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Bay-head Sand Beaches of Banks Peninsula, New Zealand

P. R. DINGWALL

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FOREWORD

The area of greatest mobility of Recent marine sediments lies in the beach and wave zones, and the same forces which produce this mobility can make observations and measurements difficult.

Until recently there has been little fundamental work on beach processes in New Zealand, though many of our coastal developments are highly susceptible to damage by erosion or accretion of beach sediments.

The author presents in this memoir results from a general study of a group of Canterbury beaches. Here the geographic features minimise the number of variables in the hydrological environment and thus allow a more ready consideration of factors in the process of beach development.

This manuscript has been technically edited and prepared for publication by Dr D. A. Burns, N.Z. Oceanographic Institute.

J. W. BRODIE, *Director,*
New Zealand Oceanographic Institute,
Wellington

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Bay-head Sand Beaches of Banks Peninsula, New Zealand

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Abstract

Analysis of the physical and mineralogical attributes of sands on 13 bay-head sand beaches of Banks Peninsula indicates that the beaches consist of medium sand derived from the bedrock of the peninsula and fine sand from greywacke-derived sediments mantling the adjacent continental shelf, and a contribution from the cover of loess on the peninsula. This indication is strongly supported by an evaluation of the capability of waves and currents in the vicinity of the peninsula to transport material. The beaches are arranged into three categories according to the origin of their sands: (1) those consisting predominantly of medium-grained heavy mineral sands derived largely from weathering of the peninsula's basic igneous rocks; (2) those consisting predominantly of fine, or very fine, light mineral sands derived from offshore sediments by constructive wave action; (3) those whose sands contain significant contributions from both the peninsula's bedrock and the detrital material on the shelf. On individual beaches the relative abundance of material derived from each of the two primary sources depends on the degree of exposure of the beach to wave action, which controls the strength of water movements in the bay head.

The results of beach surveying and sediments sampling indicate that the interplay between the beach deposit and hydrological forces in the bay head is analogous to that on exposed coastlines. Variation in sediment characters show correlations with differences in beach morphology. Gently sloping, smooth profiles on fine sands contrast with conspicuous berms and moderately steep beach faces on medium-grained sands. Sediment properties vary slightly, both across and along the beach as a result of selective sorting by wave and tidal action. The beaches change in response to differing wave and tide regimes. For example, large winter waves smooth out summer beach profiles by cutting back berms and redepositing the sediment on the lower foreshore. Similarly spring tides destroy small neap tide berms. Measurements of sand level changes during single tidal cycles show that beach material is being continually resorted. In addition to movement of sand normal to the shore there are lateral shifts caused by changes in the direction of wave approach. On the medium sand beaches changes in the beach profile are greater and more rapid than on beaches composed of fine sand. Successive surveys of profiles over a period of seven months showed that sand levels on the medium sand beaches fluctuated through a vertical range of as much as 4 ft (1.2 m) whereas the range on the fine sand beaches was commonly no more than 2 ft (0.6 m). On some beaches short-term changes in the profile were superimposed upon long-term progradation of the beach deposit itself.

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INTRODUCTION

This paper describes studies carried out on 13 of the larger sandy bay-head beaches of Banks Peninsula (*figure 1*), excluding those within Lyttelton and Akaroa Harbours. The area is covered by the New Zealand topographical 1 inch to 1 mile series (NZMS 1) Sheets S84 (Christchurch), S94 (Akaroa), and S85/95 (Okains and Goughs). Basic areal geology is outlined on the N.Z. Geological Survey Sheet No. 21, Christchurch, 1: 250 000.

Figure 1 Location of bay-head sand beaches on Banks Peninsula. The names of the 13 beaches investigated are underlined.

Acknowledgments

I express my sincere thanks to Dr D. E. Hurley and Dr H. M. Pantin of N.Z. Oceanographic Institute for use of echo-soundings and sediment samples; to Mr N. G. Robertson, N.Z. Meteorological Service, for wind data; to Dr D. W. Lewis, Geology Department, University of Canterbury, for permission to use laboratories and equipment; and to Messrs J. Dow and K. Liggett for assistance with mineralogical analyses. I am indebted to Dr R. F. McLean, Geography Department, University of Canterbury, for his guidance when the study was being planned, and for constructive criticism of the manuscript. Thanks are due also to Messrs R. Macefield and K. Taylor for accommodation; to Mr D. Johnson for the aerial photographs; to Mr B. Knight for the use of his fishing boat; to commercial fishermen at Akaroa and Lyttelton and to local residents, for useful information.

AREA STUDIED

BANKS PENINSULA

Banks Peninsula comprises two dominating calderas and is characterised by a radial pattern of drowned valleys and near-vertical plunging cliffs that terminate long sloping interfluves separating small bay-head beaches. The sweeping shore lines to north and south bordering the Canterbury alluvial plain emphasise the unique character of the peninsula among New Zealand coastal features.

The Peninsula occupies a roughly elliptical area, 50 km by 30 km with a circumference of 130 km, the highest point being 3014 ft (914 m) above sea level. The peninsula is the eroded remnant of two Late Tertiary or Pleistocene volcanic domes composed predominantly of andesitic and basaltic flow rocks. The eruptive centres were located in the area which is now the upper parts of Lyttelton and Akaroa Harbours (Liggett & Gregg 1965). After erosion of the Lyttelton and Akaroa calderas and the cutting of an almost radial series of valleys, olivine basalt flows were erupted as valley fillings at the western end of the peninsula. Isostatic adjustments and eustatic rises of sea level formed the two harbours from the calderas and drowned the lower reaches of the radial valleys to produce a series of fiord-like inlets.

Because of periodic changes of sea level during successive Pleistocene glaciations the peninsula has been isolated as an island several times. The lower reaches of valleys on the western flank of the Lyttelton volcano are now filled with alluvium deposited by aggrading Canterbury rivers. Valleys to the north, east, and south, however, have remained open to the sea so that most of the bays indent the margin of the Akaroa volcano. Taylors Mistake beach is the only one investigated which lies on the flank of the Lyttelton volcano.

