type programs are now in use or are being developed to aid researchers. These programs are being designed to use older data punched on cards in India as well as data

received over the IIOE region through the period 1963–1965.

5. Training and auxiliary equipment

In January 1963 a training course covering basic 1620 machine language was presented by the IBM staff in Bombay to meteorologists at IMC. This course of training was followed by a workshop period in which programming techniques were applied to meteorological problems of immediate interest. Prior to the arrival of the computer several data checking programs were developed by members assigned to the computer section. Some initial program check-out and testing was carried out on a 1620 computer at the Physical Research Laboratory, Ahmedabad, India, approximately 350 miles north of Bombay. During late October 1963 an applied course in 1620 FORTRAN programming was presented for the benefit of U. N. research fellows and interested personnel from the Indian Meteorology Department (IMD).

In addition to the computer, an IBM 870 Document Writing System was installed at IMC. Data generated in the computer and punched on cards in a special format can be put into the 870 system to obtain plotted graphs and curves. By means of a wired control panel, the 870 system can be programmed to read 5 channel paper tape and simultaneously punch and print out data selected to be read. Some time in the future this system will be used to selectively read and punch ship data from paper tape perforated from weather data received over teletype circuits. Other auxiliary equipment consists of an IBM automatic sorter, IBM 514 reproducing punch, an IBM 402 accounting machine and several automatic key punch and verifying machines.

6. Concluding remarks

During 1963 and the first half of 1964, research meteorologists of IMD, under the directions of P. R. Pisharoty and C. R. V. Raman and the U. S. group, sponsored by the National Science Foundation, have worked together as a team. All members assigned to IMC have collectively pooled their skills and efforts to ensure successful data collection, analyses and research programs. The U. S. group at IMC will move to the University of Hawaii by mid-1964 to join other members of the IIOE Meteorology staff now working there. In the future active collaboration in research, training and data processing will continue among scientists of the University of Hawaii, the U. N. Special Fund Mission and IMD at the International Meteorological Centre, Bombay, India. Regardless of where the meteorological research will be carried out, an electronic computer will continue to serve as the silent and efficient aid to researchers on the International Indian Ocean Expedition.

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EQUATORIAL UNDERCURRENT IN THE WESTERN INDIAN OCEAN

By Dr. J. C. SWALLOW,

R.R.S. *Discovery*, c/o General Post Office, London

FOUR times during March–June this year, the equatorial undercurrent has been observed by the R.R.S. *Discovery* in the course of its participation in the International Indian Ocean Expedition. We have found much higher speeds than those reported by Knauss and Taft[1] in the same season of the previous year, and a brief preliminary account may be of interest although not all the results have yet been processed.

Knauss and Taft found only a weak undercurrent in the western Indian Ocean, with maximum speeds generally less than 50 cm/sec and sometimes scarcely any significant eastward flow at all. In contrast, two of our sections showed speeds exceeding 120 cm/sec, comparable with those found in the Pacific undercurrent, and some subsurface eastward movement was always found.

On the first three crossings of the equator, a buoy was anchored at each of the stations shown (Figs. 1–3). Water movement relative to the ship was measured with direct-reading current-meters[2] and the ship's drift was determined by radar relative to the anchored buoy. Drogues were also used for measuring the near-surface current.

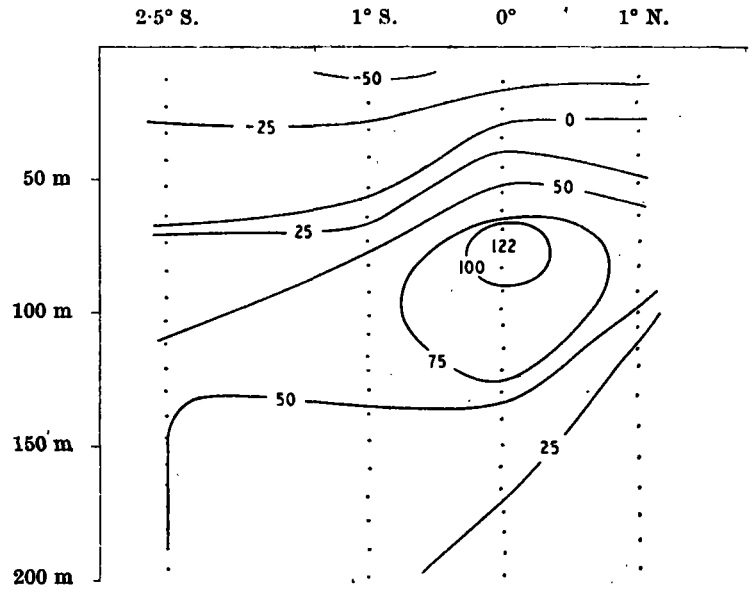


Fig. 1. Section 1, 58° E. March 18–23, 1964. Eastward component of velocity in cm/sec

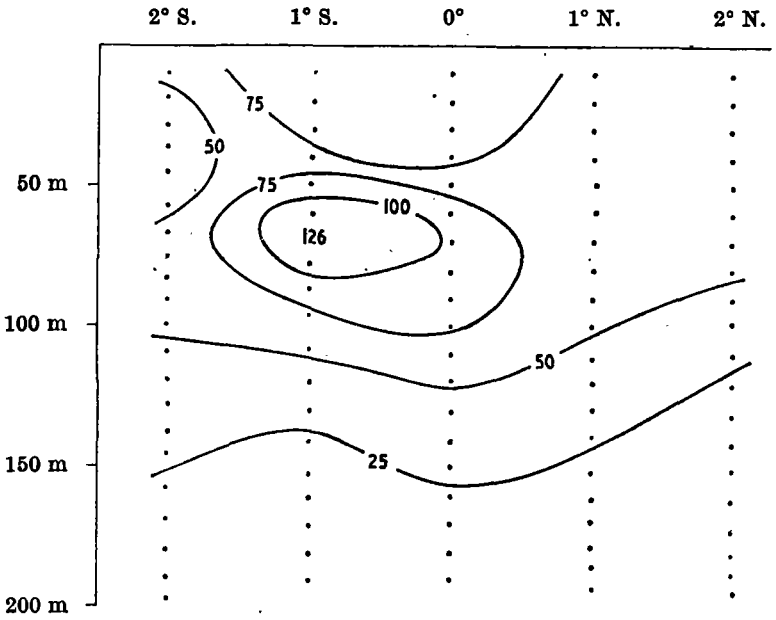


Fig. 2. Section 2, 67° 30′ E. April 26–May 1, 1964. Eastward component of velocity in cm/sec

Section 1, 58° *E., March* 18–23, 1964. The undercurrent was centred on the equator, with a maximum eastward speed of 122 cm/sec at 75 m depth, in the thermocline. The meridional component there was 28 cm/sec southward. The eastward speed falls to about half-value at 1° N. and 1° S. and meridional flow in the undercurrent was relatively weak at all stations. Spreading of the thermocline was only slight, the separation of the 15° C and 25° C isotherms being 105 m at the equator, and 80–95 m at 2° S. and 2° N. The water in the undercurrent had a high salinity, the maximum values decreasing from north to south. At the equator the maximum was 35·55 parts per thousand at 100 m, slightly deeper than the high-speed core. Surface currents were north-west, 30–60 cm/sec, at 1° N., the equator and 1° S., and south-west, 50 cm/sec, at $2\frac{1}{2}$° S.

This section would be very similar to typical Pacific sections but for the asymmetry due to the deeper eastward flow at the southern end of the section.

Evidence in support of the persistence in time, and continuity with longitude, of the undercurrent comes from an observation made 2 weeks after this section was completed, by H.M.S. *Owen*[3]. At an anchor station on the equator in 55° 40′ E. on April 7, 1964, an eastward current of 90 cm/sec was found at a depth of 50 fathoms (91 m) with much weaker currents above and below.

Section 2, 67° 30′ *E., April* 26–*May* 1, 1964. On this section the surface currents were eastward, with speeds of about 90 cm/sec and meridional components converging

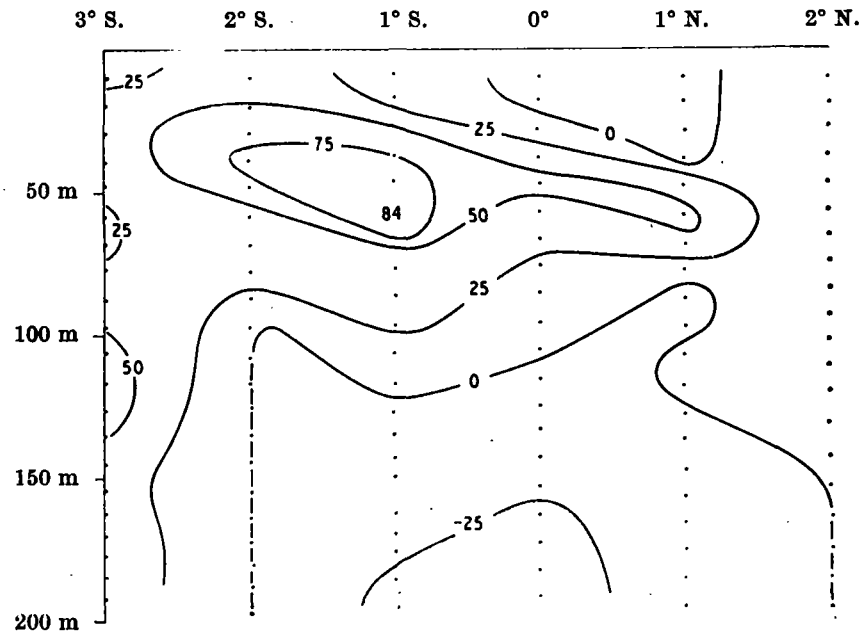


Fig. 3. Section 3, 58° E. June 2–7, 1964. Eastward component of velocity in cm/sec

on the equator. At the equator and 1° S. there was a significant sub-surface maximum of eastward flow, reaching 126 cm/sec at 70 m depth at 1° S. The meridional components of this sub-surface current were weak, with a tendency to diverge from the equator, and again there was a salinity maximum slightly deeper than the high-velocity core, decreasing in strength from north to south. It had a value of 35·42 parts per thousand at 92 m at the equator. The steepest part of the thermocline was deeper than the velocity maximum which lay between the 28° C and 29° C isotherms. There was a distinct spreading of the thermocline on this section, the separation of the 25° C and 15° C isotherms being 85 m at the equator, and only 53 m and 44 m at 2° N. and 2° S. Some indication of possible instability comes from one of the repeat observations at 2° S.; there appeared to be an eastward surge which would increase the speeds shown at that station by 30 cm/sec, exaggerating even more the asymmetry about the equator.

Section 3, 58° *E., June* 2–7, 1964. The undercurrent was still present, though weaker and shallower and displaced still farther south from the equator. The maximum eastward speed observed was 84 cm/sec at 39 m at 2° S. Surface currents had only weak zonal components and tended to diverge from the equator, being north-east at 2° N. and south-east to south at 1° S. to 3° S., 30–60 cm/sec. At the equator and 1° N. there was a weak westward surface current.

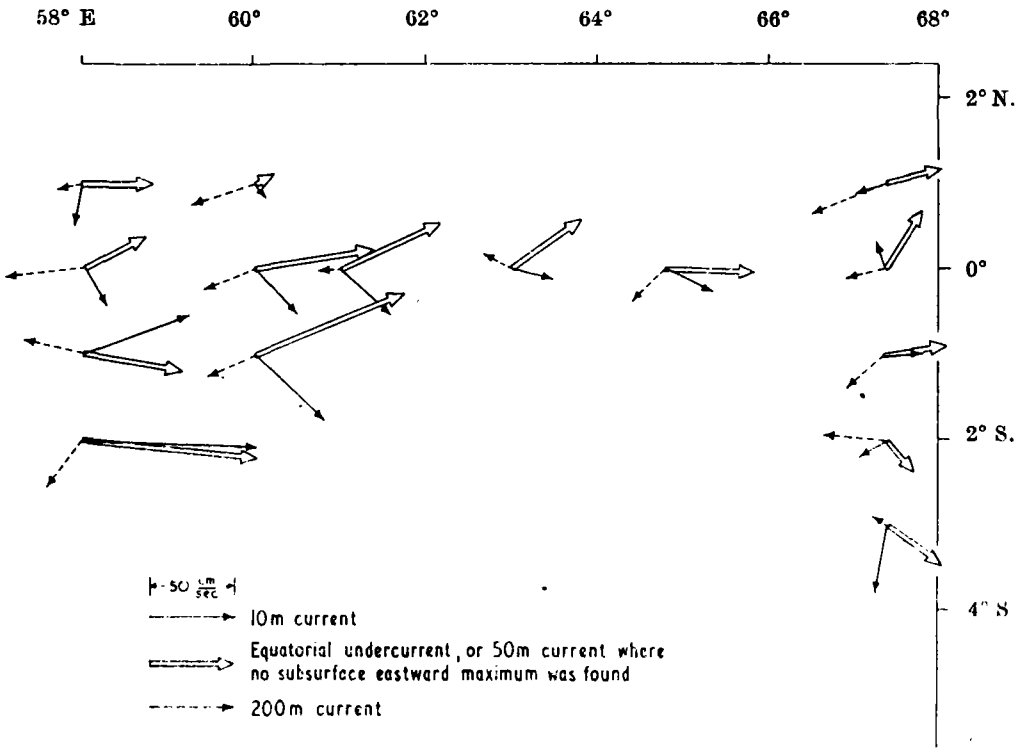


Fig. 4. Current vectors using mean of observations at 500–1,500 m depth as reference value. Lengths of arrows indicate speed. Examples shown represent 50 cm/sec. June 13–21, 1964

In the high-speed core, meridional components were northward, with a maximum of 49 cm/sec associated with the 84 cm/sec eastward maximum, but below that, between the 50 cm/sec and 25 cm/sec isotachs, the meridional flow was southward. The salinity maxima lay close to this lower zone, with a value of 35·30 parts per thousand at 79 m at the equator, and the steepest part of the thermocline was at about the same depth. There was no significant spreading of the thermocline, with the 25° C and 15° C isotherms varying between 75 m and 90 m separation throughout the section.

On our fourth visit to the equator, during June 13–21, 1964, short sections were worked in 58° E., 60° E. and 67½° E. with stations along the equator between the latter two. It seems more convenient to present these observations in plan view instead of vertical profiles. Time did not permit anchoring buoys; instead, at each station the usual current-shear measurements to 200 m were supplemented by observations at a few depths to 1,500 m using a telemetering current-meter provided by the Chr. Michelsen Institute and the Geophysical Institute, Bergen. The mean shear between 10 m and 500–1,500 m depths has been taken as representing the near-surface current, to which the upper part of the shear profile has

been fitted. In Fig. 4, current vectors derived in this way are shown for each station at 10 m and 200 m depths, and in the sub-surface eastward maximum, which is generally near 50 m depth. Where no sub-surface maximum was found, the 50 m value has been plotted.

Conditions at 58° E. and 60° E. were not very different from those in section 3, surveyed two weeks previously. The undercurrent appeared to slow down towards the east, but this could equally well be a time change. The salinity maxima and thermocline were again found a little deeper than the eastward velocity maxima, as in section 3, and there was little or no evidence of thermocline spreading.

Evidently, comparing these observations with those of Knauss and Taft, the equatorial undercurrent in the western Indian Ocean undergoes more complicated fluctuations than simple seasonal ones. It is hoped that it may be possible to relate these fluctuations to differences in the winds in the two years.

The work of the R.R.S. *Discovery* described here was carried out by the National Institute of Oceanography as part of the U.K. contribution to the International Indian Ocean Expedition. I thank Commander D. W. Haslam, R.N., in command of H.M.S. *Owen*, and also the Hydrographer of the Navy for permission to refer to H.M.S. *Owen's* results in advance of publication.

[1] Knauss, J. A., and Taft, B. A., *Science*, **143**, 354 (1964).

[2] Cartwright, D. E., and Woods, A. J., *Dtsch. hydrog. Z.*, **16**, 64 (1963).

[3] Personal communication from the commanding officer, H.M.S. *Owen*.

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Participation française à l'Expédition internationale

de

l'océan Indien

PRESENTATION D'OBSERVATIONS FAITES AU G.E.K.

EN 1962 *

par

Michel CREPON

Océanographe physicien au Laboratoire d'Océanographie physique

du Muséum national d'Histoire naturelle

I - INTRODUCTION

Un courantomètre à électrodes remorquées (G.E.K.) a été installé par la Direction des Constructions et Armes navales de l'arsenal de Diégo-Suarez à bord de l'aviso de la Marine nationale "Commandant Robert Giraud" durant les 4ème et 5ème campagnes océanographiques de ce navire**. De nombreuses mesures de courant superficiel ont été effectuées avec cet appareil dans l'océan Indien, le golfe d'Aden et la mer Rouge. Nous présentons ici les résultats obtenus sur deux trajets Diégo-Suarez - cap Guardafui, faits à deux époques différentes de l'année : l'une en juillet 1962 (mousson d'été boréal), l'autre en décembre 1962 (mousson d'hiver boréal).

Ces campagnes ont été effectuées dans le cadre de l'Expédition Internationale de l'Océan Indien (E.I.O.I.). Elles ont été mises au point sous l'égide du Comité National Français de la Recherche Océanique (C.N.F.R.O.) et financées en grande partie par le Comité d'Exploitation des Océans (C.O.M.E.X.O.).

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* Manuscrit reçu le 31 août 1964

** Voir "Cahiers Océanographiques" XV, 4 (avril 1963) p.224 et 8 (septembre-octobre 1963) pp.510-511.

Extrait des CAHIERS OCEANOGRAPHIQUES, XVI^e année, n°10, décembre 1964

Le "Commandant Robert Giraud" était commandé par le Capitaine de frégate RAYNAUD-LACROZE. La mission scientifique était dirigée par M. MENACHE, Directeur de Recherche à l'ORSTOM. Les mesures G.E.K. ont été faites sous la direction de M. CREPON, Océanographe physicien du Laboratoire d'Océanographie physique du Muséum d'Histoire naturelle, effectuant à cette époque son service militaire.

II - DESCRIPTION DE L'APPAREIL UTILISE

Le G.E.K. dont nous nous servions était identique à celui décrit par J. MARTIN (1956). La différence de potentiel créée par induction dans le champ magnétique terrestre est enregistrée sur un potentiomètre MECI, type speedomax. Le câble sur lequel sont fixées les électrodes est un câble co-axial de même densité que l'eau de mer. Ce câble se maintenant au voisinage immédiat de la surface marine, il n'y a pas de correction d'immersion, ce qui simplifie considérablement le dépouillement, élimine certains risques d'erreurs et donne au navire une plus grande possibilité de manoeuvre (il n'est pas nécessaire de maintenir constante la vitesse).

Le conducteur extérieur s'étant rapidement détérioré, nous avons utilisé, lors de la 5ème campagne (décembre 1962), deux câbles identiques au précédent, reliés par du lusin, chacune des électrodes étant branchée sur le conducteur central mécaniquement beaucoup plus résistant.

Les électrodes étaient distantes de 100 mètres; l'électrode la plus rapprochée de la coque métallique du bateau était à 200 mètres.

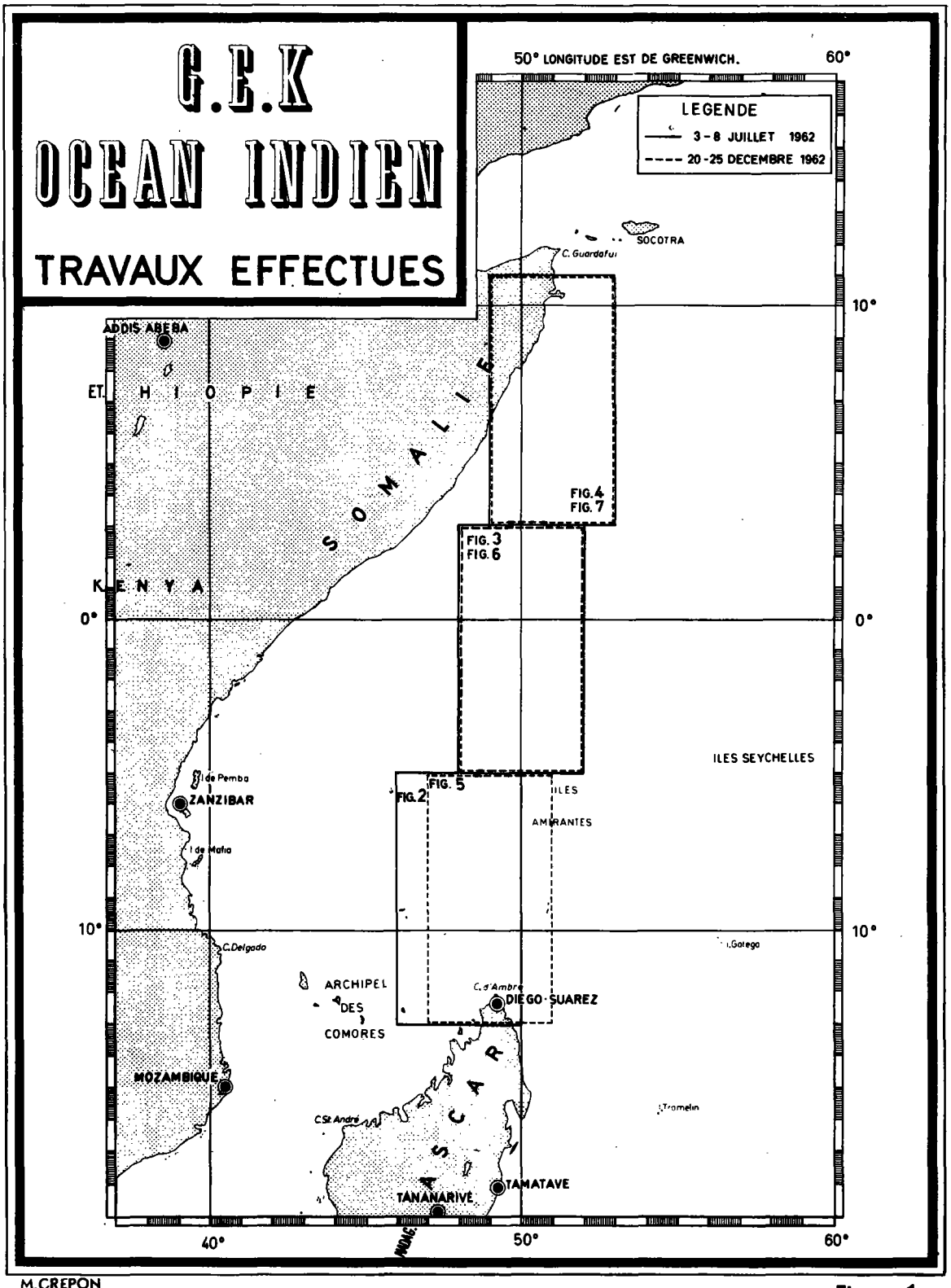
III - TECHNIQUES DE MESURE

Nous avons suivi les directives données par J. MARTIN (1956).

La vitesse du navire était à peu près constante, soit de 11 noeuds environ.

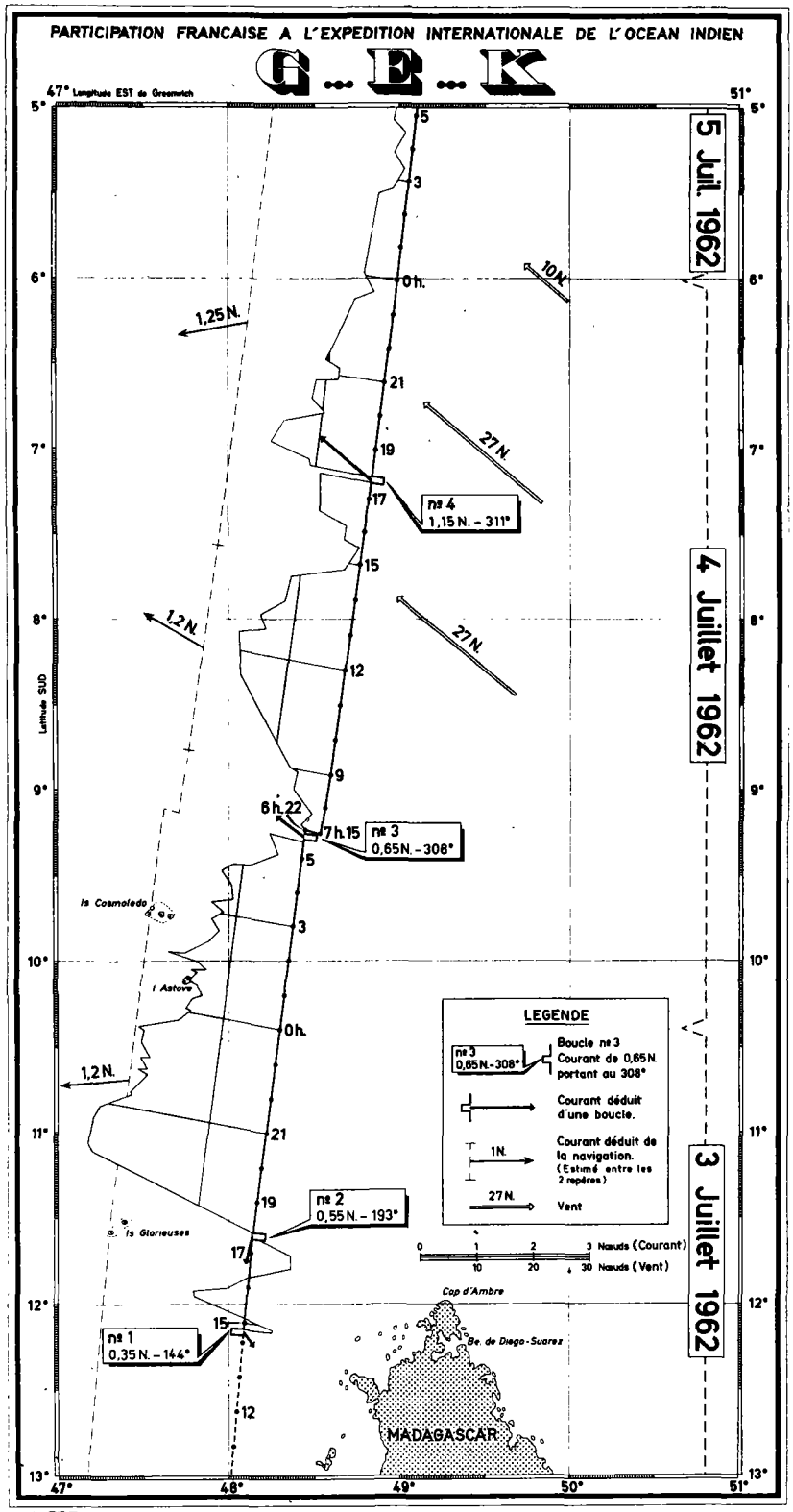
Le vecteur courant et la polarisation des électrodes ont été déterminés par la méthode des boucles. On parcourait une boucle toutes les douze heures lors de la 4ème campagne (tous les deux degrés de latitude environ) et toutes les six heures lors de la 5ème campagne (tous les degrés de latitude).

La constante de temps du filtre de vagues était choisie pour que l'amplitude des petites oscillations parasites soit environ de 0,5 cm sur l'enregistrement obtenu; la constante de temps n'a jamais été supérieure à 10 secondes.



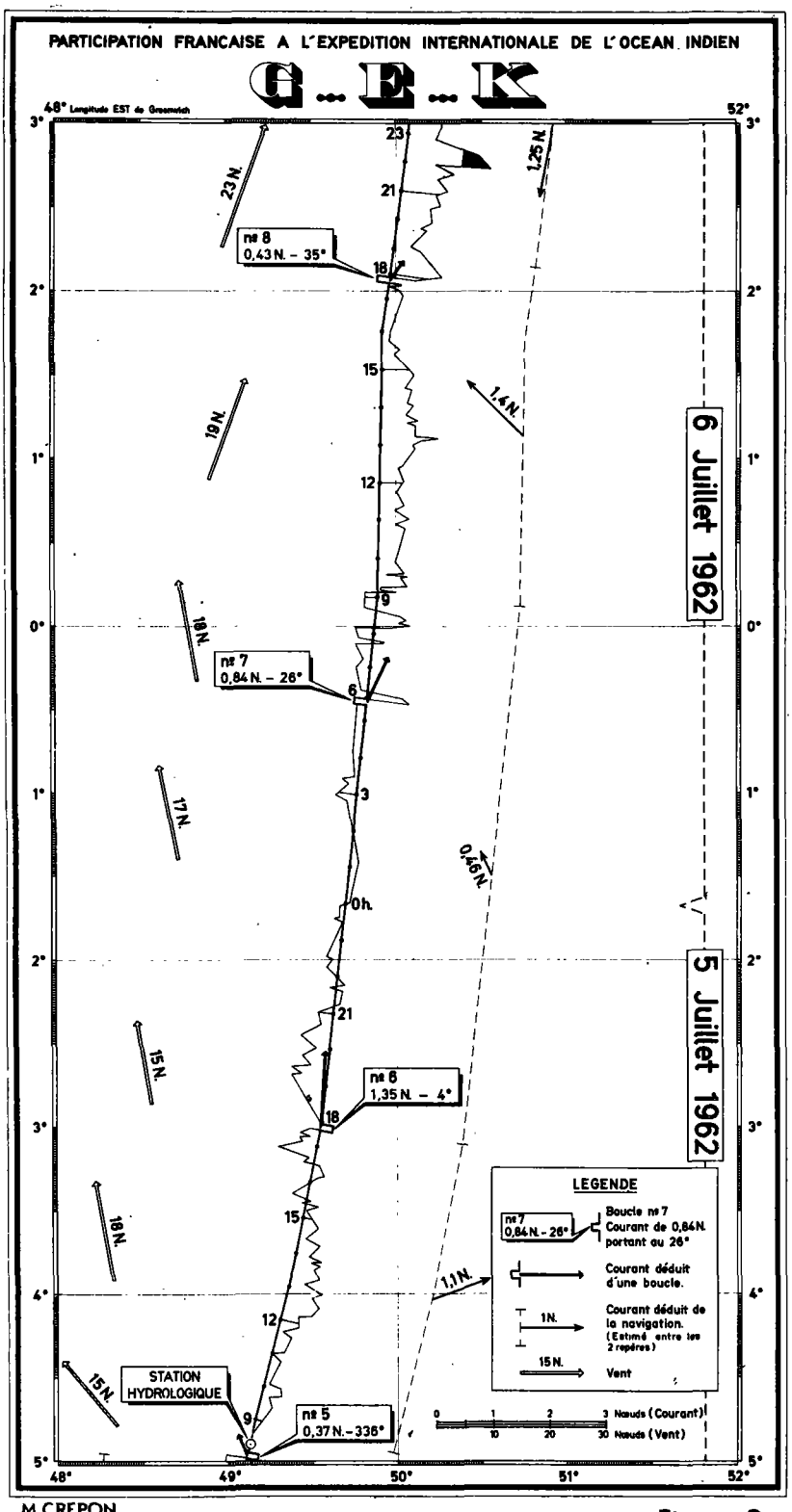
M.CREPON

Figure 1



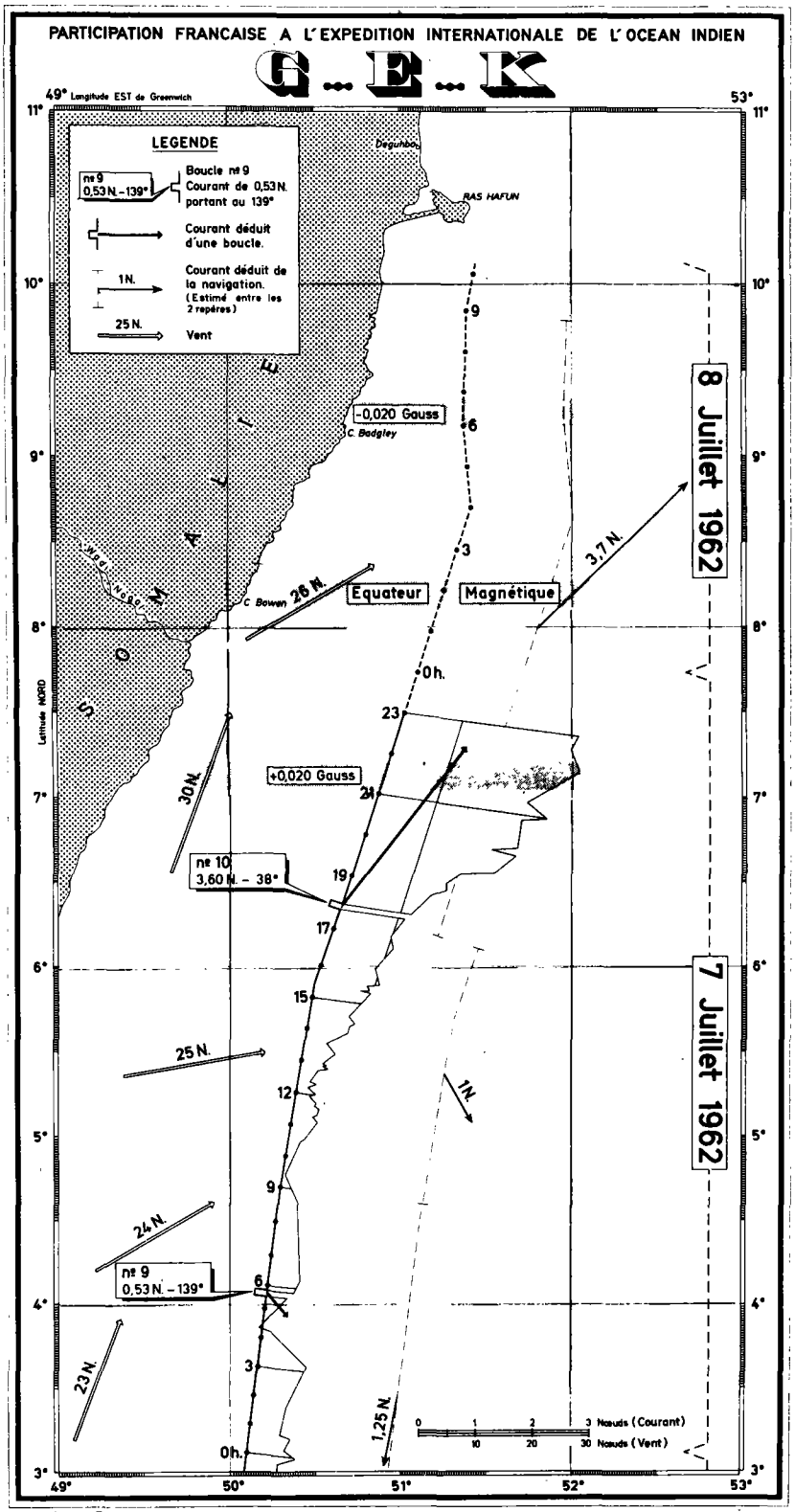
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Figure 2



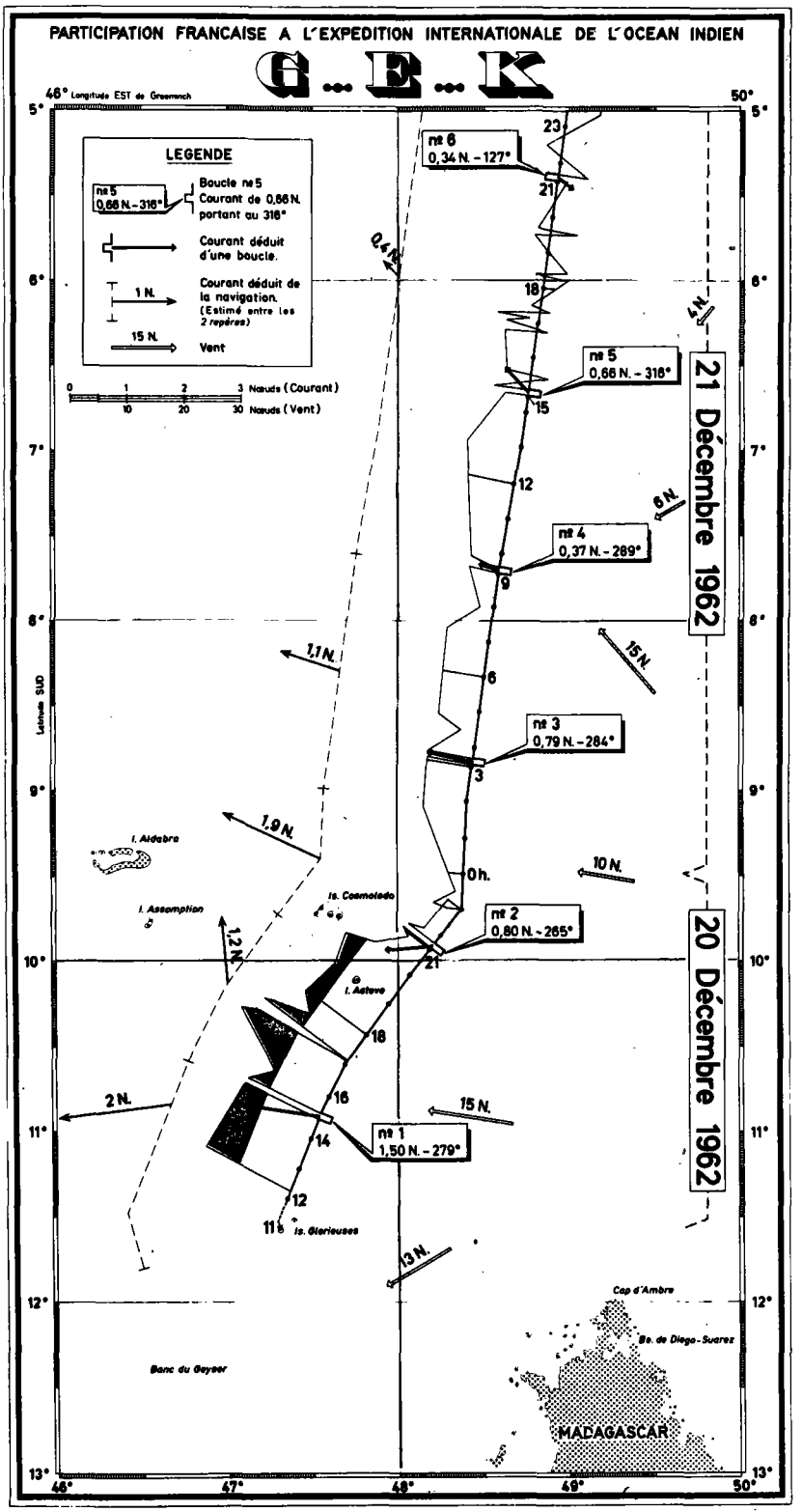
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Figure 3



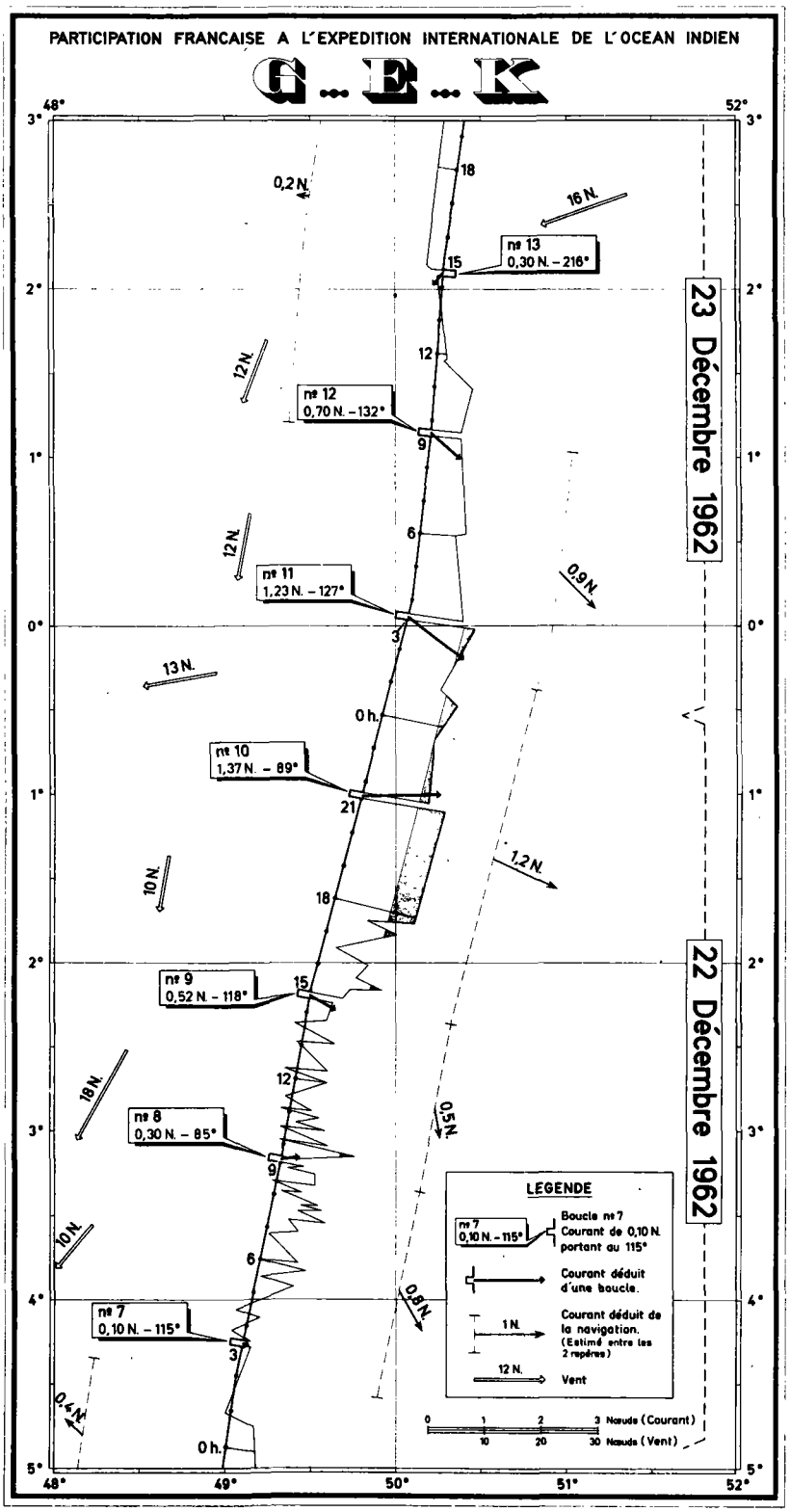
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Figure 4



M. CREPON

Figure 5



M.CREPON

Figure 6

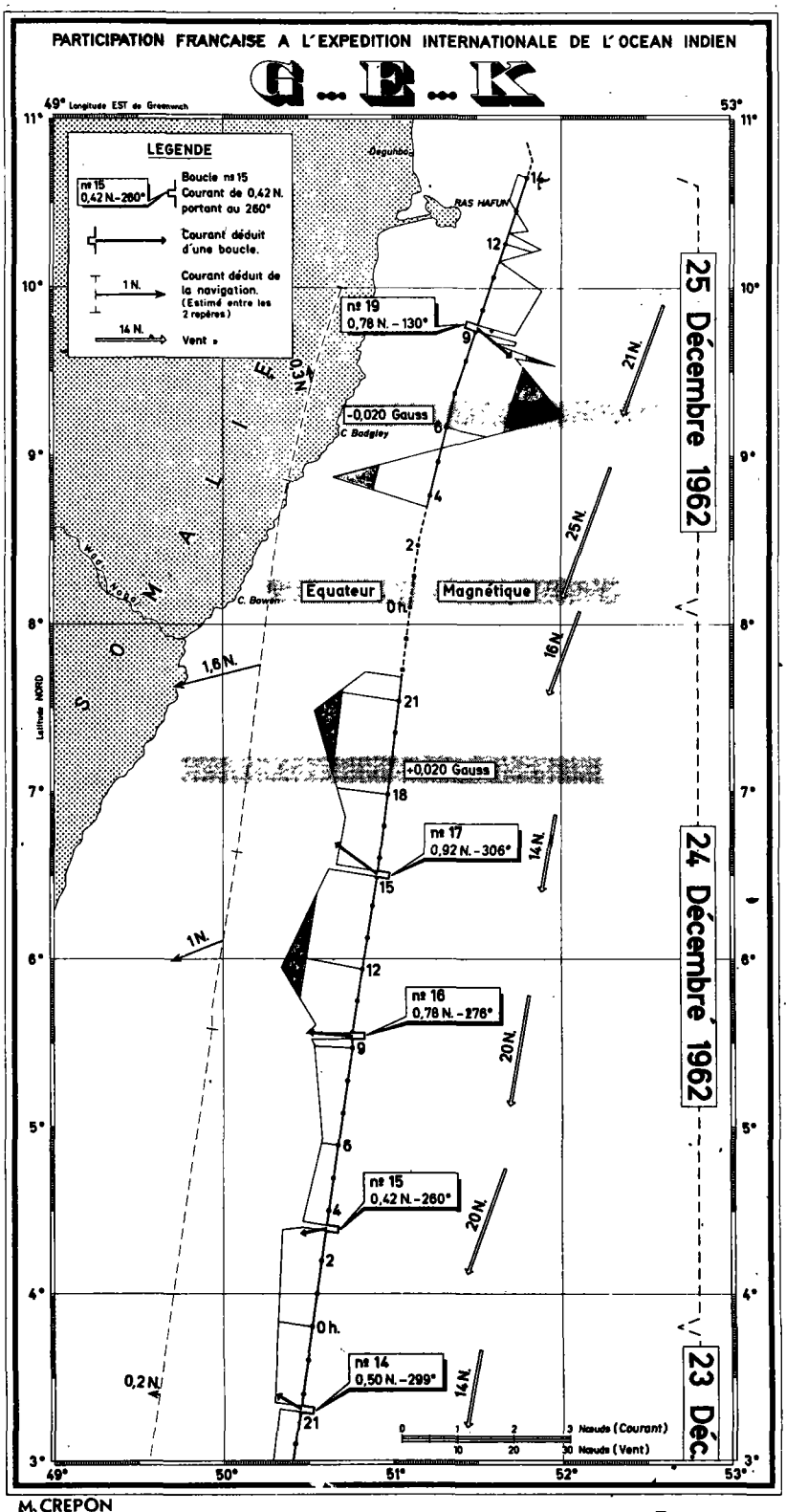

PARTICIPATION FRANCAISE A L'EXPEDITION INTERNATIONALE DE L'OCEAN INDIEN
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0 h.
+0,020 Gauss
nº 17 0,92 N. - 306°
nº 16 0,78 N. - 276°
nº 15 0,42 N. - 260°
nº 14 0,50 N. - 299°
0,3 N.
1,6 N.
1 N.
0,2 N.
21 N.
25 N.
16 N.
14 N.
20 N.
20 N.
14 N.
25 Décembre 1962
24 Décembre 1962
23 Déc.
Latitude NORD
0 1 2 3 Nœuds (Courant)
0 10 20 30 Nœuds (Vent)
49° 50° 51° 52° 53°
M. CREPON

Figure 7

IV - PRESENTATIONS DES OBSERVATIONS

En l'absence de vent, le câble du G.E.K. est orienté selon le Cap vrai (Cv). La composante mesurée qui lui est perpendiculaire et la normale à la Route-fond (Rf) font entre-elles un angle égal à la seule dérive due au courant (dc).

En présence du vent on constate que le câble G.E.K. reste dans le sillage du navire qui correspond sensiblement à la Route-vraie (Rv) c'est-à-dire au Cap vrai + la dérive due au vent (dv).

L'angle (câble G.E.K., Route-fond) est donc donné par $[(Cv + dv + dc) - (Cv + dv)]$ et sera toujours en lère approximation égal à la dérive due au courant.

Le vent peut intervenir lors des boucles en donnant, en particulier, une fausse valeur du zéro des électrodes. On n'a pas tenu compte de cet effet qui sera précisé par une étude ultérieure de J. MARTIN.

On a tracé la Route-fond, en trait plein lorsqu'il y a des mesures G.E.K., en pointillé lorsqu'il n'y a pas de mesures. On a porté, à partir de la Route-fond, en chaque point, un vecteur dont le module est proportionnel à la composante du courant donnée par le G.E.K. et dont la direction est perpendiculaire à la Route-vraie. On a joint par une ligne les extrémités de ces vecteurs.

Ces vecteurs sont tracés toutes les 3 heures. On a colorié en vert clair la partie de la composante transversale du courant inférieure à 1 noeud, en vert foncé celle supérieure à 1 noeud.

Chaque boucle est schématisée par un petit créneau dont le sens a été choisi uniquement par des considérations de dessin.

Les heures figurant sur la Route-fond, sont les heures T.U.

On a représenté également le vent et le courant, déduit de la navigation.

V - RESULTATS

On observe en juillet (fig.2) et en décembre (fig.5) un courant intense portant à l'Ouest entre 12°S et 5°S (Courant équatorial Sud). La valeur de ce courant est plus élevée en juillet.

En juillet de 5°S à 2°N (fig.3), le courant porte au Nord en s'infléchissant vers l'Est de 0° à 2°N. De 3°N à 5°N le courant porte vers le Sud (boucle 9 et courant déduit de la navigation). Il semble donc y avoir une convergence entre 2°N et 3°N (entre les boucles 8 (fig.3) et 9 (fig.4)). A partir de 5°N, le courant qui porte au Nord-Est croît constamment pour atteindre des valeurs très élevées vers 7° et 8°N (3 noeuds et plus). Malheureusement on est dans les parages de l'équateur magnétique et aucune mesure au G.E.K. ne devient plus possible. [On démontre que (J. MARTIN - 1956) l'erreur commise sur la vitesse transversale du courant v_t est égale à :

$$\frac{d\,v_t}{v_t} = \frac{d\,mv}{mv} - \frac{d\,H_z}{H_z}$$

où mv figure la tension lue sur l'enregistreur, H_z la valeur de la composante verticale du champ magnétique terrestre; près de l'équateur magnétique H_z tend vers 0 par définition, l'erreur relative sur le courant augmente donc indéfiniment].

En décembre (fig.6), entre 3°S et 2°N, le contre-courant équatorial portant à l'Est est bien marqué (plus de 1 noeud entre 2°S et 0°). Sa position en latitude est plus au Nord qu'il n'est classiquement admis : il se situe de part et d'autre de l'équateur. Entre 2°N et 7°N, le courant porte à l'Ouest, donc est de sens opposé à celui du courant violent observé au mois de juillet.

On observe une bonne concordance entre navigation et G.E.K. ce qui devient précieux près de l'équateur magnétique où une grande incertitude règne sur la méthode G.E.K.

VI - DETERMINATION DE L'EQUATEUR MAGNETIQUE

D'après les enregistrements G.E.K., l'équateur magnétique serait de 30' plus au Sud qu'il n'est indiqué sur la carte n°1.702, de l'US Navy Hydrographic Office. On a situé l'équateur magnétique sur le méridien 51°E, à 8°10'N de latitude.

Le Capitaine de Frégate RAYNAUD-LACROZE, les officiers et l'équipage du "Commandant Robert Giraud" ont participé efficacement à la réalisation de ces mesures.

Le dépouillement des enregistrements a été fait au Laboratoire d'Océanographie physique du Muséum d'Histoire naturelle.

La navigation a été reconstituée par R. DE REALS, Capitaine au long-cours qui nous a donné de précieux conseils lors de la rédaction de la présente note.

Les figures ont été dessinées par l'Equipe cartographique du Laboratoire.

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Large-Amplitude Internal Waves Observed off the Northwest Coast of Sumatra

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Abstract. Internal waves of large amplitude were observed north of Sumatra by the U. S. Coast & Geodetic Survey ship *Pioneer* in June 1964. The bathythermograph investigation which defined these waves was initiated after observation of curious periodic surface phenomena resembling tide rips. Analysis of bathythermograph records indicates that internal waves with a maximum observed wave height of 82 meters are the probable cause of the surface disturbances.

Introduction. The existence of internal waves in the sea, along surfaces separating layers of contrasting density, has been inferred from oceanographic observations for many years. A better understanding of these waves is important because of their effect on dynamic height computations, current measurements, marine life, undersea navigation, and submarine warfare. Large internal waves, and surface disturbances believed to be associated with these waves, were observed in the Andaman Sea area between Great Nicobar Island and Sumatra by the U. S. Coast & Geodetic Survey ship *Pioneer* in June 1964 during the vessel's participation in the International Indian Ocean Expedition.

Setting. The Andaman Sea is separated from the Bay of Bengal by the Andaman and Nicobar islands (see Figure 1) and a submerged, north-south trending ridge from which the exposed island peaks rise, the Andaman-Nicobar ridge (see Figure 2). The sea is bordered by Burma, Thailand, the northern end of the Strait of Malacca, and the northwest coast of Sumatra. Between Great Nicobar Island, the southernmost island of the group, and Sumatra, the waters of the Andaman Sea connect with those of the Indian Ocean through the Great Channel, a passage in the submerged ridge characterized by rugged sea-bottom topography and depths greater than 2000 m.

General summaries of meteorological and oceanographic conditions in the Bay of Bengal–Andaman Sea area are given in *U. S. Navy Hydrographic Office Special Publication 53* [1960] and by *Sewell* [1932]. They indicate that in June a well-mixed surface layer of water, having lower salinity and higher temperature than the surface waters in the Bay of Bengal, flows southwest through the Great Channel. Temperature profiles taken by the *Pioneer* in June 1964 showed a well-mixed layer extending to a depth of about 100 m. A recent analysis of oceanographic conditions in the area indicates that surface currents in the Great Channel set to the west at about 0.8 m/sec during much of the year and that a subsurface flow sets to the east, into the Andaman Sea, below the thermocline depth (R. H. Sullivan, Jr., U. S. Navy Fleet Weather Service, personal communication).

Observations. On the morning of June 12, 1964, distinct zones of whitecaps ranging from 200 to 800 m in width and stretching from horizon to horizon (approximately 30 km) in a north-south direction were observed in the Andaman Sea north of Sumatra (see Figure 2). At least five of these zones, with a spacing of about 3200 m between each zone, were observed. The observed zones or bands of choppy water had short, steep, randomly oriented waves with heights of about 0.3 to 0.6 m. Each band stood out distinctly in an otherwise undisturbed sea. A 4-m/sec NNW wind and a surface water temperature of 29°C were observed, but neither changed significantly as the ship crossed the bands of choppy water. Detailed salinity measurements were not made while crossing the bands; however, routine bi-hourly salinity samples showed a maximum regional salinity gradient of 0.03‰ per km. Later in the day, several other bands of similar dimensions, but having smaller waves, were observed.

On June 13, similar north-south trending

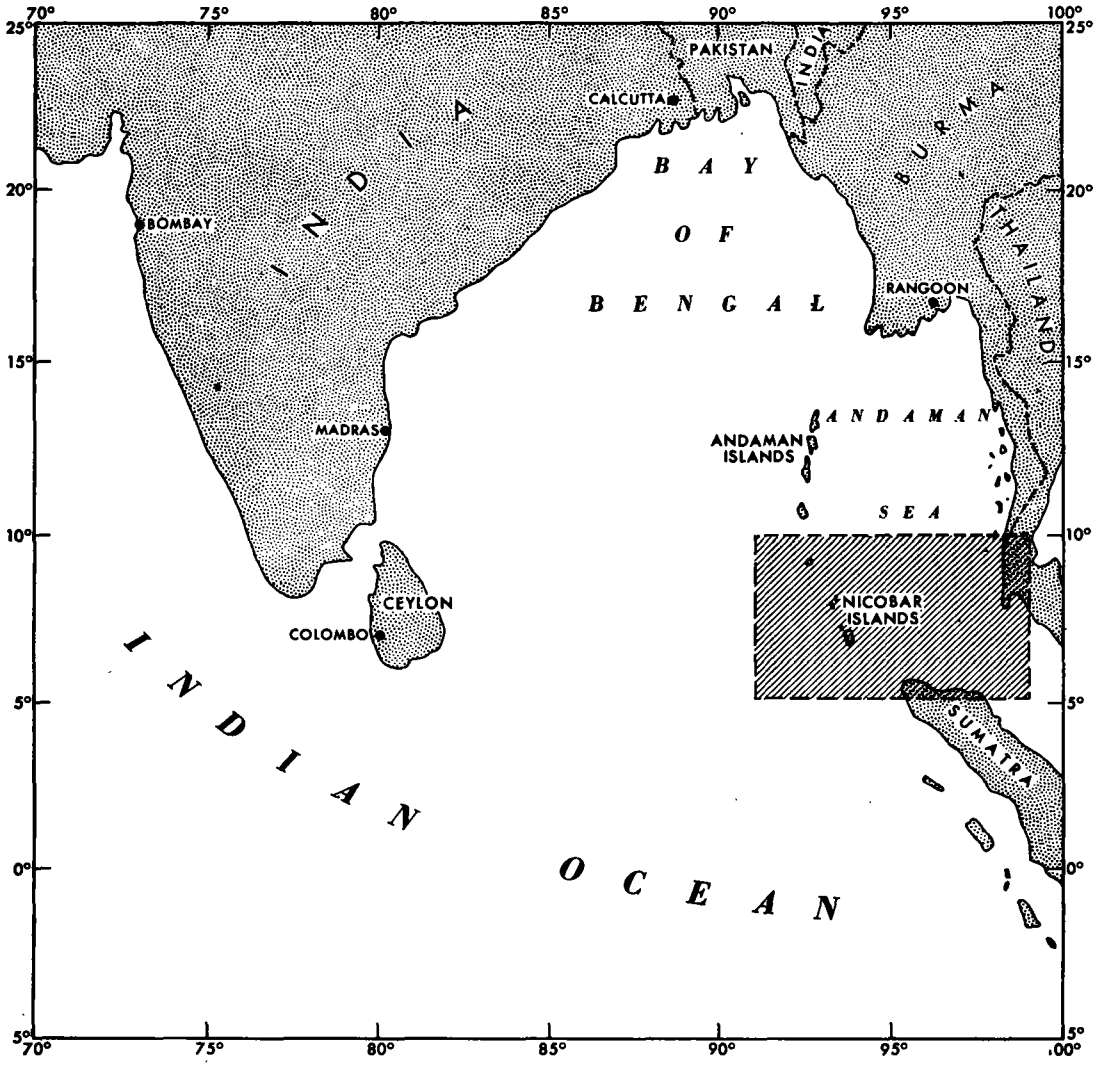


Fig. 1. Indian Ocean area.

bands of choppy water were seen farther to the west in the Great Channel, near 06°09′N, 94° 37′E. Ten bands, each approximately 200 m wide and 800 m apart, were observed. In some instances, the water between the bands of choppy water had a slicked appearance despite a 9-m/sec SSW wind. Similar slicks were not apparent on the preceding day when the bands of choppy water were farther apart. Boundaries of the choppy water were all well defined. After crossing a number of the bands, the ship changed course to an easterly direction to initiate a bathythermograph (BT) investigation of the observed phenomenon. The time at which the bow of the ship entered a chop line and the time the stern entered the same line was observed. By using the ship's course and average speed as determined by visual fixes on land, it was possible to compute the rate at which the bands were moving, assuming their direction of progress to be perpendicular to their long axis. The bands were computed to be moving eastward at 2.6 m/sec. A series of five BT observations was obtained by repeatedly lowering the instrument while the ship steamed west at 4.7 m/sec, approximately perpendicular to the long axis of the chop lines. Four well-defined bands of choppy water were crossed during the BT

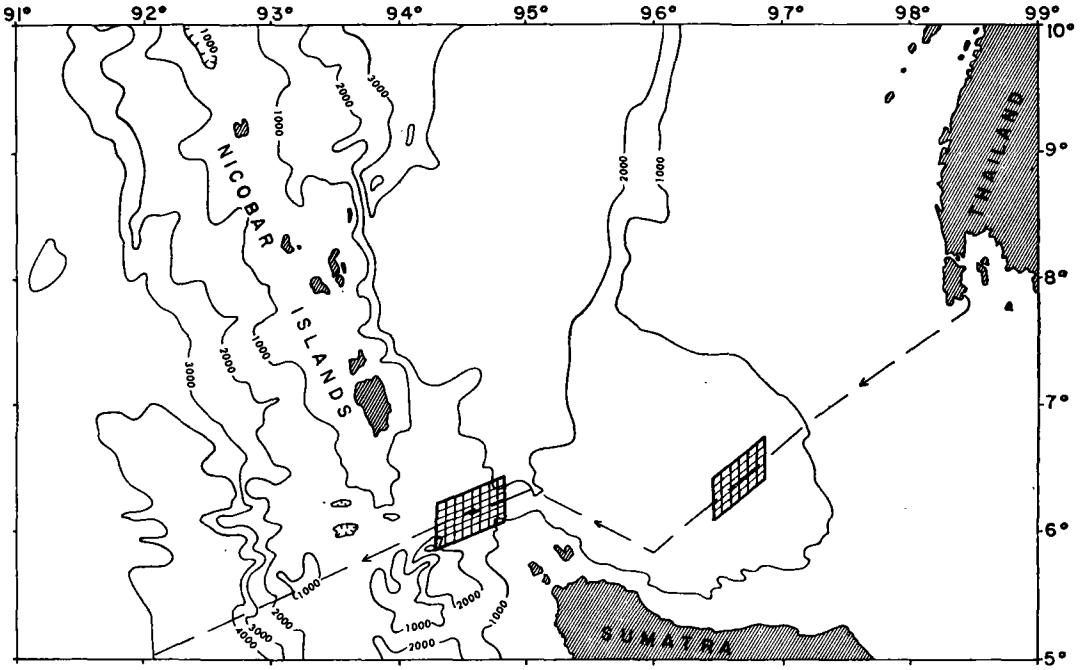


Fig. 2. Trackline of USC&GS ship *Pioneer*, June 12–13, 1964. Crosshatched areas indicate places where surface disturbances were observed. Depth contours in meters.

observations (see Figure 3). Each BT record taken while crossing the chop lines showed a split trace in the thermocline region. A maximum separation of nearly 15 m was recorded on one lowering. Since the bathythermograph functioned properly on previous and subsequent measurements, the cause of the split trace was attributed to pronounced horizontal temperature gradients, possibly associated with internal waves.

The temperature profile in Figure 3 was derived by plotting the depth of the isotherms from the five BT traces against the time elapsed during the observations. The temperatures recorded during the descent of the BT are separated from those recorded during the ascent. In the resulting profile the periodic undulations of the closely spaced isotherms, which depict the depth of the thermocline, strongly suggest the presence of internal waves. The maximum height of the apparent waves is approximately 80 m. If they are indeed internal waves, and moving at the same speed and in the same direction as the surface chop lines, then the wavelength is calculated to be about 2000 m.

Upon completing the special BT observations, the *Pioneer* resumed its westward course through the Great Channel into the Bay of Bengal. As the ship proceeded westward, the surface waves in the bands of choppy water were observed to increase in size. The last and westernmost chop line sighted, at 06°03′N, 94° 21′E, was a very choppy north-south zone characterized by seas of 1.8 to 2.1 m and extending from horizon to horizon.

During the ship's westward course through the area where the internal waves were found, the routine bi-hourly BT observations indicated an intensification of the temperature gradient in and a rising of the thermocline. From the point where the last line of surface chop was observed, and westward into the Bay of Bengal, the thermocline depth gradually increased and its temperature gradient became somewhat less intense.

Discussion. In the Bay of Bengal and adjacent waters, surface phenomena similar to that observed aboard the *Pioneer* have been previously observed and variously described as current rips, tide rips, lines of demarcation, and disturbed and rippled water [*Marine Observer*, 1958, 1959, 1962*a*, 1962*b*, 1963, 1964]. Alternate

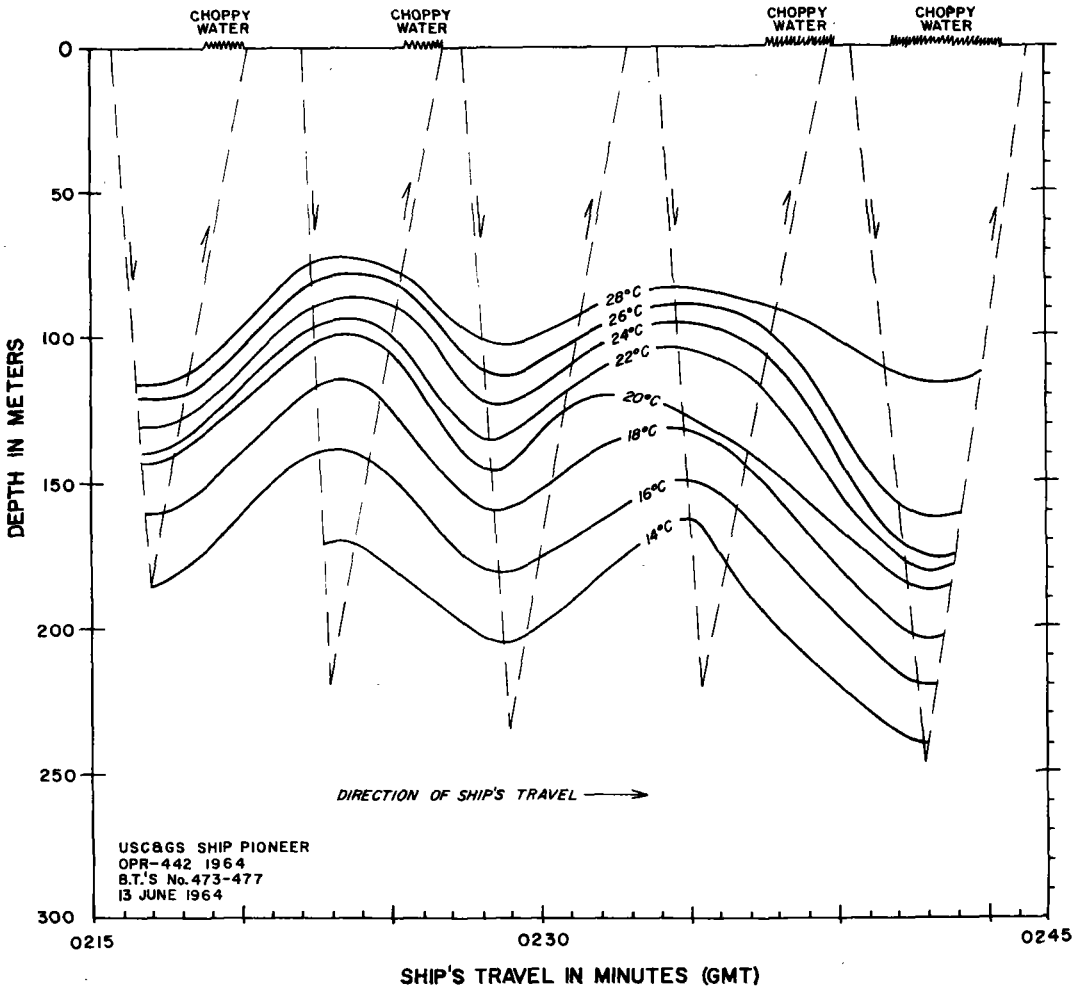


Fig. 3. Temperature profile as defined by bathythermograph. Dashed lines indicate path followed by bathythermograph.

bands of rough and smooth water passed the R.V. *Anton Bruun* at four oceanographic stations in the Andaman Sea in March 1963 while that ship was operating under the National Science Foundation Program in Biology for the International Indian Ocean Expedition. At one of these stations a low roar accompanied by breaking whitecaps was observed as the bands passed the ship in a flat calm sea (E. C. LaFond, U. S. N. Electronics Laboratory, 1965, written communication).

In more restricted areas similar but smaller-scale, elongated surface features occasionally are caused by converging currents, by tide rips, or by the influence of bottom topography. *Pickard* [1961] has observed similar surface phenomena on a much reduced scale in certain inlets along the British Columbia mainland. His surface phenomena were related to progressive internal waves associated with a shear zone between inflowing bottom water and outflowing surface water in a positive estuarine situation.

Bands of surface chop have also been associated with oceanic fronts. Such fronts are generally characterized by strong horizontal temperature gradients at the surface and by marked faunal and color changes [*Knauss*, 1963]. A pronounced lateral shear in the surface flow is often in evidence as the observing ship crosses the disturbed band of water. The *Pioneer* ex-

perienced no difficulty in maintaining a true course while crossing the bands of disturbed water. There were no noticeable horizontal temperature or salinity gradients at the surface for a distance of more than 145 km on either side of the five special BT observations taken on June 13. Therefore, the possibility that the observed phenomena were directly associated with an oceanic front can be dismissed.

The possibility of bottom topographical influence as a causative factor has been considered because remarkable correlations have been made between sightings of disturbed water and sharp rises in the bottom topography at relatively great depths. Such a correlation was noted aboard the *Pioneer* earlier in the expedition while in the Andaman Sea. However, the jumbled and rugged topographical features and great depth of the sea floor in the immediate vicinity of the chop lines (Figure 2) make it hard to conceive of the bottom features giving rise to long, straight, narrow surface disturbances stretching from horizon to horizon.

Surface slicks have been related to internal waves in shallow water areas [*Ewing*, 1950; *Dietz and LaFond*, 1950]. In many cases, slicks are particularly noticeable in waters close to shore, where they usually are associated with wave heights of 10 m or less. *Pickard* [1961] pointed out the basic difference between these slicks and the bands of choppy water which we observed.

Internal waves of greater height than 10 m have been observed in the deep oceans by means of Nansen bottles with reversing thermometers, BT's, and, more recently, thermistor chains. Generally, these internal waves have been long waves with periods of the same order of magnitude as the tidal period. Slicks or disturbed surface conditions have not been associated with internal waves in deep water far from shore before these observations.

The mechanism for generating internal waves is frequently in question. In coastal areas the rise and fall of the tides over the continental shelf [*Rattray*, 1960] and shear caused by one mass of water flowing over another [*Proudman*, 1953] are among the mechanisms proposed for the generation of internal waves. The internal waves observed by the *Pioneer* were of such short wavelength that tidal generation hardly seems to be a reasonable explanation. On the other hand, because of their large amplitude, it seems somewhat speculative in the absence of direct current measurements to propose that shear flow was the generating mechanism. However, investigations by R. H. Sullivan, Jr. U. S. Navy Fleet Weather Service, personal communication, 1964), indicate that a strong shear flow may occur in the vicinity of the observed phenomena during most of the year. If this is the case, the situation seems directly analogous to that observed by *Pickard* [1961].

Defant [1961] wrote, 'the appearance of waves at the boundary surface between two water layers has for a long time escaped the attention of observers because, even when the amplitude of the oscillation at the boundary surface is large, the free surface of the upper layer is only slightly disturbed and remains practically at rest.' In the case at hand, the density of ρ' the upper well-mixed layer was 1.021 g/cm^3. From the previous observations of *Sewell* [1932] and *USN H. O. Special Publication 53* [1960], the density ρ of the lower layer can be reckoned as 1.026 g/cm^3. Using 40 m for the amplitude of the internal wave, and the formula $\eta_0 = -Z(\rho - \rho')/\rho$ [*Defant*, 1961], where η_0 is the amplitude of the wave at the free surface and Z is the amplitude of the internal wave, we compute a 0.2-m amplitude for the wave at the free surface.

The generating mechanism of the highly agitated bands of chop is not clear, but they probably are caused by a redistribution of mass that takes place with the passage of the internal wave. Pickard's observations in Canadian waters indicate that his 'ruffled bands' are associated with the convergence taking place at the surface just behind the advancing internal wave crest. As seen in Figure 3, it was not possible to establish a clear relationship between the bands of chop at the surface and a particular phase of the wave.

There is no direct correlation of wind effects and the observed phenomena since they were observed on June 12 in a relatively calm sea. Also the waves of the chop zone showed variable heights under relatively constant wind conditions on June 13. A topographic influence seems unlikely because of the irregular character and depth of the bottom.

Owing to the prevailing oceanographic conditions north of Sumatra during much of the year,

and reported sightings of disturbed bands of water stretching from horizon to horizon, we believe that the existence of the phenomenon reported herein may be common in this part of the world, and its occurrence on June 13, 1964, probably was not unique.

More comprehensive investigations of this phenomenon might include the use of aircraft for aerial reconnaissance and aerial photography to chart the extent and periodicity of the surface disturbances. Current measurements and detailed thermal investigations should also be made using at least two ships equipped with thermistor chains.

Conclusions. The zones or narrow bands of choppy water sighted by the USC&GS ship *Pioneer* in the Andaman Sea area are believed to have been caused by internal waves. Internal waves, which were observed to occur simultaneously with the choppy surface phenomena, had uncommon dimensions of approximately 80 m in height and 2000 m in length.

Although the limited observational data preclude any conclusive demonstrations of a generating mechanism for these waves, the cause may be related to a shear zone resulting from a well-mixed upper layer of warm, low-salinity water flowing westward over cooler, higher-salinity water flowing eastward through Great Channel north of Sumatra.

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RAPID CHANGES IN THE CHARACTERISTICS OF THE DEEP SALINITY MAXIMUM OF THE SOUTH-EAST INDIAN OCEAN

By D. J. ROCHFORD*

[*Manuscript received November* 23, 1964]

Summary

Salinities of the deep salinity maximum at SCOR-UNESCO reference stations 1 and 2 in the south-east Indian Ocean have varied much more (± 0·01–0·02‰ about the mean) than those at a CSIRO reference station in the south-west Pacific Ocean (± 0·004‰ about the mean) during 1959–63. At the SCOR-UNESCO reference stations, and other stations between, the changes in salinity of this maximum during 1959–63 were paralleled by changes in other properties, consistent with an annual increase in the advection of a north Indian Ocean deep water mass during March–July. Changes in the properties of the deep water at the CSIRO Reference Station during 1962–63 were within the precision limits of the Australian analytical methods found during the intercalibration tests on R.S. *Vityaz* in August 1962.

Seasonal changes of the same, or greater magnitude than those at SCOR-UNESCO reference stations 1 and 2 can be expected at other sites chosen for SCOR-UNESCO reference stations in the Indian Ocean, whenever they fall within the boundaries of the north Indian Ocean deep water mass. Such stations will be unsuitable, therefore, for comparing analytical accuracies but could be very useful for monitoring changes in the deep circulation.

I. INTRODUCTION

SCOR-UNESCO reference stations 1 and 2 (Fig. 1) have been sampled to depths greater than 4000 m since 1959 (No. 1) and 1962 (No. 2). Sufficient chemical data have now been obtained at these stations to decide whether the original intention of using their deep water as a standard for the intercalibration of chemical methods is feasible. Unfortunately, so little is known about the magnitude of the changes that can occur in the deep waters of the Indian Ocean that no acceptance or rejection of any suspect value can be based upon statistical considerations of probability. Much of this paper, therefore, has had to be devoted to a consideration of the limiting ranges of chemical properties of the water masses of the deep salinity maximum of the whole Indian Ocean. This consideration provides a framework against which the properties of all observations within this deep salinity maximum at these reference stations can be viewed and on which their acceptance or rejection can be based.

II. MATERIAL AND METHODS

The location of the stations used in Section IV, of the three reference stations, and of the 110° E. meridional section are shown in Figure 1. Tables 1, 2, and 3 list particulars of stations used in Sections III and V; Table 4 lists particulars of stations used in Section IV; Table 5 lists particulars of stations used in Section VI. At each of these stations the potential temperature and the salinity of the deep salinity maximum were read from a smoothed salinity–potential temperature curve. Potential temperatures were calculated by use of the tables of Helland-Hansen (1930).

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Methods used by CSIRO for the determination of salinity, phosphate, and oxygen have been published (CSIRO Aust. 1962*a*). Those used by other laboratories can be found in the original data sources of Table 4. Differences of 0·01‰ in salinity were considered definitive for locating a salinity maximum on salinity–potential temperature curves of *Diamantina*, *Gascoyne*, *Vema*, and *Crawford* data. For data where titration was used to determine salinity, a difference of 0·02‰ or more was required. The depth, oxygen, and inorganic phosphate of the deep salinity maximum were calculated by linear interpolation from the tabulated station data.

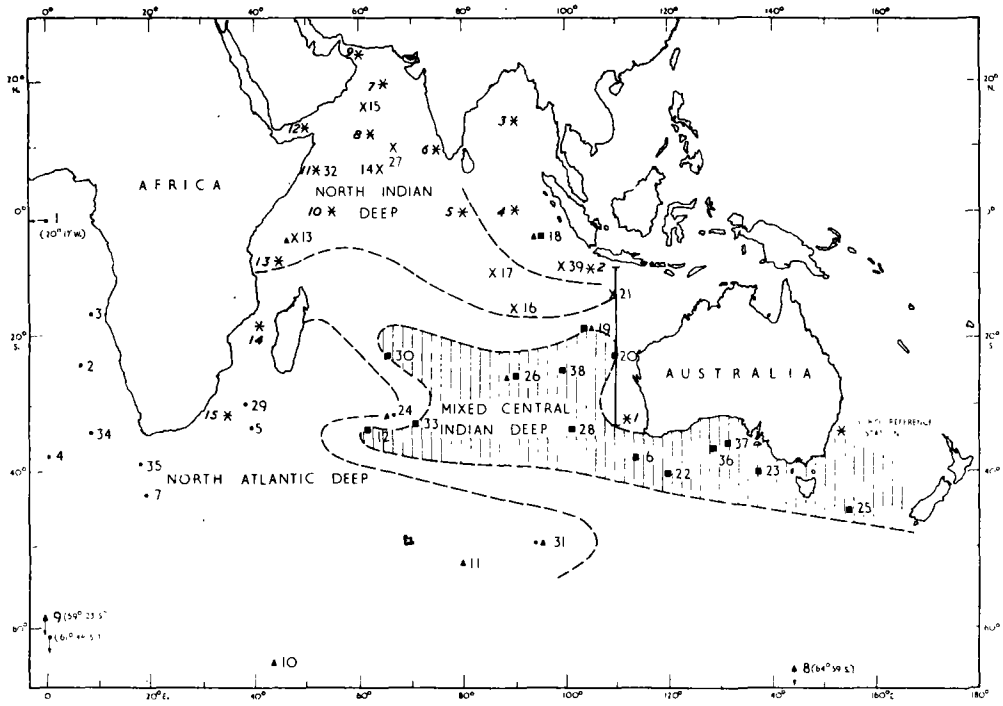


Fig. 1.—Chart of the stations used and approximate boundaries of the three major water masses comprising the deep salinity maximum of the Indian Ocean. × North Indian deep; ● North Atlantic deep; ■ Central Indian deep; ▲ Representative Antarctic bottom water stations; *SCOR-UNESCO reference stations (IIOE Information Paper No. 1, 1962).

III. Changes in the Salinity of the Deep Salinity Maximum at Reference Stations during 1959–63

Figure 2 shows the changes that occurred in the salinity–potential temperature curves of the deep waters at the CSIRO Reference Station (Fig. 1) during 1962–63. The curves were of very regular shape and showed a maximum range of ±0·004‰ about the mean value of the deep salinity maximum. Such a deviation lies within the precision limits of the inductively coupled salinometer used by CSIRO (Brown and Hamon 1961). At depths below 3000 m the changes in salinity were less than ±0·003‰ about the mean (Fig. 2). However, at SCOR-UNESCO Reference Station 1 the changes in salinity of the deep salinity maximum during 1959–62 (Fig. 3) and during

1962–63 (Fig. 4) were much greater (±0·01‰ about the mean.) The shapes of the curves were much more irregular at this station than at the CSIRO Reference Station

TABLE 1

SAMPLING AT SCOR-UNESCO REFERENCE STATION 1

Station	Vessel	Date	Source of Data	Figure and Symbol
134	*Diamantina*	18.xi.59	CSIRO (1962*a*)	Fig. 3 ●
114	*Diamantina*	22.iii.60	CSIRO (1962*b*)	×
115	*Diamantina*	12.vii.60	CSIRO (1963*a*)	▲
350	*Diamantina*	17.x.60	CSIRO (1962*c*)	■
10	*Diamantina*	21.ii.61	CSIRO (1963*b*)	+
49	*Diamantina*	2.v.61	CSIRO (1963*c*)	○
43	*Diamantina*	24.iii.62	CSIRO (unpublished data)	△
101	*Diamantina*	24.viii.62	CSIRO (unpublished data)	□
102	*Diamantina*	25.ix.62	CSIRO (unpublished data)	*
181	*Gascoyne*	19.viii.62	CSIRO (unpublished data)	Fig. 4 ●
126	*Diamantina*	16.x.62	CSIRO (unpublished data)	×
161	*Diamantina*	12.xi.62	CSIRO (unpublished data)	▲
1	*Gascoyne*	18.i.63	CSIRO (unpublished data)	■
35	*Gascoyne*	16.ii.63	CSIRO (unpublished data)	+
1	*Diamantina*	29.iii.63	CSIRO (unpublished data)	○
54	*Diamantina*	27.iv.63	CSIRO (unpublished data)	△
55	*Diamantina*	7.v.63	CSIRO (unpublished data)	□
89	*Diamantina*	10.vii.63	CSIRO (unpublished data)	*
146	*Diamantina*	5.ix.63	CSIRO (unpublished data)	△

TABLE 2

SAMPLING AT SCOR-UNESCO REFERENCE STATION 2

Station	Vessel	Date	Source of Data	Symbol used in Figure 5
199	*Gascoyne*	29.viii.62	CSIRO (unpublished data)	●
200	*Gascoyne*	7.ix.62	CSIRO (unpublished data)	×
143	*Diamantina*	26.x.62	CSIRO (unpublished data)	▲
144	*Diamantina*	3.xi.62	CSIRO (unpublished data)	■
18	*Gascoyne*	28.i.63	CSIRO (unpublished data)	+
19	*Gascoyne*	7.ii.63	CSIRO (unpublished data)	○
36	*Diamantina*	7.iv.63	CSIRO (unpublished data)	△
37	*Diamantina*	18.iv.63	CSIRO (unpublished data)	□
72	*Diamantina*	16.v.63	CSIRO (unpublished data)	*
73	*Diamantina*	25.v.63	CSIRO (unpublished data)	▽
106	*Diamantina*	19.vii.63	CSIRO (unpublished data)	▼
108	*Diamantina*	2.viii.63	CSIRO (unpublished data)	⊗
157	*Diamantina*	11.ix.63	CSIRO (unpublished data)	△

(Figs. 3 and 4). Salinities of waters below the deep salinity maximum varied much more at SCOR-UNESCO reference stations than at the CSIRO Reference Station (Figs. 2, 3, and 4). At SCOR-UNESCO Reference Station 2 (Fig. 1) the salinity of the deep

salinity maximum changed some 0·03‰ during 1962–63 (Fig. 5). Even at greater depths (Fig. 5; 3500 m) the salinity changed by 0·02‰ during this period.

When plotted on an annual scale the salinities of the deep salinity maximum of the two SCOR-UNESCO reference stations showed evidence of a repeated annual cycle (Fig. 6). It is possible that the lower than average salinities during August–April 1962–63 were caused by increased vertical mixing since lower salinity water occurs within 500 m above or below this maximum (Fig. 7). However, it is considered very unlikely that vertical mixing could account for the higher than average salinities in March–July 1962–63 (Fig. 6). Such an increase in salinity would require the redistribution, within several months, of the salt content of an overlying column some 1500 m thick (Fig. 7). It is almost certain, therefore, that horizontal advection caused the increases in salinity during 1962–63. There remains the possibility, however (see Section I), that these higher than average salinities were in error.

TABLE 3

SAMPLING AT CSIRO REFERENCE STATION (34°01′S., 153°05′E.)

Station	Vessel	Date	Source of Data	Symbols used in Figure 2
54	*Gascoyne*	4.vi.62	CSIRO (unpublished data)	●
76	*Gascoyne*	10.vii.63	CSIRO (unpublished data)	×
132	*Gascoyne*	20.viii.63	CSIRO (unpublished data)	▲
133	*Gascoyne*	9.ix.63	CSIRO (unpublished data)	■
222	*Gascoyne*	14.xi.63	CSIRO (unpublished data)	+

IV. HYDROLOGICAL CHARACTERISTICS OF THE DEEP SALINITY MAXIMUM OF THE INDIAN OCEAN

A selection of recent stations (Fig. 1) has been used to determine the characteristics of the water masses which occur within the deep salinity maximum of the Indian Ocean. The salinity–potential temperature (Fig. 8), oxygen–potential temperature (Fig. 9), and inorganic phosphate–potential temperature relations (Fig. 10) all showed that three high salinity water masses (Figs. 8–10; *A*, *C*, and *D*) occurred within this salinity maximum and that Antarctic bottom water (Fig. 8; *B*) was important in forming at least water mass *C*. Water mass *A* was found south-west of Africa (Fig. 1;1) and is of the north Atlantic deep origin. Water mass *D* was found in the central Arabian Sea (Fig. 1; 15 and 27) and is identical with the north Indian deep water of Sverdrup, Johnson, and Fleming (1942). Water mass *C* which occupies a central belt of the Indian Ocean, from Madagascar to Australia and southward to the Pacific Ocean (Fig. 1), is thought to be a mixture of *A*, *B*, and D^1 (Figs. 8–10) and will be referred to as central Indian deep water. Waters with the salinity characteristics of D^1 cannot be formed by direct mixing between *D* and *C* (Fig. 8)

although their oxygen and phosphate characteristics would indicate this mode of formation (Figs. 9 and 10). Further data from the Arabian Sea will perhaps show that the salinity or potential temperature of D has not been correctly established. For

TABLE 4
STATIONS USED IN SECTION IV

Station	Vessel	Date	Source of Data	Reference No. (Fig. 1)
484	*Crawford*	22.xi.58	Metcalf (1960)	1
442	*Crawford*	19.x.58	Metcalf (1960)	2
150	*Crawford*	21.iv.57	Fuglister (1957)	3
2027	*Discovery*	2.iv.37	'Discovery' Committee (1947*b*)	4
1763	*Discovery*	5.v.36	'Discovery' Committee (1947*a*)	5
1734	*Discovery*	5.iv.36	'Discovery' Committee (1947*a*)	6
1556	*Discovery*	30.iii.35	'Discovery' Committee (1942)	7
1699	*Discovery*	15.iii.36	'Discovery' Committee (1947*a*)	8
2015	*Discovery*	25.iii.37	'Discovery' Committee (1947*b*)	9
1545	*Discovery*	28.ii.36	'Discovery' Committee (1942)	10
1636	*Discovery*	30.xi.35	'Discovery' Committee (1947*a*)	11
1756	*Discovery*	29.iv.36	'Discovery' Committee (1947*a*)	12
1583	*Discovery*	30.iv.35	'Discovery' Committee (1942)	13
4707	*Vityaz*	29.iii.60	*Vityaz*	14
4722	*Vityaz*	13.iv.60	*Vityaz*	15
4582	*Vityaz*	21.xii.59	*Vityaz*	16
4599	*Vityaz*	14.i.60	*Vityaz*	17
71	*Diamantina*	7.viii.62	CSIRO (unpublished data)	18
95	*Diamantina*	20.viii.62	CSIRO (unpublished data)	19
14	*Diamantina*	2.iv.63	CSIRO (unpublished data)	20
29	*Diamantina*	5.iv.63	CSIRO (unpublished data)	21
70	*Diamantina*	5.iii.60	CSIRO (1962*b*)	22
88	*Diamantina*	9.iii.60	CSIRO (1962*b*)	23
129	*Ob*	25.v.56	USSR Acad. Sci. (1958)	24
11	*Gascoyne*	18.i.61	CSIRO	25
4577	*Vityaz*	18.xii.59	*Vityaz*	26
4709	*Vityaz*	30.iii.60	*Vityaz*	27
69	*Vema*	16.xi.60	Friedman (1960)	28
47	*Vema*	26.iv.58	Friedman (1960)	29
132	*Ob*	28.v.56	USSR Acad. Sci. (1958)	30
291	*Ob*	14.iv.57	USSR Acad. Sci. (1959)	31
1588	*Discovery*	4.v.35	'Discovery' Committee (1942)	32
1752	*Discovery*	26.iv.36	'Discovery' Committee (1947*a*)	33
1769	*Discovery*	20.v.36	'Discovery' Committee (1947*a*)	34
1801	*Discovery*	16.vi.36	'Discovery' Committee (1947*a*)	35
176	*Gascoyne*	10.iii.61	CSIRO (unpublished data)	36
38	*Diamantina*	6.iii.61	CSIRO (1963*b*)	37
45	*Diamantina*	19.vii.62	CSIRO (unpublished data)	38
58	*Diamantina*	24.vii.62	CSIRO (unpublished data)	39

the purpose of this paper, however, it is sufficient to consider D^1 as the third high salinity water mass of the deep salinity maximum. The envelopes in Figure 8 show the mixing circuits which maintain the salinity of the deep salinity maximum of the Indian Ocean. These envelopes have been transferred to Figures 9 and 10 by using

TABLE 5
STATIONS ALONG THE 110°E. MERIDIAN

Station	Vessel	Date	Source of Data	Symbols used in Figs. 11, 12, and 13
182	*Gascoyne*	20.viii.62	CSIRO (unpublished data)	▽
186	*Gascoyne*	22.viii.62	CSIRO (unpublished data)	
190	*Gascoyne*	24.viii.62	CSIRO (unpublished data)	
192	*Gascoyne*	25.viii.62	CSIRO (unpublished data)	
194	*Gascoyne*	26.viii.62	CSIRO (unpublished data)	
196	*Gascoyne*	27.viii.62	CSIRO (unpublished data)	
197	*Gascoyne*	27.viii.62	CSIRO (unpublished data)	
203	*Gascoyne*	9.ix.62	CSIRO (unpublished data)	
205	*Gascoyne*	10.ix.62	CSIRO (unpublished data)	
207	*Gascoyne*	11.ix.62	CSIRO (unpublished data)	
209	*Gascoyne*	12.ix.62	CSIRO (unpublished data)	
211	*Gascoyne*	13.ix.62	CSIRO (unpublished data)	
213	*Gascoyne*	14.ix.62	CSIRO (unpublished data)	
215	*Gascoyne*	15.ix.62	CSIRO (unpublished data)	
103	*Diamantina*	26.ix.62	CSIRO (unpublished data)	▲
105	*Diamantina*	27.ix.62	CSIRO (unpublished data)	
107	*Diamantina*	28.ix.62	CSIRO (unpublished data)	
109	*Diamantina*	29.ix.62	CSIRO (unpublished data)	
111	*Diamantina*	30.ix.62	CSIRO (unpublished data)	
113	*Diamantina*	1.x.62	CSIRO (unpublished data)	
116	*Diamantina*	3.x.62	CSIRO (unpublished data)	
127	*Diamantina*	17.x.62	CSIRO (unpublished data)	×
131	*Diamantina*	19.x.62	CSIRO (unpublished data)	
133	*Diamantina*	20.x.62	CSIRO (unpublished data)	
137	*Diamantina*	22.x.62	CSIRO (unpublished data)	
141	*Diamantina*	24.x.62	CSIRO (unpublished data)	
147	*Diamantina*	5.xi.62	CSIRO (unpublished data)	
149	*Diamantina*	6.xi.62	CSIRO (unpublished data)	
151	*Diamantina*	7.xi.62	CSIRO (unpublished data)	
153	*Diamantina*	8.xi.62	CSIRO (unpublished data)	
155	*Diamantina*	9.xi.62	CSIRO (unpublished data)	
157	*Diamantina*	10.xi.62	CSIRO (unpublished data)	
159	*Diamantina*	11.xi.62	CSIRO (unpublished data)	
2	*Gascoyne*	19.i.63	CSIRO (unpublished data)	■
4	*Gascoyne*	20.i.63	CSIRO (unpublished data)	
10	*Gascoyne*	23.i.63	CSIRO (unpublished data)	
12	*Gascoyne*	24.i.63	CSIRO (unpublished data)	
14	*Gascoyne*	25.i.63	CSIRO (unpublished data)	
16	*Gascoyne*	26.i.63	CSIRO (unpublished data)	
22	*Gascoyne*	9.ii.63	CSIRO (unpublished data)	
24	*Gascoyne*	10.ii.63	CSIRO (unpublished data)	
26	*Gascoyne*	11.ii.63	CSIRO (unpublished data)	
28	*Gascoyne*	12.ii.63	CSIRO (unpublished data)	
30	*Gascoyne*	13.ii.63	CSIRO (unpublished data)	
31	*Gascoyne*	14.ii.63	CSIRO (unpublished data)	
33	*Gascoyne*	15.ii.63	CSIRO (unpublished data)	

TABLE 5 (*Continued*)

Station	Vessel	Date	Source of Data	Symbols used in Figs. 11, 12, and 13
2	*Diamantina*	30.iii.63	CSIRO (unpublished data)	+
5	*Diamantina*	31.iii.63	CSIRO (unpublished data)	
10	*Diamantina*	1.iv.63	CSIRO (unpublished data)	
14	*Diamantina*	2.iv.63	CSIRO (unpublished data)	
19	*Diamantina*	3.iv.63	CSIRO (unpublished data)	
24	*Diamantina*	4.iv.63	CSIRO (unpublished data)	
29	*Diamantina*	5.iv.63	CSIRO (unpublished data)	
34	*Diamintana*	6.iv.63	CSIRO (unpublished data)	
40	*Diamantina*	20.iv.63	CSIRO (unpublished data)	
42	*Diamantina*	21.iv.63	CSIRO (unpublished data)	
44	*Diamantina*	22.iv.63	CSIRO (unpublished data)	
46	*Diamantina*	23.iv.63	CSIRO (unpublished data)	
48	*Diamantina*	24.iv.63	CSIRO (unpublished data)	
50	*Diamantina*	25.iv.63	CSIRO (unpublished data)	
52	*Diamantina*	26.iv.63	CSIRO (unpublished data)	
56	*Diamantina*	8.v.63	CSIRO (unpublished data)	⊙
58	*Diamantina*	9.v.63	CSIRO (unpublished data)	
60	*Diamantina*	10.v.63	CSIRO (unpublished data)	
62	*Diamantina*	11.v.63	CSIRO (unpublished data)	
64	*Diamantina*	12.v.63	CSIRO (unpublished data)	
66	*Diamantina*	13.v.63	CSIRO (unpublished data)	
68	*Diamantina*	14.v.63	CSIRO (unpublished data)	
70	*Diamantina*	15.v.63	CSIRO (unpublished data)	
76	*Diamantina*	27.v.63	CSIRO (unpublished data)	
78	*Diamantina*	28.v.63	CSIRO (unpublished data)	
80	*Diamantina*	29.v.63	CSIRO (unpublished data)	
82	*Diamantina*	30.v.63	CSIRO (unpublished data)	
86	*Diamantina*	1.vi.63	CSIRO (unpublished data)	
88	*Diamantina*	2.vi.63	CSIRO (unpublished data)	
90	*Diamantina*	11.vii.63	CSIRO (unpublished data)	▼
92	*Diamantina*	12.vii.63	CSIRO (unpublished data)	
94	*Diamantina*	13.vii.63	CSIRO (unpublished data)	
96	*Diamantina*	14.vii.63	CSIRO (unpublished data)	
98	*Diamantina*	15.vii.63	CSIRO (unpublished data)	
100	*Diamantina*	16.vii.63	CSIRO (unpublished data)	
102	*Diamantina*	17.vii.62	CSIRO (unpublished data)	
104	*Diamantina*	18.vii.63	CSIRO (unpublished data)	
111	*Diamantina*	4.viii.63	CSIRO (unpublished data)	
113	*Diamantina*	5.viii.63	CSIRO (unpublished data)	
115	*Diamantina*	6.viii.63	CSIRO (unpublished data)	
117	*Diamantina*	7.viii.63	CSIRO (unpublished data)	
119	*Diamantina*	8.viii.63	CSIRO (unpublished data)	
121	*Diamantina*	9.viii.63	CSIRO (unpublished data)	

corresponding station numbers and show that the oxygen and inorganic phosphate of this deep maximum are maintained by the same mixing circuits. Exceptions to this are stations 13, 17, and 19 which have too low an oxygen content (Fig. 9) and stations 13, 17, and 31 (Fig. 10) which have too high phosphate values.