Modification of the peninsula since the post-glacial rise of sea level has been effected largely by marine processes. Longshore drift has washed gravels northwards from the actively retrograding shore line further south (Speight 1930) and sands have been moved southwards along the shore line of Pegasus Bay (Jobberns 1928), "landlocking" several former bays. Present-day continuation of this process of bay filling is discussed below.

THE BAY-HEAD SAND BEACHES

Within the valleys (*figure 2*) sediments washed from surrounding slopes and offshore areas form the foundations for the beaches. Where the sediment is largely locally derived, small bay-head deltas are formed consisting of volcanic cobbles and boulders, the coarse fraction of the load carried by local streams. Where valley plains have been built up by wave action, sand and silt are the dominant constituents. Lateral extension of the valley plains is limited by the valley walls, but the longitudinal extent is a function of the quantity of material accumulated. The landward boundaries of some beaches are characterised by steep cliffs or boulder banks, but elsewhere mudflats, sand ridges, and dunes occur.

The beaches are 200 to 800 m long and 85 to 200 m wide, and display a variability in the quantity of beach material. For example, in Flea, Peraki, and Te Oka bays, the beach is no more than a shallow veneer of sand on the outer margin of the alluvial delta, whereas Okains and Le Bons bays, have a large accumulation of sand. The beaches differ also in their degree of exposure to the action of waves and currents (*table 1*). At Goughs Bay the beach lies only 0.5 km inside the adjacent headlands, which stand 1.5 km apart, whereas the beaches of Long, Flea, Peraki, and Te Oka bays are 1.5 km or more from their headlands and less than 0.8 km in width. Several of the beaches are well protected because the bay changes direction from beach to entrance.

GEOLOGICAL SETTING

ROCKS OF BANKS PENINSULA

The peninsula is formed from the Lyttelton and Akaroa volcanoes. The Lyttelton volcano consists of lava flows with some pyroclastics and dykes (Liggett & Gregg 1965). Basalt and andesite are the dominant rock types, trachyte is common and olivine basalt rare. A sequence of younger olivine-rich basalts form valley fillings within Lyttelton Harbour, Port Levy, and Kaituna Valley. Similar basalts crop out on the western Port Hills (Liggett & Gregg 1965). The Akaroa volcano is less well known geologically than the Lyttelton volcano, but appears to be similar in structure and composition. It is younger and has buried much of the south-eastern flank of the Lyttelton volcano.

Deep dissection of the flanks of the Lyttelton and Akaroa volcanoes initial domes by consequent streams, coupled with mature cliffing of the distal ends of spurs by wave action, have produced large quantities of erosional debris from the igneous rocks of the peninsula.

Greywacke-derived loess forms an extensive mantle over the peninsula. The average thickness of the deposit being 6 ft (1.8 m) but more than 25 ft (7.5 m) in places near the coast (Raeside 1964). The loess contains 60 percent coarse silt and fine sand (Birrell & Packard 1953). Much of the loess has been eroded from the steep slopes and deposited on the shelf. A small area of basement greywacke rock outcrops at the head of Lyttelton Harbour.

SEDIMENTS OF THE CONTINENTAL SHELF

There has been considerable accretion of sandy and muddy sediments on the continental shelf around the peninsula. Underlying this detrital material is river alluvium representing the former extension of the Canterbury Plains beneath present sea level (Suggate 1968).

Reed (1951) analysed offshore sediments and Cullen and Gibb (1966) mapped the general surface sediment distribution (*figure 3*). The floor of Pegasus Bay to a depth of 10 fm (18 m) is mantled with greywacke-derived fine and medium sands. Beyond this the dominant covering is mud, with fine sand as a subsidiary fraction in some areas (Reed 1951, Cullen & Gibb 1966, Hydrographic Chart NZ63). East of the peninsula, medium and fine sands dominate the superficial shelf sediments, though they are frequently associated with mud and organic residues.

South of the peninsula the sediments are predominantly fine grey sand, though sandy muds and shelly sands are present over small areas.

Offshore relief is illustrated by the contoured chart (*figure 3*) which also shows the location of the representative shelf profiles in *figure 4A*.

SHELF MORPHOLOGY

The outstanding features of the shelf surface in Pegasus Bay and Canterbury Bight are its regularity and flatness. Across Pegasus Bay gradients are generally less than 1 in 1200 with few surface irregularities. Off Birdlings Flat the bottom dips very gradually; for a distance of 15 km from the beach the gradient is only 1 in 800. Beyond this, between the 10 fm (18 m) and 40 fm (72 m) contours, the gradient increases slightly to 1 in 460. Forty-five kilometres from shore the water depth is still less than 50 fm (90 m). Off the peninsula's eastern margin the shelf surface is more irregular, being formed of steep slopes falling away from cliff bases and bay entrances and merging into moderate slopes with an average gradient of 1 in 120 as far as the 40 fm (72 m) contour. Between the 40 fm (72 m) and 50 fm (90 m) contours, however, the undulating surface has an overall gradient of only 1 in 1000.

A flat and notably shallow area lies off the north-eastern bays within the 10 fm (18 m) contour. Although this contour is only 1.8 km offshore at Pigeon Bay and 0.5 km at East Head (the easternmost extremity of the peninsula), it is almost 9 km offshore at Raupo Bay. This indicates shoaling in the lee of the peninsula, a phenomenon of importance in the supply of sediment to neighbouring beaches.

Sedimentation in the bays since postglacial submergence has created gently sloping bay floors. Longitudinal profiles show the regularity of the bay floor from beach to bay entrance (*figure 4B*), slopes being steeper in the more exposed bays. The most outstanding feature is illustrated by the transverse profiles (*figure 4C*), located approximately midway between beach and bay entrance, showing the marginal cliffs of the bays plunging without interruption to flat bay floor. This box-like transverse profile is very atypical of drowned river valleys. The silts in the deepest part of a typical ria grade uniformly into sands and gravels at the channel sides so that the floor assumes a rather stable V-shaped cross profile. However, sands and gravels derived by local wave erosion are generally absent from the peninsula's shores. The superficial sediments are silts derived from weathered

	BEACHES							Mineralogy (% by wt.)			BAYS			
	orient- ation	*length* m	*width* m	*expo- sure* (1)	*dominant sediment grade* (2)	*sorting* (3)	*mean roundness coefficient*	*quartz*	*magne- tite*	*other heavy mins.*	*entrance orient- ation*	*expo- sure* (4)	*entrance width* km	*length* km
Group I														
Taylors Mistake	ENE	320	90	e	m s	v w	0.30	12	37	28	NE	w	2.0	1.2
Goughs	E	500	80	e	m s	w	0.30	9	54	32	E	w	1.6	1.0
Ikoraki	WSW	300	80	e	m s	m w	0.30	8	53	35	WSW	w	0.4	0.4
Group II														
Raupo	ENE	685	185	s	f s	v w	0.39	52	5	2	E	w	1.2	1.0
Okains	NE	800	200	s	f s	v w	0.36	58	3	2	NE	m	1.2	2.4
Le Bons	NE	730	200	s	f s	v w	0.35	54	6	3	ENE	m	1.2	2.4
Peraki	S	320	105	s	v f s and silt	w	0.34	59	5	1	SW	l	0.8	2.4
Group III														
Lavericks	NE	320	120	s	f s	v w	0.35	41	21	9	ENE	l	0.5	0.8
Hickory	SE	640	100	s	f s	w	0.32	19	33	20	SE	w	1.6	1.2
Long	SE	185	105	s	f s	w	0.35	13	34	22	SE	l	0.5	1.6
Flea	S	230	45	s	f s	v w	0.33	34	27	10	SE	l	0.5	1.6
Te Oka	SSW	185	90	s	f s	v w	0.34	34	14	14	SSW	l	0.8	1.6
Tumbledown	S	185	185	s	f s	v w	0.32	30	18	16	SW	l	0.4	0.5