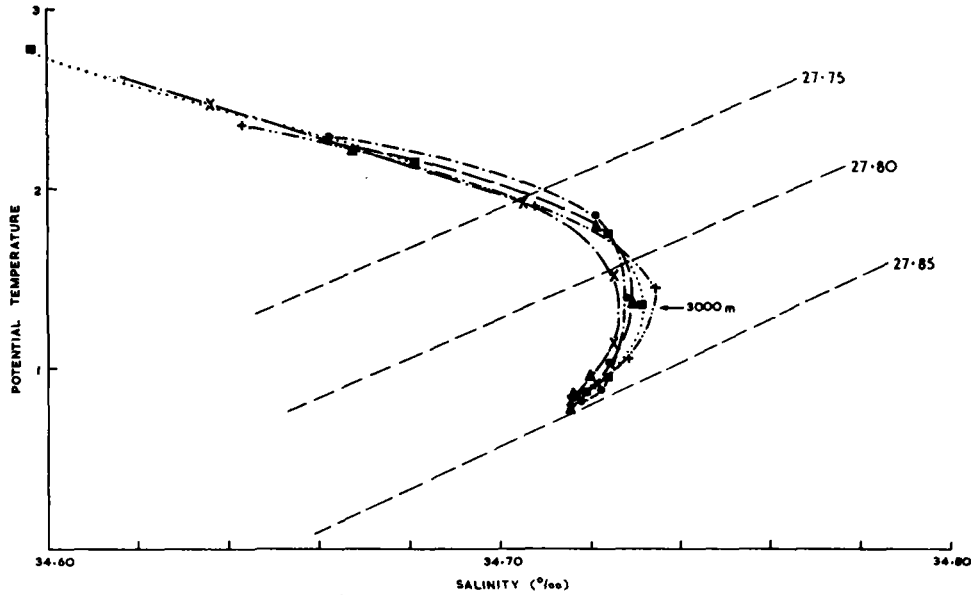


Fig. 2.—Salinity–potential temperature curves of deep water at CSIRO Reference Station (see Fig. 1). (– – –) Potential density. The mean position of the 3000 m depth is indicated. For symbols used see Table 3.

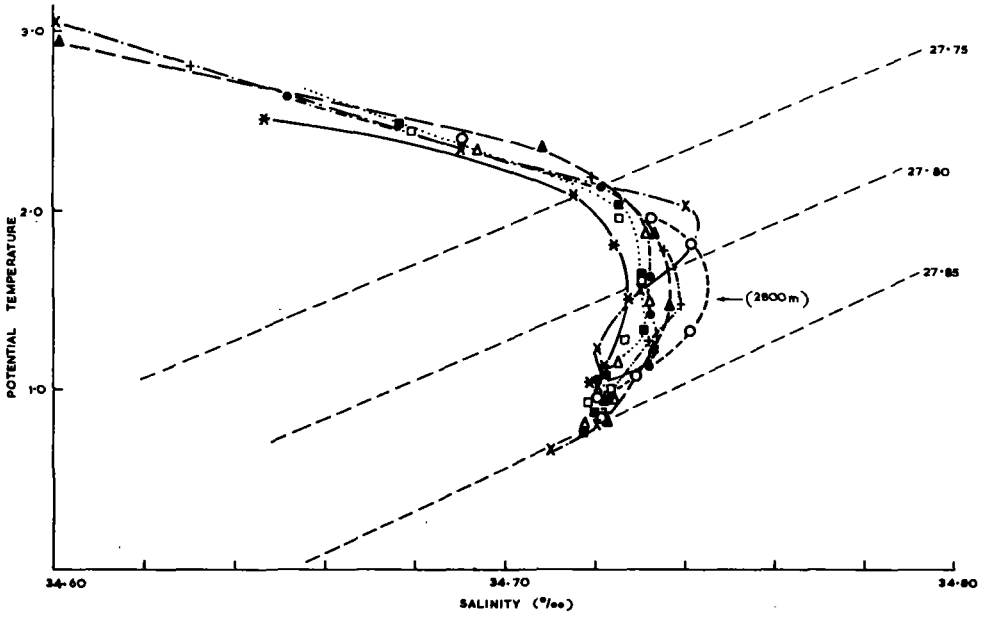


Fig. 3.—Salinity–potential temperature curves of deep water at SCOR-UNESCO Reference Station 1 (see Fig. 1) during 1959–62. (– – –) Potential density. The mean position of the 2800 m depth is given. For symbols used see Table 1.

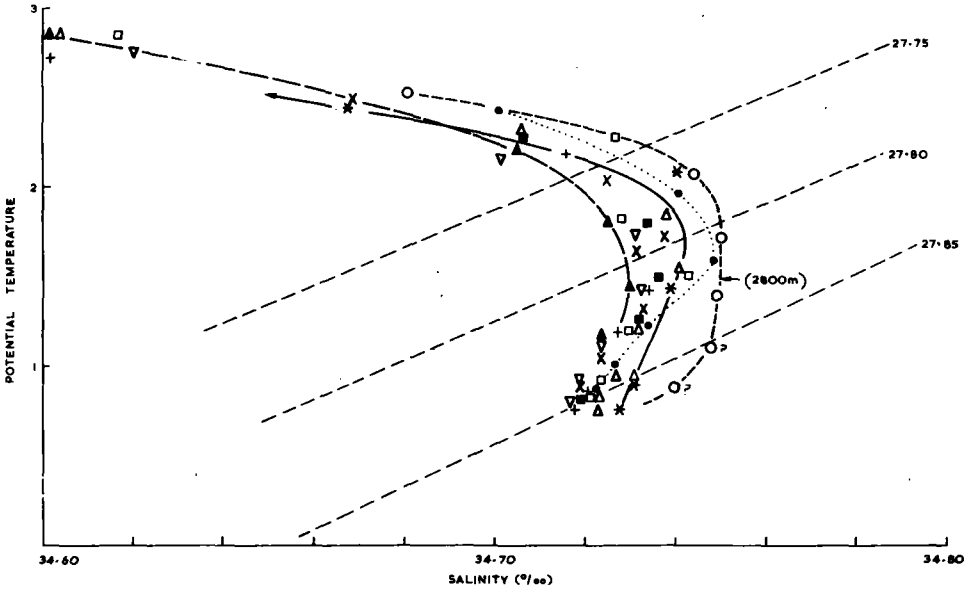


Fig. 4.—Salinity–potential temperature curves of deep water at SCOR-UNESCO Reference Station 1 (see Fig. 1) during 1962–63. (– – –) Potential density. The mean position of the 2800 m depth is shown. For symbols used see Table 1.

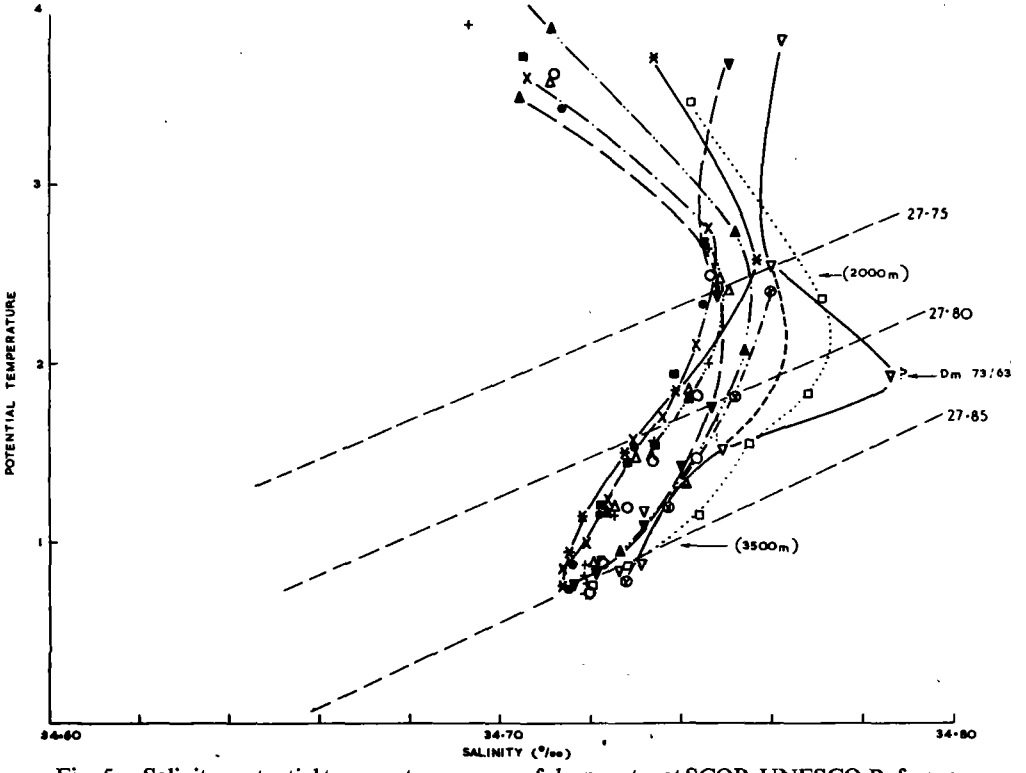


Fig. 5.—Salinity–potential temperature curves of deep water at SCOR-UNESCO Reference Station 2 (see Fig. 1) during 1962–63. (– – –) Potential density. Mean positions of the 2000 and 3500 m depths are indicated. For symbols used see Table 2.

V. Comparison of Deep Characteristics of Reference Stations and Mixing Envelopes of Section IV

The observed oxygen–potential temperature combinations of the deep salinity maximum of SCOR-UNESCO reference stations 1 and 2 lay within the mixing envelope of the Indian Ocean (Fig. 11). There were only a few anomalies in the inorganic

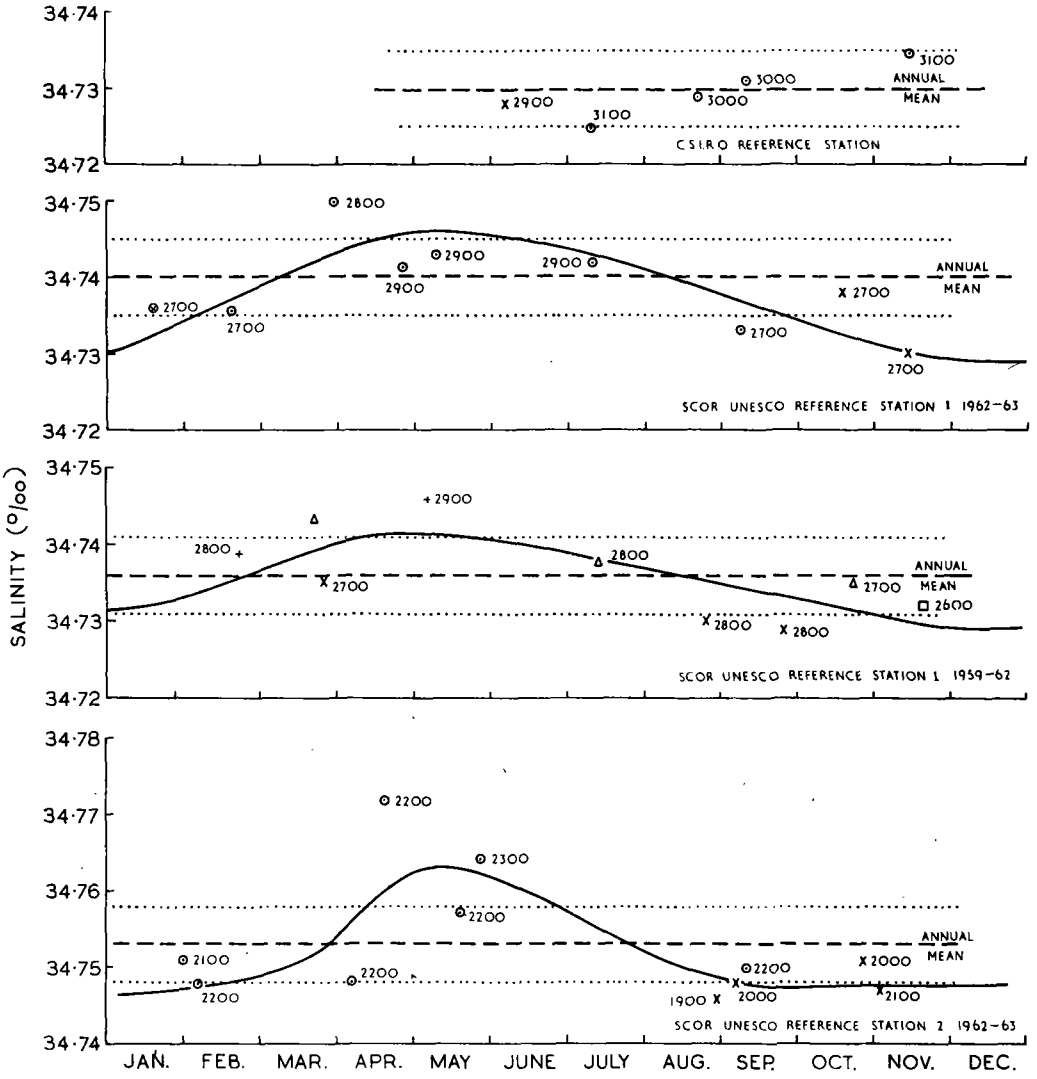


Fig. 6.—The monthly variation in salinity of the deep salinity maximum at the CSIRO and SCOR-UNESCO reference stations 1 and 2. □ 1959; △ 1960; + 1961; × 1962; ⊙ 1963. The depth (m) of the maximum is shown. The annual mean (– – –) and its precision limits (· · · ·) with a curve of the mean annual cycle (———) have been drawn.

phosphate–potential temperature combinations (Fig. 12) but the salinity–potential temperature combinations (Fig. 13) showed sufficient anomalies to warrant investigation. Very probably these anomalies were caused by salinities being lower than those

of the mixing envelope at a given potential temperature. They were mostly found at SCOR-UNESCO Reference Station 2.

Profiles of properties at a station representative of conditions near this reference station are shown in Figure 7. When transferred to the mixing envelopes of Figures 11, 12, and 13, these profiles show that vertical mixing with shallower layers would reduce the salinity (and to a lesser extent the phosphates) without appreciable effect on the oxygen–potential temperature relation. The salinity–potential temperature

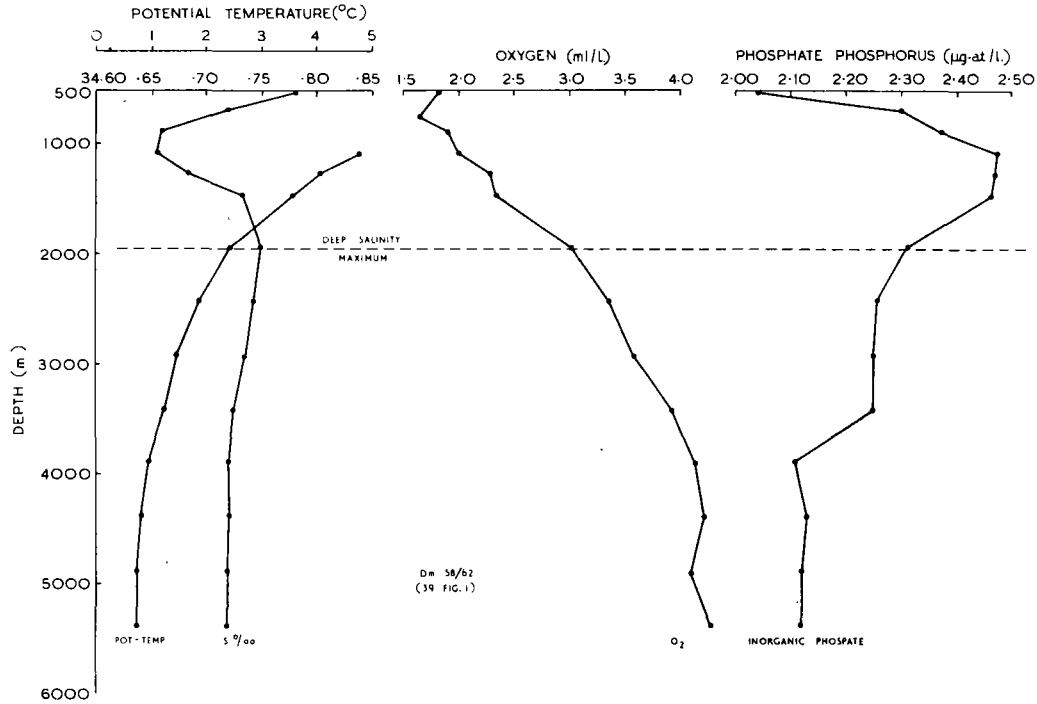


Fig. 7.—Profiles of salinity, potential temperature, oxygen, and inorganic phosphates (500 m–bottom), at Station Dm 58/62 (Fig. 1; 39) of the south-east Indian Ocean in July 1962.

relations lying outside the mixing envelope of the north Indian deep water (Fig. 11) can be explained, therefore, by a secondary mixing of north Indian deep water with the waters above. This mixing would be facilitated in this region by the relatively shallow depth (Fig. 8; 1900–2000 m) of the deep salinity maximum.

The deep salinity maximum of Dm 73/63 had a salinity–potential temperature ratio outside of the mixing envelope (Fig. 13), although its oxygen and inorganic phosphate to potential temperature ratios (Figs. 11 and 12) were within the limits of the mixing envelopes. This was considered sufficient to reject the observed salinity value for Dm 73/63 and to use an interpolated value from a smooth curve through remaining values (Fig. 5).

For the most part, however, the changes in properties at these reference stations and stations between, along the 110° E. section (Section VI), are consistent with variations in the intensity of horizontal advection of waters of the deep salinity maximum of the adjoining Indian Ocean. Moreover, the consistent decrease in oxygen and increase

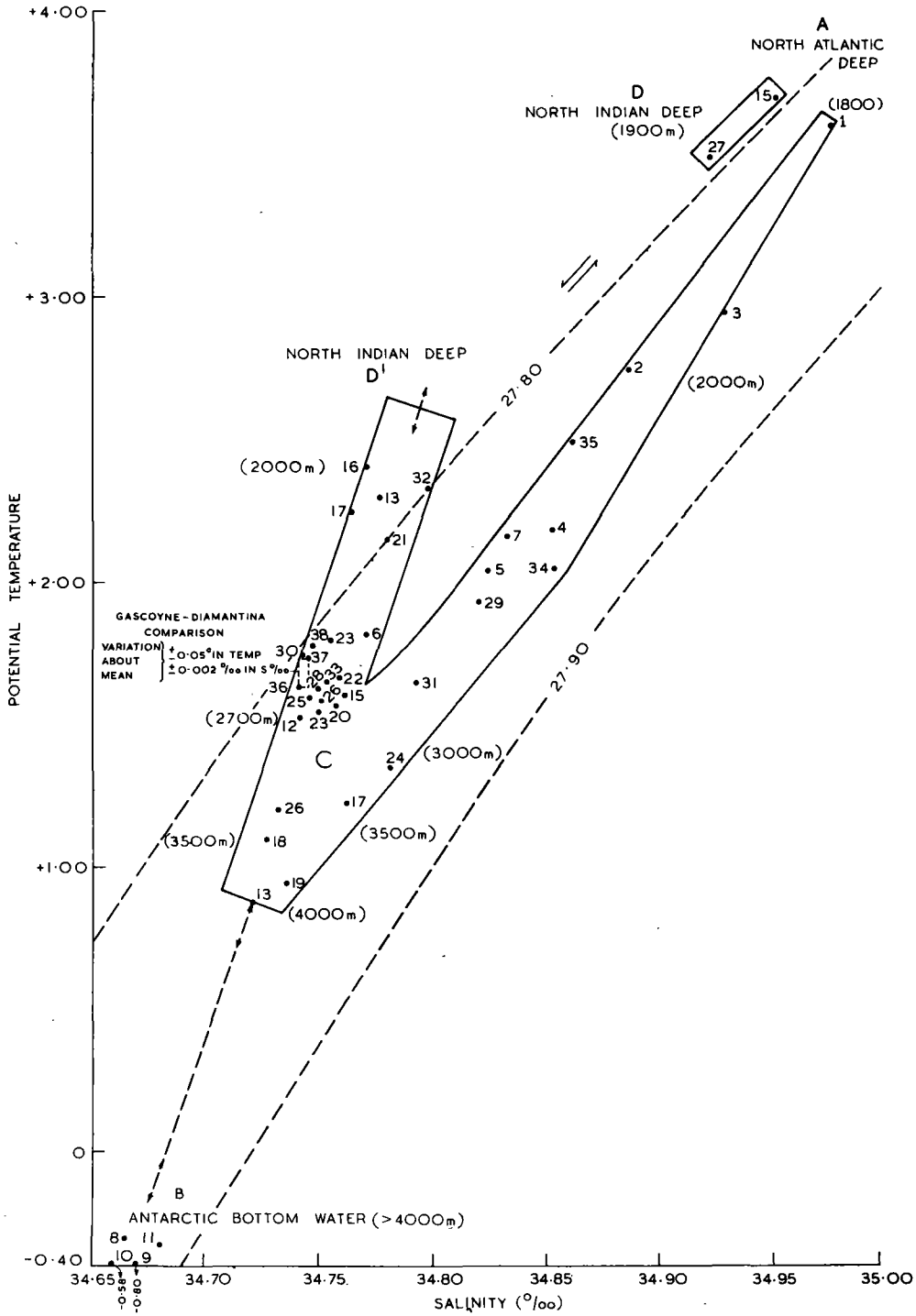


Fig. 8.—Salinity–potential temperature relations of the deep salinity maximum of the Indian Ocean and parts of the south-east Atlantic and south-west Pacific oceans. Letters refer to water masses (see Section IV) and numbers indicate stations (Fig. 1). Bracketed numbers indicate depth (m), and broken lines potential density (σ_t). The boxed values are from stations 36 and 37 (Table 4) occupied by H.M.A.S. *Gascoyne* and *Diamantina* at nearly the same position and time. These show the differences in salinity.

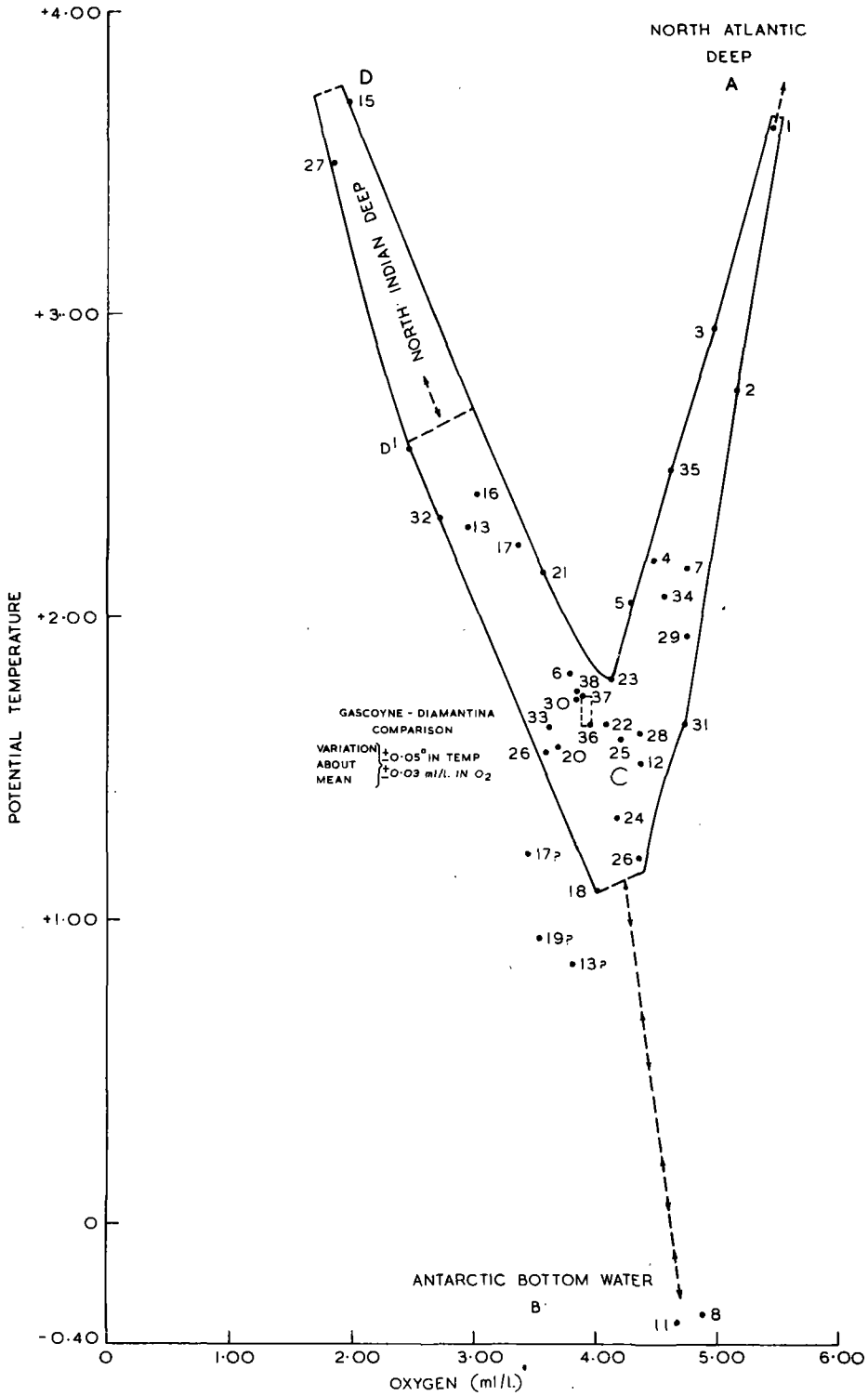


Fig. 9.—Oxygen–potential temperature relations of the deep salinity maximum of the corresponding stations of Figure 8. Boxed values from stations 36 and 37 (Fig. 1) show differences in oxygen values of H.M.A.S. *Gascoyne* and *Diamantina*.

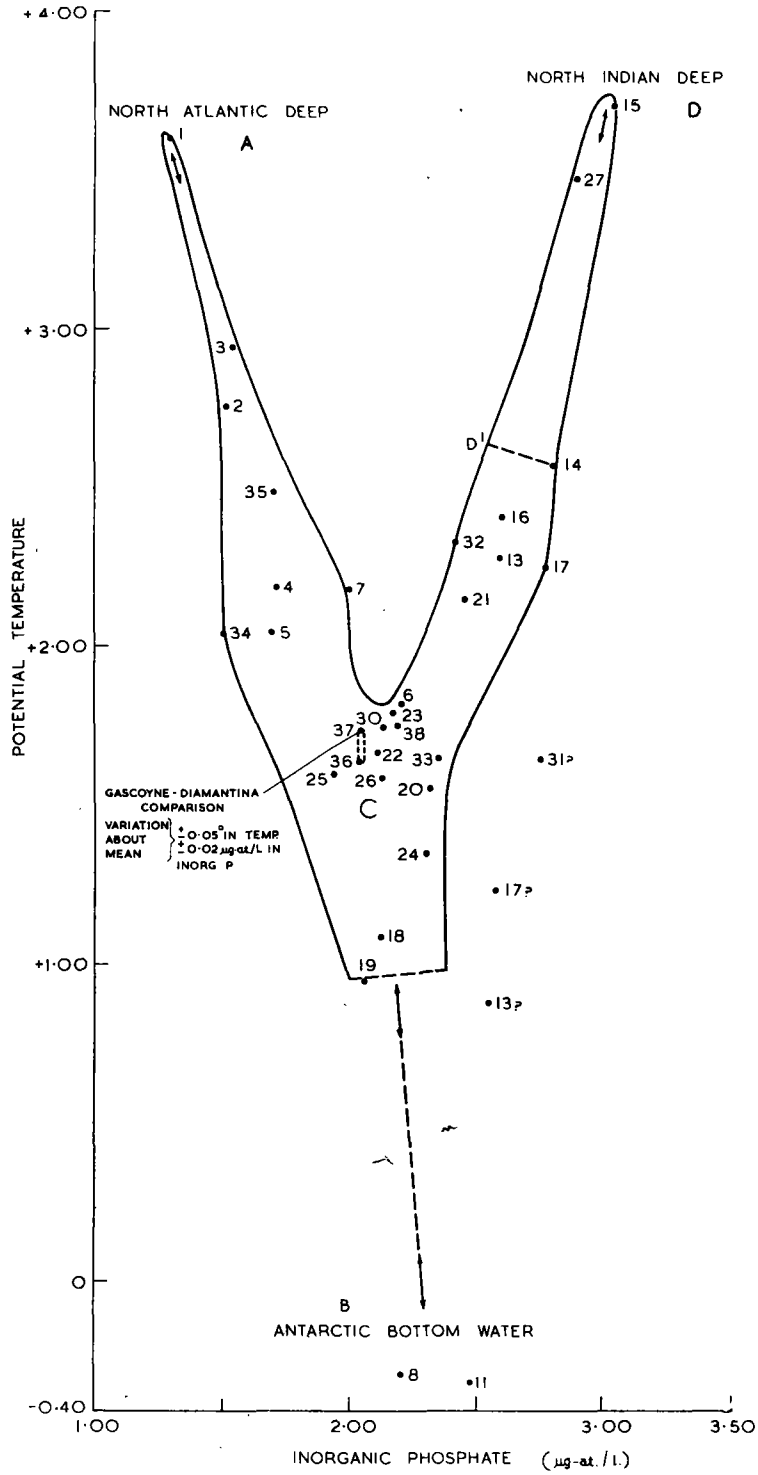


Fig. 10.—Inorganic phosphate–potential temperature relations of the deep salinity maximum of corresponding stations of Figures 8 and 9. Boxed values from stations 36 and 37 (Fig. 1) show differences in phosphate values of H.M.A.S. *Gascoyne* and *Diamantina*.

in inorganic phosphate accompanying increases in salinity (Figs. 11 and 12), show that such advection is principally of waters from the north Indian part of the deep salinity maximum. The monthly changes in salinity (Fig. 6) show that this advection was at a maximum in March–July.

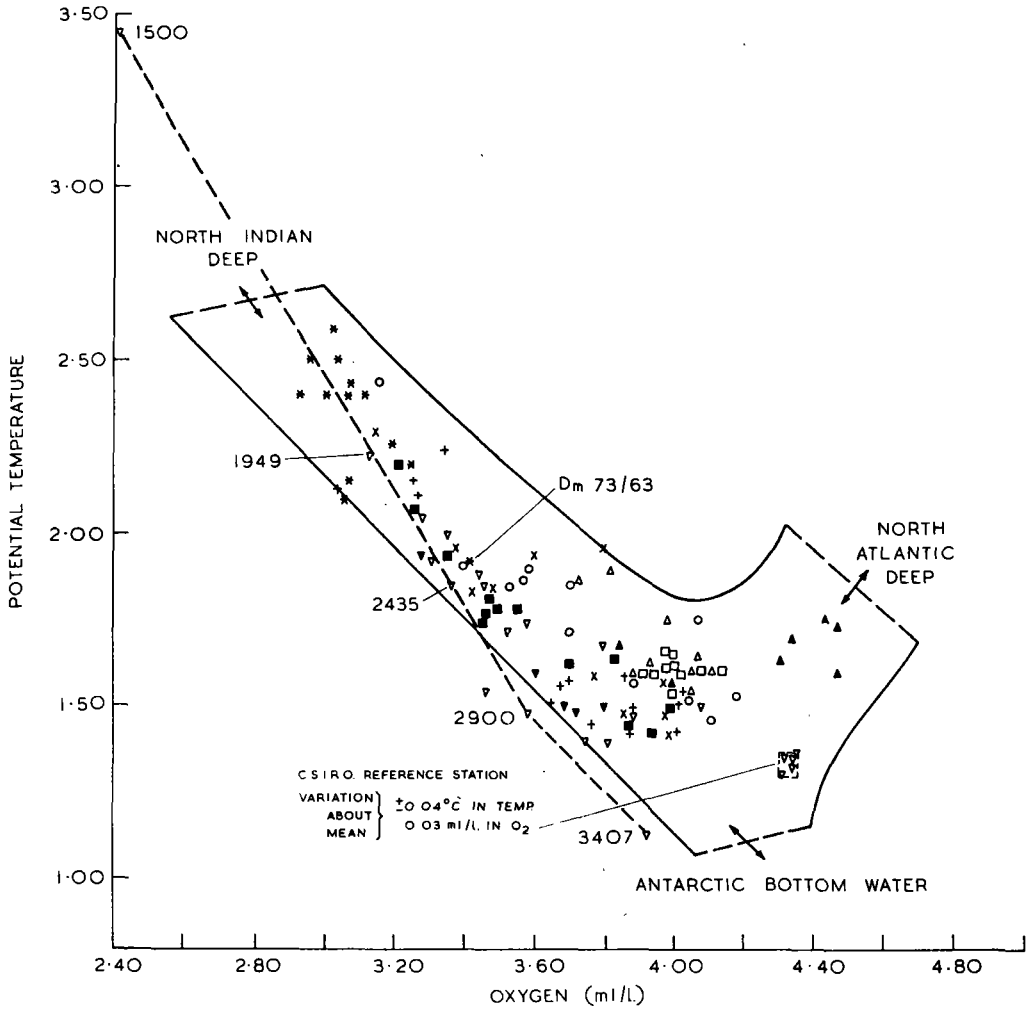


Fig. 11.—Oxygen–potential temperature relations of the deep salinity maximum of the CSIRO Reference Station, of the SCOR-UNESCO reference stations 1 and 2 and stations along the 110°E. meridian during 1962–63 (Fig. 1). The envelope has been drawn to correspond to that of Fig. 9. △ Reference Station 1, 1959–62; □ Reference Station 1, 1962–63; *Reference Station 2, 1962–63; ▽ Pacific Reference Station 1962–63. For other symbols see Table 5. Broken line shows the change of the oxygen–potential temperature relation with depth at station 39 (Fig. 1). The boxed values show the variation in oxygen values at the CSIRO Reference Station.

VI. Seasonal Changes in Salinity along the 110°E. Meridian

Salinities and potential temperatures of the deep salinity maximum for stations along this meridian (Table 5) were read from smoothed salinity–potential temperature curves and the oxygen and inorganic phosphate of this maximum were interpolated

from the tabulated data (Table 5). The salinity–potential temperature, oxygen–potential temperature, and the inorganic phosphate–potential temperature ratios of these maxima were compared with those of the reference stations and of the deep salinity maximum of the Indian Ocean (Figs. 11, 12, and 13). Below a potential

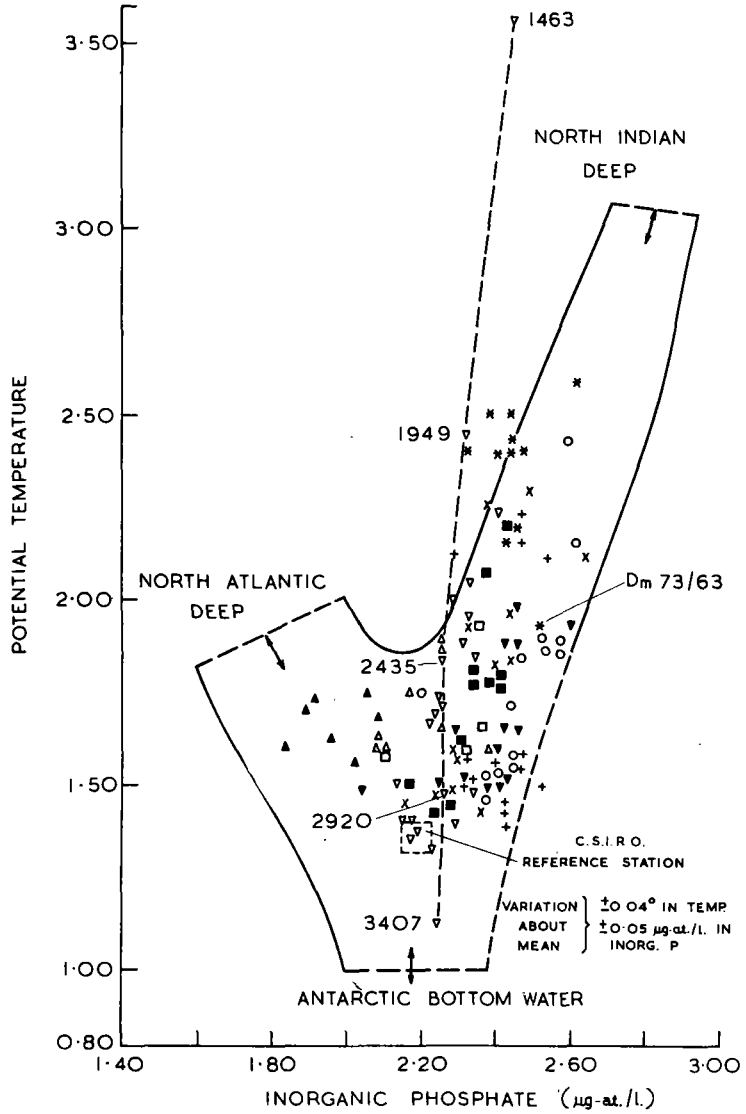


Fig. 12.—Inorganic phosphate–potential temperature relations of the deep salinity maximum of stations of Figure 11. The envelope has been drawn to correspond to that of Figure 10. Broken line shows the change in the above relation with depth at station 39 (Fig. 1). The boxed values show the variation in phosphates at the CSIRO Reference Station.

temperature of 1·80°C the width of the mixing envelope at constant potential temperature increased as north Atlantic deep water and Antarctic bottom water entered the mixing circuit.

It is quite difficult in this part of the mixing envelopes (Figs. 8, 9, and 10) to decide the water mass significance of any relation of salinity, oxygen, and inorganic phosphate to potential temperature. Above a potential temperature of 1·80°C, however, the mixing envelope is separated into the north Atlantic deep and north

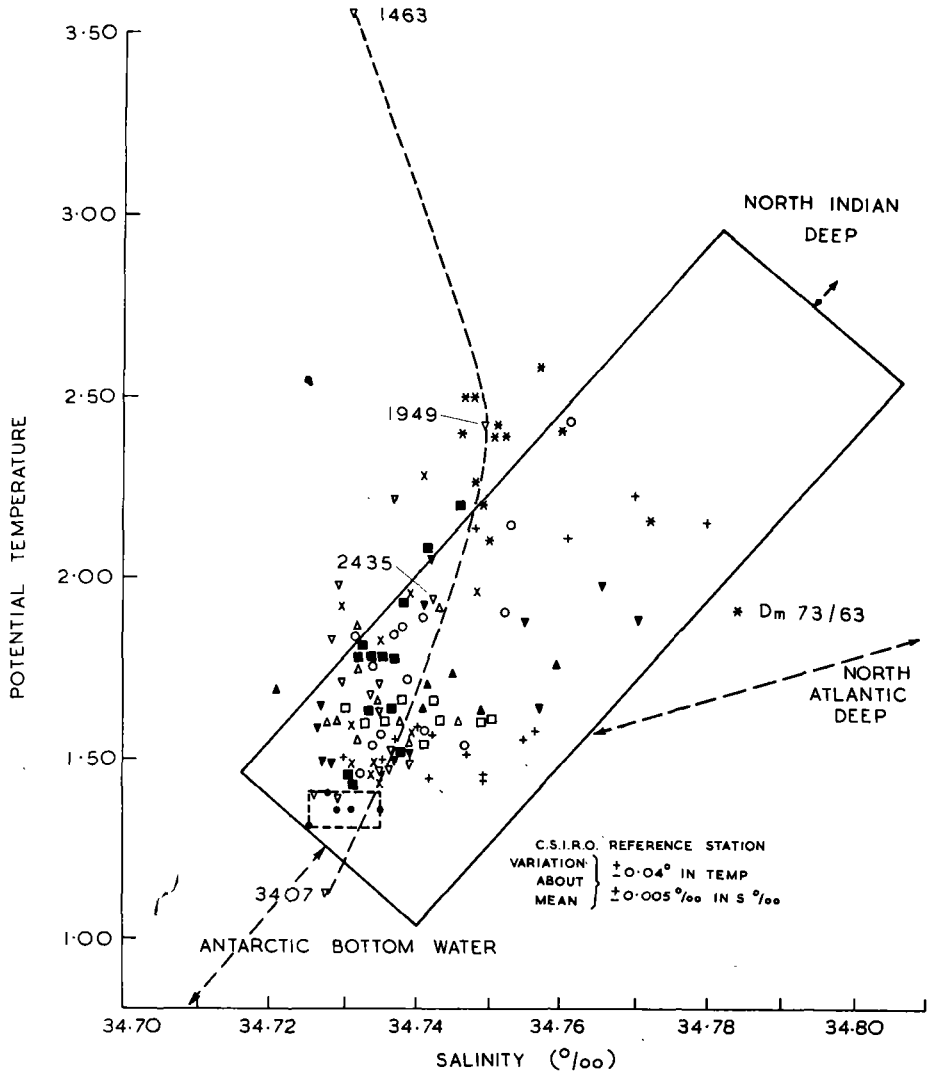


Fig. 13.—Salinity–potential temperature relations of the deep salinity maximum of stations of Figure 11. The envelope has been drawn to correspond to that of Figure 8. Broken line shows the change in the above relation with depth at station 39 (Fig. 1). The boxed values show the variation in salinity at the CSIRO Reference Station.

Indian deep circuits. The salinity–potential temperature relations of the deep salinity maximum along the 110° E. meridian (Fig. 14) belonged to the north Indian deep part of the mixing circuit. Salinities greater than 34·76‰, and in high probability greater than 34·740‰, indicate conclusively the advection of north Indian deep water across

the 110° E. meridian. This advection occurred during March–July 1963 north of 18° S. (Fig. 14) and in August 1962 around 26° S. North of 30° S. salinities were greater than 34·740‰ in March–April.

The oxygen content of the deep salinity maximum along the 110° E. meridian, northward of 30° S., was lower (less than 3·70 ml/l) in March–April than at other times, except for August 1962 when increased advection of north Indian deep water

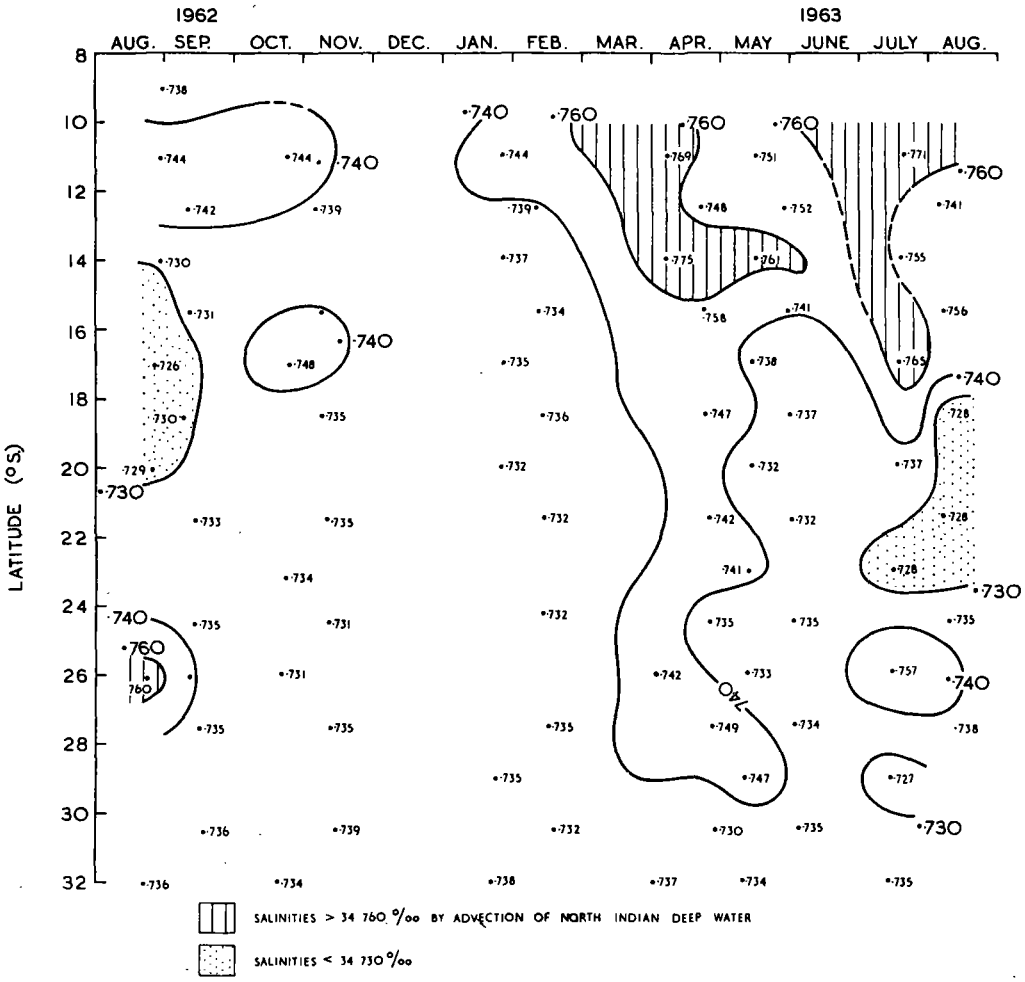


Fig. 14.—Salinity of the deep salinity maximum as a function of time and latitude along the 110°E. meridian (Fig. 1). 34·000 to be added to values to give true value. Vertical line shading, salinity greater than 34·760‰ by advection of north Indian deep water; stippled shading, salinity less than 34·730‰.

caused lowered oxygen values (3·58 ml/l) around 26° S. (Fig. 15). These seasonal changes in oxygen are of the appropriate sign to confirm that increases in salinity along this meridian are basically caused by advection of north Indian deep water. The advection of this north Indian Ocean water occurred at about the same period of the year as was previously found for SCOR-UNESCO reference stations 1 and 2 (Fig. 6).

VII. Long-term Precision of the Australian Deep Chemical Results

During the SCOR-UNESCO chemical intercalibration tests off Fremantle, in August 1962, the precision of the Australian methods of oxygen and inorganic phosphate analyses were tested by a series of replicate determinations of the same water. From these tests standard deviations of 0·05 μg-atom/l at a mean of 2·00

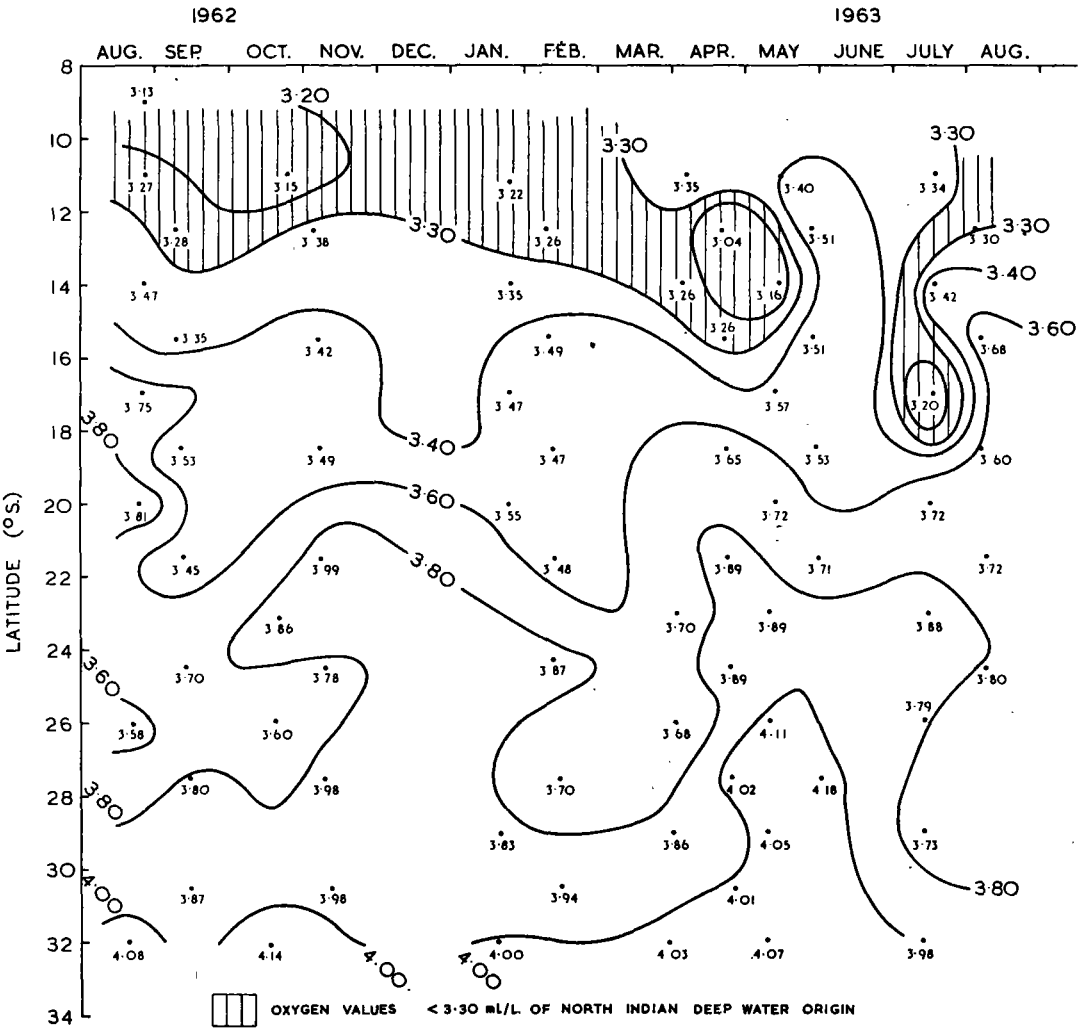


Fig. 15.—Oxygen (ml/l) of the deep salinity maximum as a function of time and latitude along the 110°E. meridian (Fig. 1). Vertical line shading, oxygen values less than 3·30 ml/l by advection of north Indian deep water.

μg-atom/l and of 0·02 ml/l at a mean of 4·00 ml/l were obtained for the phosphate and oxygen analyses, respectively (Rochford 1963). However, it was felt that these precisions might not be maintained on a series of cruises extending over several years, and involving different analysts and field conditions.

The changes in salinity of the deep salinity maximum during 1962–63 at the CSIRO Reference Station were less than the experimental error of the salinometer and show that the deep waters were little affected by mixing during this period. Figures 11 and 12 show the variation in oxygen and inorganic phosphate in relation to potential temperature of these waters during the same period. Deviations of $\pm 0{\cdot}03$ ml/l in oyxgen, $\pm 0{\cdot}05$ μg-atom/l in inorganic phosphate about the mean were found and these are similar to the precisions obtained on *R.S. Vityaz*. There does not appear, therefore, to be any long-term change in the precision of the Australian chemical data. In March 1961 a comparison was made of the deep chemical results of H.M.A.S. *Gascoyne* and *Diamantina* at two stations south of Australia in nearly the same position (Fig. 1; 36 and 37) and time (Table 4). The differences between the salinity, potential temperature, oxygen, and inorganic phosphate values obtained on the two ships (Figs. 8, 9, and 10) were less than the differences in values obtained by the one ship at the Pacific Reference Station. On this occasion at least there was no evidence of inter-ship discrepancies in the Australian chemical data.

VIII. Stability of Deep Waters of other SCOR-UNESCO Reference Stations

For a deep reference station to be used to compare analytical accuracies it must have deep water with chemical characteristics that are stable for several years and longer if possible. SCOR-UNESCO reference stations 1 and 2 have large seasonal changes in their deep chemical properties, principally caused by advection of north Indian deep water (Section V) and are not suitable for comparison of analytical accuracies. The probable boundaries of this north Indian deep water (Fig. 1) encompass SCOR-UNESCO reference stations 4, 5, 7, 8, 10, 11, and 13 which are deeper than 3000 m. The seasonal changes in deep properties at these stations will be too large to allow their use for comparison of analytical accuracies.

The central Indian deep water mass (*C*) varied little in salinity and other properties (Figs. 8–10) throughout its widespread distribution in the Indian and southwest Pacific oceans (Fig. 1). At the CSIRO Reference Station (Fig. 1) the properties of this deep water remained virtually unchanged during 1962–63 (Figs. 11–13). Reference stations within the boundaries of this water mass would be ideal for comparison of analytical accuracies, but to date no such reference stations have been established (Fig. 1). Between stations 35 and 31 (Fig. 1) the salinity of the north Atlantic deep water influx decreased rapidly by mixing (Fig. 8) indicating a region of strong advection. In such a region large periodic changes in deep properties would seem very probable. The recently established SCOR-UNESCO Reference Station 15 (Fig. 1) within the boundaries of this water mass will in all probability be unsuitable for checking analytical accuracies. It is likely, therefore, that none of the existing SCOR-UNESCO reference stations in the Indian Ocean will prove useful for comparison of analytical accuracies of the various IIOE ships, although their use for monitoring the rapid changes in deep circulation will be very important.

IX. Conclusions

The extent of annual change in the chemical properties of the deep salinity maximum at the SCOR-UNESCO reference stations 1 and 2 makes the deep water of those stations unsuitable for intercalibration of chemical data.

This annual change is caused by an increase in the advection of north Indian Ocean deep water into the south-east Indian Ocean during March–July. The deep waters of a CSIRO reference station east of Sydney have not changed their properties beyond limits of experimental error of the chemical analyses, which were found on R. S. *Vityaz* in August 1962. This station is quite suitable for intercalibration of chemical data.

Many of the other SCOR-UNESCO reference stations in the Indian Ocean are located within the distributional limits of the north Indian Ocean deep water mass and are expected to be unsuitable for chemical intercalibration.

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RECONNAISSANCE OF THE SOMALI CURRENT DURING THE SOUTHWEST MONSOON

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Communicated April 29, 1965

Previous observations off the coast of East Africa are inadequate in density or extent to identify the Somali Current as a true western boundary current, or to establish its width, velocity, dynamic topography, etc. In August and September 1964, the research vessel *Argo* was engaged with *Discovery* on a joint Anglo-United States expedition to the Somali Current; our purpose is to present here a brief notice of some of the *Argo* observations. Detailed discussions and complete results, including presentation of the oceanographic station data and the results of direct measurements of currents by various meters will be reported elsewhere.

Our work in the Somali Current was of an exploratory nature. We were uncertain as to whether we would be able to trace the axis of the current at all by the topography of the temperature field: indeed, similar work in the Guiana Current had proved disappointing in the past. Some results of *Atlantis II* in 1963 suggested that the Somali Current might be broad and diffuse and difficult to pinpoint. We found, on the contrary, that it is a clearly marked, definite, intense, narrow stream, easily measurable and identifiable.

The Somali Current as we found it appears to be of theoretical interest because, although like the Gulf Stream and Kuroshio it flows toward the north as an intense boundary current along the western coast of a great ocean basin, it differs from them in fundamental ways: (1) it is present during only part of the year, since the driving wind stresses reverse with the monsoons (a period rather short theoretically for baroclinic equilibrium), (2) it flows across the equator (where geostrophy breaks

down), (3) the current separates from the coast line in a region where the coast is very straight and steep, and where the bottom topography is smooth (whereas the Gulf Stream and Kuroshio leave the coast at prominent capes[1]), and (4) there is a conspicuous isolated cold upwelling region just north of the point of separation.

Figure 1 shows the location of *Argo* hydrographic stations and bathythermograph

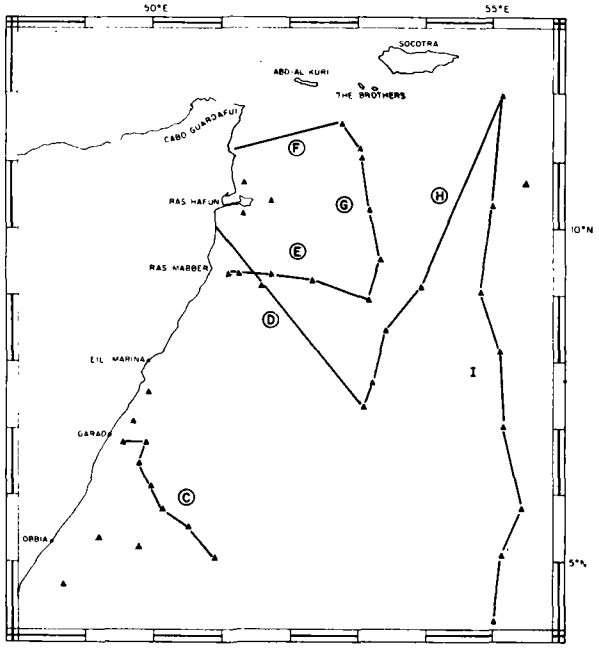


FIG. 1.—Location of bathythermograph sections *C* through *I*, north of 5°N. Location of sections *A* and *B* shown on Fig. 4.

sections north of 5°N, and Figure 2 shows these bathythermograph sections *C*, *D*, *E* *G*, *H*, and *I*. In each case the section is drawn so that the southernmost end is toward the right, temperature is in degrees Centigrade, and depth is in meters. Thus, in section *C* the isothermal surfaces slope sharply downward from the coast toward the open-ocean values at the right-hand side. At a section further north (section *D*) the slope of the isotherms is greater due to the latitudinal increase of Coriolis force (assuming constant transport in the current). Sections *H* and *I* are normal to the axis of the current after it turns to flow eastward, but also show two other currents to the north which seem to be part of a large clockwise-flowing eddy. This interpretation is shown in Figure 3 by the depth of the 20° isotherm. The interpretation is as follows: the Somali Current flows strongly close to the coast at Garad as can be seen by following the 100-meter contour. Farther north, by Eil Marina, this contour turns eastward and never goes farther north than 8°30'N. This appears to be the main axis of the Somali Current. The clockwise half-loop farther north appears to be a different water mass. The southeastern portion of the chart shows the smooth thermal topography characteristic of the interior regions of the Indian Ocean. Dr. A. Laughton's charts of bottom topography (not here reproduced) show a steep smooth continental slope all the way up to 11°N. so there is

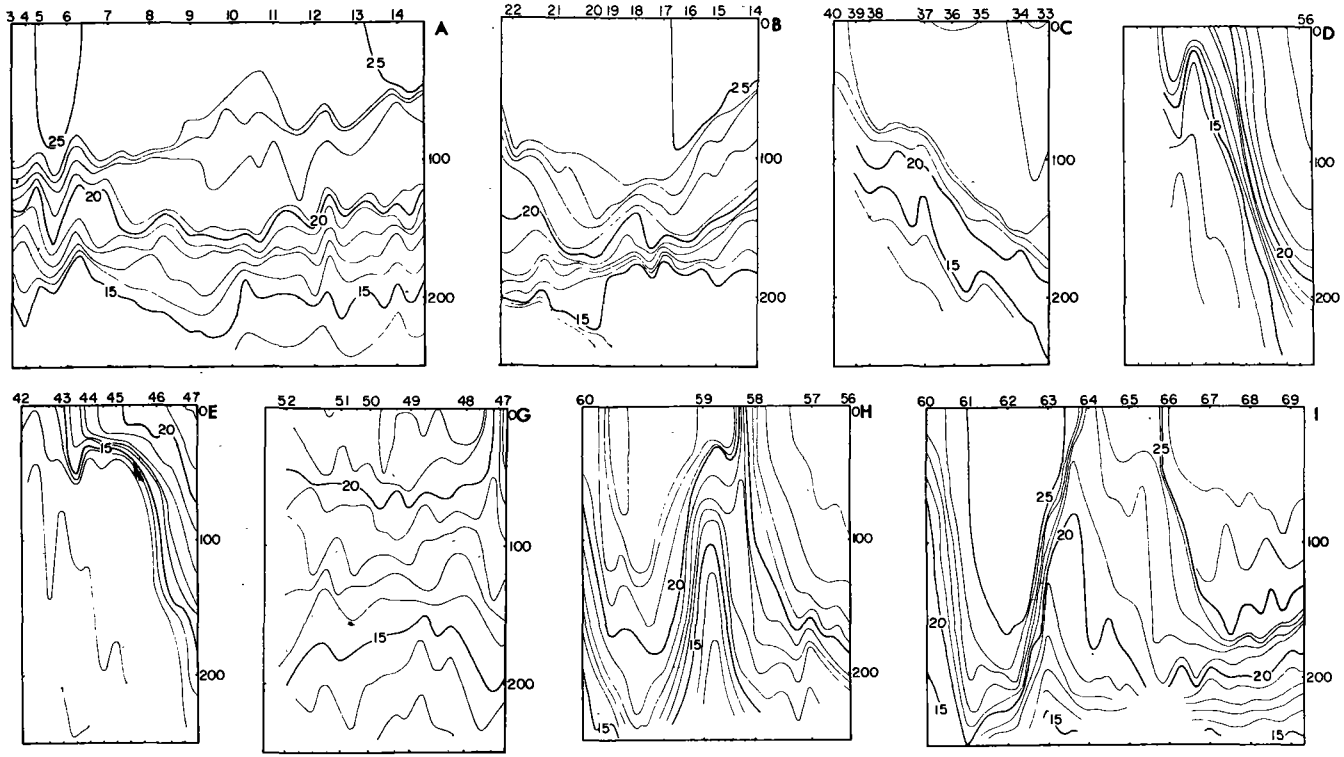


FIG. 2.—The bathythermograph sections of *Argo*. Location of *A* is section at 2°S on Fig. 4; location of *B* from 4°S, 49°E to Mogadiscio. Location of sections *C* through *I* on Fig. 1. Temperature in degrees Centigrade. Depth in meters. Each section is drawn with coast on the left, open ocean on the right; thus in general the Somali Current flows into the plane of the figure.

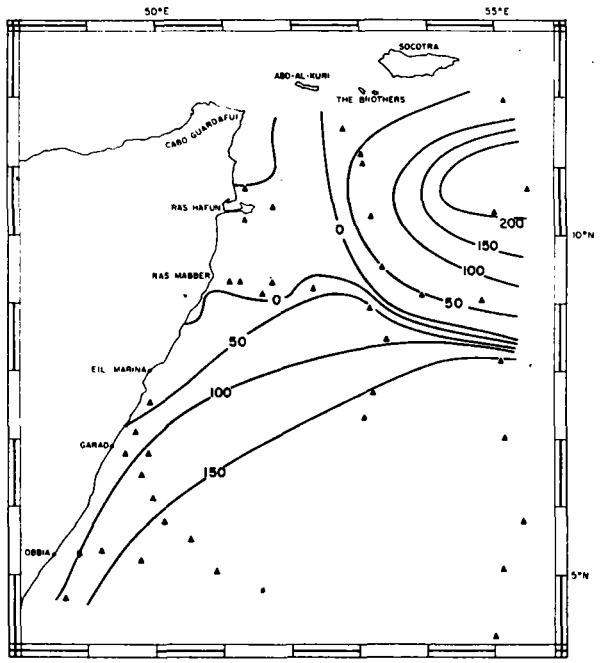


FIG. 3.—Depth of the 20°C isotherm in meters.

no obvious local bathymetrical feature which causes the observed separation near Garad.

We were able to obtain estimates of the surface velocity of the current farther upstream in the vicinity of the equator using towed electrodes as shown in Figure 4—which includes some data from *Discovery* as well. The two bathythermograph sections (Fig. 2, sections *A* and *B*) taken along the lines in Figure 4 show very weak topography, in contrast to sections further north.

At certain places there are good radar targets on the coast itself, and the current runs so close to the coast that it can also be determined from drift of the vessel hove to. Maximum speeds, as measured by GEK or surface drift, were observed to increase in a roughly linear fashion with latitude, from 178 cm/sec at 2°S to about 350 cm/sec at 8°N.

It has long been known to seafarers that during the south-west monsoon there is a region of low surface temperature near Ras Hafun, and Mrs. Mary Swallow of the British National Institute of Oceanography and Captain Britten of the Royal Naval Air Weather Service produced for us historical charts of the area which they plan to publish separately. The location of this region is shown in Figure 3 by the absence of any 20° isotherm off Ras Hafun and Ras Mabber. It is more clearly illustrated by the chart of surface temperature (Fig. 5) where the notably cold (as low as 13.3° C) small region off Ras Mabber is revealed. The bathythermographic section *E* also cuts into this region. We were delighted to find such a highly developed cold region, marked as well by surface fog, dead fish, and undersaturated oxygen. From differences between the observations of *Argo* and *Discovery*[2] it appears that there is considerable variability in detail in this cold area, especially near Ras Mabber

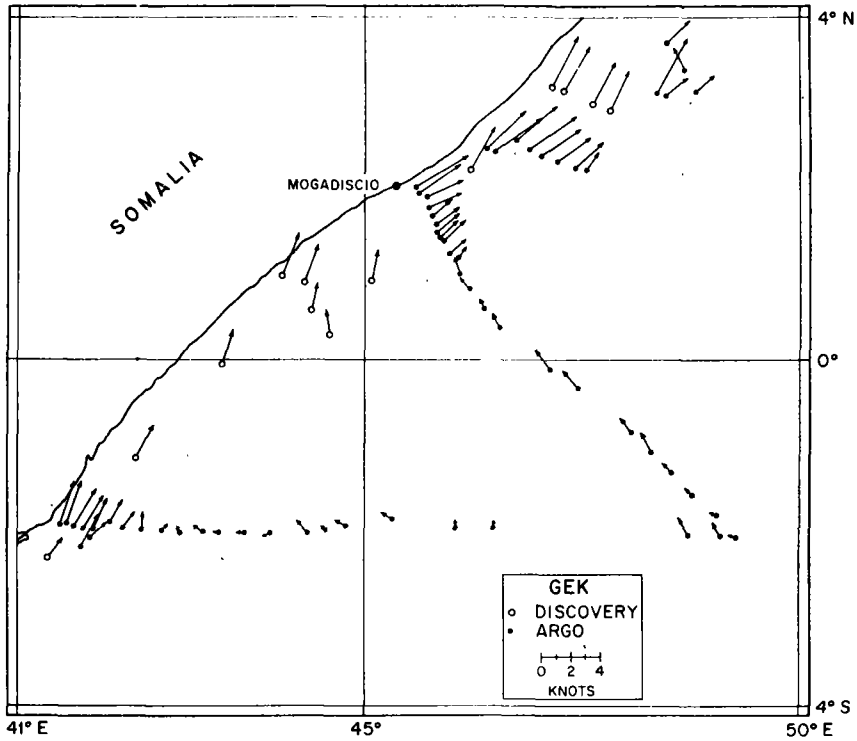


FIG. 4.—Currents determined by towed electrodes near the equator showing current crossing the equator. Bathythermograph section *A* is located along 2°S with eastern end on right. Section *B* is the diagonal line from Mogadiscio down to 2°S, this latter end being on right.

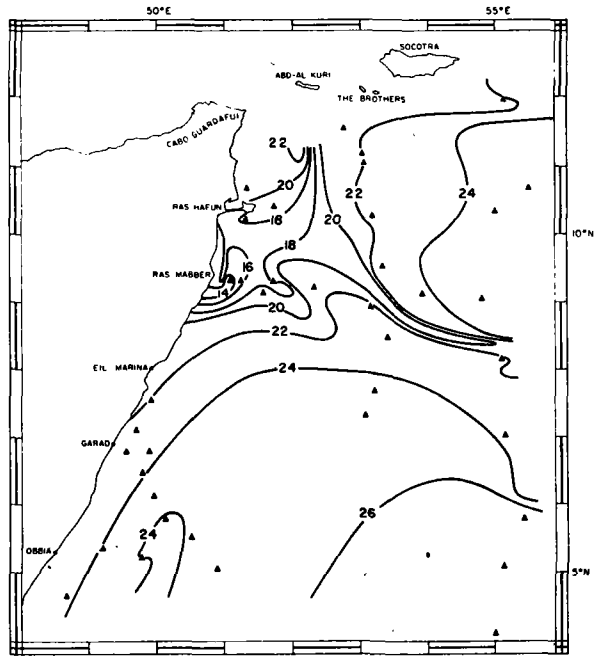


FIG. 5.—Surface temperature in degrees Centigrade.

and in the long thin tongue of cold water extending far to the east, but we do not have enough observational material to discuss this variability.

The only other place in the world ocean where such low surface temperatures are found at such low latitudes is the Peruvian coast, and even there it is uncommon to find surface temperatures lower than 15°C within 10° of the equator. Such cold regions are often attributed to transport of surface waters away from the coast due to local winds. The southwest monsoon is in proper direction to act in such a manner along this part of the Somali coast, but it seems to us that the intensity and location of the cold region is also to a large extent determined by the steep topography associated with the western boundary current itself—and this, of course, is a result of wind distribution over the entire ocean, not merely locally. The relative importance of the two influences is not clear.

The authors are grateful to Drs. R. Currie, J. Swallow, and J. C. Crease aboard the *Discovery* for their collaboration on this survey, to Mrs. Mary Swallow for her constant interest, to the National Science Foundation and the Office of Naval Research for financial support, and to the officers, crew, and scientific parties of both vessels.

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Part IV

Marine geology and geophysics

Geophysical studies in the Indian Ocean

Reprinted from *Endeavour*, vol. 23, 1964, p. 43-47

B. D. Loncarevic

The Indian Ocean is important to the densely populated countries that surround it, but it has been very little investigated. An International Indian Ocean Expedition is now in progress, and this article is intended to provide a background to the accounts of that expedition. It describes the results of the expedition of H.M.S. *Owen* to the Indian Ocean in 1961, a preliminary to the main British expedition, and discusses them, particularly in the light of the drifting-continent theory.

The Indian Ocean is bordered by some of the most densely populated areas in the world and crossed by the oldest routes of oceanic commerce. Nevertheless, up to a few years ago it was the least known of the oceans of the world. Oceanography had bypassed it, and the question of the origin, characteristics, and effects of the monsoons, for example, were as much a puzzle as they had been to the ancient Arab mariners in their dhows. To solve some of these problems, an expedition has been organized, involving some 30–40 ships from ten nations, as an international contribution to the development of the countries bordering the Indian Ocean. This will study the large-scale interactions between wind and sea, the equatorial currents, the productivity of the ocean, and the structure and composition of the ocean bottom, and will provide data for many years of research and interpretation. This article describes recent work in the Indian Ocean, and is intended to give a background for the forthcoming reports of the International Indian Ocean Expedition.

In 1961, H.M.S. *Owen*, one of Her Majesty's surveying ships, was given the task of carrying out a reconnaissance survey of the area bounded by Africa on the west, Pakistan and India on the north and east, and the latitude of Mauritius on the south. The Department of Geodesy and Geophysics, Cambridge University, supplied scientific instruments and personnel and undertook the reduction and preliminary interpretation of the data. The purpose of the reconnaissance expedition was to outline the major features, and to delineate areas for future detailed studies by the British ships of the International Indian Ocean Expedition. The results of the survey have been published by the Hydrographic Department of the Admiralty [1] and form the basis of the following discussion. Figure 1 shows the ship's track.

Instrumentation

The most important instrument used was a precision echo-sounder, designed and built by A. S. Laughton at the National Institute of Oceanography. This instrument used an outboard transducer, and the time required for the echo to return from the ocean bottom was measured accurately with reference to the constant frequency of a tuning fork. Changes in depth of one to two metres could be detected even when the depth was more than five kilometres.

The second instrument in continuous use was a magnetometer developed by M. N. Hill at Cambridge University and built commercially in Edinburgh. This instrument measures the proton-precession frequency, which is a function of the local magnetic field, with an accuracy of one part in 100 000. The sensor, a bottle of water with a coil wound round it, was towed 130 metres behind the ship to minimize the distortion of the Earth's field by the presence of the ship. The associated electronic apparatus, chart recorder, and punched-tape output device were installed in the chart room.

The third instrument used routinely throughout the survey was an Askania-Graf sea gravimeter. This instrument is a very sensitive spring balance, highly damped in order to eliminate the effect of heaving of the ship, and mounted on a gyro-stabilized platform to compensate for roll and pitch of the ship. A gravimeter can measure with great precision the variations, due to the variations in the shape and structure of the ocean bottom, of the gravitational attraction. However, because of the residual effect of ship motions and inherent errors in navigation by star fixes alone, the overall accuracy of the gravity measurements was only of the order of one part in 100 000. Instruments for precise measurement of depth, of magnetic and gravitational fields, and of the sediment thickness

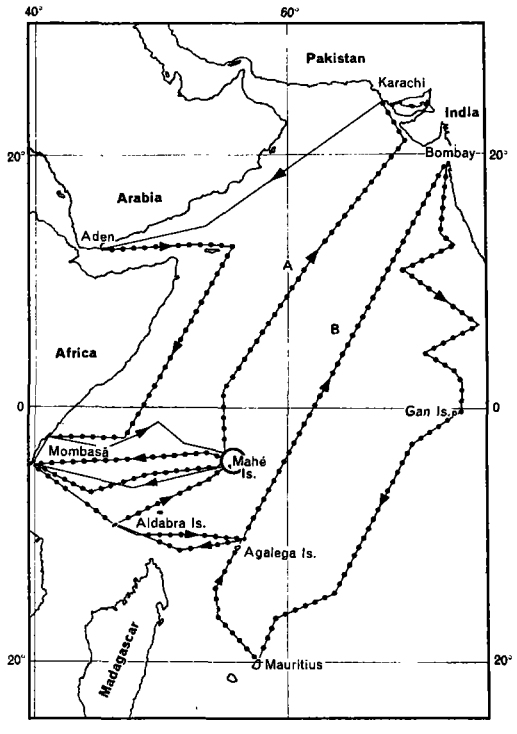


Figure 1 Tracks of H.M.S. *Owen* in the Indian Ocean during the 1961–62 surveying season. Dots show the places where observations were made.

B. D. Loncarevic, *M.A., Ph.D.*

Was born in 1930 in Belgrade, Yugoslavia. After graduation from the University of Toronto, he worked with an airborne geophysical unit on the development of an electromagnetic prospecting instrument. In 1958, he went to Cambridge on an Athlone Fellowship to work at the Department of Geodesy and Geophysics on the problem of gravity measurement at sea. During 1961–62 he was a member of the U.K. scientific team taking part in the International Indian Ocean Expedition. He is now a Senior Scientific Officer at the Bedford Institute of Oceanography, Dartmouth, Nova Scotia, where he is in charge of the marine geophysical programme.

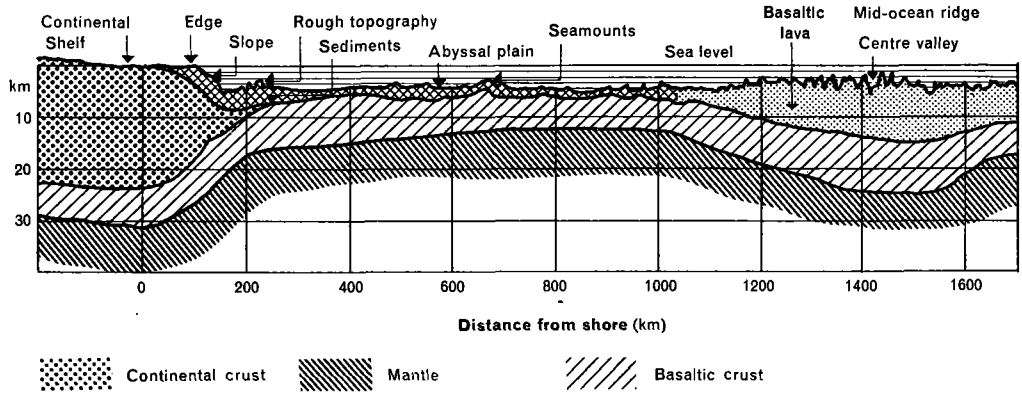


Figure 2 A diagrammatic cross-section through the continental and oceanic crust.

are indispensable tools in the study of the characteristic features of the ocean bottom.

It is only in the last ten or twenty years that the fascinating variety of the ocean-bottom features has been recognized. The crust, which is the outer layer of the solid Earth overlying the more dense and more uniform layer called the mantle, has a different structure and composition under the oceans from those under the continents. The continents are composed of granitic rocks of about 35 km thickness, though this increases to 60 km under some mountain ranges. The oceanic crust is made up of sediments underlain by basaltic rocks. The total thickness is about 10 km, with an increase under the oceanic mountains. Granitic rocks are normally completely absent, although there is one notable exception, the Seychelles Islands, which is discussed at length below. Figure 2 is a diagram of a typical cross-section of the crust, showing the difference between the continents and the oceans.

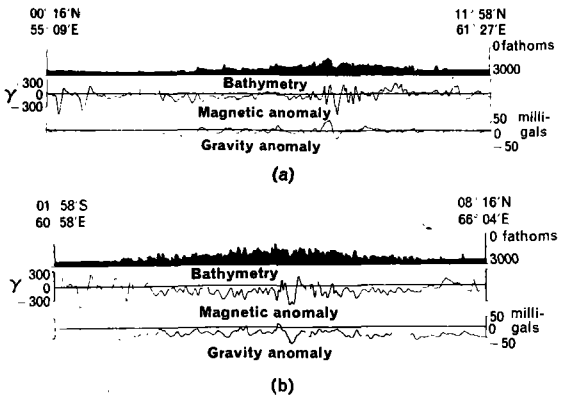
All the oceans are broadly similar. Beyond the edge of the continental shelf, the depth of the sea increases rapidly and some rough topography at the base of the continental slope leads to a plain. The surface of this abyssal plain, which slopes away from the continents with a gradient of less than one part in 1000, consists of slowly deposited sediments; it is not perfectly smooth, because of burrowing animals, ripple marks, and an occasional river channel or mid-ocean canyon. Abyssal hills, rising a couple of hundred metres, appear scattered on the plain; if they reach a height of over 1000 m they are called seamounts. As one moves away from the continents towards the middle of the ocean, the topography becomes rougher, until a mountain ridge is encountered with rugged peaks and deep valleys. This ridge follows the median line of the oceans round the world and represents the longest mountain chain on the Earth. Occasionally, the mountain peaks reach above the sea surface, giving rise to islands such as the Azores. Islands also occur away from the ridge, either isolated, as, for example, Madeira, or in chains. Of special interest are island arcs, which are curved chains of islands with a deep trench and a large negative gravity anomaly on the convex side of the arc.

Most of the major ocean-bottom physiographical features are present in the north-western Indian Ocean. There are two fully developed abyssal plains, and abyssal hills that merge with the mid-ocean ridge. The ridge is a branch of the world-wide system of mid-ocean ridges and may have a continental extension at its northern end. The area is studded with islands and coral atolls, and there are seamounts and submarine banks and even a deep-sea trench. The area is an attractive one for geophysical studies, and it is hoped that some major advances of knowledge will come from further investigations.

The Carlsberg Ridge

The major physiographic feature in the area is the Carlsberg Ridge, an impressive chain of mountains over 4000 km long. It emerges from a complicated and little known area of rough topography somewhere south of Mauritius and stretches to the entrance of the Gulf of Aden. It was first recognized on a crossing by the 'Dana' expedition in 1930 between latitudes 1° and 2°N, and on the basis of this single crossing Johannes Schmidt postulated the existence of a ridge and gave it the name 'Carlsberg' after the sponsor of the expedition. It was further investigated by the 'John Murray' expedition in 1934 [2] and has been crossed by many expeditions since then. These crossings have established the continuity of the ridge and some of its major characteristics. The abyssal plains in the north are well developed right up to the flanks of the ridge. Its width on the two crossings in the northern section is 750 km and 950 km and the peak is at 1850 m, thus rising 2350 m from the level of the abyssal plain. The sections of the ridge at A and B (figure 1) are illustrated with the profiles of bathymetric, magnetic, and gravitational anomalies in figure 3. The most striking feature of these profiles is the appearance of a deep valley near the crest of the ridge. At A the north wall is over 2200 m high, the south wall is about 1500 m high, and the valley is 20 km wide. At B, both sides of the valley are about 1500 m high and at 500 m elevation the valley is 12 km wide. On both crossings the depth to the floor of the valley is 4200 m and represents the greatest depth within the central part of the ridge. Although the valley seems to be a characteristic of the ridge, its continuity throughout the length of the ridge is questionable. Detailed investigations around 5°N and 62°E have shown that the valley is disrupted there by fractures and faults. It seems likely that the valley has been disrupted, blocked, and twisted in various places, but at the same time it remains a basic characteristic of the ridge system and deserves more detailed study.

The magnetic anomaly (figure 3) across the ridge shows a disturbed field with generally poor correlation between the magnetic and bathymetric profiles. The only place where there is a clear correlation between the two profiles is over the central valley itself. A distinct negative anomaly equivalent to



Figures 3a and 3b Profiles illustrating the topography of the Carlsberg Ridge and the associated magnetic and gravity fields. (1 gal=1 cm/sec²; 1 $\gamma = 10^{-5}$ oersted)

more than 1 per cent of the local magnetic field was measured when crossing the valley.

It is impossible to say from the magnetic profile what causes the anomaly. However, it is possible to calculate magnetic anomalies over assumed bodies of varying shape, size, and magnetic contrast, and to compare these calculated values with the observed one, thus obtaining some general idea about the possible source of the observed anomaly. These calculations have been made, taking into account the strength and inclination of the local magnetic field and the general direction of orientation of the ridge. It was found that a rectangular prismatic body of some 5–10 km cross-section, very long compared with its cross-section and only a few kilometres under the valley, would give an anomaly corresponding fairly closely in shape and magnitude with the observed one. Similar results have been obtained in the Atlantic ocean, around 45°N, and both there and in the Indian Ocean, they can be explained by assuming that there is a dyke intrusion underlying the valley floor. This would also conveniently explain the high heat-flows observed in the centre of the ridge. This provides further evidence that the chains of mountains on the ocean floor are a part of a world-wide system, and that the same mechanism was responsible for all of them.

There are no other anomalies on the ridge that compare with the anomalies over the valley. However, on the smooth abyssal plains bordering the ridge similar large magnetic anomalies were encountered, and these were completely unexpected. The type and shape of the magnetic anomalies under the abyssal plains on either side of the Carlsberg Ridge can be seen on the south (left) end of the profiles in figure 3; they were even more marked and persistent north of the ridge. There were no visible seamounts associated with magnetic anomalies on the flanks of the Carlsberg Ridge, and it is extremely unlikely that there were seamounts hidden under the sediments, as they would then have been detected on the gravimeter trace. The gravimeter trace on the abyssal plain remained very steady and indicated that under these plains were uniform layers. The origin of these magnetic anomalies is still a mystery, but it is possible to guess the depth of a body that could cause these anomalies by assuming that the depth is roughly equal to the 'half-width' of the anomaly. Using this rule, the approximate depth of the body causing the anomaly is 25 km. Thus, it seems that the cause of these anomalies is in the upper mantle, below the base of the crust.

Two hypotheses can be put forward to explain the abyssal plain anomalies, but it will be some time before they can be evaluated. The first one derived from the obvious similarity in shape and magnitude between the abyssal plain anomalies and those under the median valley. If convective motion is assumed in the hot, relatively plastic mantle, then a volcanic intrusion and its associated magnetic anomaly might be due to the material brought up by a convection current. This convection current would rise under the median valley and cause the magnetic anomaly over it. While coming up, this material would be hot and non-magnetic, but after it cooled down below its Curie point it would become magnetized and the magnetization would become 'frozen' into the intrusion. The nature and mechanism of the convection current motion is not well understood, but, according to one hypothesis, there is a period of rest after the current completes one cycle. During this period of quiescence, the intrusion might be cooling down and acquiring the frozen-in magnetic anomaly. During the next cycle of motion of the convection current, new material is brought up from the depths and material brought up in the previous cycle is pushed along the base of the crust. It eventually disappears under the continents and sinks to the depths, thus replacing the material rising under the ridge. The movement under the crust carries along the frozen-in anomalies. They appear as distinct anomalies because of the postulated pulsating nature of the convection currents. The movement envisaged would be intermittent and the distance travelled during the mobile phase would be represented by the distance between the anomalies.

The hypothesis in the above form has many points that could be criticized, but it does fit in with recent ideas of H. Hess and R. Dietz [3] about the spreading of the ocean floor. It also fits in with some ideas of J. Tuzo Wilson [4], who collected all the known age determinations from the oceanic islands and showed that the ages increase with distance from a ridge. This is presumably because the older islands have travelled further. Thus the postulated motion of the upper mantle could be the driving force for the crustal movements.

The second hypothesis explaining the magnetic anomalies under the abyssal plains is also based on the concept of convection currents, but does not involve the median valley anomaly. It is again assumed that the convection current is rising under the ridge, flowing under the crust away from the ridge, and sinking under the continents. The upper boundary of this flow might not be smooth, indeed it is more likely to be undulating, so that the depth of the isothermals is variable. This would imply a variable depth of materials, at temperatures below the Curie point, which could acquire a magnetization that would manifest itself as the observed magnetic anomaly. The density differences between material above and below Curie point would be too small to be detected with the present equipment for measuring gravity at sea. On the other hand, the undulations of the upper boundary of the convection current could account for some of the observed variations of the heat flow. Indeed, a dense profile of heat-flow stations might be a way of testing this hypothesis.

Seychelles Bank and Amirantes Trench

To the south and west of the Carlsberg Ridge lies the Seychelles Bank with about 100 islands, 24 of which are inhabited. While most of the outlying islands are low coral islands, the central part of the Mahé-Praslin group is granitic in structure and over 600 million years old (Precambrian) [5]. It is the only known mid-ocean island group composed of granite, and a special explanation is required for its origin and present location, as granitic rocks have always been considered as

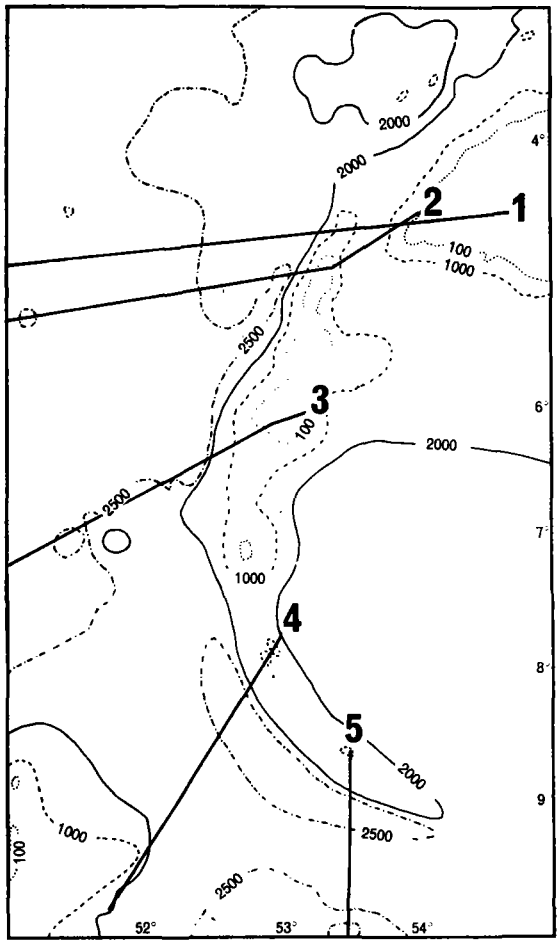


Figure 4 Bathymetric chart of the Amirantes Trench. Crossings 4 and 5 were made by the Soviet research ship *Vityaz*, the others by H.M.S. *Owen*.

typically continental. While there remain many objections to the theory of Continental drift, it is slowly gaining more support. In the case of the Seychelles it provides acceptable explanations of a number of phenomena, and these will be now discussed.

If there were general rearrangement of continents that opened up the Indian Ocean as we know it today, it is natural to suggest that the continental part of the Seychelles has dropped off and was left behind, but where did it belong originally? If the Carlsberg Ridge divides the Indian Ocean, the Seychelles could reasonably be classified as part of the original African continent. The other possible connection is via Madagascar, and even a cursory glance at the map of the Indian Ocean will show the remarkable straightness of its east coast, which points towards the Seychelles. A large linear fault has been mapped on this coast, and it was only natural that a northward drift along this fault has been postulated for the Seychelles, despite the paucity of evidence. The evidence is still not conclusive. But new facts have emerged that support the idea. Seychelles Bank is bounded on the west side by a low-lying ridge of coral islands called the Amirantes. Repeated crossings with a shipborne magnetometer have indicated that the ridge is underlain by highly magnetic rocks rising close to

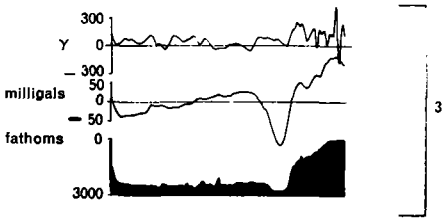


Figure 5 Magnetic, gravity, and bathymetric profiles on the third crossing (figure 4) of the Amirantes Trench.

the surface underneath the coral. This ridge is directly in line with the Madagascar fault. Five crossings of the western approaches to the ridge are shown in figure 4. The striking feature on these crossings is the trench recently noticed by A. S. Laughton and called by him the Amirantes Trench. The gravitational anomaly profile reproduced in figure 5 indicates a uniformly increasing gravitational anomaly on top of which is superimposed a local negative anomaly of $-0{\cdot}12$ cm/sec^2. The magnitude of this anomaly is comparable to that observed over other oceanic trenches, such as the Aleutian Islands Trench.

The deep-ocean trenches have been investigated in other areas, notably the Pacific, and a general conclusion is that they are of tectonic origin. Together with the east coast of the Madagascar Fault, the Amirantes Trench is the most important new evidence for tectonic activity in this area. If the strike-slip origin for this trench could be proved, the riddle of the Seychelles might be solved and their ancient connection with Africa reconstructed by moving them south to the east coast of Madagascar.

If the above were true, it would be natural to expect further evidence of cracking of the Indian Ocean floor to the north of Seychelles. This area has not been systematically investigated because, until now, nobody expected to find anything interesting or unusual there. Further north, where the Carlsberg Ridge approaches the Horn of Africa (Cape Guardafui), D. H. Matthews [6] and his colleagues have recently shown, by skilful synthesis of bathymetric and seismic evidence, that the ridge has been fractured and the western section moved perhaps as much as 300 km to the north. Between Matthews' fault and the Amirantes Trench, the evidence might be buried or confusing. Nevertheless, these two features indicate that there might be an enormous fault on the bottom of the ocean stretching from the southern tip of Madagascar up to the northern shore of the Gulf of Aden and beyond. If this crack could be confirmed, its existence would profoundly affect our thinking about the structure of ocean floors.

Future work

In order to investigate further many fascinating puzzles on the bottom of the Indian Ocean, the new tools and techniques of marine geophysics will have to be applied on a large scale. In particular, seismic surveys of the thickness of various crustal layers will have to be extended. Both American and Russian scientists have conducted some measurements, but there is certainly room for an extension of their work. Many more heat-flow measurements will be required, and they will have to be densely spaced along selected profiles. Palaeomagnetic measurements should be made on rock specimens from Seychelles and Madagascar. But, above all, systematic, detailed surveys and investigations of selected portions of the ocean floor must be carried out in spite of the difficulties, cost, and tedious nature of the work. The progress from wild idea to hypothesis and thence to theory can be based only on factual survey information.

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5. RATES OF SEDIMENT ACCUMULATION IN THE INDIAN OCEAN

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Abstract

Three sedimentary cores from the Indian Ocean, a calcareous ooze, a siliceous ooze and an essentially biogenous-component free clay, were assayed for their rates of accumulation by the ionium/thorium technique. The average rate (on a calcium carbonate and opal free basis) was about 1 mm/10^3 years, a value intermediate to those of the South Pacific (0.5 mm/10^3 years) and of the North Pacific and Atlantic Oceans ($>$ 1 mm/10^3 years). Disequilibrium in the upper 15 cm or so of these cores between ionium (Th^{230}) and its successor in the U^{238} series, Pb^{210}, suggests that the hypothesis of Koczy concerning the migration of radium from the sediments into the sea water is valid. A model for such radium transfer is presented.

Previous studies on the rates of accumulation of deep-sea sediments by the ionium/thorium method (GOLDBERG and KOIDE [1962]) have indicated that the observed values for a given oceanic area are related to the relative quantities of continental contributions to the deposits. For example, rather uniform depositional rates (0.3–0.6 mm/10^3 years) are found for the South Pacific deep-sea sediments while in the North Pacific the figures were in general at least several times higher. It should be noted that such rates are averages over the last few hundred thousand years. These observations are compatible with the introduction of large amounts of quartz, feldspars and clay minerals from adjacent land masses in the northern sites while nearly all of the non-biogenous solid phases in the South Pacific can be attributed to local marine volcanic activity (PETERSON and GOLDBERG [1962]).

A series of sediment samples collected in the Indian Ocean during the 1960–61 "Monsoon Expedition" of the Scripps Institution of Oceanography provided the opportunity to extend these studies. Although two groups of Russian workers have previously studied depositional rates by similar techniques (STARIK *et al.* [1958]; BARANOV and KUZMINA [1958]), their results are not strictly comparable to ours. First of all, the entire

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sediment sample was assayed for its thorium isotopes, whereas we analyzed only the leachates from hydrochloric acid treatment, presumably containing thorium isotopes derived from sea water, not from the land-derived detrital materials in addition. This leaching process usually removes about 70 per cent of the total thorium from the samples. Secondly, their computed rates have not been corrected for dilution both by the opaline and by calcareous biological phases in order that sedimentation rates for the non-biogenous components can be ascertained.

During this work our attention was also directed to the hypothesis of KOCZY [1958] that radium born through the radioactive decay of ionium (Th^{230}) in the deep-sea deposits does diffuse into the adjacent sea water. Inasmuch as several of his water profiles were from areas near our sampling sites, it was considered worthwhile to determine if disequilibrium could be found between ionium and its daughters in our sediments.

1. Methodology

All of the techniques employed have been previously described in work from this laboratory: thorium isotope analyses as applied to sedimentation rate determination (GOLDBERG and KOIDE, *op. cit.*); lead-210 analyses (RAMA, KOIDE and GOLDBERG [1961]); clay mineral analyses (GRIFFIN and GOLDBERG [1963]); a modification of opal determinations (GOLDBERG [1958]); and quartz analyses (REX and GOLDBERG [1958]).

2. Results

Three cores were chosen for analyses on the basis that they represented different sediment types: (1) a siliceous ooze, Monsoon 49G; (2) a calcareous ooze, Monsoon 57G; and (3) a sediment with only minor amounts of biogenous-components, Monsoon 68G. Detailed analyses are given in Appendix 1.

2.1. MONSOON 49G

This core, collected from a depth of 5214 meters at 14° 27′ S and 78° 03′ E, contained calcium carbonate in amounts under 3% as determined both by X-ray diffraction data and by chemical analyses. The opal concentrations measured at 0–3 cm and 65–69 cm were 58 and 56 per cent by weight respectively. The overall sedimentation rate of 2.75 mm/10^3 years (Fig. 1) reduces to a value of 1.1 mm/10^3 for the non-biogenous com-

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ponents. The exponential decay of the Io/Th ratio is seen to occur for at least four half-lives, indicating that the appearance of uranium supported ionium does not become significant until times of the order of 300 000 years. Bottom disturbances, resulting from burrowing organisms and/or bottom water currents, cause deviations of the near-surface Io/Th values from a linear curve as drawn in Fig. 1 (GOLDBERG and KOIDE, *op. cit.*) and evidently are effective to depths of only 6 cm. The core contains unusually high thorium concentrations — levels of 20 ppm on an opal free basis. The principal detrital minerals were quartz and feldspars at concentrations under 5% by weight for each mineral class. This

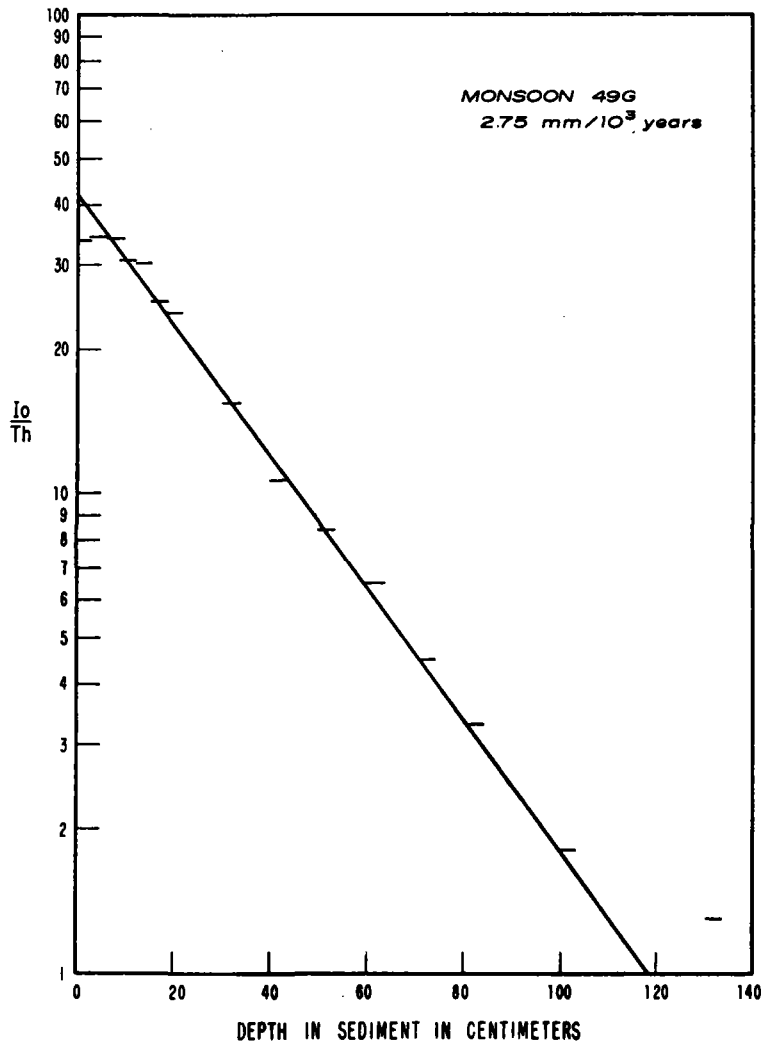


Fig. 1. The Io/Th ratio in units of disintegrations of ionium per disintegration of thorium for Monsoon 49G.

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core comes from an area where significant amounts of acidic volcanic debris are present in the deposits.

2.2. MONSOON 57G

This core was collected from a depth of 4110 meters at 26° 22′ S and 74° 08′ E. Opal was absent from the non-calcareous portions of the sediment whereas the calcium carbonate content ranged between 43.6% and 87.5% with an average value of 74%. The gross sedimentation rate of 3 mm/10^3 years (Fig. 2) yields a value of 0.8 mm/10^3 years on a calcium

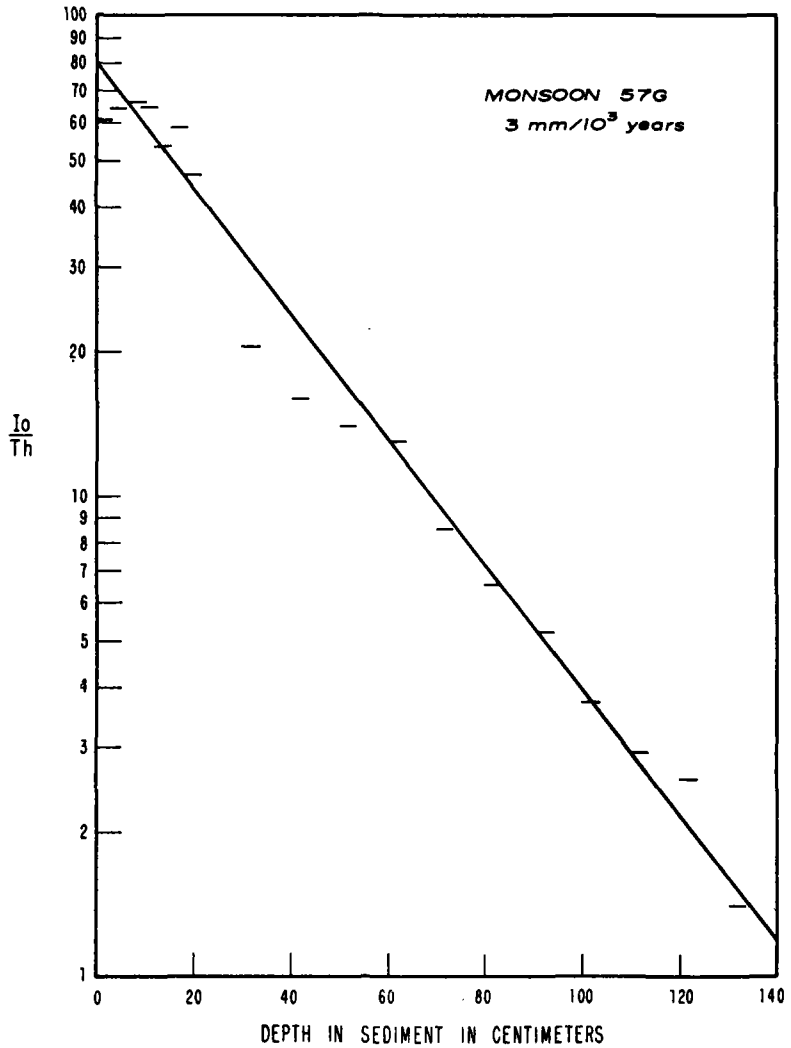


Fig. 2. The Io/Th ratio in units of disintegrations of ionium per disintegration of thorium for Monsoon 57G.

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carbonate free basis. Surface disturbances are evident to depths of 7 cm. Thorium concentrations on a calcium carbonate free basis range between 8.2 and 14.4 ppm with an average of 11 ppm. Exponential decrease in the ratio occurs over a time span of five half-lives, demonstrating the absence of appreciable quantities of uranium in the sediments. There is evidence for a modest change in rate at about 40 to 70 cm. On a calcium carbonate free basis the quartz contents were under 2%, while X-ray diffraction spectra indicated the feldspars to have an even smaller concentration.

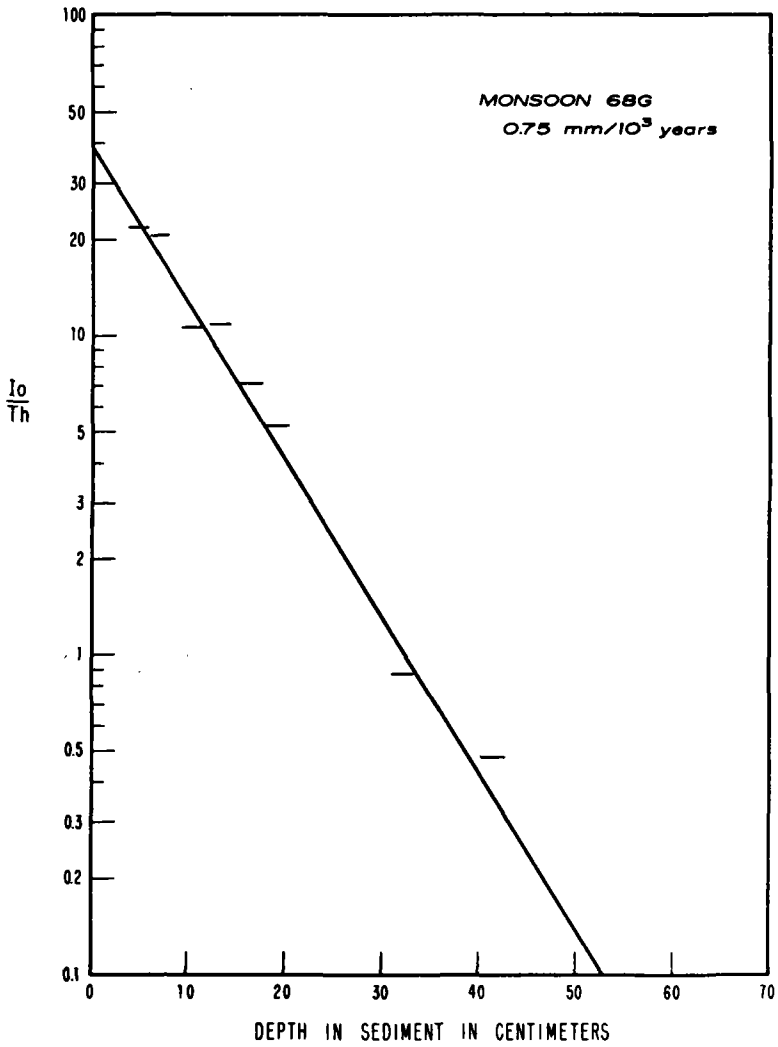


Fig. 3. The Io/Th ratio in units of disintegrations of ionium per disintegration of thorium for Monsoon 68G.

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2.3. MONSOON 68G

This core was recovered from a depth of 4941 meters at 39° 18′ S and 119° 52′ E. There was no discernible opal but the content of calcium carbonate varied between 0 and 24.8 % with the highest values within the first 9 cm. The sedimentation rate measured over three half-lives gave a value of 0.75 mm/10^3 years (Fig. 3). Detrital quartz contents on a calcium carbonate free basis were 7 % at the surface and 3 % at a depth of 64–68 cm. Surface disturbances again appear to be significant to depths of about 6 cm. This deposit, near the Australian continent, contained quartz and feldspars typical of a continental origin.

Lead-210 analyses were made on aliquots of the leachates from which the ionium measurements were carried out. These results are included in Appendix 1.

3. Discussion

The average rate of accumulation of the non-biogenous components, around 1 mm/10^3 years is intermediate to the values observed by us for the South Pacific (0.5 mm/10^3 years) and those of the North Pacific and Atlantic Oceans (> 1 mm/10^3 years).

The surface intercepts of the ionium/thorium ratio (in units of disintegrations of ionium per disintegration of thorium) vary between 38 and 80, values somewhat higher than those previously reported by us (GOLDBERG and KOIDE, *op. cit.*) for two cores recovered in the southwestern Indian Ocean, but comparable to those obtained from the two previously cited Russian papers (Table 1). Thus, the Indian Ocean

TABLE 1

The ionium/thorium ratio surface intercepts and average leachable thorium concentrations from Indian Ocean cores

Core	Latitude	Longitude	Io/Th surface intercepts	Leachable Thorium (ppm)	Reference
V-14-85	24°59′ S	51°18′ E	20	7	GOLDBERG and KOIDE [1962]
V-14-86	23°37′ S	53°08′ E	27	10	GOLDBERG and KOIDE [1962]
Monsoon 49G	14°27′ S	78°03′ E	42	20	This paper
Monsoon 57G	26°22′ S	74°08′ E	80	11	This paper
Monsoon 68G	39°18′ S	119°52′ E	40	15	This paper
Russian # 129	30°07′ S	60°35′ E	80		Starik *et al.* [1958]
Russian # 127	30°41′ S	60°42′ E	37		BARANOV and KUZMINA [1958]
Russian # 103	50°21′ S	110°12′ E	50		BARANOV and KUZMINA [1958]
Russian # 97	40°32′ S	120°35′ E	30		BARANOV and KUZMINA [1958]

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possesses surface intercepts that lie between and slightly overlap those of the South Pacific and those of the North Pacific and Atlantic Oceans (Table 2). This rather wide spread of values, compared to those of other oceanic areas, will be discussed in a subsequent paragraph.

Both of the above observations, the intermediate values of the ionium/thorium ratio and the regional rates of sedimentation in the world ocean,

TABLE 2

Surface intercepts of the ionium/thorium ratio and thorium concentrations in marine sidements compared with oceanic areas and the land areas draining into them.

Oceanic area	(1) Area in* $km^2 \times 10^3$	(2) Land area* drained $km^2 \times 10^3$	(2)/(1)	Io/Th	Th (ppm)
Atlantic	98 000	67 000	0.68		
North				1.5–6	12
South				9.4–19	8
Pacific	165 000	18 000	0.11		6.0
South				143–158	
East Equatorial				50–58	
Northeast Coastal				16–25	
Northeast				48–57	
Mid-Central				30	
Indian	65 500	17 000	0.26	28–80	13

* From Lyman [1958].

are apparently related to the relative amounts of surface drainage to oceanic areas. The ionium-production from uranium in the oceans, which accounts for nearly all of this thorium isotope in the surface deposits, is essentially constant, due to the uniform distribution of uranium in all sea waters. On the other hand, the amounts of thorium-232 introduced to a given oceanic area per unit time is determined by the relative input of river waters. From Table 2, it is apparent that the Indian Ocean receives land-run-off at a value intermediate to those of the South Pacific and of the North Pacific and Atlantic Oceans.

A disturbing feature in these studies of thorium isotopes in the Indian Ocean deposits is the range in values of the surface intercepts of the ionium/thorium ratios such that even adjacent cores, as Russian 129 and 127, display variations of a factor of two (Table 1). Such discrepancies were not found in our previous studies of the Pacific and Atlantic.

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An explanation most probably lies in the introduction of thorium isotopes from the detrital minerals into some of the samples where the surface ratio is low. Inasmuch as thorium, on the average, is three times greater in crustal rocks than uranium, the activity of ionium will be about

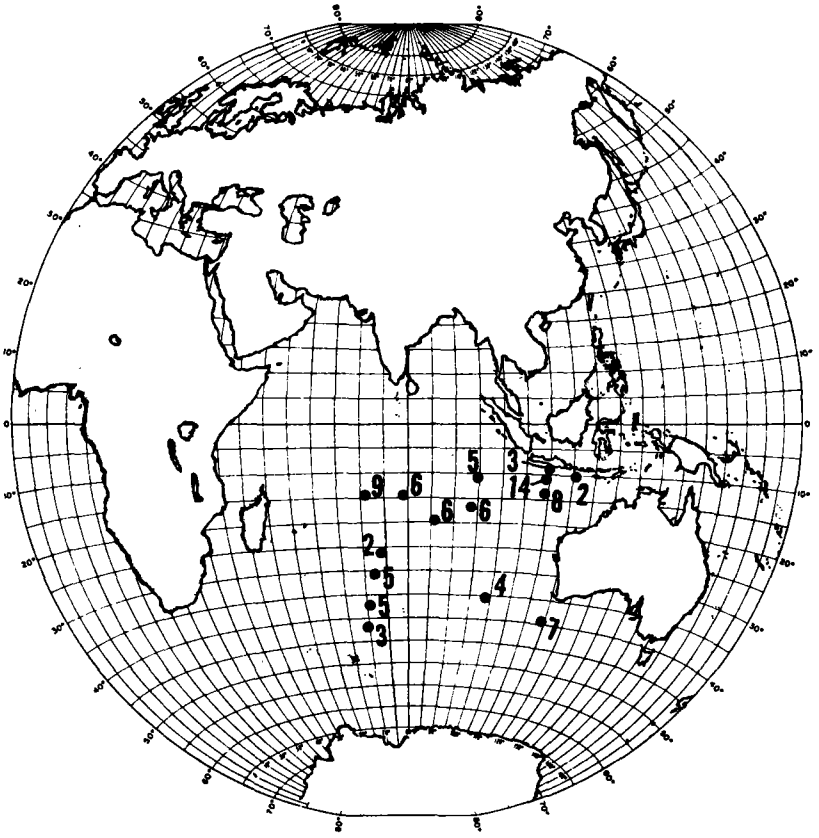


Fig. 4. The quartz concentrations (on a calcium carbonate and opal free basis) in surface samples from Indian Ocean sediments. Values are in weight per cent of the solid materials dried at 110°C.

equal to that of the thorium-232 due to the difference in half-lives ($t_{\frac{1}{2}}$ U-238 $= 4.5 \times 10^9$ years; $t_{\frac{1}{2}}$ Th-232 $= 1.4 \times 10^{10}$ years). Hence the unwanted release of thorium isotopes from lithogenous phases will result in an ionium/thorium ratio less than that from the authigenic minerals alone and the resultant computed rate of sedimentation will have a value slightly too high.

The detrital minerals in the sediments below the equator have a variety of origins. LISITZIN [1960] emphasizes the complex mineral assemblages,

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introduced by ice-rafting from the Antarctic land areas, which are found in the sediments at least as far north as 40° S. He also stresses the importance of the volcanic contributions in the Indian Ocean sector of the Antarctic. Of greater pertinence to the problem at hand would be the eolian or water transported materials from the western continental areas, Madagascar and Africa, which have extensive exposures of granites and other acidic rocks, enriched in thorium containing minerals. This argument obtains support from the disposition of quartz, on a calcium carbonate and opal free basis, as illustrated in Fig. 4. It is clear that in the open ocean latitudes between 10^0 and 20^0 S there is more quartz than in the areas below 25° S. Such a result could arise from a transport of these detrital grains from the west. In Monsoon 49G, at 14° 27′ S, tourmaline, pyroxene, apatite, sphene, garnet, hornblend, zircon and possibly allanite were observed in the heavy mineral separates as detrital grains often in the form of somewhat rounded fragments under 20 microns in size. Minor contributions of allanite or monazite could markedly affect the ionium/thorium ratios. Some confirmation of such a hypothesis may be found in the leachable thorium values – in the case of Monsoon 49G, a value of 20 ppm on a biogenous component free basis – which are much higher than those of the Atlantic or Pacific deposits (Tables 1 and 2).

3.1. RADIUM LOSS FROM THE SEDIMENTS

From an inspection of the Th^{230} and Pb^{210} activities in these cores as given in Appendix 1, it is evident that to depths between 10 and 15 cm from the surface, these two nuclides are not in radioactive equilibrium. If the Pb^{210} deficit, relative to ionium, results from a migration of the radium from the sediments to the overlying sea water as postulated by KOCZY [1958], a model can be formulated in the following way. (Note that we consider that the nuclides have come from the authigenic phases of the sediments only.) Initially, we make the assumptions:

(1) Th^{230} does not diffuse in the deposits.
(2) The sediments accumulate at a constant rate of C cm/sec.
(3) The arriving sedimentary components have a constant concentration of Th^{230}.
(4) Steady state conditions prevail.
(5) The Ra^{226} activity can be given by the Pb^{210} activity.

The following notation will be adopted:

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Z = depth from instantaneous bottom, positive downward
t = time
λ_1 = decay constant of Th^{230}
λ_2 = decay constant of Ra^{226}
n = concentration of Ra^{226} in atoms/cm^3
N = concentration of Th^{230} in atoms/cm^3
C = velocity of accumulation of sediment
N_0 = concentration of Th^{230} in freshly deposited sediment
K = migration coefficient of Ra^{226}
n_0 = concentration of Ra^{226} in freshly deposited sediment.

Using the relationship $N = N_0 e^{-\lambda_1 t}$ and $Z = Ct$, the concentration of Th^{230} at depth Z is given by

$$N = N_0 e^{-\frac{\lambda_1}{C} Z}.$$

In order to determine the relationship of Ra^{226} with depth, let Z' be the depth measured from some fixed horizon, positive downward at the time t'. Then

$$\frac{\partial n}{\partial t'} = K \frac{\partial^2 n}{\partial Z'^2} + \lambda_1 N - \lambda_2 n$$

but, $t' = t$ and $Z' = Z - Ct$, so

$$\frac{\partial}{\partial t'} = \frac{\partial t}{\partial t'} \frac{\partial}{\partial t} + \frac{\partial Z}{\partial t'} \frac{\partial}{\partial Z} = \frac{\partial}{\partial t} + C \frac{\partial}{\partial Z} \text{ and}$$

$$\frac{\partial}{\partial Z'} = \frac{\partial t}{\partial Z'} \frac{\partial}{\partial t} + \frac{\partial Z}{\partial Z'} \frac{\partial}{\partial Z} = \frac{\partial}{\partial Z}$$

thus,
$$\frac{\partial n}{\partial t} + C \frac{\partial n}{\partial Z} = K \frac{\partial^2 n}{\partial Z^2} + \lambda_1 N - \lambda_2 n .$$

Now in the steady state $\frac{dn}{dt} = 0$, so

$$K \frac{\partial^2 n}{\partial Z^2} - C \frac{\partial n}{\partial Z} - \lambda_2 n = - \lambda_1 N_0 e^{-\frac{\lambda_1}{C} Z} ;$$

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if $K\left(\frac{\lambda_1}{C}\right)^2 + \lambda_1 - \lambda_2 \neq 0$, the general solution is

$$n(Z) = \left[\frac{\lambda_1 N_0}{K(\lambda_1/C)^2 + \lambda_1 - \lambda_2}\right]\left[\exp\frac{(C - \sqrt{C^2 + 4K\lambda_2})\,Z}{2K} - \exp\left(-\tfrac{\lambda_1}{C}z\right)\right]$$

$$+ n(0)\exp\frac{(C - \sqrt{C^2 + 4K\lambda_2})\,Z}{2K}.$$

Using values of $\lambda_1 = 8.66 \times 10^{-6}$ years^{-1}, $\lambda_2 = 4.33 \times 10^{-4}$ years^{-1}, $C = 2.75 \times 10^{-4}$ cm/year for Monsoon 49G and $C = 3.0 \times 10^{-4}$ cm/year for Monsoon 57G, values of K of about 10^{-9} cm^2/sec are found for these two deposits. The calculations were not made for Monsoon 68G where the ratio Pb^{210}/Th^{230} was essentially constant to depths of 9 cm, apparently resulting from a homogenization of the upper sedimentary layers by organisms and/or bottom water currents.

These low values of K, compared to diffusion coefficients of electrolytes in water which are of the order of 10^{-5} cm^2/sec, strongly suggest that simple diffusion does not explain the migration of radium from the sediments to the sea water. It appears that diffusion of radium out of the sedimentary solid phases into the interstitial water and sorption reactions of radium on the surfaces of these solids limits the migration of radium. Hence, a more sophisticated model, taking such effects into account is needed to quantitatively describe the behavior of radium.

Acknowledgements

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Appendix 1

Chemical and mineralogical measurements on Indian Ocean cores.

Monsoon 49G

Depth (cm)	Io/Th	Th^{232}* (ppm)	Th^{230}**	Pb^{210}**	% $CaCo_3$	% Quartz	% Opal
0–3	33.8	9.8	76.6	37.6	2.94	2.5	58
3–6	34.3	10.1	79.0	48.5			
6–9	34.0	8.7	67.8	43.0			
9–12	30.7	7.8	55.0	43.4			
12–15	30.3	7.4	51.3	51.0			
15–18	25.2	7.5	47.0	44.0			
18–21	23.9	6.9	37.7	37.7			
30–33	15.4	10.4	36.8				
40–43	10.7	8.9	22.0				
50–53	8.4	8.1	15.7	18.1			
60–63	6.5	7.5	11.1				
65–69					0.52	4.5	56
70–73	4.5	8.9	9.2				
80–83	3.3	8.3	6.3	5.6			
100–103	1.8	9.0	3.8	3.0			
130–133	1.3	10.2	2.3				
163–166	0.43	9.2	0.90				

* On a calcium carbonate free basis. ** Given in arbitrary activity units.

Appendix 2

Chemical and mineralogical measurements on Indian Ocean cores.

Monsoon 57G

Depth (cm)	Io/Th	Th^{232}* (ppm)	Th^{230}**	Pb^{210}**	% $CaCO_3$	% Quartz	% Opal
0–3	60.7	9.9	137	72	70.9	0.49	0
3–6	64.1	14.4	213	162	85.5		
6–9	66.5	14.0	219	173	86.6		
9–12	64.6	12.1	181	167	83.6		
12–15	53.7	11.5	144		81.2		
15–18	58.4	8.8	134	127	79.3		
18–21	46.7	8.6	92	98	87.5		
30–33	20.3	9.3	44	44	78.9		
40–43	16.9	11.7	46	44	78.1		
50–53	13.9	8.2	26	28	63.1		
60–63	12.9	11.6	34		68.0		
70–73	8.5	11.6	23	28	78.2		
73–77					74.4	0.27	0
80–83	6.5	11.4	17		51.6		
90–93	5.2	10.8	13		64.3		
100–103	3.7	10.4	9.0	8.7	43.6		
110–113	2.9						
120–123	2.6						
130–133	1.4	11.9	3.9		68.7		

* On a calcium carbonate free basis. ** Given in arbitrary activity units.

References p. 102.

Appendix 3

Chemical and mineralogical measurements on Indian Ocean cores.

Monsoon 68G

Depth (cm)	Io/Th	Th^{232}* (ppm)	Th^{230}**	Pb^{210}**	% $CaCO_3$	% Quartz	% Opal
0–3	18.7	15.5	66.8	42.6	24.8	5.2	0
3–6	21.4	12.1	59.3	39.8	28.2		
6–9	20.5	13.6	65.0	41.6	22.3		
9–12	10.7	14.9	36.7	34.1	7.0		
12–15	10.8	16.3			0.0		
15–18	7.1	15.6			7.9		
18–21	5.2	11.0			2.6		
30–33	0.87	13.9			2.0		
40–43	0.48	13.8			0.0		
50–53					0.0		
60–63	0 33	18.3			0.0		
64–68					0.0	3.0	0
70–73	0.27	15.1			2.7		
80–83	0.24	18.0			13.7		
94–97	0.52	15.9			6.8		

* On a calcium carbonate free basis. ** Given in arbitrary activity units.

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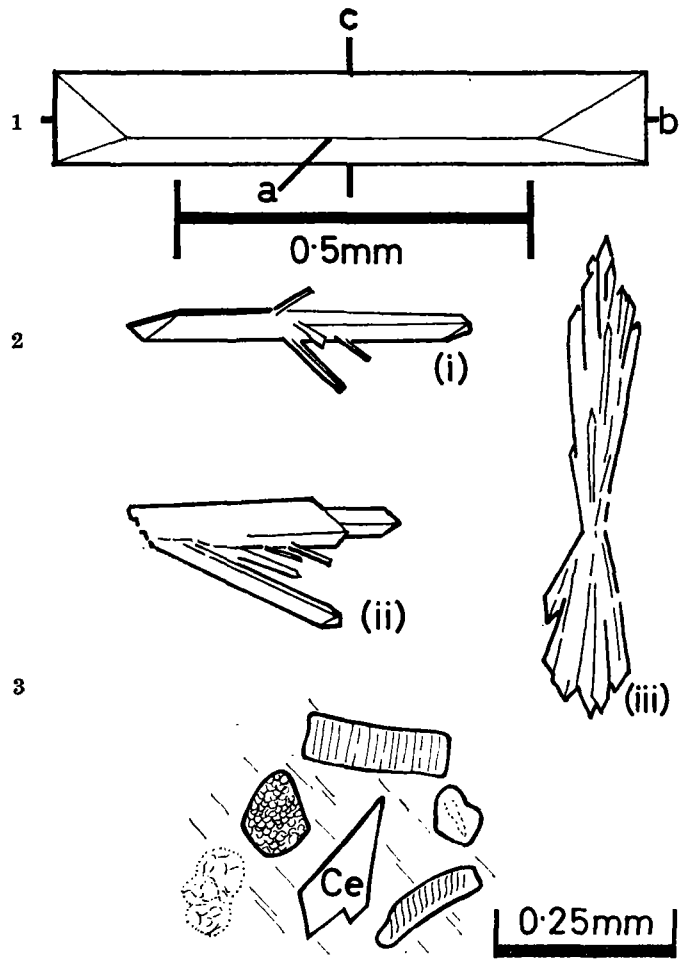
Recent Celestine from the Sediments of the Trucial Coast of the Persian Gulf

CELESTINE of Recent origin was first recorded in 1958 by Skinner[1] from shallow coastal lagoons in the south-east of South Australia. It has since been found as an early diagenetic mineral in the Recent sediments of the coastal flats of the Sheikdom of Abu Dhabi, Trucial Coast of the Persian Gulf.

The islands and lagoons of the coast of Abu Dhabi are backed by a wide coastal flat, the sabkha, the surface of which stands only slightly above high-tide level[2]. The sediments of the sabkha consist of Recent uncemented aragonitic and calcitic deposits similar to those accumulating around the present islands and lagoons. Anhydrite, dolomite, gypsum, and halite occur as early diagenetic minerals[3–5], and appear to have formed largely as a result of reactions between the saline ground-waters of the sabkha and the calcium carbonate of the original sediment. The celestine which is described in this communication was found in samples collected during reconnaissance traverses over approximately 120 miles of coast and sabkha, west of Abu Dhabi Island. Although only present as a minor accessory mineral, it is apparently widespread in the sediments beneath algal mats in the uppermost part of the present intertidal zone.

Celestine has been found as euhedral single crystals and as mutually interfering aggregates. The single crystals are elongated parallel to the *b*-crystallographic axis, and are up to 1 mm in length. They show a combination of prism and macrodome (Fig. 1). The clusters may be simple radiating aggregates of a few individuals (Figs. 2(i) and 2(ii)), or radiating sheaves (Fig. 2(iii)). The latter resemble sectors of spherulitic aggregates. Although it is possible that the simple clusters may represent an early stage in the development of the radiating sheaves, no intermediate forms have been found; for this reason they are treated as distinct types.

Many of the occurrences of celestine were closely associated with gypsum, which also shows a variety of habits. Sheaf-like bundles of celestine (Fig. 2(iii)) occurred with small lenticular gypsum crystals in the sediments within and beneath some of the algal mats in the upper parts of the intertidal zone. This appears to be the earliest phase of diagenetic gypsum and celestine. The two have also been found together with the same habits, approximately 2 ft. below the surface, in a short core taken from the sabkha several miles inland. The core also showed relics of an algal mat immediately above the gypsum and celestine. This horizon appears to represent a former intertidal zone.



Figs. 1–3

Large, sand-filled gypsum crystals, up to 8 in. across, occur in abundance at the surface over wide areas of the sabkha. Celestine clusters of the type shown in Figs. 2(i) and 2(ii) have been found in the sediment around the sand-filled gypsums, and also poikilitically enclosed within them (Fig. 3). The large sand-filled gypsum crystals have only been found in the sediments of the sabkha inland of the high-tide mark, and appear, therefore, to have formed at a later phase than the gypsum of the intertidal zone.

The euhedral crystals of celestine (Fig. 1) have so far only been found in samples collected from the surface of the sabkha. At one locality, they occur within a surface crust of mutually-interfering anhedral gypsum crystals.

Although the strontium of the celestine must ultimately have come from sea-water, much of it may have been derived indirectly from strontium-bearing aragonite, and possibly calcite, of the original sediment. However, Skinner[6] has claimed that celestine precipitates directly

from sea-water in the shallow lagoons of south-east Australia, and this may have happened also in the sabkha sediments. Any diagenetic changes which result in the solution or replacement of aragonite and calcite would be expected to release strontium into the pore-waters. In the sediments of the sabkha there has been extensive replacement of the original aragonite and calcite by early diagenetic dolomite: one phase of celestine and gypsum formation may be a by-product of this process. Some of the strontium released from the carbonate would accommodate itself in the calcium sulphate lattice, while the excess would be free to crystallize as celestine.

The fieldwork which led to this communication is part of a research programme, financed by the Department of Scientific and Industrial Research, being carried out by the Geology Department of Imperial College, London, on the Recent deposits of the Persian Gulf. We thank Dr. R. Walls and Mrs. P. E. Whyman, of British Petroleum Research Centre, Sunbury-on-Thames, for the original optical and X-ray determinations of the celestine. We also thank Mr. R. Curtis for confirming the X-ray analysis and Mrs. R. Evans for drafting the figure.

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ORIGIN OF THE COASTAL FLATS, THE SABKHA, OF THE TRUCIAL COAST, PERSIAN GULF

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THE coast of the Sheikdom of Abu Dhabi, Trucial States, in the south-western part of the Persian Gulf, is bordered for most of its length by low coastal flats which stand just above normal high-tide level. These flats are known locally as sabkha. They are composed of unconsolidated carbonate sediment with minor amounts of quartz and other minerals and are the site of deposition of various evaporitic minerals[1,2].

The flats stretch from Ras Ghanada in the east to almost the Qatar peninsula in the west, a total distance of almost 200 miles. In their widest part, they are almost 20 miles across, and are everywhere bordered on their landward side by low bluffs of Tertiary and Quaternary rocks. In the east the flats are broad and continuous apart from a few isolated hills of older rocks, which project up above the flat surface. In the west the bluffs extend seawards as ridges to reach the coast as headlands. Here the sabkha is separated into a series of isolated pockets opening to seaward. In the extreme west, the Sabkha Mutti, a wide area of coastal flats extending far inland, is split in two by a long gravel and sand ridge which runs down to the coast. Similar areas of sabkha occur on other parts of the Arabian coast of the Persian Gulf, for example, at Umm Said, Qatar, and small areas occur on some of the offshore islands, while areas with a similar surface, but which are completely landlocked can be found inland.

On the seaward side the sabkha is bordered by broad intertidal flats. Seaward of these flats, in the west, is a large lagoon, the Khor al Bazm. This lagoon is separated from the open Gulf by a chain of islands (Fig. 1). In the east, the intertidal flats pass seawards into a complex of channels and shallow embayments with an outer chain of islands (Fig. 1). This latter complex protects the mainland coast with its intertidal flats much more, from the violent storms produced in the open Gulf, than does the Khor al Bazm and its islands to the west.

The western part of the sabkha plain is separated from the intertidal flats by a low beach ridge on a series of

ridges which are often capped by low dunes and on which sparse vegetation grows. The beach face of this ridge is usually covered with thick deposits of weed torn up from the shallow water areas to seaward. In the east only a line of flotsam with occasional bushes marks the high-water level. Well-developed beaches are thus found on the more exposed western coasts whereas in the sheltered eastern areas there is a gradation between the sabkha and the intertidal flats. At intervals, the beach ridges or lines of flotsam are cut through by shallow channels, which die out when traced inland. At extreme high water the tidal waters move in along these channels and flood the outer part of the sabkha plain. However, during the coincidence of high tides with strong onshore gale-force winds and rain the coastal dune ridge can be breached and the greater part of the sabkha plain can be under water.

The surface of the sabkha is, over large areas, blistered and encrusted with salt. Scattered crystals of gypsum project from it at various localities and locally nodules of anhydrite occur on the surface. A planed off surface of cross-bedded Quaternary limestone is exposed in some places and sometimes it is found just beneath the sabkha surface. Elsewhere the sediment of the sabkha is much thicker.

Although the sabkha is in general a plain just above normal high-water-level with little relief, a series of low linear ridges can be found particularly in the west. These ridges are clearly developed on the outer part of the sabkha plain and decrease in height inland. They provide good transport routes over a surface which is apt to be treacherous for motor vehicles. The ridges can be seen to parallel the present coastline; and small low depressions cut across them at intervals. Where the Tertiary and Quaternary rocks form headlands these ridges can be seen to fan out from these features. The ridges are undoubtedly old beach ridges. Like the present-day outer seaward ridge they are sometimes almost pure gastropod shell concentrates and generally contain more quartz in the west. In the eastern, more protected area, the sabkha plain does not show these well-developed ridges, but old strand lines and patterns of old drainage channels can be seen from the air.

The beach ridges and old strand lines clearly mark various stages in the outward growth of the sabkha plain[3]. The extension seawards has probably not been a smooth continuous process but has been intermittent, with periods of rapid advance alternating with periods when the coastline has been stationary or has been slightly receded.

The outward growth of the sabkha plain is the result of the extensive and prolonged intertidal flat sedimentation, the sediment having partly originated in the lagoons to seaward and also partly having formed in

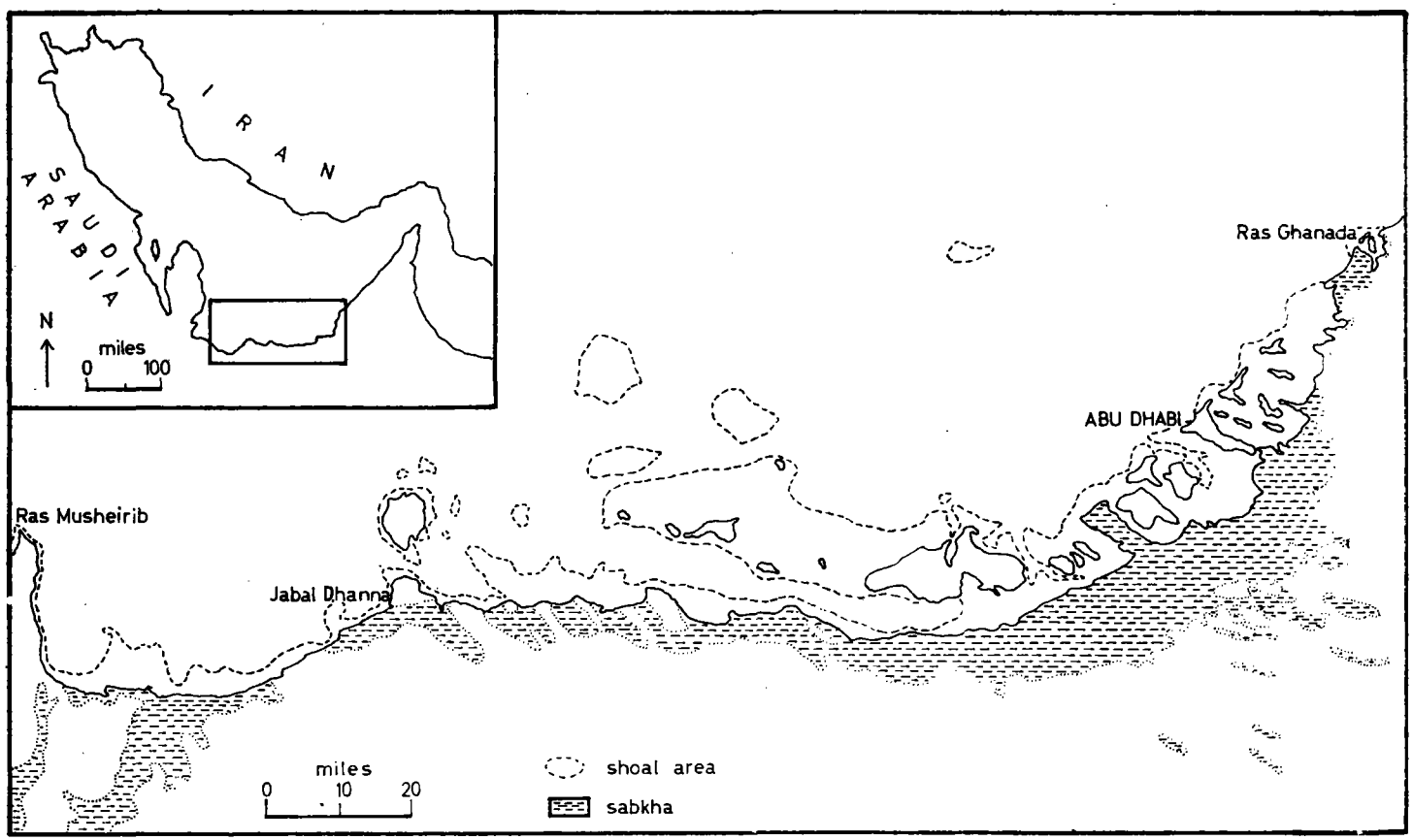

I R A N
SAUDI ARABIA
N
miles
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Ras Ghanada
ABU DHABI
Ras Musheirib
Jabal Dhanna
miles
0 10 20
shoal area
sabkha

Fig. 1

place by chemical deposition and the growth of calcareous organisms, for example, gastropods, etc., and the production of fæcal pellets. Wind-blown dust from inland and from the offshore islands also makes up a small proportion of the sediment. Locally, outwash from the hills surrounding the sabkha plain may be important. This outgrowth has been interrupted by phases of beach building dominantly in the west. Cores, taken from behind the outer beach ridges, sometimes show algal layers beneath the surface and all the features of the most recent intertidal flat sediments to seaward. Outside the outer beach ridge the upper parts of the intertidal flats themselves often show a sabkha-type surface. Where sedimentation continues undisturbed, these parts may build up and extend seawards. From time to time, probably as a result of storm action, a new beach ridge may develop to cut the sabkha flat off from the sea. In the east, the outward growth appears to have proceeded without the extensive development of beach ridges, mainly because of the greater shelter afforded to the coast here by the complex of islands and shallow embayments. In places, especially on the inner part, shoal bays or lagoons might have existed as in the inner part of the Louisiana chenier plain[4].

As the ridges and sabkha flats become isolated from the sea, wind becomes the important agent of change. The dominant wind in this region is onshore. It deflates the surface and more material inland. The saline crust, produced by evaporation of water drawn up to the surface by capillary action, protects the sediment surface and where it is broken, for example, along roads, a wide area of dusty sand stretching away to the leeward can be observed. A lag deposit of gastropod shells is left on the surface. Around the hills of Tertiary and Quaternary rocks thin haloes of wind-driven material are developed, again extending to leeward, and on the sides of the hills themselves small dunes are seen moving to leeward. Further evidence of deflation is provided by the projecting gypsum crystals and anhydrite nodules which grow beneath the sabkha surface. The wind is thus reducing the features constructed by marine agencies, such as the beach ridges which become lower when traced inland, and is tending to lower the sabkha surface. Also there is scouring and redistribution of material when the sabkha becomes flooded under exceptional storm conditions.

As the sabkha plain shows no major break in level when traced inland from the intertidal flats to the low bluffs of Tertiary and Quaternary rocks, it seems reasonable to conclude that there has been no significant change in sea-level during its development. There is, of course, the possibility that such a feature might have been removed by deflation, but this is thought to be unlikely. The sabkha plain is therefore thought to be very young.

After the last rise of the sea to its present level, the coastline appears to have lain far inland along the foot of the Tertiary bluffs. As intertidal flat sedimentation proceeded the flats and their associated beach ridges in the west grew seawards. The beach ridges also grew out from the low headlands and knolls of older rocks and the areas behind became infilled. This caused a regression over a considerable stretch of almost 20 miles without any significant change in sea-level. The deposits are therefore diachronous and the sabkha plain in this respect resembles the Chenier plain of Louisiana[4], the 'silt-lands' of the Wash[5] and strand-plains in other parts of the world[6,7]. However, it does differ significantly from these in being composed dominantly of calcareous sediment and also being an environment of formation of a suite of evaporitic minerals.

This article presents some of the results of work financed by the Department of Scientific and Industrial Research, which is being carried out by the Geology Department of this College on the recent deposits of the Persian Gulf. We also thank Mrs. R. Evans for drafting the figure, and Dr. J. Watson and Mr. D. J. Shearman for their advice with the manuscript.

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Disappointing Interim Palæomagnetic Results from the Seychelles

RECENT seismic refraction experiments made in connexion with the International Indian Ocean Expedition have confirmed that the shallow Seychelles Bank has crustal structure of a continental type and represents an isolated continental fragment in the middle of the north-west Indian Ocean[1,2]. The late Precambrian granites exposed on the central islands of the Seychelles group have been shown to be cut by two sets of dolerite dykes which are of a Precambrian and early Tertiary age, respectively[3,4].

Du Toit and other writers have suggested that the Seychelles represent a fragment left behind during the break-up of Gondwanaland[5], and it is clear that this hypothesis is now in need of testing. Accordingly, in November 1963 (ref. 2) we collected 71 orientated specimens from 40 different dykes, sampling all the more accessible dykes shown on Mr. B. H. Baker's geological map[4] on the islands of Mahé, Praslin, Cousin, La Digne, Felicité and Marianne. The natural remanent magnetization directions of these specimens have been measured by one of us (T. A. R.) using an astatic magnetometer in Nairobi. The results are widely scattered and strongly suggest that the rocks are unstable. It is to be hoped that the a.c. demagnetization and thermal 'washing' techniques, which are now being tried, will reveal a significant grouping of the magnetic vectors.

This disappointing preliminary result would certainly not warrant publication in the normal course of events. However, the Seychelles are of current interest in connexion with the International Indian Ocean Expedition, and as this experiment is a particularly obvious one, we imagine that other groups are likely to consider going to these remote islands to collect palæomagnetic material. We wish them better luck than we have had.

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L. M. J. U. van Straaten (Editor)
Deltaic and Shallow Marine Deposits

THE RECENT CARBONATE SEDIMENTS NEAR HALAT EL BAHRANI, TRUCIAL COAST, PERSIAN GULF

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INTRODUCTION

The general physiography of the area to be described has been given in the paper by EVANS et al. (1963). Herein the dashed rectangle of fig.3 indicates the area concerned. The more detailed physiography can be seen from Fig.1 of this paper; here, the high water mark is indicated by a solid line, with the land areas ornamented within. Low water mark is indicated by a simple dashed line, the inter-tidal areas inside it being marked by a vertical ornament. Bathymetric countours of 1, 3 and 5 fathoms are also indicated. All depths are expressed in fathoms below Admiralty Datum which is approximately the level of low water spring tides. The maximum tidal range is 6–7 ft. and mean sea level is 4 ft. above datum. All depths indicated on the maps and profiles (Fig.1, 3) have been corrected for tidal difference and are related to datum. The tidal range is at a maximum on the open seaward coasts and decreases landwards across the shoal areas and channels.

The dominant wind and wave approach is from the northwest. On reaching the delta edges, which coincide almost exactly with the 1 fathom contour line, the waves steepen and break; the seaward limit of the deltas is characteristically marked by a line of breakers. Waves affect the entire subaqueous delta surfaces as far back as the channels. In the channels the tidal currents reach speeds of up to 2 knots and effectively damp out the waves which have crossed the delta tops. Thus the areas lying inside the channels are little affected by wave action at all. The waters of the flood tide flow in along the channels and also in over the shoal delta areas, whereas on the ebb tide the drainage is mainly through the channels. Asymmetric "megaripples" orientated across the channel floors, together with scour features all indicate the ebb currents to dominate over the flood currents. Where the two main branches of the channel meet turbulence has effected a deep scouring of the channel floor to a depth of 7 fathoms. Seawards the channel becomes shallower (Fig.3, profile 2) until at the delta edge it is present only as a 1–2 ft. feature. The mouths of some channels become completely infilled as for example that lying parallel but immediately northeast of the main channel.

Seawards of the 1 fathom contour the sea bed falls rapidly to 3 fathoms; this is considered as the delta slope zone. In comparison with the wide shoal areas the zone below

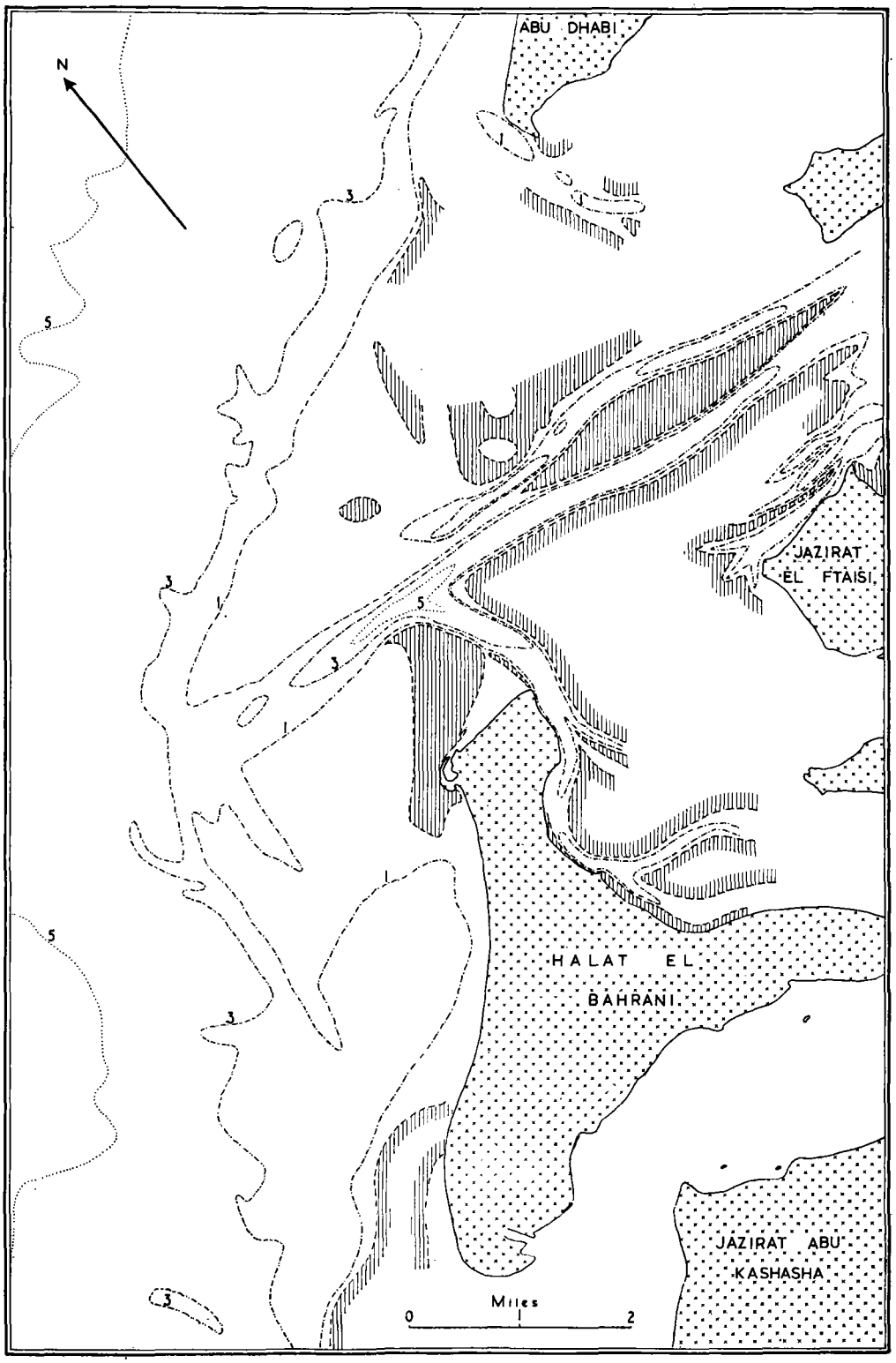


Fig.1. The Halat el Bahrani–Abu Dhabi region of the Trucial Coast, showing land areas, (solid line), inter-tidal areas (simple dashed line), and detailed bathymetry. All depths are accurate to within 1 ft. For location, see inset of fig.3 in accompanying paper by EVANS et al. (1963).

3 fathoms may be considered as relatively deep. Below this depth the sea bed slopes gently seawards; this foreset zone of the delta is developed to a depth of 5 fathoms and this may be readily seen from Fig.1, where the parallelism of this contour with the delta edge is most obvious. Deeper than 5 fathoms evidence of the deltas is entirely lacking and the sea bed deepens irregularly to 20 fathoms.

Between the two deltas which impinge upon the northeast and southwest tips of Halat el Bahrani stretches a poorly developed coral reef behind which relatively deep water (1–2 fathoms) extends almost to the coast. This arrangement of deltas, in response to channels which drain seawards between the islands, and coral reefs and inshore deeper water in the inter-delta positions is typical of much of this region.

SEDIMENTARY SUB-ENVIRONMENTS

The sedimentary sub-environments are closely controlled by depth as may be seen from a comparison of Fig.1 and Fig.2. They are also biological sub-environments. In general, the sediments are produced within the area; the only materials which originate beyond the local area of accumulation have a windblown origin. These windblown additions are considered to cover the entire region. Some fine carbonate as well as non-carbonate material will have a windblown origin as the rocks exposed inland are largely calcareous in nature. A description of the several sub-environments of deposition follows.

Deep water sub-environment

This sub-environment is limited on its inner margin by the 3-fathom line; it represents the fore-set area of the delta and slopes gently seawards from the base of the delta-slope. The sediments, although no doubt subject to wave action under storm conditions, are not as continually affected by wave activity as are those of the delta top. The sediments are generally medium to dark grey in colour and are usually somewhat foetid. They are neither well sorted nor rounded, consisting of fine and very fine sands with an admixture of medium and coarse shelly debris. The medium and coarse grades of the sediment consist almost entirely of molluscan and echinoderm debris; many lamellibranch valves are still articulated, or if separated they show little sign of abrasion; unbroken, extremely thin-walled shells are commonly present; broken shells nearly always have angular edges. Other shelly materials such as Foraminifera, fragile Polyzoa and ostracods all occur unabraded. The fine and very fine grades of the sediment contain appreciable quantities of non-carbonate materials; one total sample showed 75% carbonate and 25% non-carbonate. Many of the very fine sand and silt sized non-carbonate grains are angular, although occasional fine or medium sand sized, well rounded, typical aeolian quartz grains do occur.

Some composite grains are found, consisting of the finer grades of the sediment cemented together by granular aragonite. Many of the finer grains also have an irreg-

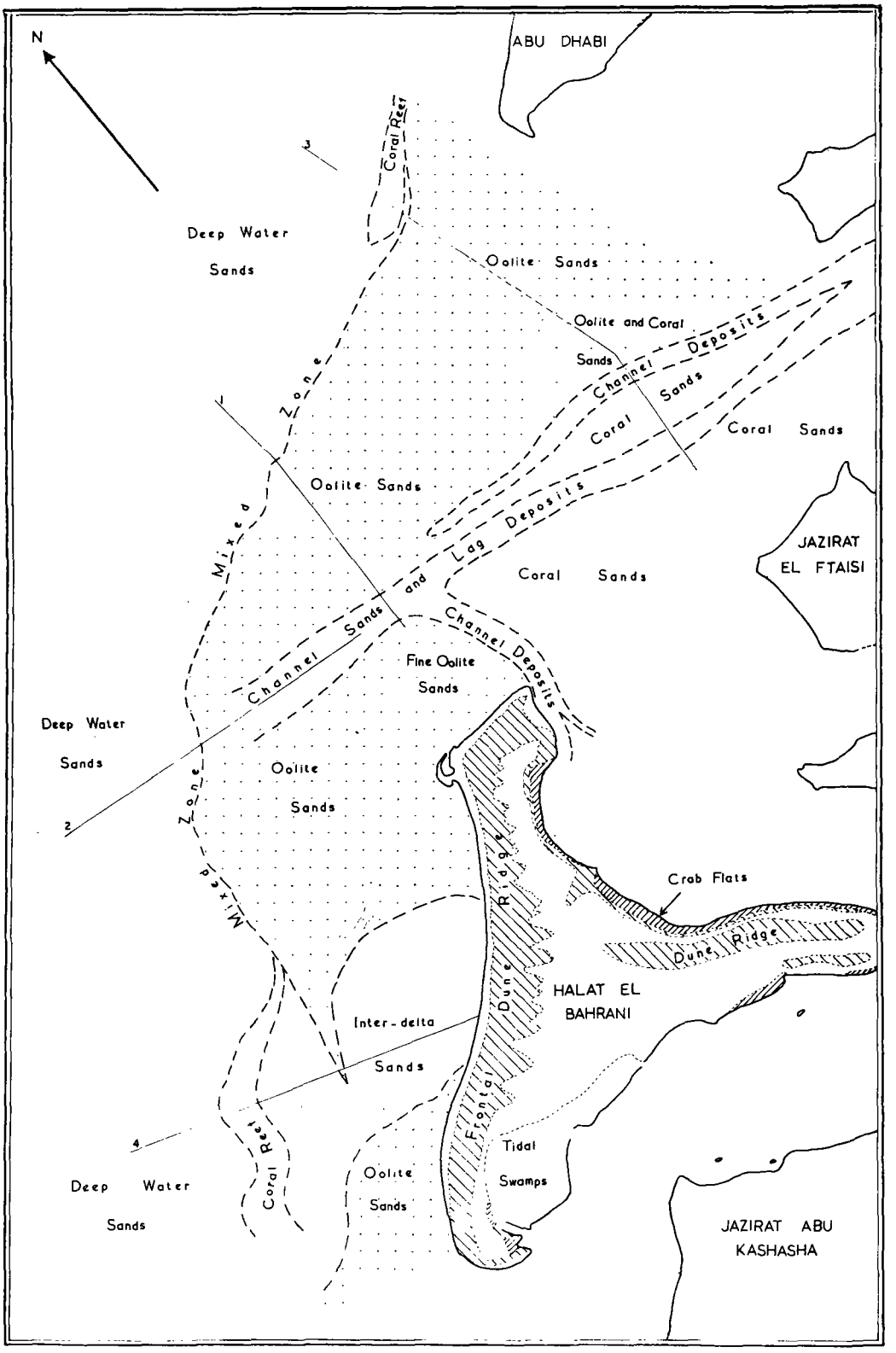


Fig.2. The sedimentary sub-environments in the Halat el Bahrani–Abu Dhabi region.

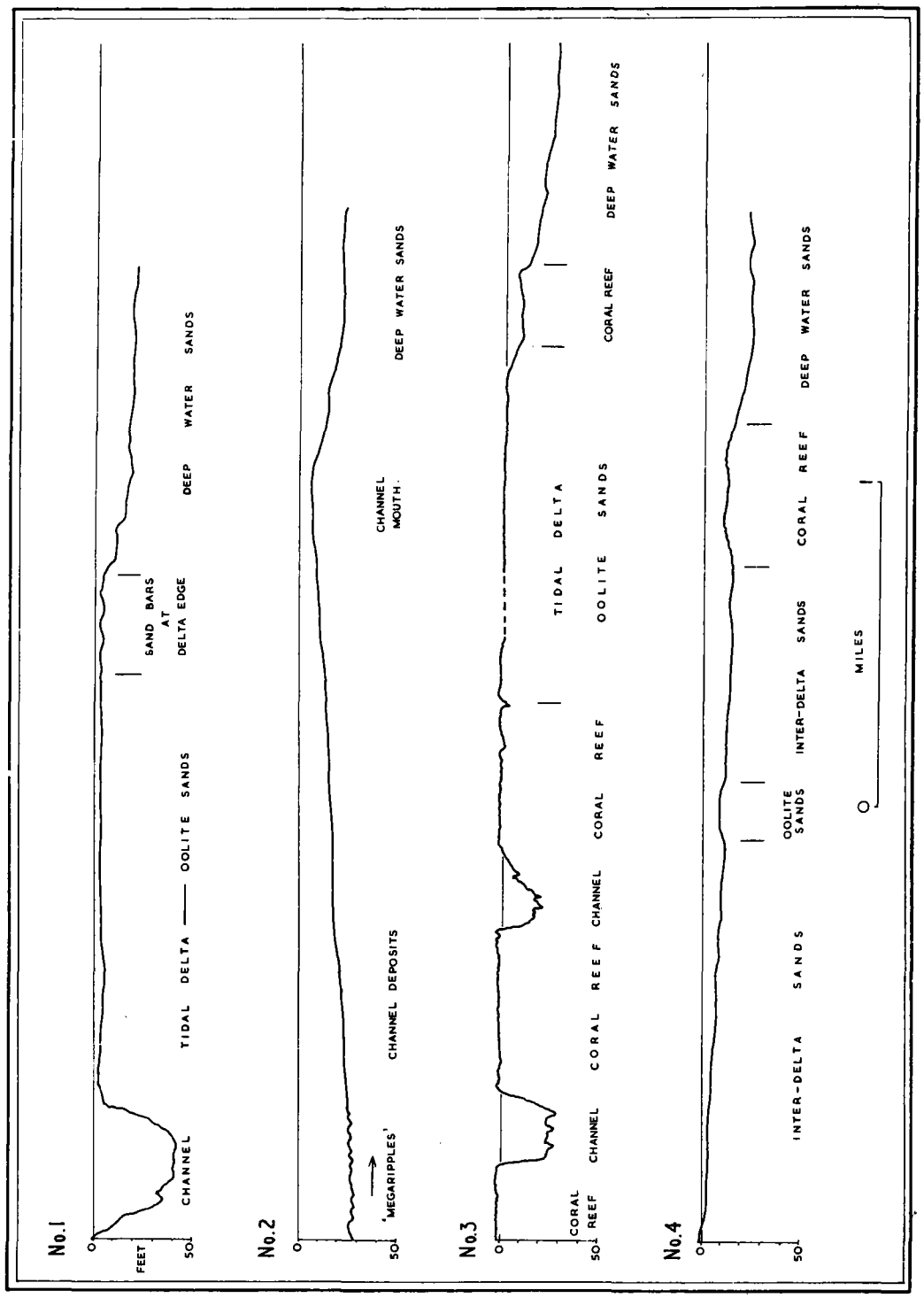


Fig.3. Profiles across the several sub-environments; profile lines are shown on Fig.2.

ular and incomplete coating of such granular aragonite. The deposition of aragonite is common inside many shells; lamellibranchs, gastropods, Foraminifera and Polyzoa may all show an infilling of small detrital grains cemented together by granular aragonite. The deposition of aragonite in this specialised micro-environment may be influenced by organic agencies. A mixed zone of deep water and delta top sediments occurs in the delta slope zone between 1 and 3 fathoms.

Delta top sub-environment

The deltas are limited seawards by the 1 fathom line and extend inwards either to the main ebb channels or to the island coasts. The waves, approaching dominantly from the northwest, build long, en échelon bars of the delta sands, sub-parallel to the delta-edges. These bars are several hundred feet in wavelength and 2–4 ft. in amplitude. They may be seen in fig.2 of the earlier paper by EVANS et al. (1963) and Fig.3 of the present paper. The bars parallel the northwesterly facing delta edges but extend across the delta tops where they swing southwest in towards the island coasts. This southwestward movement of the delta sands has resulted in the addition of a large spit to the northern tip of Halat el Bahrani since 1958 when the aerial photographs were taken. The delta top sediments are always well ripple marked, and in places seaweed growth is prolific.

The sediments are predominantly medium and fine grained oolite sands, with subordinate skeletal fragments, but become coarser grained towards the delta edge. The sands of the intertidal banks north and southwest of Halat el Bahrani are slightly finer in grain-size. The oolite content of these sediments is generally greater than 60%. The skeletal debris consists dominantly of rounded, thick shelled material. Little thin shelled debris occurs except for the occasional rather abraded Foraminifera and small lamellibranch shells. Noncarbonate grains are present, some showing the first stages of oolitisation. Small abraded spines of the burrowing echinoid *Echinodiscus bisperforatus* are fairly common together with occasional very abraded spine fragments of the reef echinoid *Echinometra mathaei*. In general, there is a lack of the lighter and more fragile organic remains such as Foraminifera, Ostracoda and Polyzoa; those materials which are present are all heavily abraded.

Inter-delta sub-environment and offshore coral reefs

Coral reefs are typically developed in the inter-delta areas. Seaward of the reef extends the deep water zone. The reef is composed mainly of *Acropora* although much of the coral is dead; *Platygyra*, *Porites* and other massive corals also occur, together with the reef echinoid *Echinometra mathaei*. Landwards of the coral reef extends the inter-delta zone; here the water is typically 1–2 fathoms in depth. The sediment surface is gently ripple-marked and littered with coral and coarse shell fragments. The sediments of this zone have many characters in common with those of the deep water zone together with the addition of fine oolite and coral sand. They are usually grey in colour and somewhat foetid.

Inner coral reef sub-environment

This sub-environment occurs in shoal areas sheltered from wave action by the channels. It can be seen from Fig. 1 that the area lies above datum and thus dries during very low tides. *Acropora* is the dominant coral and along the channel sides, which mark the edge of this sub-environment, is extremely prolific. On the reef flat itself, coral growth is rather more patchy and wide areas of sands occur between the coral heads, many of which are dead and bear luxuriant growths of seaweed. *Acropora* is joined on the reef top by massive corals such as *Platygyra*. The reef echinoid *Echinometra mathaei* is often extremely abundant, as also are many species of crabs, molluscs, foraminifera and fish. On the reef top the coral heads grow up to 2 ft. above the level of the sediment. Near the base of the coral clumps, the calcareous Alga *Lithothamnium* is abundant. The broken coral and calcareous algal debris form the main components of the coral sands, although unabraded spines of *Echinometra* are also fairly abundant. The sands are extremely angular and ill sorted; fragments may range in size from entire coral heads to silt and clay sized particles. The reduction of debris to small particle size is considered to be largely biological; much breakdown is probably effected by the activities of *Echinometra*.

An area of mixed coral and oolite sands is found to the north of the main channel; coral growth here is rather poor and the sediments are better sorted and rounded than the true coral sands.

Channel sub-environment

The channel walls, except for the seaward 1–2 miles, bear a prolific growth of the branching coral *Acropora*. The channel deposits comprise components from several sub-environments and are thus of an extremely heterogeneous character. The surface is littered with a coarse lag deposit of coral and shell material; finer coral and oolite sand occupy an interstitial position. The finer materials are carried seawards by the ebb currents and where these currents slacken, become gradually deposited; thus the deposits of the main channel, just in from its mouth, are generally medium and fine-grained in character and at its mouth oolites predominate.

Beach, island and inner sub-environments

The beach deposits bear a close relationship to the offshore sediments. Thus a beach inland of an oolite sand area is composed largely of oolites, one inland of a coral sand area, largely of coral debris. The sands of the seaward coast of Halat el Bahrani are mixed, containing oolites and much medium and coarse shell debris, derived from the inter-delta area. The sands of the upper beach and berms become winnowed by wind action and moved inland to the frontal dune ridge. Much of the finer fraction is blown further inland, across the wind stripped central area, finally to the shoal inner banks between Halat el Bahrani and Jazirat Ftaisi. Thus the sediments of the extensive crab

flats (Fig.2) are fine and very fine sand but have largely originated in other sub-environments. Both inner coasts of Halat el Bahrani are characterised by a succession of spits and wide crab flats; the latter lie just above the level of mean high water; seaward of the crab flats, where spits enclose especially sheltered environments, a gastropod flat is developed which is covered by every tide. Here, the sediments often contain some silt and clay grade materials. The finest sediments of the region are those of the tidal swamps; an area of tidal swamps lies behind the frontal dune ridge of Halat el Bahrani and a much larger area extends from the southeastern tip of the island almost to the mainland. The sediments comprise precipitated aragonite muds together with coarser wind blown materials.

It is readily apparent from the two papers which have described the Trucial Coast region that the detailed physiography is rather complex. This complexity is mirrored in the sedimentary sub-environments. It is the physiography which has largely given rise to the complex sediment pattern, but the reverse is also in part true, the sedimentary and biological sub-environments having given rise to the complex physiography.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to D.S.I.R. for financing this project, to the Hydrographer of the Royal Navy, Captain and crew of H.M.S. "Dalrymple" for much assistance and cooperation, to the British Museum of Natural History for identification of fauna and flora, to the Oil Companies working in the area, to G. Evans and D. J. Shearman for assistance in the field and laboratory respectively and to Mrs. F. Kelk for assistance in the preparation of the figures.

SUMMARY

A description is given of the detailed physiography of an area of recent carbonate sedimentation. The relationship of tidal waters to the area is discussed and the several sedimentary sub-environments are described.

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EVANS, G., KINSMAN, D. J. J. and SHEARMAN, D. J., 1963. A reconnaisance survey of the environment of recent carbonate sedimentation along the Trucial Coast, Persian Gulf. In: L. M. J. U. VAN STRAATEN (Editor), *Deltaic and Shallow Marine Deposits*.. Elsevier, Amsterdam, pp. 129–135.

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Deltaic and Shallow Marine Deposits

A RECONNAISSANCE SURVEY OF THE ENVIRONMENT OF RECENT CARBONATE SEDIMENTATION ALONG THE TRUCIAL COAST, PERSIAN GULF

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INTRODUCTION

The Persian Gulf is a relatively shallow sea being rarely deeper than 50 fathoms[1] (90 m). Communication with the Indian Ocean is through the Strait of Hormuz, which although narrow is not restricted by a submarine sill, as occurs for example at the southern end of the Red Sea. The deepest water lies, in fact, at its entrance. The Gulf is asymmetric in cross section with the deeper water axis lying close against the Persian shore, inland of which rise the Zagros Mountains. Along the southern or Arabian half of the Gulf the water is nowhere deeper than 20 fathoms (Fig.1).

EMERY (1956) made a description of the sediments and waters of the area, based on records and samples obtained by Royal Naval and United States Survey vessels. He showed that the area is one of carbonate sedimentation with appreciable amounts of terrigenous detritus occurring only around the Tigris–Euphrates delta at the head of the Gulf and along the Persian shore. HOUBOLT (1958) made a detailed study of the offshore sediments to the north and east of the Qatar Peninsula. The shallow water sediments were found to be essentially skeletal calcarenites and these pass laterally into calcilutites and marls towards the deeper water axis. The coastal lagoons of Qatar were investigated by BRAMKAMP and POWERS (1955) where they reported a series of carbonate and evaporitic sediments to be accumulating. SUGDEN (1963) studied the Recent sediments of the shallow Gulf of Salwa (to the west of the Qatar Peninsula) where he found a widespread development of aragonite muds, ooliths and pseudo-ooliths. He also made a regional survey of the variation in salinity, with particular reference to the remarkably high values occurring in the Gulf of Salwa and along the Trucial Coast, where salinities as much as 60% above that of normal ocean water occur. He concluded that these high salinities had little effect on the diversity and abundance of the marine fauna. Recently, WELLS and his co-workers (1962) made the interesting discovery of the formation of Recent dolomite in the sediments of the higher parts of the tidal flats around the Qatar Peninsula and CURTIS et al. (1963)

[1] All depths are expressed in fathoms below Admiralty Chart Datum (approximately Low Water Spring Tides).

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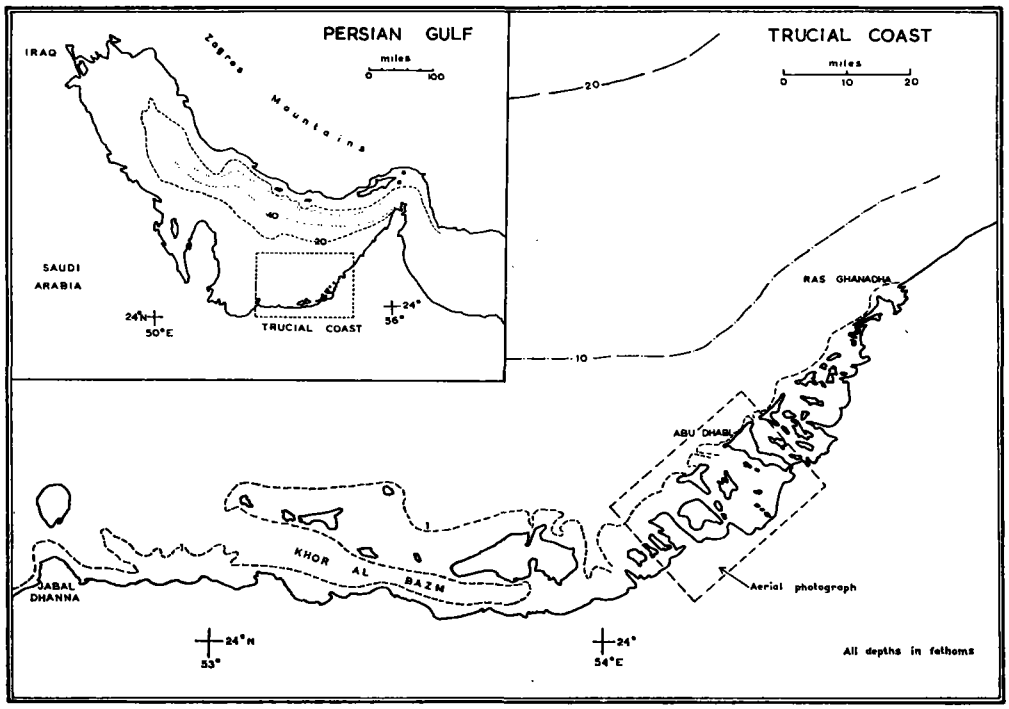


Fig.1. Inset map of Persian Gulf showing broad bathymetry and asymmetric character in cross section. Map of Trucial Coast showing nearshore bathymetry and distribution of islands and embayments.

showed that both dolomite and anhydrite occur in the sediments of the Sabkha near Abu Dhabi. WELLS and ILLING (1963) have reported most interesting observations on the instantaneous precipitation of calcium carbonate in the waters of the southern Gulf.

It was against the background of the work by Emery, Houbolt and Bramkamp and Powers, that the Departments of Geology, and Geophysics of the Imperial College of Science and Technology, London, initiated in 1961 a programme of research on the Recent sediments along the Trucial Coast. The nearshore zone above 5 fathoms (9 m) was found to be an area of carbonate sedimentation in which skeletal calcarenites, oolite sands and aragonite muds are being deposited, together with biohermal accumulations and accessory contributions from windblown materials. An evaporitic facies occurs immediately inland. The purpose of this paper is to describe the physiographic setting in which these various sediments occur, in the region between Ras Ghanadha in the northeast and Jabal Dhanna in the west, with more detailed reference to the area around Halat el Bahrani. The sediments of the latter area are described in the accompanying paper by KINSMAN (1963).

PHYSIOGRAPHY

The region consists of a broad coastal strip, up to 15 miles wide, of islands and penin-

sulas which enclose a series of large, shallow tidal embayments. In the west, the islands are joined by sandy shoals and are separated from the mainland by a long lagoon, Khor al Bazm, which is not completely closed at its eastern end (Fig.1). Apart from a few small channels which cut across this offshore barrier the main ebb tide drainage is westwards. In the east, however, the offshore islands are separated from each other by deep ebb channels which drain the large shallow embayments behind them (Fig.1, 2, 3). Initially the small ebb channels have a dendritic pattern but these coalesce to form one or more major channels which then drain between the islands and across broad sub-aqueous deltas before reaching the open sea. The long profiles of the ebb channels are of particular interest. The channels deepen as they approach the gap between the islands, to depths of 5–7 fathoms, but shallow again, commonly to less than 1 fathom as they flow out across the seaward edge of the sub-aqueous deltas. In some places the channels lose their identity completely. The deltas are bounded seawards by the 1 fathom depth contour and shelve steeply at their outer edge to 3 fathoms. They are simple in form at the mouth of a single ebb channel, e.g., that northeast of Abu Dhabi island, or complex where more than one channel discharges between the islands, as for example the deltas northeast and southwest of Halat el Bahrani. They are being deflected partly southwestwards by the dominant wave approach which is largely controlled by the prevalent northwest or "Shamal" winds. The deltas probably have a complex origin, perhaps representing several stages of deposition separated by periods of elevation which may correlate with Pleistocene and post-Pleistocene sea-level changes. They are also in part erosional platforms cut into earlier Quaternary limestones on which the Recent sediments are accumulating. However, their general arcuate form and their close relationship to the present channel systems suggests that they are dominantly of tidal origin.

The seaward islands are composed largely of unconsolidated Recent sediments. Limestones, probably Quaternary in age, underlie these desiments in some parts, and on the mainland often overlie older Tertiary deposits. This complex of lagoons, embayments and islands is bordered in some places on its landward margin by broad, low beach ridges and isolated hills of Tertiary and Quaternary sediments; in other places, extensive areas of intertidal flats, with wide stretches of Algae in some localities, occur along the inner coastline. Inland of the mainland coast is a wide flat sandy plain, often with a saline crust, the Sabkha. The Sabkha lies just above the level of high spring tides and may be up to 15 miles wide. It is bounded on its inland margins by low Tertiary hills capped occasionally by Quaternary limestone and often covered locally with a thin veneer of blown sand. In places a few, flat-topped, steep-sided, isolated hillocks, buttes, stand up from the Sabkha surface, surrounded by a fringe of blown desert sand. To the west the hills reach the coast and the Sabkha here occurs as isolated patches occupying the low ground.

A detailed description of the area between Halat el Bahrani and Abu Dhabi will now be given; this area is fairly typical of the eastern part of the coastal region. The seaward facing coasts of these islands are aligned southwest to northeast and parallel the general coast trend. The beaches are fairly steep and are backed by large frontal



Fig.2. Aerial mosaic of Abu Dhabi region. (Royal Air Force Photograph, Crown Copyright Reserved.)

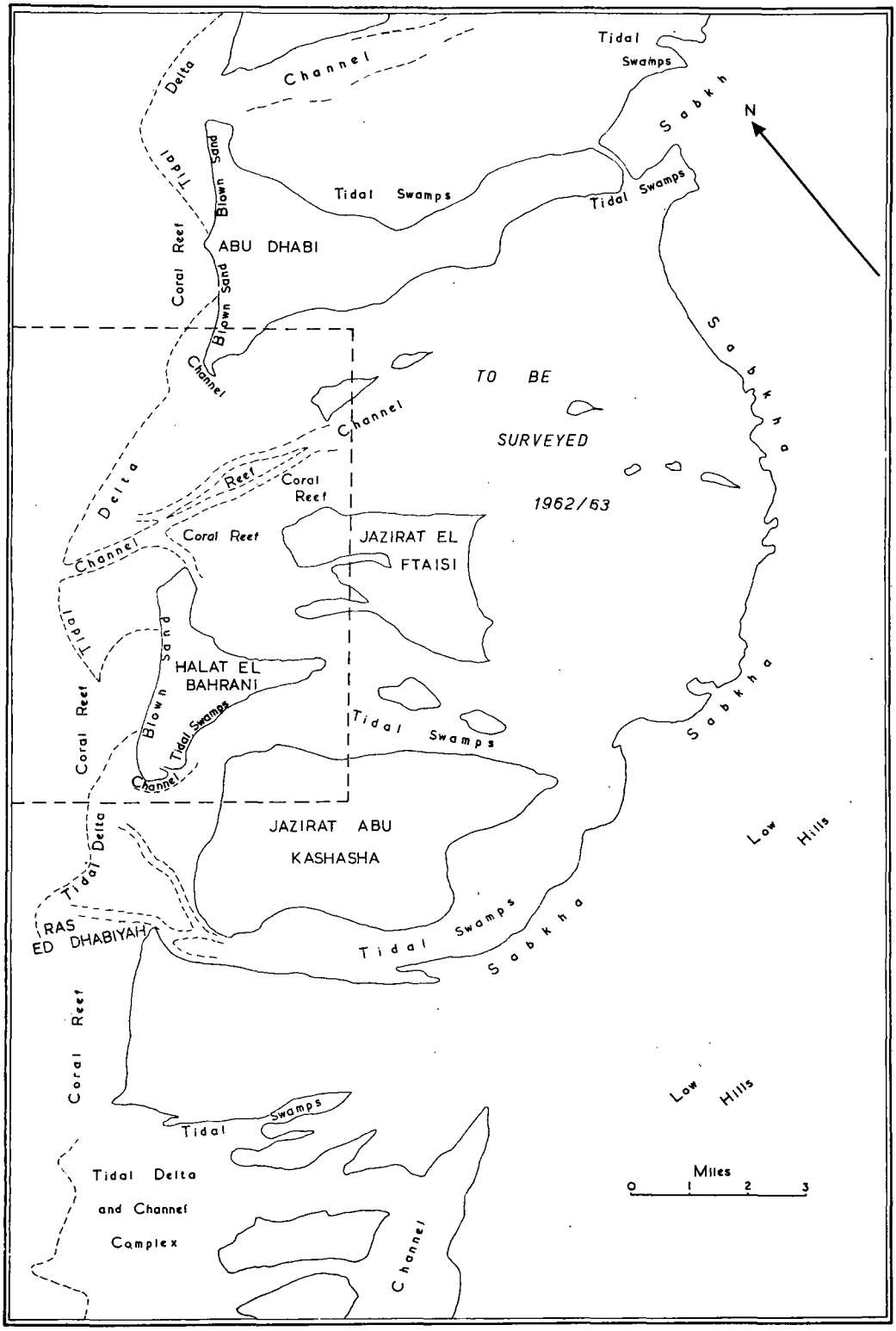


Fig.3. Map showing salient features of area covered by aerial mosaic. Inset area is discussed by KINSMAN (1963).

dune ridges. The maximum tidal range is about 6 ft. but this may be increased during periods of strong northwesterly winds. The orientation of the beaches and the frontal dune ridges is a response to this onshore wind. The steep beach faces are characterised by the development of cusps and are fronted by a narrow low tide terrace. At the top of the beaches one or more berms are usually developed, often extensively colonised by the burrowing crab *Ocypoda aegyptica*. The berms are succeeded landwards by a wind stripped terrace. Low, hummocky, partly vegetated dunes lead inland from this upper terrace and merge into the frontal dune ridge which on Halat el Bahrani reaches 30 ft. in height and is the highest part of the island. Behind this ridge is an extensive flat, wind stripped area with a surface lag deposit of coarser debris; smaller dunes are present, especially near the inner southeastern corner of the island. In the southwest of Halat el Bahrani, however, behind the frontal dune ridge is a wide swampy area with a typical dendritic drainage pattern of creeks. This area is densely vegetated by *Arthrocnemum glaucum*.

The sheltered inner coasts of Halat el Bahrani are characterised by a succession of spits. These are arranged en échelon and are all directed inwards toward the mainland. The tongues between the spits are colonised by large numbers of gastropods and crabs. Faecal pellets and trails cover much of the gastropod zone, which is inundated by every tide. The small burrowing crab *Scopimera* lives in the higher zone which is inundated only during high spring tides; the surface of this zone is covered by the burrowing pellets produced by *Scopimera*, although these are destroyed whenever the zone is flooded. Wide crab flats extend along most of these coasts, often landwards of the spit area. The gastropod flats become very extensive in the extreme southeast of the island. Further again southeast an extensive area of tidal swamps is developed extending almost to the mainland coast.

Between the deltas, directly fronting the islands are coral reefs, predominantly of *Acropora* with subordinate *Platygyra* and other massive corals. The main ebb channel flowing across the delta between Halet el Bahrani and Abu Dhabi bifurcates 3 miles from its mouth around the island of Jazirat el Ftaisi. This latter island is thus separated from the open sea by the wide shoal area of the delta and does not have the coastline typical of the more seaward islands. The shoal area enclosed by the main branches of the ebb channel is another area of coral growth. The coral here is diffuse and occurs in patches, whereas on the steep walls of the ebb channels the growth of the dominant coral, *Acropora*, is extremely prolific.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to D.S.I.R. for financing this project; to the Hydrographer of the Royal Navy, Captain and crew of H.M.S. Dalrymple for much assistance and co-operation; to the British Museum of Natural History for identification of fauna and flora; to Abu Dhabi Petroleum Co., and to Mrs. F. Kelk for assistance in the preparation of the figures.

SUMMARY

The physiographic setting of an area of Recent carbonate sedimentation along the Trucial Coast, Persian Gulf is described. Previous work on the sediments and waters of the Persian Gulf is briefly reviewed. The paper forms the background for the description of the sediments of part of the area discussed (see KINSMAN, 1963).

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К характеристике органического вещества донных отложений Тихого и Индийского океанов

О. К. Бордовский

Основной задачей настоящих исследований являлось изучение органического вещества глубоководных океанских осадков в аспекте проблемы происхождения нефти.

Одним из ведущих направлений в решении проблемы происхождения нефти является изучение состава и условий преобразования органического вещества в осадочных породах. Необходимым звеном в этих исследованиях, неразрывно связанным со всем остальным комплексом работ, является изучение происхождения, условий накопления и состава органического вещества в современных осадках. Процесс дальнейшего преобразования органического вещества и его потенциальные возможности в отношении генерации нефтяных углеводородов во многом определяются его первоначальным обликом.