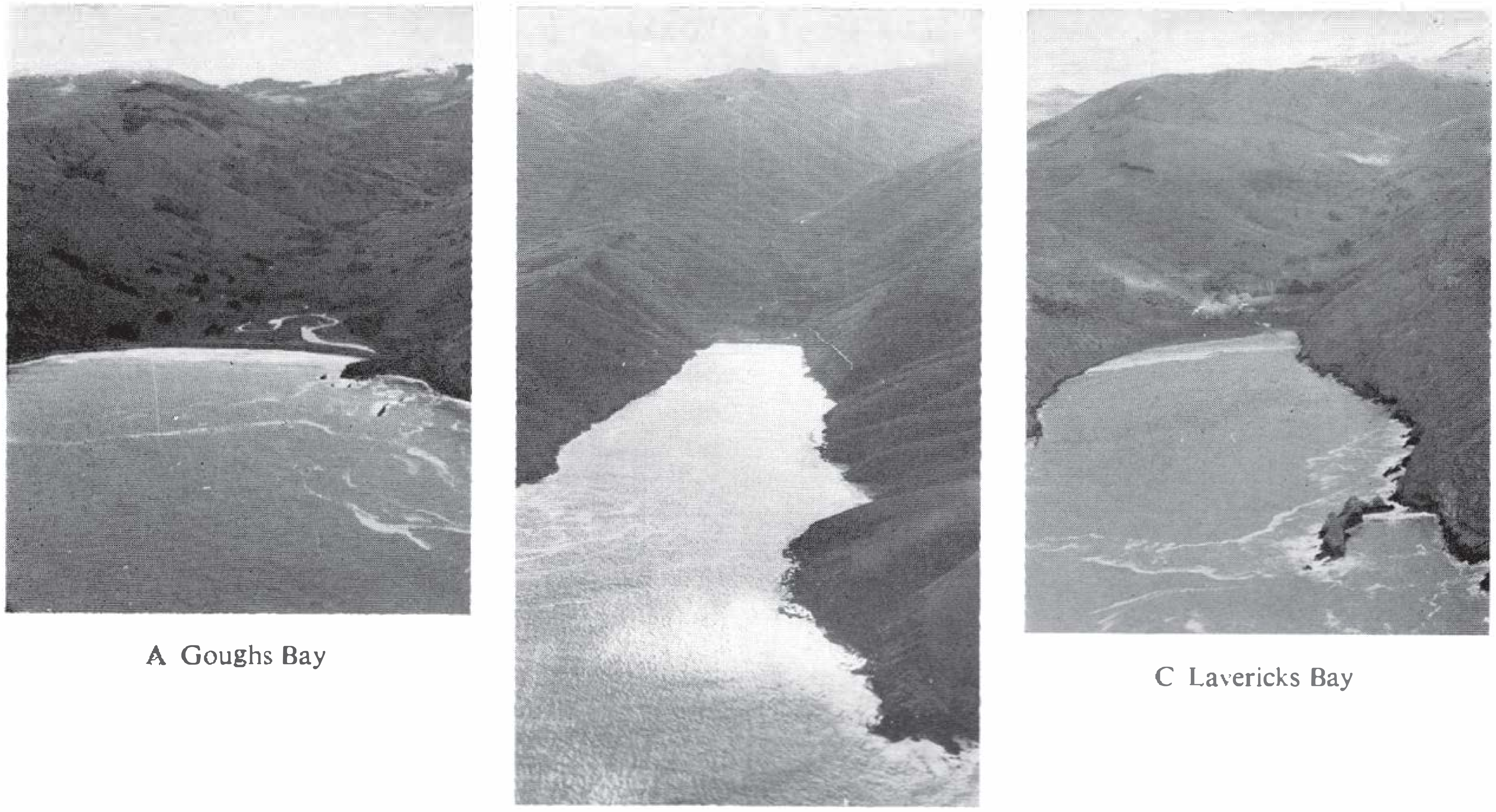
(1) e = exposed, s = sheltered

(2) m s = medium sand, f s = fine sand,
v f s = very fine sand

(3) w = well sorted, m w = moderately well sorted
v w = very well sorted

(4) w = well exposed, m = moderately exposed,
l = least exposed

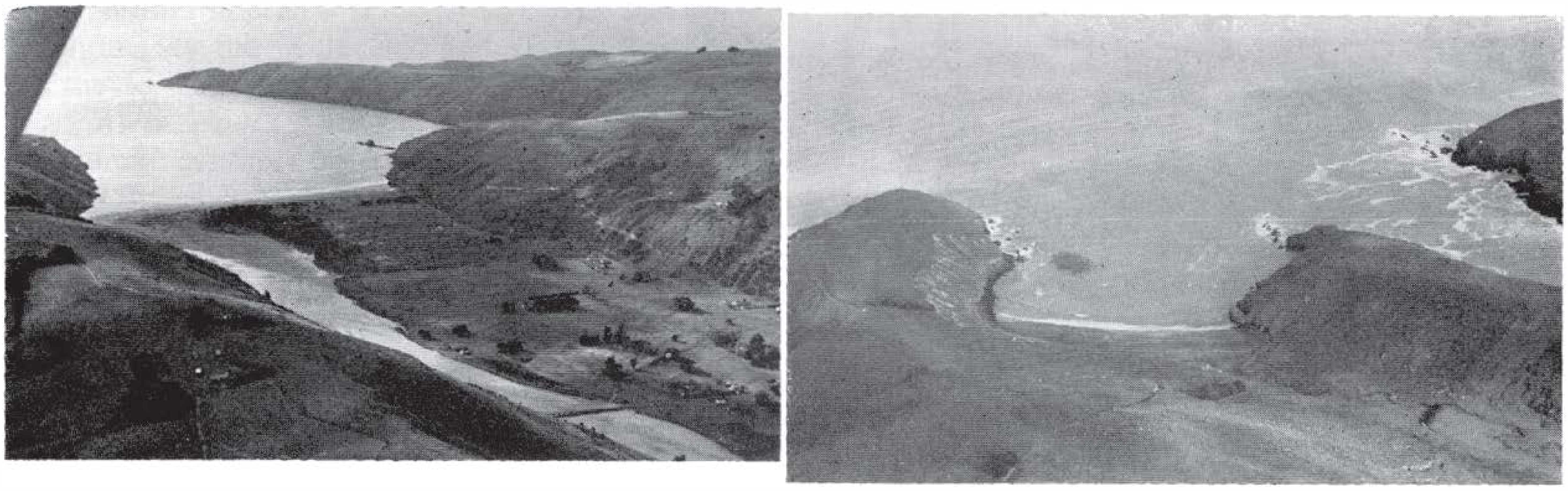
Table 1 Properties of bays and beaches investigated and a grouping of beach types



A Goughs Bay

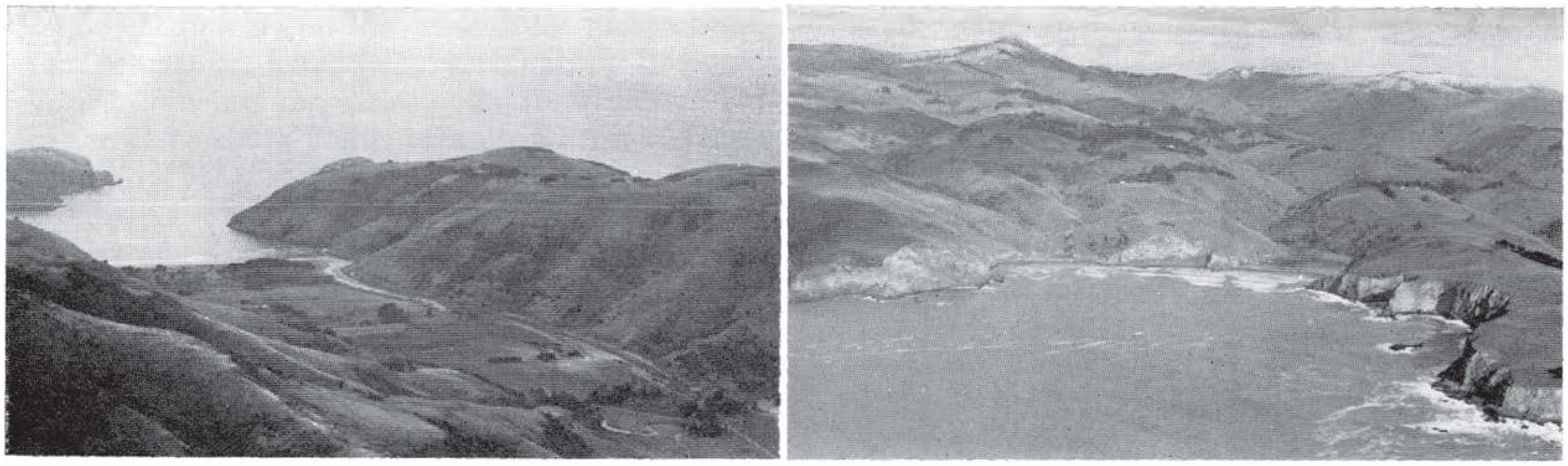
B Te Oka Bay

C Lavericks Bay



D Okains Bay

E Ikoraki Bay

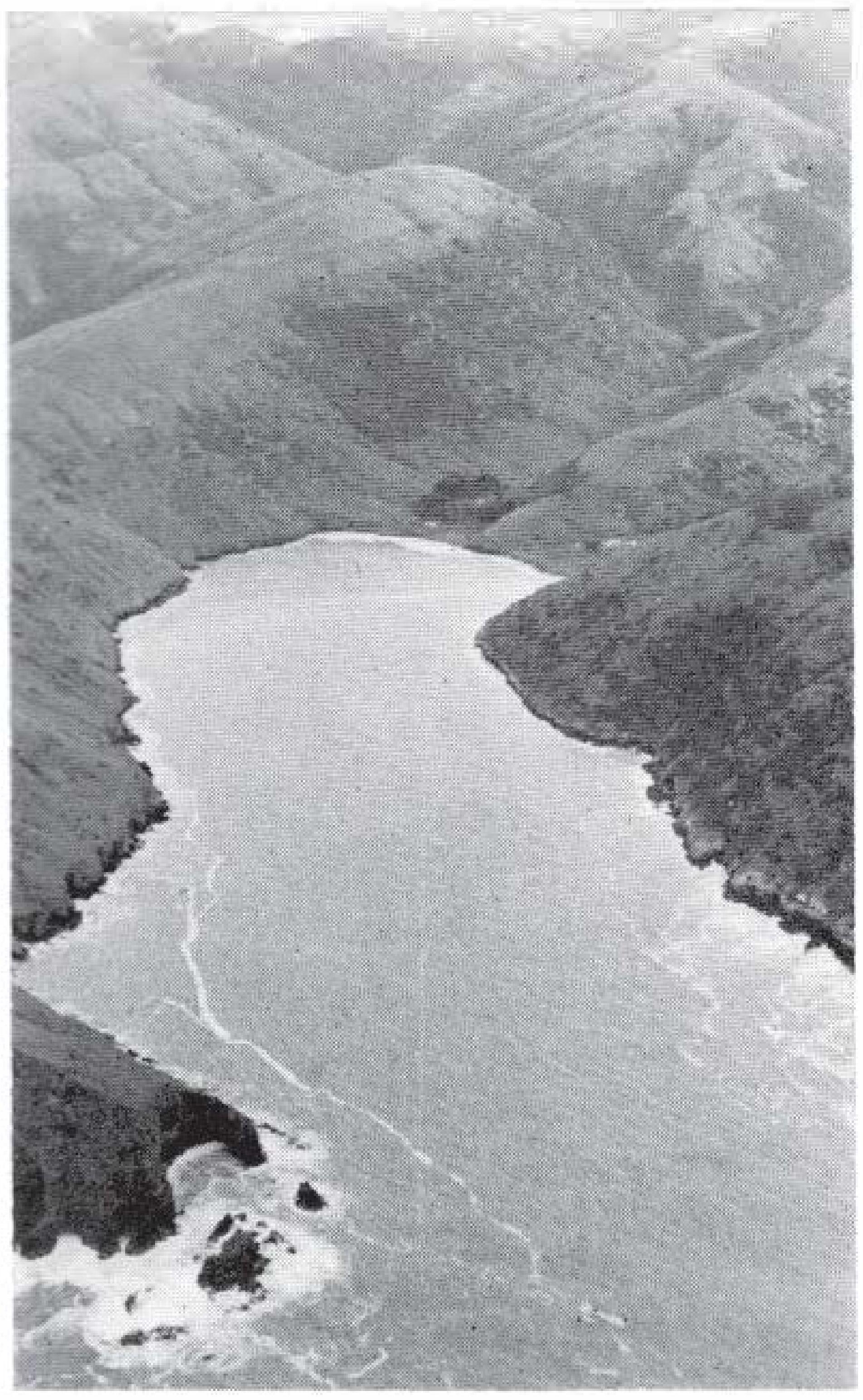


F Le Bons Bay

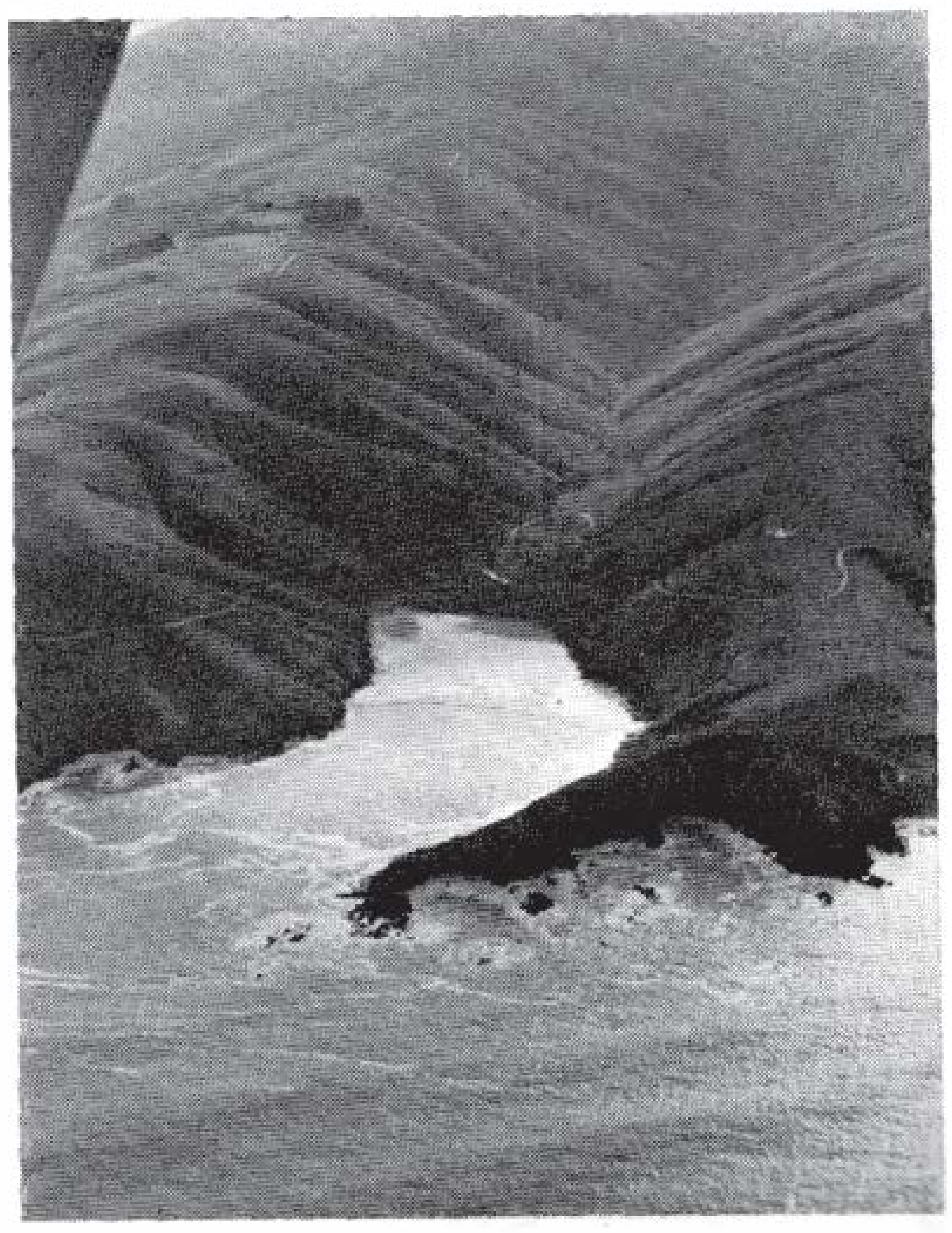
G Raupo Bay

Figure 2 General views of beaches investigated.