Существенным пробелом в изучении органического вещества современных осадков является то обстоятельство, что исследования были сосредоточены в основном на прибрежных и шельфовых осадках и лишь в малой степени затрагивали глубоководные. Это обстоятельство обусловлено широко распространенным мнением, что в осадках, отлагающихся на глубинах более 200—300 *м*, т. е. за пределами шельфа, попадает ничтожное количество органического вещества, находящегося в глубокой стадии разложения (Вебер, 1947; Вебер и др., 1956). Поэтому ожидать в подобных осадках процессов битуминизации не приходится. Это положение по сути отрицает возможность формирования нефтепроизводящих отложений в глубоководных частях бассейнов с нормальным газовым режимом.

Вместе с тем, в настоящее время известно, что скопления нефти обнаружены как в мелководных частях ископаемых бассейнов, так и в глубоководных их частях. Поэтому выяснение потенциальных возможностей органического вещества глубоководных отложений в отношении его дальнейшего преобразования в сторону нефти представляет значительный интерес. Однозначное решение этого вопроса явилось бы одним из важных критериев при диагностике нефтематеринских отложений.

Настоящие исследования и были направлены на выяснение источников органического вещества, условий его накопления и характера с точки зрения возможностей как нефтеобразователя в разнообразных типах современных глубоководных океанских осадков. Главное внимание в исследовании было обращено на состав и распределение битуминозных веществ, как наиболее близких в генетическом отношении нефти. С этой же целью производилось также изучение аналогичных веществ в планктонных организмах — главном источнике органического вещества осадков.

Исследовались также гуминовые кислоты — вещества о происхождении которых и роли в процессе нефтеобразования существуют диаметрально противоположные представления.

Поскольку в преобразовании органического вещества огромную роль играют физико-химические условия среды, производилось также определение таких физико-химических характеристик, как pH и Eh осадков.

Другим важным вопросом, на освещение которого были направлены данные исследования, явилось изучение накопления органического вещества в жидкой фазе — в грунтовых растворах осадков на ранних стадиях формирования отложений.

Как было доказано рядом работ, на состав и концентрацию органического вещества огромное влияние оказывают минерализация и присутствие некоторых веществ в растворе (Бейкер, 1960; Барс и Коган, 1962). В связи с этим в жидкой фазе осадков нами производилось определение щелочности и аммонийного азота — показателей, непосредственно связанных с преобразованием органического вещества.

Материалом для исследований послужили пробы осадков, собранные в 26 рейсе экспедиционного судна «Витязь», проведенном в центральной части Тихого океана (станции № 3778—3876) и в 31 рейсе, проведенном в Индийском океане (станции № 4511—4730). Для исследований были использованы также образцы Антарктической экспедиции (станции № 17—151), любезно предоставленные нам ст. научным сотрудником Института океанологии АН СССР А. П. Лисицыным.

Исследованиями были охвачены преимущественно глубоководные осадки, в том числе отложения глубоководных океанских впадин Тонга, Кермадек и Яванской и лишь отчасти сравнительно мелководные. Исследовались как поверхностные осадки, собранные при помощи дночерпателей, так и колонки донных отложений, охватывающие уже значительный промежуток времени. Чтобы по возможности исключить влияние литологических различий, в колонках для исследований выбирались горизонты с однородным составом.

Схема расположения исследованных станций представлена на рис. 1.

Краткая характеристика осадков

Образование осадков в океанах происходит за счет терригенного, вулканогенного, биогенного и хемогенного материала. Как отмечает П. Л. Безруков, в распределении осадков в океанах наблюдается географическая зональность, выражающаяся в закономерной смене состава осадков по мере перехода от одной климатической зоны к другой (климатическая зональность), зональность, связанная с увеличением глубины океана (вертикальная), а также зональность, зависящая от расстояния до континентов (циркумконтинентальная). Все три зональности, сложно накладываясь друг на друга, в той или иной степени отражаются как на вещественном, так и на гранулометрическом составе осадков (Безруков и др., 1961).

Терригенные осадки распространены в пределах шельфа, на материковом склоне, а местами на ложе океана и в глубоководных желобах, расположенных по окраинам океана (например, Яванская впадина).

Учитывая, что водосборная площадь Тихого океана (три четверти которой приурочено к азиатскому континенту) составляет примерно 16×10^6 *км*^{2} или только $^1/_{10}$ площади океана, следует признать роль терригенного материала в осадконакоплении весьма скромной. Особенно мало его участие в таком удаленном от континентов районе как исследованная центральная часть океана.

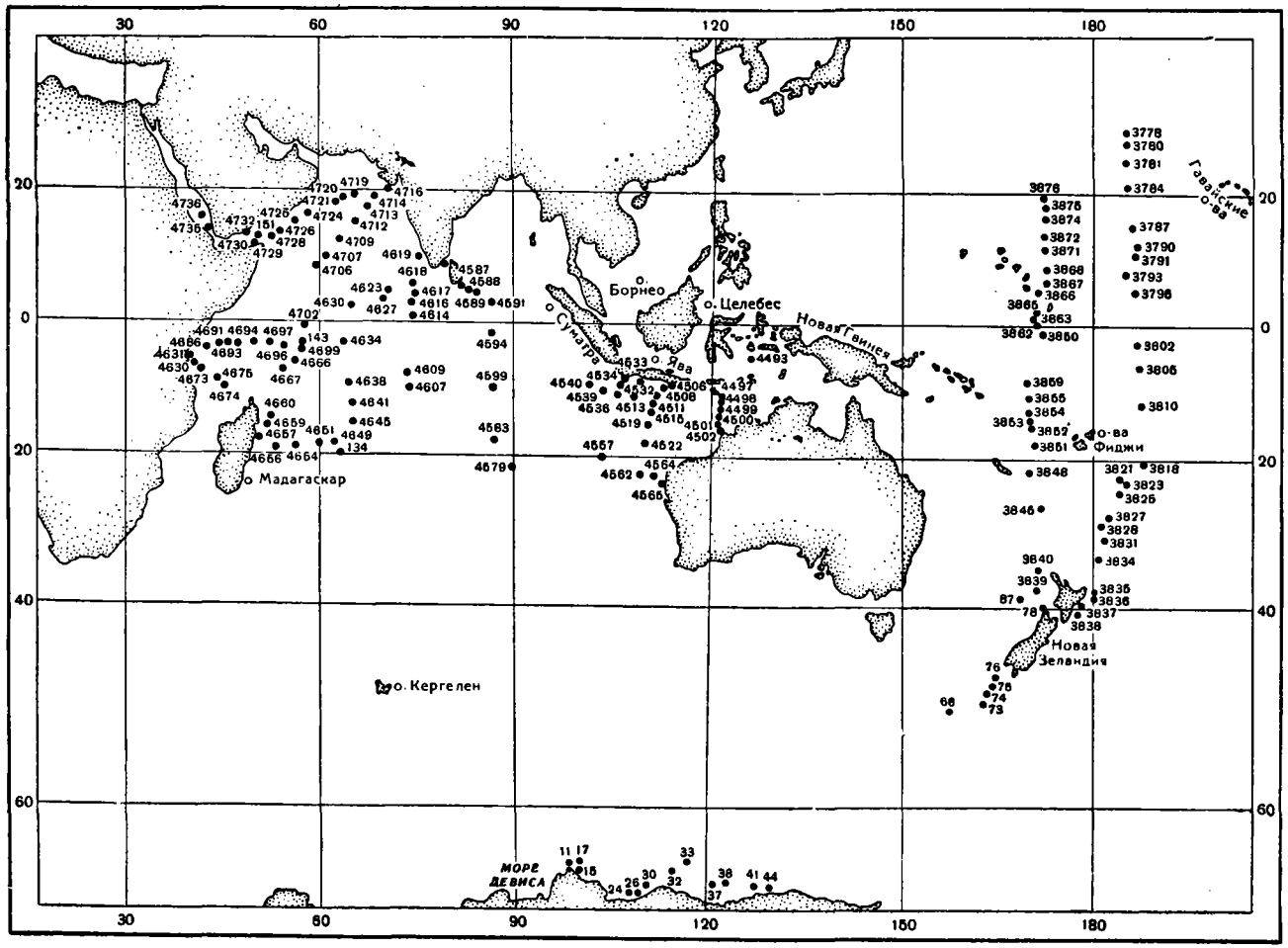


Рис. 1. Схема расположения исследованных станций

Несколько большую роль играет терригенный материал в образовании осадков Индийского океана. Особенно много его приносят реки со стороны Индии и гористых Зондских островов. С берегов же Сев. Австралии и Аравийского полуострова, обладающих засушливым климатом, терригенного материала поступает мало, и в океане уже вблизи берегов преобладают биогенные осадки, состоящие из скелетов морских организмов (Безруков, 1961).

Биогенный материал в осадконакоплении в океанах играет огромную роль. Среди органогенных осадков наиболее распространены в океанах известковые. В Тихом океане они выстилают 36,2% дна, а в Индийском — 54,3% (Sverdrup et, 1942).

Более скромную роль играют кремнистые осадки (14,7% в Тихом океане и 20,4% в Индийском). Наибольшее распространение среди них имеют диатомовые осадки, образующие широкий пояс вокруг Антарктиды и непрерывную полосу в северной части Тихого океана. Другим типом кремнистых осадков, распространенным в экваториальной зоне Тихого и Индийского океанов, являются радиоляриевые илы, развитые на глубинах более 4300—4500 *м*. Наконец, в открытых глубоководных районах океана развиты так называемые «красные глины». Это также бескарбонатные глинистые осадки, обогащенные высшими окислами марганца и железа.

По мере увеличения глубин происходит смена состава осадков. На глубинах до 4500 *м* преобладают биогенные осадки — преимущественно фораминиферовые илы. Глубже 4500—4700 *м* они исчезают, так как слагающий их карбонат кальция постепенно растворяется в толще холодных глубинных вод. Поэтому в центральных частях океана на глубинах 4700—6000 *м* распространены бескарбонатные осадки, так называемые красные глины, в которых часто встречаются железомарганцовые конкреции.

В связи с этими обстоятельствами осадки по вещественному составу условно подразделяются на карбонатные и бескарбонатные.

К категории бескарбонатных отложений принадлежат глинистые илы. Типичным представителем глинистых илов является «красная глина». Осадки этого типа покрывают ложе океана в открытых, наиболее глубоководных частях. Малая скорость осадконакопления и ничтожные количества терригенного материала приводят к заметному обогащению этих отложений в тропической зоне остатками радиолярий. Другим районом развития глинистых илов являются глубоководные впадины (Тонга, Кермадек, Яванская), в которых осадки подобного типа выполняют центральную часть.

Типом осадков, занимающим промежуточное положение между бескарбонатными и карбонатными отложениями, являются глинисто-известковые илы.

Чрезвычайно широким распространением среди исследованных отложений пользуются карбонатные осадки, встречающиеся в различных фациальных обстановках и охватывающие широкий гранулометрический спектр — от алевритово-глинистых илов до песков. В формировании осадков этого типа ведущую роль играют остатки планктонных и донных фораминифер. В некоторых случаях, на меньших глубинах, дополнительным источником карбонатного материала являются обломки кораллов, фрагменты раковин и моллюсков, а также сами раковины и т. п.

Известковые алеврито-глинистые илы распространены преимущественно на глубинах от 3 до 4—4,5 *км*. Вместе с тем на ряде станций осадки указанного типа были встречены на гораздо меньших глубинах — в нижней части материкового склона.

Алевритовые илы также пользуются развитием, как на больших глубинах (2,5—3,5 *км*), так и на меньших, в пределах материкового склона и у его основания.

Наконец, карбонатные осадки органического происхождения играют немаловажную роль также в образовании песчаных осадков, и были встречены как на больших глубинах, так и на малых — в области шельфа.

В распределении перечисленных типов осадков в большинстве случаев наблюдается определенная устойчивость. Многие грунтовые колонки на всю свою мощность представлены каким-либо одним типом осадка. Вместе с тем, в ряде случаев в колонках наблюдается переслаивание различных осадков, вызванное в одних случаях появлением прослоев вулканического пепла, в других — возможно деятельностью суспензионных потоков. Кроме того, как уже говорилось, колонки охватывают значительный промежуток времени, за который в океане не раз происходили климатические и тектонические изменения[1].

Органическое вещество осадков

В водах Мирового океана заключено до $1{,}3\times10^{12}$ *т* органического углерода. Эта величина того же порядка, что и содержание $C_{орг}$ в мировых запасах каменного угля или торфа. Хотя подавляющая часть органического вещества морских вод имеет автохтонное происхождение некоторая его доля приносится реками. Ежегодно реки приносят в океан до $7{,}0\times10^{8}$ *т* органического вещества, что составляет сотые доли процента от всего органического вещества, содержащегося в водах океана. Таким образом, материковый сток имеет подчиненное значение в питании морских и океанских бассейнов органическим веществом.

Основным источником органического вещества в морских водах является свое местное живое органическое вещество, преобладающую роль среди которого играют организмы фитопланктона. В распределении планктона в океане видна определенная закономерность. Его мало в приполярных частях и в широкой экваториальной полосе. Между этими зонами, как в южном, так и в северном полушари и, расположена зона его высоких концентраций. Таким образом, в распределении планктона видно тяготение к высоким широтам и прибрежным областям. Особенно многочислен планктон в приустьевых участках рек и в зоне восходящих течений, где на поверхность поднимаются воды, обогащенные биогенными элементами. Это явление отчетливо выражено в Индийском океане (рис. 2).

Движение вод, влияющее на распределение питательных веществ, обусловливает увеличение количества планктона в поверхностном фотосинтезирующем слое. Поэтому его много вблизи берегов, где пассатные или муссонные ветры вызывают подъем глубинных вод, богатых питательными солями (Богоров и Виноградов, 1961). Таковы районы к югу от Индонезийских островов и к западу от Австралии, Индии, Цейлона, Мальдивских островов. Особенно богато планктоном Аравийское море, много его и в Бенгальском заливе.

Обилие островов в западной половине океана и наличие двух дивергенций благоприятствует поднятию богатых питательными веществами глубинных слоев воды к поверхности. Поэтому вся западная часть океана в два-три раза богаче планктоном, чем восточная. Области, богатые планктоном, вытянуты в широтном направлении, как и поверхностные течения. Южнее 16° ю. ш. повсеместно очень мало планктона, что объ-

[1] В колонках для исследований выбирались по возможности горизонты с близким литологическим составом.

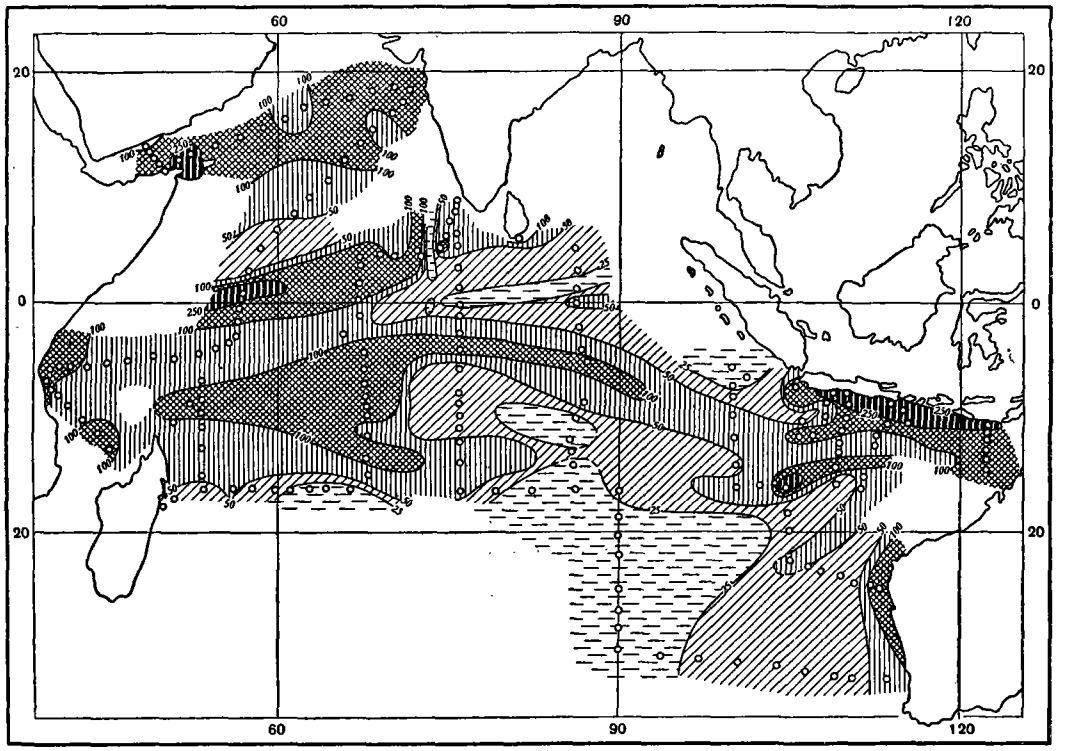


Рис. 2. Распределение биомассы планктона в Индийском океане в $см^3/1000\ м^3$ (по В. Г. Богорову и А. П. Виноградову, 1961)

ясняется отсутствием условий для поднятия глубинных вод к поверхности. Далее к югу (после 38° ю. ш.) количество планктона снова увеличивается (Богоров и Виноградов, 1961).

Аналогичные черты проявляются и в распределении планктона в Тихом океане, где биомасса его увеличивается в экваториальной зоне в связи с выходом на поверхность глубинных вод.

По отношению к фитопланктону все остальные организмы моря являются потребителями и могут лишь трансформировать органическое вещество, но не созидать его. Обычно вслед за развитием фитопланктона бурно развивается зоопланктон, который в значительной мере его выедает. Та же часть планктона, которая не потребляется непосредственно другими организмами, а погибает естественной смертью, подвергается интенсивному, бактериальному разложению. Экспериментальными исследованиями было установлено, что разложение отмерших организмов планктона, осуществляемое микрофлорой, происходит с убывающей скоростью и стабилизируется в сравнительно короткий срок.

В процессе потребления органического вещества другими организмами большая часть его подвергается распаду и вновь возвращается в воду в виде биогенных элементов. Это разрушение органического вещества в некоторой степени компенсируется синтезом его в телах гетеротрофных организмов. Кроме того, гетеротрофные организмы никогда не усваивают его полностью, некоторая часть выбрасывается организмами и в условиях водоема попадает в осадки. В целом из гетеротрофного цикла гидросферы по мнению В. А. Успенского выпадает около 0,8% органического вещества, созданного автотрофными организмами (Успенский, 1956).

Однако прежде чем перейти в осадок, все живое вещество в морских бассейнах проходит сложные пищевые цепи и благодаря этому подвергается интенсивной перестройке, что отражается на изменении его химического состава.

Изучение химического состава планктона Индийского океана показало, что содержание $C_{орг}$ изменяется в нем от 19,97 до 31,11%, общего азота — от 5,58 до 9,60. Таким образом, по содержанию указанных элементов планктон различных районов Индийского океана заметно различен между собой, несмотря на то, что в видовом отношении он довольно близок.

В еще большей степени эти различия ощутимы в содержании липидов. Количество последних колеблется от 6,42 до 13,63%. Более 90% липидов представлено мало полярными соединениями, переходящими при экстракции в хлороформенный экстракт. Это положение подтверждается также данными компонентного анализа липидной фракции (в %):

Масла	48,25
Смолы бензольные	3,35
Смолы спиртобензольные	33,20
Асфальтены	6,55

В липидной фракции было обнаружено также присутствие значительного количества аминокислот.

Если сравнить содержание углерода и азота в планктоне с содержанием этих элементов в океанских водах, то можно заметить, что последние примерно вдвое беднее азотистыми соединениями. Судя по отношению C/N, которое в среднем равно 10, органическое вещество океанских вод по своему составу гораздо ближе стоит к органическому веществу современных донных осадков, чем веществу исходных организмов.

В целом исследованные осадки характеризуются невысоким содержанием органического вещества. Количество $C_{орг}$ лишь в редких случаях поднимается до 1—1,5%. Наиболее бедны органическим веществом глинистые осадки центральных областей океанов. Например в глинистых илах Тихого океана содержание $C_{орг}$ составляет в среднем 0,20%.

Примерно такой же низкой концентрацией характеризуются глинисто-алевритовые илы (0,26%). Концентрация органического вещества в алевритово-глинистых илах несколько возрастает (0,35%) и достигает максимального значения в алевритовых (0,40%). В песках вновь наблюдается некоторое снижение содержания органического вещества (0,34%).

Таким образом, в распределении органического вещества в океанских осадках не отмечается обычной связи с гранулометрическим составом осадков, выражающейся в возрастании его концентрации по мере увеличения дисперсности осадков.

Обращает на себя внимание тот факт, что наиболее обогащены органическим веществом менее дисперсные-алевритовые и алевритово-глинистые илы, тогда как более дисперсные глинистые илы характеризуются пониженной концентрацией. Аналогичная черта наблюдалась и в распределении органического вещества в глубоководных осадках Берингова моря, где также максимальные концентрации органического вещества были встречены в алевритовых и алевритово-глинистых илах из района основания материкового склона (Лисицын, 1955).

В распределении органического вещества по площади дна в океанских осадках наблюдается определенное тяготение повышенных концентраций к районам, изобилующим планктоном.

Гуминовые кислоты

В подавляющем большинстве исследованных осадков были обнаружены гуминовые кислоты, которые широко распространены также во многих ископаемых осадочных породах. Некоторые исследователи отводят этой группе веществ немаловажную роль в образовании нефти (Соколов, 1951; Мехтиев и Дигурова, 1952). В частности, А. Ф. Добрянский отмечает, что способность гуминовых структур легко терять в процессе преобразования карбоксильные группы при сохранении фенольных заслуживает внимания в связи с вопросом происхождения циклинических компонентов нефтей (Добрянский, 1948). Другие исследователи, напротив, в возникновении гуминовых веществ видят фактор отрицательный для битуминизации (Вебер, 1950).

Гуминовые кислоты возникают в окислительных условиях благодаря воздействию микроорганизмов на органические остатки. Часть органического вещества, избежавшая полного разложения, преобразуется при этом в более стабильную в данных условиях структуру. Характерно, что несмотря на разнообразие исходного материала, возникающие гуминовые кислоты обладают близким химическим составом (Успенский и Радченко, 1955).

Гуминовые кислоты в осадках морских и океанских бассейнов имеют двоякое происхождение. Часть гуминовых кислот, поступающая с речными водами, по мнению Б. А. Скопинцева, способна проникать в дальние морские просторы (Скопинцев, 1947). Однако подобные аллохтонные гуминовые кислоты могут приобретать существенное значение лишь в бассейнах, где велика роль речного стока.

Основным источником гуминовых кислот, как и всего органического вещества осадков, в морских и океанских бассейнах служит автохтонное вещество, связанное, главным образом, с планктоном.

Об этом свидетельствует наличие гуминовых кислот в осадках центральных областей океана, достаточно удаленных от влияния материкового стока, а также в отложениях района Антарктиды, где поступление гуминовых кислот с суши не происходит.

Содержание гуминовых кислот в исследованных осадках колеблется от 0 до 0,75% и составляет в среднем 0,13% [1]. Для сравнения можно указать, что в осадках Каспийского моря содержание гуминовых кислот составляет 0,02—0,20%, в окраинных морях 0,13—0,80%, а в отложениях Черного моря 0,14—0,38% (Вебер, 1956; Горская, 1956).

Таким образом, современные субаквальные осадки различных морских и океанских бассейнов характеризуются довольно близким содержанием гуминовых кислот.

В распределении гуминовых кислот по типам осадков определенно видна тенденция к увеличению их концентрации в осадках обогащенным органическим веществом. В глинистых илах среднее содержание составляет 0,10%, в глинисто-известковых —0,07%. Более высокие концентрации наблюдаются в карбонатных осадках. В алевритово-глинистых илах содержание составляет 0,10% и достигает максимальной концентрации в алевритовых илах — 0,23%; в песках содержание их вновь снижается (0,13%). Таким образом, максимальные концентрации гуминовых кислот приурочены к осадкам, обогащенным органическим веществом.

Прямая зависимость между концентрацией органического вещества и содержанием гуминовых кислот была установлена ранее автором в отложениях Берингова моря (Бордовский, 1957; 1960), а также

[1] Под понятием «гуминовые кислоты» подразумеваются вещества, экстрагированные 2%-ным раствором КОН при температуре 60—70° С из образцов, предварительно освобожденных от битума. Содержание гуминовых кислот определялось колориметрически.

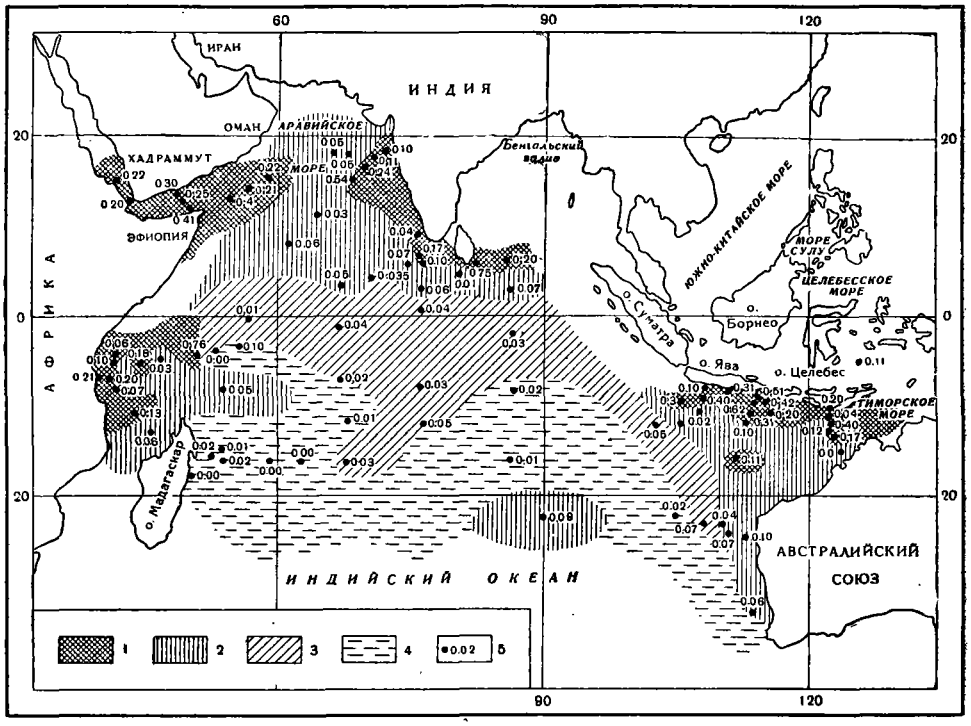


Рис. 3. Схема распределения гуминовых кислот в верхнем слое осадков Индийского океана

Концентрация гуминовых кислот: *1* — более 0,1%; *2* — от 0,1 до 0,05%; *3* — от 0,05 до 0,03%; *4* — менее 0,03%; *5* — содержание гуминовых кислот в процентах на осадок

Е. А. Романкевич в осадках северо-западной части Тихого океана (Романкевич, 1962) и В. В. Вебером в различных осадках фаций заливов Каспийского моря (Вебер, 1956). Увеличение содержания гуминовых кислот с возрастанием концентрации органического вещества наблюдается также и в некоторых ископаемых осадочных породах (Мехтиев и Дигурова, 1952; Андреев и др., 1953). Таким образом, эта особенность характерна, по-видимому, как для современных донных осадков, так и для некоторых ископаемых пород.

Связь с органическим веществом проявляется и в распределении гуминовых кислот по площади дна бассейна. В Индийском океане зона повышенной концентрации гуминовых кислот явно тяготеет к прибрежным высокопродуктивным районам (рис. 3).

Особенно обогащены гуминовыми кислотами отложения глубоководной Яванской впадины, района о. Цейлон и западного побережья полуострова Индостан, осадки Аденского залива и восточного побережья Африки. Все перечисленные районы изобилуют планктоном, что обусловлено выходом на поверхность обогащенных биогенными элементами водных масс.

Несколько меньшим содержанием гуминовых кислот характеризуются отложения глубоководной океанской области до 15° ю. ш., что также соответствует обеднению планктоном водной массы этого района.

Чрезвычайно низкие концентрации гуминовых кислот свойственны осадкам, распространенным ниже 15° ю. ш. Этот район соответствует зоне центральной индийской водной массы и отличается исключительной бедностью планктоном.

Приведенные данные показывают, что между количеством гуминовых кислот в осадках и распределением биомассы планктона в водной толще наблюдается прямая связь, что отражается и в сходстве схем. Аналогичная связь наблюдается в распределении гуминовых кислот в осадках Тихого океана.

Эти факты с несомненностью свидетельствуют о том, что основным источником гуминовых кислот являются остатки планктонных организмов [1].

Относительное содержание гуминовых кислот в составе органического вещества исследованных осадков, или гуминовый коэффициент, изменяется от 1 до 10%. Таким образом, роль гуминовых кислот в составе органического вещества океанских осадков весьма невелика.

В распределении гуминовых кислот в толще осадков определенной связи с глубиной захоронения не наблюдается. В одних колонках содержание их остается на протяжении всей исследованной толщи довольно постоянным, в других — колеблется в широком диапазоне величин, что видимо связано с изменением условий осадконакопления.

Битумы

Хотя битумы составляют незначительную долю органического вещества в морских осадках, большинство исследователей отводит им ведущую роль в образовании нефти. Именно в связи с решением этой проблемы было начато исследование рассеянных битумов в ископаемых породах и современных осадках, так как в них видели источник, обладающий наибольшими потенциальными возможностями для образования нефти. Особенно возрос интерес к ним в последнее время в связи с открытием в составе битумов современных морских осадков жидких углеводородов.

Присутствие битумов в современных морских осадках обусловлено с одной стороны наличием их в живом веществе исходных организмов, с другой — возникновением в клетках организмов-потребителей при биологическом преобразовании этого вещества.

В основном источнике органического вещества морских осадков — в организмах планктона, как уже говорилось выше, содержится значительное количество битумов (липидов). Битумы и особенно содержащиеся в них углеводороды являются довольно устойчивыми по отношению к биологическому окислению компонентами органического вещества и благодаря этому могут аккумулироваться в осадках. Бо́льшая же часть органического вещества планктона, представленная углеводами и белками, после гибели организмов легко подвергается микробиологическому разложению. Развивающаяся за счет подобных легко усвояемых веществ микрофлора трансформирует часть их в свои клетки, в которых также содержится битум. По различным данным, в клетках бактерий заключено от 3,4 до 6,5% битумов на сухой вес и в составе́ их содержатся углеводороды (Stone and Zobell, 1952). Таким образом, благодаря микробиологическим процессам часть небитумных компонентов органического вещества может преобразовываться в битумы.

Битуминозность исследованных осадков колеблется от 0,01 до 0,07% на сухой осадок и в среднем составляет 0,03%, тогда как по данным Траска средняя битуминозность современных морских осадков составляет 0,06% [2]. Таким образом, океанские осадки отличаются пониженной

[1] Это положение полностью согласуется с выводом Л. А. Гуляевой, что гуминоподобные вещества в породах доманика Башкирии возникли при окислении в толще воды мельчайших телец планктонных организмов (Гуляева и Гамаюнова, 1962).

[2] Битуминозность определялась путем экстракции на аппарате Сокслета смесью, состоящей из 70% бензола, 15% ацетона и 15% метанола.

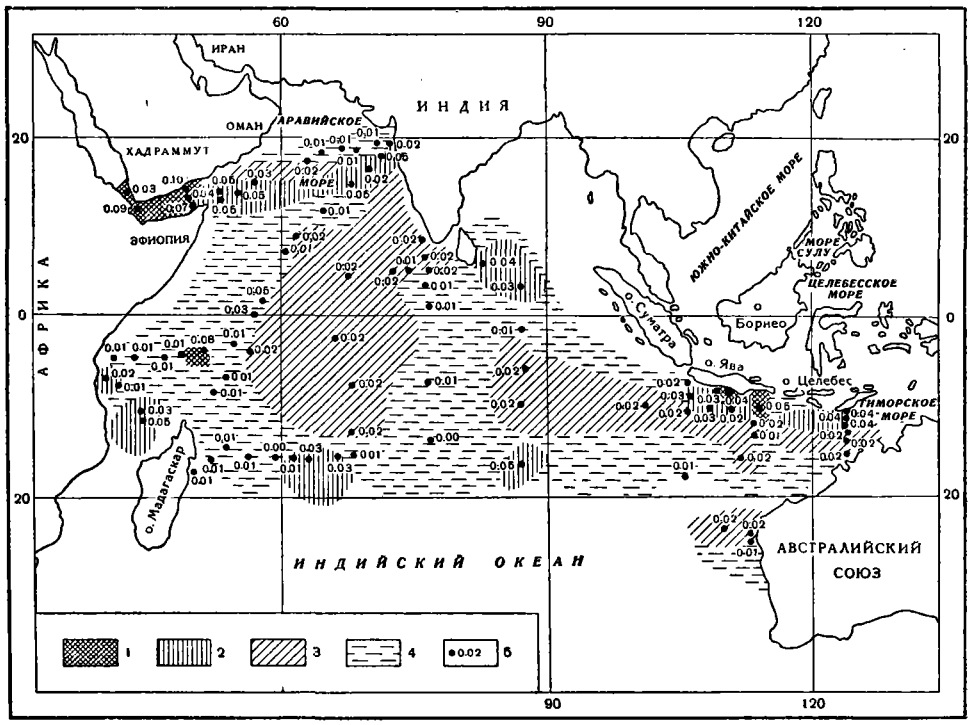


Рис. 4. Схема распределения битуминозных веществ в верхнем слое осадков Индийского океана

1 — более 0,05%; *2* — 0,05—0,03%; *3* — 0.02%; *4* — 0,01%; *5* — содержание битума в % на осадок

битуминозностью, что, по-видимому, обусловлено пониженной концентрацией органического вещества.

В распределении битумов по типам осадков определенной связи битуминозности с типами отложений не наблюдается и все они характеризуются довольно близкими средними величинами концентрации битуминозных веществ. В пределах каждого типа осадков битуминозность меняется в довольно широких пределах и более общей закономерностью является зависимость битуминозности осадков от концентрации органического вещества. Прямая связь между битуминозностью осадков и содержанием органического вещества была установлена автором также в донных отложениях Берингова моря (Бордовский, 1957).

Относительное содержание битуминозного вещества в составе органического вещества осадков или битумный коэффициент колеблется в пределах от 1 до 10% и более высокие его значения приурочены к бескарбонатным глинистым илам. Для сравнения можно указать, что в отложениях Берингова моря битумный коэффициент изменяется в пределах от 2,3 до 11,3% и в среднем составляет 5,0%. В целом, по степени битуминизации органическое вещество современных морских и океанских осадков отличается несколько более высокими битумными коэффициентами, чем органическое вещество ископаемых осадочных пород, в которых битумный коэффициент составляет в среднем около 3% (Успенский и др., 1948).

По сравнению с относительным содержанием битуминозных веществ в составе органического вещества планктона, органическое вещество осадков в 5—8 раз беднее битумом. Даже самые высокие значения битумного коэффициента осадков далеки от исходной величины.

Вместе с тем, между битуминозностью осадков и биомассой планктона в водной толще видна прямая связь (рис. 4). Повышенной битуминозностью осадков отличаются отложения глубоководной Яванской

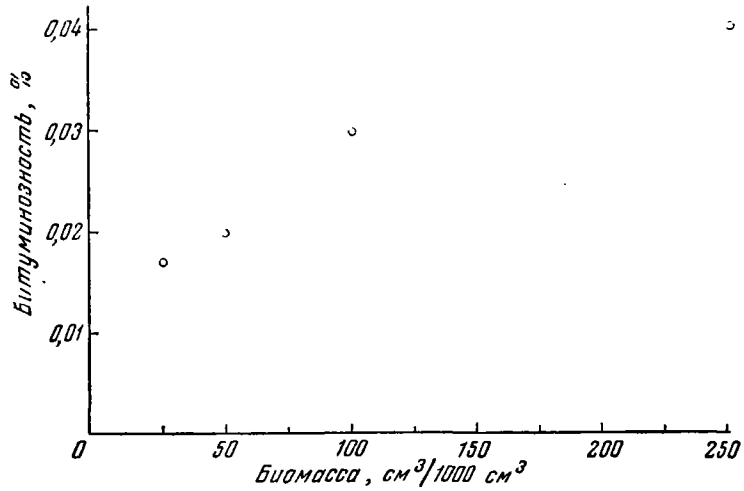


Рис. 5. Зависимость между битуминозностью осадков и биомассой планктона в поверхностных водах в Тихом океане (по осредненным данным)

впадины, о. Цейлон, Аравийского моря и восточного побережья Африки. Особенно высокой битуминозностью характеризуются отложения Аденского залива. Как уже говорилось, эти районы отличаются чрезвычайно высокой биомассой планктонных организмов.

С удалением от высокопродуктивных районов битуминозность осадков снижается и особенно низкой битуминозностью характеризуются осадки зоны распространения малопродуктивной центральной водной массы Индийского океана.

В осадках Тихого океана также наблюдается прямая связь между битуминозностью донных отложений и биомассой планктона (рис. 5).

Таким образом, основным источником битуминозных веществ в осадках, как и всего органического вещества, являются планктонные организмы.

Выше было показано, что между распределением планктонных организмов в водной толще и накоплением гуминовых кислот в осадках наблюдается прямая зависимость.

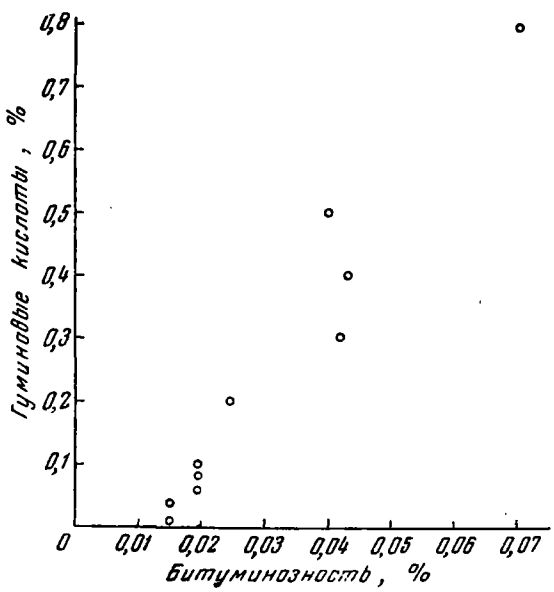


Рис. 6. Зависимость между битуминозностью осадков и содержанием гуминовых кислот (по осредненным данным)

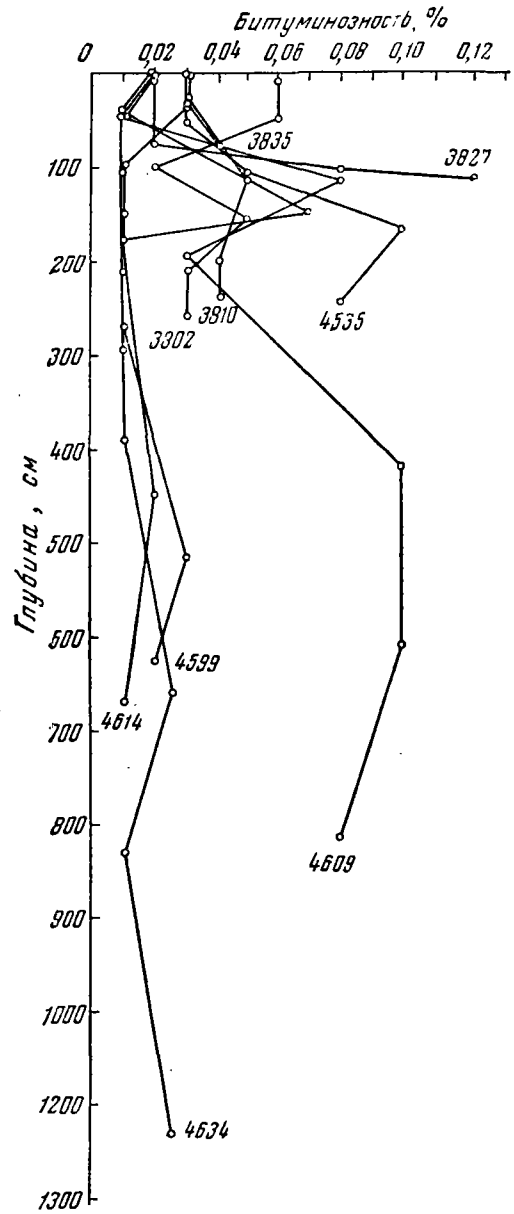


Рис. 7. Распределение битуминозных веществ в толще океанских осадков

Схема распределения гуминовых кислот в донных отложениях в отдельных районах полностью соответствует распределению биомассы планктонных организмов в водной толще. Аналогичная картина наблюдается и в распределении битуминозных веществ в исследованных осадках. Из этого можно сделать вывод, что основным источником как гуминовых, так и битуминозных веществ в осадках являются планктонные организмы.

В связи с этим намечается близкая к прямой зависимость между битуминозностью осадков и содержанием в них гуминовых кислот (рис. 6).

Этот факт свидетельствует о том, что образование гуминовых кислот происходит за счет не битумных компонентов исходного органического вещества, а за счет более лабильных (белковых и углеводных) веществ, и в этом смысле процесс гумификации не является обратным процессу битуминизации.

В колонках осадков указанной зависимости между гуминовыми кислотами и битуминозностью не наблюдается, что, возможно, обусловлено различными путями преобразования этих компонентов в процессе диагенеза осадков.

По изменению битуминозности в толще осадков исследованные колонки можно разбить на несколько групп (рис. 7).

В ряде колонок (станция 4609 — глинисто-радиоляриевый ил, станция 3827 и 4535 — глинистые илы, станция 3840 — карбонатный алевритово-глинистый ил) битуминозность возрастает от верхних горизонтов к нижним в толще осадков. Все эти колонки, несмотря на различный состав осадков и разнообразие батиметрических условий, отличаются пониженными или отрицательными значениями окислительно-восстановительного потенциала и повышенной минерализацией грунтового раствора.

К другой группе относятся колонки, в которых битуминозность не только не возрастает вниз по разрезу, но в отдельных случаях даже снижается (например станция 3802). Эта группа охватывает разнооб-

разные типы осадков: глинисто-радиоляриевый ил — станция 3802, слабокарбонатные глинисто-алевритовые илы — станции 4614 и 4634 и карбонатный алевритово-глинистый ил — станция 3835.

Характерной чертой окислительно-восстановительного состояния всех этих колонок являются высокие положительные значения Eh, более-менее стабильные pH, а в ряде случаев — заметное снижение щелочности грунтовых растворов.

Наконец, особое положение занимает колонка станции 4599, где на горизонте 400—600 *см* битуминозность возрастает, хотя вся толща осадка характеризуется высокими положительными значениями Eh и низкой щелочностью грунтового раствора.

Как видно из приведенных данных, намечается тенденция к увеличению содержания битуминозных веществ в процессе раннего диагенеза в тех осадках, где наблюдается интенсивное преобразование органического вещества (о чем свидетельствует понижение Eh и увеличение щелочности грунтовых растворов). В тех отложениях, где процессы преобразования органического вещества осуществляются крайне вяло, увеличение битуминозности не наблюдается. И, наконец, в отдельных случаях, несмотря на окислительные условия среды осадка и низкую щелочность грунтового раствора, на некоторых горизонтах битуминозность возрастает, что, возможно, связано с нестабильностью условий осадконакопления.

По данным элементарного анализа, битумы исследованных осадков характеризуются следующим составом: C — от 61,59 до 72,48%, H — от 8,71 до 10,56% и N — от 1,23 до 3,80%. Отношение C/H изменяется в пределах от 6,09 до 7,42 (табл. 1).

Таблица 1

Элементарный состав битумов океанских осадков

Осадки	Элементарный состав				
	C	H	N	C/H	O+S
Глинистые илы . .	64,69—71,94	8,71—10,56	1,23—2,96	6,65—7,42	15,61—24,33
Алевритово-глинистые илы	61,59—71,19	10,10—10,11	3,21—3,55	6,09—7,12	15,16—24,51
Алевритовые илы	71,42—72,48	10,08—10,12	2,87—3,04	7,09—7,14	14,53—15,46
Пески	66,92—70,24	9,31—10,21	1,32—3,41	6,69—7,29	18,00—20,36

Для большинства образцов колебания в содержании указанных элементов укладываются в более узкие пределы, что свидетельствует о близком составе битумов.

Не удается заметить и какой-либо систематической связи между составом битумов и типами осадков. Несмотря на отдельные отклонения, средние данные элементарного состава битумов осадков различного типа достаточно близки между собой.

Не наблюдается также заметных различий в элементарном составе битумов однотипных осадков, взятых из различных фациальных обстановок. Например глинистые илы, взятые на глубине 240 *м* (станция 78), характеризуются примерно таким же составом, как и аналогичный осадок с глубины более 2 *км* (станция 33).

	C	H	N	C/H
Станция 78 (глубина 240 *м*)	67,84	10,20	1,23	6,65
» 33 (» 2230 *м*)	68,51	9,92	2,84	6,95

Это же положение наблюдается и в других группах осадков.

Близкий состав битумов исследованных осадков, по-видимому, следует объяснять однообразием исходного органического вещества, основным источником которого, как уже говорилось, является фитопланктон.

Для дальнейшей характеристики битумов проводилось исследование их группового состава.

Количество асфальтенов определялось путем осаждения легким петролейным эфиром. Дальнейшее разделение осуществлялось хроматографически на колонке с силикагелем. Фракция масел определялась отмывкой петролейным эфиром, а адсорбированные силикагелем смолы извлекались смесью бензола, ацетона и метанола.

Представление о групповом составе исследованных битумов дает табл. 2.

Таблица 2

Групповой состав битумов океанских осадков

Тип осадков	Асфальтены	Среднее	Смолы	Среднее	Масла	Среднее
Бескарбонатные глинистые илы	69,6—77,1	73,3	17,7—21,3	19,0	5,2—5,4	5,3
Слабокарбонатные глинисто-алевритовые илы	71,8—75,0	73,4	16,0—17,6	16,8	4,4—7,3	5,9
Карбонатные алевритово-глинистые илы . . .	58,8—66,1	62,4	19,3—32,4	25,9	6,2—8,8	7,5

Как видно из табл. 2, отличительной чертой состава битумов является высокое содержание асфальтенов (от 59 до 77%). Содержание смол колеблется от 16 до 32%. Количество масел во всех исследованных битумах составляет величину порядка 4,4—8,8%.

Сопоставление группового состава битумов показывает, что несмотря на некоторые колебания состав их отличается достаточным однообразием. Это положение подтверждает сделанный ранее на основании элементарного состава вывод о близком составе исследованных битумов.

Так же как и в том случае, нет заметных различий между групповым составом осадков разных типов. Не оказывают существенного влияния на состав битумов и различия в батиметрических условиях нахождения осадков. Например, битум известкового алевритозо-глинистого ила, взятого на глубине 890 *м* (станция 4728), характеризуется, примерно, таким же составом, как и битум глинистого ила с глубины около 4 *км* (ст. 4511).

		Смолы	Масла
Станция 4728 (глубина 890 *м*)	66,1	19,3	6,2
» 4511 (» 3875 *м*)	69,6	21,3	5,4

В среднем битумы исследованных осадков на 70% состоят из асфальтенов, на 20% — из смолистых веществ и на 6—7% — из масел. Примерно таким же составом характеризовались битумы современных осадков Берингова моря, исследованные аналогичным методом (асфальтены — 65%, смолы — 24% и масла — около 10%). Таким образом, битумы современных глубоководных субаквальных осадков характеризуются довольно близким составом, причем подавляющую часть их составляют асфальтены, а роль наиболее близких в генетическом отношении к нефти масляных компонентов весьма скромна.

Существенно иным составом характеризовался битум из обломков кораллового рифа (Мальдивские острова). Отличительной чертой его состава является пониженное содержание асфальтенов и соответственно более высокое содержание смол и масел (асфальтены — 36,1%,

смолы — 33,4% и масла — 23,9%). По своему групповому составу исследованный битум весьма напоминает липидную фракцию исходных живых организмов.

Как уже говорилось, основным источником органического вещества исследованных осадков является продукция планктонных организмов. В этой связи интересно сопоставить групповой состав липидной фракции планктона с групповым составом битумов донных отложений. Это сравнение показывает, что липидная фракция в процессе седиментации подвергается существенному преобразованию, в результате чего в ее составе заметно возрастает роль асфальтеноподобных веществ, при соответствующем снижении относительного содержания смол и масел.

Чрезвычайно малые количества битуминозных веществ не позволили разделить на компоненты битумы исследованных колонок. Компонентный состав (в %) был определен только в двух образцах колонки станции 4609 (горизонты 433—460 *см* и 550—590 *см*):

	Асфальтены	Смолы	Масло
Станция 4609 горизонт 433—460 *см*	69,8	14,3	15,1
» » » 550—590 *см*	71,3	15,2	12,6

По содержанию асфальтенов данные битумы не имеют заметных отличий от битумов верхнего слоя осадков. В отношении содержания смолистых компонентов наблюдается некоторое уменьшение их относительного количества при соответствующем увеличении роли масел.

Подобные же черты преобразования битуминозных веществ были прослежены нами в толще отложений Берингова моря (Бордовский, 1959). В процессе диагенетического преобразования в этих отложениях наблюдалось постепенное увеличение содержания масел в составе битумов при одновременном снижении содержания смолистых компонентов. Возможно, что подобным же путем преобразуются битуминозные вещества в колонке станции 4609, в которой, как уже говорилось, наблюдается увеличение содержания битума на фоне процесса энергичного преобразования органического вещества, о чем свидетельствуют пониженные значения Eh и значительная минерализация грунтового раствора.

Растворенное органическое вещество, щелочность и аммонийный азот в грунтовых растворах осадков

Растворенное органическое вещество представляет значительный интерес как для проблемы происхождения нефти, так и для выяснения процессов ее миграции и образования скоплений. В нефтяной геологии широко распространено представление, что совместно с водой, выжимаемой из осадков в результате седиментационного уплотнения, могут мигрировать нефтяные углеводороды.

Исследования Е. Г. Бейкера показали, что в экспериментальных условиях некоторые ароматические и парафиновые углеводороды в электролитах типа седиментационных вод обладают растворимостью, причем последняя заметно изменяется в зависимости от состава самих растворов. Бейкер (1960) пришел к выводу, что существует определенная связь между составом нефти и растворимостью углеводородов в разбавленных коллоидных растворах электролитов.

Реальность процессов миграции растворенного органического вещества в грунтовых растворах в природной обстановке была доказана И. А. Юркевичем, которым обнаружено вторичное обогащение песчаных осадков некоторыми органическими компонентами за счет миграции их из вышележащих органогенных илов на ранних стадиях диагенеза (Юркевич, 1955; 1956; 1962). Было отмечено также явное

качественное отличие органического материала песков от органического материала самих илов. Оказалось, что доля гидролизуемых веществ в песках составляет 50—70%, тогда как в илах — всего 20—30%.

Как это было установлено Е. А. Барс, количество и состав органического вещества в пластовых водах являются прямым поисковым признаком на нефть (Барс, 1957; Барс и Коган, 1962). Однако, как справедливо отмечает Е. А. Барс, растворенное органическое вещество природных вод остается до сих пор одним из наименее исследованных компонентов (Барс и Носова, 1962). Естественно поэтому, что изучение условий его образования и дальнейших превращений представляет один из актуальных вопросов нефтяной геологии.

Таблица 3

Содержание органического углерода в грунтовых растворах некоторых океанских осадков

Номер станции	Горизонт	Физико-химическая характеристика осадков		Химический состав грунтовых растворов		
		pH	Eh, *мв*	ΔIK, *мг·экв/л*	NH_4—N, *мг/л*	$C_{орг}$, *мг/л*
			Красные глины			
3793	2—10	7,52	+512	0,505	0,93	22,6
	55—60	7,36	+532	1,124	1,239	12,3
	100—110	7,35	+547	1,693	0,592	9,3
	260—270	8,72	+357	2,487	0,980	6,4
	320—330	7,35	+483	2,267	0,654	6,5
3827	0—10	7,22	+475	1,858	0,531	14,2
	22—35	7,14	+405	9,888	0,480	12,0
	64—76	7,26	+436	1,524	0,746	11,4
	100—112	7,64	+218	3,356	0,725	10,6
3856	2—15	7,28	+450	2,500	0,036	12,0
	102—120	7,52	+439	2,497	0,281	11,0
	222—240	7,54	+469	2,087	0,390	9,0
3802	0—12	7,60	+529	2,868	0,178	14,0
	50—62	7,34	+532	2,480	0,138	12,3
	150—162	7,24	+502	1,585	0,370	11,0
	246—256	7,52	+492	2,009	0,104	9,1
			Алевритово-глинистые илы			
3838	0—10	7,42	+231	1,996	1,126	23,1
	42—52	6,98	+193	4,208	1,020	—
	106—116	7,20	+195	5,954	0,788	28,2
	232—242	7,38	+190	8,002	0,847	43,4
	292—306	7,50	+177	9,801	0,826	48,8
			Глобигериновые илы			
3840	0—5	6,74	+317	2,987	0,672	16,8
	22—40	7,48	+328	2,838	0,480	20,3
	100—115	7,52	+208	2,399	0,417	16,3
	182—200	7,32	+314	3,616	0,390	14,6
			Фораминиферовые илы			
3835	0—10	7,38	+430	2,412	—	15,6
	32—45	7,74	+249	1,975	—	16,8
	72—80	7,60	+157	1,865	—	14,6
3854	22—40	8,02	+363	2,957	0,308	16,1
	152—172	8,42	+389	2,767	0,282	10,0
	202—220	—	+395	2,477	0,432	8,3

Определение содержания органического углерода в грунтовых растворах океанских осадков показало, что концентрация его [1] по крайней мере на порядок выше, чем в водной толще (табл. 3).

В красных глинах концентрация органического углерода изменяется от 22,6 до 6,4 *мг/л* (рис. 8). Характерной чертой распределения $C_{орг}$ по колонкам осадков этого типа является отчетливое понижение концентрации углерода в грунтовых растворах. В отдельных случаях содержание его сокращается почти в четыре раза (станция 3793).

Аналогичное явление наблюдается и в глинисто-радиоляриевых илах (станция 3802), где концентрация С снижается от 14,0 *мг/л* в верхнем горизонте до 9,1 *мг/л* в нижнем.

Несколько иное распределение органического углерода характерно для алевритово-глинистых илов (станция 3838), где концентрация его, наоборот, возрастает от 23,1 *мг/л* в верхнем слое до 43,8 *мг/л* на нижнем горизонте.

Следует отметить, что это сравнительно мелководная прибрежная станция. Судя по величине Eh и концентрации аммонийного азота в грунтовом растворе, в этих отложениях осуществляется интенсивное преобразование органического вещества.

В глобигериновых илах также содержание $C_{орг}$ в жидкой фазе изменяется от 16,8 в верхнем горизонте до 14,6 *мг/л* в нижнем (станция 3840).

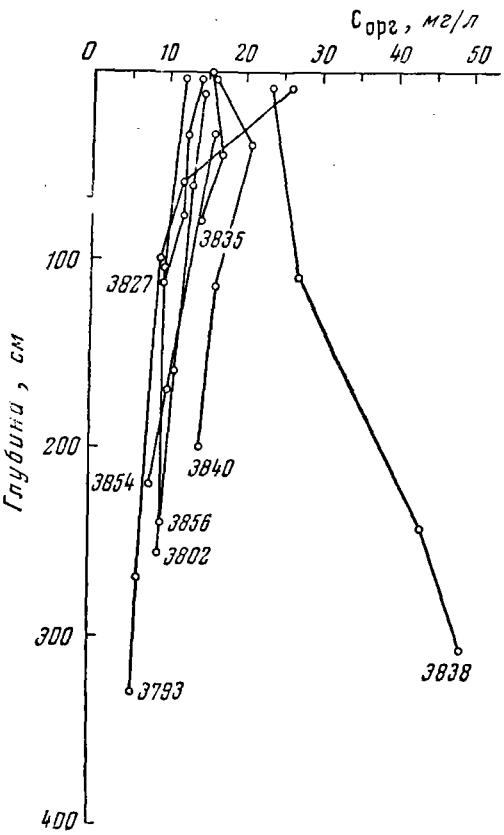


Рис. 8. Распределение органического углерода в грунтовых растворах океанских осадков

Снижение концентрации органического углерода в жидкой фазе наблюдается и в фораминиферовых илах (станции 3825 и 3854).

Приведенный материал показывает, что в осадках, характеризующихся окислительными условиями и незначительной минерализацией грунтовых растворов, накопление органического вещества происходит только в верхних горизонтах, а ниже, видимо, в связи с распадом, концентрация его снижается. В отложениях, отличающихся пониженными значениями окислительно-восстановительного потенциала и заметной минерализацией грунтового раствора, содержание органического углерода, напротив, продолжает возрастать углублением в толщу осадков. Поэтому подобные отложения являются более перспективными в отношении дальнейшей миграции органического вещества, находящегося в жидкой фазе.

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[1] *Определение* $C_{орг}$ в собранных нами пробах было любезно проведено Н. Д. Стариковой, ст. научным сотрудником Химического отдела Института океанологии АН СССР.

Щелочность грунтовых растворов тесно связана с минерализацией органического вещества. Как указывает С. В. Бруевич, повышение щелочного резерва грунтовых растворов в значительной степени является результатом восстановления сульфатов за счет органического вещества осадков. Распад органического вещества в осадках и выделение свободной углекислоты, а также, вероятно, и влияние полупродуктов распада являются одним из главнейших действующих факторов дальнейших процессов диагенеза осадков (Бруевич, 1956).

Характерной особенностью распределения щелочности в исследованных осадках является то обстоятельство, что величина ее в большинстве случаев не только не превышает щелочность придонной воды, но и в ряде случаев значительно ниже ее (табл. 4).

Таблица 4

Щелочность и аммонийный азот в придонной воде и в грунтовых растворах океанских осадков

Номер станции	Глубина, *м*	Придонная вода		Грунтовый раствор	
		щелочность, *мг·экв/л*	NH_4—N, *мг/л*	щелочность, *мг·экв/л*	NH_4—N, *мг/л*
3874	5237	2,737	—	0,467	—
3793	6008	2,687	—	0,505	0,93
3802	5349	2,857	0,061	2,868	0,18
3827	8927	2,519	0,075	1,858	0,531
3856	5306	2,500	0,036	2,497	0,281
3872	5738	2,227	—	2,087	0,070
3834	4604	2,432	—	1,616	—
3845	3798	2,421	—	2,440	0,36
3854	3422	2,617	—	3,326	0,34

В верхнем слое исследованных осадков щелочность меняется от 0,42 до 5,43 *мг·экв/л*. В красных глинах величина ее колеблется от 0,42 до 3,48 *мг·экв/л*, причем для большинства станций характерны значения, близкие по величине щелочности придонной воды. Значительное увеличение щелочности наблюдается в грунтовых растворах глинистых илов Яванской впадины, где щелочность достигает 3,528—3,587 *мг·экв/л* (станции 4530, 4535).

Отрицательные значения окислительно-восстановительного потенциала, низкие значения pH и высокая щелочность с несомненностью свидетельствуют, что несмотря на большую глубину впадины и окислительный режим водных масс, в осадки попадает органическое вещество, способное к дальнейшему активному преобразованию.

Невысокими показателями характеризуются глинистые известковые илы. Повышенные их значения были обнаружены только на станции 3837, расположенной у побережья Новой Зеландии и в грунтах Аравийского моря (станции 4707, 4709, 4713 и 4714).

Пониженная величина щелочности обнаружена также в алевритово-глинистых илах (станции 3831, 4680, 4649 и др.). Наряду с этим в ряде случаев в этих осадках встречена щелочность, превышающая щелочность придонной воды.

В алевритовых илах щелочность изменяется от 2,280 до 3,196 *мг·экв/л* и нигде не опускается ниже щелочности придонной воды. Щелочность песков изменяется в узких пределах — 2,152—2,734, что, повидимому, обусловлено как небольшим содержанием органического вещества, так и хорошей промываемостью этих грубодисперсных осадков.

Распределение щелочности в толще осадков имеет весьма прихотливый характер (рис. 9). В большинстве колонок щелочность, возрастая на отдельных горизонтах, не только не обнаруживает систематического увеличения книзу, но и, напротив, в ряде случаев снижается и достигает весьма низких величин (станции 3802, 4599, 4614, 4634, 3835).

Встречаются колонки, в которых почти вся толща осадков характеризуется устойчивыми низкими величинами щелочности.

Систематическое планомерное увеличение щелочности с глубиной в толще осадков наблюдалось лишь в нескольких случаях; при этом отложения характеризовались пониженными или отрицательными значениями Eh (станции 3827, 4535, 3840).

Рядом предыдущих работ было установлено, что в толще морских осадков щелочность, как правило, закономерно возрастает с переходом к нижним горизонтам. Как показывает приведенный материал, в исследованных океанских осадках щелочность в большинстве случаев в толще осадков остается близкой к щелочности придонной воды или даже несколько ниже ее. Закономерное увеличение щелочности в толще осадков встречается сравнительно редко и характерно в большинстве случаев для прибрежных районов.

Низкая щелочность специфична не только для отложений исследованного района. Подобное явление было отмечено Е. Д. Зайцевой для глубоководных отложений Берингова моря и С. В. Бруевичем для осадков Северо-западной части Тихого океана. Однако причины этого интересного явления до сих пор остаются неясными.

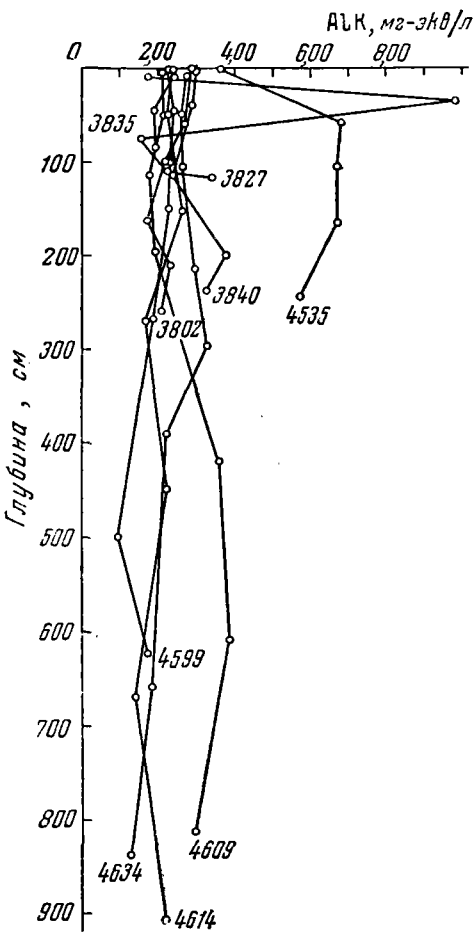


Рис. 9. Распределение щелочности в грунтовых растворах океанских осадков

Если щелочность в грунтовых растворах исследованных осадков, как было показано, близка к щелочности придонной воды или даже ниже ее, то концентрация аммонийного азота в грунтовом растворе, как правило, значительно выше, чем в придонной воде (см. табл. 4). Количество аммонийного азота варьирует в исследованных осадках от 0,03 до 1,13 *мг/л*. Красные глины отличаются весьма низким содержанием аммиака (0,06—0,77 *мг/л*). Подобными же низкими величинами характеризуются глинисто-известковые илы и лишь на станции 3838 концентрация аммиака поднимается до 1,13 *мг/л*. Несколько большими концентрациями отличаются карбонатные осадки, что, возможно, вызывается не только большим содержанием органического вещества, но и меньшей поглотительной способностью карбонатных илов.

Как известно, часть аммонийного азота входит в поглощающий комплекс осадка и поэтому концентрация его в грунтовом растворе не соответствует всему количеству, выделившемуся в процессе разложения органического вещества. По данным Е. Д. Зайцевой, содержание

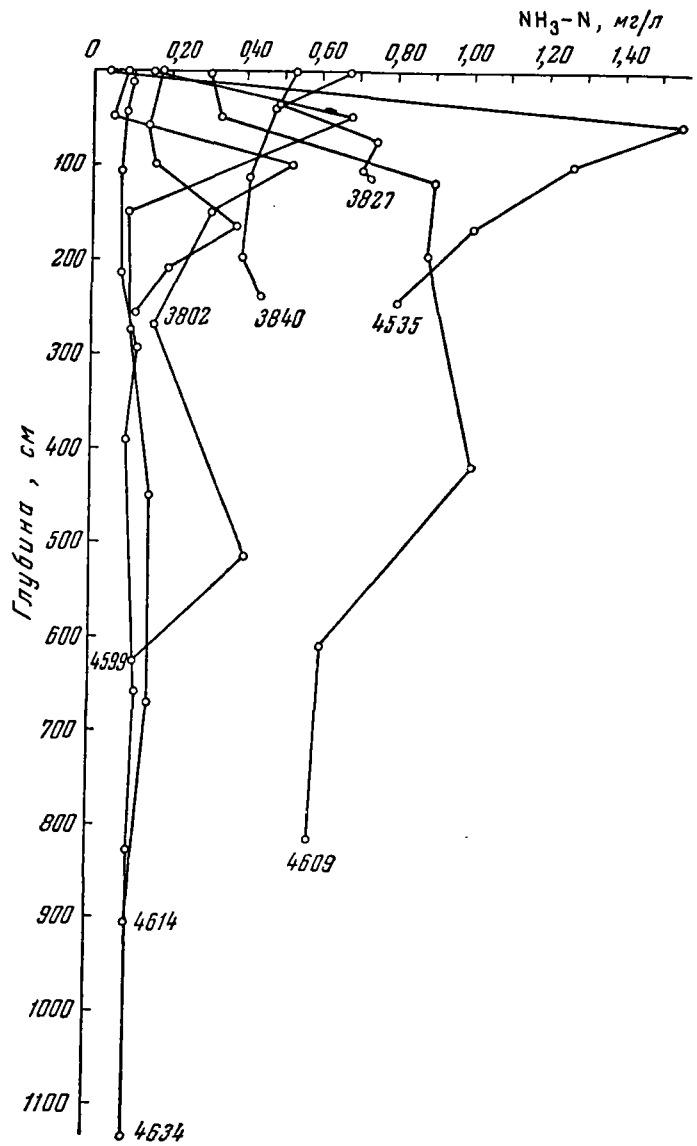


Рис. 10. Распределение аммонийного азота в грунтовых растворах океанских осадков

аммония в грунтовом растворе и в адсорбированном состоянии количественно близки (Зайцева, 1956). Так как изменение щелочности и аммонийного азота обусловлено одной и той же причиной — разложением органического вещества, то изменение этих показателей происходит обычно согласованно и в толще морских осадков они, как правило, явно увеличиваются с глубиной.

В исследованных осадках концентрации аммонийного азота в большинстве случаев остается довольно постоянной по всей толще исследованных отложений и в некоторых случаях даже несколько уменьшается к нижним горизонтам. Встречаются, правда, горизонты, из которых концентрация значительно возрастает, но в целом тенденция к увеличению содержания аммиака вниз по колонкам выражена не столь явно, как в обычных морских осадках (рис. 10).

Таким образом, в толще типичных океанских осадков, отличающимися высокими положительными значениями окислительно-восстановительного потенциала, характеристики грунтового раствора, связанные с преобразованием органического вещества (щелочность и аммонийный азот), мало изменяются по сравнению с верхними горизонтами осадков. Щелочность в этих отложениях не только не возрастает, но, в ряде случаев, заметно уменьшается по сравнению с придонной водой. Напротив, в отложениях, где наблюдается понижение окислительно-восстановительного потенциала, щелочность и содержание аммонийного азота в грунтовом растворе возрастает, что свидетельствует о процессах преобразования органического вещества. В этих отложениях наблюдается заметная минерализация грунтового раствора по сравнению с водной толщей.

Физико-химическая характеристика осадков[1]

Величина pH в осадках связана прежде всего с преобразованием органического вещества. В исследованных осадках она колеблется в пределах от 6,47 до 8,61. Для сравнения можно указать, что в образцах морских осадков района Калифорнии подобная величина варьировала от 6,4 до 9,5 (Zobell, 1946). В красных глинах она колеблется от 6,96 до 8,34, что скорее всего связано с вялой минерализацией и малым содержанием органического вещества, разложение которого не вызывает существенных изменений в концентрации водородных ионов в осадке.

Обращает на себя внимание тот факт, что пониженными значениями pH отличаются осадки с относительно низкими положительными значениями окислительно-восстановительного потенциала. В глинистых илах Яванской впадины эта связь выступает более отчетливо: пониженные значения pH приурочены к осадкам с отрицательными и низкими положительными значениями окислительно-восстановительного потенциала (станция 4535).

Указанная зависимость, по-видимому, обусловлена процессами распада органического вещества, при которых концентрация углекислоты в растворе возрастает, что вызывает изменение карбонатного равновесия и сопровождается понижением pH[2]. Одновременно распад органического вещества вызывает понижение окислительно-восстановительного потенциала всей системы.

В глинисто-известковых илах pH изменяется от 6,52 до 8,33, причем связь между изменением pH и окислительно-восстановительного потенциала проявляется достаточно ярко. Интересно отметить, что максимальные величины pH приурочены к наиболее глубоководным осадкам,

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[1] Определение pH и Eh производилось потенциометрически при помощи потенциометра ЛП-5.

[2] На величину pH оказывает также влияние температура. Как известно, глубоководные осадки характеризуются низкими температурами, близкими к 0°. Поэтому pH осадка in situ должно быть несколько выше. Вместе с тем высокое давление, господствующее на глубинах, изменяет константы диссоциации углекислоты, в результате чего pH снижается (Харвей, 1948).

тогда как минимальные значения, напротив, связаны с более мелководными осадками.

В карбонатных осадках — в алевритово-глинистых илах, алевритах и песках pH варьирует в широких пределах — от 6,47 до 8,07, причем указанная зависимость проявляется не во всех случаях достаточно отчетливо. Возможно, что это обстоятельство связано с обилием карбонатного материала, подщелачивающего среду.

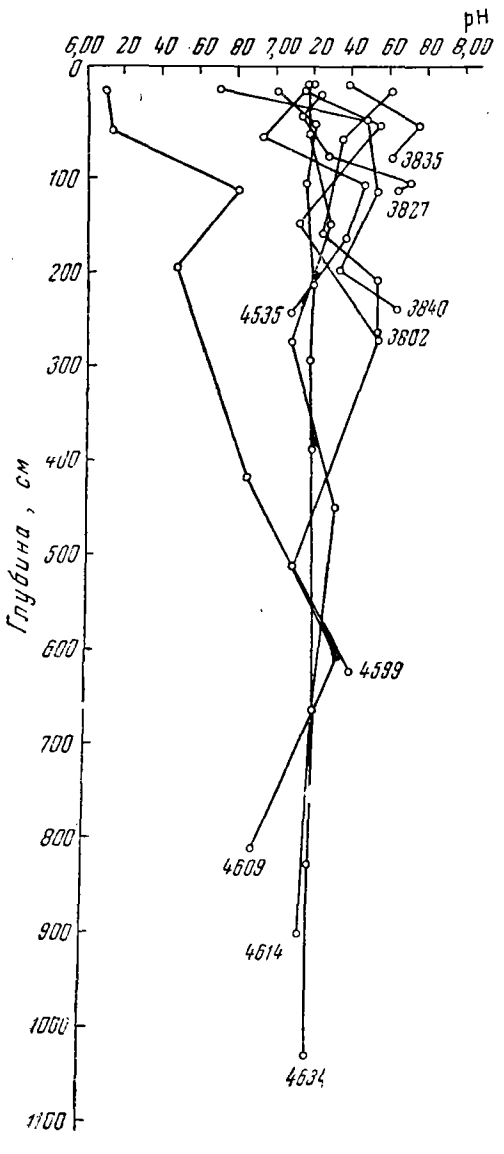


Рис. 11. Распределение pH в толще океанских осадков

Изучение рядом исследователей распределения pH в толще осадков показало, что в большинстве случаев pH заметно возрастает с глубиной. Однако в толще исследованных осадков величина pH изменяется различно (рис. 11). В одних колонках pH остается практически постоянной по всему разрезу (станции 3802, 4614). Характерно, что колонки этих отложений отличаются высокими положительными значениями окислительно-восстановительного потенциала.

Другую группу колонок составляют отложения, в которых pH возрастает от верхних горизонтов к нижним (станции 3827, 3835, 3840, 4599, 4634), при этом наблюдается снижение окислительно-восстановительного потенциала.

Согласованное изменение обоих этих величин говорит о том, что основным фактором, влияющим на изменение концентрации водородных ионов в процессе раннего диагенеза является преобразование органического вещества.

В верхнем слое исследованных осадков окислительно-восстановительный потенциал колеблется от —348 до +591 *мв*, причем большинство осадков характеризуется весьма высокими положительными значениями его. Наиболее высокими положительными значениями потенциала отличаются красные глины, в которых величина его изменяется в сравнительно узких пределах — от +462 до +591 *мв*. Высокая окисленность осадков этого типа прежде всего обусловлена стабильностью и малой концентрацией органического вещества, а также значительной концентрацией высших окислов железа и марганца. Значительное содержание последних способствует стабилизации состояния высокой окисленности всей системы.

Известно, что для редукции элементов группы железа в процессе диагенеза требуются значительные количества органического вещества и по отношению к нему эти элементы можно рассматривать как активный окислитель. Поэтому высокая концентрация в красных глинах окислов железа и марганца является своего рода буфером, способствующим сохранению окислительных условий в осадке даже при значительной концентрации органического вещества.

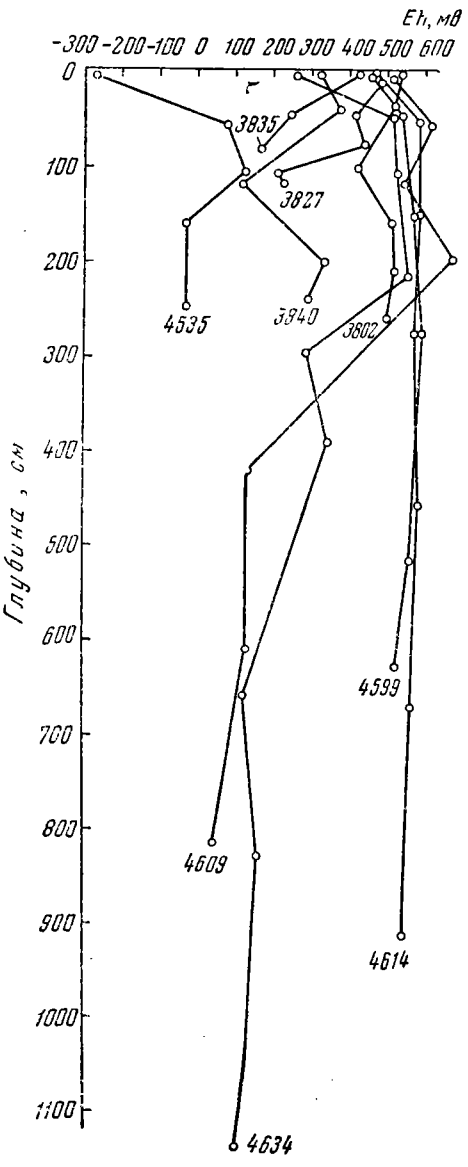


Рис. 12. Распределение Eh в толще океанских осадков

В отличие от красных глин. в глинистых илах Яванской впадины были встречены отрицательные и низкие положительные значения потенциала, свидетельствующие (как и повышенная щелочность в грунтовых растворах) об интенсивном преобразовании органического вещества. Исключение составляет лишь станция 4536, отличающаяся высоким положительным потенциалом (+524 *мв*) и, судя по цвету грунта (светло-серовато-коричневый), повышенным содержанием окислов железа и марганца.

В глинисто-известковых илах окислительно - восстановительный потенциал колеблется от —348 до +556 *мв*. Характерно. что отрицательные и низкие положительные значения его были встречены в Аравийском море (станции 4707, 4709, 4713) в районе, отличающемся высокой продуктивностью, а также у африканского побережья (станция 4694).

В целом повышенными значениями отличаются более глубоководные осадки этого типа, тогда как более мелководные характеризуются пониженными значениями.

В группе алевритово-глинистых илов окислительно-восстановительный потенциал колеблется от —316 до +524 *мв*, причем также отрицательными и низкими положительными значениями потенциала отличаются осадки района африканского побережья (станции 4674, 4675, 4681, 4693) и Аравийского моря (станции (4712, 4719, 4728 и 4730). Напротив, алевритово-глинистые илы открытых океанских районов характеризуются высокими положительными потенциалами, часто достигающими величин высокоокисленных красных глин. Эта близость физико-химических условий подчеркивается также тем обстоятельством, что в нескольких случаях в подобных высококарбонатных алевритово-глинистых илах были встречены железо-марганцевые конкреции.

В близких пределах изменяется окислительно-восстановительный потенциал и в алевритовых илах (от —343 до +548 *мв*), причем во всех случаях отрицательные и низкие положительные величины потенциала были зарегистрированы в осадках станций, расположенных в прибрежных районах (станции 4532, 4533, 4564, 4616, 4617, 4618, 4623 и 4688).

Отрицательными и низкими положительными потенциалами (от —218 до +124 *мв*) отличаются также песчаные осадки, хотя в органогенных карбонатных песках станции 4565, расположенной близ побережья Австралии, был зарегистрирован потенциал +417 *мв*. Высоким Eh отличаются также глобигериновые пески Тихого океана.

По изменению окислительно-восстановительного состояния в толще осадков, исследованные отложения резко делятся на две группы (рис. 12). В типичных глубоководных океанских отложениях в большинстве случаев Eh изменяется в незначительной степени и осадки на всем протяжении колонок характеризуются весьма высокими положительными значениями потенциала (станции 3802, 4599, 4614).

В некоторых колонках величина потенциала даже несколько увеличивается к нижним горизонтам.

Характерно, что горизонты, отличающиеся высокими значениями потенциала (+500—600 *мв*), во многих случаях содержат железо-марганцовые конкреции, которые встречаются как в глубоководных бескарбонатных глинистых илах, так и в высококарбонатных-глобигериновых, что также подтверждает вывод о близости физико-химических условий этих осадков. Вместе с тем наличие горизонтов железо-марганцевых конкреций в толще осадков свидетельствует о стабильности окислительно-восстановительного состояния осадка. В этой связи интересно отметить, что железо-марганцевые руды осадочного происхождения отличаются также весьма высокими значениями окислительно-восстановительного потенциала: +550—650 *мв* (Пустовалов и Соколова, 1957).

Другую группу колонок составляют отложения, в которых окислительно-восстановительный потенциал заметно снижается от верхних горизонтов к нижним (станции 4609, 3827, 4634, 3835, 3840).

Указанные различия в изменении физико-химических характеристик связаны, прежде всего, с процессами преобразования органического вещества. В типичных океанских отложениях эти процессы протекают крайне вяло и благодаря этому физико-химические свойства осадков остаются более-менее стабильными. В тех случаях, когда преобразование органического вещества протекает энергично, происходят заметные изменения физико-химических характеристик осадков. Этот вывод согласуется также с изменениями химического состава грунтовых растворов.

Выводы

Как видно из приведенного материала, основным источником органического вещества в исследованных осадках являются планктонные организмы. Намечается прямая связь между обилием планктона и концентрацией органического вещества в осадках. Районы с высокой биомассой планктонных организмов отличаются более высокой концентрацией органического вещества в осадках.

Хотя главным источником органического вещества осадков служат планктонные организмы, между составом органического вещества донных отложений и составом исходного живого вещества наблюдаются заметные различия.

Характерной чертой органического вещества осадков является появление такого новообразования, как гуминовые кислоты. В исходном веществе они отсутствовали и возникновение их обусловлено преобразованием части органического вещества в процессе седиментации.

Нахождение гуминовых кислот в осадках центральных частей океанов — в районах, достаточно удаленных от влияния материкового стока, а также в донных отложениях района Антарктиды, где поступление органического вещества с суши мало вероятно, говорит за их автохтонное происхождение. Кроме того, прямая связь между распределением гуминовых кислот в осадках и биомассой планктонных организмов в водной толще свидетельствует об образовании их из планктонных организмов.

Между содержанием гуминовых кислот в осадках и концентрацией органического углерода намечается прямая связь. Это явление наблюдается также в современных осадках других морских бассейнов и в некоторых ископаемых осадочных породах.

Содержание битуминозных веществ в исследованных осадках также находится в прямой связи с биомассой планктонных организмов. Таким образом, основным источником битумов в исследованных осадках являются остатки планктонных организмов.

Наблюдается прямая связь между битуминозностью осадков и содержанием в них органического углерода.

Подобная же зависимость была обнаружена нами ранее в донных отложениях Берингова моря.

Намечается также прямая связь между битуминозностью осадков и содержанием гуминовых кислот, из чего можно сделать вывод, что процесс гумификации органического вещества не затрагивает битуминозную фракцию.

По химическому составу битумы исследованных осадков в значительной мере однообразны, что, по-видимому, связано с единым источником образования — остатками планктона.

Как по элементарному составу, так и по компонентному, битумы исследованных океанских осадков не имеют существенных отличий от битумов современных глубоководных осадков других морских бассейнов.

В отношении преобразования органического вещества исследованные осадки резко делятся на две группы.

Подавляющая часть типичных океанских осадков характеризуется чрезвычайно вялым преобразованием органического вещества. Поэтому в течение длительного времени в таких осадках не происходит заметного изменения физико-химических условий; минерализация грунтовых растворов выражена крайне слабо и содержание битуминозных веществ сохраняется довольно постоянным.

В другой группе осадков, напротив, преобразование органического вещества протекает сравнительно энергично. В связи с этим физико-химические условия соответствующим образом преобразуются: заметно возрастает минерализация грунтового раствора (увеличивается щелочность, содержание аммонийного азота и растворенного органического вещества), и несколько возрастает содержание битуминозных веществ. В этих осадках намечается также тенденция к увеличению содержания масел в составе битума.

Указанные различия в преобразовании органического вещества, по нашему мнению, связаны прежде всего с тем, что в первом случае захоронению в осадок подвергается уже глубоко преобразованное органическое вещество, тогда как во втором захоранивается более дееспособная — лабильная органика.

Какова же причина этого явления? Широко распространено мнение, что на преобразование органического вещества в процессе седиментации огромное влияние оказывает глубина бассейна. Считается, что органическое вещество, осаждаясь через мощную водную толщу, подвергается интенсивному разложению и благодаря этому в глубоководные

Приложение I

Геохимические характеристики верхнего слоя океанских осадков (усредненные величины)

Карбонатность	Тип осадков	Физико-химические свойства		Химический состав грунтовых растворов		Битуминозность, %	Гуминовые кислоты, %
		pH	Eh, *мв*	AlK, *мг·экв/л*	NH_4—N *мг/л*		
		Тихий океан					
Бескарбонатные	Глинистые илы . .	7,61	+474	2,10	0,45	0,03	0,04
Слабокарбонатные	Глинисто-известковые илы	7,84	+296	2,41	0,52	0,045	0,063
Карбонатные	Алеврито-глинистые илы	7,52	+399	2,34	0,25	0,015	0,047
	Алевритовые илы .	7,57	+412	3,53	0,23	—	—
	Пески	8,14	+385	2,41	0,30	0,035	0,01
		Индийский океан					
Бескарбонатные	Глинистые илы . .	7,36	+431	2,71	0,21	0,03	0,166
Слаоокарбонатные	Глинисто-известковые илы	7,90	+365	2,54	0,08	0,02	0,08
Карбонатные	Алеврито-глинистые илы	7,64	+312	2,34	0,20	0,02	0,13
	Алевритовые илы .	7,25	+319	2,64	0,198	0,018	0,12
	Пески	7,32	+223	2,72	0,19	0,037	0,235

осадки выпадает небольшое количество уже стабилизированного и мало способного к дальнейшему преобразованию органического вещества. Нам представляется такое толкование неверным. Наличие донных животных, а также бактериальной флоры свидетельствует о том, что органическое вещество, попадающее в осадки в океанских условиях, еще далеко от состояния биохимической стабилизации.

Кроме того, в осадках глубоководных океанских впадин (например в Яванской), при опадании в которые органическое вещество должно пройти почти в два раза большую толщу богатых кислородом вод, органическое вещество подвергается интенсивному преобразованию, что свидетельствует о его лабильности.

По нашему мнению, основным фактором, вызывающим вялое преобразование органического вещества в толще типичных океанских осадков, является чрезвычайно медленное осадконакопление. Благодаря этому разложение органического вещества главным образом осуществляется на поверхности осадка и в дальнейшем захоранивается уже глубоко преобразованное, стабильное органическое вещество, мало способное к дальнейшему изменению.

В тех же случаях, когда скорость накопления осадков значительна, органическое вещество быстро изолируется от непосредственного контакта с водной толщей, распад его протекает в толще осадка и в соответствии с этим перестраивается весь органо-минеральный комплекс осадка.

Если рассчитать время, необходимое для достижения отмерших планктонных организмов максимальных океанских глубин, то оно измеряется десятками дней и месяцами. В то же время для захоронения органических остатков в осадки на глубину всего 1 *мм* в океанских условиях требуются десятки лет. Естественно, что благодаря этому непосредственное влияние глубины бассейна на состав накопляющегося в осадках органического вещества отходит далеко на второй план.

В связи с этим огромное влияние на состав органического вещества и на весь процесс его дальнейшего диагенетического преобразования оказывает скорость осадконакопления.

Геохимические характеристики колонок океанских осадков

Номер станции и горизонт в *см*	Физико-химические свойства		Химический состав грунтовых растворов		Битуминозность, %	Гуминовые кислоты, %
	pH	Eh, *мв*	щелочность, *мг-экв/л*	NH_4—N, *мг/л*		
			Бескарбонатные осадки			
			а) Глинисто-радиоляриевые илы			
Станция 3802						
0—12	7,60	+529	2,868	0,178	0,06	0,07
50—62	7,34	+532	2,480	0,138	0,06	Следы
90—100	—	+433	2,127	0,159	0,02	»
150—162	7,24	+502	1,585	0,370	0,05	»
200—210	7,51	+521	2,147	0,195	0,03	»
246—256	7,52	+492	2,009	0,104	0,03	»
Станция 4599						
0—11	7,16	+462	2,336	0,08	0,11	Нет
31—46	7,53	+563	2,212	0,05	0,03	»
80—100	—	—	2,155	0,52	0,01	»
135—150	7,11	+573	2,155	0,32	0,01	»
233—272	7,53	+563	1,648	0,16	0,01	»
476—514	7,07	+553	0,956	0,40	0,03	»
605—625	7,39	+513	1,543	0,11	0,02	»
Станция 4609						
0—10	6,10	+513	2,112	0,30	0,02	0,03
40—50	6,12	+603	2,102	0,33	0,02	0,02
90—115	6,80	+523	1,796	0,90	0,08	0,05
185—195	6,47	+633	1,817	0,88	0,07	0,04
405—420	6,83	+143	3,153	1,00	0,10	0,03
600—610	7,32	+143	3,754	0,60	0,11	0,04
800—815	6,98	+ 23	2,953	0,57	0,08	0,05
			б) Глинистые илы			
Станция 3827						
0—10	7,22	+475	1,853	0,531	0,02	0,20
22—35	7,14	+405	9,888	0,480	0,02	0,10
67—76	7,26	+436	1,524	0,746	0,02	0,10
92—102	7,70	+206	2,487	0,705	0,07	0,21
110—112	7,64	+218	3,356	0,725	0,12	0,03
Станция 4535						
0—10	7,18	—326	3,528	0,03	0,03	0,02
40—57	6,92	+ 76	6,700	1,55	0,03	0,03
95—105	7,46	+132	6,631	1,29	0,06	0,03
150—166	7,36	— 38	6,708	1,00	0,11	0,03
235—245	7,06	— 38	5,632	0,81	0,09	0,12
			Слабо-карбонатные осадки			
			Глинисто-алевритовые илы			
Станция 4614						
0—10	7,16	+472	2,407	0,15	0,02	0,06
40—55	7,16	+583	2,247	0,67	0,01	0,03
140—150	7,28	+593	2,522	0,09	0,07	0,01
256—275	7,06	+578	1,708	0,10	0,01	0,01
430—450	7,30	+573	2,099	0,12	0,02	0,01
650—670	7,18	+558	1,284	0,12	0,01	0,01
880—905	7,13	+518	2,099	0,10	—	—

Приложение II (продолжение)

Номер станции и горизонт в *см*	Физико-химические свойства		Химический состав грунтовых растворов		Битуминозность, %	Гуминовые кислоты, %
	pH	Eh, *мв*	щелочность, *мг·экв/л*	NH_4—N, *мг/л*		
Станция 4634						
0—10	7,00	+263	2,682	0,10	0,02	0,04
30—45	7,20	+502	2,714	0,08	0,01	0,03
95—107	7,15	+527	2,714	0,07	0,01	0,05
200—212	7,18	+552	2,979	0,07	0,01	0,03
280—295	7,16	+282	3,128	0,11	0,01	0,03
375—390	7,18	+332	2,096	0,09	0,01	0,03
615—660	7,19	+102	1,870	0,11	0,01	0,02
803—830	7,18	+152	1,253	0,11	0,01	0,02
1108—1132	7,18	+107	—	0,10	0,02	0,01
Карбонатные осадки						
Алевритово-глинистые илы						
Станция 3835						
0—10	7,38	+430	2,412	—	0,06	0,03
32—45	7,74	+249	1,975	—	0,03	0,20
72—80	7,60	+157	1,865	—	0,04	0,20
Станция 3840						
0—5	6,74	+317	2,987	0,672	0,02	0,35
22—40	7,48	+328	2,838	0,480	0,03	0,33
100—115	7,52	+208	2,399	0,417	0,05	0,31
182—200	7,32	+314	3,616	0,390	0,04	0,33
220—240	7,62	+284	3,128	0,432	—	—

Под таким углом зрения более благоприятными возможностями в отношении битуминизации органического вещества обладают районы с повышенной скоростью накопления осадков.

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РАСПРЕДЕЛЕНИЕ ПЛАНКТОННЫХ ФОРАМИНИФЕР В ВОДАХ И НА ДНЕ ИНДИЙСКОГО ОКЕАНА

Планктонные фораминиферы являются важной составляющей частью планктона. Наличие известковых раковин делает возможным захоронение этих организмов в осадках. В современных океанах многочисленные остатки планктонных фораминифер образуют глобигериновые илы, которые в Тихом океане покрывают 36% площади дна, в Атлантическом — 67%, и в Индийском — 54%, занимая в общем 126 млн. *км*^{2} (Swerdrup a. oth., 1946). Глобигериновые илы существуют с мелового времени. Такое широкое распространение планктонных фораминифер во времени и пространстве и тесная связь с условиями среды определяет их огромное значение для реконструкции условий геологического прошлого. Действительной основой для палеоэкологических и палеогеографических построений может быть знание экологии современных фораминифер, основанное на изучении их в тех водных массах, где они живут, и сравнение их распределения по площади в поверхностном слое воды с распределением пустых раковин на дне.

До последнего времени все сведения об экологии планктонных фораминифер базировались на изучении распределения их раковин в осадках. Работы Бе (Be, 1960) и Брэдшоу (Bradshow, 1959), основанные на материалах, собранных в Тихом и Атлантическом океанах, были первыми экологическими работами по современным пелагическим фораминиферам.