H Long Bay

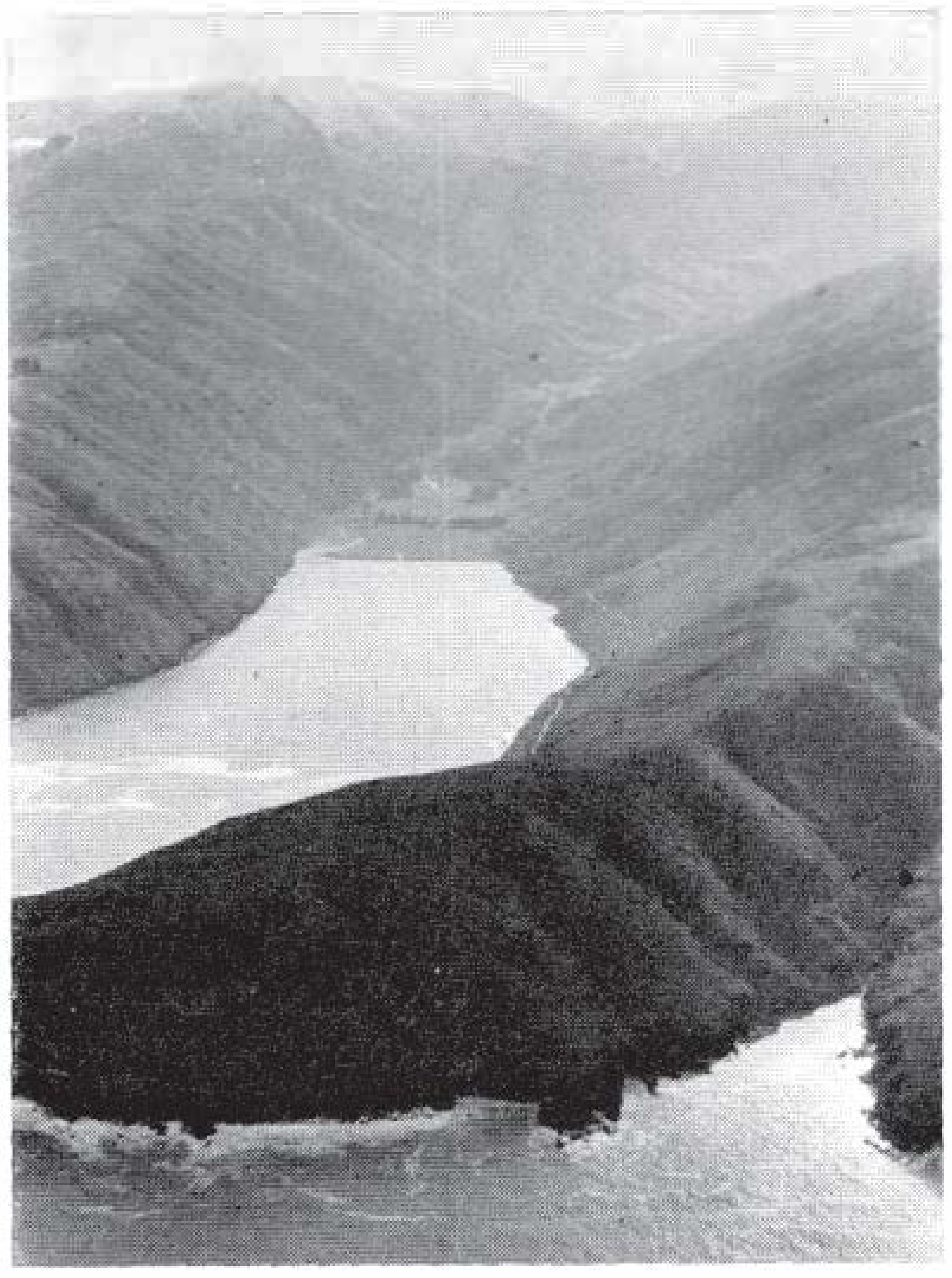


J Flea Bay



K Tumbledown Bay

M Taylors Mistake



L Peraki Bay

N Hickory Bay

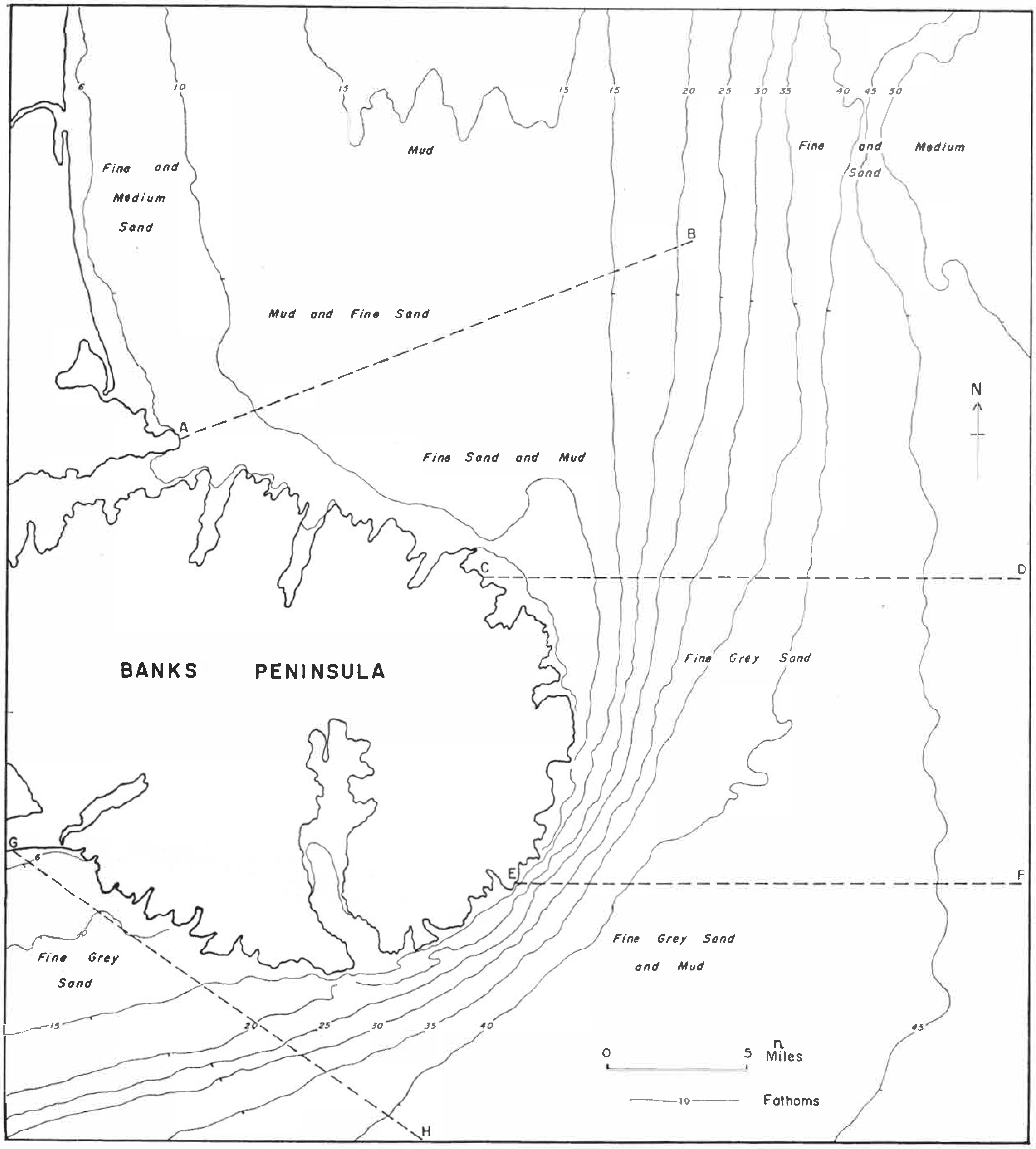
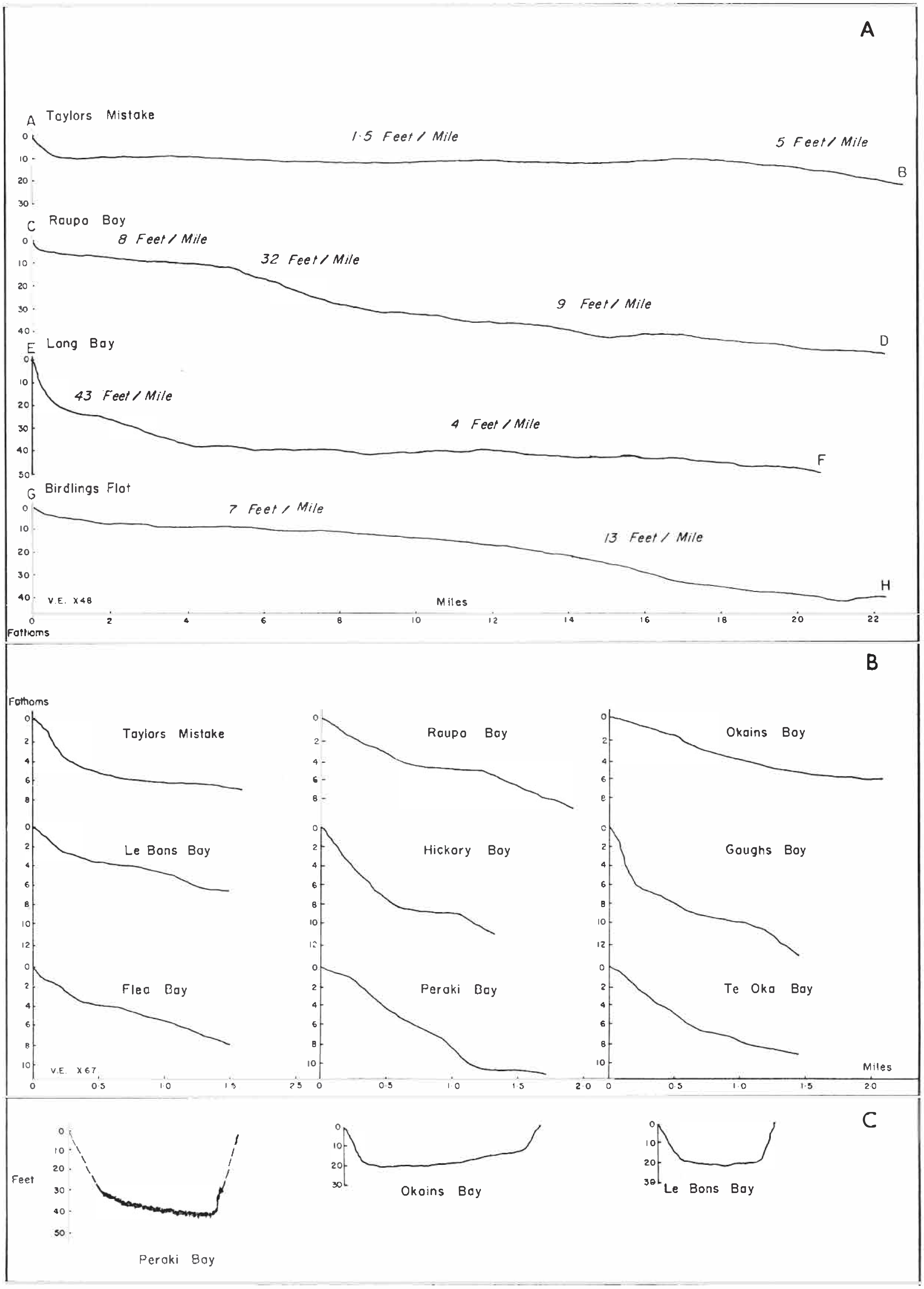