В Индийском океане планктонные фораминиферы изучались мало. Чепмен (Chapman, 1895) описал видовой состав фораминифер всего с шести станций Аравийского моря, Херон-Аллен и Ирланд (Heron-Allen a. Earland, 1914) — с 16 станций из района архипелага Керимбо. Список видов из Аравийского моря дан также Стаббингом (Stubbings, 1939).

Основные задачи данной работы — исследование экологии современных планктонных фораминифер, изучение их количественного и видового распределения по акватории и на дне Индийского океана, а также условий жизни и захоронения. Выполнялась она в отделе морской геологии Института океанологии АН СССР. Исходным материалом послужили пробы планктона и донных осадков, собранные в Индийском океане в 1956—1958 гг. в первом и втором рейсах Комплексной антарктической экспедиции АН СССР на д/э «Обь» (начальник геологического отряда А. П. Лисицын) и в 1959—1960 гг. в 31-м рейсе Комплексной океанографической экспедиции Института океанологии АН СССР на э/с «Витязь» (начальник геологического отряда П. Л. Безруков). Всего было изучено 409 проб планктона и 286 проб донных осадков (рис. 1 и 2). Обработка материалов проводилась методом математической статистики. Для выяснения закономерностей распределения живых фораминифер привлечены

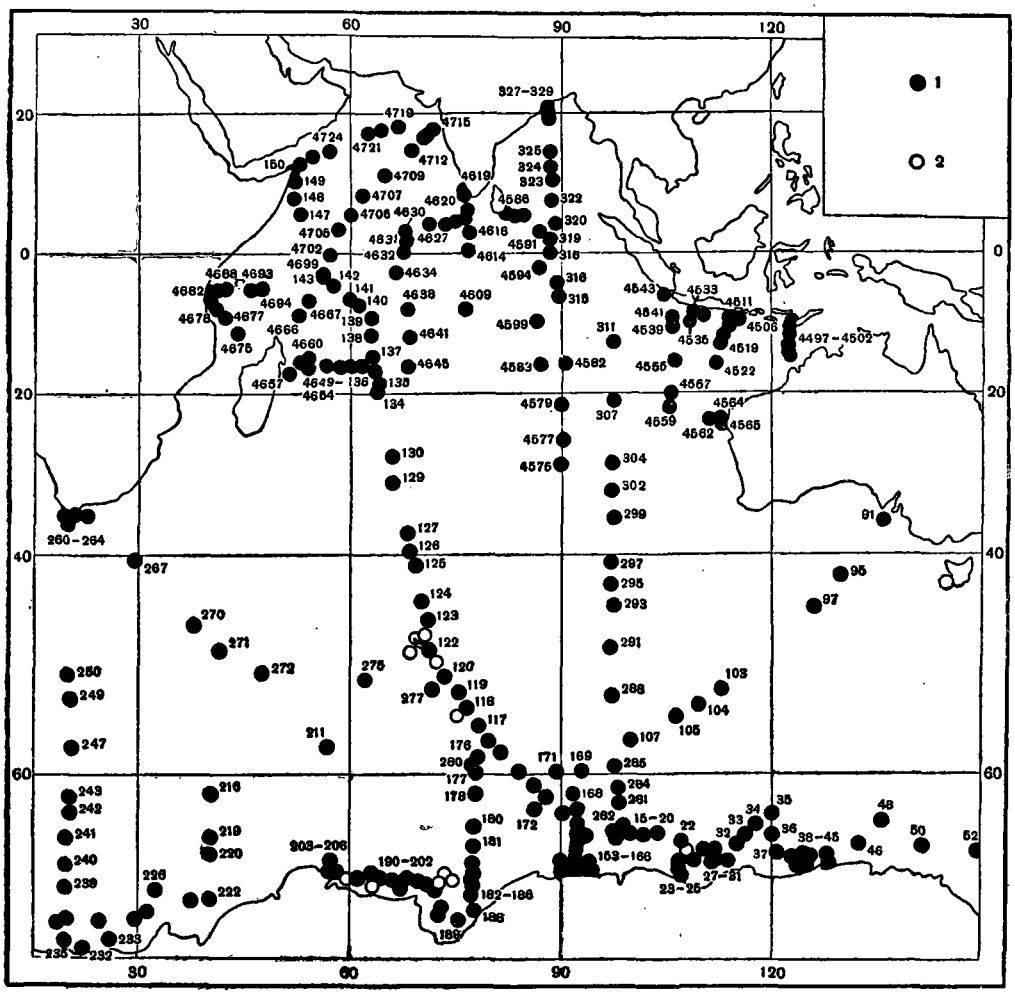


Рис. 1. Расположение станций, на которых брались пробы для изучения распределения фораминифер на дне Индийского океана

1 — станции д/э «Обь» (1—329) и э/с «Витязь» (4497—4726); *2* — станции Антарктической экспедиции 1929—1931 гг.

литературные данные по температуре, солености вод, содержании в них фосфора, кислорода и кремния и по другим вопросам. В качестве батиметрической основы использована карта рельефа дна Индийского океана из Морского Атласа с учетом некоторых новых сведений, полученных в 31-м рейсе э/с «Витязь».

МЕТОДИКА СБОРА И ОБРАБОТКИ ПРОБ

Пробы донных осадков брались дночерпателем «Океан-50» с площадью захвата 0,25 $м^2$. Для более полного и правильного представления о видовом составе и количественном распределении планктонных фораминифер нами были взяты из дночерпательных проб навески по 10—25 *г*. Осадок промывали через мельничный газ № 76. Полученный «фораминиферовый остаток» подвергался количественной оценке (штук) по видам

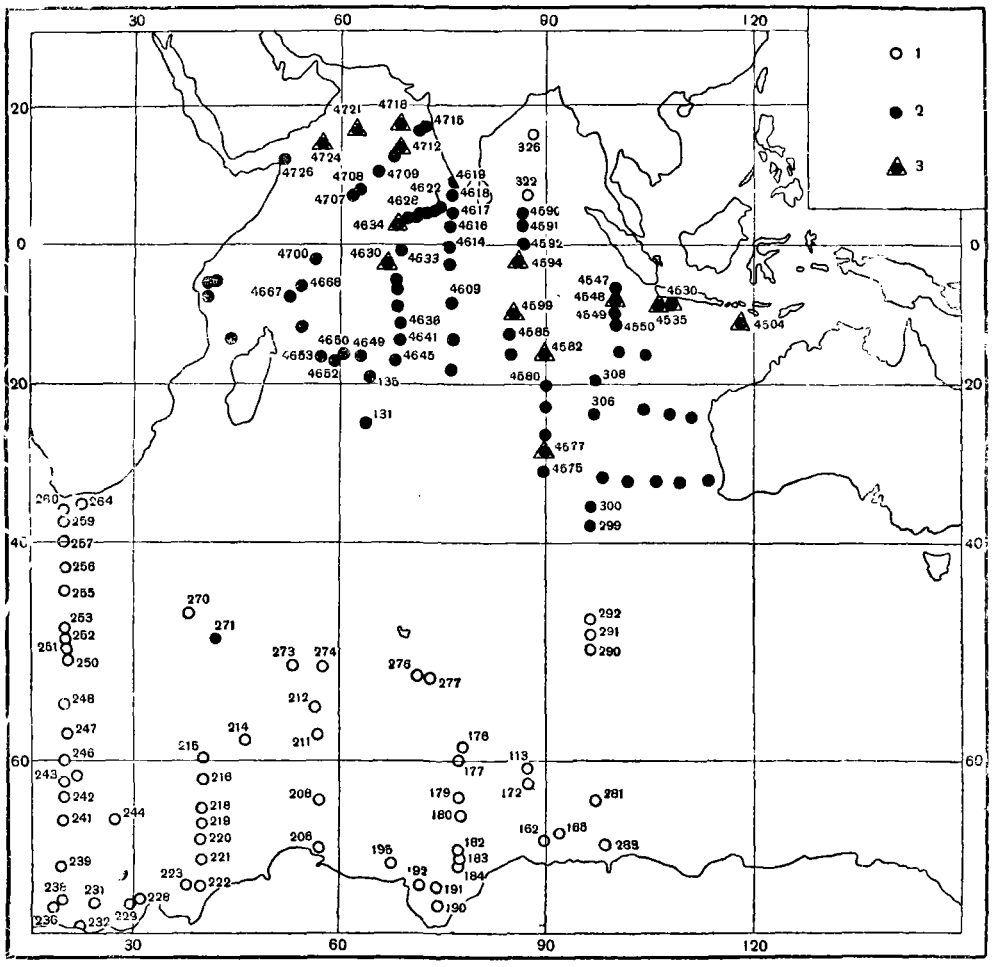


Рис. 2. Расположение станций, на которых брались пробы для изучения распределения фораминифер в толще вод Индийского океана

1 — [изучен] видовой состав фауны в поверхностном слое воды (0—200 *м*); *2* — изучено количественное распределение в том же слое; *3* — изучено распределение в толще воды от 0 до 4000 *м*

в 10 *г* осадка. На основании полученных цифр были построены карты общего количественного распределения планктонных фораминифер (в пересчете на 1 *г* осадка) и распределения отдельных видов на дне Индийского океана. Изолинии содержания фораминифер проведены на картах с учетом рельефа дна, который оказывает большое влияние на распределение их раковин (Саидова, 1961).

Распределение фораминифер по вертикали в толще воды было изучено по пробам, собранным отрядом планктона (начальник отряда М. Е. Виноградов) в 31-м рейсе э/с «Витязь» в период с октября 1959 г. по апрель 1960 г. Всего было исследовано 104 пробы с 14 станций, расположенных в Индийском океане между 20 и 28° с. ш. Сбор планктона в экспедиции осуществлялся по методике, принятой в Институте океанологии АН СССР. Орудием сбора служила сеть БР с диаметром входного отверстия 113 *см* и диаметром фильтрующего конуса 140 *см* (сито № 15). Этой сетью на

каждой станции проводились вертикальные обловы по слоям: 0—50, 50—100, 100—200, 200—500, 500—1000, 1000—2000 *м* или 1000—1500 и 1500—2000, 2000—3000, 3000—4000 *м*. Из каждой пробы были отобраны все фораминиферы. Далее они были окрашены бенгальской розовой краской в целях выделения живых экземпляров. Для этого фораминиферы на 1—2 дня погружали в раствор краски, затем промывали. По цвету протоплазмы (красный или интенсивно-розовый) выделялись живые [1] организмы. Методика окрашивания впервые описана Волтоном (Walton, 1952). Фледжер (Phleger, 1954) указывал, что протоплазма в раковинах фораминифер разлагается через 12—14 часов, поэтому все фораминиферы с протоплазмой практически могут считаться живыми. В каждой пробе было подсчитано общее количество экземпляров и отдельно число живых и мертвых особей, а также количество видов. Все приведенные цифры даны по общепринятой методике в пересчете на 1000 $м^3$ (Be, 1960a; Parker, 1960).

Характер горизонтального распределения фораминифер в поверхностных водах Индийского океана был изучен по пробам, собранным в первых трех рейсах д/э «Обь» и в 31-м рейсе э/с «Витязь». Прежде всего были рассмотрены 93 пробы с 39 станций «Оби», предоставленные нам К. А. Бродским и К. В. Беклемишевым. Сбор осуществлялся сетями Джеди (из сита № 38) с диаметром входного отверстия 37 *см*. В толще воды на большинстве станций отмечено растворение фораминифер, либо частичное, либо полное, что делает невозможным использование этих проб при количественных подсчетах. При изучении распределения видов фораминифер эти данные учитывались. Растворение раковин отмечено на всех антарктических станциях и на меридиональных разрезах до 40° ю. ш. К северу от этих станций, по материалам первого и второго рейса д/э «Обь», растворения не наблюдалось. По-видимому, растворение в этих пробах не связано с воздействием формалина, как предполагалось вначале, а происходит в результате агрессивности холодных антарктических вод по отношению к карбонату кальция.

Наиболее подробному качественному и количественному анализу была подвергнута фауна тропических районов; при этом было изучено 310 проб планктона (31-й рейс «Витязя»), собранных сетью Джеди с диаметром входного отверстия 80 *см* и фильтрующего конуса (сито № 38) 113 *см*. Исследовались пробы из слоев 0—25, 25—50, 50—100, 100—200 *м*. Карты распределения фораминифер и отдельных их видов (в экз. на 1000 $м^3$ воды) построены для слоя 0—200 *м*.

При изучении количественного распределения фораминифер автором впервые были использованы методы математической статистики [2].

Содержание фораминифер от места к месту колеблется. Если интервал колебаний в ряде точек невелик, то содержание считается равномерным, если же он значителен, то констатируется неравномерность распределения. Как в первом, так и во втором случае это — величина переменная. Характерной особенностью величины содержания фораминифер является непрерывность, т. е., как бы ни были близки два значения этой величины, при бесконечном повторении определений в данном танатоценозе, можно встретить содержание, промежуточное между ними. Кроме того, содержание фораминифер в осадках является случайной величиной, так как нельзя заранее предсказать, какое значение оно примет в результате

[1] В момент взятия пробы.

[2] При этом использовались работы Д. А. Родионова (1961а, б, в; 1962а, б; Родионов и Ляхович, 1961).

единичного определения. Таким образом, в любом осадке, в любых танатоценозе и биоценозе мы имеем дело с совокупностью случайных значений, которые сплошь заполняют некоторый интервал. Из этого следует, что задача сопоставления содержания фораминифер в различных танатоценозах и биоценозах сводится к сопоставлению совокупностей случайных значений этих содержаний, а не отдельных результатов определений. Поэтому исключительную важность приобретает вопрос о правильном выборе характеристики таких совокупностей.

До последнего времени широко использовалось среднее арифметическое результатов отдельных определений. Однако оно не дает полного описания совокупности содержаний. Так, только по среднему арифметическому нельзя судить об интервале колебаний наблюдаемых значений содержаний, а тем более нельзя сказать, какие значения из этого интервала встречаются чаще, а какие реже. Кроме того, две совокупности, обладающие одинаковыми средними содержаниями, могут быть в корне отличными друг от друга. Например, из двух танатоценозов или двух типов осадка с приблизительно одинаковыми средними содержаниями какого-либо вида в одном вид распределен довольно равномерно и значения его содержаний заключены в весьма узком интервале, а в другом — наряду с весьма малыми содержаниями могут наблюдаться участки заметного обогащения. Следует отметить, что в природе нередки случаи, когда содержания, близкие по своему значению к среднему арифметическому, наблюдаются гораздо реже, чем значительно отличающиеся от него.

О всех этих особенностях совокупности содержаний фораминифер нельзя судить только по одному среднему арифметическому. Из теории вероятностей известно, что универсальной характеристикой случайной величины является функция ее распределения. Эта функция выражает вероятность того, что случайная величина примет в результате единичного наблюдения значение меньшее заданного или равное ему. Весьма важное свойство функции распределения — ее однозначность для совокупности, т. е. данная случайная величина обладает только одной функцией распределения, которая полностью описывает все ее свойства. Две совокупности с одинаковыми функциями распределения характеризуются одинаковыми свойствами. В зависимости от своего вида функция распределения случайной величины определяется тем или иным числом параметров. Если вид ее известен, то, пользуясь соответствующими статистическими оценками параметров, можно дать полное описание данной совокупности.

Наиболее распространенным видом распределения фораминифер является логарифмически-нормальный. Для него характерно нормальное распределение логарифмов данной случайной величины, т. е.

$$F(lg\,x) = F(x) = \frac{1}{\sigma_{\lg\eta}\sqrt{2\pi}} \int_{-\infty}^{\lg x} e^{-\frac{(lg\,x - m_{lg\,\eta})^2}{2\sigma^2 lg\,\eta}} d(\lg x).$$

Кривая плотности вероятности распределения логарифмически-нормально распределенной величины обладает существенно выраженной положительной асимметрией. Уравнение этой кривой можно получить, продифференцировав $F(x)$ по x:

$$\frac{dF(x)}{dx} = f(x) = \frac{1}{\sigma_{\lg\eta}\sqrt{2\pi}} e^{-\frac{(\lg x - m_{\lg\eta})^2}{2\sigma^2 \lg\eta}} - \lg x.$$

Как видно из этого уравнения, логарифмически-нормальное распределение определяется двумя параметрами $m_{\lg\eta}$ и $\sigma_{\lg\eta}$, истинное значение которых для нас остается неизвестным. О приближенном значении

этих параметров ($m_{\lg \eta}$ и $\sigma_{\lg \eta}$) мы можем судить на основании фактического материала по содержанию фораминифер в водах и осадках. Оценки параметров логарифмически-нормального распределения производятся по следующим формулам:

$$\overline{m}_{\lg \eta} = \frac{1}{n} \sum_{i=1}^{n} \lg x_i = \overline{\lg x},$$

$$\overline{\sigma}_{\lg \eta} \approx S^2_{\lg \eta} = \frac{1}{n-1} \sum_{i=1}^{n} (\lg x_i - \overline{\lg x})^2.$$

Следовательно, для того чтобы охарактеризовать с максимальной полнотой совокупность значений логарифмически-нормально распределенной величины содержания фораминифер в осадках, необходимо использовать среднее арифметическое логарифмов содержаний ($\overline{\lg x}$)[1] и дисперсию логарифмов содержаний ($S^2_{\lg \eta}$).

Определение вида функции распределения осуществляется оценкой отношений асимметрии распределения логарифмов (γ_1) к стандартному отклонению асимметрии ($\sigma\gamma_1$) и эксцесса распределения логарифмов (γ_2) к стандартному отклонению эксцесса ($\sigma\gamma_2$). В том случае, если эти отношения окажутся меньше или равны трем, гипотеза логарифмически-нормального распределения будет подтверждена.

Распространенность фораминифер в осадках и водах предлагается характеризовать частотой встречаемости (p), выраженной в долях единицы.

Наиболее часты в Индийском океане глубины от 4 до 5 тыс. *м*. Редко встречаются глубины более 6 тыс. *м*, максимальная глубина — 7450 *м* — обнаружена в Яванском глубоководном океаническом желобе. Самое крупное поднятие — Центральный Индийский хребет, протягивающийся к югу от п-ова Индостан. Он разветвляется в своей южной части на три ветви: Австрало-Антарктическое поднятие, хребет Кергелен-Гауссберг и плато Крозе, переходящее далее на запад в Африканско-Антарктическое поднятие. В северной части Центрального Индийского хребта отчленяется Аравийско-Индийский подводный хребет. Системой подводных поднятий дно Индийского океана расчленяется на девять котловин с глубинами 4—6 тыс. *м*. В центральной части океана дно котловин, так же как и поверхность подводных хребтов, обычно очень неровное. По окраинам океана дно котловин в основном представляет собой аккумулятивные равнины (Живаго, 1960; Лисицын, 1961; Безруков, 1962).

В Индийском океане выделяются три основные климатические зоны: антарктическая полярная, умеренная и тропическая. Основные климатические границы тесно связаны с зонами конвергенции (опускания) и дивергенции (подъема) вод.

Антарктическая полярная зона простирается от берегов континента на 900—1200 миль к северу до зоны антарктической конвергенции. На вертикальном разрезе здесь выделяются три типа вод: холодные поверхностные, теплые глубинные и холодные придонные. Для первых характерна температура от +4 до —1,9° и низкая соленость (33,8—34,2‰); мощность этого слоя колеблется от 60 до 400 *м*. Мощность теплого слоя колеблется от 800 до 4000 *м*, температура — от 0 до 2,5°, соленость — от 34,1 до 34,9‰.

[1] Для характеристики распределений в данной работе используется среднее геометрическое содержаний ($\tilde{x}$), которое получается как антилогарифм среднего арифметического логарифмов содержаний.

Придонные холодные воды характеризуются температурой 0,1—0,5° и соленостью 34,6—34,8‰. В области развития антарктических вод есть зона подъема теплых глубинных вод на поверхность, где с глубины выносится большое количество биогенных элементов. Эта зона антарктической дивергенции расположена на границе водных масс Восточного дрейфа и Прибрежного западного течения, температура воды в которых ниже 0°, а соленость ниже 34,5‰ (Лисицын, 1961).

Между антарктической и субтропической конвергенциями находится умеренная зона; средние годовые температуры здесь от +10° до +20°. К северу от субтропической конвергенции расположена тропическая зона (Лисицын, 1961). По 10—12° ю. ш. Индийский океан пересекается фронтальной зоной, которая в поверхностных слоях является зоной дивергенции между Экваториальным противотечением и Южным пассатным течением. Южнее последней слой до глубины 600 *м* занят индийской центральной водной массой (ИЦВ), характеризующейся температурой 10—23° С, соленостью 34,7—35,7‰, большим запасом кислорода, малой продуктивностью и глубоко расположенным (400—500 *м*) слоем скачка pH, фосфатов и кремнекислоты.

К северу от фронтальной зоны выделяются две водные массы. В верхнем слое (до 200 *м*) — более «молодая» Индийская экваториальная водная масса (ИЭВ), образующаяся в Аравийском море благодаря сильному испарению. Она отличается высокой температурой (от 14 до 28°) и высокой соленостью (от 35,1 до 36,5‰). Ниже (от 200 до 2000 *м*) расположен мощный слой более «старой» соленой воды. Это — вода Аравийского моря (ВАМ) с температурой 3—25°, соленостью 34,8—35,3‰, слоем кислородного минимума, высоко поднятым (до 50—100 *м*), слоем скачка pH, фосфатов и кремнекислоты и высокой продуктивностью (Иванов-Францкевич, 1961; Мокиевская, 1961). Водообмен между северо-восточной и южной частями океана ограничен; он происходит главным образом в поверхностных слоях и, возможно, на глубинах более 2000 *м*. Основной водообмен между северной и южной частями океана происходит на западе, в районе Мадагаскара.

Зоны конвергенций в океане определяют не только климат, с ними связано распределение и фито- и зоопланктона. Планктонные организмы характерны для различных водных масс и служат хорошим индикатором температурных, соленостных и других особенностей океанов. Смена видов в открытом океане наиболее резко выражена в меридиональном направлении, и поэтому планктон является хорошим показателем широтных зон. Правда, последние исследования показали, что области конвергенций и дивергенций не представляют собой непреодолимой преграды для видов. При изменении метеорологических условий и положения полярного фронта планктонные организмы могут его пересекать, чем и объясняется широкое распространение некоторых видов (Козлова, 1963).

Для антарктической области характерно небольшое количество видов, имеющих массовое развитие. Фитопланктон здесь представлен в основном диатомовыми водорослями; очень редко и в малых количествах встречаются перидинеи. Эта область разделяется антарктической дивергенцией на две подобласти — высокоантарктическую, ограниченную водами Прибрежного западного течения, и нижнеантарктическую, ограниченную водами Восточного дрейфа.

Умеренная зона очень бедна фитопланктоном. Зоопланктон представлен в ней видами Calanus semillimus, Limacina balea, Pleuromamma robusta и Eucalanus sp. Для этой зоны характерно малое число эндемичных видов (Беклемишев, 1960; Короткевич и Беклемишев, 1960).

Тропическая область отличается большим видовым разнообразием планктона, но бедна им количественно. В этой области преобладает перидиниевый фитопланктон, лишенный кремневого скелета (Коротке-вич и Беклемишев, 1960).

Как видно, в общем распределение планктонных организмов в верхних слоях вод Южного полушария четко обрисовывает антарктическую, умеренную и тропическую зоны.

Наибольшее количество планктона в северной части Индийского океана отмечается в районах прибрежного поднятия глубинных вод к югу от о-ва Явы, на севере Аравийского моря, а также в зоне дивергенции между Экваториальным противотечением и Северным экваториальным (муссонным) течением и в районе циклонического круговорота к юго-западу от островов Чагос; наименьшее — южнее 15—16° ю. ш. Вследствие неглубокого залегания глубинных вод в районе экватора они вовлекаются в турбулентное перемешивание и поверхностные слои воды во всей экваториальной зоне обогащаются биогенными элементами. В районах дивергенции экваториальных течений богатые биогенами глубинные воды особенно интенсивно выносятся к поверхности и вызывают обильное развитие планктона. В тропических районах богатые биогенными элементами воды лежат глубоко и почти не попадают в поверхностные слои. Поэтому планктон в тропических районах открытого океана гораздо беднее, чем в экваториальных. Основную роль в регулировании продукции планктона играет снабжение вод эуфотической зоны питательными солями. В районе исследований в большинстве случаев максимумы содержаний фито- и зоопланктона совпадали с зоной подъема вод (Богоров и Виноградов, 1961; Виноградов, Воронина и Суханова, 1961).

В распределении донных осадков в Индийском океане отчетливо выражена климатическая и вертикальная зональность (Безруков, 1961, 1962; Лисицын, 1958, 1960, 1961; Безруков и др., 1961).

В южной части Индийского океана развиты терригенные айсберговые осадки. Они сплошной полосой опоясывают материк Антарктиды, покрывая поверхность шельфа, материковый склон и прилегающие части ложа океана. Ширина полосы этих осадков колеблется от 400 до 1200 *км*. Обломочный материал в айсберговых осадках составляет 80—90% и более. По гранулометрическому составу эти осадки весьма разнообразны — от валунов и щебня до тонких пелитовых илов (Живаго и Лисицын, 1957; Лисицын и Живаго, 1958, 1958а). В ряде мест к обломочному материалу примешиваются биокомпоненты: диатомовые водоросли, спикулы губок, мшанки, фораминиферы. Содержание $CaCO_3$ в айсберговых осадках колеблется от 0 до 20%, но чаще всего не превышает 3%. Содержание $SiO_{2аморфн}$ колеблется от 0,8 до 20%. При повышенном содержании кремнистого и реже карбонатного материала (свыше 10%) айсберговые осадки могут быть названы слабокремнистыми и слабокарбонатными Количество $C_{орг}$ в них также невелико (от 0,04 до 1,2%). Таким образом, айсберговые осадки являются типичными обломочными с очень незначительной примесью биокомпонентов.

В ряде мест шельфа встречаются осадки с высоким содержанием карбоната кальция. Наиболее типичные из них карбонатные, сложенные мшанками и содержащие до 15% $CaCO_3$. Фораминиферовые осадки встречены несколько севернее на подводных поднятиях ложа океана. На шельфе Антарктиды с особенно холодными водами фораминиферовые осадки не обнаружены, хотя в ряде мест фораминиферы в качестве примеси встречены в заметных количествах. Самая южная из всех известных проб фораминиферовых осадков получена на отмели Ганнерус, на широте 67°28′. Фораминиферовые осадки подводных поднятий антарктической

полярной зоны приурочены к теплым промежуточным водам в интервале глубин 934—4017 *м*. В них присутствует каменный материал, спикулы кремневых губок, диатомовые водоросли. Содержание $CaCO_3$ в этих осадках достигает 40%. В пределах ледовой зоны фораминиферовые осадки наиболее широко распространены на вершинах подводных хребтов и гор, там, где последние омываются теплыми промежуточными водами.

К северу от зоны айсберговых илов простирается пояс диатомовых илов шириной 900—2000 *км*. Северная граница их приблизительно совпадает с антарктической конвергенцией. Диатомовые илы встречаются на самых различных глубинах. По гранулометрическому составу это обычно алевритово-глинистые и глинистые илы, содержащие до 60—85% пелитового материала (мельче 0,01 *мм*). В южной части Индийского океана диатомовые илы обычно содержат меньше 10% $CaCO_3$; по мере продвижения к северу количество карбонатного материала возрастает до 30—50% и диатомовые илы постепенно переходят в карбонатные фораминиферовые. Биогенные компоненты ($CaCO_3$, $SiO_{2аморфн}$, органическое вещество) в диатомовых осадках составляют более 70% (Лисицын, 1961).

К северу от зоны антарктической конвергенции наиболее широко распространены фораминиферовые осадки. Они занимают обширные пространства дна также в центральной и северной частях Индийского океана на глубинах до 4500—4700 *м*. Кроме того, эти осадки развиты на шельфах и на материковых склонах Африки, Азии и Австралии (Лисицын, 1960, 1961; Лисицын и Живаго, 1958, 1958а, б, в). На мелководье в их составе обычно преобладают бентосные фораминиферы, с увеличением глубин главным компонентом становятся планктонные виды. Содержание карбоната кальция в фораминиферовых осадках достигает 90—95%. По гранулометрическому составу они весьма разнообразны: от мелких песков и крупных алевритов до тончайших пелитовых илов; в последних раковины фораминифер в основном находятся в измельченном состоянии.

Помимо фораминиферовых илов, в тропической части Индийского океана широко распространены коралловые осадки. Птероподовые отложения выражены мелкими пятнами по западной и северной окраинам океана и приурочены к относительно небольшим глубинам (до 1500 *м*).

В центральной части океана на глубинах свыше 4500—4700 *м* карбонатные осадки постепенно переходят в красные глубоководные глины. На переходных глубинах (4500—4700 *м*) часто можно видеть остатки раковин фораминифер со следами растворения. Красные глины состоят из тончайшего терригенного и вулканогенного материала, продуктов растворения планктонных фораминифер и скелетов радиолярий; содержание окислов марганца и железа в них повышено. По подсчетам Свердрупа, Джонсона и Флеминга (Swerdrup, Johnson, a. Fleming, 1946), фораминиферовые осадки занимают около 54,3% площади дна Индийского океана, а красные глины — 25,3%. Последние в значительной мере образовались в результате растворения планктонных фораминифер на больших глубинах и являются обломочной частью фораминиферовых осадков. Содержание $CaCO_3$ в красных глубоководных глинах обычно меньше 10%. Количество аморфного кремнезема того же порядка, что и в фораминиферовых осадках. Кремнезем связан с радиоляриями и тропическими диатомовыми водорослями. В области распространения глобигериновых осадков и особенно красной глубоководной глины широко распространены железо-марганцевые конкреции. Они образуются в районах с низкими скоростями седиментации, совершенно не встреча-

ются в области распространения айсберговых осадков и редки в зоне диатомовых илов.

При увеличении содержания в красных глинах скелетов радиолярий они переходят в радиоляриевые илы. Эти осадки развиты в Индийско-Австралийской и Сомалийской котловинах, преимущественно на глубинах свыше 5 *км* (Безруков, 1961). Вулканогенные осадки встречаются отдельными пятнами в области распространения диатомовых илов к западу от хребта Кергелен-Гауссберг. В северной части океана они отмечены близ Суматры, Явы и Коморских островов. Терригенные осадки залегают преимущественно на шельфах и в верхней части материкового склона у побережий Африки, Австралии, Индии, Индонезии и субантарктических островов. В Яванском желобе терригенные осадки спускаются на его максимальные глубины (свыше 7 *км*).

ЭКОЛОГИЯ СОВРЕМЕННЫХ ПЛАНКТОННЫХ ФОРАМИНИФЕР

До экспедиции на «Челленджере» (1872—1874 гг.) планктонный образ жизни фораминифер подвергался сомнению. Однако Меррей (Murray, 1897) на основании изучения планктонных ловов показал, что они обитают в поверхностных слоях воды. Мерреем и Брэди (Brady, 1884) установлены три фауны этих фораминифер — тропическая, умеренная и полярная. Интерес к планктонным фораминиферам особенно возрос после того, как Филиппи (Phillippi,1910) указал на возможность их использования при решении вопросов палеоклиматологии.

Большинство сведений по экологии планктонных фораминифер основано на их встречаемости в осадках на дне океанов. Вопросы систематики и некоторые сведения о географическом распределении их приведены в работах Кешмена, Чепмена, Херон-Аллена, Ирланда.

Шоттом (Schott, 1935) было введено «фораминиферовое число» — количество фораминифер в 1 *г* осадка (для фракции $> 0{,}1$ *мм*). Им же (Schott, 1935, 1952), а также Фледжером (Phleger, 1960a; Phleger a. oth., 1953) установлено, что широтное распределение видов в экваториальной и северной частях Атлантического океана в основных чертах согласуется с распределением поверхностных температур и широтной зональностью. Количественную оценку встречаемости видов Шотт дал в процентах от всей фауны планктонных фораминифер. Такое выражение не всегда достаточно полно характеризует распространение вида и его экологию, тогда как распределение абсолютных количеств позволяет выяснить районы максимальных и минимальных концентраций, установить связь количественного распределения вида с условиями среды и выяснить оптимальные условия его обитания.

Овей (Wiseman a. Ovey, 1950), изучив девять проб из Атлантического океана, взятых между 66° ю. ш. и 69° с. ш., выделил арктические и антарктические виды — Globigerina pachyderma (Ehrenberg), Globigerina dutertrei Orbigny, виды умеренных широт — Globigerina bulloides Orbigny, Globigerina inflata Orbigny, Globorotalia crassula Cushman and Stewart, Globorotalia canariensis (Orbigny), Globorotalia hirsuta (Orbigny), Globorotalia truncatulinoides (Orbigny) и тепловодные виды — Orbulina universa Orbigny, Globigerina dubia Egger, Globigerinella aequilateralis (Brady), Globigerinoides ruber (Orbigny), Globigerinoides sacculifer (Brady), Globigerinoides conglobatus (Brady), Globorotalia menardii (Orbigny), Globorotalia tumida (Brady), Globorotalia scitula (Brady), Sphaeroidinella dehiscens (Parker et Jones), Pulleniatina obliquiloculata (Parker et Jones).

Ряд авторов (Murray, 1897; Phleger, 1945, 1951; Phleger a. Hamilton, 1946; Cushman, 1948б; Bandy, 1960) отметил большое видовое

разнообразие планктонных фораминифер в тропиках. В Арктике и Антарктике известно менее пяти видов, причем доминируют один или два.

Бэнди (Bandy, 1960) установил широтное распределение планктонных фораминифер в современных океанах, выделив в полосе широт от 0° до 30 ± 10° тропические виды — Candeina nitida Orbigny, Globorotalia menardii (Orbigny), Globorotalia truncatulinoides (Orbigny), Globorotalia tumida (Brady), Orbulina universa Orbigny, Pulleniatina obliquiloculata (Parker et Jones), Sphaeroidinella dehiscens (Parker et Jones), виды умеренных широт (между 30 и 60°) — Globigerina bulloides Orbigny, Globigerina eggeri Rhumbler, Globigerina quinqueloba Natland, Globigerina pachyderma (Ehrenberg), Globigerinita glutinata (Egger), Globigerinoides minuta Natland, Globorotalia punctulata (Orbigny), Globorotalia truncatulinoides (Orbigny) и арктический и антарктический вид — Globigerina pachyderma (Enrenberg).

Приведенные данные позволяют судить о высокоширотной, среднеширотной и низкоширотной фауне. Хотя эти построения были сделаны по материалам, полученным в Северной Атлантике, предполагается, что подобное географическое распределение существует и в Тихом океане. На основании обобщения литературных данных Сигаль (1956) дал следующую картину распространения планктонных фораминифер:

а) холоднолюбивые формы — Globigerina pachyderma (Ehrenberg), Globigerina dutertrei Orbigny;

б) формы из вод умеренной температуры — Globigerina bulloides Orbigny, Globigerina inflata Orbigny, Globorotalia crassula Cushman et Stewart, Globorotalia canariensis (Orbigny), Globorotalia hirsuta (Orbigny), Globorotalia truncatulinoides (Orbigny);

в) теплолюбивые тропические или субтропические формы — Globigerina dubia Egger, Globigerinella aequilateralis Brady, Globigerinoides ruber (Orbigny), G. sacculifer (Brady), Globigerinoides conglobatus (Brady), Orbulina universa Orbigny, Candeina nitida Orbigny, Pulleniatina obliquiloculata (Parker et Jones), Sphaeroidinella dehiscens (Parker et Jones), Globorotalia menardii (Orbigny), G. tumida (Brady), G. scitula (Brady).

Закономерное увеличение числа планктонных фораминифер на больших глубинах по мере удаления от берега отмечали Паркер (Parker, 1958), Чепмен (Chapman, 1901, 1902), Валлер и Польский (Waller a. Polsky, 1959), Фледжер (1954), Кешмен с соавторами (Cushman a. oth., 1954) и Бэнди (Bandy, 1956). Последний отметил также, что большие скопления планктонных фораминифер указывают на площади открытого моря и площади высокой продуктивности их в толще воды.

Польский (Waller a. Polsky, 1959) связал увеличение количества планктонных фораминифер по мере удаления от берега с приуроченностью видов к разным горизонтам в столбе воды (видовая стратификация). Поэтому в наибольшем водном столбе отмечается максимальное число видов и максимальное число фораминифер на единицу площади. Низкие содержания планктонных фораминифер у берегов он также объяснил видовой стратификацией и свои предположения подтверждает тем, что различные виды в осадке встречаются на разных глубинах, а именно: Globigerina bulloides — на 150 футах, G. subcretacea — на 160 футах, Globorotalia trigonula — на 200 футах, Pulleniatina obliquiloculata — на 220 футах, Orbulina universa — на 260 футах, Globorotalia menardii — на 300 футах; Globigerina quinqueloba — на 300 футах, Globigerinoides conglobatus — на 310 футах. Такие выводы, на наш взгляд, недостаточно обоснованны. По нашим данным изучение фораминифер в столбе воды не подтверждает их видовую стратификацию. Надежное знание экологии может дать только изучение видов в тех водных массах, в которых они живут.

Так, Шотт (1935), в частности, отметил, что распределение планктонных фораминифер в общих чертах совпадает с распределением фосфатов и общего количества планктона, т. е. оно связано с содержанием питательных веществ в воде. В Мексиканском заливе планктонные фораминиферы в больших количествах обнаружены Фледжером (1945, 1951) вдали от берега. Согласно Бе (1959), в районе Бермудских островов наибольшие количества планктонных фораминифер тяготеют к Гольфстриму (до 12 400 экз. на 1000 $м^3$ воды). Там же отмечается и наибольшее видовое разнообразие фораминифер. В водах близ Бермудских островов были выделены холодноводные и тепловодные виды. К холодноводным отнесены Globigerina inflata, Globigerina bulloides, Globigerina eggeri, Globigerina pachyderma, Globigerinita glutinata; Globorotalia hirsuta и Pulleniatina obliquiloculata встречаются редко, их распределение неясно. Тепловодными Бе считает Hastigerina pelagica, Globigerinella aequilateralis, Globigerinoides sacculifer, Globorotalia punctulata. Globorotalia menardii, Globigerinoides ruber, Orbulina universa, Candeina nitida, Globigerinoides conglobatus; эти виды приурочены в основном к Гольфстриму.

Брэдшоу (Bradshow, 1959) установил распределение 27 видов планктонных фораминифер в северной и экваториальной частях Тихого океана. Максимальные количества приурочены к верхним 100 *м*. На основании распределения видов в этом слое Брэдшоу выделил четыре фауны: холодноводную — «субарктическую», представленную большими количествами Globigerina cf. «g. dutertrei», Globigerina pachyderma, G. quinqueloba, Globigerinoides cf. g. minuta; переходную между субарктической и тепловодной (смешенную), в которой наиболее часты Globigerina bulloides, G. eggeri (крупные), G. quinqueloba, Globigerinoides ruber, Orbulina universa; тепловодную, состоящую из сообщества центральной водной массы и сообщества экваториальной западно-центральной водной массы. Первое сообщество включает виды Globorotalia truncatulinoides и Globigerina inflata; для второго характерны Globigerina conglomerata, Globorotalia tumida, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens.

Паркер (1960) провела аналогичную работу в южной и экваториальной частях Тихого океана и обнаружила сходную картину распределения 16 видов планктонных фораминифер. Она также выделила четыре фауны: экваториальную и южно-центральную, представленную видами Globigerina eggeri, Globigerinoides sacculifer, G. conglobatus; экваториальную, включающую Globigerina conglomerata, G. hexagona, Globorotalia menardii, Pulleniatina obliquiloculata; южно-центральную и субантарктическую, характеризуемую присутствием Globigerina bulloides, G. inflata, Globorotalia punctulata и G. truncatulinoides; субантарктическую, представленную лишь одним видом — Globorotalia scitula. Globigerinella aequilateralis, Globigerinoides ruber, Hastigerina pelagica, Orbulina universa встречены повсеместно и отнесены к широко распространенным видам. Наибольшие популяции приурочены к верхним 200 *м* воды. В этом слое фораминиферы наиболее многочисленны в экваториальных районах. Отдельные участки с высоким содержанием их отмечены также у Южно-Американского побережья и в северной части субантарктического района.

Результаты перечисленных исследований позволяют сделать ряд очень интересных экологических обобщений. Живые фораминиферы обитают до глубины 1000 *м*, но наибольшие концентрации их приурочены к верхнему слою воды. На основании детального изучения распределения фораминифер в поверхностном слое выделены их фауны. Смену видового состава ряд авторов объясняет изменением температуры воды, т. е. распределение большинства видов в общем соответствует широтам (Bradshow, 1959).

Физиологический эффект влияния температуры на живые планктонные фораминиферы неизвестен. Лабораторные исследования скорости роста бентосного вида Strebilus beccari (Linnei) var. tepida (Cushman) показали, что при температуре воды меньше 10° и выше 35° рост прекращается, причем при температуре меньше 10° возможна жизнь, а при температуре выше 35° наступает быстрая гибель (Bradshow, 1957, 1961). Между этими пределами наблюдался рост раковины, усиливавшийся по мере возрастания температуры. Воспроизводство отмечено в более жестких температурных границах — от 20 до 35°. Температура влияет и на продолжительность существования каждой генерации, т. е. на продуктивность. Поэтому обилие видов в районах тропиков Брэдшоу связывает с температурой. Колебания солености, в пределах которой происходит рост и воспроизводство фораминифер, могут быть более значительными — от 20 до 40‰. Рядом авторов (Phleger, 1960; Be, 1959, 1960a; Bradshow, 1959) отмечалось важное значение для распределения фораминифер и других факторов, таких, как соленость, характер и количество пищи, pH, гидростатическое давление, волнение, мутность, биологическая конкуренция, хищники, болезни.

Существенное влияние на жизнь организмов оказывают редкие элементы, в малых количествах широко распространенные в морской воде. Это — кобальт, йод, магний, бром, бор, цинк, медь, свинец. По данным Тэча (Tasch, 1953), присутствие катионов меди, свинца, ртути, серебра, олова в достаточно больших количествах ведет к гибели организмов или задерживает их рост.

Болтовским (Boltovsky, 1956) установлена связь химического состава раковин с химическим составом воды и зависимость количества фораминифер от последнего. Так, в заливе Сан-Блас, где есть соли свинца, фораминифер мало (табл. 1), а к югу от Терра дель Фуго, где солей свинца нет, те же виды фораминифер образуют большие скопления.

Таблица 1

Зависимость между количеством фораминифер и наличием редких элементов в воде

Вид фораминифер	Редкие элементы	
	в водах с большим содержанием вида	в водах, где вид малочислен
Quinqueloculina seminulum	Ca, Mg, Fe, Si, Ti, Mn, Sn, Sr	Те же + Pb
Buccella frigida	Ca, Mg, Sr, Si, Al, Ti, Fe	Те же + Mn, Sn, Cu, Bi, Ag, Pb

На основании изложенного можно заключить, что географические фауны фораминифер различны, потому что они приспособлены к различным водным массам. География планктонных фораминифер — это география водных масс.

Как уже отмечалось, впервые мысль о приуроченности планктонных фораминифер к поверхностным слоям воды была высказана Мерреем (Murray, 1897) на основании распределения пустых раковин на дне океана и частично по данным проб воды. Карпентер (Carpenter, 1875) и Брэди (Brady, 1884) отметили наличие молодых мелких форм в поверхностных слоях воды, а более крупных — на дне. По Ломану (Lohmann, 1920), наивысшие концентрации планктонных фораминифер приурочены к верхним 100 *м*,

что подтверждено и исследованиями Шотта (Shott, 1935). Данные Шотта и Ломана выражены в экземплярах на лов без учета объема профильтрованной воды.

Фледжер (Phleger, 1945, 1951) впервые разделил организмы на живые и мертвые путем окрашивания раковин, провел и изучил их вертикальное распределение в Северной Атлантике и в Мексиканском заливе. Во всех пробах на глубинах от 20 до 2000 *м* наблюдались живые фораминиферы; высокие концентрации их тяготеют к слою 0—200 *м*. Брэдшоу (Bradshow, 1959) отметил, что в Тихом океане высокие концентрации фораминифер приурочены обычно к слою 6—30 *м*; ниже 100 *м* высоких концентраций не отмечено.

Бе (Be, 1960a) рассмотрел распределение отдельных видов в водной толще в Северной Атлантике и установил, что наибольшее общее количество фораминифер и максимальные содержания отдельных видов приурочены к верхним 200 *м*. Особенно благоприятными для жизни фораминифер внутри этого слоя являются глубины 25—50 и 100—150 *м*. Такое распределение Бе объясняет взаимосвязью между фораминиферами и фитопланктоном как источником пищи. Число видов, по Бе, с глубиной уменьшается. Стенобатные виды не были обнаружены.

Таблица 2

Концентрации планктонных фораминифер в дневных и ночных ловах в районе Бермудских островов
(по Be, 1960)

Вид	Среднее число экз. на 1000 $м^3$ воды	
	дневной лов	ночной лов
Globorotalia menardii	98	42
G. hirsuta	79	3
G. punctulata	2	0
G. truncatulinoides	5833	5088
Globigerinita glutinata	163	17
Globigerina inflata	45	3
G. bulloides	554	38
G. eggeri	168	3
Globigerinoides ruber	665	99
G. sacculifer	18	0
Orbulina universa	20	14
Pulleniatina obliquiloculata	700	134
Hastigerina pelagica	27	14
Globigerinella aequilateralis	1320	687
Общее количество фораминифер	9692	6142

Бе, Фледжер и Брэдшоу доказали, что отдельные виды планктонных фораминифер не приурочены к определенным глубинам, а поэтому ряд построений Эмилиани (Emiliani, 1954, 1955) и Польского (Waller a. Polsky, 1959), в основе которых лежит видовая стратификация фораминифер в толще воды, ошибочны.

Количество фораминифер в ловах зависит также от времени суток (табл. 2). Ночью оно в большинстве случаев меньше, чем днем (Rhumbler, 1911; Bradshow, 1959).

Количество пустых раковин фораминифер с возрастанием глубины увеличивается (Phleger, 1951; Be, 1960), и соответственно увеличивается их роль в составе форминиферовой фауны. Пустые раковины составляют около 1% в поверхностном слое воды и около 35% на глубине 1000 *м*. Вопрос о скорости падения раковин на дно освещен пока недостаточно. Фледжер (Phleger, 1954) пишет о медленном их опускании, но вместе с тем отмечает отсутствие заметного горизонтального переноса во время падения. На наш взгляд, малое количество пустых раковин в верхних слоях, наоборот, свидетельствует об их быстром опускании. Соотношение между планктонными фораминиферами в воде и их остатками на дне установлено Мерреем (Murray, 1897) и подтверждено данными Шотта (Schott, 1935) и Фледжера (Phleger, 1951). Соответствие видового и количественного распределения фораминифер в воде и на дне подтверждает вывод Меррея об отсутствии большого переноса в горизонтальном направлении.

Корренс (Correns, 1935) предложил следующую формулу для вычисления переноса раковин течением от места их обитания:

$$E = T \cdot \frac{S}{v},$$

где T — глубина станции в *м*; s — скорость придонного течения в *м/сек*; v — скорость падения фораминифер, которая, по Туле, для особей диаметром 0,4 *мм* равна 2,11 *см/сек*.

Пересчеты, сделанные по этой формуле Шоттом (Schott, 1935), подтверждают, что во время падения раковин на дно горизонтальный перенос их незначителен.

Сезонное распределение планктонных форминифер освещено в работе Бе (Be, 1960а). В основу ее легли многолетние наблюдения в районе Бермудских островов. Наивысшие концентрации форминифер (2160 экз. на 1000 $м^3$ воды) были отмечены в марте 1958 г., т. е. в период, следующий за весенним цветением фитопланктона в этом районе. Период апрель — сентябрь характеризовался сравнительно низкими коцентрациями (до 500 экз. на 1000 $м^3$). В октябре вновь отмечен максимум (до 1500 экз. на 1000 $м^3$), а в декабре — минимум (до 200 экз. на 1000 $м^3$). На основании встречаемости в течение года и количественных характеристик различных видов все они были объединены Бе в три группы (табл. 3).

Группа I включает холодноводные, стенотермные виды, которые составляют большую часть популяции в период от января до марта; между июлем и декабрем они встречаются редко, а иногда отсутствуют. Эти виды характерны для средних широт Северной Атлантики (Phleger a. oth., 1953; Phleger, 1954) и могут быть названы умеренными или, более точно, теплоумеренными. Эти стенотермные виды живут в районе, где средние годовые температуры воды ниже 20°, зимние не ниже 10° и летние — порядка 16—25° (Stephenson, 1947).

Группа II состоит из видов: а) эвритермных, многочисленных в течение всего года и обильных в летние месяцы, и б) видов, встречаемых в малых количествах в течение всего года, но с максимальным содержанием в летние месяцы.

Группа III включает теплостенотермные виды, приуроченные к июню—декабрю с пиком развития в октябре; с января по июль они встречаются редко или отсутствуют. Виды этой группы в больших количествах обнаружены в низких широтах и относятся, по определению Стефензона (1947), к тропическим или субтропическим. Средняя годовая температура воды на поверхности в районе обитания этих видов равна 25° и выше, зимняя — ниже 20° и летняя — от 25° и бол е.

Таблица 3

Связь сезонного распределения планктонных фораминифер в районе Бермудских островов с температурой и соленостью поверхностных вод
(по Be, 1960)

Вид	Сезон	Поверхностная температура, °С	Поверхностная соленость, ‰
Группа I			
Globorotalia hirsuta, G. truncatulinoides, Globigerina inflata, G. bulloides	Январь — май, максимальные количества в феврале-марте	18,5—23	36,4—36,6
Группа II			
Orbulina iniversa, Hastigerina pelagica, Globigerinella aequilateralis, Globigerinoides ruber, Globorotalia punctulata	Весь год, максимальные количества летом и осенью	18,5—27 (наиболее часты при 23—27°)	36,1—36,6
Pulleniatina obliquiloculata, Globigerinita glutinata, Globigerina eggeri	В течение года, редко		
Группа III			
Globigerinoides sacculifer, G. conglobatus, Globorotalia menardii	Июнь — декабрь, максимальные количества в октябре	23—27	36,1—36,4

Сезонность ярко проявляется в смене групп в период с января по июнь (виды I группы) и с июля по декабрь (виды III группы). Это тесно связано с изменением содержания фитопланктона. Максимальные количества фораминифер отмечены в период весеннего цветения фитопланктона.

РАСПРЕДЕЛЕНИЕ ПЛАНКТОННЫХ ФОРАМИНИФЕР В ТОЛЩЕ ВОДЫ

Планктонные фораминиферы распределены в толще воды неравномерно. Нами исследовано распределение фораминифер по материалам 14 вертикальных разрезов, сделанных в тропической зоне Индийского океана. Распределение живых и мертвых раковин различно и поэтому рассматривается отдельно.

Распределение живых фораминифер

Количественное распределение живых фораминифер по вертикали представлено в табл. 4, из которой следует, что наибольшее количество живых планктонных фораминифер приурочено повсеместно к слою 0—200 *м*. Следовательно, в этом слое условия для жизни наиболее благоприятны. Большое число молодых экземпляров позволяет считать, что здесь имеются благоприятные условия и для воспроизводства потомства, что совпадает с точкой зрения Бе (Be, 1960a) и нашей (Беляева, 1961).

Резкое уменьшение общего числа фораминифер и почти полное отсутствие молодых экземпляров наблюдалось в слое 200—500 *м* и особенно в более глубоких слоях. Количество особей в этом слое находится в прямой зависимости от их количества в верхних слоях. На станциях, где

Таблица 4

Распределение живых планктонных фораминифер в толще воды, экз. на 1000 *м*³

№ станции	Горизонт, *м*								
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000	2000—3000	3000—4000
4504	211	626	1310	265	157	Нет проб			
4530	647	673	220	166	258	0	0	Нет проб	
4535	150		120	0	0	0	0	0	0
4548	60	0	33	8	0	0	0	0	0
4577	59		1104	87	24	0	0	0	0
4582	1840	2312	550	88	8	0	0	0	0
4594	155	2160	622	77	72	55	0	0	0
4599	105	418	560	74	0	0	0	Нет пробы	0
4630	1060	552	82	4	12	8	0	0	Нет пробы
4634	306	1800	329	33	12	0	0	0	»
4712	3810		260	329	9	0	0	0	»
4718	3529	Нет пробы	570	533	232	133	0	0	»
4721	82	423	160	26	104	52	0	0	0
4724	20	60	20	23	18	34	46	0	0

отмечено особенное обилие планктонных фораминифер у поверхности воды, количество их в слое 200—500 *м* также наибольшее. Малому содержанию фораминифер в верхних слоях соответствуют и очень малые количества их в слое 200—500 *м*, иногда фораминиферы в этом слое отсутствуют (ст. 4535). Судя по распределению молодых и взрослых экземпляров и по соотношению их количества на разных горизонтах, можно предположить, что часть жизненного цикла планктонных фораминифер протекает в слое ниже 200 *м*.

Распределение фораминифер в выделенных зонах несомненно связано с физико-химическими условиями (табл. 5). Верхняя зона (0—200 *м*) характеризуется температурой воды от 29,3 до 12,9° (в среднем —18°), соленостью от 34,1 до 36,2‰, O_2— от 0,1 до 5,2 *мл/л*; pH — от 7,71 до 8,13, доступом солнечного света и мощным развитием фитопланктона. В нижней зоне (200—2000 *м*) температура воды колеблется от 2,44 до 18,1°, соленость — от 34,6 до 35,7‰, O_2— от 0,1 до 5,2 *мл/л*, pH — от 7,61 до 8,01. Наличие симбионтов в раковинах фораминифер и их связь с солнечным светом определяют тяготение фораминифер к верхней эуфотической зоне.

Из сравнения видно, что характер вертикального распределения фораминифер зависит от распределения фитопланктона, наличия солнечного света и температуры воды.

Наиболее важное значение, на наш взгляд, имеет распределение фитопланктона.

Температура воды оказывает некоторое влияние на вертикальное распределение фораминифер. Так, виды с высокой концентрацией в теплых водах не могут встречаться в больших количествах в холодных глубинных водах, но температура не является решающим фактором, так как резкому изменению количества фораминифер на глубине 200 *м* нет соответствующего резкого изменения температуры. Распределение фосфора, кремния, кислорода также не оказывает большого влияния на вертикальное распределение планктонных фораминифер.

Таблица 5

Зависимость распределения живых фораминифер в тропической зоне Индийского океана от условий среды

Горизонт, *м*	Содержание, экз. на 1000 $м^3$ воды				*t*, °C	*s*, ‰	O_2, *мл/л*	pH
	от	до	средняя геометрическая ($\tilde{x}$)	дисперсия (σ)				
0—50 *[1]	20	3529	307	0,510	25,70—29,30	34,1—36,2	0,36—5,04	8,08—8,13
50—100 *[2]	60	2312	655	0,239	20,00—28,40	34,1—36,2	0,77—5,04	7,76—8,11
100—200 *[3]	20	1310	245	0,290	12,90—25,50	34,6—36,2	0,10—5,2	7,71—7,11
200—500 *[4]		533	63	0,383	18,10—7,79	34,6—35,75	0,10—5,2	7,61—8,01
500—1000 *[5]	8	258	38	3,470	12,26—5,00	34,6—35,6	0,13—5,25	7,61—8,01
1000—1500 *[6]	8	133	40	0,201	5,95—4,01	34,6—35,44	0,13—4,3	7,64—7,93
1500—2000 *[7]	—	46	—	—	5,29—2,44	34,73—35,07	0,37—3,66	7,64—7,86

Примечания: *[1] Популяция представлена в основном мелкими молодыми экземплярами. *[2] На ст. 4504, 4530, 4582, 4594, 4599, 4634, 4721, 4724 количество особей в этом слое выше, чем в слое 0—50 *м*. Почти вся популяция представлена мелкими молодыми экземплярами. *[3] На ст. 4504, 4577, 4594, 4599, 4634, 4721 содержание в этом слое выше, чем в слое 50—100 *м*, а на станциях 4530, 4535, 4548, 4582, 4630, 4712, 4718, 4724 — ниже. Количество молодых и взрослых экземпляров приблизительно одинаково. *[4] Ниже 200 *м* на всех станциях наблюдается резкое уменьшение количества особей. Популяция состоит почти целиком из взрослых крупных экземпляров. *[5] Молодые экземпляры не встречены. На трех станциях фораминифер не было. *[6] Фораминиферы отмечены на семи станциях. *[7] Фораминиферы отмечены только на одной станции.

Распределение пустых раковин планктонных фораминифер

Пустые раковины обнаружены до предельных глубин опробования (4000 *м*) на всех 14 станциях тропической зоны Индийского океана (табл. 6). Средние арифметические содержания [1] и их частота встречаемости приведены в табл. 7.

Из сопоставления табл. 4 и 6 следует, что до глубины 1000 *м*, реже до 2000 *м*, совместно с живыми фораминиферами встречаются и пустые раковины. В слое 0—200 *м* пустые раковины составляют около 1% всех фораминифер, в слое 200—500 *м* — около 10%, в слое 500—1000 *м* — около 30%, а ниже 2000 *м* — уже 100%. Абсолютные количества пустых раковин невелики. Максимальное число (124 экз. на 1000 $м^3$ воды) отмечено на ст. 4594. Количество пустых раковин во всех слоях, лежащих ниже поверхностного, прямо пропорционально количеству живых организмов в слое 0—200 *м*. Малые абсолютные количества пустых раковин на глубинах можно объяснить быстрым опусканием раковин на дно после отмирания организмов. Наиболее часто пустые раковины встречались в слоях от 100 до 1000 *м*, максимальное же число отмечено в слоях от 500 до 3000 *м* (табл. 7).

При изучении планктонных фораминифер в толще воды (даже на ст. 4634, обследованной до дна) признаков растворения раковин не было отмечено, на дне же лежит много экземпляров с явными следами растворения. Это позволяет сделать вывод о том, что только длительное пребыва-

[1] Недостаточное количество цифрового материала не позволило провести математическую обработку.

Таблица 6

Распределение пустых раковин планктонных фораминифер в толще воды, экз. на 1000 м³

№ станции	Горизонт, м								
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000	2000—3000	3000—4000
4504	0	0	10	24	54	Нет пробы	Нет пробы	Нет проб	
4530	0	0	10	21	75	0	0	Нет проб	
4535	10		10	0	0	0	0	0	0
4548	0	0	0	0	0	0	0	0	0
4577	0	0	10	10	12	0	0	0	0
4582	20		10	9	6	14		33	43
4594	0	20	10	8	20	28	124	19 →	■
4599	0	4	6	8	6	6		Нет пробы	0
4630	20	10	10	3	6	8	25	18	Нет пробы
4634	0	0	10	12	10	7		2	» »
4712	20		26	30	9	41		16	» »
4718	20	Нет пробы	6	6	23	48	57	270	» »
4721	0	0	10	10	35	52	42	32 →	■
4724	0	20	0	9	9	17	23	0	0

ние на дне приводит к разрушению раковин. Отсутствие следов растворения у раковин из глубинных слоев воды подтверждает предположение о быстром падении их на дно.

Таблица 7

Частота встречаемости (p) и средние арифметические содержания пустых раковин фораминифер в толще воды

Горизонт, м	p	$\bar{x}$ экз. на 1000 м³	Горизонт, м	p	$\bar{x}$ экз. на 1000 м³
0—50	0,21	5	1000—1500	0,60	17
50—100	0,35	7	1500—2000	0,60	30
100—200	0,85	9	2000—3000	0,60	30
200—500	0,85	10	3000—4000	0,20	7
500—1000	0,85	22			

Распределение отдельных видов фораминифер

Видовое распределение планктонных фораминифер по вертикали первоначально было изучено на тех же материалах, что и суммарное их распределение в толще воды. В планктонных ловах от поверхности до глубины 2000 м нами было встречено 19 описанных в литературе видов. Ниже приводятся сведения об их вертикальном распределении (табл. 8) и частоте встречаемости (табл. 9).

Globorotalia menardii (Orbigny) обнаружена на 13 станциях, на глубинах от 0 до 1500 м (табл. 10).

В наибольшем количестве она отмечена в слое 50—200 м; для этого слоя характерна и наиболее высокая частота встречаемости вида (см. табл. 8).

Ниже 200 *м* содержание вида резко падает (в 8—10 раз) и уменьшается частота его встречаемости.

Orbulina universa Orbigny распространена также до глубины 1500 *м* (табл. 11). Максимальные содержания и наибольшая частота встречаемости отмечены в слое до 200 *м* (см. табл. 8 и 9). Ниже количества экземпляров резко уменьшаются (в 10—15 раз).

Globigerinoides ruber (Orbigny) обнаружен на глубинах до 2000 *м* (табл. 12), но наиболее распространен в слое 0—100 *м* (табл. 8 и 9).

Таблица 8

Частота встречаемости (*p*) некоторых видов планктонных фораминифер в толще воды тропической зоны Индийского океана

Вид	Горизонт, *м*						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
Globorotalia menardii	0,57	0,64	0,64	0,42	0,28	0,21	Нет
Orbulina universa	0,57	0,70	0,57	0,42	0,35	0,15	»
Globigerinoides ruber	0,64	0,81	0,50	0,57	0,57	0,33	0,08
G. sacculifer	0,29	0,29	0,50	0,50	0,29	0,29	Нет
G. conglobatus	0,14	0,14	0,35	0,29	0,21	0,07	»
Globigerinella aequilateralis	Нет	0,50	0,35	0,29	0,42	0,29	»
Hastigerina pelagica	»	0,29	0,50	0,57	0,35	0,14	»
H. digitata	»	0,07	0,21	0,29	0,21	0,07	0,07

Globigerinoides sacculifer (Brady) встречается до глубины 1500 *м* (табл. 13), но наиболее часто — на глубинах от 100 до 500 *м*. Частота встречаемости и средние содержания вида показаны в табл. 8 и 9. Наибольшие содержания приурочены к слою 50—100 *м*.

Globigerinoides conglobatus (Brady) обитает в той же толще (табл. 14), но наиболее распространен в слое 100—200 *м*, а максимальные количества отмечены на глубине 50—100 *м* (см. табл. 9).

Таблица 9

Средние арифметические содержания некоторых видов планктонных фораминифер в толще воды тропической зоны Индийского океана, экз. на 1000 *м*³

Вид	Горизонт, *м*						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
Globorotalia menardii	90	247	167	22	10	<1	Нет
Orbulina universa	75	127	100	8	3	<1	»
Globigerinoides ruber	438	178	24	22	21	10	»
G. sacculifer	20	46	36	21	5	5	»
G. conglobatus	9	18	5	1	<1	<1	»
Globigerinella aequilateralis	Нет	32	26	31	18	1	»
Hastigerina pelagica	»	17	23	3	2	<1	»
H. digitata	»	1	8	2	1	<1	<1

Globigerinella aequilateralis (Brady) обнаружена на глубинах от 50 до 1500 *м* (табл. 15). Сравнительно высокое среднее содержание вида отмечается в интервале глубин от 50 до 500 *м*. Ниже 500 *м* оно уменьшается. Частота встречаемости с глубиной меняется незначительно (см. табл. 8).

Hastigerina pelagica (Orbigny) отмечена в том же интервале глубин (табл. 16). Этот вид наиболее распространен на глубинах от 100 до 500 *м* при повышенных содержаниях в слое от 50 до 200 *м* (см. табл. 9).

Таблица 10

Распределение Globorotalia menardii в толще воды, экз. на 1000 *м*³

№ станции	Горизонт, *м*						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	77	479	1126	211	131	Нет проб	
4530	0	73	37	0	0	0	0
4535	0	0	0	0	0	0	0
4548	20	0	22	0	0	0	0
4577	0	0	67	6	0	0	0
4582	220	604	330	58	0	0	0
4594	0	160	0	3	2	2	0
4599	0	63	61	0	0	0	0
4630	520	41	0	0	0	4	0
4634	224	1300	247	7	6	0	0
4712	40		10	0	0	0	0
4718	0	0	342	30	4	4	0
4721	0	0	0	0	0	0	0
4724	20	0	0	0	0	0	0

Таблица 11

Распределение Orbulina universa в толще воды, экз. на 1000 *м*³

№ станции	Горизонт, *м*						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	96	84	9	0	12	Нет проб	
4530	0	146	9	6	7	0	0
4535	70		110	0	0	0	0
4548	20	0	0	0	0	0	0
4577	0	0	961	55	10	0	0
4582	680	646	20	7	0	0	0
4594	0	20	0	0	6	2	0
4599	21	313	224	32	0	0	0
4630	40	82	0	0	0	0	0
4634	41	160	41	0	2	0	0
4712	70		0	13	0	0	0
4718	0	0	0	0	0	7	0
4721	0	77	30	3	0	0	0
4724	0	0	0	0	0	0	0

Таблица 12

Распределение Globigerinoides ruber в толще воды, экз. на 1000 м³

№ станции	Горизонт, м						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	0	42	0	0	2	Нет проб	
4530	627	36	0	93	138	0	0
4548	20	0	0	0	0	0	0
4582	700	875	30	7	4	0	0
4594	640	26	20	8	8	0	0
4599	63	42	31	16	0	0	0
4630	200	82	0	0	0	0	0
4634	40	41	0	0	0	0	0
4712	3560		10	40	7	0	0
4718	3529	Нет пробы	139	110	31	66	0
4721	82	327	90	20	98	38	0
4724	0	60	10	3	8	26	24

Таблица 13

Распределение Globigerinoides sacculifer в толще воды, экз. на 1000 м³

№ станции	Горизонт, м						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4530	20	236	74	16	20	0	0
4582	140	104	40	7	0	0	0
4594	0	260	207	17	21	19	0
4599	0	0	10	0	0	0	0
4630	100	0	10	0	0	0	0
4634	0	0	20	0	0	0	0
4712	60		90	47	0	0	0
4718	0	0	76	193	33	42	0
4721	0	0	0	3	4	10	0

Таблица 14

Распределение Globigerinoides conglobatus в толще воды, экз. на 1000 м³

№ станции	Горизонт, м						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	0	0	0	6	2	Нет проб	
4530	0	73	9	0	0	0	0
4535	0	0	10	0	0	0	0
4548	0	0	11	4	0	0	0
4582	100	0	0	0	0	0	0
4594	0	160	26	7	8	6	0
4630	20	0	0	0	0	0	0
4634	0	0	0	0	2	0	0
4718	0	0	13	3	0	0	0

Таблица 15

Распределение Globigerinella aequilateralis в толще воды, экз. на 1000 м³

№ станции	Горизонт, м						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	0	21	9	0	0	Нет проб	
4530	0	73	27	13	69	0	0
4535	20		0	0	0	0	0
4594	0	200	104	3	6	0	0
4599	0	0	31	0	0	0	0
4630	0	102	41	0	4	4	0
4712	80		160	223	2	0	0
4718	0	0	0	197	168	7	0
4721	0	19	0	0	2	2	0

Таблица 16

Распределение Hastigerina pelagica в толще воды, экз. на 1000 м³

№ станции	Горизонт, м						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	0	0	9	3	6	Нет проб	
4530	0	0	55	13	8	0	0
4535	30		0	0	0	0	0
4548	0	0	0	4	0	0	0
4577	59		38	10	10	0	0
4582	0	0	110	3	0	0	0
4594	0	60	9	0	17	2	0
4599	0	0	51	10	0	0	0
4630	0	143	10	4	6	0	0
4634	0	0	0	3	0	0	0

Таблица 17

Распределение Hastigerina digitata в толще воды, экз. на 1000 м³

№ станции	Горизонт, м						
	0—50	50—100	100—200	200—500	500—1000	1000—1500	1500—2000
4504	0	0	57	0	0	Нет проб	
4540	0	0	0	13	7	0	0
4594	0	20	0	7	0	2	0
4712	0	0	0	3	0	0	0
4721	0	0	40	0	0	0	0
4724	0	0	10	10	10	0	22

Hastigerina digitata Brady встречается на глубинах от 50 до 2000 *м* (табл. 17), но нигде в толще воды не образует массовых скоплений (см. табл. 9). Несколько повышенные содержания тяготеют к слою 100—200 *м*.

Globigerina conglomerata Schwager обнаружена на трех станциях на глубинах до 200 *м*. Этот вид редок и малочислен в водах изученного района; несколько повышенные содержания (100—300 экз.) отмечены в слое 50—100 *м*.

Pulleniatina obliquiloculata(Parker et Jones) найдена на пяти станциях на глубинах до 500 *м* в количестве от 3 до 20 экз. на 1000 $м^3$ воды.

Globorotalia tumida (Brady) отмечена на четырех станциях, на тех же глубинах. Количество экземпляров колеблется от 3 до 38 на 1000 $м^3$ воды.

Sphaeroidinella dehiscens (Parker et Jones) встречена на трех станциях, на глубинах до 200 *м*, в количестве от 9 до 36 экз. на 1000 $м^3$ воды.

Hastigerinella rhumbleri Galloway встречена также на трех станциях на глубинах 200—500 *м* в количестве от 3 до 6 экз. на 1000 $м^3$.

Globigerina bulloides Orbigny обнаружена на пяти станциях на глубинах от 50 до 1500 *м*, причем в слое 50—100 *м* вид встречен один раз (p = = 0,07), а в слое 100—200 *м* и более глубоких — два, иногда три раза.

Globorotalia punctulata (Orbigny) и Globorotalia truncatulinoides (Orbigny) найдены в слое ниже 200 *м*. G. *truncatulinoides* тяготеет к глубинам 200—500 *м*, а G. punctulata в количестве нескольких экземпляров на 1000 $м^3$ воды отмечена на глубинах от 200 до 1500 *м*.

Globigerina eggeri, Globigerina hexagona и Hastigerina murrhay были обнаружены всего на одной-двух станциях в незначительных количествах. Поэтому выявить закономерности их вертикального распределения не удалось.

Большинство описанных видов относятся к тропическим. По частоте встречаемости и количественным характеристикам они могут быть отнесены к следующим двум группам.

1. Виды, обитающие на всех глубинах от 0 до 1500 *м* (иногда до 2000 *м*). Это — Globorotalia menardii, Orbulina universa, Globigerinoides conglobatus, G. sacculifer. Для них характерна приуроченность больших концентраций к верхнему слою (до 200 *м*) воды. Ниже количество экземпляров резко уменьшается. Сравнительно небольшие изменения частот встречаемости говорят о соответствии (для этих видов) видового состава верхних и нижних слоев на большинстве станций. К этой же группе могут быть отнесены виды Globigerinella aequilateralis, Hastigerina pelagica и H. digitata, отсутствующие лишь в самом приповерхностном слое (0—50 *м*).

2. Виды, обнаруженные только на глубинах до 500, а иногда и до 200 *м*, и всегда в малых количествах. К ним относятся Pulleniatina obliquiloculata, Globorotalia tumida, Globigerina conglomerata, Sphaeroidinella dehiscens, Globigerina eggeri и др. Ограниченное распространенние этих видов по глубине объясняется не приуроченностью их к малым глубинам, а малой продуктивностью в данном месте в данное время года.

Виды умеренных широт (Globorotalia truncatulinoides, G. punctulata и Globigerina bulloides), приуроченные в основном к глубинам больше 200 *м*, встречались редко и в малых количествах. В умеренных широтах они обитают в верхних слоях воды и многочисленны (Parker, 1960), а в тропиках опускаются в более глубокие и холодные воды. Такие виды получили название «тропические утопленники». В Атлантике к ним относятся Globigerina inflata, Globorotalia truncatulinoides и Globigerina bulloides (Phleger, 1954; Wiseman a. Ovey, 1950).

Этим и объясняется тот факт, что на глубинах 100—500 *м* нами отмечено наибольшее число видов, большее, чем в слое 0—100 *м*, где нет видов умеренных широт, и большее, чем в слое 500—1500 *м*, где исчезают некоторые тропические виды.

РАСПРЕДЕЛЕНИЕ ПЛАНКТОННЫХ ФОРАМИНИФЕР ПО ПЛОЩАДИ В СЛОЕ 0—200 *м* И ИХ БИОЦЕНОЗЫ

Количественное распределение

Количественное распределение планктонных фораминифер в поверхностных водах (0—200 *м*) тропической части Индийского океана в период зимнего муссона было исследовано по материалам 409 станций. Первоначально было определено количество фораминифер, содержащихся в слоях 0—25, 25—50, 50—100 и 100—200 *м*, на основании чего установлены основные закономерности распределения их в слое 0—200 *м* по всей акватории.

В слое 0—25 *м* планктонные фораминиферы встречены на большинстве станций (95%) в количестве от 20 до 8055 экз. на 1000 $м^3$ воды [1]. Среднее геометрическое содержание их в слое ($\tilde{x}$) равно 1070 экз., дисперсия—0,309. Как видно из табл. 18, наиболее часто в этом слое встречаются количества более 1000 экз. ($p = 0{,}51$).

Таблица 18

Частота встречаемости (p) различных количеств планктонных фораминифер в слое 0—200 *м*

Горизонт, *м*	Количество фораминифер, экз. на 1000 $м^3$ воды			
	< 100	100—150	500—1000	> 1000
0—25	0,03	0,32	0,06	0,51
25—50	Нет.	0,19	0,23	0,58
50—100	0,09	0,42	0,24	0,24
100—200	0,22	0,47	0,16	0,14
0—200	0,06	0,22	0,34	0,36

В слое 25—50 *м* планктонные фораминиферы обнаружены повсеместно в количестве от 240 до 5400 экз., $\tilde{x} = 1090$ экз., дисперсия — 0,132. Также, как и в предыдущем слое, преобладают количества больше 1000 экз. ($p = 0{,}58$). Однако содержания 500—1000 экз. и более в данном слое встречаются чаще, что вместе с высоким средним геометрическим содержанием свидетельствует о наличии здесь оптимальных условий для жизни фораминифер.

В слое 50—100 *м* фораминиферы присутствуют на всех станциях в количестве от 23 до 3525 экз.; $\tilde{x} = 403$ экз., т. е. в 2—2,5 раза ниже, чем в верхних слоях, дисперсия — 0,255. Большие скопления фораминифер в этом слое, как и в предыдущем, обнаружены только в тех местах, где имеются их высокие концентрации, и в лежащих выше слоях, но встречаются они значительно реже (на 24% станций). Наиболее характерны количества от 100 до 500 экз. ($p = 0{,}42$).

В слое 100—200 *м* фораминиферы отмечены также на всех станциях в количестве от 20 до 1810 экз.; $\tilde{x} = 217$ экз., дисперсия — 0,266. Большие количества (500—1000 экз. и более) встречаются реже, чем в предыдущих слоях. Резко возрастает частота встречаемости количеств от 100 до 500 экз. ($p = 0{,}47$) и менее 100 экз. ($p = 0{,}22$).

[1] Так как все цифры в дальнейшем даны в пересчете на 1000 $м^3$ воды, ссылки на объем профильтрованной воды будут опускаться.

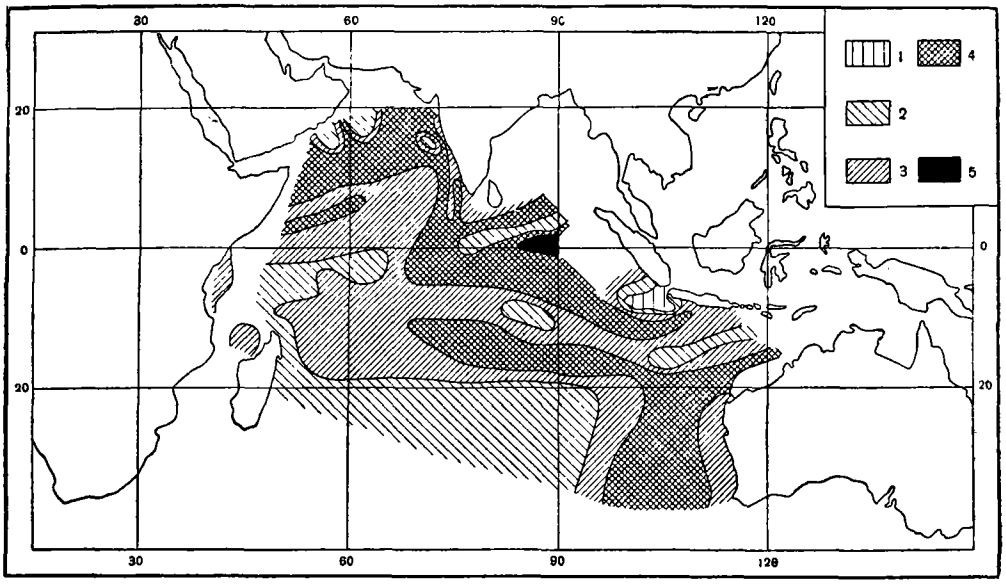


Рис. 3. Распределение планктонных фораминифер (экз. на 1000 $м^3$ воды) по площади Индийского океана в слое 0—200 *м*

1 — до 100 экз.; *2* — от 100 до 500 экз.; *3* — от 500 до 1000 экз.; *4* — от 1000 до 5000 экз.; *5* — больше 5000 экз.

Учитывая распределение планктонных фораминифер и частоту встречаемости различных количеств, можно отметить, что максимумы их тяготеют к слоям 0—25 и 25—50 *м*, где температура воды колеблется в пределах от 24,92 до 29,21° (на поверхности океана). В слое 50—100 и 100—200 *м* количество фораминифер уменьшается соответственно в два и пять раз. Температура воды на глубине 200 *м* колеблется от 12,14 до 18,84°, т. е. уменьшается приблизительно на 10°.

Распределение фораминифер внутри слоя 0—200 *м* и тяготение максимальных количеств к слою 0—50 *м* связано с высокоподнятым (до 50—100 *м*) слоем скачка pH, фосфатов, кремнекислоты, а также вертикальным распределением температуры воды и фитопланктона.

Количество фораминифер в слое до 200 *м* в целом колеблется от 33 до 5557 экз., средне**е** геометрическо**е** содержани**е** равно 744 экз., дисперсия — 0,221. На большинстве станций (36 %) встречалось более 1000 экз. или от 500 до 1000 экз. (34 % станций). Максимальные количества (от 1000 до 5557 экз.) обнаружены в Аравийском море, в районе о-ва Ява, у Кокосовых и Мальдивских островов, а также в открытых частях океана (рис. 3). По 500—1000 экз. отмечено в районе о-ва Ява, Мальдивских островов, близ берегов Индии, к востоку от Мадагаскара, в Аравийском море и в открытых частях океана. Содержание 100—500 экз. (22 % станций) не характерно для слоя 0—200 *м* в тропической части океана, оно отмечено близ о-ва Суматра, у Мальдивских островов, к северу и к востоку от Мадагаскара, в Аравийском море и в открытом океане (рис. 3). Менее 100 экз. встречалось редко (6 % станций). Такое распределение планктонных фораминифер в общих чертах согласуется с распределением всего планктона и определяется в основном теми же причинами.

Наибольшее количество фораминифер (500 экз. и более) наблюдается в районах поднятия глубинных вод в северной части Аравийского моря и

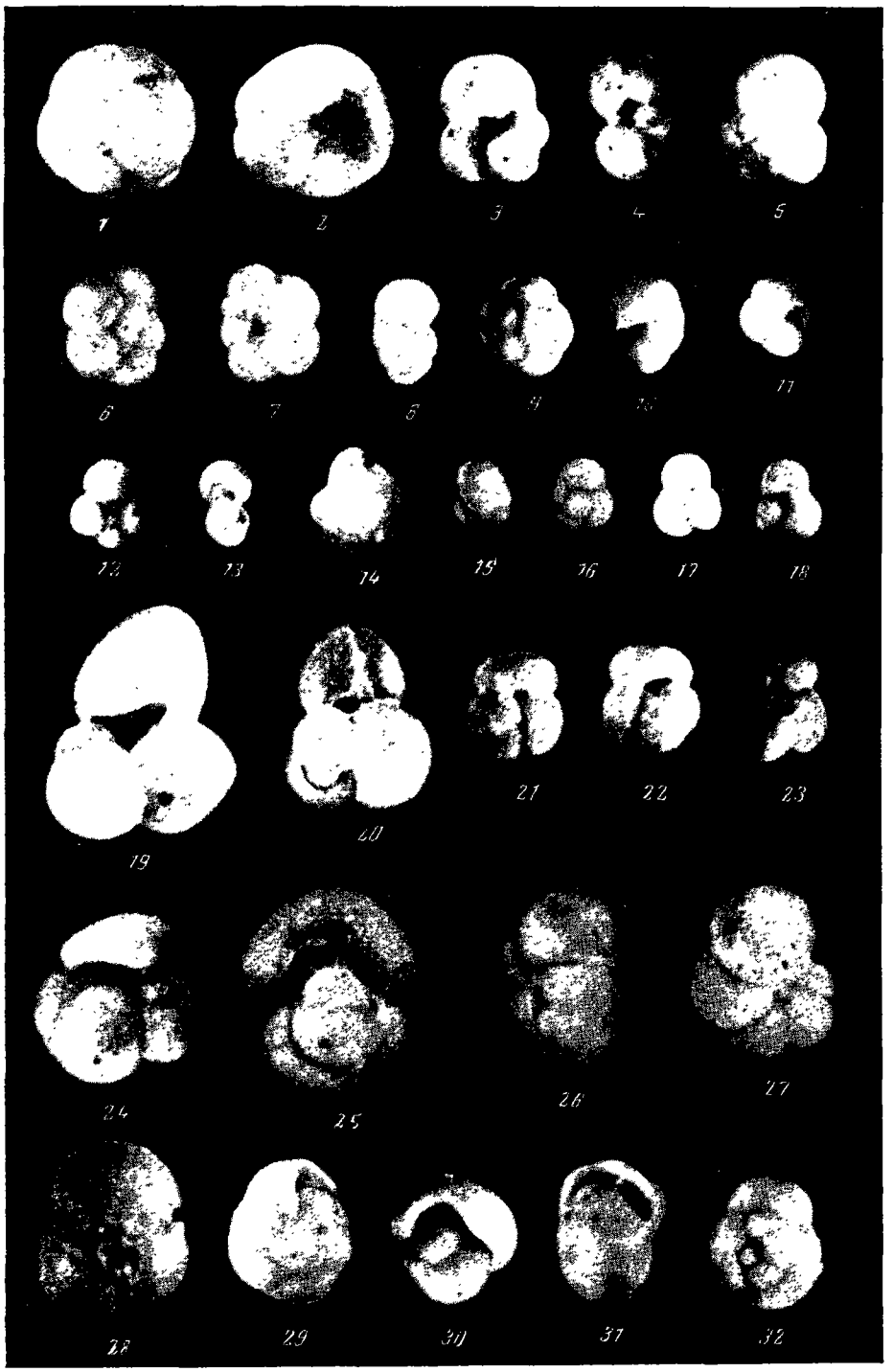
в районе экваториальных течений; оно приурочено к водным массам Аравийского моря и индийской экваториальной водной массе, для которых характерно высокое положение слоя скачка, подъем глубинных вод, богатых биогенными элементами, особенно в районах дивергенций Южного экваториального течения и противотечения. Мощные дивергенции образуются также при прохождении струй Муссонного течения и противотечения в промежутках между Мальдивскими и Лаккадивскими островами и архипелагом Чагос. Им тоже соответствуют большие количества фораминифер. Обилие фораминифер в восточной части Аравийского моря обусловлено влиянием северо-восточного муссона, который вызывает подъем вод у берегов Индии, а скопления у берегов Явы связаны с влиянием южного пассата, который, отгоняя воду от берега, вызывает подъем глубинных вод.

В пределах распространения индийской центральной водной массы количество фораминифер не превышает 500 экз. Для этой водной массы характерно слабое вертикальное перемешивание с недостаточным выносом биогенных элементов на поверхность. Распределение планктона (Богоров и Виноградов, 1961; Бродский и Виноградов, 1958) к югу от 18° с. ш. позволяет считать, что эта сравнительно бедная фораминиферами область протягивается до 40° ю. ш. и покрывает все пространство, занятое центральноиндийской водной массой. В южной части Тихого океана (Parker, 1960) область минимальных количеств фораминифер также приурочена к центральным водным массам (от 16—18 до 40° ю. ш.).

У берегов Австралии количество фораминифер увеличивается до 1000 экз. и более. Это связано с наличием сильных меридиональных течений (Овчинников, 1961), способствующих вертикальному перемешиванию водных слоев и выносу биогенных компонентов.

Распределение отдельных видов в поверхностных водах тропической зоны

Globigerinoides ruber (Orbigny) (табл. I) является наиболее распространенным видом ($p = 0{,}9$) в тропической зоне Индийского океана (табл. 19). Он обнаружен в количествах до 3150 экз. и составляет от 1 до 98% фауны фораминифер (рис. 4), причем на большинстве станций — более 50%. Максимальные количества (больше 1000 экз.) отмечены в восточной половине Аравийского моря, в открытой части океана в виде двух полос, протягивающихся от Мальдивских островов к северо-востоку и к Кокосовым островам, а также отдельными пятнами. Частота встречаемости этих количеств равна 0,20 (табл. 19). Количествами от 500 до 1000 экз. характеризуются две полосы широтного направления (одна из них длинная, прослеживается от 55° в. д. до о-ва Ява, другая — более короткая) и район в западной части Аравийского моря. В количестве 100—500 экз. этот вид встречен у южной оконечности Индии, на экваторе, у берегов Австралии, у о-ва Ява и в районе Мадагаскара и Сейшельских островов; две узкие полосы с таким содержанием прослеживаются в открытом океане на 10 и 18° ю. ш. ($p = 0{,}28$). Количества менее 100 экз. обнаружены в западной части Аравийского моря, к западу от о-ва Ява, у восточного побережья Африки и к югу от 20° ю. ш. Частота встречаемости их 0,22. Не обнаружен G. ruber на одной станции в Аравийском море, близ экватора (ст. 4592) и к югу от 20° ю. ш. на 90° в. д. Среднее геометрическое содержание вида в слое 0—200 *м* — 266 экз., что по сранению с другими видами является максимальным, дисперсия — 0,481. Температура поверхностных вод на станциях, где он встречается, колебалась в пределах от 24,92 до 29,21°, соленость — от 33,52 до 35,90‰.



Планктонные фораминиферы Индийского океана. Увеличено в 20 раз.

1,2 — Globigerina conglomerata Schwager, ст. 319; *3,4,5* — Globigerina bulloides Orbigny, ст. 4594; *6,7,8* — **Globigerina eggeri** Rhumbler, ст. 139; *9,10,11* — Globigerina pachyderma Ehrenberg, ст. 177; *12,13* — Globigerina **hexagona** Natland, ст. 4726; *14* — Globigerina quinqueloba Natland, ст. 4726; *15,16,17,18* — Globigerinita glutinata **Egger, ст.** 4619; *19,20* — Globigerinoides sacculifer (Brady), ст. 4582; *21,22,23* — Globigerinoides ruber (Orbigny), **ст. 135;** *24* — Globigerinoides conglobatus (Brady), ст. 4504; *25,26,27* — Globigerinella aequilateralis (Brady), **ст. 4630;** *28* — Sphaeroidinella dehiscens (Parker et Jones), ст. 324; *29,30,31* — Pulleniatina obliquiloculata (Parker et Jones), ст. 319; *32* — Candeina nitida Orbigny, ст. 4575.

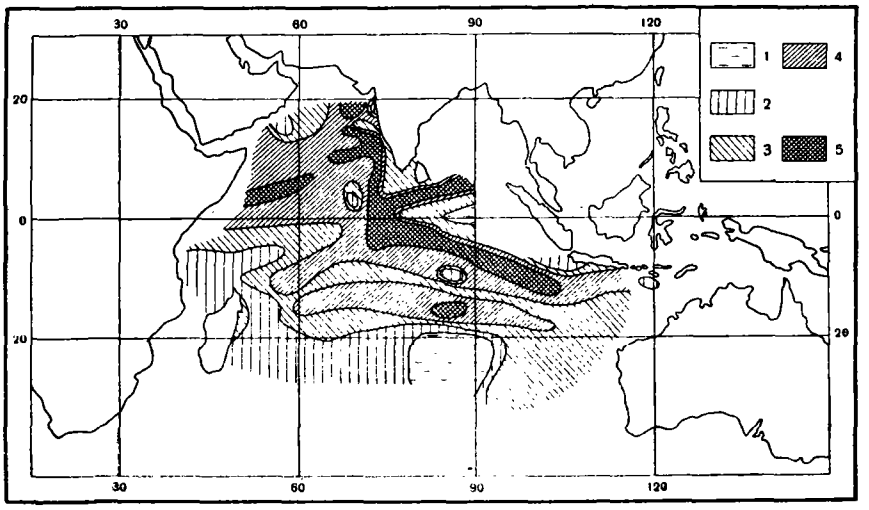


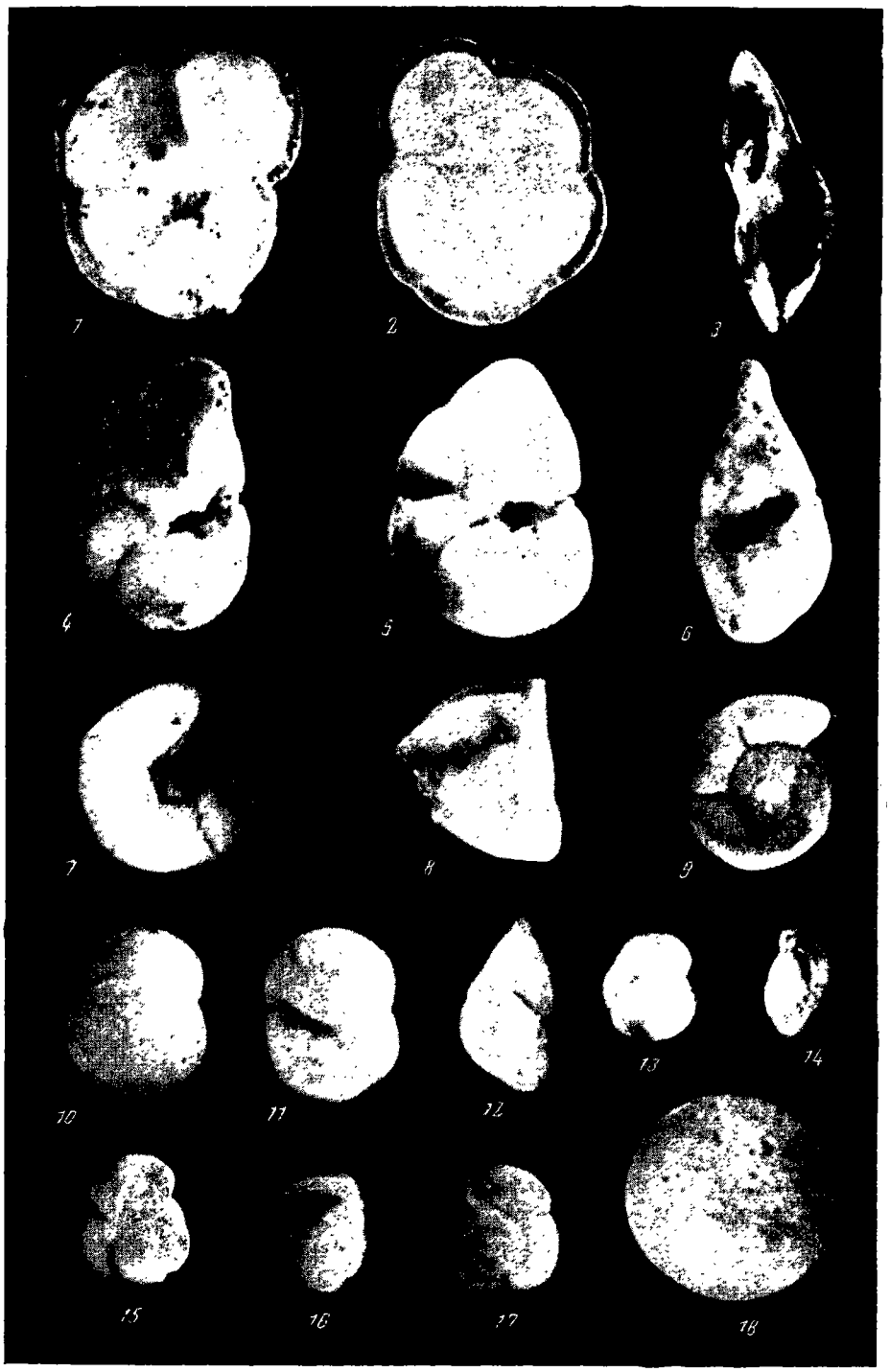
Рис. 4. Распространение Globigerinoides ruber в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

1 — вид не найден; 2 — до 100 экз.; 3 — от 100 до 500 экз.; 4 — от 500 до 1000 экз.; 5 — больше 1000 экз.

Таблица 19

Частота встречаемости (p) различных количеств планктонных фораминифер (по видам) в слое 0—200 м

Вид	Общая ($p_{общ}$)	Количество экз. на 1000 $м^3$ воды			
		< 100	100—500	500—1000	> 1000
Globigerinoides ruber	0,90	0,22	0,28	0,20	0,20
Globorotalia menardii	0,83	0,51	0,22	0,08	0,02
Orbulina universa	0,75	0,59	0,17	Нет	Нет
Hastigerina pelagica	0,67	0,65	0,02	»	»
Globigerinella aequilateralis	0,65	0,51	0,14	»	»
Globigerinoides sacculifer	0,60	0,32	0,22	0,04	0,02
Globigerina bulloides	0,55	0,47	0,08	Нет	Нет
Globigerinoides conglobatus	0,49	0,44	0,04	»	»
Hastigerina digitata	0,45	0,40	0,06	»	»
Globigerina eggeri	0,40	0,40	Нет	»	»
Globorotalia punctulata	0,20	0,20	»	»	»
Globigerina hexagona	0,16	0,16	»	»	»
G. conglomerata	0,16	0,14	0,02	»	»
Pulleniatina obliquilocutata	0,14	0,14	Нет	»	»
Globigerina inflata	0,12	0,12	»	»	»
Sphaeroidinella dehiscens	0,08	0,08	»	»	»
Globigerina quinqueloba	0,08	0,08	»	»	»
G. glutinata	0,08	0,08	»	»	»
Globorotalia tumida	0,06	0,06	»	»	»
G. truncatulinoides	0,05	0,05	»	»	»
Candeina nitida	0,04	0,04	»	»	»
Hastigerinella rhumbleri	0,02	0,02	»	»	»
Hastigerina murrhayi	0,02	0,02	»	»	»



Планктонные фораминиферы Индийского океана. Увеличено в 20 раз

1, 2, 3— Globorotalia menardii (Orbingy), ст.4682; *4, 5, 6* — Globorotalia tumida (Brady), ст. 139; *7, 8,9*—Globorotalia truncatulinoides (Orbingy), ст. 302; *10, 11, 12*—Globorotalia hirsuta (Orbingy), ст.297; *13, 14* — Globorotalia punctulata (Orbigny), ст. 149; *15, 16, 17* — Globigerina inflata Orbigny, ст. 261; *18* — Orbulina universa Orbigny, ст. 4718.

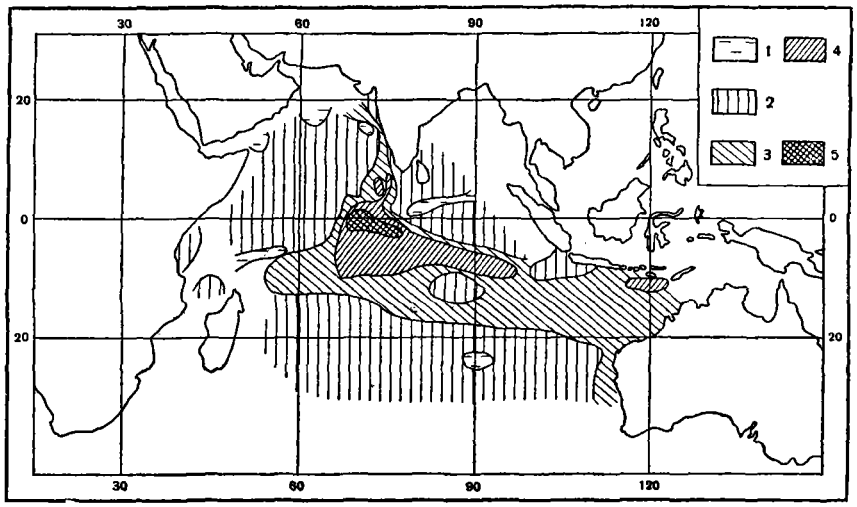


Рис. 5. Распространение Globorotalia menardii в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

1 — вид не найден; *2* — до 100 экз.; *3*— от 100 до 500 экз.; *4*—от 500 до 1000 экз.; *5* — больше 1000 экз.

Высокие концентрации вида (больше 1000 экз.) встречены только в пределах распространения Индийской экваториальной воды, к северу от 20° ю. ш. В Тихом океане вид отмечен в экваториальных и центральных водных массах северного и южного полушария (Bradshow, 1959; Parker, 1960). По данным Брэдшоу, G. ruber встречается при температуре вод от 15 до 32°, максимальные концентрации приурочены к температурам порядка 19—31°.

Globigerinoides ruber широко распространен в экваториальных и центральных водных массах Тихого и Индийского океанов с наивысшими концентрациями в экваториальных водах. Удельный вес этого вида в Индийском океане выше, чем в Тихом, где он составляет только около 20% фауны фораминифер (Bradshow, 1959).

Globorotalia menardii (Orbigny) (табл. II) встречается в тропической части Индийского океана почти повсеместно ($p = 0{,}83$) в количествах до 1400 экз. (см. табл. 19) и составляет от 1 до 83% фауны фораминифер (рис. 5). Содержание его на большинстве станций составляло менее 20 % фауны планктонных фораминифер. Концентрации выше 1000 экз. встречались очень редко ($p = 0{,}02$), а 1400 экз. отмечено только в одном районе, к юго-востоку от Мальдивских островов. В количестве 500—1000 экз. этот вид обнаружен в открытой части океана, в районе архипелага Чагос, к северу и востоку от него, и к юго-востоку от о-ва Ява. Частота встречаемости таких количеств 0,08. Более часто ($p = 0{,}22$) встречаются количества в 100—500 экз. Полоса таких концентраций протягивается вдоль восточного побережья Индии, захватывает район Мальдивских островов, на западе доходит до 55° в. д. и по параллели 15—20° ю. ш. достигает о-ва Ява и западных берегов Австралии. В общем, в количествах более 100 экз. G. menardii обнаружена в индийской экваториальной водной массе. Наиболее характерны для нее, однако, количества менее 100 экз. ($p = 0{,}51$), которые отмечены в Аравийском море, индийской центральной водной массе, у восточного побережья Африки, к западу от Центрального Индийского хребта, у южной оконечности Индии, на экваторе, у о-ва Явы, к западу от 90° в. д. и к югу от 13—20° ю. ш. Отсутствовал этот

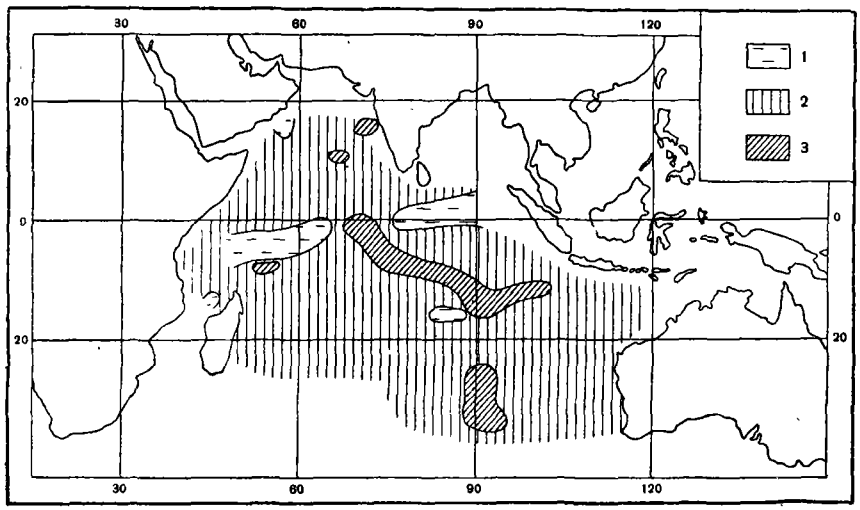


Рис. 6. Распространение Orbulina universa в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

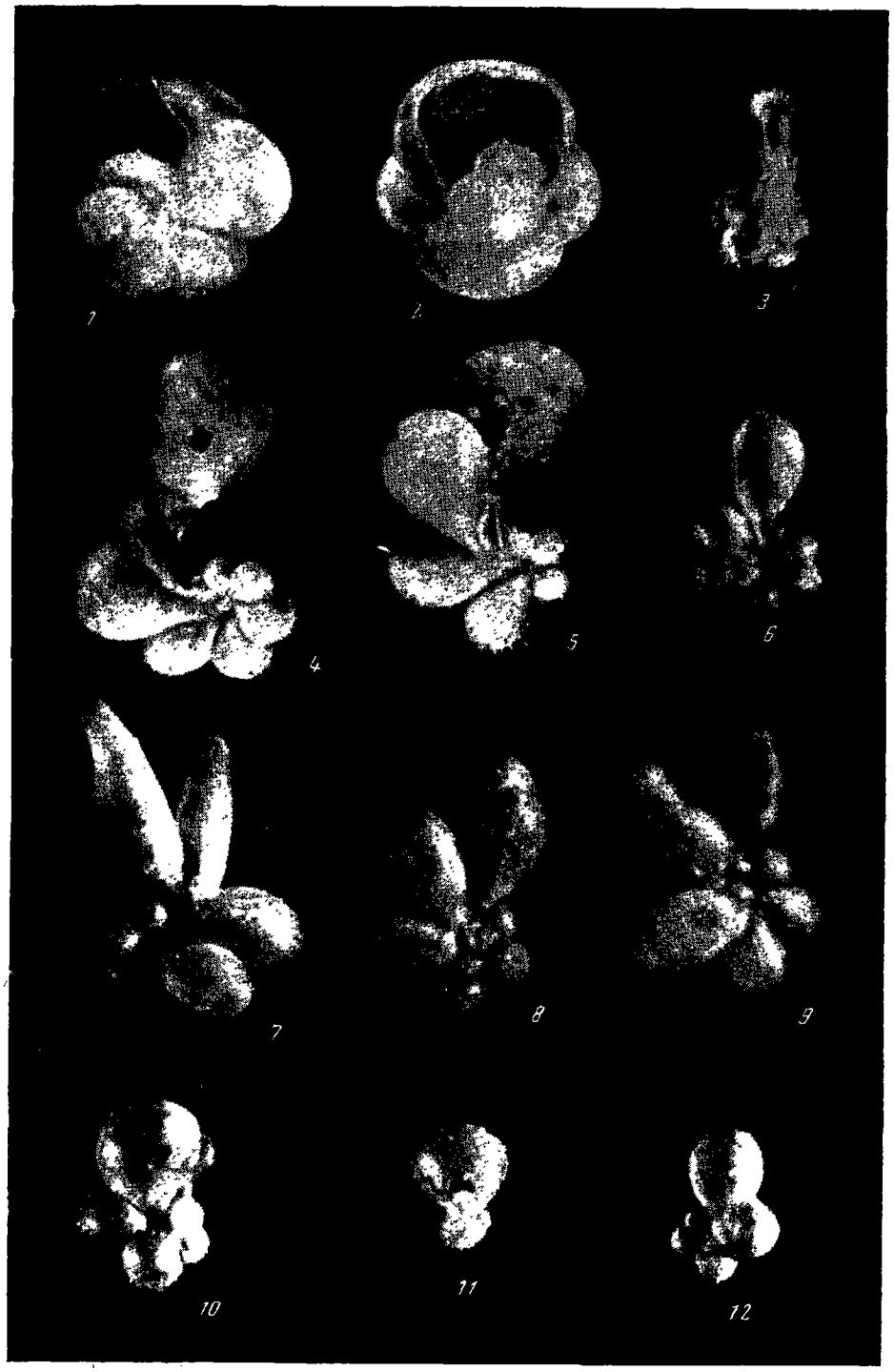
1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.

вид на трех станциях в Аравийском море, к юго-западу от Сейшельских островов, на 90° в. д. к северу от экватора и южнее 30° ю. ш. Среднее геометрическое содержание его 64 экз., дисперсия 0,476. Температура поверхностных вод в местах нахождения 24,92—29,21°, а соленость 33,52—35,70‰.

В Тихом океане G. menardii обнаружена только в водах тропической и теплой умеренной зоны (Bradshow, 1959), в основном также в количестве менее 20% от всей фауны планктонных фораминифер. Обитает при температуре от 10 до 35°, но наибольшие концентрации отмечены на экваторе при температуре 27—32°. В южной части Тихого океана (Parker, 1960) этот вид приурочен также к экваториальным и южно-центральным водам и составляет в основном менее 20% фауны. Температура поверхностных вод в местах обитания его колеблется в пределах 17,7—27,3°, соленость — от 34 до 35,9‰; наивысшие концентрации отмечены на экваторе.

Orbulina universa Orbigny (табл. II) также относится к видам, очень распространенным в Индийском океане ($p = 0{,}75$), и встречается в количествах до 480 экз. (рис. 6). Он составляет от 0,3 до 35% всей фауны планктонных фораминифер, а иногда содержание этого вида достигает 83%. Количества более 100 экз. отмечены в открытой части океана, к северу и юго-востоку от архипелага Чагос и у Кокосовых островов; отдельные пятна повышенных концентраций наблюдались в восточной части Аравийского моря, к востоку от о-ва Коэтиви и южнее 20° ю. ш. Частота встречаемости этих количеств равна 0,18 (табл. 19). Менее 100 экз. часто встречается ($p = 0{,}59$) в Аравийском море, у восточного побережья Африки, в Яванском районе, у западного побережья Австралии и южнее 40° ю. ш. на станциях меридиональных разрезов д/э «Обь». Среднее геометрическое содержание вида 39 экз., дисперсия 0,298. Вид обнаружен при температуре поверхностных вод от 10,92 до 29,05° и солености 33,52—35,85‰. Наибольшие количества приурочены к индийской центральной водной массе.

В Тихом океане этот вид распространен в тропической и умеренной зонах (Bradshow, 1959), где он составляет от 1 до 50% фауны. Максимальные концентрации отмечены близ Гавайских островов и в области холодного



Планктонные фораминиферы Индийского океана. Увеличено в 20 раз.

1, *2*— Hastigerina murrayi Thomson, ст. 4504; *3* — Hastigerinella rhumbleri Galloway, ст. 4633; *4*, *5*, *6*—Hastigerina digitata Rhumbler, ст. 4724; *7*, *8*, *9* — то же, ст. 4712; *10*, *11*, *12* — Hastigerina pelagica (Orbigny), ст. 4632.

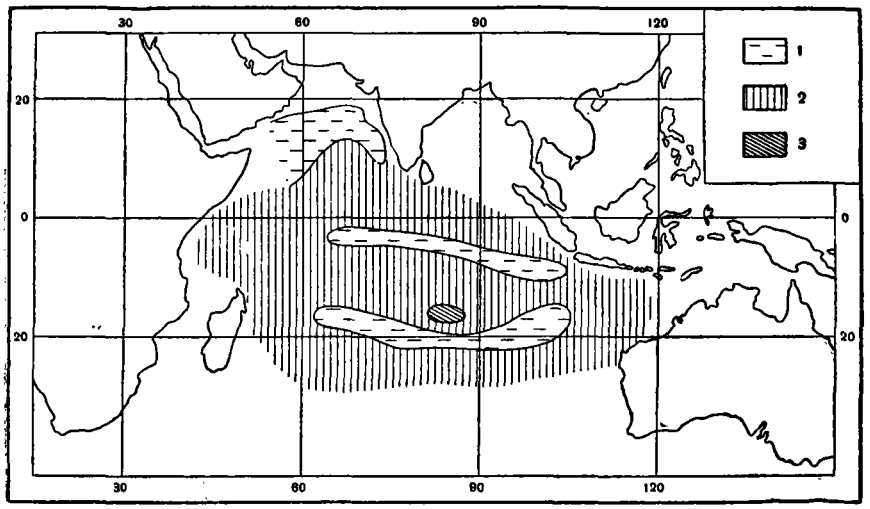


Рис. 7. Распространение Hastigerina pelagica в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.

Калифорнийского течения, а также в виде отдельных пятен на экваторе и на границе течений Ойя-Сио и Куро-Сио (более 50%). Этот вид наиболее характерен для фауны, переходной от субарктической к центральной. В северной части Тихого океана он обитает при температуре воды 11—31° (наибольшие количества обнаружены при температуре 11—16°), в южной части (Parker, 1960) распространен широко, но в основном в малых количествах (до 50% фауны). Значения температуры в местах обитания составляют 9,2—27°, а солености — 33,6—36,5‰.

Широкий диапазон значений температуры и солености вод и широкое географическое распространение дают возможность предположить вслед за Хофкером (Hofker, 1959), что вид Orbulina universa является собирательным и представляет собой стадию воспроизводства нескольких видов. Наличие внутри шаровидной камеры не определимых до вида глобигерин подтверждает это.

Hastigerina pelagica (Orbigny) (табл. III) довольно часто встречается в тропическом районе Индийского океана ($p = 0{,}67$) в количествах до 449 экз. и составляет от 0,4 до 22,7% фауны форминифер (рис. 7). Количество 449 экз. ($p = 0{,}02$) отмечено в центральной части океана на 18° ю. ш. при температуре воды 27,04° и солености 34,65‰, на остальных станциях количество вида (табл. 19) не превышало 100 экз. ($p = 0{,}65$). Этот вид отсутствует почти на всей площади Аравийского моря и в центральной части океана между экватором и 20° ю. ш. Среднее геометрическое содержание 23 экз., дисперсия 0,166. Температура воды в районах распространения H. pelagica колеблется от 26,76° до 29,04°, а соленость — от 33,52 до 35,85‰. Максимальное количество отмечено в индийской центральной водной массе. В водной массе Аравийского моря и в экваториальной вид не дает высоких концентраций.

В северной части Тихого океана он обнаружен в фауне, переходной от субарктической к умеренной, и в экваториальной (менее 50%) при температуре 14—31° (Bradshow, 1959), но наиболее характерен для центральной

фауны (свыше 50%). Возле Гавайских островов количество его превышает 700 экз. Наиболее благоприятна для жизни температура 17—24°. Широко распространен вид также в южной части Тихого океана (Parker, 1960), где составляет от 1 до 50% фауны, а к югу от 20° ю. ш.— более 50%. Температура поверхностных вод в местах его обитания равна 9—27°, а соленость—34—36,5‰. В северной Атлантике этот вид отмечен к югу от 60° с. ш.

Таким образом, H. pelagica может быть отнесена к видам центральных водных масс.

Globigerinella aequilateralis (Brady) (табл. I) встречается в тропической зоне Индийского океана ($p = 0{,}65$) в количестве от 6 до 252 экз. и составляет от 0,6 до 13% фауны пелагических фораминифер (рис. 8). Наибольшие количества (от 100 до 252 экз.) отмечены вдоль западного побережья Индии, у Мальдивских островов, в районе Кокосовых островов и к северо-западу от них ($p = 0{,}14$). В количестве менее 100 экз. вид обнаружен на всей площади ($p = 0{,}51$). Среднее геометрическое содержание 34 экз., дисперсия, 0,224. Отсутствует в Аравийском море, в районе Сейшельских островов, к востоку от Мадагаскара и в районе 20° ю. ш. Характерен для Индийских экваториальных вод с температурой 24,92—29° и соленостью 33,52—35,0‰.

В северной части Тихого океана этот вид приурочен к районам переходной, центральной и экваториальной фауны и составляет до 20%. Наивысшие концентрации отмечены в экваториальных водах (более 20%). Температура воды в местах его обитания колеблется от 15 до 32° (Bradshow, 1959). В южной части Тихого океана наибольшие концентрации (более 33%) отмечены на экваторе; в южно-центральных и субантарктических водах содержание вида не превышает 20% (Parker, 1960). Температуры в этих районах равны 10—24°, соленость —34—36‰.

Globigerinoides sacculifer (Brady) (табл. I) довольно широко распространен в пределах тропического района Индийского океана ($p = 0{,}6$) в количествах до 5454 экз. (рис. 9) и составляет до 98% фауны экваториальных вод. Максимальные концентрации с частотой встречаемости 0,02 отмечены на экваторе (88° в. д.). Количества от 500 до 1000 экз. обнаружены у северо-западного побережья Индии и к юго-западу от Мальдивских островов. Частота встречаемости их (табл. 19) равна 0,04. По 100—500 экз. вида ($p = 0{,}22$) было обнаружено к северо-востоку от Мадагаскара, у западного побережья Индии, к западу от Мальдивских островов, в открытом океане к югу от экватора, у о-вов Рождества и Кокосовых. Чаще этот вид встречался в количествах менее 100 экз. ($p = 0{,}32$); такие концентрации отмечены в восточной части океана и в широкой полосе, протягивающейся от о-ва Мадагаскар до Австралии. Он обнаружен при температуре поверхностных вод 26,76—29,04° и солености —33,52—35,85‰. Отсутствует G. sacculifer в центральной части Аравийского моря, к востоку от архипелага Чагос, к югу от о-ва Рождества, в районе о-ва Суматра и к югу от 20° ю. ш. Среднее геометрическое содержание 86 экз., дисперсия 0,528.

В северной части Тихого океана вид характеризует экваториальную и центральную фауну и составляет до 30% фауны фораминифер, а в западной части на 10—20° с. ш.—более 80% (Bradshow, 1959). Температура воды в местах его обитания равна 17—32°; максимальные концентрации приурочены к водам с температурой 23—32°. В южной части G. sacculifer распространен в экваториальных и южно-центральных водах, но встречается и в переходных к субантарктическим; наивысшие концентрации (более 98%) наблюдаются в юго-западной части экваториального района (Parker, 1960). Температура в местах распространения вида колеблется от 17,7 до 28°, соленость — от 34,7 до 36,5‰.

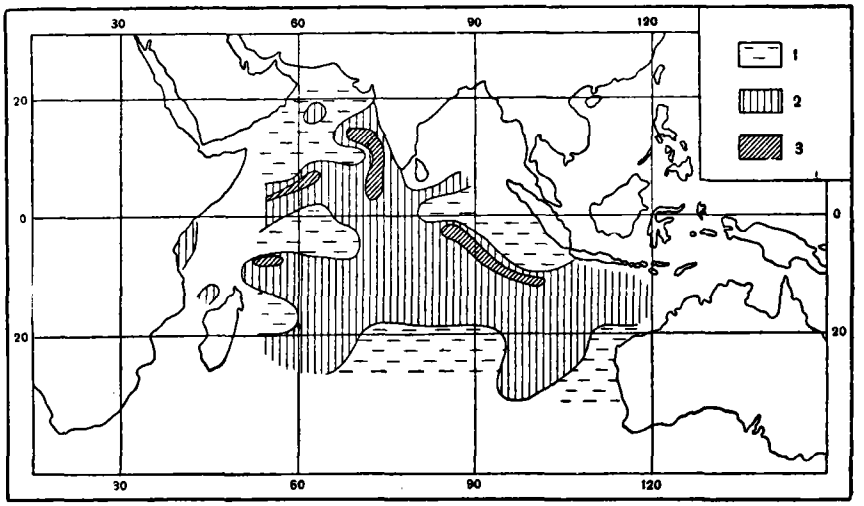


Рис. 8. Распространение Globigerinella aequilateralis в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.

Globigerina bulloides Orbigny (табл. I) встречается в тропической зоне Индийского океана в количествах до 435 экз. при частоте встречаемости 0,55 (рис. 10). Содержание вида колеблется от 0,1 до 12% фауны форами-

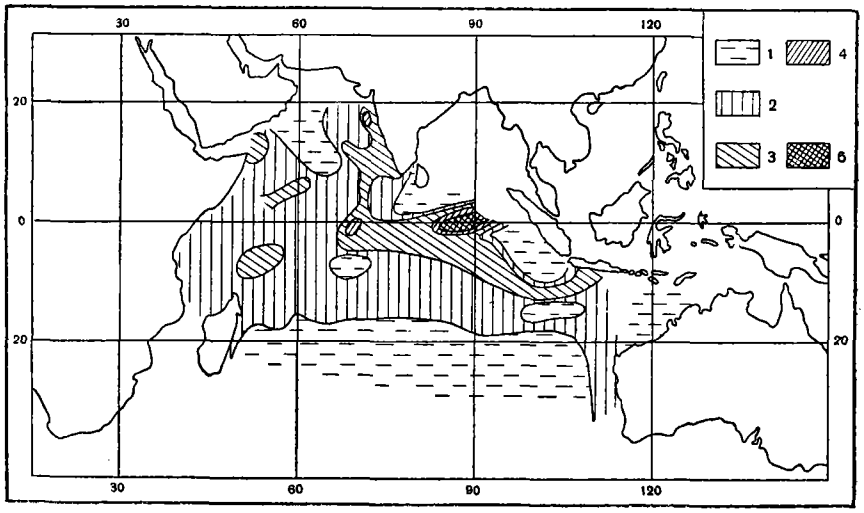


Рис. 9. Распространение Globigerinoides sacculifer в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.; *5* — более 1000 экз.

нифер; исключение составляют несколько станций, где оно было 20—50%. Количества более 100 экз. редки ($p = 0{,}08$), отмечены в районе южнее Суматры, у Мальдивских островов и на 20° ю. ш. Количества до 100 экз. встречены у восточных берегов Африки и на большей части Аравийского

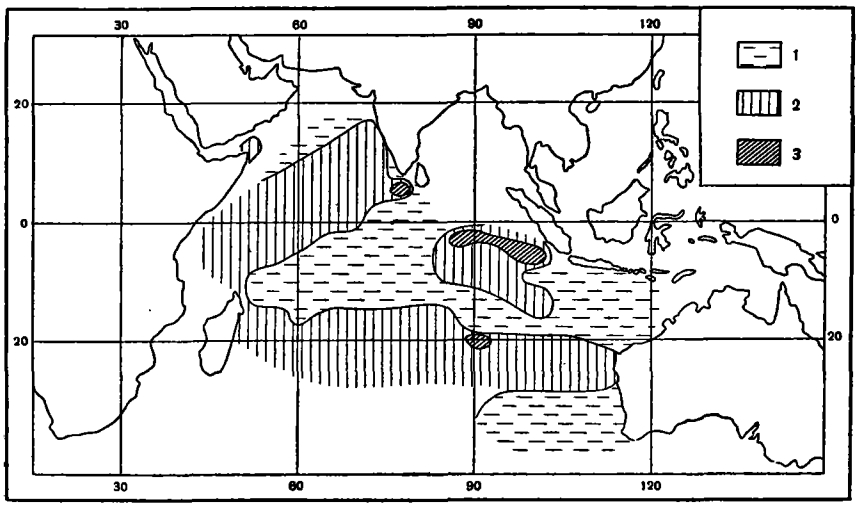


Рис. 10. Распространение Globigerina bulloides в поверхностном слое Индийского океана (экз. на 1000 $м^3$ воды)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.

моря, а также в открытом океане к северо-западу от Кокосовых островов и к югу от 17—20° ю. ш. ($p = 0{,}47$). Среднее геометрическое содержание в тропической зоне 32 экз., дисперсия 0,239. Вид обнаружен также во всех пробах, взятых южнее 40° ю. ш., а южнее 60° ю. ш. представляет всю фауну фораминифер. Температура поверхностных вод в местах его обитания колеблется от 24,75 до 29,01°, а соленость — от 33,64 до 35,85‰.

Восемь проб планктона было нами взято в Атлантическом океане между 45 и 60° с. ш. G. bulloides обнаружен во всех пробах, и составляет до 70—80%, а иногда и до 100% фауны.

В северной части Тихого океана этот вид широко представлен в субарктической фауне (более 20%), а отдельными пятнами встречается также в переходной и в экваториальной (до 20%) (Bradshow, 1959). Температура поверхностных вод в местах, где он обнаружен, равна 8—32°, но наиболее высокие концентрации приурочены к температуре 11—12°. В южной части G. bulloides отмечен в субантарктических водах южнее 40° ю. ш. и у южноамериканского побережья между 10 и 25° ю. ш.; содержание его здесь не превышает 20% фауны (Parker, 1960). Температура воды в местах распространения составляет 10—24°, соленость — от 34,0 до 35,3‰.

G. bulloides найден на всех широтах Мирового океана, иногда в большом количестве, но только в субантарктических и субарктических районах представляет почти полностью всю фауну фораминифер (70% и более). Поэтому он может считаться типичным субантарктическим и субарктическим видом.

Globigerinoides conglobatus (Brady) (табл. I) обнаружен в тропической зоне Индийского океана в количествах до 154 экз. при частоте встречаемости 0,49 (см. табл. 19). Содержание его колеблется от 0,3 до 10% фауны фораминифер. Количества более 100 экз. отмечены на нескольких станциях в открытом океане и у Кокосовых островов ($p = 0{,}04$). Более часты ($p = 0{,}44$) концентрации менее 100 экз.; они приурочены к району Мальдивских ост-

ровов, о-ва Ява, о-вам Каргадос и западному побережью Индии. Этот вид обитает в местах с температурой поверхностных вод от 26,76 до 29,00° и соленостью от 33,64 до 35,70‰. Среднее геометрическое содержание его 15 экз., дисперсия 0,242.

В северной части Тихого океана данный вид приурочен к центральным и экваториальным водам, где он составляет от 1 до 10% фауны фораминифер; несколько повышенные содержания отмечены в экваториальном районе (Bradshow, 1959). Встречается в местах с температурой поверхностной воды 17—32°. В южной части приурочен к экваториальным и (наибольшие содержания) южно-центральным водам (20° с. ш. и 35° ю. ш.) с температурой на поверхности от 17,7 до 27,3° и соленостью от 34,7 до 36,3‰. В северной Атлантике на широтах 66—45° с. ш. не обнаружен.

Hastigerina digitata Rhumbler (табл. III) встречается в тропической части Индийского океана в количествах до 326 экз. ($p = 0,45$) и составляет от 0,3 до 9% фауны фораминифер; только на двух станциях (4652 и 4680) содержание этого вида достигало 33 и 57%. В количестве более 100 экз. (см. табл. 19) H. digitata встречена всего на нескольких станциях ($p = 0,06$) в районе Мальдивских островов и островов Каргадос. Менее 100 экз. обнаружено в Аравийском море, к юго-западу от Индонезии и на отдельных участках открытых частей океана до 20° ю. ш. ($p = 0,40$). Среднее геометрическое содержание 26 экз., дисперсия 0,249. Температура поверхностных вод в местах встречаемости вида 24,92—29,00°, соленость 33,52—35,70‰.

В Тихом океане, по материалам Брэдшоу и Паркер, H. digitata встречается очень редко.

Globigerina eggeri Rhumbler (табл. II) найдена в тропических водах Индийского океана и значительно реже ($p = 0,4$), чем предыдущие виды (табл. 19). Содержание ее колеблется от 2 до 75 экз. и составляет от 0,1 до 16% фауны фораминифер. Этот вид обнаружен на отдельных станциях у восточных берегов Африки, к югу от Аравийского моря и на востоке — у Кокосовых островов. В Аравийском море южнее 10° ю. ш. он отсутствует. Среднее геометрическое содержание 17 экз., дисперсия 0,209. Температура в местах обитания от 27,40 до 29,21°, соленость от 33,52 до 35,47‰.

В северной части Тихого океана G. eggeri распространена в водах, переходных от субарктических к центральным (более 20% фауны фораминифер), в центральных и экваториальных водах — менее 20% (Bradshow, 1959). Исключение составляет район южноамериканского побережья между экватором и 10° ю. ш. Вид встречается при температуре 8—31°, наибольшие количества приурочены к температурам 8—12 и 17—21°. В южной части океана он обитает в экваториальных и центральных водах (10° с. ш.—35° ю. ш.), но к западу от 135° з. д. не встречается (Parker, 1960). На большинстве станций G. eggeri составляет 20% фауны. Температура воды в местах его распространения от 16 до 27°, соленость от 34,0 до 36,4‰.

В северной Атлантике отмечены единичные экземпляры на 56° с. ш. Globorotalia punctulata (Orbigny) (табл. II) отмечена отдельными небольшими пятнами в экваториальных водах у берегов Индии, к северу и востоку от Мадагаскара и у Кокосовых островов ($p = 0,2$); встречается единичными экземплярами (см. табл. 19) и составляет не более 1,5% фауны. Среднее геометрическое содержание 4 экз., дисперсия 0,058. Температура в местах обитания — от 27,4 до 29,0°, соленость от 33,64 до 35,47‰.

В северной части Тихого океана этот вид не отмечен (Bradshow, 1959). В южной части попадается в субантарктических водах, водах, переходных

к южно-центральным, и в южно-центральных, везде составляет менее 35% фауны фораминифер. Температура в этих районах от 9 до 18°, соленость — от 34 до 35‰.

Globigerina hexagona Natland (табл. I) встречается в районе островов Сейшельских, Каргадос, Мальдивских и к востоку от последних в количествах от 5 до 90 экз. ($p = 0{,}16$) и составляет до 10% фауны (см. табл. 19). Температура поверхностных вод в этих местах 27,61—29,21°, соленость 33,52—35,25‰. Средняя геометрическая содержания 23 экз., дисперсия — 0,164.

В северной части Тихого океана этот вид обнаружен в центральной и экваториальной фауне (около 1%) при температуре от 13 до 29°. В южной части океана он приурочен к экваториальным водам (между 20° с. ш. и 10° ю. ш.) и составляет до 3% фауны планктонных фораминифер. Температура воды в местах его обитания колеблется от 24,4 до 26,7°, соленость — от 34,7 до 35,7‰.

G. hexagona является видом экваториальных вод, но не дает высоких концентраций и не образует широких ареалов распространения.

Globigerina conglomerata Schwager (табл. I) обнаружена в тропической зоне Индийского океана в количествах до 113 экз., и составляет до 14% фауны фораминифер. Частота встречаемости 0,16 (см. табл. 19). К северо-западу от архипелага Чагос вид встречается в количестве 113 экз. ($p = 0{,}02$), но более часты ($p = 0{,}14$) количества меньше 100 экз., приуроченные к восточному побережью Африки, к западным берегам Индии, к району северо-западнее архипелага Чагос, к Кокосовым островам и берегам Суматры.

Температура поверхностных вод в местах обитания вида равна 27,40—28,53°, соленость —33,64—35,46‰. Средняя геометрическая содержания 19 экз., дисперсия 0,321.

В Тихом океане этот вид приурочен также к экваториальным водам (Bradshow, 1959; Parker, 1960) и составляет от 1 до 30% фауны. Температура в местах, где он встречается, равна 24—30°, а соленость — 34—35‰.

Таким образом, G. conglomerata является типично экваториальным видом, но сравнительно редким и не дающим высоких концентраций.

Pulleniatina obliquiloculata (Parker et Jones) (табл. I) обитает у восточного побережья Африки, у западного побережья Индии, в районе Мальдивских островов, у о-ва Ява и в открытом океане. Встречается вид очень редко ($p = 0{,}14$) в количестве от 0 до 31 и составляет от 0,3 до 3,3% фауны фораминифер (см. табл. 19). Температура вод, в которых она обнаружена, колеблется от 26,79 до 28,49°, соленость — от 33,85 до 35,46‰. Средняя геометрическая содержания 10 экз., дисперсия 0,138.

В Тихом океане этот вид встречается в экваториальных водах довольно часто и образует высокие концентрации (более 1000 экз.) к югу от Гавайских островов (Bradshow, 1959). Высокие содержания (более 20% фауны) отмечены на экваторе. Температура в местах обитания равна 16—32°; высокие концентрации приурочены к температуре 27—30°. По Паркер (1960), P. obliquiloculata отмечена в экваториальных водах в количестве около 5% фауны при температуре от 24 до 27° и солености от 34,5 до 35,4‰. Разница в его количестве, по Брэдшоу, Паркер и нашим материалам, объясняется сезонными изменениями. Этот вид можно считать типично экваториальным.

Globigerina inflata Orbigny (табл. II) в тропической зоне Индийского океана попадается весьма редко ($p = 0{,}12$) в количестве до 75 экз. (см. табл. 19) и составляет от 0,1 до 9,6% фауны фораминифер. Она отмечена отдельными пятнами у восточных берегов Африки, а также у Сейшель-

ских, Мальдивских и Кокосовых островов, при температуре от 27,40 до 29,21° и солености от 33,85 до 35,43‰.

В Тихом океане этот вид приурочен к центральным водным массам (отдельные нахождения бывают и в переходных водах) и составляет около 10% фауны (Bradshow, 1959); в тропической зоне не встречается. Температура в местах обитания равна 15—24°, наибольшие количества отмечены при 21—22°. В южной части океана G. inflata живет в субантарктических и южно-центральных водах южнее 25° ю. ш. при поверхностной температуре 10—23° и солености от 34 до 35,7‰.

В Северной Атлантике G. inflata также была обнаружена нами на большинстве станций между 60 и 45° с. ш.; следовательно, это типичный вид субарктических, субантарктических и центральных вод.

Sphaeroidinella dehiscens (Parker et Jones) (табл. I) в Индийском океане встречается очень редко ($p = 0{,}08$) в количестве до 15 экз. и составляет от 0,5 до 3% фауны форминифер (см. табл. 19). Распространен отдельными пятнами к северу от 10° ю. ш. при температуре поверхностных вод 28,00 до 28,51° и солености от 34,38 до 35,28‰. В Тихом океане он обитает в экваториальных водах при температуре 23—30° (Bradshow, 1959); в западной и восточной частях океана (по экватору) составляет менее 5% фауны, в центральной — несколько более. Паркер (Parker, 1960) также находила его в экваториальных водах, но очень редко. Таким образом Sphaeroidinella dehiscens представляет собой вид типично тропический, очень редкий и не образующий массовых скоплений.

Globigerina quinqueloba Natland (табл. II) обнаружена в Индийском океане всего на нескольких станциях к северу от 10° ю. ш. ($p = 0{,}08$) в количестве от 3 до 15 экз. (табл. 19), и составляет менее 2% фауны. Температура на этих станциях была 27,61—29,21°, а соленость — 33,82—35,43‰.

В Тихом же океане к северу от 40° с. ш. этот вид, по Брэдшоу (Bradshow, 1959), составляет более 50% фауны форминифер. Встречается он и в водах, переходных от субарктических к центральным (Калифорнийское и Перуанское течения), но очень редок в экваториальных водах. Температура поверхностных вод, в которых найдена G. quinqueloba, колеблется от 8 до 28°; наибольшие концентрации отмечены при 11—17°.

В южной части Тихого океана данный вид не обнаружен. Очень редок он и в Южной Атлантике (Boltovskoy, 1961), в то время как в субарктических водах Северной Атлантики и Тихого океана составляет до 50% фауны.

Globigerinita glutinata Egger (табл. I) тоже очень редка в тропических водах Индийского океана ($p = 0{,}08$) (см. табл. 19). Количества ее колеблются от 6 до 50 экз., и она составляет до 2,5% фауны форминифер. Обнаружена при температуре поверхностных вод, равной 28,08—28,60°, и солености 34,62—35,26‰.

В восточной части тропического района Тихого океана он очень многочислен; в малом количестве отмечен также в центральных и субарктических водах. Холодноводные виды мельче, чем тропические. Этот вид встречается при температуре воды 9—32°; максимальные концентрации приурочены к водам с температурой 23—32°. В южной части Тихого океана весьма редок. В Северной Атлантике (между 56 и 60° с. ш.) попадается очень часто.

Globorotalia tumida (Brady) (табл. II) встречена в Индийском океане лишь на нескольких станциях ($p = 0{,}06$) в количестве до 19 экз. (см. табл. 19) и составляет от 1 до 3% фауны форминифер, температура поверхностных вод в местах ее обитания равна 27,27—28,51°, а соленость колеблется от 34,4 до 35,80‰.

В Тихом океане найдена в экваториальном районе при температуре 17—29°, но наибольшие количества приурочены к 27—28° (Bradshow, 1959). G. tumida составляет от 1 до 20% фауны. В южной части Тихого океана не встречается.

В отличие от G. menardii этот вид обладает более узкими ареалами распространения, приурочен к водам с более высокой температурой, не дает высоких концентраций и составляет незначительную часть фауны фораминифер. Он типичен для экваториальных водных масс.

Globorotalia truncatulinoides (Orbigny) (табл. II) обнаружена всего на двух станциях (4554 и 4583) в количестве 12 и 22 экз. соответственно, при температуре 27,04° и солености 34,65‰. Частота встречаемости ее равна 0,05.

В Тихом океане вид часто встречается в центральных водных массах между 20 и 40° с. ш.; наивысшие концентрации отмечены на границе Куро-Сио и Ойя-Сио (Bradshow, 1959). Отдельные нахождения отмечены в водах, переходных от субарктических к центральным. Вид составляет до 10% фауны фораминифер и более. Температура вод, в которых она обитает, равна 13—26°, максимальные концентрации отмечены при 18—20°. В южной части океана G. truncatulinoides приурочена к южным центральным водам (25—30° ю. ш.) и к переходным от субантарктических к центральным; встречается при температуре 20,6—23,5°, солености 34,8—35,7‰. Это — вид центральных водных масс.

Candeina nitida Orbigny (табл. I) встречена нами на двух станциях ($p = 0{,}04$), где она составляла менее 1% фауны фораминифер (см. табл. 19). Температура воды была 27,40—28,25°, соленость —33,96—34,91‰.

В Тихом океане G. nitida обнаружена отдельными пятнами в экваториальных водах (Bradshow, 1959). Более широко этот вид распространен в центральной водной массе, но содержание его нигде не превышает 10% фауны. Температура вод в местах обитания вида равна 13—29°, но наибольшие концентрации приурочены к 13—14°. В южной части Тихого океана не встречается.

Hastigerinella rhumbleri Galloway (табл. III) обнаружена только на одной станции (4633) в количестве 25 экз. при температуре 28,73° и солености 35‰ (см. табл. 19). В Тихом океане она также очень редка; встречается в экваториальных и умеренных широтах и составляет до 5% фауны фораминифер (Bradshow, 1959).

Hastigerina murrhayi Thomson (табл. III) найдена нами на одной станции при температуре 27,27° и солености 34,4‰ (см. табл. 19). Впервые она отмечена в планктонных ловах Учио (Uchio, 1960).

Globigerina pachyderma Ehrenberg (табл. I) в Индийском океане нам не встречалась. В Тихом океане к северу от 40° с. ш. этот вид обнаружен в субарктической водной массе и отдельными пятнами отмечен в Калифорнийском течении, а также к северу от Японии. В первых двух районах он составляет от 1 до 20% фауны фораминифер, а в третьем — более 20%. Температура поверхностных вод в местах его обитания колеблется от 10 до 20° (Bradshow, 1959). В южной части Тихого океана вид не найден (Parker, 1960).

В планктонных пробах, взятых на д/э «Обь», и в пробах Учио (Uchio, 1960) из антарктических вод G. pachyderma не была обнаружена, хотя этот вид почти целиком представляет танатоценоз холодноводных видов. В водных пробах из этих районов отмечена только G. bulloides. В пробах планктона северной части Атлантического океана G. pachyderma также не попадалась (Be, 1960a), тогда как в донных пробах этот вид преобладал. G. bulloides, наоборот, реже встречалась на дне и почти полностью представляла фауну фораминифер в планктонных ловах.

Такое распределение может быть объяснено двояко: или G. pachyderma не является планктонным видом, или в толще воды она живет глубже слоя опробования (200 *м*). Данные Брэдшоу (Bradshow, 1959) позволяют опровергнуть первое предположение. Вероятно, G. pachyderma обитает на большей глубине. Действительно, на одной станции в северной части Атлантического океана она была нами обнаружена в слое ниже 300 *м*. Чтобы окончательно удостовериться в этом, необходимо более детально изучить вертикальное распределение вида в толще воды.

Globorotalia hirsuta (Orbigny) (табл. II) в тропической зоне Индийского океана тоже не найдена.

В Тихом океане она отмечена на отдельных участках к северу от экватора и составляет менее 10% фауны фораминифер (Bradshow, 1959). В северной части Атлантического океана G. hirsuta встречается к югу от 50° с. ш.

Отсутствие этого вида в водах и осадках тропической зоны Индийского океана и наличие его в осадках умеренных широт позволяет отнести его к видам центральных водных масс.

Биоценозы планктонных фораминифер

Изучение фораминифер в пробах воды по меридиональным разрезам, использование основных закономерностей распределения фито- и зоопланктона (Короткевич и Беклемишев, 1960; Беклемишев, 1960; Богоров и Виноградов, 1961) позволило выделить основные биоценозы и их границы, которыми являются фронтальные зоны конвергенции и дивергенции. В водах Индийского океана нами выделено пять биоценозов (рис. 11).

Биоценоз холодноводных видов приурочен к водным массам Западного прибрежного течения (высокоантарктическая подобласть) с температурой 0° и соленостью 34,5‰. Он представлен видом Globigerina bulloides, обнаруженным в количестве нескольких экземпляров на 1000 $м^3$ воды, и зоной антарктической дивергенции отделяется от биоценоза умеренно-холодноводных видов.

Биоценоз умеренно-холодноводных видов приурочен к водной массе Восточного дрейфа с температурой 0° и соленостью 34,5‰ (низкоантарктическая подобласть). Этот биоценоз представлен тем же видом G. bulloides, но в большем количестве. Изредка встречаются виды умеренных широт, что дает право считать его переходным от холодноводного к биоценозу видов умеренных широт. Качественная бедность фауны фораминифер в этих биоценозах хорошо согласуется с малым количеством видов планктона в целом (пять видов). Северной границей является зона антарктической конвергенции.

Биоценоз видов умеренных широт включает в себя Globigerina inflata, Globorotalia truncatulinoides, Gl. hirsuta и др. Эти виды приурочены к поверхностным водам с температурой от —1,06 до 9,73° и соленостью от 33,72 до 35,70‰. Северной границей биоценоза является зона субтропической конвергенции. К северу от нее выделяется переходный биоценоз умеренно-тропических видов, приуроченный к центральной водной массе с температурой от 10 до 23° и соленостью 34,7—35,7‰. В пределах биоценоза распространены виды умеренных и тропических широт — Globigerinoides ruber, Orbulina universa, Globigerinoides conglobatus, G. sacculifer и др.

Биоценоз тропических видов выделен к северу от фронтальной зоны ~10—12° ю. ш. Он приурочен к экваториальной водной

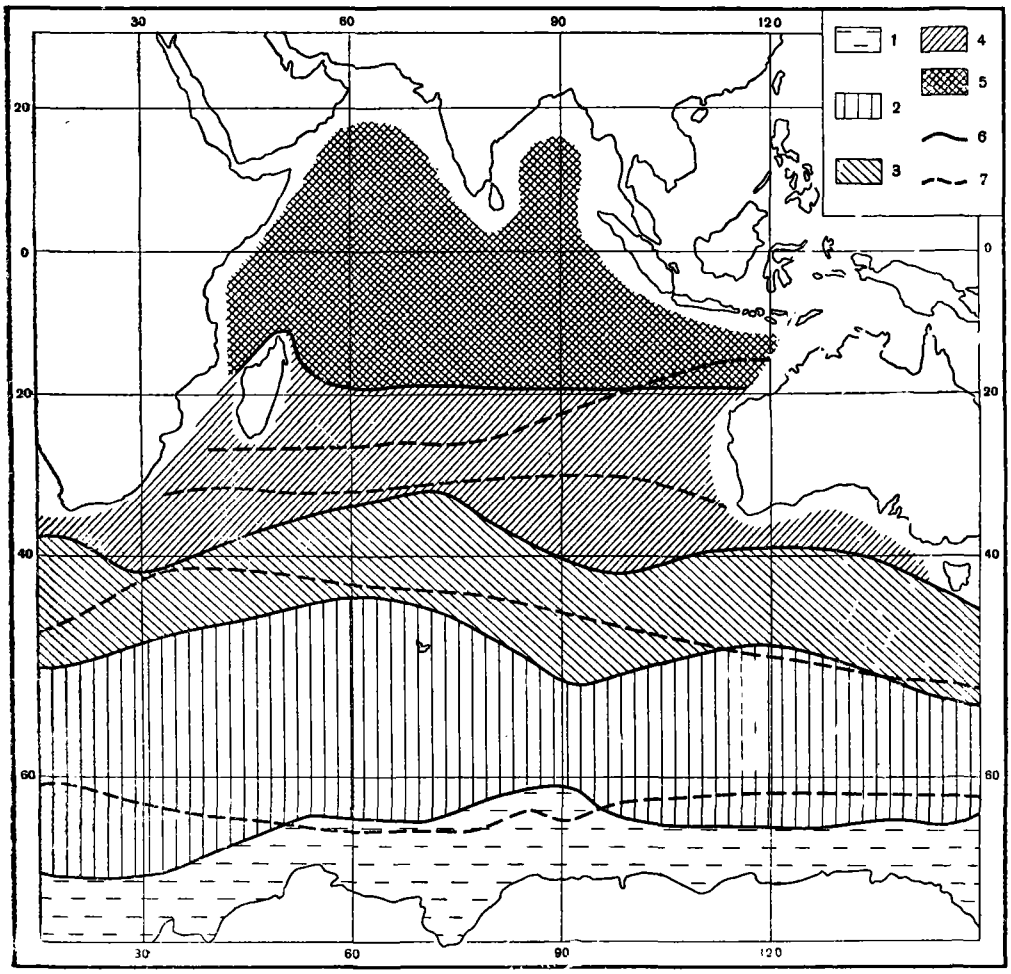


Рис. 11. Распространение биоценозов планктонных фораминифер в Индийском океане

1 — биоценоз холодноводных видов, *2* — умеренно-холодноводных видов, *3* — видов умеренных широт, *4* — умеренно-тропических видов, *5* — тропических видов, *6* — границы биоценозов, *7* — границы танатоценозов

массе с температурой от 14 до 28° и высокой соленостью — от 35,1 до 36,5‰. В этом биоценозе больше всего видов, в основном тропических, — Globorotalia menardii, Globigerina conglomerata, Globorotalia tumida, Sphaeroidinella dehiscens, Pulleniatina obliquiloculata. Редко и в малых количествах встречаются виды других биоценозов.

Из сказанного видно, что большинство видов встречается одновременно в двух, иногда трех биоценозах. Поэтому для выделения биоценозов особенно важны количественные оценки содержаний отдельных видов, полученные методом математической статистики.

Границы выделенных биоценозов хорошо совпадают с границами водных масс и со сменой видового состава всего планктона. Переходные биоценозы содержат элементы географически смежных фаун. Видовой состав их зависит от расстояния до границ соседних биоценозов и степени смешения. Минимальные количества фораминифер отмечены в антарктических районах в Индийском океане — это биоценозы холодноводных и умерен-

но-холодноводных видов (количество фораминифер не превышает 10—20 экз. на 1000 $м^3$ воды). Экваториальные воды и воды умеренных широт характеризуются высокими концентрациями, особенно в районе экваториальных течений (несколько тысяч экземпляров на 1000 $м^3$ воды). В центральных водных массах Индийского океана отмечены низкие концентрации фораминифер (до 500 экз. на 1000 $м^3$). Таким образом, количественное распределение фораминифер в поверхностном слое воды зависит от широтной зональности и тесно связано с водными массами. Подобное распределение фораминифер в общих чертах характерно и для Тихого океана (Bradshow, 1959; Parker, 1960).

РАСПРЕДЕЛЕНИЕ РАКОВИН ПЛАНКТОННЫХ ФОРАМИНИФЕР НА ДНЕ

Количественное распределение

Раковины отмерших планктонных фораминифер очень широко распространены на дне океана. Они встречаются на шельфе, материковом склоне, подводных хребтах, поднятиях и в глубоких котловинах. Общее количественное распределение их уже рассматривалось автором (Беляева, 1961, 1963); оно определяется, с одной стороны, продуктивностью организмов в верхнем слое воды, а с другой — глубиной океана. Распределение планктонных фораминифер по площади зависит от рельефа дна. На материковом шельфе их мало (менее 100 экз. на 1 *г* осадка), что вполне согласуется с распределением живых фораминифер в водах над шельфом.

В области материкового склона планктонные фораминиферы встречаются на дне значительно чаще и в больших количествах, за исключением Антарктиды (менее 100 экз. на 1 *г* осадка), где развиты главным образом айсберговые, терригенные и диатомовые осадки. Большие количества (до нескольких тысяч на 1 *г* осадка) приурочены к отдельным поднятиям. На материковом склоне более северных районов океана в пределах тропической и умеренной зоны на 1 *г* осадка приходится более 1000 экз., что согласуется с количественным распределением фораминифер в поверхностных водах. Здесь развиты главным образом фораминиферовые осадки.

На ложе океана на глубинах до 4500—4700 *м* в области развития фораминиферовых осадков планктонные фораминиферы всюду присутствуют в количестве более 1000 экз., а максимально до 7000 экз. на 1 *г* осадка.

На подводных хребтах и возвышенностях, в центральных частях океана на глубинах от нескольких сот до 4500—4700 *м* количество фораминифер достигает 18 000 экз. Здесь развиты преимущественно фораминиферовые илы. Центральный Индийский хребет характеризуется очень большими концентрациями фораминифер (до нескольких десятков тысяч на 1 *г* осадка): в южной его части максимальные количества приурочены к глубинам от 1500 до 2257 *м*, в северной — к интервалу глубин от 2234 до 4400 *м*. Приуроченность больших концентраций к меньшим глубинам в южной части хребта связана с тем, что в более холодных районах растворение карбоната кальция происходит именно на этих глубинах. Высокие концентрации раковин фораминифер характерны и для Аравийско-Индийского хребта, на поверхности которого развиты фораминиферовые осадки.

В глубоководных котловинах океана на глубинах свыше 4500—4700 *м* раковины встречаются в количестве менее 100 экз. на 1 *г* осадка; в этих впадинах развиты преимущественно красные глины. Малые количества фораминифер на дне котловин не отражают количественного распределения живых организмов в толще воды, а обусловлены растворением их ра-

ковин на больших глубинах. В Яванском желобе (глубина 6000—7450 *м*) планктонные фораминиферы отсутствуют; здесь распространены бескарбонатные глинистые илы.

Количественное распределение фораминифер зависит от широты. От Антарктики до 61—62° ю. ш. они отмечены не на всех станциях (p=0,65); средняя геометрическая содержания их ($\widetilde{x}$) на этих широтах —1,6 экз.[1], дисперсия 2,275. Между 52—61 и 48—52° ю. ш. фораминиферы встречаются чаще (p = 0,75); $\widetilde{x}$ = 70 экз., дисперсия 2,197. Между широтами 48—52 и 30—36° ю. ш. p =1, $\widetilde{x}$ = 942 экз., дисперсия 0,622. В полосе от 30—36 до 18—26° ю. ш. также p = 1,0, но $\widetilde{x}$ = 61 экз., дисперсия 1,636. К северу от 18—26° ю. ш. фораминиферы встречаются несколько реже (p = 0,92); $\widetilde{x}$ = 89 экз., дисперсия 1,796.

Таким образом, распределение раковин планктонных фораминифер в осадках отражает и вертикальную, и климатическую зональность.

Распределение раковин отдельных видов

Globigerina bulloides Orbigny широко распространена в Индийском океане ($p_{общ}$=0,43),особенно к югу от 40° с.ш.Она обнаружена на 123 станциях в количествах до 22000 экз. (табл. 20). Содержание ее составляет от 0,1 до 100% фауны фораминифер (рис. 12). Максимальные количества приурочены к глубинам от 204 до 4624 *м*. Более 1000 экз. в 1 *г* осадка встречается редко (p = 0,04) — на Центральном Индийском хребте, к югу от Африки, на обширной площади между хребтом и западным побережьем Австралии, у берегов о-ва Явы и близ п-ова Сомали. Также редко (в виде узких полос у берегов Африки и Явы, по окраинам глубоководных котловин и отдельными пятнами у Сейшельских островов и в море Дейвиса на глубине от 110 до 1358 *м*) встречаются количества от 500 до 1000 экз. (p = 0,01). В количестве от 100 до 500 экз. вид найден на глубинах от 95 до 4900 *м* во всех перечисленных районах, а также у западных берегов Австралии и у Мальдивских островов; p = 0,06. Наиболее часты концентрации менее 100 экз. (p = 0,30), отмеченные на глубинах от 59 до 4988 *м* у берегов Антарктиды, на обширной площади открытых частей океана, к востоку и западу от Центрального Индийского хребта, в Аравийском море, у берегов Австралии и на отдельных участках дна Индийско-Аравийской котловины. Кроме того, этот вид найден в архипелаге Керимбо (Heron-Allen a. Earland, 1914), у берегов Тасмании и Кергелена и на побережье Антарктиды (Parr, 1950; Heron-Allen a. Earland, 1922).

В Атлантическом океане G. bulloides встречается на всех широтах. На экваторе она составляет менее 1% фауны фораминифер, на склоне северо-восточного побережья США—до 50%, в районе 60° с. ш.—18% (Phleger a. oth., 1953). В небольших количествах вид найден в Мексиканском заливе и Карибском море (Parker, 1954; Phleger, 1951; Cushman, 1924 б), у берегов Исландии (Cushman, 1948a; Norvang, 1945; O. Terquem a. E. Terquem, 1886), у Фолклендских островов (Heron-Allen a. Earland, 1932; Earland, 1934) и островов Южной Георгии (Earland, 1933); отдельные находки отмечены к югу от линии антарктической конвергенции и у ледового барьера (Earland, 1936). В Средиземном море G. bulloides часто встречается.

В Тихом океане этот вид обнаружен во всех пробах «Челленджера» (Brady, 1884), а также у Гавайских (Cushman, 1914) и у Филиппинских (Cushman, 1921) островов, у островов Самоа (Cushman, 1924a) и у западного побережья Южной Америки близ экватора (Cushman a. Kellett, 1929).

[1] Содержание раковин фораминифер здесь и в дальнейшем дается на 1 *г* осадка, а поэтому величина навески особо оговариваться не будет.

Таким образом, G. bulloides широко распространена во всех океанах с максимальными концентрациями в умеренных широтах.

Globigerina pachyderma Ehrenberg найдена нами на 104-х станциях ($p_{общ} = 0{,}36$) в количествах до 5120 экземпляров (рис. 13) и составляет от 0,1 до 100% фауны фораминифер (см. табл. 20). В количестве более 1000 экз. попадается редко ($p = 0{,}03$) — на хребте Кергелен и на поднятиях у берегов Антарктиды ($p = 0{,}03$) на глубине от 934 до 2257 *м*. От 500 до 1000 экз. встречается также редко ($p = 0{,}02$) на глубинах от 486 до 3850 *м* в тех же местах и к югу от Африки и к востоку от хребта Кергелен. В концентрациях от 100 до 500 экз. G. pachyderma обнаружена на глубинах от 141 до 3122 *м* в виде отдельных пятен ($p = 0{,}03$) вдоль побережья Антарктиды, у южных берегов Африки, на хребте Кергелен и к востоку от него. Менее 100 экз. встречается чаще ($p = 0{,}27$), в основном в полосе вдоль побережья Антарктиды, на хребте Кергелен и к востоку от него, а также на отдельных участках к северу от 50° ю. ш. (до 10 экз.)

В Индийском океане G. pachyderma является типично антарктическим видом, на большинстве антарктических станций она составляла 100% фауны фораминифер и в количестве более 100 экз. была отмечена только

Таблица 20

Частота встречаемости (p) различных количеств планктонных фораминифер на дне Индийского океана (по видам)

Вид	Общая ($p_{общ}$)	Количество экз. в 1 *г* осадка			
		1000	*1000—500*	*500—100*	*<100*
Globigerina bulloides	0,43	0,04	0,01	0,06	0,30
G. pachyderma	0,36	0,03	0,02	0,03	0,27
Globigerinoides ruber	0,34	0,02	0,01	0,09	0,18
Globorotalia menardii	0,33	0,02	0,03	0,08	0,20
Pulleniatina obliquiloculata	0,30	Нет	0,007	0,07	0,22
Globigerina eggeri	0,30	»	0,01	0,08	0,19
Globigerinoides sacculifer	0,23	0,01	0,03	0,07	0,12
G. conglobatus	0,23	Нет	0,01	0,04	0,18
Globigerinella aequilateralis	0,23	»	Нет	0,03	0,20
Sphaeroidinella dehiscens	0,23	»	»	Нет	0,23
Orbulina universa	0,21	»	0,003	0,03	0,17
Globorotalia tumida	0,18	»	Нет	0,007	0,17
Globigerina inflata	0,17	0,02	0,01	0,02	0,11
Globorotalia truncatulinoides	0,17	0,007	0,007	0,04	0,12
Globigerina conglomerata	0,16	Нет	0,007	0,02	0,13
Globorotalia punctulata	0,15	»	Нет	0,003	0,14
G. hirsuta	0,06	»	»	0,003	0,06
Globigerina hexagona	0,05	»	»	Нет	0,05
Hastigerina digitata	0,03	»	»	»	0,03
Candeina nitida	0,03	»	»	»	0,03
Globigerinita glutinata	0,02	»	»	»	0,02
Globorotalia scitula	0,015	»	»	»	0,015
Hastigerina pelagica	0,01	»	»	»	0,01
Globigerina quinqueloba	0,003	»	»	»	0,003

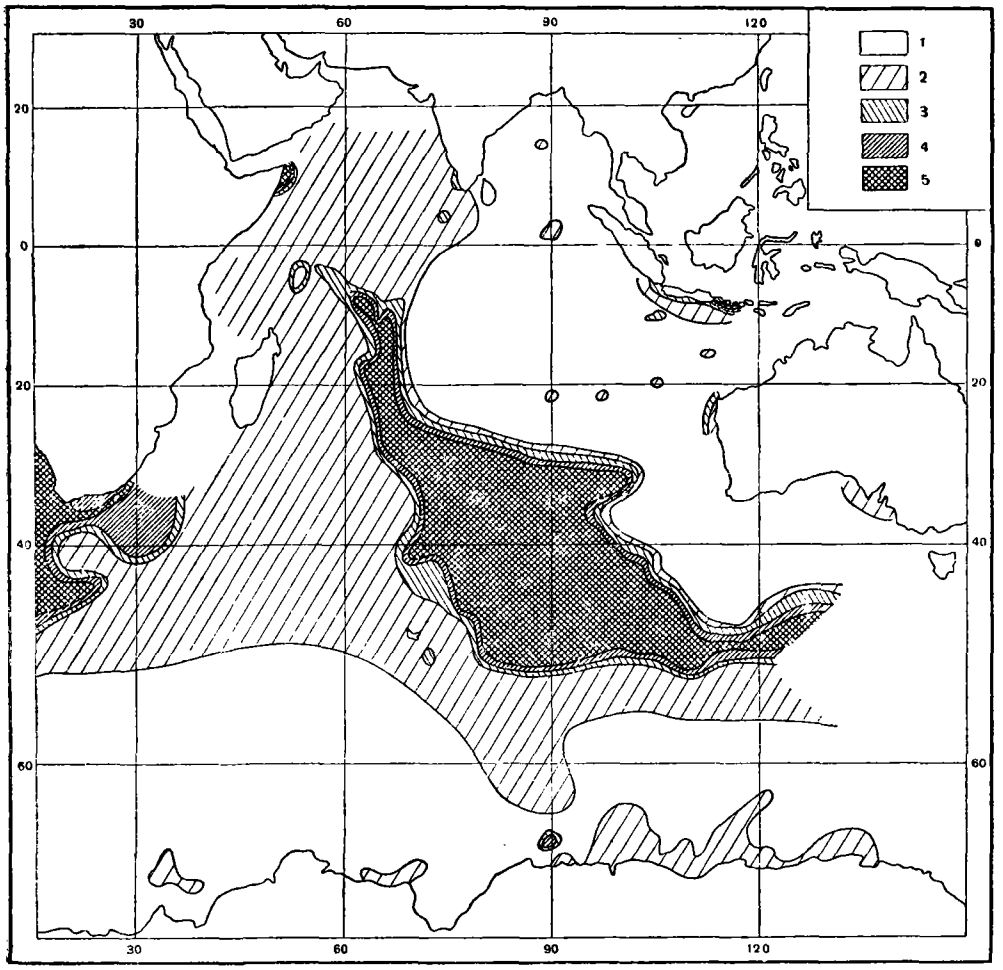


Рис. 12. Распространение Globigerina bulloides на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз., *5* — более 1000 экз.

к югу от 50° ю. ш. Максимальные количества ее приурочены к подводным поднятиям, которые находятся в области распространения промежуточных теплых вод.

В Атлантическом океане этот вид найден в районе Фаррерского порога, у берегов Исландии, Шотландии и у северо-восточного побережья США (Brady, 1884; Pearcey, 1914; Cushman, 1948a; Norvang, 1945). На 60° с. ш. он составляет 72% фауны фораминифер, юго-западнее Британских островов — 0,08%, а южнее 20° с. ш. не встречается (Phleger a. oth., 1953). Очень редко G. pachyderma попадается в Мексиканском заливе (Parker, 1954; Phleger, 1951). У Фолклендских островов и о-ва Южная Георгия является доминирующей и отмечена повсеместно (Heron-Allen a. Earland, 1932; Earland, 1933, 1934). Широко распространен вид в Антарктике (Heron-Allen a. Earland, 1922; Pearcey, 1914; Earland, 1936).

Как видно, G. pachyderma типична для Арктики и Антарктики, где со-

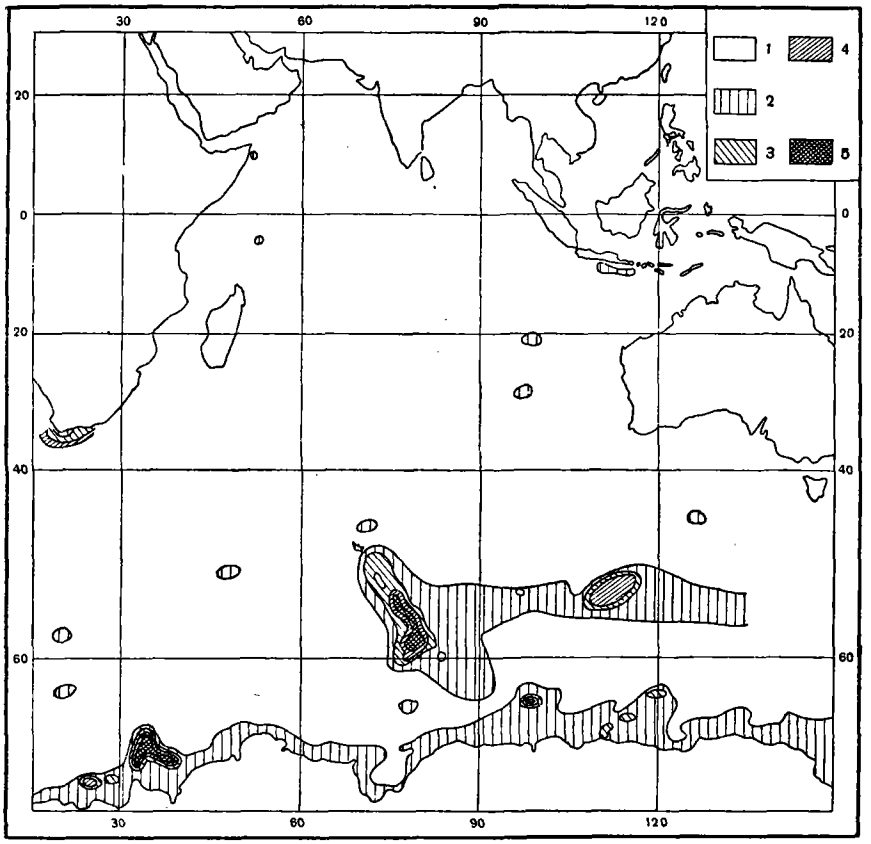


Рис. 13. Распространение Globigerina pachyderma на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.; *5* — более 1000 экз.

ставляет 100% фауны фораминифер, хотя абсолютные количества этого вида в большинстве случаев невелики.

Globigerinoides ruber (Orbigny) обнаружен на 92 станциях ($p_{общ} = 0{,}34$) в количествах до 2054 экз. (см. табл. 20), составляет от 0,1 до 68,8% всей фауны фораминифер (рис. 14). Количества более 1000 экз. ($p = 0{,}02$) отмечены на глубинах от 162 до 4830 *м* на Центральном Индийском хребте, у южной оконечности Африки и к востоку от Мадагаскара; от 500 до 1000 экз. ($p = 0{,}01$) на глубинах от 802 до 2942 *м* близ берегов Африки, Австралии, Явы, на Центральном Индийском хребте; от 100 до 500 экз. ($p = 0{,}09$) обнаружено на глубинах от 95 до 4400 *м* у южного и восточного побережья Африки, у западных берегов Индии и Австралии, на Центральном Индийском хребте и на отдельных поднятиях Индийско-Австралийской котловины. Наиболее часто вид встречается в количествах менее 100 экз. ($p = 0{,}18$) на глубинах от 50 до 5089 *м* в южной части Аравийского моря, на склонах Центрального Индийского хребта, у берегов Африки, Явы и на поднятиях Индийско-Австралийской котловины. К югу от 35° ю. ш. отмечено только по одному экземпляру на четырех станциях. Встречается вид также в архипелаге Керимбо (Heron-Allen a. Earland, 1914). В общем G. ruber распространен в Индийском океане между 35° ю. ш. и 20° с. ш. Границы

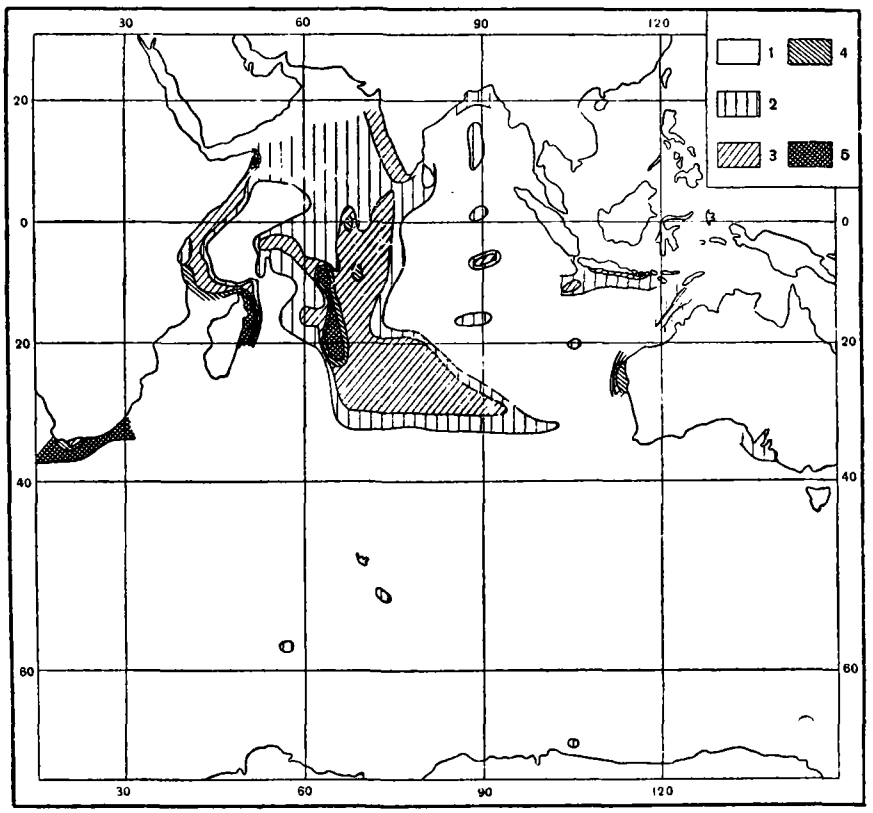


Рис. 14. Распространение Globigerinoides ruber на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден: *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.. *5* — *более 1000 экз.*

распределения вида в водном слое 0—200 *м* и в осадках совпадают, но количественное распределение существенно различается. При наличии благоприятных условий для захоронения G. ruber образует в осадках высокие концентрации. На дне котловин не найден.

В Атлантическом океане этот вид встречается между экватором и 40° с. ш. и составляет от 10 до 19% фауны фораминифер между экватором и 20° с. ш. Максимальное содержание его отмечено в Мексиканском заливе (до 30—70%) и в Карибском море. Между 20 и 40° с. ш. он составляет до 3% фауны, а севернее — до 0,1% (Cushman, 1924b; Phleger, 1951; Phleger a. oth., 1953; Parker, 1954). На 50° ю. ш. G. ruber отмечен в незначительном количестве на семи станциях (Earland, 1934; Heron-Allen a. Earland, 1932). Обнаружен и в Средиземном море (Parker, 1958).

В Тихом океане G. ruber распространен от границы диатомовых илов до Иокагамы (35° с. ш.), преимущественно в малом количестве. Высокие концентрации отмечены у Гавайских островов (Cushman, 1914, 1921, 1924a; Brady, 1884). В южной части океана встречается редко (Heron-Allen a. Earland, 1922), а в антарктических водах вовсе отсутствует (Parr, 1950). Распределение вида в Атлантическом и Тихом океанах вполне согласуется с распределением его в Индийском океане.

Globorotalia menardii (Orbigny) распространена в осадках Индийского

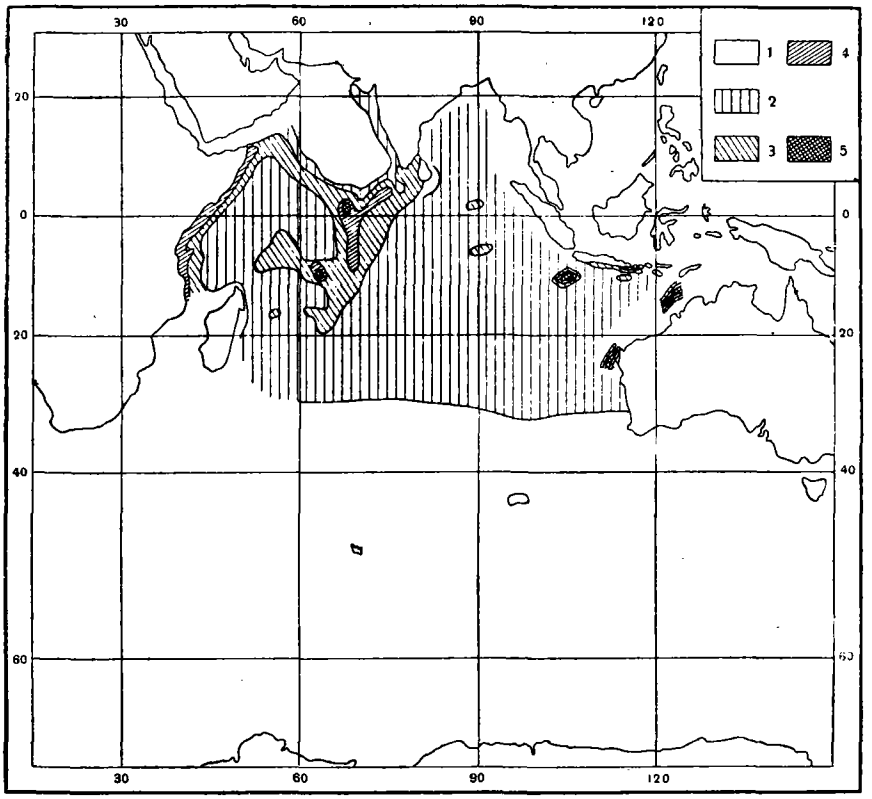


Рис. 15. Распространение Globorotalia menardii на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.; *5* — более 1000 экз.

океана между 30° ю. ш. и 20° с. ш. (рис. 15). Она обнаружена нами на 98 станциях ($p_{общ.}$=0,33) в количествах до 1670 экз. (см. табл. 20) и составляет от 0,32 до 100% фауны форминифер. Концентрации более 1000 экз. (p = 0,02) встречены на глубинах от 446 до 3500 *м* у западного и северо-западного побережий Австралии, у о-вов Рождества и на Индийском Центральном хребте (рис. 15). От 500 до 1000 экз. попадалось, кроме того, у берегов Африки и Явы и на глубинах от 250 до 3169 *м* (p = 0,03). От 100 до 500 экз. встречалось на глубинах от 109 до 4660 *м* у восточного побережья Африки, на Аравийско-Индийском и Центральном Индийском хребтах, у берегов Австралии и Явы и на поднятиях в Индийско-Австралийской котловине (p = 0,08). Наиболее часты (p = 0,20) количества меньше 100 экз., найденные нами на глубинах от 95 до 4705 *м* к северу от 30° ю. ш. на дне Индийско-Австралийской и Сомалийской котловин, в Бенгальском заливе, у западного побережья Индии и на двух станциях южнее 30° ю. ш. Отмечен этот вид также в архипелаге Керимбо (Heron-Allen a. Earland, 1914) и у южных берегов Австралии (Parr, 1950).

Широтное распределение вида в осадках и в толще воды одинаково. И там, и тут иногда образуются высокие концентрации, хотя в осадках несколько реже.

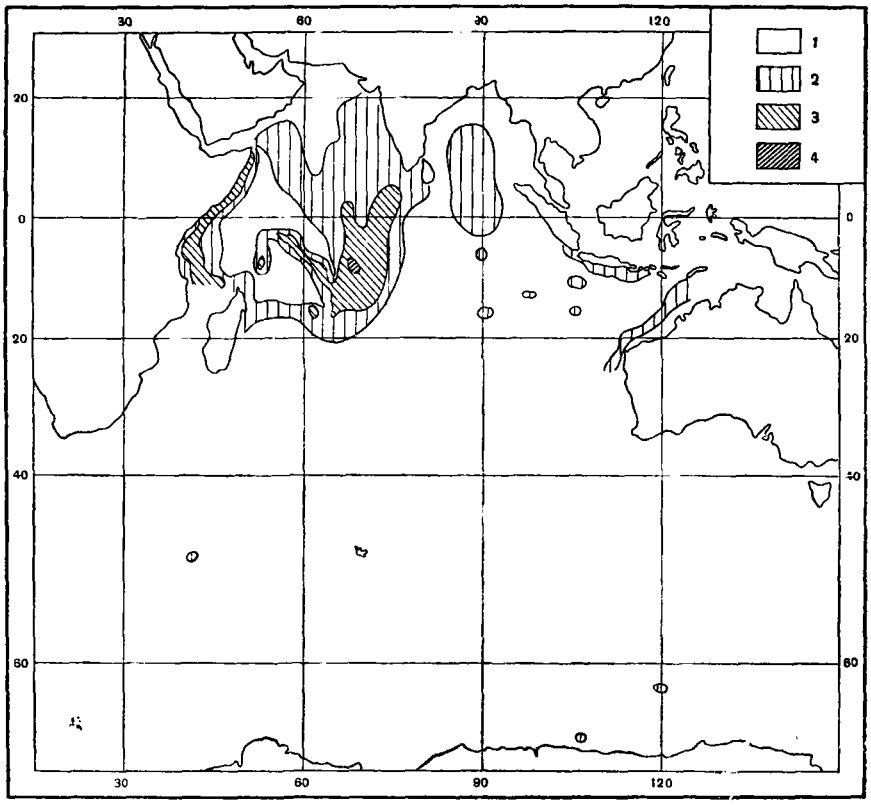


Рис. 16. Распространение Pulleniatina obliquiloculata на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.

В Атлантическом океане G. menardii широко распространена между экватором и 20° с. ш. (до 20% фауны фораминифер). Между 20 и 40° с. ш. вид встречается редко в количестве от 6 до 25 экз. (Phleger a. oth., 1953). Он очень многочислен в Карибском море и Мексиканском заливе (Cushman, 1931; Phleger, 1951; Phleger a. oth., 1953). В районе Фолклендских островов отмечено несколько экземпляров на одной станции (Heron-Allen a. Earland, 1932). В Тихом океане вид найден в районе Филиппинских островов (Cushman, 1921).

Pulleniatina obliquiloculata (Parker et Jones) обнаружена в Индийском океане на 88 станциях ($p_{общ}$=0,30) в количествах до 810 экз. (см. табл. 20) и составляет от 0,05 до 66,6% фауны фораминифер (рис. 16). Количества от 500 до 810 экз. встречались чрезвычайно редко (p = 0,007) на Центральном Индийском хребте и у о-ва Ява, на глубинах от 1610 до 2414 *м*. Концентрации от 100 до 500 экз. тоже редки (p = 0,07); они встречаются на глубинах от 250 до 4023 *м* в тех же районах и у восточных берегов Африки. Менее 100 экз. (p = 0,22) обычно попадается на глубинах от 95 до 5383 *м* к северу от 20° ю. ш. у восточного побережья Африки, в Аравийском море, на Центральном Индийском хребте и к востоку от него, в Бенгальском заливе, у берегов Явы и Австралии и на поднятиях в Индийско-Аравийской котловине. Южнее 50° ю. ш. найден в количестве менее 1 экз. P. obliquiloculata отмечена также в архипелаге Керимбо и в районе Тасмании (Heron-Allen a. Earland, 1914; Parr, 1950).

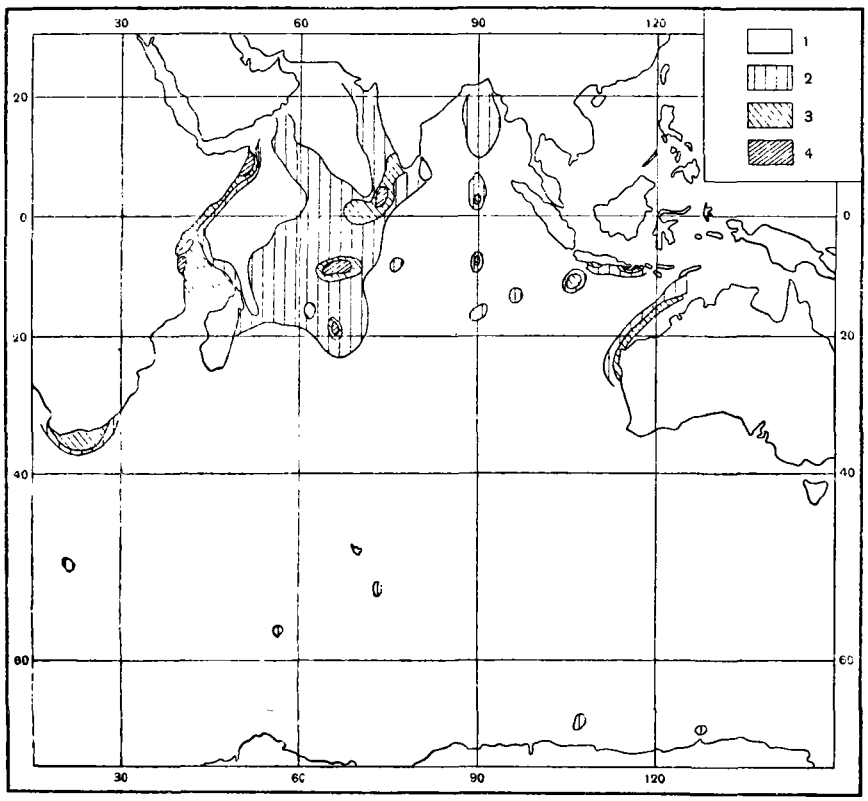


Рис. 17. Распространение Globigerina eggeri на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.

Присутствие этого вида на глубинах свыше 4700 *м* говорит об устойчивости его раковин к растворению, что подтверждается выводами Фледжера (Phleger, 1951). Широтные границы распределения вида в воде и осадках совпадают.

В Атлантическом океане P. obliquiloculata найдена на шельфе США южнее мыса Код (до 5% фауны фораминифер) и на 20° с. ш. (до 1% фауны). Наиболее распространена (10—20% фауны) она на экваторе, у побережья Южной Америки и в Мексиканском заливе (Phleger a. oth., 1953; Phleger, 1951; Parker, 1954; Cushman, 1924б). У Фолклендских островов и о-ва Южная Георгия вид очень редок (Heron-Allen a. Earland, 1932; Earland, 1933). В Средиземном море его нет, в Тихом океане отмечен на большом числе станций между Иокагамой и о-вом Гуам (Cushman, 1914). Во всех океанах вид встречается между 20° с. ш. и 20° ю. ш., но в Тихом распространен, по-видимому, более широко и в больших количествах.

Globigerina eggeri (Rhumbler) на дне Индийского океана встречена на 86 станциях ($p_{общ}$= 0,3) в количествах до 1005 экз. (см. табл. 20) и составляет от 0,3 до 76% фауны фораминифер. Количества от 500 до 1000 экз. редки (p = 0,01), приурочены к глубинам от 250 до 3203 *м* на Центральном Индийском хребте, у берегов Явы и Сомалийского полуострова (рис. 17). Концентрации 100—500 экз. (p = 0,08) отмечены у южного и восточного побережий Африки, на Центральном Индийском хребте, у берегов Австралии и Явы и на отдельных поднятиях в Индийско-Австралийской котло-

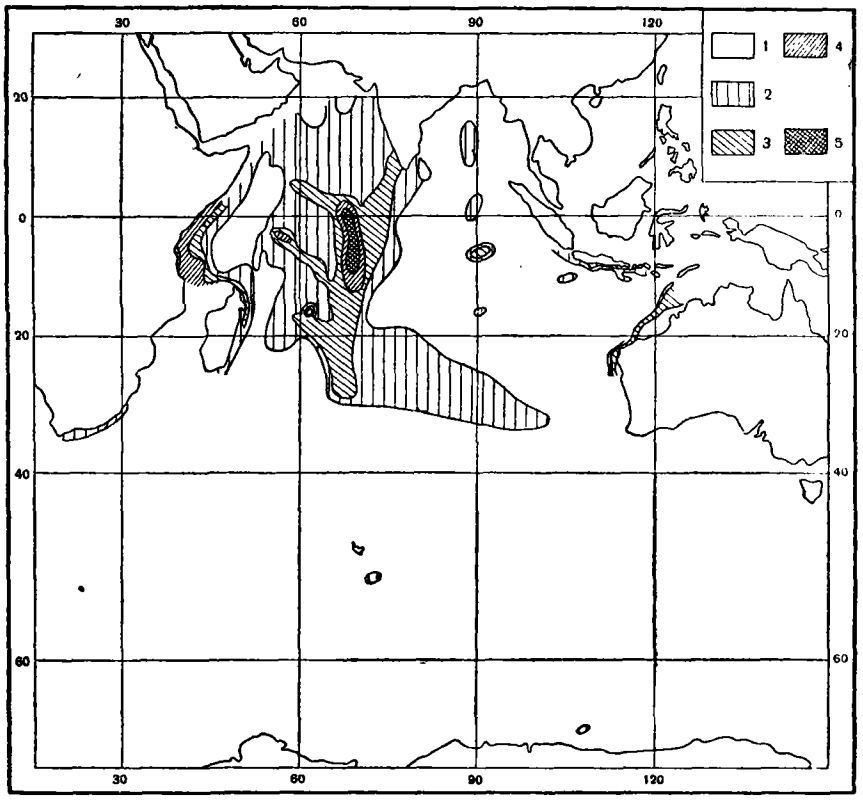


Рис. 18. Распространение Globigerinoides sacculifer на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.; *5* — более 1000 экз.

вине, на глубинах от 109 до 4350 *м*. Менее 100 экз. встречается наиболее часто ($p = 0{,}19$) у западных берегов Индии, у берегов Австралии, Явы, на Центральном Индийском и Индийско-Аравийском хребтах, а также на мелких поднятиях в Индийско-Австралийской котловине и на отдельных станциях к югу от 40° ю. ш

В Атлантическом океане этот вид отмечен у северо-восточного побережья США, в Мексиканском заливе и у Африканского побережья между экватором и 20° с. ш.; в значительных количествах он найден между 20 и 40° с. ш., севернее (до 60° с. ш.) встречается редко и в малых количествах (Phleger a. oth., 1953; Cushman, 1924b). В Тихом океане вид широко распространен в глобигериновых илах Северного полушария (Brady, 1884; Cushman, 1914, 1921) и редок в южной части (Heron-Allen a. Earland, 1922). Следовательно, G. eggeri характерна для Северного полушария.

Globigerinoides sacculifer (Brady) в Индийском океане обнаружена нами на 67 станциях ($p = 0{,}23$) в количествах до 1872 экз. (см. табл. 20) и составляет от 0,1 до 69,4% фауны планктонных фораминифер (рис. 18). Свыше 1000 экз. отмечено на Центральном Индийском хребте ($p = 0{,}01$) на глубине от 289 до 2942 *м*, от 500 до 1000 экз. ($p = 0{,}03$) — на глубинах от 82 до 3376 *м* у восточного побережья Африки, на Центральном Индийском хребте и в районе островов Сейшельских и Карагадос. Коли-

чества от 100 до 500 экз. (p = 0,07) встречаются на глубинах от 95 до 4400 *м* у восточного побережья Африки и Мадагаскара, на Индийском Центральном хребте у северо-западных берегов Австралии, близ Явы и на одном из поднятий Индийско-Австралийской котловины. Наиболее часты (p = 0,12) концентрации до 100 экз. Они отмечены на глубинах от 162 до 5383 *м* у южных и восточных берегов Африки и Мадагаскара, на большей площади Аравийского моря, к западу и юго-востоку от Центрального Индийского хребта, у берегов Австралии и Явы, на отдельных поднятиях в Индийско-Австралийской котловине. К югу от 35° ю. ш. G. sacculifer обнаружена на 2 станциях в количестве менее 1 экз. Она найдена в архипелаге Керимбо (Heron-Allen a. Earland, 1914) и у берегов Австралии (Parr, 1950).

Границы распределения вида в воде и в осадках совпадают; и в поверхностном слое, и на дне он образует высокие концентрации. В водной толще вид распространен очень широко, но в осадках котловин отсутствует.

В Атлантическом океане G. sacculaifer отмечен между 40° с. ш. и 35° ю. ш. (Brady, 1884), на экваторе составляет 20—40% фауны фораминифер, на 10° с. ш. — 60% (Phleger a. oth., 1953). Много найдено в Карибском море (Cushman, 1924b), Мексиканском заливе (Phleger, 1951; Parker, 1954) и у восточного побережья Южной Америки. Присутствует в осадках Средиземного моря (Parker, 1958). В Тихом океане он встречается у Филиппинских (Cushman, 1921) и Гавайских (Cushman, 1914) островов.

Globigerinoides conglobatus (Brady) найдена в осадках Индийского океана на 68 станциях ($p_{общ}$ = 0,23) в количествах до 666 экз. (табл. 20) и составляет от 0,3 до 24% фауны фораминифер. В концентрациях от 500 до 666 экз. (p = 0,01) вид обнаружен на глубине 1018—3376 *м* у восточного побережья Африки и на Центральном Индийском хребте (рис. 19) Количества от 100 до 500 экз. (p = 0,04) встречаются у восточного побережья Африки, к северу от Мадагаскара в районе островов Каргадос и Сейшельских и на Центральном Индийском хребте, на глубинах от 289 до 3325 *м*. Наиболее распространены (p = 0,18) концентрации меньше 100 экз.— у южного и восточного побережий Африки, на Индийско-Аравийском и Центральном Индийском хребте, у западных побережий Индии и Австралии, к северу от Мадагаскара, отдельными пятнами на дне котловин и в Бенгальском заливе. Кроме того, вид отмечен у архипелага Керимбо (Heron-Allen a. Earland, 1914). Южнее 35° ю. ш. G. conglobatus не найдена. Широтное распределение вида в воде и осадках Индийского океана совпадает.

В Атлантическом океане распространен между 40° с. ш. и 35° ю. ш. (Brady, 1884), но нигде не образует больших скоплений. На экваторе G. conglobatus составляет до 5% фауны фораминифер (Phleger a. oth., 1953), встречается в Мексиканском заливе и Карибском море (Phleger, 1951; Parker, 1954; Cushman, 1924b), очень редок в южной части океана у о-ва Южная Георгия (Earland, 1933). В Средиземном море вид встречается довольно часто (Parker, 1958). В Тихом океане он известен у Гавайских островов (Brady, 1884), довольно многочислен между Гавайями и Сан-Франциско (Cushman, 1914), у островов Самоа (Cushman, 1924a) и у Филиппин (Cushman, 1921).

Globigerinella aequilateralis (Brady) встречена нами в Индийском океане на 67 станциях (p = 0,23) в количествах до 292 экз. (см. табл. 20) и составляет от 0,1 до 14,2% фауны фораминифер. Концентрации от 100 до 292 экз. (рис. 20) отмечены на глубинах от 250 до 4380 *м* (p = 0,03) у восточного побережья Африки, на Центральном Индийском хребте и на одном из поднятий Индийско-Австралийской котловины. Менее 100 экз. попадается чаще (p = 0,20), такие количества обнаружены на глубинах от 109 до 4988 *м* у южного и восточного побережий Африки, на Индийском

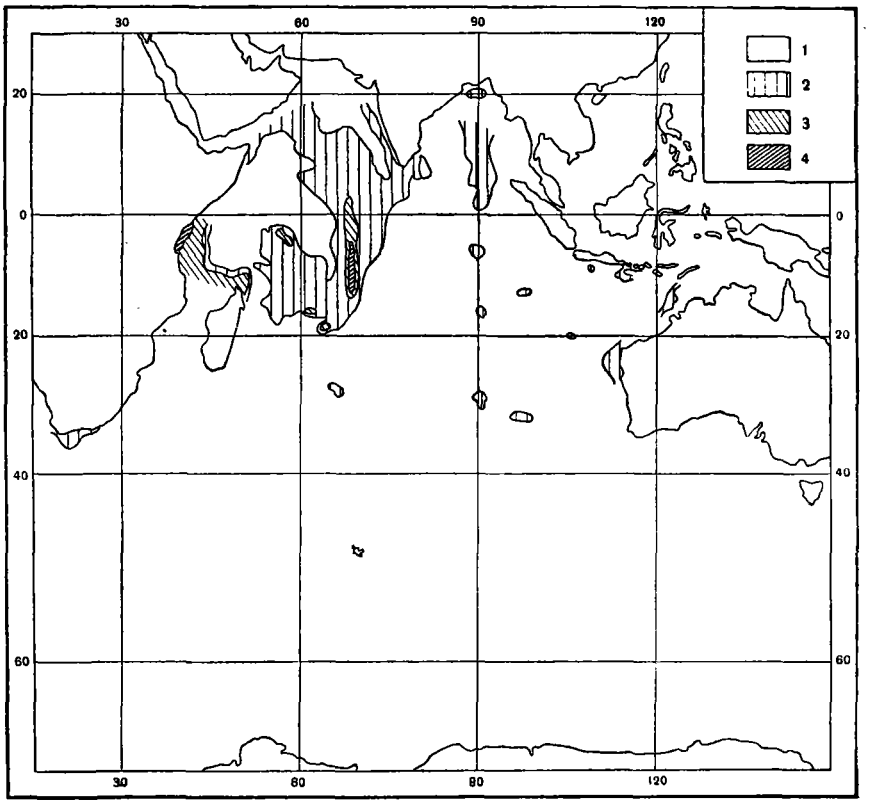


Рис. 19. Распространение Globigerinoides conglobatus на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.

Центральном и Индийско-Аравийском хребтах, у западного побережья Индии, в Бенгальском заливе, у берегов Австралии, Явы и на поднятиях в Индийско-Австралийской котловине. Встречается вид и в архипелаге Керимбо (Heron-Allen a. Earland,1914). Южные границы его распространения на дне и в толще воды (0—200 *м*) совпадают. На дне котловин G. aequilateralis не обнаружена.

В Атлантическом океане этот вид распространен между 50° с. ш. и 35° ю. ш. (Brady, 1884); высоких концентраций также не образует. На экваторе его содержание колеблется от 1 до 7% фауны фораминифер (Phleger a. oth., 1953, Wiseman a. Ovey, 1950), в Мексиканском заливе, Карибском море и к востоку от Кубы повышается до 5—13% (Cushman, 1924b; Phleger, 1951; Parker, 1954). Часто встречается в Средиземном море. В Тихом океане вид обнаружен у Филиппинских (Cushman, 1921), Гавайских (Cushman, 1914) и Галапагосских островов. Во всех океанах вид отсутствует южнее 35° ю. ш.; северная граница его распространения менее постоянна и в Атлантическом океане, в небольшом количестве он попадается до 50° с. ш.

Sphaeroidinella dehiscens (Parker et Jones) на дне Индийского океана обнаружена на 68 станциях ($p_{общ} = 0{,}23$) в количестве до 70 экз. (см. табл. 20). В большинстве случаев вид составляет менее 5% фауны фора-

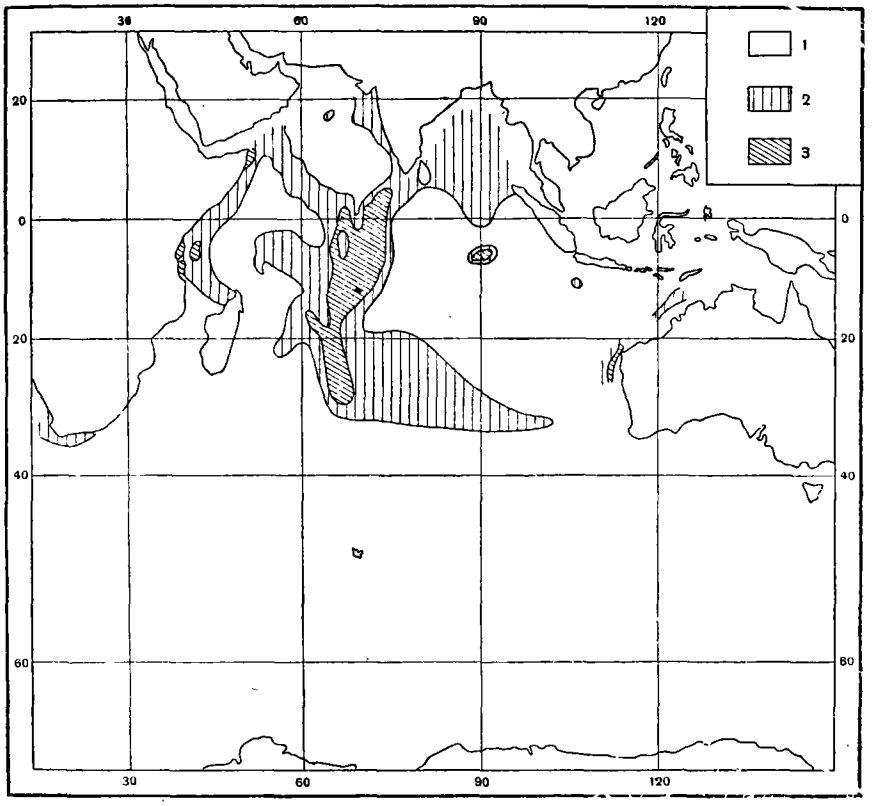


Рис. 20. Распространение Globigerinella aequilateralis на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — больше 100 экз.

минифер, распространен преимущественно к северу от 20° ю.ш. на глубинах до 4607 *м* (рис. 21). Границы распространения в воде и в осадках совпадают. Высоких концентраций он не образует. В Атлантическом океане этот вид в малом количестве найден в тропических и субтропических районах (Brady, 1884). В Мексиканском заливе, Карибском море и между экватором и 20° с.ш. он составляет от 0,7 до 1% фауны фораминифер (Cushman, 1924б; Phleger a. oth., 1953; Phleger, 1951; Parker, 1954). В Тихом океане вид найден у Гавайских о-вов (Cushman, 1914; Brady, 1884) и у Филиппин (Cushman, 1921). Во всех океанах он распространен между 20° с. ш. и 20° ю. ш.

Orbulina universa (Orbigny) отмечена в Индийском океане на 61 станции ($p_{общ}$ = 0,21) в количествах до 867 экз. (см. табл. 20), что составляет от 0,02 до 23,4% фауны планктонных фораминифер. Концентрации более 500 экз. встречаются очень редко (p = 0,003) — у восточного побережья Африки на глубине до 1018 *м* (рис. 22). От 100 до 500 экз. отмечается тоже редко (p = 0,03) на глубинах от 2172 до 4380 *м* у восточного побережья Африки, на Центральном Индийском хребте и на отдельных поднятиях в Индийско-Австралийской котловине. Наиболее часты количества менее 100 экз. (p = 0,17); они встречаются на глубинах от 109 до 5383 *м* вдоль восточного побережья Африки и Мадагаскара, на Центральном Индийском и Индийско-Аравийском хребтах, у северо-западных берегов Австралии,

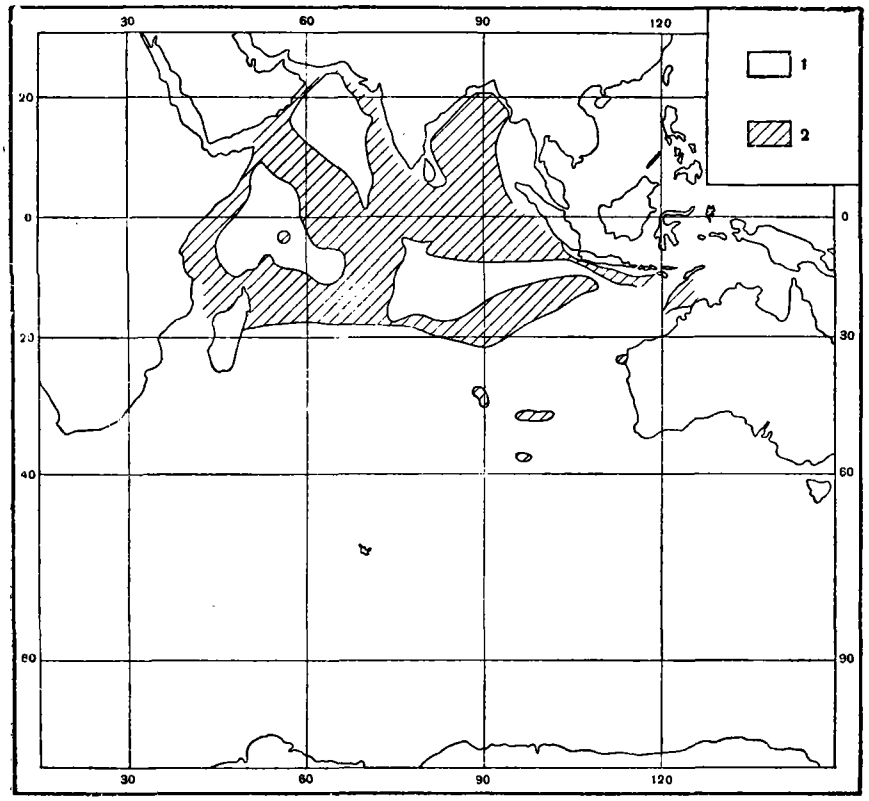


Рис. 21. Распространение Sphaeroidinella dehiscens на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.

близ Явы, на отдельных поднятиях Индийско-Австралийской котловины, у южной оконечности Африки и в нескольких местах в районе 40° ю. ш. Вид найден также в архипелаге Керимбо (Heron-Allen a. Earland, 1914) и у южных берегов Австралии и Тасмании (Parr, 1950), но наиболее распространен в осадках тропической части океана к северу от 20° ю. ш.; южнее отмечены лишь редкие находки, хотя в толще воды он здесь попадается очень часто и в довольно больших количествах. Такое несоответствие объясняется, вероятно, тем, что тонкостенные раковины O. universa к югу от 20° ю. ш. растворяются на меньших глубинах, чем в экваториальном районе, и поэтому не всегда сохраняются в осадке.

В Атлантическом океане O. universa отмечена между 70° с. ш. и 50° ю. ш. (Brady, 1884). К югу от 40° с. ш. она составляет 1—2% фауны планктонных фораминифер, а на экваторе до 7%. Наиболее высокие концентрации (23% фауны) отмечены восточнее Кубы (Phleger a. oth., 1953). В Мексиканском заливе вид составляет до 5% фауны (Parker, 1954; Phleger, 1951) и в большом количестве встречается в Карибском море (Cushman, 1924b). Найден этот вид также на двух станциях у Фолклендских островов и о-ва Южная Георгия (Heron-Allen a. Earland, 1932; Earland, 1933, 1934); есть он и в Средиземном море (Parker, 1958). В Тихом океане отмечено два нахождения вида — в районе Филиппинских островов (Cushman, 1921) и у берегов Калифорнии (Cushman a. Moyer, 1930).

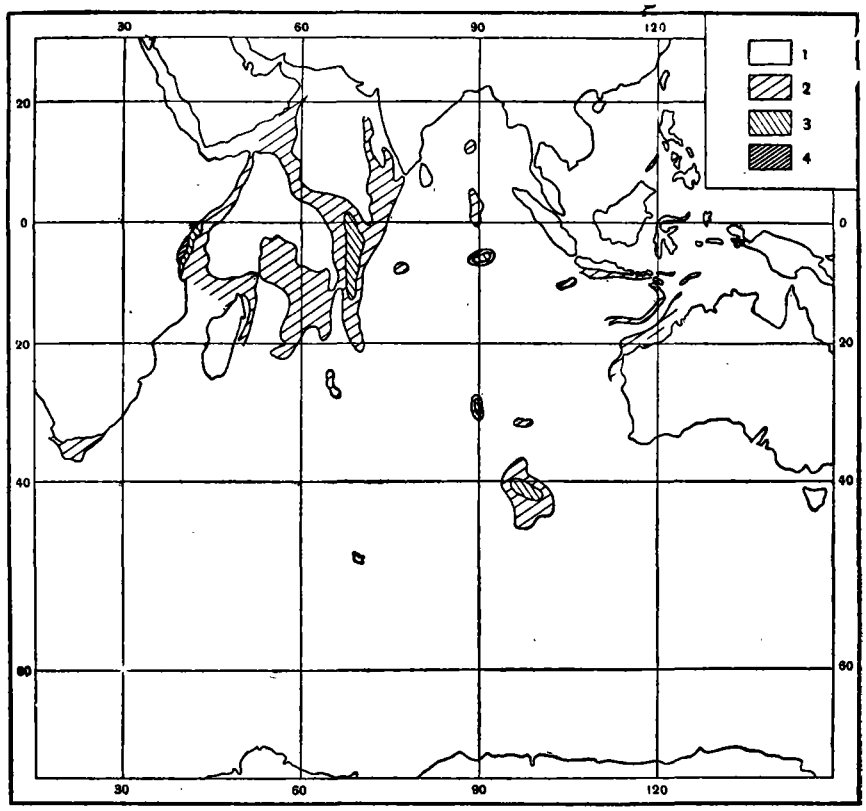


Рис. 22. Распространение Orbulina universa на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.

Globorotalia tumida (Brady) в осадках Индийского океана обнаружена на 53 станциях ($p_{общ}$=0,18) в количествах до 208 экз. (см. табл. 20) и составляет от 0,2 до 67% фауны фораминифер, а на одной станции (4597)—100 %. Количество от 100 до 208 экз. (рис. 23) было встречено только близ о-ва Каргадос на глубине 2234—4350 *м* (p = 0,007). Находки менее 100 экз. обычны для областей к северу от 20° ю. ш. — на Индийско-Аравийском хребте, у восточного побережья Африки, к северу и востоку от Мадагаскара, на отдельных поднятиях Индийско-Австралийской котловины, близ о-ва Ява, островов Рождества и Кокосовых. Южнее этот вид найден лишь у южного побережья Африки (35° ю. ш.).

В Атлантическом океане G. tumida распространена между 35° с. ш. и 35° ю. ш.(Brady, 1884). У побережья США содержание вида не превышает 1% фауны фораминифер, в Мексиканском заливе достигает 5%. Высокие содержания (от 20 до 40%) отмечены у берегов Африки между 20° с. ш. и экватором, а очень высокие — у островов Фернанду-ди-Норонья близ побережья Южной Америки (Phleger a. oth., 1953). В Средиземном море этот вид не встречается. В Тихом океане он обнаружен у Филиппин (Cushman, 1921). Широтное распределение вида одинаково во всех океанах, но, по-видимому, наиболее распространен он в Атлантическом.

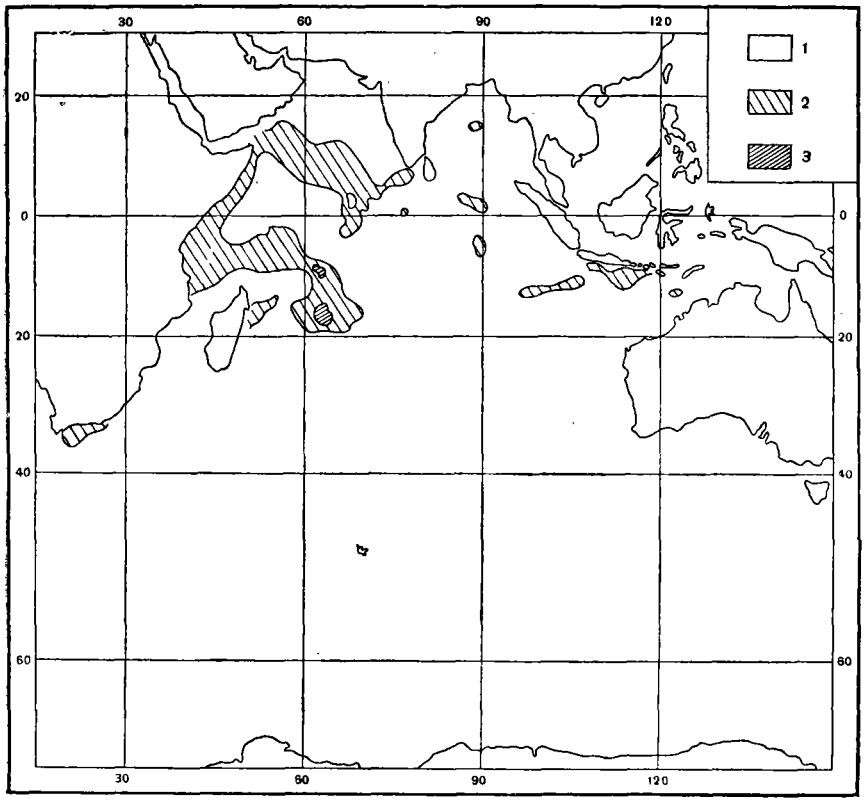


Рис. 23. Распространение Globorotalia tumida на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 208 экз.

Globigerina inflata (Orbigny) найдена нами на 50 станциях Индийского океана ($p_{общ}$ = 0,17) в количествах до 2846 экз. (см. табл. 20) и составляет от 0,1 до 79% фауны планктонных фораминифер (рис. 24). Концентрации более 1000 экз. (p = 0,02) отмечены на глубинах от 142 до 4642 *м* в открытом океане между 40 и 50° ю. ш., у островов Принца Эдуарда и Крозе и у южной оконечности Африки. Количества от 500 до 1000 экз. (p = 0,01) обнаружены у южных берегов Африки, в районе субантарктических островов, на Центральном Индийском хребте и к юго-востоку от островов Св. Павла и Новый Амстердам, на глубинах от 1358 до 4400 *м*. От 100 до 500 экз. (p = 0,02) встречается во всех перечисленных районах и в открытой части океана к северу от 40° ю. ш., на глубинах от 2807 до 4900 *м*. Концентрации менее 100 экз. наиболее часты (p = 0,11) между 40 и 20° ю. ш. на глубинах от 110 до 6841 *м* — к югу от Мадагаскара и Африки и на Центральном Индийском хребте; южнее и севернее вид очень редок. Обнаружен вид также в архипелаге Керимбо (Heron-Allen a. Earland, 1914) и у берегов Тасмании (Parr, 1950).

В Атлантическом океане G. inflata известна между 88° с. ш. и 53° ю. ш. (Brady, 1884). Наивысшие концентрации отмечены между 35 и 54° с. ш., дальше к северу содержание вида снижается до 5% фауны планктонных фораминифер. В районе экватора, в Мексиканском заливе и Карибском

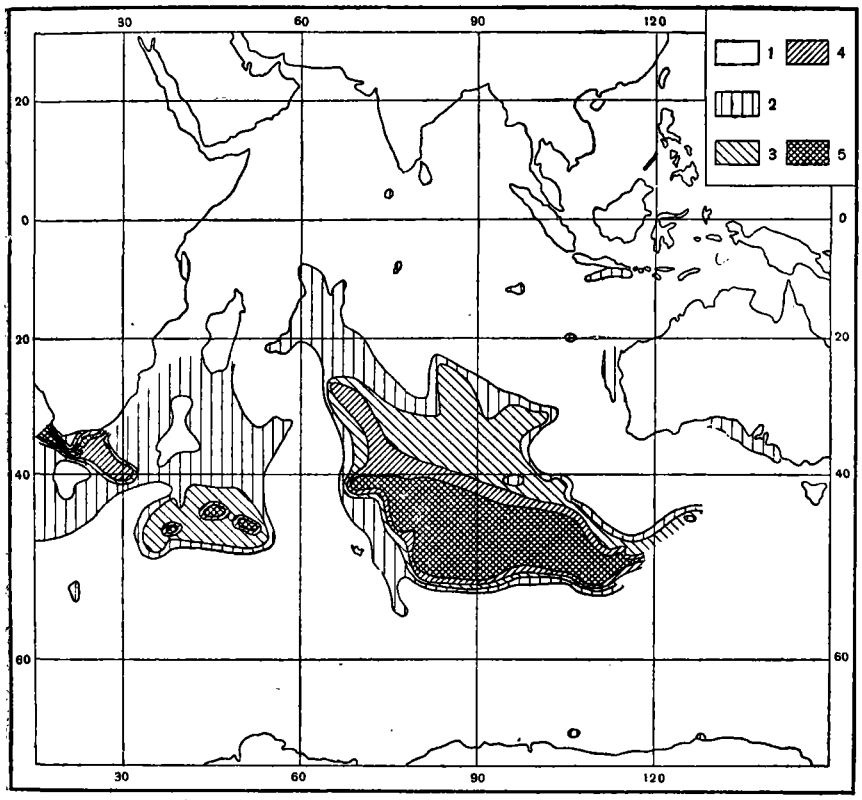


Рис. 24. Распространение Globigerina inflata на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.; *5* — более 1000 экз.

море вид составляет не более 1% фауны (Phleger, 1951; Phleger a. oth., 1953; Cushman,1924 b;Parker,1954).В районе Фолклендских о-вов, о-ва Южная Георгия и моря Уэделла он встречается в малых количествах (Heron-Allen a. Earland, 1932; Earland. 1933,1934, 1936).В Тихом океане обнаружен на 5 станциях в северной части (Brady,1884) и у Филиппин (Cushman,1921).

Globorotalia truncatulinoides (Orbigny) в Индийском океане обнаружена на 49 станциях ($p_{общ}$ = 0,17) в количествах до 1186 экз. и составляет от 0,2 до 52% фауны планктонных фораминифер (см. табл. 20). Количества более 1000 экз. встречались очень редко (p = 0,007),в частности у островов Принца Эдуарда и на ст. 4575 в открытой части океана на глубине 2807 *м* (рис. 25). Концентрации от 500 до 1000 экз. встречались также редко (p = 0,007) на глубине до 4132 *м* в районе субантарктических островов и на станциях 297 и 4575. Для обширной площади открытого океана, а также прибрежной зоны Южной Африки и о-ва Ява и района субантарктических островов, на глубинах от 204 до 4642 *м* характерны величины от 100 до 500 экз. (p = 0,04). Наиболее часты (p = 0,12) количества менее 100 экз. Они отмечены на глубинах от 319 до 4988 *м* в районе субантарктических островов, у южного и восточного побережий Африки и в открытой части океана в виде узких полос или отдельных пятен. Этот вид распространен в осадках между 50 и 20° ю. ш.; севернее он попадается очень редко.

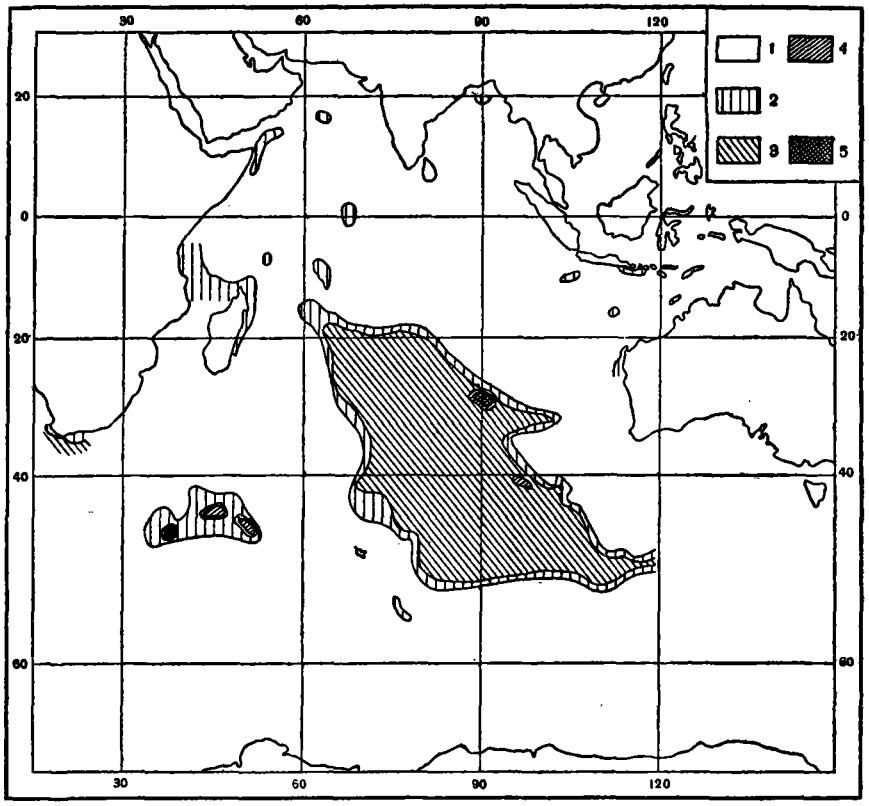


Рис. 25. Распространение Globorotalia truncatulinoides на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден: *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.; *5* — более 1000 экз.

В Атлантическом океане G. truncatulinoides отмечена между 79°26′ с. ш. и 46°46′ ю. ш. (Brady, 1884). На 60° с. ш. вид составляет менее 1% фауны фораминифер, юго-западнее Британских островов содержание его повышается до 2%. Наиболее часто и в большом количестве G. truncatulinoides обнаружена между Британскими островами и побережьем США и в Мексиканском заливе. На экваторе доля ее в фауне фораминифер равна 1% (Phleger, 1951; Phleger a. oth., 1953; Parker, 1954). Присутствует вид у Фолклендских островов и у о-ва Южная Георгия (Heron-Allen a. Earland, 1932; Earland, 1933, 1934).

В Средиземном море он встречается редко (Parker, 1958). В Тихом океане вид найден у Филиппин и у берегов Калифорнии (Cushman, 1921). Максимальных концентраций и наибольшего распространения во всех океанах G. truncatulinoides достигает между 40 и 50° с. и ю. широты.

Globigerina conglomerata (Schwager) на дне Индийского океана встречена на 47 станциях ($p_{общ} = 0{,}16$) в количествах до 713 экз. (см. табл. 20), что составляет от 0,3 до 33,3% фауны фораминифер. Концентрации более 500 экз. (рис. 26) очень редки ($p = 0{,}007$), они отмечены всего в двух местах на Центральном Индийском хребте (глубина 2460—2942 *м*). От 100 до 500 экз. встречалось тоже редко ($p = 0{,}02$) и также на Центральном Индийском хребте и на поднятиях в Индийско-Австралийской котловине,

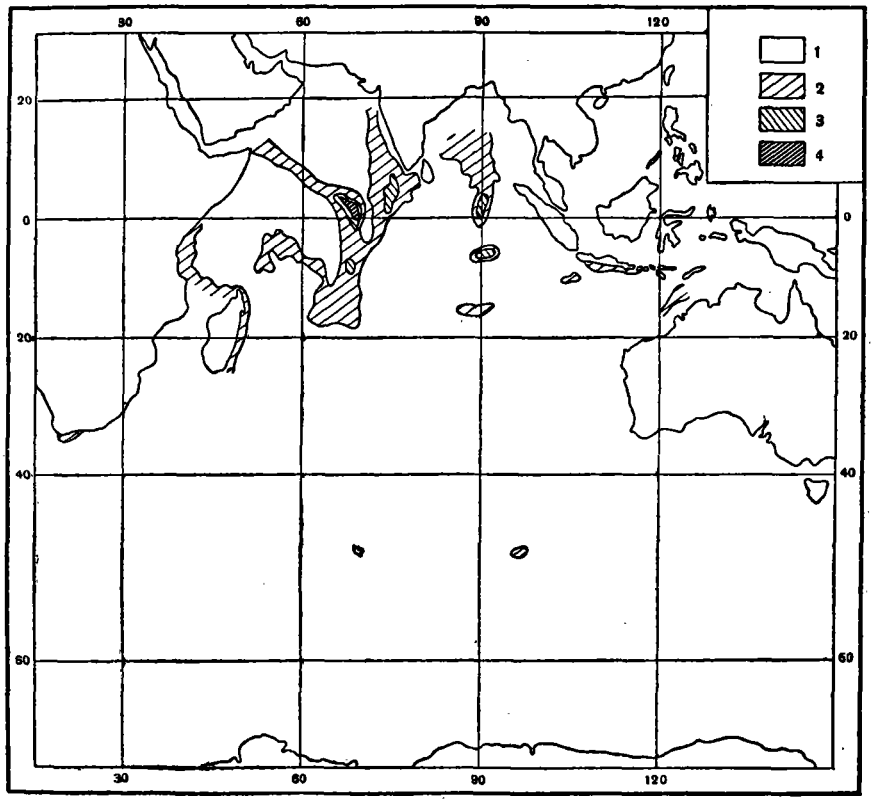


Рис. 26. Распространение Globigerina conglomerata на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 500 экз.; *4* — от 500 до 1000 экз.

на глубинах от 250—4023 *м*. Количества менее 100 экз. (p = 0,13) характерны для восточного и южного побережий Африки и Мадагаскара, Центрального Индийского и Аравийско-Индийского хребтов, прибрежной зоны о-ва Явы и Сейшельских островов, а также для поднятий в Индийско-Австралийской котловине; распространены на глубинах от 289 до 5164 *м*. В основном вид встречается к северу от 18° ю.ш., что совпадает с распространением его в слое воды 0—200 *м*.

В Атлантическом океане очень редкие находки этого вида отмечены у Фолклендских островов и о-ва Южная Георгия (Heron-Allen a. Earland, 1932; Earland, 1933, 1934). В Тихом океане G. conglomerata найдена в районе Филиппинских островов (Cushman, 1921).

Globorotalia punctulata (Orbigny) найдена в Индийском океане на 44 станциях ($p_{общ}$= 0,15) в количествах до 155 экз., что составляет от 0,06 до 6% фауны планктонных фораминифер (см. табл. 20). Находки приурочены к глубинам от 312 до 4640 *м* у восточных побережий Африки и Мадагаскара, на Индийско-Аравийском хребте, на Центральном Индийском хребте к северу от 20° ю. ш., а также отдельными пятнами к югу. В Атлантическом океане вид в небольших количествах отмечен юго-западнее Британских островов, в Мексиканском заливе, в районе Кубы, у побережья Африки (Phleger a. oth., 1953) и в области экватора (Wiseman a. Ovey, 1950). Северная граница его распространения — 55° с. ш. В Ти-

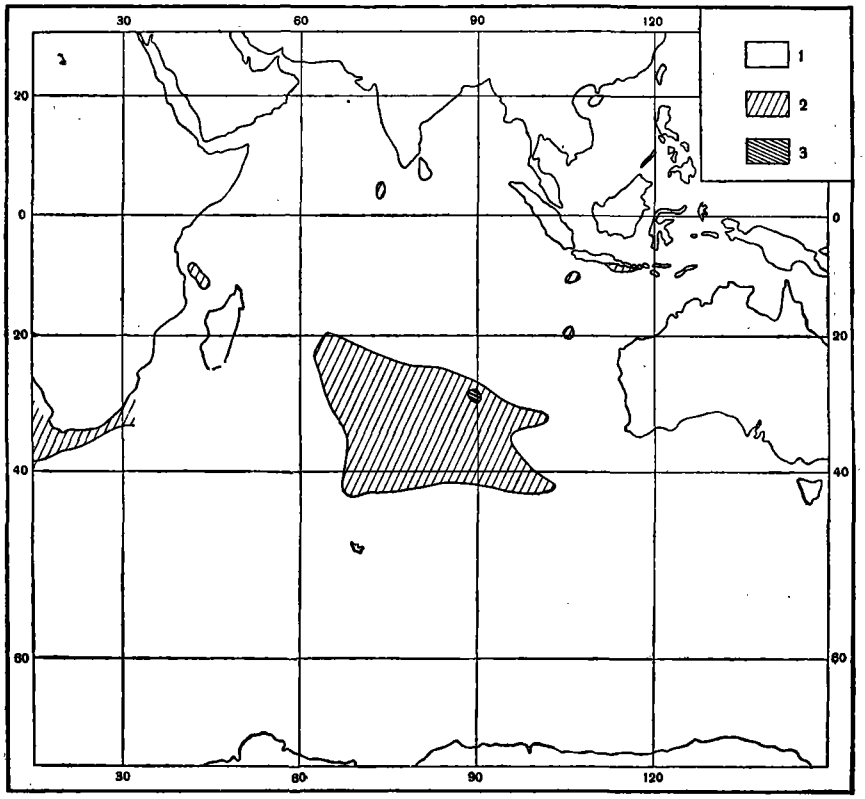


Рис. 27. Распространение Globorotalia hirsuta на дне Индийского океана (экз. на 1 *г* осадка)

1 — вид не найден; *2* — до 100 экз.; *3* — от 100 до 182 экз.

хом океане G. punctulata найдена в районе Филиппинских островов (Cushman, 1921). Таким образом, во всех океанах этот вид встречается в умеренных и экваториальных широтах; больших скоплений не образует.

Globorotalia hirsuta (Orbigny) на дне Индийского океана обнаружена на 18 станциях ($p_{общ}$= 0,06) в количествах до 182 экз. (см. табл. 20); вид составляет до 2% фауны фораминифер, за исключением трех станций, где содержание его достигало 7,33 и 41% (рис. 27). Более 100 экз. (p = 0,003) отмечено только на ст. 4575 (глубина 2807 *м*). Меньшие концентрации обнаружены на Центральном Индийском хребте и к востоку от него на 20—40° ю. ш. и у южного побережья Африки и в интервале глубин от 250 до 5164 *м*. Севернее вид очень редок (p = 0,06).

В Атлантическом океане G. hirsuta найдена к югу от 60° с. ш., у северо-восточного побережья США и юго-западнее Британских островов. В этих районах она встречается довольно часто, но составляет менее 1% фауны фораминифер. В Мексиканском заливе, к востоку от Кубы и в полосе между экватором до 20° с. ш. этот вид редок (Cushman, 1931; Phleger, 1951; Phleger a. oth., 1953; Parker, 1954; Cushman a. Henbest, 1940). В небольших количествах он найден у Фолклендских островов и о-ва Южная Георгия (Heron-Allen a. Earland, 1932; Earland, 1933, 1934). В Тихом океане вид обнаружен у Филиппин (Cushman, 1921) и у Новой Зеландии (Heron-Allen a. Earland, 1922).

G. hirsuta — типичный вид умеренных широт. Она не образует высоких концентраций в осадке и составляет незначительную часть фауны фораминифер.

Globigerina hexagona (Natland) обнаружена в Индийском океане на 15 станциях ($p_{общ}$= 0,05) в количествах до 59 экз. (см. табл. 20) на глубине от 446 до 4988 *м* и составляет менее 1% фауны фораминифер. Встречается на Индийско-Аравийском и Центральном Индийском хребтах и на отдельных поднятиях дна к северу от 18° ю. ш. В Атлантическом океане встречается очень редко и в малых количествах между экватором и 20° с. ш. (Phleger a oth., 1953).

Hastigerina digitata Rhumbler найдена на 10 станциях Индийского океана ($p_{общ}$= 0,03) в количествах от 2 до 64 экз. и составляет менее 3% фауны планктонных фораминифер (см. табл. 20). Она присутствует на глубинах от 95 до 4705 *м* к северу от 17° ю. ш. на Центральном Индийском хребте, у южной оконечности п-ова Индостан и у восточных побережий Африки и Мадагаскара. Широтное распределение вида в воде и осадках очень сходно, но на дне он встречается реже. В Атлантическом океане H. digitata попадается редко и не образует больших скоплений (Phleger a. oth., 1953; Parker, 1954), в Тихом океане встречается, по-видимому, чаще; отмечена у Гавайских и Филиппинских островов и о-вов Самоа (Cushman, 1914, 1921, 1924a). H. digitata — типичный тропический вид.

Таблица 21

Частота встречаемости (p) планктонных фораминифер на дне Индийского океана

Вид	Танатоценоз				
	холодноводных видов	умеренно-холодноводных видов	видов умеренных широт	умеренно-тропических видов	тропических видов
Globigerina pachyderma	0,62	0,47	0,32	0,27	0,06
G. bulloides	0,21	0,52	0,96	0,78	0,53
G. inflata	0,018	0,19	0,97	0,90	0,15
Globorotalia truncatulinoides	0,027	0,09	0,61	0,39	0,24
G. punctulata	0,009	0,027	0,44	0,22	Нет
G. scitula	0,018	Нет	0,06	0,13	0,02
Globigerina eggeri	0,018	0,08	0,23	0,52	0,67
Globigerinoides ruber	0,009	0,05	0,49	0,64	0,70
Pulleniatina obliquiloculata	0,009	0,09	0,06	0,39	0,76
Globigerinoides sacculifer	Нет	0,018	0,16	0,52	0,66
Globorotalia hirsuta	»	Нет	0,44	0,27	0,07
G. menardii	»	»	0,22	0,77	0,87
Sphaeroidinella dehiscens	»	»	0,11	0,27	0,61
Globigerinoides conglobatus	»	»	0,22	0,64	0,54
Globigerinella aequilateralis	»	»	0,28	0,64	0,58
Orbulina universa	»	»	0,49	0,53	0,45
Globorotalia tumida	»	»	0,06	Нет	0,49
Globigerina conglomerata	»	»	0,06	»	0,43
G. hexagona	»	»	Нет	0,14	0,13
Hastigerina digitata	»	»	»	Нет	0,14
Candeina nitida	»	»	»	0,14	0,10
Globigerinita glutinata	»	»	»	0,14	0,05
Globigerina quinqueloba	»	»	»	Нет	0,03
Hastigerina pelagica	»	»	»	»	0,02

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Candeina nitida (Orbigny) обнаружена на дне Индийского океана на 11 станциях ($p_{общ}$= 0,03) в количествах от 2 до 50 экз., что не превышает 2,5% всей фауны фораминифер (см. табл. 20). Найдена она на глубинах от 446 до 4380 *м* близ восточных берегов Африки и Мадагаскара, у Сейшельских островов, в Аравийском море, близ южных берегов Индии, у северных берегов Австралии и на ст. 4575 в открытом океане. В Атлантическом океане в большом количестве данный вид встречается в Карибском море, у побережья Бразилии и Флориды, иногда в Мексиканском заливе (Phleger a. oth., 1953; Cushman, 1924a; Brady, 1884). У побережья Африки между экватором и 20° с. ш. он редок или отсутствует (Schott, 1935), найден на одной станции у Фолклендских островов. Судя по распределению в осадках, C. nitida можно отнести к тропическим, но очень редким видам.

Globigerinita glutinata Egger встречена в Индийском океане на шести станциях ($p_{общ}$= 0,02) в количествах до 13 экз. (см. табл. 20) и составляет от 0,3 до 4,2% фауны фораминифер. Все эти станции расположены севернее 18° ю. ш., и нахождения вида приурочены к глубинам от 95 до 3953 *м*. В Атлантическом океане он отмечен у побережья Африки на 10° с. ш. (Egger, 1893) и в северо-западной части Мексиканского залива (Parker, 1954), присутствует также в осадках Средиземного моря.

Globorotalia scitula (Brady) на дне Индийского океана (глубины от 284 до 4488 *м*) найдена только на пяти станциях (p = 0,015) в количестве от 5 до 24 экз. (см. табл. 20) и составляет от 0,3 до 29% фауны форамини-

Таблица 22

Средние геометрические содержания фораминифер в танатоценозах

Вид	I холодноводных видов	II умеренно-холодноводных видов	III видов умеренных широт	IV умеренно-тепловодных видов	V тропических видов
Globigerina pachyderma	3			6	
G. bulloides	1		535	—	16
Globorotalia truncatulinoides	—*	—	120	—	7
Globigerina inflata	4		145	—	1
Globorotalia punctulata	—	—	14		8
G. hirsuta			6,5		
Globigerina eggeri	5		98		25
Globigerinoides conglobatus	Нет	Нет	12		26
G. ruber	—	—	130		23
G. sacculifer	Нет	—	11		33
Sphaeroidinella dehiscens	»	»	—		6
Globorotalia menardii	»	»	8		39
Globigerinella aequilateralis	»	»	7		14
Orbulina universa	»	»	16		13
Pulleniatina obliquiloculata		1			17
Globigerina conglomerata	Нет	Нет	—	Нет	29
Globorotalia tumida	»	»	—	»	13
Globigerina hexagona	»	»	Нет	—	6
Hastigerina digitata	»	»	»	»	13
Candeina nitida	»	»	»	—	5
Все фораминиферы	1,6	70	942	61	89

* Виды встречены в пределах танатоценоза, но так редко, что обработка данных с помощью математической статистики невозможна.

фер. Это чрезвычайно редкий и малочисленный в Индийском океане вид, так что говорить о закономерностях его распределения здесь пока невозможно. В Атлантическом океане он отмечен Брэди (Brady, 1884) между 40 и 60° с.ш., кроме того, найден в Мексиканском заливе и к востоку от Кубы (Cushman, 1931; Phleger, 1951; Phleger a. oth., 1953; Parker, 1954), а также у Фолклендских островов и о-ва Южная Георгия (Heron-Allen a. Earland, 1932; Earland, 1933, 1934). Везде вид составляет менее 5 % фауны фораминифер и встречается в малых количествах.

Hastigerina pelagica (Orbigny) на дне Индийского океана обнаружена всего на четырех станциях ($p = 0{,}01$) в количестве от 5 до 48 экз. (см. табл. 20) и составляет менее 1 % фауны фораминифер. Встречается на глубинах от 2172 до 3272 *м* у восточного побережья Африки, у Сейшельских островов и на Центральном Индийском хребте, всюду севернее 17° ю. ш. В поверхностном слое (0—200 *м*) вид распространен значительно шире. Такое несоответствие между распределением в воде и в осадках объясняется малой устойчивостью его к растворению на глубинах свыше 3300 *м*. В Атлантическом океане H. pelagica обнаружена в Карибском море (Cushman, 1924b), Мексиканском заливе (Parker, 1954) и на одной станции у Фолклендских островов (Earland, 1934). В Тихом океане она найдена между Гавайскими островами и о-вом Гуам (Flint, 1899), а также в северной части океана (Brady, 1884).

Globigerina quingueloba Natland обнаружена в Индийском океане только на одной станции (4627) в количестве 5 экз. (см. табл. 20).

По видовому и количественному распределению фораминифер и частоте встречаемости их на различных широтах были выделены танатоценозы на дне океана (Беляева, 1963). В табл. 21 приведены частоты встречаемости, а в табл. 22 — средние геометрические содержания видов в различных танатоценозах; границы танатоценозов показаны на рис. 11.

ВЫВОДЫ

1. Применение методов математической статистики позволяет проводить сравнение содержаний и характера распределения фораминифер в биоценозах и танатоценозах. Параметры, полученные при статистической обработке, являются исчерпывающей характеристикой распределения содержаний, так как они показывают не только средние содержания, но и величину отклонения от них, а также частоту встречаемости различных содержаний, наблюдаемых в данной совокупности.

2. Наивысшие концентрации живых планктонных фораминифер во всех географических зонах приурочены к поверхностному слою воды (0—200 *м*), что свидетельствует о наличии здесь оптимальных условий для жизни и воспроизводства этих организмов. Основным фактором, определяющим распределение живых фораминифер в водной толще, является наличие пищи — фитопланктона, который может развиваться только в зоне проникновения солнечного света (до глубины 100 *м*). Присутствие симбионтов (zooxantellae) в раковинах также объясняет тяготение фораминифер к поверхностному слою. Большое значение в вертикальном распределении фораминифер имеет и температура воды, но она не является определяющим фактором, так как резкому изменению количества особей на глубине порядка 100 *м* не сопутствует резкое изменение температуры.

3. Ниже 200 *м* концентрация живых фораминифер в толще воды резко уменьшается, но в незначительном количестве они встречаются до глубины 2000 *м*. Количество фораминифер в нижних слоях зависит от количества их в поверхностном слое. Это явление связано с тем, что часть их жизнен-

ного цикла проходит в слое ниже 200—300 *м*. В районах высоких концентраций фораминиферы отмечены на бо́льших глубинах, чем в районах малых концентраций.

4. Распределение отдельных видов подчинено тем же закономерностям, что и общее распределение фораминифер. Максимальные количества всех видов приурочены к поверхностному слою, где развит фитопланктон. Никакие виды не образуют высоких концентраций ниже 200 *м*. Видовой стратификации, т. е. приуроченности различных видов к разным глубинам в столбе воды, о которой говорят Польский (Waller a. Polsky, 1959) и Эмилиани (Emiliani, 1954), нами не обнаружено.

Продуктивность вида в слое 0—200 *м* определяет его численность в глубоких слоях и закономерности вертикального распространения.

5. Наряду с живыми фораминиферами в толще воды до предельных глубин опробования есть пустые раковины. В слое до 200 *м* их не более 1% от общего количества фораминифер, но с глубиной содержание возрастает и ниже 2000 *м* достигает 100% (только пустые раковины). Имеется прямая зависимость между количеством живых фораминифер в верхнем слое воды и количеством пустых раковин в нижних слоях. Абсолютные количества пустых раковин нигде в водной толще не превышают нескольких десятков экземпляров, тогда как живые организмы образуют в верхнем слое концентрации до нескольких тысяч экземпляров в 1000 $м^3$ воды. Это связано, по-видимому, с быстрым опусканием раковин на дно после отмирания организмов. Растворение раковин становится заметным только после длительного пребывания их в придонных водах. Отсутствие следов растворения у раковин из глубинных слоев воды подтверждает предположение о их быстром падении на дно.

6. Общее количественное распределение планктонных фораминифер по площади в поверхностном слое тесно связано с распространением фитопланктона и зависит от характера водных масс и течений. Максимальные концентрации живых фораминифер отмечены в районах умеренных широт при температуре поверхностных вод от 1 до 10°. В экваториальной и аравийской водных массах с температурой поверхностных вод +30° характерны высокие концентрации, особенно в районах поднятия глубинных вод, богатых биогенными элементами.

Низкие концентрации отмечены в центральной водной массе, которая характеризуется слабым вертикальным перемешиванием и недостаточным выносом биогенных элементов с глубин, минимальные — в антарктической зоне при температуре поверхностных вод около 0° (водные массы Прибрежного западного течения и Восточного Дрейфа).

7. Видовой состав фауны фораминифер и количество видов тесно связаны с водными массами океана и меняются по широте в соответствии с изменением последних. Наиболее важную роль при этом играет температурный фактор; так, количество видов в тропических районах в 10—20 раз больше, чем в антарктических. Границами водных масс, а следовательно и границами видов, приуроченных к определенным водным массам, являются линии конвергенции и дивергенции.

8. Фораминиферы из поверхностного слоя воды (0—200 *м*) могут быть отнесены к следующим группам.

а. Виды, живущие только в экваториальной водной массе,— Globorotalia tumida, Globigerina conglomerata, G. hexagona, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens. Как правило, они не образуют высоких концентраций.

б. Виды, живущие в экваториальной и центральной водных массах,— Globigerinoides ruber, G. sacculifer, G. conglobatus, Globorotalia menardii, Hastigerina digitata, Globigerinella aequilateralis. В больших количест-

вах (до 1000 и более экземпляров в 1000 $м^3$ воды) они встречаются только в экваториальной водной массе.

в. Виды, характерные для центральной водной массы,— Hastigerina pelagica, Globorotalia hirsuta, G. punctulata, G. truncatulinoides, Candeina nitida, Globigerina eggeri, G. inflata. В небольшом количестве они попадаются и в экваториальной водной массе.

г. Виды субантарктических и антарктических вод — Globigerina bulloides, G. quingueloba и Globigerinita glutinata.

9. Распределение отдельных видов в поверхностном слое воды легло в основу выделения биоценозов, приуроченных к определенным водным массам и характеризующихся определенным набором видов. Границами биоценозов служат также линии конвергенции и дивергенции. В Индийском океане нами выделено три основных биоценоза.

а. Биоценоз холодноводных видов, приуроченный к водным массам антарктического Прибрежного западного течения с температурой 0°. Характерным видом биоценоза является Globigerina billoides, а северной границей его служит зона антарктической дивергенции.

б. Биоценоз видов умеренных широт, приуроченный к водам с температурой в поверхностном слое от —1 до +9,7°. Он представлен видами Globigerina inflata, Globorotalia truncatulinoides, G. hirsuta и другими (всего 18 видов). Границами биоценоза служат зоны антарктической и субтропической конвергенции.

в. Биоценоз тропических видов, приуроченный к экваториальной и аравийской водным массам с температурой поверхностного слоя 14—28°. В этом биоценозе насчитывается более 20 видов — Globorotalia menardii, Globigerinoides conglobatus, Globigerina conglomerata, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens и др. В областях между районами обитания этих биоценозов выделены еще два переходных биоценоза.

10. Количественное распределение раковин планктонных фораминифер на дне океана определяется, с одной стороны, продуктивностью верхней толщи воды, а с другой — глубиной. Наибольшие количества их приурочены к глубинам от 1000 до 4700 *м*. Распределение по площади зависит от рельефа и геоморфологических особенностей дна. Меньше всего раковин на материковом шельфе. На материковом склоне, подводных хребтах, горах, поднятиях и на ложе океана до глубин 4500—4700 *м* отмечены максимальные концентрации. На дне глубоководных котловин (глубже 4500—4700 *м*) планктонные фораминиферы встречаются редко и в малых количествах независимо от концентрации их в толще воды. Объясняется это тем, что на этих глубинах раковины растворяются.

11. Отмечается связь между количественным распределением видов в воде и осадках на глубинах менее 4500—4700 *м*. Виды, образующие большие скопления в воде, и в осадках дают высокие концентрации. Виды, редкие и малочисленные в воде, не создают высоких концентраций и на дне. Широтные границы распределения видов в толще воды и в осадках совпадают. Ареалы распространения отдельных видов в воде в большинстве случаев непрерывные, а в осадках — прерывистые из-за растворения раковин отдельных видов. Характер и границы ареалов в осадках зависят не только от распределения вида в воде, но и от рельефа дна.

12. Среди планктонных фораминифер только немногие виды имеют узкие ареалы распространения, большинство отмечено во всех широтах. В то же время количество, содержание вида по отношению ко всей фауне фораминифер и частота встречаемости на разных широтах сильно варьируют, достигая максимальных значений в условиях, благоприятных как для жизни, так и для захоронения. При широких ареалах распростране-

ния планктонных фораминифер количественные оценки являются надежными критериями для выделения танатоценозов.

13. Распределение отдельных видов планктонных фораминифер на дне дает возможность выделить три основных танатоценоза (холодноводных видов, видов умеренных широт и тропических видов) и два переходных (см. рис. 11). Количество видов в танатоценозах увеличивается с юга на север. Наибольшее число их отмечено в тропическом танатоценозе, а максимальные концентрации приурочены к району распространения видов умеренных широт.

14. Границы основных танатоценозов совпадают с границами основных биоценозов (см. рис. 11). На глубинах до 4500—4700 *м* почти полностью совпадает также видовой состав и процентное содержание видов внутри био- и танатоценозов. На дне глубоководных котловин, происходит растворение раковин. Поэтому наиболее легко растворимые виды (род Hastigerina) на больших глубинах в осадках не встречаются. Большинство видов (Globorotalia menardii, Sphaeroidinella dehiscens, Globorotalia tumida и др.) растворяются лишь частично и встречаются в виде обломков, определимых до вида. Наиболее устойчивы к растворению Pulleniatina obliquiloculata, Globigerina inflata и др.

В общем по видовому составу и соотношению отдельных видов в танатоценозе можно судить о соответствующем биоценозе и условиях его жизни (палеобиогеографическая зона, водная масса, температура и т. д.), а также и об условиях захоронения (глубина, рельеф).

15. Данные о распределении планктонных фораминифер в водной толще и в осадках Индийского океана могут быть использованы при дальнейшем изучении стратиграфии донных отложений и восстановлении палеогеографических условий геологического прошлого. Изучив условия жизни и захоронения современных фораминифер, можно решать и обратную задачу — по танатоценозам восстанавливать условия в соответствующих биоценозах. Математическая обработка материалов из более древних отложений обеспечит большую надежность палеогеографических построений.

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DISTRIBUTION OF PLANKTONIC FORAMINIFERA IN THE WATER AND ON THE FLOOR IN INDIAN OCEAN

Planktonic foraminifera were examined from 286 bottom samples and over 400 plankton samples in the Indian ocean. The quantitative distribution of the more common planktonic species in the water masses and sediments of ocean are plotted.

The planctonic foraminifera in the water of Indian ocean were grouped into five biocoenoses cold-water (Coast West Current water mass, $t° = 0°$ C, $S = 34{,}5‰$), transitional (East drift water mass, $t° = 0°$C, $S = 34{,}5‰$), temperature (water mass of temperate latitude $t° = -1° - +10°$ C, $S = 33{,}72—35{,}70‰$), transitional (Central water mass, $t° = 10—23°$ C, $S = 34{,}7 — 35{,}7‰$), tropical (Equatorial water mass, $t° = 14—28°$ C, $S = 35{,}1—36{,}5‰$). Five tanatocoenoses were established on the bottom of ocean respectively.

PRELIMINARY RESULTS OF THE 1964 CRUISE OF R/V CHAIN TO THE INDIAN OCEAN

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Synopsis

Geophysical investigations of the northern Somali Basin and the Seychelles-Mauritius Ridge conducted aboard R/V CHAIN of the Woods Hole Oceanographic Institution are described and some results presented. Gravitational and total magnetic fields and bathymetry were measured continuously, and continuous seismic reflection profiles were recorded over a major portion of the track. Cores, dredge samples, heat flow measurements, and underwater photographs were also obtained.

It is considered that the northern portion of the Somali Basin is a deep sedimentary basin partially enclosed to the east by a submarine ridge from which alkaline gabbro has been dredged and to the south by partially buried abyssal hills.

On the evidence from seven crossings of the Seychelles-Mauritius Ridge, it is proposed that the Ridge comprises two sections. The northern section, composed of nearly horizontally stratified rocks, extends from near the northern part of Saya de Malha Bank to the Seychelles Platform. The southern section is a linear, probably volcanic ridge that extends from north of Mauritius through Saya de Malha Bank, and may continue as a subsurface feature to the northeast. The two sections abut near Saya de Malha Bank, forming a continuous topographic feature.

Preliminary Results of the 1964 Cruise of R/V CHAIN to the Indian Ocean

by

Elizabeth T. Bunce, C. O. Bowin and R. L. Chase

A broad area of the northwest Indian Ocean was investigated during April and May 1964 on a voyage of R/V CHAIN (figure 1). This report presents preliminary results and some conclusions concerning structural relationships for two particular areas: the northern Somali Basin and the Seychelles-Mauritius Ridge.

Underway observations discussed here are measurements of free-air gravity anomaly and total intensity magnetic field with a LaCoste-Romberg gravimeter and proton magnetometer respectively, bathymetric profiles determined by precise echo-sounding, and continuous seismic profiling (spark source) to record the deeper sub sea-floor structure (Hersey, 1963). Cores, dredge samples, and underwater photographs also contribute to the findings.

Northern Somali Basin

A number of traverses were made across Owen Ridge, near the eastern border of the northern Somali Abyssal Plain. The traverses were planned to determine whether separated hills or sea mounts shown on an earlier version of the diagram of figure 1 are instead part of a ridge and to investigate the associated magnetic anomaly. The ridge was traced as a topographic feature of 1000 to 1700 fms relief above the abyssal

plain as far south as 3°30' north latitude. The magnetic anomaly associated with the ridge is lower than would be expected for a recent volcanic feature. This interpretation is reinforced by samples of alkaline gabbro, a rock of deep seated origin, dredged from the southeastern slope of the ridge between the depths indicated at 5.75 and 6.75 sec reflection travel time (figure 2, d).

Profiles of the total-field magnetic intensity, free-air gravity anomaly, and sub sea-floor structure of the continental rise south of Socotra and of the Somali abyssal plain as far south as Owen Ridge are shown in figure 2. The significant departures from regional trends are a magnetic anomaly of 300 gamma associated with the subbottom structure (a), the increase in the negative free-air anomaly over the deep, uniform layers of the abyssal plain (b), and the relatively low amplitude magnetic anomaly over the northwestern slope of Owen Ridge (c).

Echo soundings made with very short pulses reveal sequences of thinly layered sediments at the top of the subbottom sequence which are continuous over great distances on the continental rise (figure 3, top) and on the abyssal plain to the south. The deeper structure of the northern basin, which extends as far south as Owen Ridge, is shown by the seismic reflection profile. Flat uniform layers 2 seconds of travel time below seabottom are evident. A photograph of a portion of the original record, obtained over the continental rise, is shown in figure 3 (bottom).

There is a marked difference between the subbottom structure north and south of Owen Ridge. The topography to the south is slightly rougher than to the north, although some shallow stratification occurs between small hills (50-200 fm) rising above the bottom. A reflection more or less continuous at 0. 25 second after the bottom echo is shown on the reflection profiles, but the deep echoes from uniform reflectors similar to those of the northern part of the basin are not present. Instead, echoes suggesting a rough reflecting surface at an average delay of 1 second after the sea bottom echo, with relief of 0. 5 second or greater, suggests buried and partially buried hills. The section resembles those found in areas of abyssal hills in the North Atlantic.

It appears that the northwest portion of the Somali Basin is a deep sedimentary basin partially enclosed to the east by Owen Ridge and to the south by buried and exposed abyssal hills. Corroboration of this hypothesis is furnished by seismic reflection profiles recorded during two traverses made by R/V VEMA of Lamont Geological Observatory (Langseth, personal communication, 1964). The VEMA profiles show the structure west of Owen Ridge to be the same as that to the north, already described, while to the southwest it resembles the section of abyssal hills. These structures to the south may be an extension of the Ridge.

The Seychelles-Mauritius Ridge

Seven crossings were made of the ridge lying between the Seychelles Islands and the island of Mauritius. The bearings of the crossings vary, some being less normal to the trend of the Ridge than others.

The profiles of figure 4 present sections across the northern part of the Ridge, from the Seychelles Platform to Saya de Malha Bank. The effects of the regional gradient on total intensity magnetic field and those of topography on the free air gravity anomaly are clearly to be seen. A possible magnetic anomaly is associated with the Ridge or series of hills which rise from the western slope of the central Ridge. This anomaly is small on profile 1 but more distinct on profiles 2 and 3.

The seismic reflection profiles over the central Ridge on the three northern crossings (profiles 1-3) although not presented in figure 4, show rather uniform echo sequences suggesting sub sea-floor layering. The echoes arrive up to 0.5 sec after the bottom echo.

In profile 4, across the northern section of Saya de Malha Bank, and in the three profiles to the south of it shown in figure 5 the central part of the Ridge has relatively steep slopes and a flat top. The seismic reflection records contain no evidence that the flat top is underlain by flat lying sediments: although the water depth is shallow, the bottom reflects

sound so poorly here that only one multiple of the bottom reflection is detectable on the records, and it would be possible to detect flat lying subbottom reflectors if they existed.

In the three southern profiles (nos. 5-7, figure 5), as on Saya de Malha Bank, there is no seismic reflection evidence for layering of the flat, high central part of the Ridge. However, reflecting horizons with echo delays as great as 0.65 sec beyond the bottom echo can be traced east and west up the flanks of the ridge to the 1000- or 700-fathom level on each of these crossings. Therefore it is tentatively concluded that the flat top is a product of erosion, not deposition. The fourth magnetic profile shows no high intensity anomaly over the central part of the Ridge. The corresponding gravity profile and others to the south are incomplete because rough seas encountered in this area prevented uninterrupted operation of the gravimeter.

The high amplitude magnetic anomalies associated with the center of the flat top of the Ridge in profile 7 and with its western edge in profiles 5 and 6 are in contrast with those of relatively low amplitude in profile 4.

Profile 7, shown again in figure 6, presents the structure shown by the seismic reflection record. The distinctive feature is the layering suggested beneath the lower eastern part of the Ridge by echo sequences at 1.75 sec (700 fm) water depth. A layered section of the same thickness is suggested by the seismic records at the foot of the eastern slope of the

Ridge, at a depth of over 2000 fathoms. Thus the eastern slope of the Ridge in this area may be a zone of faulting. It is also possible, however, that the higher layered sequence consists of sediments derived from the central part of the Ridge, and, further, that the deeper sequence is not related to it, but is derived from the area south of the Ridge (figure 1), or from elsewhere.

Twenty-five dredge lowerings were made, on and along the flanks of the Seychelles-Mauritius Ridge. Except for one small piece of granite SE of Seychelles Platform and one pebble of volcanic (?) rock obtained northeast of Saya de Malha Bank, all the samples obtained are limestone, coral fragments, or calcareous sand whose foraminifera have been identified as Recent by Dr. Wm. A. Berggren (personal communication, 1964).

Figure 4 shows a portion of a mosaic of underwater photographs covering about a half mile of the southwest slope of Saya de Malha Bank at 1100 fathoms depth. The mosaic shows quite clearly that a considerable area of the bottom consists of outcrop of nearly horizontally layered rocks. In light of the dredged material these rocks are considered to be limestone. Ripple marks indicate current activity at this depth.

Discussion

It is reasonable to postulate that the northern part of the Seychelles-Mauritius Ridge is structurally different from the southern part. In the former, layered structures, probably sedimentary in origin, occur beneath the central part of the Ridge. No evidence for sedimentary layering is found on Saya de Malha Bank nor beneath the central part of the Ridge to the south. The magnetic anomalies associated with the northern Ridge (figure 4, profiles 1-3) are weaker than those to the south and are apparently associated with a local structure, a small topographic high near or on the western margin of the Ridge. South of Saya de Malha Bank magnetic anomalies of 400 gamma or greater are associated with the western margin of the Ridge and with the central portion south of Cargados Carajos Shoals (figure 5, profiles 5-7). Shor and Pollard, (p. 49, 1963), in a discussion of seismic refraction data from the Seychelles and Saya de Malha Banks, suggested that the difference between the two areas might be explained by the presence of a "linear volcanic ridge (similar to the Hawaiian Ridge) extending from Mauritius through Cargados Carajos shoals to Saya de Malha Bank, caused by volcanic outpourings from a line of weakness in the ocean floor." They further suggested that the line continues north and passes close to the Seychelles granitic block, a feature probably much older. The hypothesis is presented here that the magnetic

anomaly over the center of Cargados Carajos shoals is continuous with those observed along the western margin of the Ridge as far north as Saya de Malha Bank and is indicative of the trend of a linear feature, probably younger than the Ridge, and possibly representing a more recent zone of weakness and volcanic outpouring. Further, the presence of layered structure on the northern part of the Ridge argues sedimentary origin, older than the volcanic section to the south.

It would be interesting to explore the possibility that the hypothesized younger volcanic ridge structure trends northeast, abuts the sediment covered feature extending south from the Seychelles platform, thus forming an apparently homogeneous topographic feature, and passes east of the older granitic structure, or alternatively that it continues along the arcuate line of the Ridge, becoming more deeply buried to the north, as far as the Seychelles Platform.

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LEGEND OF FIGURES

Figure 1: Physiographic Diagram of Northwest Indian Ocean (Heezen and Tharp, 1964) showing track of R/V CHAIN.

Figure 2: Northern Somali Basin: Continental Rise and Abyssal Plain. Total intensity magnetic field, free air gravity anomaly, and seismic reflection profiles.

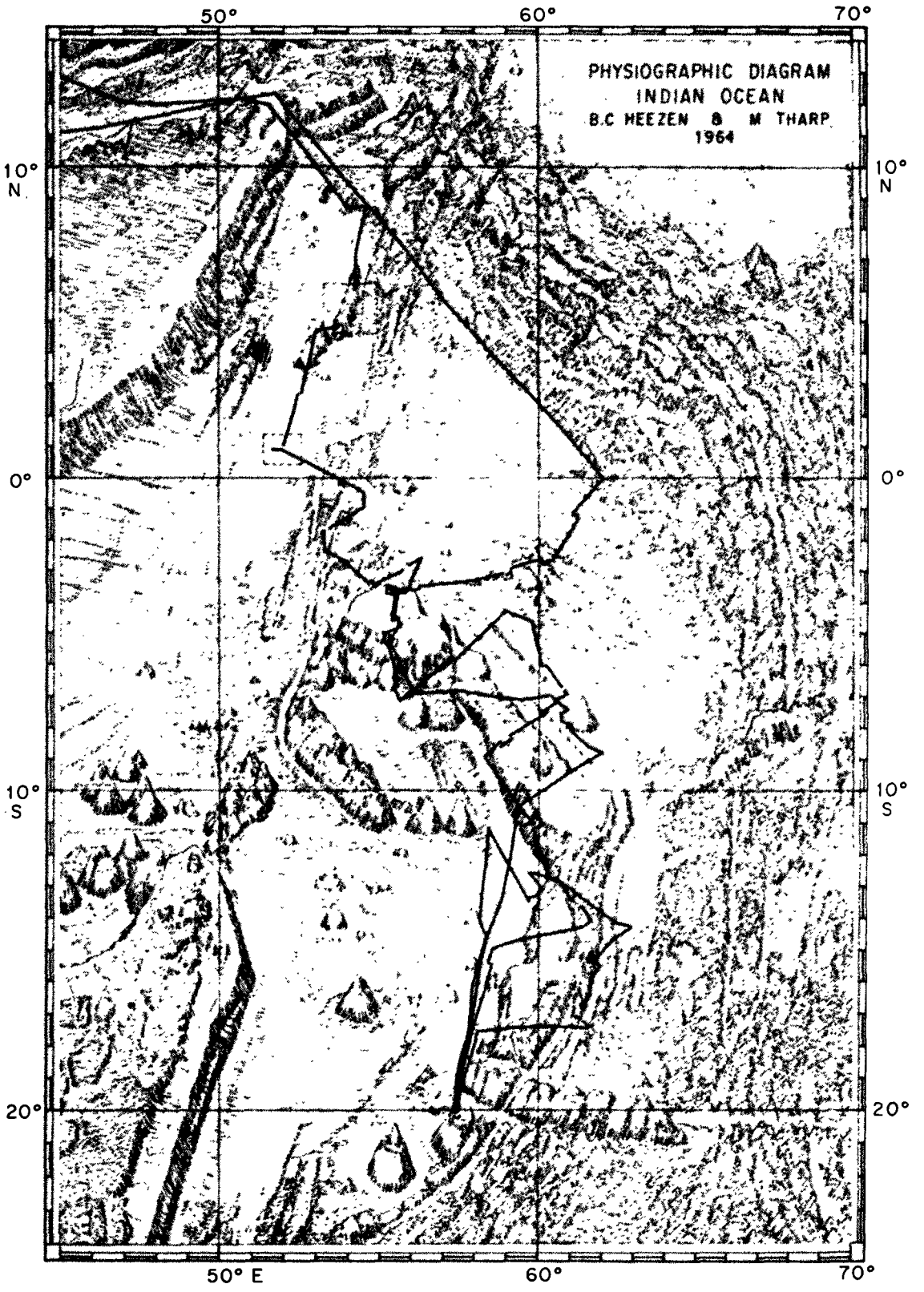
Figure 3: Somali Abyssal Plain: Echo sounding record (top) and Reflection profile (bottom).

Figure 4: Seychelles-Mauritius Ridge: Profiles immediately south of Seychelles Platform to north part of Saya de Malha Bank. Total intensity magnetic field, free air gravity anomaly, and bathymetry.

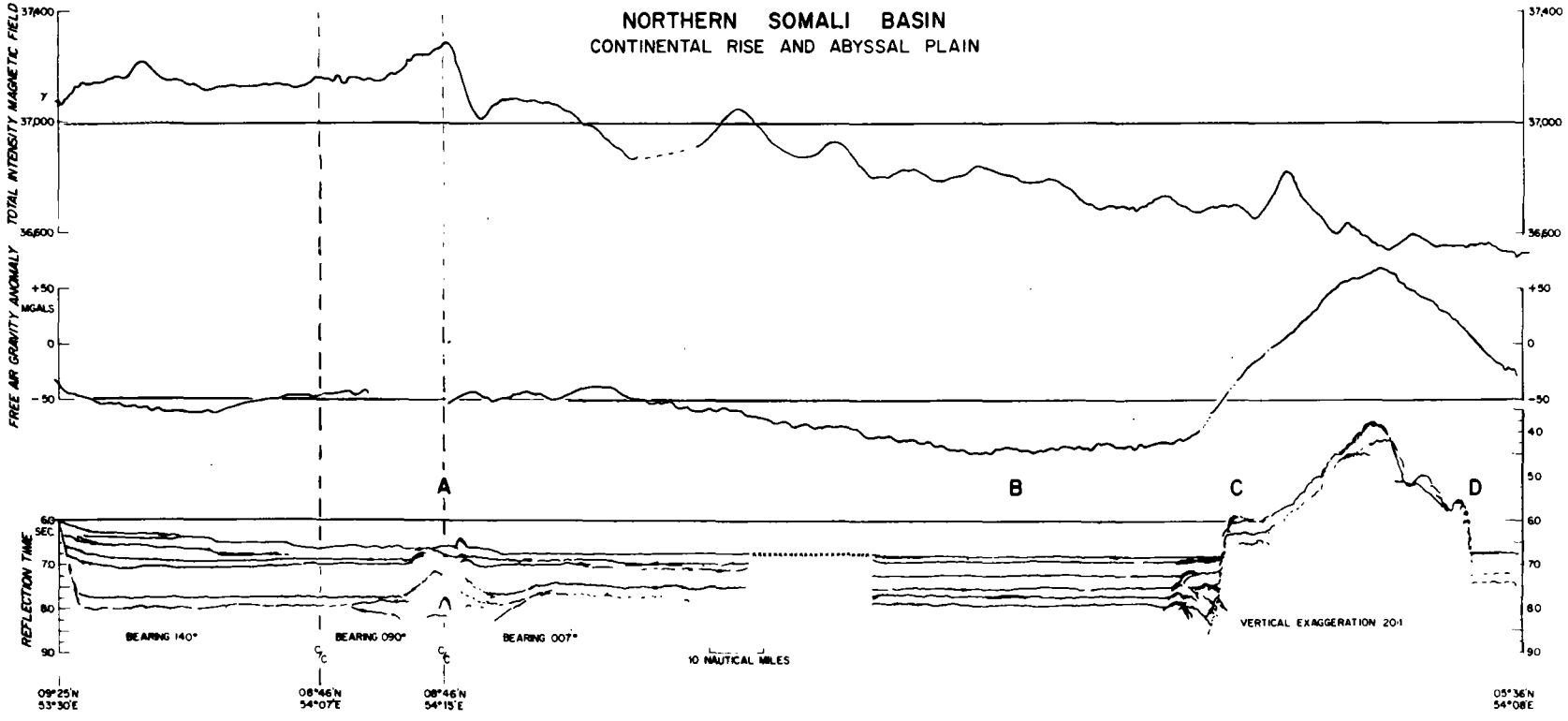
Figure 5: Seychelles-Mauritius Ridge: Profiles south of Saya de Malha Bank to south of Cargados Shoals. Total intensity magnetic field, free air gravity anomaly, and bathymetry.

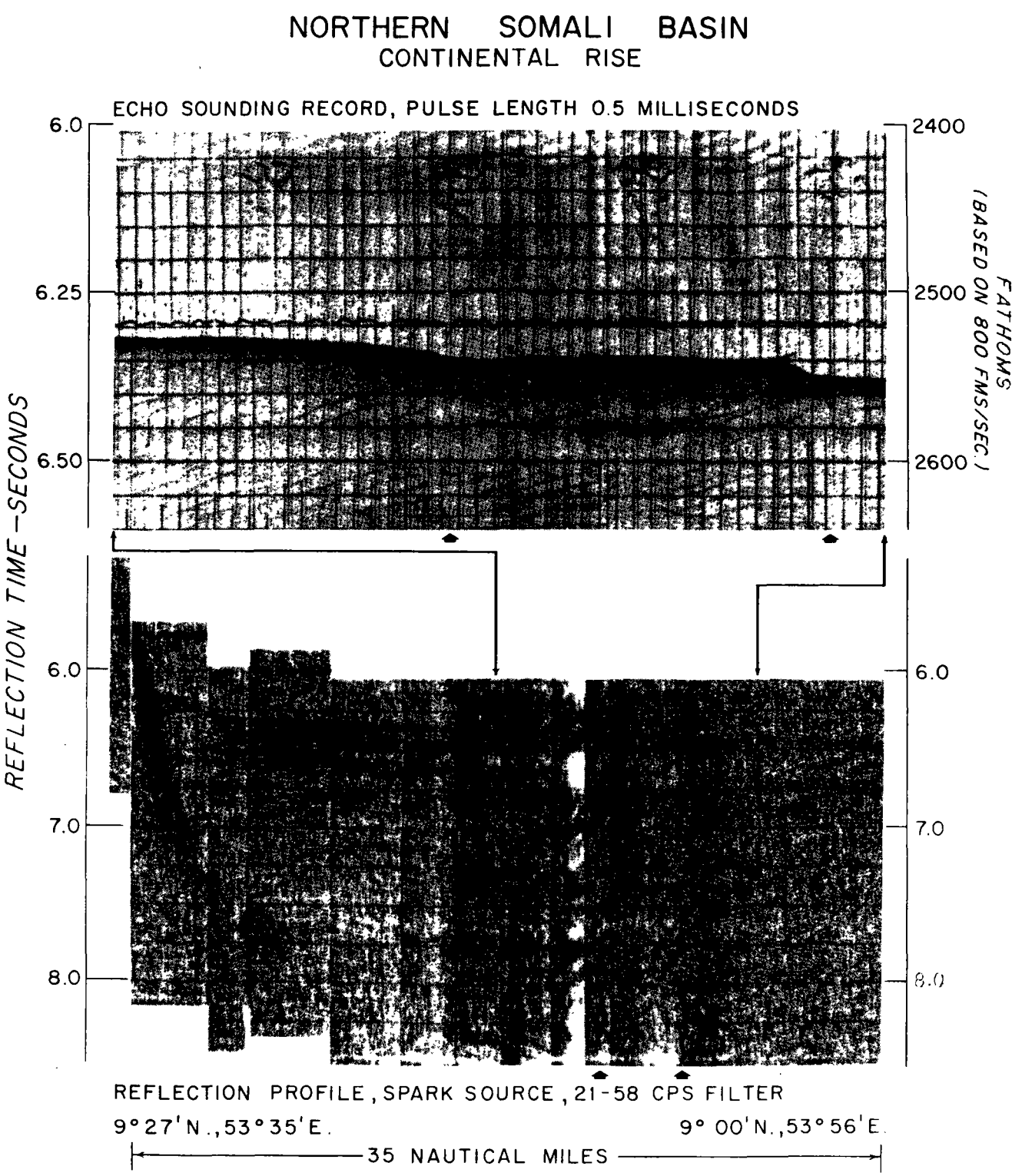
Figure 6: Seychelles-Mauritius Ridge: South of Cargados Carajos Shoals. Total intensity magnetic field, free air gravity anomaly, and seismic reflection profiles.

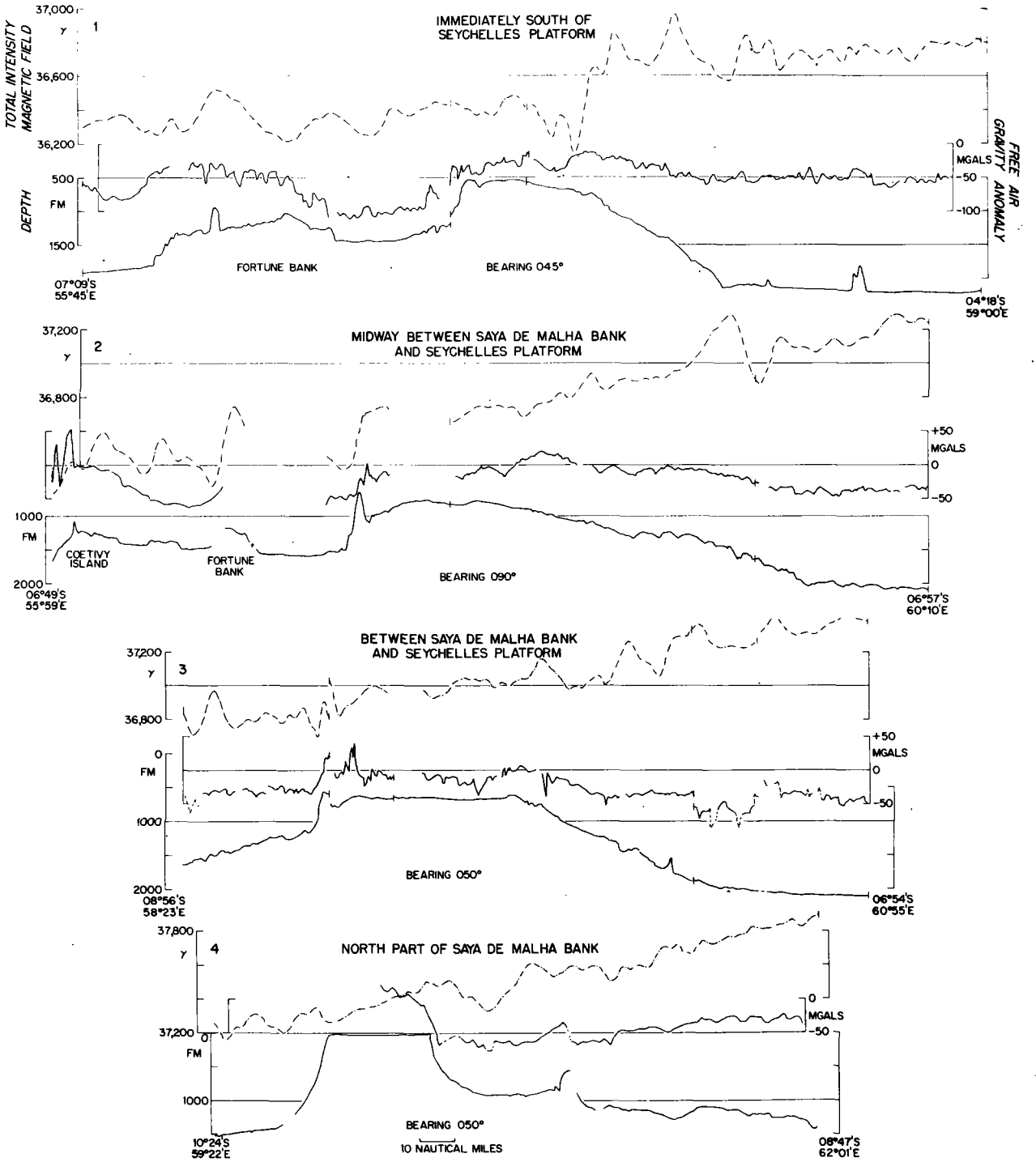
Figure 7: Mosaic of underwater photographs; western slope of the Seychelles-Mauritius Ridge at Latitude 8°30'S, Longitude 58°51'E, water depth 1100 fathoms.

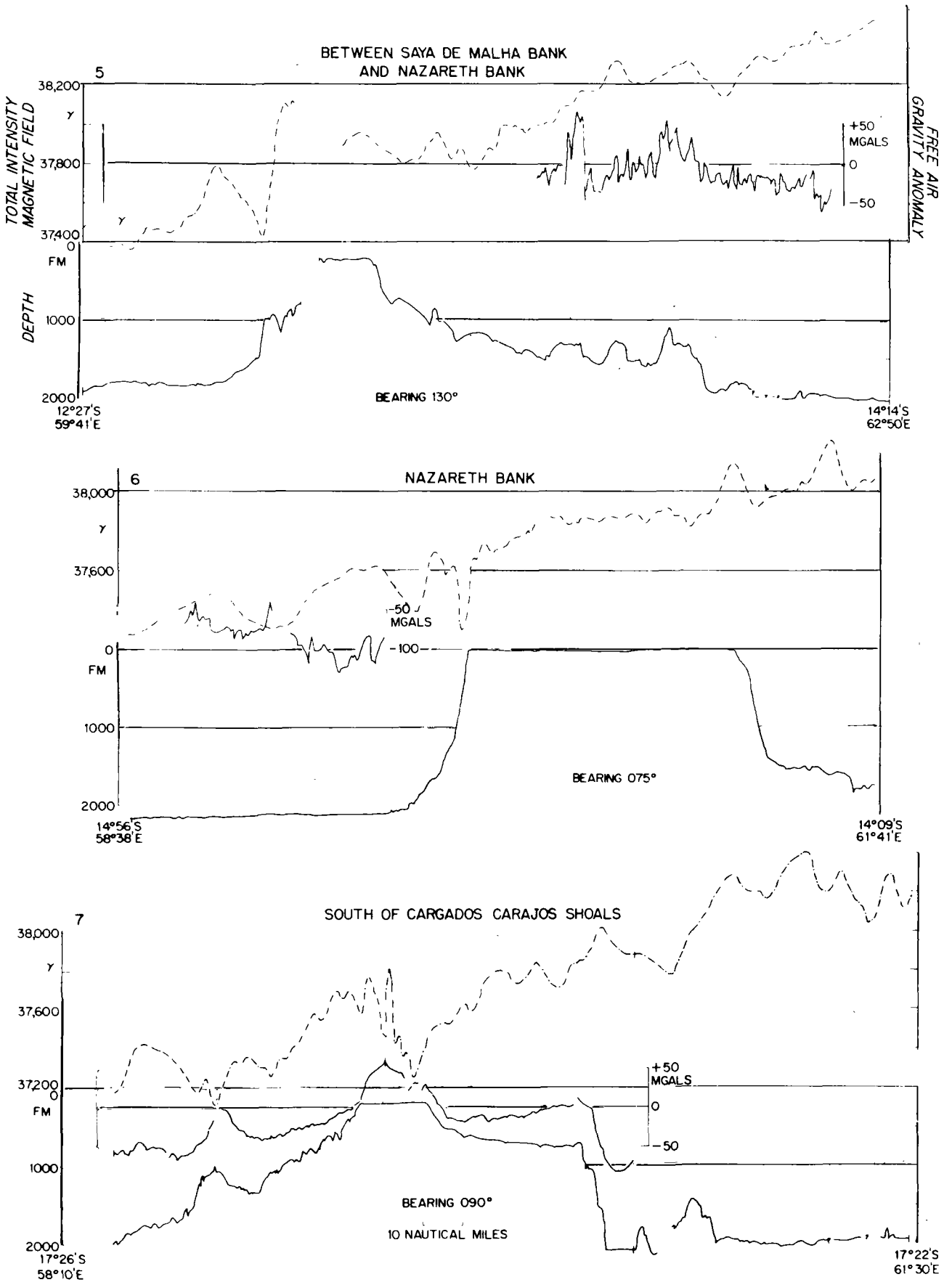


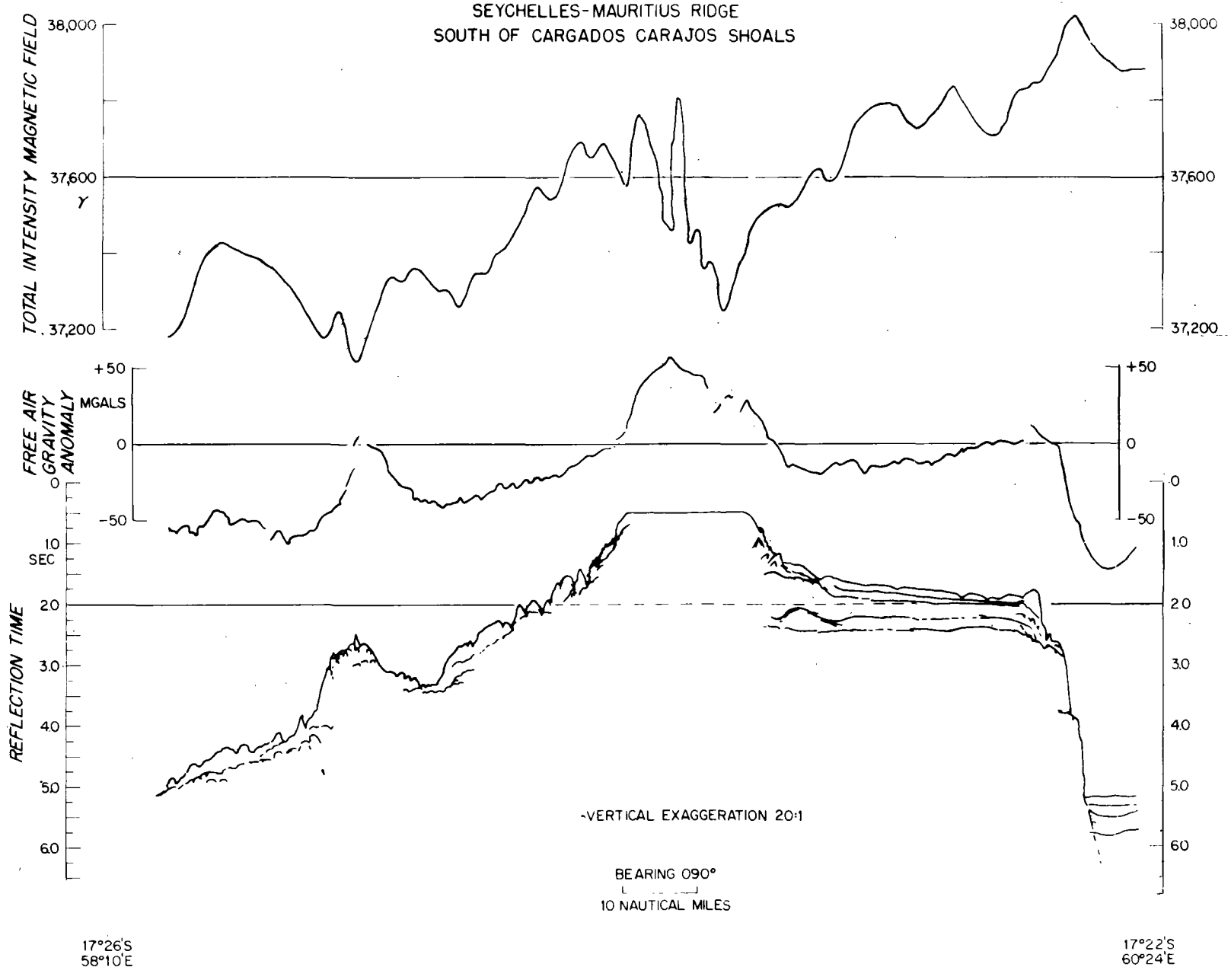
CHAIN 43 — INDIAN OCEAN
31 MARCH — 3 JUNE 1964

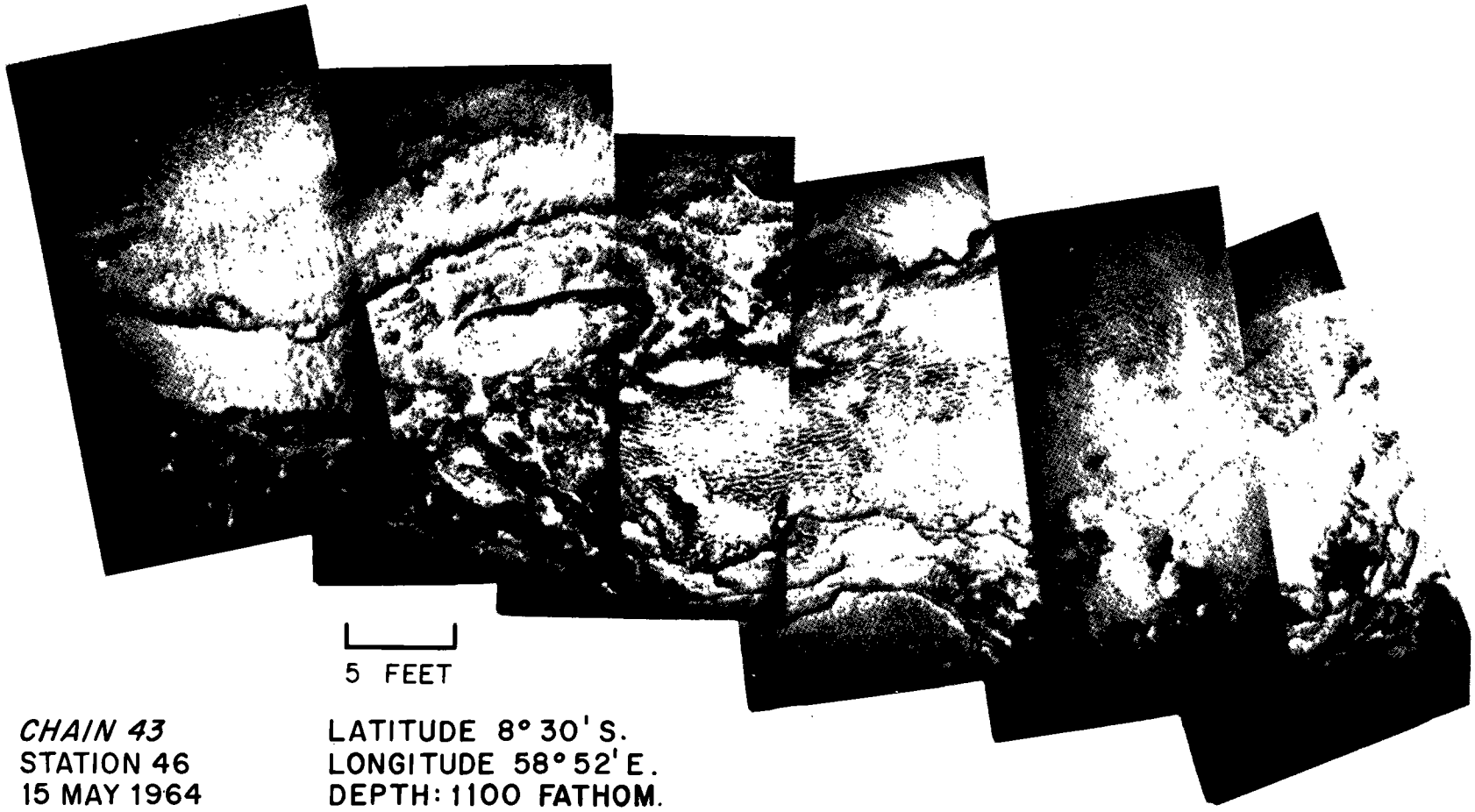

NORTHERN SOMALI BASIN
CONTINENTAL RISE AND ABYSSAL PLAIN
TOTAL INTENSITY MAGNETIC FIELD
37,400
γ
37,000
36,600
FREE AIR GRAVITY ANOMALY
+50
MGALS
0
-50
REFLECTION TIME
SEC.
A
B
C
D
BEARING 140°
BEARING 090°
BEARING 007°
10 NAUTICAL MILES
VERTICAL EXAGGERATION 20:1
09°25'N
53°30'E
08°46'N
54°07'E
08°46'N
54°15'E
05°36'N
54°08'E


NORTHERN SOMALI BASIN
CONTINENTAL RISE
ECHO SOUNDING RECORD, PULSE LENGTH 0.5 MILLISECONDS
6.0
6.25
6.50
2400
2500
2600
FATHOMS (BASED ON 800 FMS/SEC.)
REFLECTION TIME—SECONDS
6.0
7.0
8.0
6.0
7.0
8.0
REFLECTION PROFILE, SPARK SOURCE, 21-58 CPS FILTER
9°27'N., 53°35'E.
9° 00'N., 53°56'E.
35 NAUTICAL MILES


37,000
γ
1
TOTAL INTENSITY MAGNETIC FIELD
36,600
36,200
IMMEDIATELY SOUTH OF SEYCHELLES PLATFORM
0
MGALS
-50
-100
FREE AIR GRAVITY ANOMALY
DEPTH
500
FM
1500
FORTUNE BANK
BEARING 045°
07°09'S
55°45'E
04°18'S
59°00'E
37,200
γ
2
MIDWAY BETWEEN SAYA DE MALHA BANK AND SEYCHELLES PLATFORM
36,800
+50
MGALS
0
-50
1000
FM
COETIVY ISLAND
FORTUNE BANK
BEARING 090°
2000
06°49'S
55°59'E
06°57'S
60°10'E
37,200
γ
3
BETWEEN SAYA DE MALHA BANK AND SEYCHELLES PLATFORM
36,800
0
FM
+50
MGALS
0
-50
1000
BEARING 050°
2000
08°56'S
58°23'E
06°54'S
60°55'E
37,800
γ
4
NORTH PART OF SAYA DE MALHA BANK
0
MGALS
-50
37,200
0
FM
1000
BEARING 050°
10 NAUTICAL MILES
10°24'S
59°22'E
08°47'S
62°01'E


5
BETWEEN SAYA DE MALHA BANK
AND NAZARETH BANK
TOTAL INTENSITY
MAGNETIC FIELD
38,200
γ
37,800
γ
37,400
+50
MGALS
0
−50
FREE AIR
GRAVITY ANOMALY
0
FM
DEPTH
1000
2000
BEARING 130°
12°27'S
59°41'E
14°14'S
62°50'E
6
NAZARETH BANK
38,000
γ
37,600
−50
MGALS
0
−100−
FM
1000
2000
BEARING 075°
14°56'S
58°38'E
14°09'S
61°41'E
7
SOUTH OF CARGADOS CARAJOS SHOALS
38,000
γ
37,600
37,200
+50
MGALS
0
0
FM
−50
1000
BEARING 090°
10 NAUTICAL MILES
2000
17°26'S
58°10'E
17°22'S
61°30'E


SEYCHELLES-MAURITIUS RIDGE
SOUTH OF CARGADOS CARAJOS SHOALS
TOTAL INTENSITY MAGNETIC FIELD
38,000
37,600
γ
37,200
FREE AIR GRAVITY ANOMALY
+50
MGALS
0
-50
REFLECTION TIME
0
1.0
SEC
2.0
3.0
4.0
5.0
6.0
VERTICAL EXAGGERATION 20:1
BEARING 090°
10 NAUTICAL MILES
17°26'S
58°10'E
17°22'S
60°24'E



CHAIN 43
STATION 46
15 MAY 1964

LATITUDE 8° 30' S.
LONGITUDE 58° 52' E.
DEPTH: 1100 FATHOM.

WESTERN SLOPE-SEYCHELLES MAURITIUS RIDGE

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Sea Bottom Heat-Flow Measurements in the Andaman Sea

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The participation of the USC&GSS *Pioneer* in the International Indian Ocean Expedition included a major geophysical investigation of the Andaman Sea during April and May of 1964. A program of heat-flow measurements was motivated by known volcanism within the basin, indications of warmer bottom water than can be explained by simple adiabatic heating, and a general lack of data on the major seismic belt that runs through the Andaman-Nicobar area from Burma into Sumatra.

As part of operations in the area, four successful measurements were made of the heat flow associated with the inner or volcanic trend of the primary arc that encloses the Andaman Sea. A modified form of the thermograd [*Gerard et al.*, 1962] was used to obtain a recording of the temperature gradient in the bottom sediment and a core, from which the coefficient of thermal conductivity of the bottom sediment can be determined. The heat flow defined here is a flow per unit area; it is determined as the product of the temperature gradient in the bottom sediment and the thermal conductivity of the sediment.

The temperature gradient in the sediment is determined by three thermistors fastened to the barrel of a coring tube at a fixed vertical separation of 104 cm. The thermistors are switched into a Wheatstone bridge circuit in alternating sequence with fixed-calibration resistors. The temperature at the penetration depth of each thermistor is determined as a function of the current flow in the bridge circuit, which is recorded on film.

The thermistors were calibrated both before and after the operation in the Andaman Sea. On the basis of these two calibrations, an error in absolute temperature of 0.05°C could be present in the measurements. However, an additional calibration of the thermistors was made at each station by comparing the thermistor-indicated temperatures of the near-bottom water both before and after the coring device penetrated the bottom. The maximum range of indicated temperatures in these comparisons was 0.02°C. Hence, the temperatures used to determine the temperature gradient in the sediment are considered to be precise within ±0.02°C. The separation of the thermistors is known to within 1%.

Since equipment was lacking to make direct measurements of the thermal conductivity of sediment from the core [*Von Herzen and Maxwell*, 1959], an indirect determination based on the water content of the core sample was used [*Ratcliffe*, 1960]. Sections were cut from the core at positions corresponding to the location of the thermistors. These samples were then capped and sealed with paraffin. Subsequently, the mean value of thermal conductivity was determined for each station on the basis of water content of the samples and on corrections for bottom temperature and pressure. Special precautions were taken during the procedure to prevent drying of the sediment sample, which might result in related errors in the conductivity values. Such errors are difficult to evaluate, but higher water content in the in situ sediment samples would result in lower values of thermal conductivity than those given in this report. Examination of the thermal conductivity values indicates that they are comparable at the four stations and are lower than the average reported from other areas [see for example *Foster*, 1962; *Uyeda et al.*, 1962; *Von Herzen and Uyeda*, 1963; *Yasui et al.*, 1963]. At each of the stations in the Andaman Sea, all determinations of thermal conductivity were within ±10% of the mean value listed for the station.

The heat flow measured at the four stations in the Andaman basin is shown in Table 1.

Although significant regional interpretation of the limited data is hardly possible, several observations of interest are noted:

TABLE 1. Heat-Flow Measurements in the Andaman Basin

Station No.	Location	Depth, m	Temperature Gradient*	Thermal Conductivity†	Heat Flow‡
A-I	10°01′N 93°45′E	4206	31	1.70	5.27
A-II	11°01′N 93°42′E	2562	13	1.83	2.38
A-III	11°56′N 93°22′E	1390	5	1.79	0.90
A-IV	12°44′N 93°58′E	2151	11	1.76	1.94

* 10^{-4} °C cm^{-1}.
† 10^{-3} cal $°C^{-1}$ cm^{-1} sec^{-1}.
‡ 10^{-6} cal cm^{-2} sec^{-1}.

1. The highest heat flow is associated with the deepest portion of the basin (station A-I), and, for the measurements available, it correlates with depth. *Von Herzen and Uyeda* [1963] considered the effect of irregular rock surface buried by sediments and proposed that heat from the interior will flow out preferentially from the thinly covered areas. The deep basin at station A-I would normally be expected to have relatively thick sedimentary fill and consequently a relatively low heat flow. The fact that the heat flow is high indicates a possible lack of thick sedimentary fill in the deeper portions of the Andaman basin.

2. There is no apparent effect reflecting the volcanism at Barren Island (12°16′N, 93°50′E).

3. Initial conclusions on the relationship of heat flow to island arcs [*Uyeda et al.*, 1962; *Yasui et al.*, 1963] have been based on traverses generally normal to the structural trend. The measurements in the Andaman Sea are, on the other hand, all parallel to the major Indonesian primary arc system and have as great a variability as those on which these initial conclusions have been based.

These considerations indicate that the systematic collection of many more heat-flow measurements will be required if the relationships between heat flow and the tectonic patterns and geophysical processes of island-arc structures are to be more fully understood.

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THE SEISMICITY OF EAST AFRICA, THE GULF OF ADEN AND THE ARABIAN AND RED SEAS

By Lynn R. Sykes and Mark Landisman

ABSTRACT

Maps of earthquake epicenters are presented for East Africa, the Gulf of Aden and the Arabian and Red Seas for the period January 1955 to March 1964. Many of these epicenters were located with an accuracy of about 10 km; errors of 100 km or more were common in previous studies.

Several tectonic features can be resolved with the new epicenters. In the Gulf of Aden and in the Arabian Sea, the epicenters are confined to narrow linear segments. A large fracture zone that intersects the mid-oceanic ridge near 58°E is clearly delineated with the new epicenters. In the Gulf of Aden regions of high seismic activity are found where NNE-SSW trending faults intersect the median ridge. The seismic activity in the Red Sea is less than that in the Gulf of Aden and the Arabian Sea.

A large number of the earthquakes in East Africa are associated with various branches of the rift system. However, many well-recorded earthquakes were not located along the rift valleys. The large areal extent of seismic activity in East Africa differs from the narrow linear pattern of activity that is associated with the mid-oceanic ridge.

Introduction

During the last decade the detection and location of earthquakes in Africa and adjacent areas has improved significantly. The establishment of several new seismograph stations and the use of more precise computational methods have contributed substantially to the detection and location of seismic events in these regions. The number of earthquakes recorded in the past ten years is comparable to the total number of events detected in the previous fifty years. In addition, the epicenters of the more recent earthquakes can be located with an accuracy of about 10 to 20 km. Tectonic features with dimensions as small as a few tens of kilometers may be resolved with the new epicentral locations. Errors in location of 100 km or more were common in many previous studies of earthquakes in East Africa and the Indian Ocean.

The refined epicentral locations reported in this paper may be used to investigate the relationship between the seismicity and large-scale geological phenomena such as faults, fracture zones, the mid-oceanic ridges and the East African rift valleys. One feature of particular interest is the relationship of the mid-oceanic ridge to the rift valley system in East Africa. Similarities and differences in the seismicity of these two geological structures will be explored in this paper.

In oceanic areas precise epicentral locations may be used effectively in conjunction with bathymetric profiles. Bathymetric data suggest that several large faults are present in the Gulf of Aden and in the Arabian Sea (Matthews, 1963; Heezen and Tharp, 1964). These faults are clearly delineated by the new epicentral data.

The Location of Epicenters

All well recorded earthquakes for the period January 1955 to March 1964 in East Africa, the Gulf of Aden and the Arabian and Red seas were relocated by minimizing the residuals of the times of P and PKP. All earthquakes with five

or more consistent readings of P were reanalyzed using a computer program similar to the one described by Bolt (1960). The *Bulletin Mensuel* of the Bureau Central International de Séismologie was the principal source of arrival time information. Supplementary data were obtained from the *International Seismological Summary*, from the *Seismological Bulletin* and the cards (*Preliminary Determination of Epicenters*) of the US Coast and Geodetic Survey (USCGS), and from the seismological bulletins of Addis Ababa, Ethiopia, and the Institut pour la Recherche Scientific en Afrique Centrale (IRSAC), Republic Congo. More than 100 observations were used in relocating some of the larger earthquakes.

The relocated epicenters in the Arabian Sea, the Gulf of Aden and the Red Sea are listed in table 1. One additional epicenter in 1954 is also included in this table. Epicenters in East Africa are presented in table 2. The epicentral locations are shown in figures 1 and 2.

Focal Depth. A surface focus was assumed in all of the computations. This restraint on the depth was necessary since most of the seismograph stations were located at teleseismic distances and because the depths computed from reports of $pP - P$ often were not consistent with one another. However, the relative amplitudes of body and surface waves and the distribution of isointensity lines (Sutton and Berg, 1958) indicate that the earthquakes examined in this paper have a shallow focal depth (i.e., less than 70 km).

Accuracy of Epicentral Locations. The accuracy of the computer program was checked using P wave readings from three well recorded nuclear explosions in the Southwest Pacific during 1954. The errors relative to the locations released by the Atomic Energy Commission are shown in table 3. Errors in the computed positions of nuclear explosions were reported by Bolt (1960) and by Gunst and Engdahl (1962). More than 50 observations were used for each of the computations made by the USCGS (Gunst and Engdahl, 1962); the present authors used the same readings. For the three nuclear explosions accuracies of about 5 km were obtained when 50 or more observations were employed. With 19 readings Bolt (1960) estimated the location of the BRAVO event to within 10 km.

Herrin and Taggart (1962) showed that the locations of epicenters may be in error by as much as 30 km if the solution is based upon readings at distances shorter than 15° or 20°. Stations at these distances were not used in locating the nuclear explosions cited above. Nearly all of the epicenters in the Arabian Sea, the Gulf of Aden and the Red Sea were determined using stations at distances in excess of 20°. Readings at shorter distances were available for most of the events in East Africa. Nonetheless, only the locations of the smaller earthquakes (less than 10 readings available) are heavily weighted by readings at distances shorter than 20°.

In Africa and adjacent regions the analysis of epicenters is often complicated by a disproportionally large number of stations to the north of the earthquakes. For several of these events the weights of the individual stations were recomputed such that the sum of the weights was the same for each quadrant. Nevertheless, the solutions obtained by this normalization rarely differed from the unnormalized computations by more than 10 km. For the nuclear explosions in 1954 the azimuthal distribution of stations was more uniform, and the two types of solutions did not differ by more than 2 km. Hence, for most of the earthquakes that were recorded by 10 or more stations, the accuracy of the epicentral locations is probably about

TABLE 1

EARTHQUAKES IN THE ARABIAN SEA, THE GULF OF ADEN AND THE RED SEA FOR THE PERIOD JANUARY 1955 TO MARCH 1964

Date	Origin Time			Lat.	Long.	S.E. Sec.	N	Mag	L
	H	M	S						
Apr. 11, 1954	10	25	21.5	10.81N	57.13E	2.34	121	5.8	1
Jan. 17, 1955	15	35	13.2	12.32N	46.02E	1.45	5		
Mar. 03, 1955	00	43	40.2	16.46N	41.29E	0.43	4		
Apr. 26, 1955	01	37	19.9	14.59N	56.34E	3.15	7		
Oct. 17, 1955	20	08	53.1	17.16N	43.65E	2.61	12		
Nov. 12, 1955	05	32	14.5	25.29N	34.58E	2.01	95	6.	1
*Jan. 29, 1956	03	39	07.9	16.54N	58.31E	0.55	4		
Jun. 25, 1956	20	10	18.5	20.31N	37.95E	1.78	12		
Dec. 11, 1956	16	52	56.2	05.58N	61.53E	1.74	22		
Mar. 14, 1957	00	11	33.0	14.80N	40.22E	1.34	13		
Apr. 12, 1957	15	58	43.5	11.54N	43.05E	1.45	12	5.0	1
Dec. 19, 1957	15	56	32.0	14.36N	53.44E	1.23	11		
Jan. 09, 1958	07	56	27.2	17.71N	40.12E	1.46	7		
Feb. 13, 1958	10	23	33.7	14.34N	42.00E	1.86	20		
May 24, 1958	22	25	32.6	12.17N	43.58E	1.70	9		
May 24, 1958	23	53	38.0	12.14N	43.59E	2.61	44	5.5	1
May 25, 1958	02	53	48.4	12.13N	43.69E	1.51	37	5.	1
Jun. 28, 1958	17	05	16.2	11.94N	45.44E	2.34	9		
*Nov. 04, 1958	05	06	11.6	14.08N	53.58E	1.12	9		
Nov. 13, 1958	23	19	22.2	14.97N	53.81E	3.18	13		
*Nov. 13, 1958	23	26	37.5	13.29N	53.74E	2.83	6		
Dec. 04, 1958	10	25	48.3	13.84N	51.70E	2.06	23		
Dec. 19, 1958	11	13	56.0	06.67N	60.23E	2.28	24		
Dec. 19, 1958	23	57	00.5	06.58N	60.27E	2.15	19		
Jan. 05, 1959	08	17	14.6	13.72N	51.61E	1.36	25		
Jan. 21, 1959	13	57	29.9	13.60N	51.76E	1.97	29		
Apr. 14, 1959	01	23	08.2	14.86N	56.50E	0.99	6		
Apr. 14, 1959	01	39	52.6	15.34N	56.21E	1.56	5		
Jun. 07, 1959	09	03	44.0	14.55N	53.70E	1.78	13		
Aug. 16, 1959	13	31	10.4	14.54N	43.14E	1.16	9		
Dec. 21, 1959	11	19	15.1	13.98N	51.71E	1.92	136	6.7	11
Dec. 22, 1959	00	09	39.8	13.95N	51.40E	2.47	53		
Jan. 04, 1960	06	07	55.1	11.50N	42.87E	1.96	8		
Jan. 04, 1960	06	16	30.9	11.55N	42.77E	1.45	22		
Mar. 25, 1960	09	45	40.4	12.12N	46.42E	1.78	21		
May 31, 1960	00	23	49.5	14.87N	54.56E	1.96	32		
Jun. 07, 1960	15	34	48.9	13.74N	56.97E	1.92	44	4.8	1
Jun. 22, 1960	16	12	00.3	11.78N	57.76E	1.61	82	4.5	1
Jul. 16, 1960	00	17	56.8	12.66N	57.83E	1.87	12		
Aug. 08, 1960	12	28	07.7	12.06N	44.49E	1.59	41	5.4	2
*Aug. 13, 1960	22	28	13.6	14.70N	40.16E	0.12	5		
Sept. 12, 1960	03	13	43.7	11.78N	46.61E	0.33	6		
Oct. 23, 1960	19	21	07.7	17.50N	40.07E	1.06	8		
Dec. 16, 1960	16	49	15.0	14.65N	42.57E	1.82	28		
Feb. 07, 1961	02	57	53.4	14.65N	53.90E	1.87	24		
†Feb. 16, 1961	14	33	15.1	13.0 N	57.6E				
Mar. 11, 1961	08	41	03.6	11.65N	42.95E	2.26	85	5.9	4

TABLE 1—*Continued*

Date	Origin Time			Lat.	Long.	S.E. Sec.	N	Mag	L
	H	M	S						
Apr. 06, 1961	21	23	45.7	14.28N	54.11E	2.66	17		
†Apr. 26, 1961	12	03	48.6	09.8N	57.0E				
Jun. 20, 1961	03	21	29.5	12.23N	44.34E	1.92	77	6.1	3
Jul. 18, 1961	21	26	28.0	13.88N	56.80E	1.75	43		
Aug. 03, 1961	00	41	30.7	14.48N	52.16E	2.00	29	5.5	1
Oct. 25, 1961	16	24	12.4	14.21N	56.44E	2.05	61	5.	1
Nov. 10, 1961	13	52	33.4	13.24N	51.69E	2.48	14		
Dec. 08, 1961	10	40	36.7	13.45N	50.22E	1.54	13		
†June 16, 1962	21	42	07.3	14.3N	53.6E				
†June 24, 1962	15	08	18.6	13.0N	48.6E				
Jul. 06, 1962	02	12	07.6	11.75N	57.57E	1.71	89	5.5	6
Jul. 15, 1962	21	52	20.1	14.11N	53.51E	2.14	37	4.5	1
Aug. 15, 1962	13	08	36.5	14.51N	56.49E	2.02	38	5.0	1
Aug. 25, 1962	00	54	08.0	16.49N	40.12E	1.52	11	4.8	1
Sept. 01, 1962	00	38	12.8	12.69N	48.10E	1.79	23	5.0	1
Oct. 29, 1962	07	17	34.8	04.15N	62.69E	2.32	36	5.	1
Nov. 11, 1962	15	15	28.0	17.05N	40.58E	1.69	95	5.6	7
Nov. 29, 1962	02	20	29.4	14.70N	54.86E	2.18	10		
Dec. 21, 1962	17	47	25.6	13.87N	51.63E	1.84	44	5.3	1
Dec. 26, 1962	23	25	11.8	23.80N	65.19E	1.80	101	5.9	3
Dec. 27, 1962	00	29	32.3	23.59N	65.09E	1.73	10		
Dec. 29, 1962	08	04	20.7	23.62N	65.31E	2.00	59	5.2	5
†Feb. 07, 1963	16	44	45.3	14.4N	53.3E				
†Feb. 13, 1963	01	34	40.4	13.0N	57.9E				
†Feb. 13, 1963	19	55	36.0	11.6N	57.7E				
†Mar. 09, 1963	02	17	39.5	21.9N	62.0E			5.1	USCGS
†Apr. 25, 1963	11	09	29.5	04.3N	62.4E				
† July 21, 1963	06	01	57.3	14.8N	56.1E				
†Sept. 29, 1963	19	31	22.7	13.5N	57.5E				
†Oct. 04, 1963	13	29	44.6	18.1N	60.1E			5.3	USCGS
†Oct. 05, 1963	14	57	47.4	11.6N	42.8E			5.3	USCGS
†Oct. 05, 1963	17	18	25.0	11.7N	42.6E				
†Feb. 09, 1964	06	07	30.	25.6N	36.4E				
†Mar. 19, 1964	09	42	34.9	14.7N	56.3E				

* Solution only approximate, accuracy of locations about 50 km (usually caused by a poor distribution of stations).

† Solution by U.S. Coast and Geodetic Survey (USCGS).

S.E. = Standard error, N = number of P and PKP readings. Mag = Magnitude averaged for L readings.

Three-letter codes of USCGS used for stations.

10 km. Although the origin time depends upon the depth of focus used in the calculations, the epicentral locations do not change significantly when the source depth is varied from 0 to 100 km.

Epicenters in the Arabian Sea and the Gulf of Aden

Epicenters in the Gulf of Aden and the Arabian and Red seas during the interval 1955 to 1964 are shown in figure 1. The correlation of seismic activity with the

TABLE 2

EARTHQUAKES IN EAST AFRICA FOR THE PERIOD JANUARY 1955 TO MARCH 1964

Date	Origin Time			Lat.	Long.	S.E. Sec.	N	Mag (LWI)	Mag (Other)
	H	M	S						
Feb. 04, 1955	05	21	00.9	05.80N	36.62E	1.75	13		
Mar. 01, 1955	22	10	24.7	15.14S	41.52E	1.55	9	5.6	
Jul. 22, 1955	04	00	02.9	01.42N	30.52E	1.31	7	5.	
Sept. 02, 1955	10	24	03.3	17.30S	41.81E	2.22	10		
Sept. 04, 1955	22	12	47.0	01.66N	30.90E	1.87	23	6.3	5.9 TAC, 5.8 PAS
Oct. 16, 1955	04	41	48.5	05.42S	51.42E	0.79	12		
Nov. 09, 1955	21	58	49.5	17.18S	48.55E	1.99	19		
Dec. 15, 1955	10	18	44.8	06.25S	30.99E	0.67	6	5.	
Feb. 03, 1956	21	37	53.9	05.03S	30.21E	1.47	25	5.	
Feb. 04, 1956	22	12	47.1	06.48S	31.05E	2.03	12	6.2	
Apr. 04, 1956	21	21	14.6	04.98S	35.44E	1.40	6	6.5	
Apr. 29, 1956	21	52	32.2	06.44S	51.81E	2.25	40		
Sept. 17, 1956	22	39	57.1	10.15S	34.29E	0.23	5	6.	
Jan. 04, 1957	18	16	11.4	07.42N	12.52W	1.01	12		
Jan. 22, 1957	11	18	24.5	04.82S	28.73E	1.41	41	6.3	6.1 AST
Apr. 13, 1957	21	51	04.4	30.18S	26.91E	3.34	10	(6.4)	
May 25, 1957	18	33	03.0	07.18S	30.51E	0.86	4	5.6	
Jul. 05, 1957	15	32	05.3	01.89S	26.75E	2.19	55	5.6	6.2 MAT
Jul. 09, 1957	22	24	43.9	00.11S	29.32E	0.96	15	4.8	
Jul. 20, 1957	09	55	38.0	21.41S	33.40E	2.15	23	6.2	6.0 JOH
Sept. 05, 1957	07	22	12.5	21.36S	33.25E	1.59	7		6.0 JOH
Oct. 17, 1957	02	52	02.9	12.32S	33.68E	2.00	5	5.	
*Mar. 25, 1958	09	08	47.7	09.62S	31.08E	1.56	4	5.	
May 05, 1958	06	31	38.2	09.64S	27.83E	1.50	105	7.2	6.3 average of 7 stations
Jul. 16, 1958	21	58	18.3	11.58S	29.51E	1.94	12	6.0	
Oct. 03, 1958	17	15	21.1	14.93S	41.20E	1.32	7		
Oct. 30, 1958	02	26	08.2	00.41S	48.53E	1.35	7		
Jan. 15, 1959	23	02	33.6	00.10S	29.76E	0.49	6		
Jan. 27, 1959	05	44	03.1	00.46N	29.97E	0.26	5	4.2	
*Mar. 08, 1959	22	37	16.9	03.78N	36.94E	0.92	5		
Mar. 10, 1959	17	48	19.7	15.31S	30.16E	2.27	27	6.1	
Apr. 04, 1959	15	07	19.1	06.30S	51.75E	2.17	10		
*Apr. 14, 1959	09	36	43.2	14.55S	22.11E	3.57	11	5.8	
Apr. 21, 1959	07	42	58.6	10.51S	24.99E	1.34	6	4.8	
May 04, 1959	16	25	57.4	07.45S	32.86E	1.83	10		
May 10, 1959	10	24	55.6	03.19S	35.91E	1.11	5	4.2	
May 17, 1959	11	39	47.0	04.23S	33.40E	0.93	5	4.5	
Jun. 01, 1959	11	22	56.8	21.05S	26.75E	2.42	5		
Jun. 01, 1959	17	58	51.2	11.50S	26.46E	1.93	6	5.	
*Jun. 14, 1959	15	02	47.0	20.96S	16.99E	2.14	5		
Jun. 19, 1959	11	58	51.6	00.17S	29.38E	2.40	21	5.4	
Jun. 24, 1959	22	50	24.3	03.56S	31.08E	1.39	5	4.5	
Jul. 05, 1959	09	46	40.5	01.63S	26.50E	0.81	5		
Aug. 05, 1959	02	26	48.5	08.63S	21.21E	0.59	5		
Aug. 09, 1959	11	16	51.4	00.79N	29.91E	1.81	12	5.1	

TABLE 2—*Continued*

Date	Origin Time			Lat.	Long.	S.E. Sec.	*N*	Mag (LWI)	Mag (Other)
	H	*M*	*S*						
Aug. 12, 1959	04	05	17.1	14.96S	26.54E	2.21	51	6.6	5.2 KEW
Aug. 12, 1959	18	30	54.3	26.14S	30.25E	2.41	4		
Aug. 24, 1959	01	26	03.9	04.24S	35.04E	1.57	14	6.1	
*Aug. 24, 1959	20	05	24.	19.8S	33.4E		3		
*Sept. 09, 1959	16	54	16.0	09.12S	30.08E	0.35	4		
Sept. 22, 1959	06	43	26.6	00.91N	29.76E	1.42	5	4.5	
*Oct. 25, 1959	12	31	20.4	04.83S	35.64E	0.86	4	5.2	
*May 04, 1960	02	17	33.4	01.21S	32.46E	0.05	4	5.7	
Jul. 14, 1960	18	39	35.8	07.17N	38.46E	1.96	38	6.3	
Jul. 15, 1960	01	07	16.8	14.15S	21.85E	1.68	7	5.9	
Jul. 15, 1960	05	02	03.0	12.18S	45.54E	1.58	72		
*Jul. 22, 1960	19	31	15.9	24.87S	36.71E	0.03	4		
Sept. 22, 1960	05	38	10.0	03.60S	29.08E	2.05	97	5.4	5.8 average of 4 stations
Sept. 22, 1960	09	05	32.5	03.61S	29.03E	1.97	121		6.6 average of 3 stations
Sept. 22, 1960	09	14	55.5	02.89S	29.41E	2.62	76		6.2 PAS, KEW
Oct. 24, 1960	03	58	18.0	03.54S	28.44E	1.87	12	4.9	
Nov. 27, 1960	20	37	18.8	03.67S	28.72E	1.28	20	4.9	
Dec. 02, 1960	13	43	20.6	03.52S	29.14E	1.63	13	5.1	
Jan. 27, 1961	18	33	16.8	06.42S	30.66E	1.50	7	5.1	
May 11, 1961	14	16	59.0	03.70S	29.31E	0.11	4	4.9	
May 20, 1961	17	51	58.0	06.52S	30.66E	2.49	50	6.1	
May 29, 1961	04	59	38.9	10.50N	39.74E	1.88	21		5.0 MOS
May 29, 1961	10	51	59.5	10.39N	39.81E	1.56	55		5.5 MOS
*May 29, 1961	11	39	47.5	10.17N	40.12E	1.89	11		
May 29, 1961	19	24	01.3	10.50N	39.84E	1.70	46		5.0 MOS
May 29, 1961	19	40	24.4	10.43N	39.77E	1.69	22		
May 30, 1961	13	11	16.9	10.72N	39.79E	1.71	16		
Jun. 01, 1961	21	07	18.5	10.92N	39.57E	2.32	11		
Jun. 01, 1961	23	29	18.8	10.63N	39.81E	2.64	147		6.4 average of 12 stations
*Jun. 01, 1961	23	56	37.8	09.43N	39.89E	0.51	10		
Jun. 02, 1961	00	01	42.8	10.46N	39.63E	1.20	32		
Jun. 02, 1961	00	08	53.5	10.41N	39.90E	1.63	46		
Jun. 02, 1961	00	21	18.9	10.41N	39.70E	0.77	13		
*Jun. 02, 1961	00	57	53.2	10.03N	39.20E	2.25	16		
*Jun. 02, 1961	02	35	33.9	10.88N	40.51E	2.23	17		
Jun. 02, 1961	03	19	34.9	10.03N	40.12E	1.41	9		
*Jun. 02, 1961	03	49	04.0	09.71N	40.69E	1.82	11		
Jun. 02, 1961	04	51	10.6	10.36N	39.91E	1.60	142		6.2 average of 10 stations
Jun. 02, 1961	05	22	28.5	10.30N	40.05E	2.14	72		
Jun. 02, 1961	05	44	52.7	10.59N	40.06E	1.95	82		5.8 KIR, 5.7 KEW
Jun. 02, 1961	06	17	10.7	10.54N	39.82E	1.56	26		
Jun. 02, 1961	07	02	46.1	10.14N	39.91E	1.94	62		5.5 MOS, 5.2 KIR

TABLE 2—*Continued*

Date	Origin Time			Lat.	Long.	S.E. Sec.	*N*	Mag (LWI)	Mag (Other)
	H	*M*	*S*						
Jun. 02, 1961	07	21	43.7	10.50N	39.74E	1.29	26		
*Jun. 02, 1961	22	19	30.0	10.31N	39.89E	1.33	9		
Jun. 02, 1961	23	32	34.6	10.42N	39.95E	1.51	34		
*Jun. 03, 1961	02	05	27.5	09.80N	40.22E	1.25	11		
Jun. 03, 1961	15	20	22.4	10.17N	39.97E	1.26	33		
Jun. 03, 1961	15	23	16.4	10.49N	39.93E	1.59	68		5.8 KIR, 5.6 MAT
Jun. 03, 1961	16	25	51.8	10.61N	40.01E	1.90	15		
Jun. 04, 1961	00	41	39.2	10.40N	39.82E	2.17	9		
Jun. 06, 1961	17	46	42.8	11.08N	39.19E	1.96	8		
Jun. 07, 1961	15	01	12.2	10.59N	40.04E	1.98	11		
*Jun. 09, 1961	03	15	57.8	01.98S	27.51E	2.69	4	4.6	
Jun. 14, 1961	20	32	17.8	10.64N	39.80E	1.95	89		5.7 UPP, 5.5 BUC 5. MOS
Jun. 19, 1961	04	34	11.6	10.46N	39.96E	1.49	8		
Jun. 24, 1961	07	27	47.2	12.69S	25.83E	2.78	5		
Jun. 24, 1961	15	04	31.3	10.69N	39.89E	1.86	5		
Jul. 03, 1961	21	25	55.7	16.28S	28.77E	0.99	6		
*Aug. 16, 1961	01	08	12.0	12.04S	34.91E	0.16	4	4.8	
Sept. 13, 1961	19	20	12.7	17.01S	27.76E	1.88	7		
Nov. 12, 1961	02	15	12.0	0.51N	29.50E	1.78	70		5. PAL, 5.5 KEW
Nov. 13, 1961	04	30	43.9	11.32S	33.94E	0.41	6		
Nov. 30, 1961	13	30	16.0	08.54S	33.69E	1.76	6		
†Mar. 08, 1962	01	54	41.9	22.3S	39.2E				
†Mar. 08, 1962	21	38	35.8	03.6S	29.2E			5.	
Sept. 25, 1962	04	48	36.3	07.52S	35.12E	1.74	14		
Sept. 30, 1962	03	35	32.1	08.50S	29.63E	1.68	4	5.0	
†Jan. 09, 1963	18	22	33.4	03.3S	29.4E				
†May 26, 1963	19	24	41.8	15.0S	35.2E			5.8	5.0 USCGS
†Jul. 06, 1963	22	32	31.7	16.3S	37.7E			6.1	
†Aug. 14, 1963	00	15	07.1	16.7S	28.7E			5.9	
†Sept. 23, 1963	06	40	36.5	16.6S	28.6E			6.5	5.5 USCGS
†Sept. 23, 1963	09	01	56.8	16.6S	28.8E			7.	5.8 USCGS
†Sept. 23, 1963	15	02	23.3	16.7S	28.4E			6.2	
†Sept. 23, 1963	22	23	37.7	16.6S	28.7E			6.5	
†Sept. 25, 1963	07	03	54.6	16.7S	28.7E			6.9	5.8 USCGS
†Nov. 08, 1963	09	59	24.3	16.5S	28.5E			6.5	5.5 USCGS
†Feb. 27, 1964	02	32	23.7	07.6S	39.6E				

Symbols same as Table 1.

mid-oceanic ridge system and the continuation of the seismic belt into the East African rift valleys were recognized previously (Rothé, 1954; Ewing and Heezen, 1956; Heezen and Ewing, 1963). Likewise, several authors described the similarities in the morphology of the two regions (Wiseman and Seymour-Sewell, 1937; Ewing and Heezen, 1956; Heezen and Ewing, 1963).

In previous studies (Gutenberg and Richter, 1954; Rothé, 1954; Drake and Girdler, 1964) many of the epicentral locations in these regions were uncertain by 100 km. Several tectonic features can now be resolved with the more precise epicenters that are shown in figure 1.

In the Gulf of Aden and the Arabian Sea the earthquakes are confined almost exclusively to narrow linear belts. Epicenters in the southeast corner of the map



FIG. 1. Earthquakes in the Gulf of Aden, Arabia, and the Arabian and Red seas for the period January 1955 to March 1964. Large circles—epicenters computed using 10 or more stations; small circles—epicenters determined using less than 10 stations. Recent epicenters located by the US Coast and Geodetic Survey (USCGS) are indicated by a large or small X. Seismograph stations that were used in this study are denoted by solid triangles; three-letter codes of USCGS used for the identification of stations. The epicenters are drafted on a portion of the Physiographic Diagram of the Indian Ocean, published by the Geological Society of America (Copyright 1964 by Bruce C. Heezen and Marie Tharp. Reproduced by permission.)

follow the NW-SE trend of the Carlsberg ridge, a portion of the mid-oceanic ridge system. Between 10°N, 57°E and 13°N, 58°E, the seismic zone strikes NNE-SSW. The NW-SE trend is repeated between 13°N and 14½°N. The main seismic belt follows the crest of the median ridge in the Gulf of Aden and joins the African continent in the Gulf of Tadjoura. In the Gulf of Aden a rift valley has been found along the crest of the oceanic ridge (Heezen and Tharp, 1964). Nearly all of the epicenters are confined to the rift valley.

Matthews (1963) and Heezen and Tharp (1964) used bathymetric data to delineate a large fault that displaces the Carlsberg ridge in the Arabian Sea. The portion

of the seismic belt that strikes NNE-SSW coincides with the fault zone. Much of the seismic activity associated with the fault is confined to the region between the displaced crests of the mid-oceanic ridge. This distribution of epicenters is also typical of other fracture zones that intersect the crest of the mid-oceanic ridge

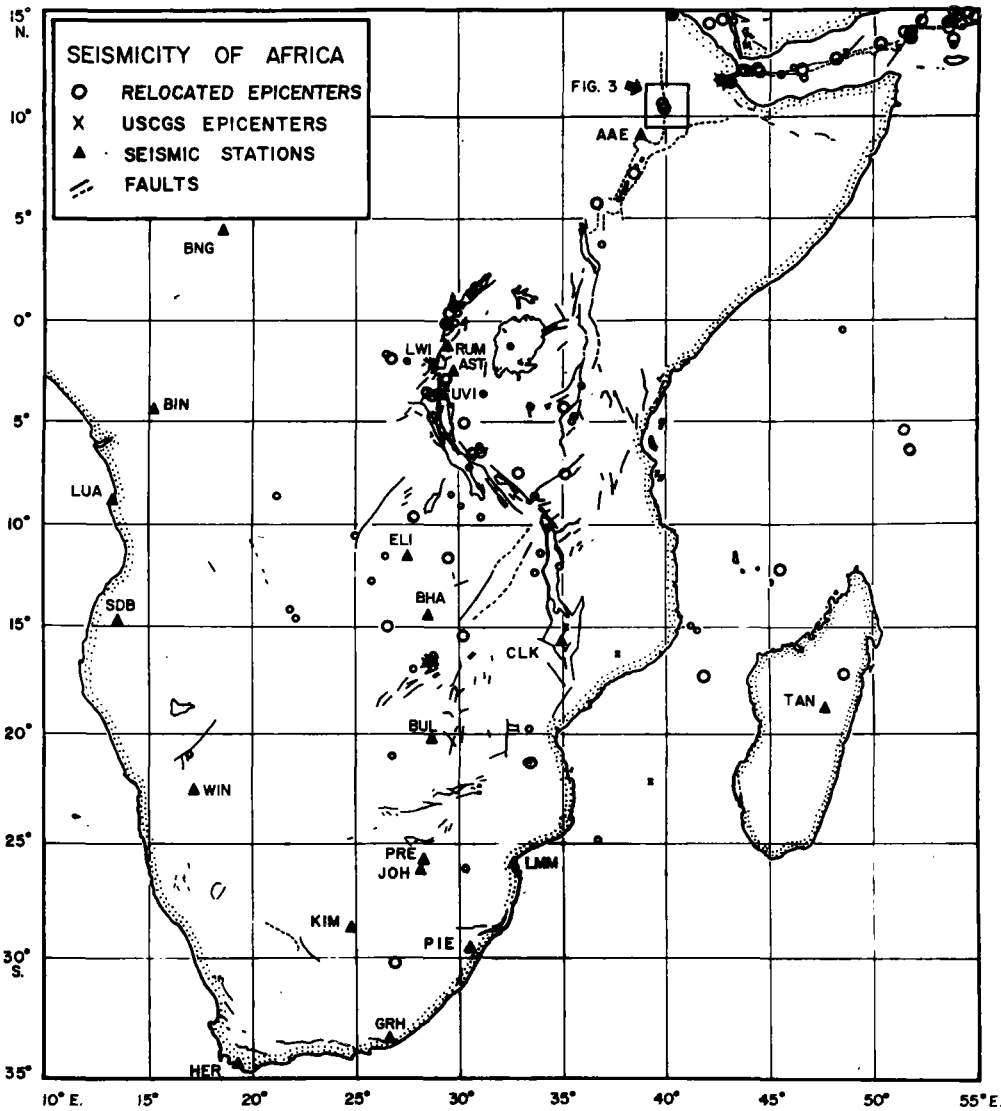


FIG. 2. Earthquakes in East Africa for the period January 1955 to March 1964. Symbols are the same as in Figure 1. Faults from the following geological maps: Congo (Cahen, 1952), East Africa (Inter-territorial conference, 1954), and Africa (Furon and Daumain, 1959; UNESCO, 1963). The area encompassed in Figure 3 is also indicated.

(Sykes, 1963; Heezen, Gerard and Tharp, 1964; Sykes, in preparation, 1965). The epicenters at 18.1°N, 60.1°E and 21.9°N, 62.0°E are located on the northern extension of the fracture zone. The reported location for the event on January 29, 1965, near 16.5°N, 58.5°E may be in error by 51 to 100 km (table 2).

Drake and Girdler (1964) and others have suggested that the Gulf of Aden and the Red Sea developed in response to a relative displacement of Arabia with respect to the African continent. In the Arabian Sea the NW-SE trend of epicenters is displaced in a right lateral sense approximately 300 km in the vicinity of the fault near 58°E. This displacement is almost exactly equal to the width of the mouth of the Gulf of Aden. The fault near 58°E may represent the southeastern boundary of the Arabian tectonic block. The concentration of epicenters along this fault indicates continued movement at the present time. A study of the focal mechanism of these earthquakes could give additional information on the sense of the movement along the fault.

Heezen and Tharp (1964) indicate that this large fault system in the Arabian Sea may extend as far south as the east coast of the Malagasy Republic. Two epicenters are found in the vicinity of the fault near 6°S, 52°E. Hence, this fault is one of the great tectonic features of the earth; its influence should be considered in future seismological investigations.

TABLE 3

ERRORS IN COMPUTED LOCATIONS FOR THREE LARGE NUCLEAR EXPLOSIONS IN THE SOUTHWEST PACIFIC IN 1954

Errors given relative to locations released by US Atomic Energy Commission (Griggs and Press, 1961). Depth constrained to the surface of the earth in all calculations

Author	BRAVO—February 28		ROMEO—March 26		UNION—April 25	
	Δlat.	Δlong.	Δlat.	Δlong.	Δlat.	Δlong.
Present Paper	.02°N	.02°W	.05°N	.01°W	.01°S	.07°W
Gunst and Engdahl (1962)	.03°N	.02°W	.05°N	.01°W	.01°S	.02°W
Bolt (1960)	.05°N	.05°E				

Heezen and Tharp (1964) also mapped other faults that are approximately parallel to the major NNE-SSW fault zone. In the Gulf of Aden regions of high seismicity are found where these faults intersect the median ridge, e.g., near 48½°E and near 51½°E. The largest earthquake reported in this study occurred at one of these intersections on December 21, 1959 (14.0°N, 51.7°E, magnitude M = 6.7). This region was a locus of seismic activity throughout the period 1955 to 1964. The concentration of epicenters near 54°E may be indicative of another NNE-SSW striking fault.

SEISMICITY OF THE RED SEA

Seismic activity in the Red Sea during the interval 1955 to 1964 was considerably less than that associated with the Gulf of Aden and the Arabian Sea. Most of the earthquakes were concentrated in the southern half of the Red Sea. The distribution of seismic activity is similar to that found by Gutenberg and Richter (1954) and by Drake and Girdler (1964). Unlike the Gulf of Aden, many of the epicenters in the Red Sea are located along marginal faults (Drake and Girdler, 1964) rather than along the median rift. The lower seismic activity in the Red Sea may be related

to an absence of faults that intersect the rift valley. Other factors such as the relative ages of the tectonic units or differences in the pattern of stress may account for the variations in seismic activity.

The US Coast and Geodetic Survey reported an earthquake in northeastern Arabia near 27°N, 47½°E on May 10, 1960. From 21 readings of P the epicenter was relocated in southern Iran near 31.77°N, 50.84°E. Thus none of the computed epicenters are associated with the Precambrian or Paleozoic rock units of Arabia.

Earthquakes in East Africa

Epicenters in East Africa for the period 1955 to 1964 are shown in figure 2. Previous studies of the seismicity of Africa are summarized in a review by Gorshkov

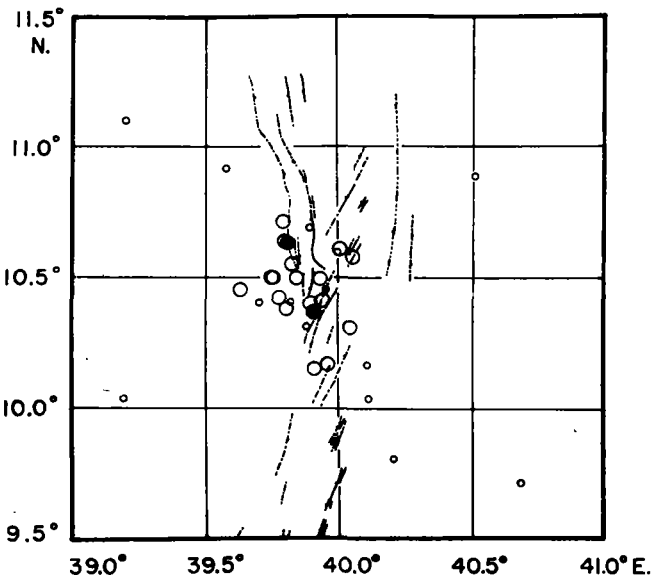


Fig. 3. Earthquakes in Ethiopia during May and June 1961. The two largest events are denoted by solid circles; well located aftershocks, large open circles; poorly located aftershocks, small open circles. Faults from preliminary map of Mohr (1960). Faults in the area between 9.5° and 10.5°N and between 40° and 41°E were not mapped.

(1963). DeBremaecker (1959) investigated earthquakes as small as magnitude 2 in a portion of the western rift; Gane and Oliver (1953) and Oliver (1956) discussed earthquakes in South Africa; Korn and Martin (1950) studied the seismicity of southwest Africa.

Many of the earthquakes in East Africa are associated with the various branches of the rift system. During the past nine years the western rift was the most seismically active region in East Africa. In a previous study Gutenberg and Richter (1954) indicated that the seismic activity in the Ethiopian rift valleys was comparable to that found in the western rift. However, a number of other epicenters such as those near Elizabethville (ELI) and Broken Hill (BHA) are not located along the rift valleys. It might be supposed that these epicenters are mislocated. There are several indications, however, that the epicentral determinations are in fact quite accurate. Several of the largest events reported in this paper were not located along the rift

valleys. These include earthquakes on July 5, 1957; May 5, 1958; August 12, 1959, and September 23, 1963. Each of these shocks was well recorded with respect to both distance and azimuth. The stated locations are consistent with the arrival times of stations within a few degrees of the epicenters. The errors in location are at least an order of magnitude smaller than the distances to the nearest rift valleys.

The epicentral determinations reported in this paper are in close agreement with the locations computed by IRSAC (Lwiro) for earthquakes within the central African network (DeBremaecker, 1959). Also the epicentral locations are consistent with the locations that may be inferred from intensities published by Sutton and Berg (1958). Several of the epicenters computed by Gutenberg and Richter (1954) and by DeBremaecker (1959) are also located outside the rift valleys. Hence, the scatter of the epicentral locations in East Africa cannot be ascribed to computational errors.

The complexity of the East African rift system and the large areal extent of seismic activity contrast considerably with the pattern of seismicity observed for various portions of the mid-oceanic ridge. Epicenters along the oceanic ridges are restricted to narrow linear belts that are less than 50 km wide. Earthquakes in other continental areas are not confined to single narrow seismic belts. Although many shocks in the Califronia-Nevada region occur along the San Andreas fault, other earthquakes are not located along this major fault zone (Richter, 1958, pp. 472–474). These contrasts in the pattern of seismicity are apparently indicative of either different stress patterns or different responses to stress between oceanic and continental regions.

Ethiopian Earthquakes During 1961

Two earthquakes of magnitude approximately $6\frac{1}{2}$ and a series of aftershocks occurred near Karakore, Ethiopia, during May and June 1961. Thirty-four of these events were relocated from teleseismic data. The epicenters are shown in figure 3, and the computations are listed in table 2. The locations denoted by large circles are probably accurate to within about 10 km. However, the earthquakes indicated by small circles may be in error by 50 or 100 km since essentially three stations were used in these computations (usually several European stations at approximately the same distance and azimuth plus Shiraz and Bangui). The region defined by the well-recorded earthquakes is assumed to represent the area of aftershock occurrence. The size of this area is consistent with the extent of the region that suffered a vertical displacement of about 6 feet (Gouin, 1963).

Since seismic readings were not available from Addis Ababa for 1961, the closest station used in any of these computations was Lwiro (17°). Figure 3 demonstrates that, even in the case of a main shock of only moderate size, teleseismic readings can be used to estimate the area involved in an aftershock sequence.

Earthquakes in Western Africa

The epicenter of an earthquake on January 4, 1957, was located in Sierra Leone near 7.4°N, 12.5°W. All other epicenters reported in this study occurred to the east of 16°E. Gutenberg and Richter (1954) list individual epicenters in Ghana (6°N, 01°W), Cameroons (2°N, 15°E), Angola (10°S, 15°E) and off the Cape of Good

Hope (39°S, 21°E). Gorshkov (1963) discusses several historical epicenters in these regions. Western Africa south of 30°N may be characterized as a region of only minor seismic activity.

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Dr. B. C. Heezen and M. Tharp furnished information from their physiographic diagram of the Indian Ocean prior to publication. Mr. Leonard Murphy of the US Coast and Geodetic Survey provided a list of *P* wave readings for the nuclear explosions in the Southwest Pacific. The authors are indebted to Drs. Heezen, Oliver and Sutton, who read the manuscript critically and offered several helpful suggestions. Mr. Joseph Brock assisted the authors in preparing the data for computation.

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SUBMARINE MORPHOLOGY OF THE SAHUL SHELF, NORTHWESTERN AUSTRALIA

Abstract: The Sahul Shelf, located between northwestern Australia and the Timor Trough, consists of a central basin surrounded by broad, shallow rises. Superimposed on the regional relief is a system of banks, terraces, and channels. The flat tops of banks and terraces form parts of several regional, subhorizontal surfaces. The steplike topography closely resembles the system of late Cenozoic erosional surfaces on the adjacent land of which it probably is the submerged extension. This requires uplift, weathering, and denudation of the shelf in middle and late Tertiary. Subsequently, the shelf was deformed to form the basin and rises. This deformation caused the original drainage to become antecedent. Lower surfaces were formed during Pleistocene low sea-level stands.

Introduction

The Sahul Shelf, off the northwest coast of Australia, is a very wide continental shelf which derives its interest primarily from its position between the continental mass of Australia and the island arches and geosynclines of Indonesia. An early study, based on conventional nautical charts, was made by Fairbridge (1953). In 1960 and 1961, Scripps Institution of Oceanography made a detailed bathymetric and sampling survey of the region and the adjacent Timor Trough (van Andel and others, 1961; van Andel and Veevers, in press) as part of the International Indian Ocean Expedition. The resulting information, supplemented by detailed sounding data for parts of the shelf provided by the Hydrographer, Royal Australian Navy, forms the basis of this report.

Regional Morphology

The regional morphology of the Sahul Shelf is unusual (Fig. 1); instead of the flat, gently seaward-sloping plain of most shelves, the Sahul Shelf contains a large central basin, the Bonaparte Depression, with a maximum depth of 120–140 m. This basin is reflected in the coast line by a deep embayment, the Joseph Bonaparte Gulf. The Bonaparte Depression is surrounded by broad rises with crest depths of 40–50 m. The Van Diemen Rise, extending seaward from Melville and Bathurst Islands, is the submerged continuation of these islands; the Londonderry Rise connects the Kimberley area with the shelf edge. The Sahul Rise separates the Bonaparte Depression from the Timor Trough. The basin is connected with deep water by a long, narrow valley with a maximum depth of 200 m, Malita Shelf Valley.

The shelf edge is represented by a gradual change in slope, usually marked by a low cliff at 110–130 m. A second shelf edge at approximately 550 m, reported by Fairbridge (1953), does not exist. Just beyond the edge of the shelf on the upper continental slope are numerous clusters of small, steep-sided banks, 1–5 km in diameter; they rise from 200 to 400 m and universally have flat tops at 20–25 m. Fairbridge (1953) has explained these banks as strings of reefs, a broken barrier originally formed in shallow water, and slowly grown up during gradual subsidence of the Timor Trough.

Superimposed on this broad regional relief is a complex fine structure of banks, terraces, and channels. The tops of the banks are generally flat; their slopes are fairly steep and occasionally interrupted by terraces. The channels are closely spaced, subparallel or in the form of a braided pattern, and steep-walled (Fig. 2). In most cases, the channels cut through the rises, suggesting antecedent systems, and are much deeper in their central portions than at either end. They lose their identity in the Bonaparte Basin and on the outer shelf, in depths of approximately 100 m.

On the Van Diemen Rise, the bank and channel topography is strikingly similar to the morphology of Melville and Bathurst Islands. On the Londonderry and Sahul Rises, the

topography is more subdued, the differences in relief smaller, and the maximum elevations lower. The Bonaparte Depression is an area of gentle slopes or flat bottoms, with only a few minor banks. The outer shelf is characterized by flat bottoms; wide, low terraces; and shallow channels. Aggraded surfaces predominate in the Joseph Bonaparte Gulf.

converge in the same direction. Surfaces III and IV (Figs. 3, 4) can be traced with confidence over most of the shelf area. On the rises, they form terraces and valley floors; in the Bonaparte Basin, they are developed as bank tops. Below surface IV, several other terrace and valley-floor levels can be traced in the basin, on the flanks of the rises, and on the

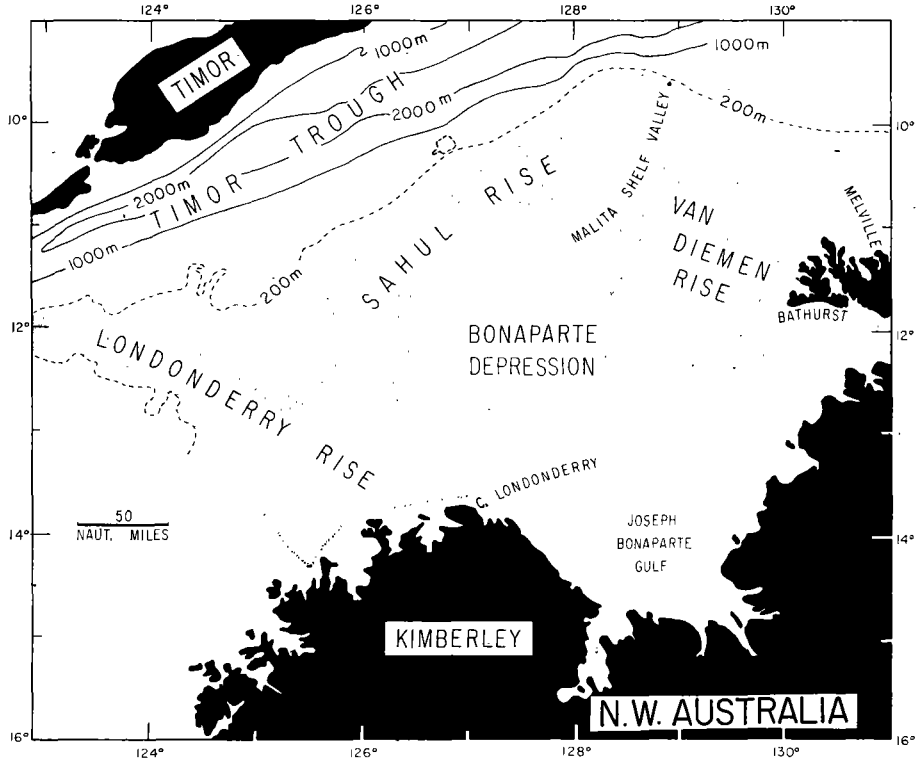


Figure 1. Regional morphology of the Sahul Shelf, northwestern Australia

The most striking feature of the shelf topography is the widespread occurrence of flat, subhorizontal surfaces, separated by short, steeper slopes (Fig. 3). Gradients on the flat surfaces are of the order of 0.05 m/km with only minor irregularities. The surfaces occur at numerous levels and are covered by unconsolidated calcareous sediments.

Many of these flat surfaces can be correlated regionally on the basis of cross-correlation between sections, tracing on detailed charts, elevation, and sequential order. The higher surfaces shown in Figures 3 and 4 (I and II) are restricted to the rises where they form the tops of higher banks. They dip northwestward and outer shelf. Surface IV and lower surfaces converge markedly on the rises and diverge toward the outer shelf and the center of the Bonaparte Depression.

Interpretation

The bank and channel topography might be attributed to formation of platform reefs, adjusted by growth and marine erosion to various sea-level stands. A few active platform reefs occur locally on the Sahul Shelf (Fairbridge, 1950). However, on the whole, the bank morphology is not similar to reef topography; little reef material has been found in some 375 samples taken, and the system of sea-level

changes needed to explain all surfaces is improbably complex.

Fairbridge (1953) has pointed out the similarity between topography of the shelf and the relief of the adjacent land. The now available detailed knowledge of the shelf relief shows that this similarity is very striking and strongly

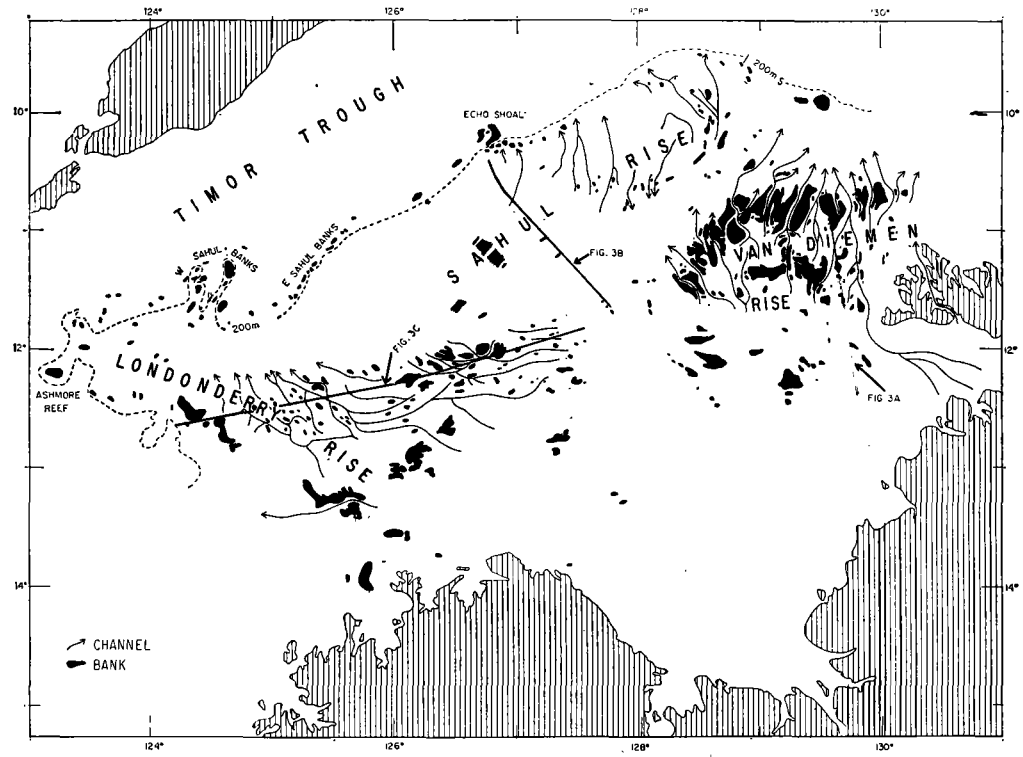


Figure 2. Bank and channel topography of the Sahul Shelf, northwestern Australia, showing only those banks that have closed contours greater than 40 m above the surrounding terrain. Arrows indicate detailed cross section in Figure 3. One degree latitude equals 60 nautical miles.

suggests that both are of the same origin. Thus, the shelf relief would be due to subaerial weathering, erosion and peneplanation, and subsequent submergence with little sedimentation. This hypothesis, although plausible, cannot be proved at this time, but its consequences are interesting enough to explore briefly in this paper.

Various authors (Hays, unpub. rept., Bur. Min. Res. Australia; King, 1949, Paterson, in press; Wright, 1963) have described series of late Tertiary and Quaternary erosion surfaces on the adjacent land. Several of these are apparently continuous over large portions of western and northern Australia although precise correlations are not yet obtainable. The oldest and highest of these surfaces, variously named the Australian, Bradshaw, or Tennant Creek surface, is probably of mid-Tertiary age and deeply laterized, indicating a long period of peneplanation and weathering before uplift. A Miocene marine-transgressive sediment, the White Mountain formation, occurs in places on the laterite and predates the uplift. Stripping of parts of the laterite resulted in the formation of a slightly younger, much less deeply weathered lower surface, the Wave Hill or Maranboy surface. Even lower are several cycles of partly erosional, partly depositional plains which are generally attributed to Pleistocene sea-level fluctuations. Tentatively, it is suggested that the Australian and Wave Hill surfaces are the landward equivalents of Sahul Shelf surfaces I and II, whereas surface III and lower surfaces represent the seaward extensions of the Pleistocene cycles.

All shelf surfaces follow the regional pattern

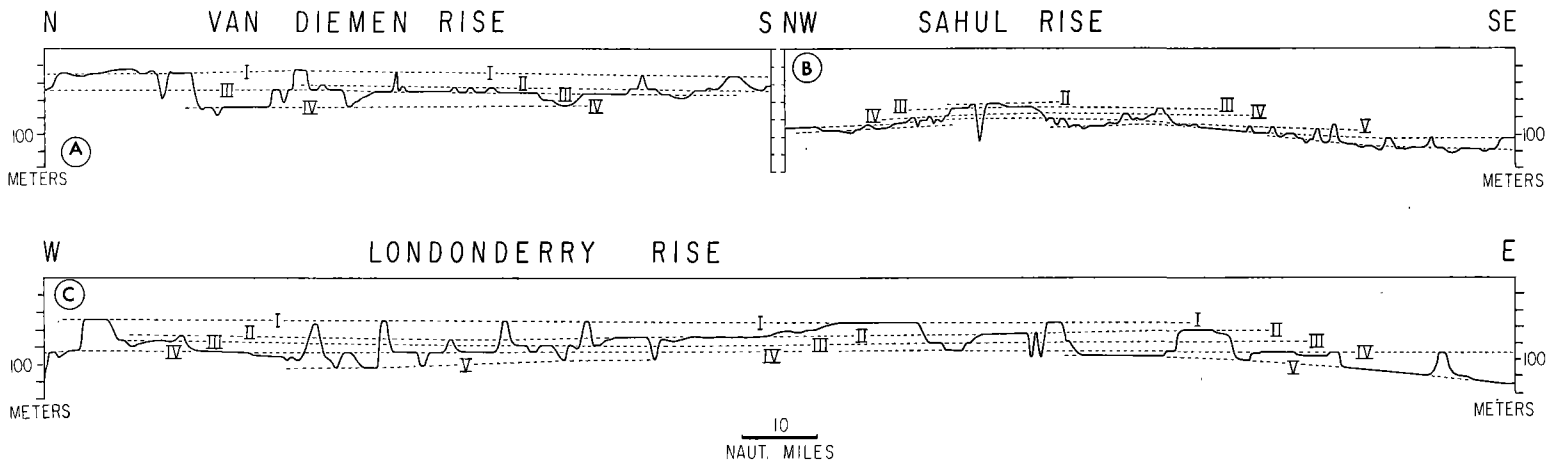


Figure 3. Topographic cross sections of the Sahul Shelf, northwestern Australia. Vertical exaggeration 200 ×. Locations (A, B, and C) on Figure 2. Prepared from echo-sounding records and detailed contour maps

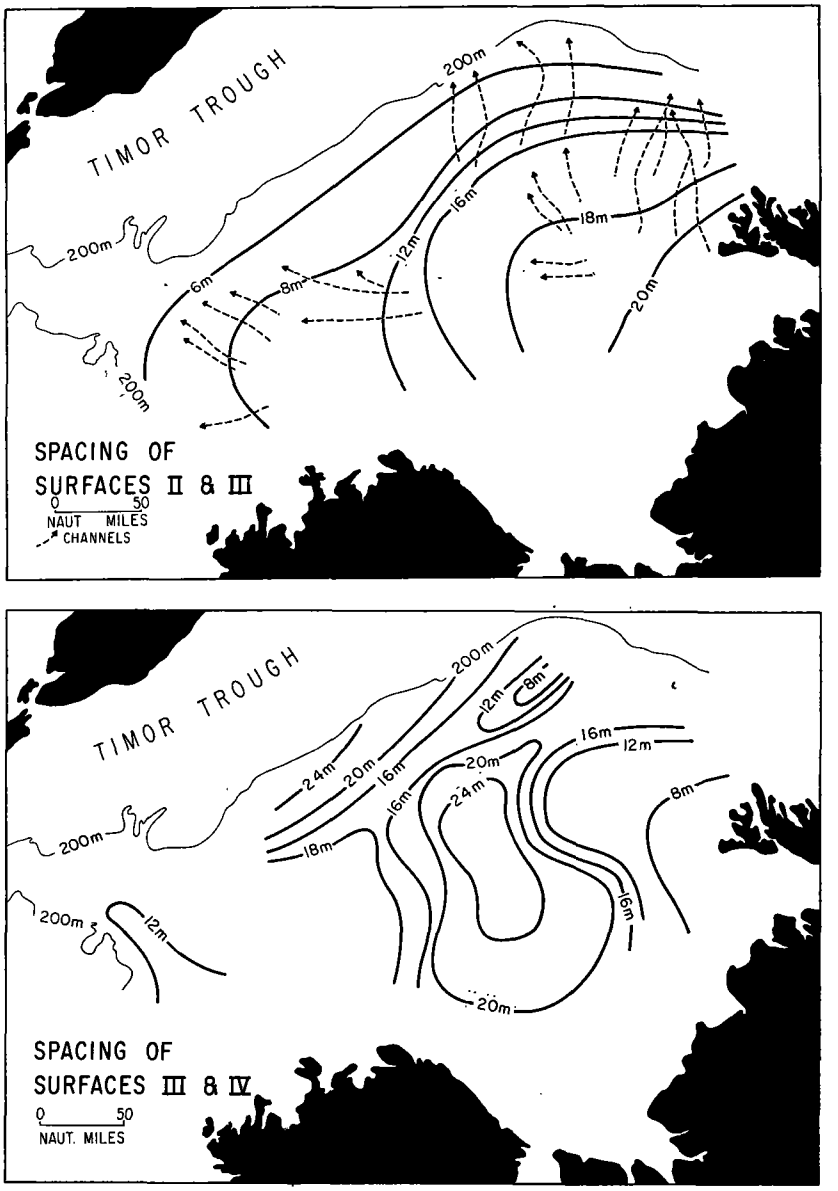


Figure 4. Spacing between surfaces II and III and surfaces III and IV (*see* Fig. 3) over the Sahul Shelf, northwestern Australia

of rises and depressions. If the hypothesis just presented is correct, this regional relief is probably due to epeiric deformation during or after the formation and uplift of the erosional surfaces. Deformation of the Wave Hill surface has been noted by Hays (unpub. rept., Bur. Min. Res., Australia) and appears to be well aligned with the regional structure of the shelf.

Because there is no convergence of surfaces I/II or II/III over the rises (Fig. 4), it may be assumed that no deformation took place until the time of uplift of surface III. The channel system of the Van Diemen Rise, now antecedent, may represent the original northerly drainage on these surfaces. When the Sahul and Van Diemen Rises developed, drainage

was diverted to the west. Subsequent uplift of the Londonderry Rise converted these channels also into an antecedent system.

Surfaces III and IV and, even more markedly, those below IV show clear divergences toward low areas and convergences over the rises (Fig. 4). Hence, deformation probably began between surfaces III and IV, possibly in the early Pleistocene, and has continued since that time.

The hypothesis of subaerial origin, if correct, requires that during most of its Cenozoic history the Sahul Shelf was above sea level and intermittently rising. Unless we assume that successive Pleistocene minima of sea level were progressively lower, this rise must have continued until relatively late in the Pleistocene. Then it was followed by a rather abrupt subsidence of some 120 m. Because the original relief seems well preserved, not much sedimentation can have taken place since the subsidence. The shelf appears to be mainly a zone of sediment bypassing. The smooth, long, gentle southeastern slope of the Timor Trough, on the other hand, suggests that a thick, continuous sequence of late Cenozoic sediments may occur here. During the period of emergence, the shelf-edge banks formed a fringe of reefs just beyond the hinge line between continental uplift and geosynclinal subsidence.

If this hypothesis, admittedly speculative, should prove to be correct through further geophysical work and drilling, this late Cenozoic history would represent one more cycle in a long series of shallow marine transgressions followed by uplifts and erosion along structural lines quite similar to the present ones (Fairbridge, 1953).

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A MAGNETIC MINERAL FROM THE INDIAN OCEAN[1]

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ABSTRACT

A high concentration of a magnetic mineral was found near the top of two cores from the Indian Ocean. Magnetic properties of the sediment suggest an *in situ* formation. *X*-ray and magnetic data show that the mineral is between magnetite and maghemite in structure, and the formation of such a mineral in the deep sea environment is considered.

During the Scripps Institution of Oceanography's Monsoon expedition a piston core and trip gravity core were taken at lat 23°56'S, long 73°53'E, in a depth of 2022 fm. The region was one of abyssal hills having maximum heights of about 200 fm, the depth of water ranging from 1700 fm to 2340 fm. The maximum slope of the hills, measured from the PDR record, was about 14°. The record shows few places where there are flat portions between the abyssal hills. The tentative position of the Indian Ocean rise (R. L. Fisher, pers. comm.) puts the position of the core 225 miles east of the center of the ridge.

In the uppermost portion of both cores, there was an anomalously high value of the magnetic susceptibility. In the piston core, measurements of magnetic susceptibility on samples taken at 2 cm, 30 cm, 41 cm, and 57 cm, from the top of the core, were all in the region of 300 micro emu/cc, whereas samples from 64 cm, 72 cm, 91 cm, and further down had magnetic susceptibilities of the order of 10 micro emu/cc (Fig. 1). In the gravity core, samples from 16 cm and 23 cm had a high susceptibility of about 1000 micro emu/cc, and samples from 6 cm, 28 cm, and 45 cm had more normal susceptibilities of between 10 and 25 micro emu/cc.

It seemed likely that a sharp contact from grayish buff to light buff calcareous ooze at 58 cm in the piston core would be diagnostic of the sediment type changing from one of high magnetic susceptibility to one of low magnetic susceptibility, and this was verified with an astatic magnetometer system. Over the portions of the core where the magnetic susceptibility was very high, the deflection of a spot of light from the magnetometer mirror was several centimeters, but over the other portions, little or no deflection was observable. All of the sediment above 58 cm gave large deflections, whereas that below 58 cm gave only small deflections.

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Contribution from the Scripps Institution of Oceanography, University of California, San Diego.

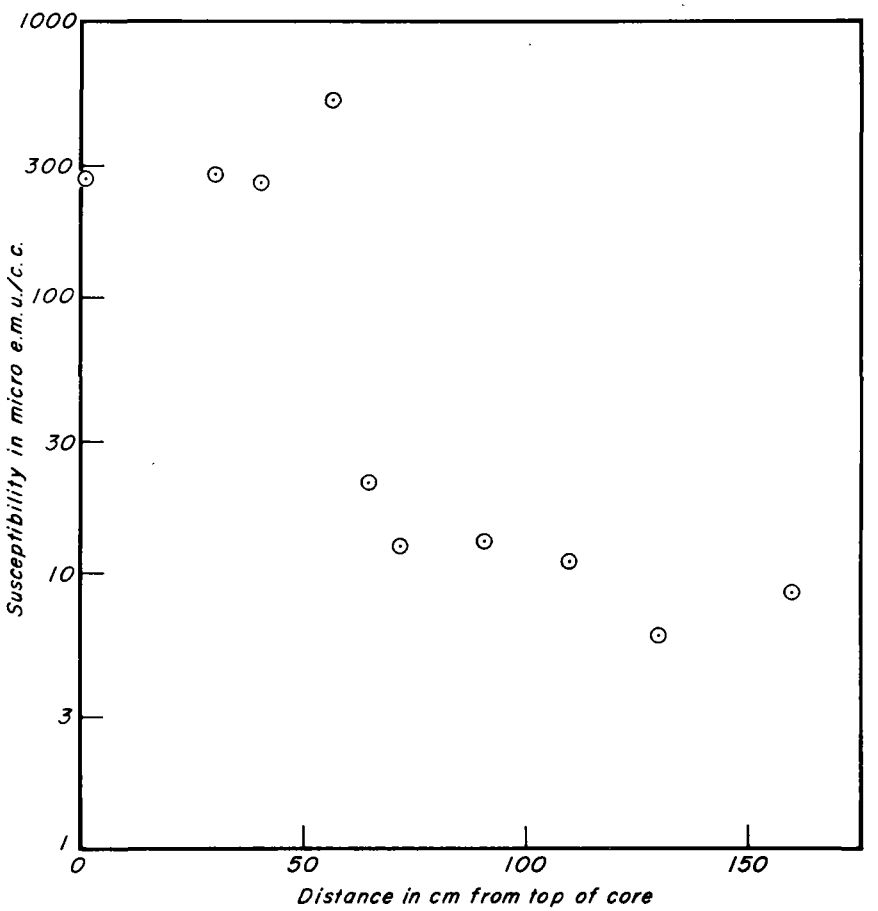


FIG. 1. Magnetic susceptibility of MSN 56 in micro emu/cc for various depths.

The gravity core (buff calcareous ooze, somewhat darker and slightly zeolitic in the lower part) was 58 cm long and only five samples were taken. The sediment in the gravity core apparently has a weakly magnetic section above as well as below the strongly-magnetic section, as the sample at 6 cm had a normal susceptibility. The two boundaries of the more magnetic section were thus between 6 and 16 cm, and between 23 and 28 cm.

The difference between the thickness of the strongly-magnetic portion in the gravity and piston cores is probably due to a shortening produced by the gravity coring process. This would also obscure the lithological boundary, which is only seen in the piston core.

The magnetic mineral occurring in the top 58 cm of MSN 56 P has been carefully studied by several methods, which are now described. The Curie temperature was determined by measuring the saturation magnetization of a small sample as a function of temperature. The heating was

done in air, allowing easy oxidation of the mineral. The Curie temperature was found to be 640° C. (Fig. 2). The magnetic susceptibility in a small field was 0.045 emu/gm/oersted. From these two observations, we can say that the mineral is neither magnetite (having a Curie point of 585° C. which is lowered by the presence of impurities), nor hematite, which has a very low initial susceptibility. The only other mineral which would seem likely is maghemite or a mineral with maghemite structure. Maghemite is unstable towards heat, being converted to hematite at a temperature between 200° and 800° C. (Mason, 1943). The Curie point of pure

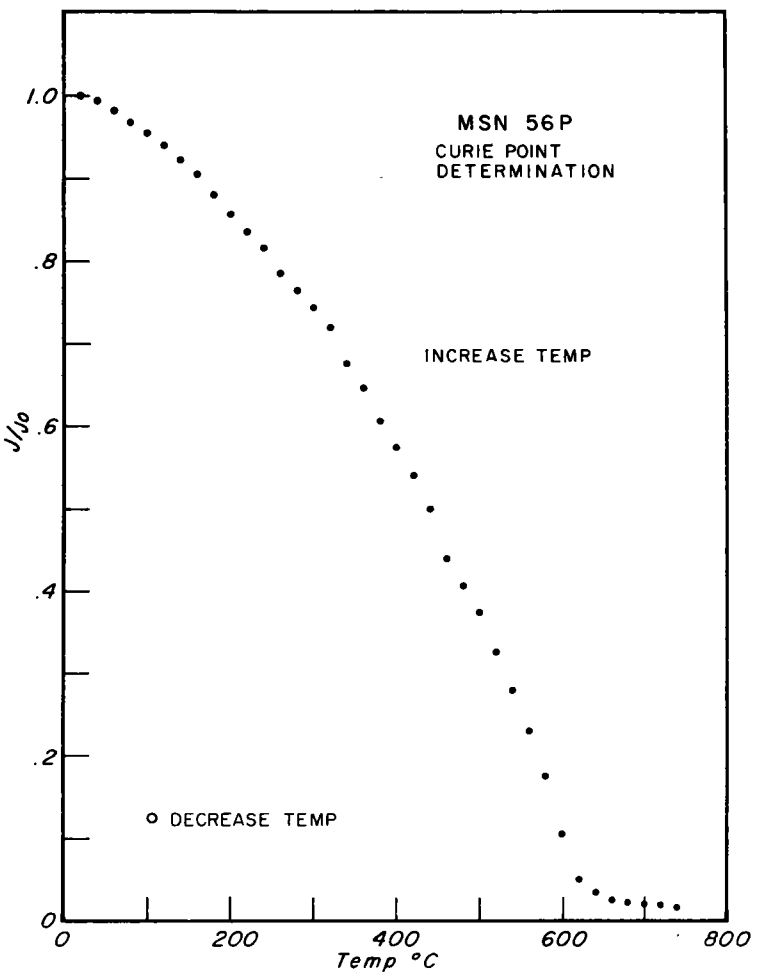


FIG. 2. Saturation magnetization of magnetic "mineral" from MSN 56 P for increasing temperature. The saturation magnetization is plotted as the fraction of the saturation magnetization at 0° C., remaining at T° C. The dots are for increasing temperature. The open circle is the fraction of saturation magnetization at 100° C. after cooling had taken place.

maghemite has never been directly determined, but by measurement of the Curie point of solid solutions of maghemite with another cation, and by extrapolation to pure maghemite it has been quoted as 680° C. (Michel and Chaudron, 1935).

This particular form is quite stable toward heat; when the Curie point was being determined, the material was kept at certain constant temperatures for periods of up to twenty minutes, in order to see if any change from maghemite to hematite (manifested by a fall in saturation magnetization) was occurring. As no such change took place below the Curie point, the material needed a temperature greater than 640° C. for the change to occur; the change from maghemite to hematite had undoubtedly occurred by the end of the experiment, as the saturation magnetization only rose slightly during cooling. It may also be that more time was needed, because of the possibility that structural water may contribute to the stability of maghemite. It should be noted that this mineral was kept wet in fresh, refrigerated core material until separated for study.

X-ray examination of the mineral confirms the above theory. The *x*-ray diffraction pattern (Table I) is generally that of maghemite (γFe_2O_3), and shows most of the important superstructure lines. Spacings are intermediate between magnetite and maghemite, suggesting that the mineral is an incompletely oxidized magnetite, in which the ordering of existing vacancies is only partial. At low angles 2θ the unit cell in the cubic system has a = about 8.34 Å. At higher angles, the pattern becomes more nearly that of magnetite than of maghemite; a is about 8.38 Å. This probably results from differences in diffraction efficiency between the magnetite that is relatively unoxidized, and retains relatively good crystallinity, and the maghemite, in which crystallinity may be considerably less perfect. Small amounts of both lepidocrocite and geothite are also present. There is no observable hematite, although the presence of a very small amount cannot be precluded, because of interference of the two strongest *x*-ray reflections of hematite (104) and (110, hex) with reflections from geothite (130) and magnetite (311) or maghemite (313, tet).

Attention was first brought to this mineral because of the possibility of its *in situ* formation. Texturally, it does not appear to be in rounded grains, which would suggest a detrital origin, nor does it have the octahedral crystal shape of magnetite that is typical of residual magnetite from altered basic volcanic material. Rather, the surface of the individual fragments is druzy, being formed of many closely crowded crystals. A slight ochre stain in places on the surface is probably the lepidocrocite and goethite observed by *x*-ray.

The magnetic anisotropy of the five highly magnetic samples from

TABLE I. COMPARISON OF *X*-RAY DATA FOR MAGNETIC "MINERAL" FROM MSN 56, WITH THAT OF OTHER IRON MINERALS OF WHICH IT IS COMPOSED

Observed Pattern	Observed Intensity	Magnetite[1]	Maghemite[1]	Lepidocrocite[1]	Goethite[1]
—	—		7.91 (1)		
6.94	VW		6.94 (2)		
6.26	W			6.27 (100)	
5.90	VVW		5.90 (6)		
5.31	W		5.33 (1)		
—	—				4.98 (10)
4.83	M	4.85 (10)	4.82 (6)		
—	—		4.29 (2)		
4.18	W				4.18 (100)
—	—		3.73 (6)		
—	—		3.40 (7)		
—	—				3.38 (10)
3.27	W			3.29 (60)	
3.20	VVW		3.20 (3)		
2.96	S	2.97 (30)	2.95 (30)		
2.78	M		2.78 (3)		
2.69	VVW				2.69 (30)
—			2.638 (4)		
—					2.58 (8)
2.524	VVVS	2.532 (100)	2.514 (100)		2.520 (3)
2.49?	VVW?				2.490 (15)
—				2.473 (30)	
2.45?	VVW?				2.452 (25)
2.419	W	2.425 (8)	2.408 (2)		
—				2.362 (15)	
2.307	W		2.315 (2)		
—					2.252 (10)
—			2.230 (2)		
—					2.192 (20)
2.095	S	2.100 (20)	2.086 (15)	2.086 (12)	
—					2.009 (2)
—				1.935 (30)	
—					1.920 (6)
—			1.865 (1)		
—				1.848 (10)	
—			1.820 (3)		
1.799	W				1.799 (7)
—					1.770 (2)
—				1.733 (15)	
—					1.721 (20)
1.712	W	1.714 (15)			
1.70?	VVW		1.701 (9)		
—					1.694 (10)
—			1.670 (2)		
—					1.661 (4)
1.613	M	1.617 (25)			
—			1.604 (20)		1.606 (6)
—				1.567 (8)	1.564 (15)
—			1.550 (2)		
—				1.532 (7)	
—			1.525 (3)	1.523 (15)	
1.483	S	1.485 (35)			1.509 (10)
—			1.474 (40)	et cetera	et cetera
1.326	VW	1.327 (6)		et cetera	et cetera
—			1.318 (6)	et cetera	et cetera
1.279	W	1.280 (10)		et cetera	et cetera
—			1.272 (8)	et cetera	et cetera

[1] Data from Brown, 1961, 38b. Data obtained with a Norelco wide angle diffractometer, using Mn filtered Fe radiation, scanning speed of $\frac{1}{4}°$ 2θ per minute, chart speed of $\frac{1}{2}''$ per minute, divergent, scatter and receiving slits of 1°, 1° and .006" respectively.

MSN 56 P and MSN 56 PG were measured on a suspended sample torque magnetometer built by Dr. A. Rees (King and Rees, 1962). The results (Fig. 3) show that all the samples have maximum magnetic susceptibilities grouped around the vertical, the first time, to our knowledge, that consistent results of this nature have ever been found in a sedimentary

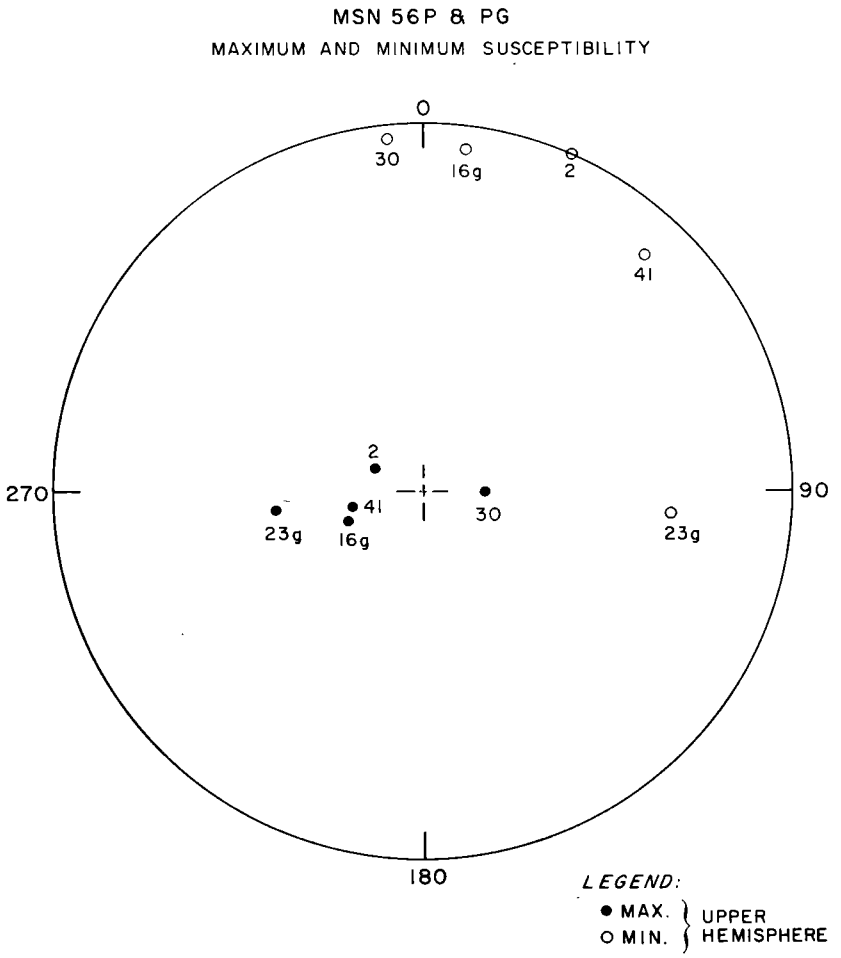


FIG. 3. Maximum and minimum susceptibility directions plotted on an equal area net. The closed circles are maxima, the open circles are minima. A "g" by the side of a number denotes that that specimen came from the gravity core.

deposit. Normally the maximum and intermediate susceptibilities tend to lie close to the horizontal plane (Rees, 1961). Another surprising fact is that, in all cases, the form of susceptibility is that of a prolate ellipsoid, rather than an oblate ellipsoid, which is normally found in sedimentary deposits. On artificially depositing some of the highly magnetic portion (*i.e.*, the entire sediment) of MSN 56 P it was found that the magnetic

susceptibility had a strong maximum in the horizontal plane and that the form of the susceptibility was that of an oblate ellipsoid, These two observations suggest that the magnetic mineral in the cores under discussion was not deposited by usual detrital processes, and that the most likely alternative is that it was formed *in situ*.

The formation of this magnetic mineral by diagenetic processes, or by volcanic-associated processes, or by some combination of these, is suggested. Textural evidence has already been mentioned against the possibility that the mineral is directly residual from the submarine alteration of volcanic debris, and also against the detrital origin for the mineral.

Several possibilities for *in situ* formation are conceivable. A number of ways of forming maghemite are listed by Bernal *et al.* (1959). Natural counterparts of some of these methods exist. Dehydration of pre-existing lepidocrocite will form maghemite that is missing the "ordering" reflections. Inasmuch as the material from MSN 56 has many of these "extra" reflections, it is considered unlikely that it has been formed in this way. Direct precipitation of maghemite and magnetite was shown to be possible, the product depending on whether there was or was not an excess of oxidizing agent, respectively. Oxidation of pre-existing magnetite can form maghemite; most natural maghemites appear to have formed in this manner. This mechanism also yields good ordering of vacancies.

The pelagic sediments of the deep sea would seem especially suited to the possible formation of authigenic magnetite or maghemite, particularly if they contain iron-rich volcanic debris. Slow deposition in oxygenated bottom waters effectively removes all easily oxidized organic material. In the resulting very small content of dissolved sulfide, Fe^{2+} would not precipitate as a sulfide. Berner (1964) has shown the stability fields of iron minerals for some typical sedimentary situations. Little is known about compositions of solutions in pelagic sediments; however, recently, on expedition "Amphitrite" (second leg) of Scripps Institution, measurements were made of pH of solutions squeezed, at 400 psi in a closed system, from red clay cored in 2500 fathoms of water near the Austral Islands. A rather dense and strong crust, composed mostly of manganese oxide material, was present at the surface of the sediment, and a typical carbonate-free red clay was beneath. The pH of the solutions was 6.9 to 7.0. If left open to the atmosphere, the pH climbed quickly to 7.3–7.4 (within minutes), and ultimately to 8.0–8.1 (within hours). Surely out-gassing of CO_2, as a result of changes in temperature and pressure, is responsible for this pH change. At high P_{CO_2}, the field of stability of magnetite becomes smaller, or vanishes completely, as it is supplanted by siderite (Berner, 1964). No siderite, however, is present in

these red clays, so it would appear that sufficient CO_2 is not dissolved in these solutions to form this mineral at the pressure and temperature involved. The sediment from the Indian Ocean, in which the maghemite was found, contained about 50% $CaCO_3$.

In a red or brown clay that is buried sufficiently to be effectively isolated from additions of oxygen, and which contains Fe^{2+} bearing minerals, such as olivine, that would be subject to further alteration, the Eh would be controlled by reactions such as:

$$\underset{\text{magnetite}}{2Fe_3O_4} + \underset{\text{liquid}}{H_2O} \leftrightarrows \underset{\text{hematite}}{3Fe_2O_3} + 2H^+ + 2e$$

involving both Fe^{2+} and Fe^{3+}. Other minerals, such as the hydrated ferric oxides, might be important in these reactions, but adequate thermodynamic data are not available. However, it is certainly permissive that magnetite could form. Once formed authigenically, it might then be further oxidized to maghemite, or possibly, in view of the direct precipitation of maghemite demonstrated by Bernal, *et al.* (1959), maghemite might form directly, howbeit, metastably. It may also be that, in some way, volcanic emanations or hydrothermal solutions have played some role. Evidence for recent volcanism, fresh glass at the surface, is present 240 miles south of the location of this magnetic mineral. If secondary oxidation has occurred, there must have been no attendant erosion and redeposition of the magnetite-maghemite bearing mud, because the maximum magnetic susceptibility direction has remained vertical. The formation of lepidocrocite and geothite is probably a still later event, being a coating on the outside of the fragments of magnetite-maghemite.

Summary

1. An unusual abundance of a highly magnetic mineral occurs in one core site from the central Indian Ocean.

2. Its magnetic and x-ray properties indicate that it is mostly maghemite, with some aspects of magnetite.

3. For the most part permissive arguments lead to the conclusion that it formed *in situ*.

4. The directions of maximum magnetic susceptibility of the sediment are generally vertical and the form of the susceptibility is that of a prolate ellipsoid.

Acknowledgments

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