Figure 3 Submarine relief and sediments offshore from Banks Peninsula. The locations of shelf profiles *(figure 4A)* are shown.

Figure 4 A Selected continental shelf profiles. For locations see *figure* 3.
B Longitudinal profiles on central axes of bays.
C Transverse bay profiles located approximately midway between bay-head and entrace. That for Peraki Bay is an echograph tracing.


A
A Taylors Mistake
1·5 Feet / Mile
5 Feet / Mile
B
C Raupo Bay
8 Feet / Mile
32 Feet / Mile
9 Feet / Mile
D
E Long Bay
43 Feet / Mile
4 Feet / Mile
F
G Birdlings Flat
7 Feet / Mile
13 Feet / Mile
H
V.E. X48
Miles
Fathoms
0 2 4 6 8 10 12 14 16 18 20 22
B
Fathoms
Taylors Mistake
Raupo Bay
Okains Bay
Le Bons Bay
Hickory Bay
Goughs Bay
Flea Bay
Peraki Bay
Te Oka Bay
V.E. X67
Miles
0 0·5 1·0 1·5 2·5 0 0·5 1·0 1·5 2·0 0 0·5 1·0 1·5 2·0
C
Feet
Peraki Bay
Okains Bay
Le Bons Bay

loess washed from surrounding slopes. The box-like transverse profile is attributable to the steep drowned cliffs and the mobile nature of the loess-derived sediments on the bay floors (Cotton 1949).

The trench-like form of the bays produces an uncommon pattern of dissipation of wave energy and influences the supply of material to the beaches.

PREVIOUS INVESTIGATIONS

The structural and erosional geology of Banks Peninsula has been described by von Haast (1879), Speight (1943, 1944), and Cotton (1949, 1951). A further account by Liggett and Gregg (1965) incorporates some of the findings of more recent research. Some descriptions of beach sand deposits have been made by zoologists whose studies of faunal populations necessitated an analysis of the substratum (Dawson 1953, Knox 1954, MacIntyre 1963).

Few studies of beaches on deeply indented coast have been carried out elsewhere. Krumbein (1947) and Shepard (1950) discussed the movement of beach sand in restricted bays on the Californian coastline, and Trask (1955) investigated the movement of sand between bays. Elliot (1958) and Hodgson (1966), studying beaches of Otago Peninsula, dealt with an area structurally similar to Banks Peninsula, but in which the beach deposits are formed of spits which bridge the bay mouths. This contrasts with the bay-head beaches examined in the present study.

PURPOSE OF INVESTIGATION

On embayed coastlines bay-head beaches can be isolated from potential sources of sediment by headlands which prevent the movement of material along the shore. Such beaches are composed mainly of material supplied from their immediate hinterlands. Baak (in King 1959, p. 154) found that in a French coastal area of varied geological composition each bay had its own particular mineral assemblage composed wholly of locally derived material. Similar investigations of Californian beaches (Trask 1955) however, have shown that they can be nourished by material which is transported around headlands.

The study was carried out:

1. To describe the bay-head beaches in the light of known beach processes in terms of–
   (i) shape of the beach
   (ii) variation in beach sediment properties and responses both normal and parallel to the shore
   (iii) changes in beach plan and profile
   (iv) hydrological forces
2. To examine the relative significance of long-shore drift, emplacement from shelf deposits, and local sources in the supply of sediment to bay-head beaches; and the environmental factors controlling the processes of beach formation.

METHODS OF STUDY

The investigation involved a total of 48 days field observations between February and August 1966. Thirteen bay-head beaches were studied. All beaches (except Flea Bay to which access was difficult) were visited at least twice, and those with easier access were visited six times.

The relationship between beach morphology, sediment characteristics, and hydrological parameters was investigated. At each locality, therefore, either two or three beach profiles extending from fixed reference points out to the low tide surf zone were surveyed with tape and Abney level. Sediment samples were collected from the different morphological zones and hydrological and meteorological conditions were observed. Interviews with local residents and commercial fishermen yielded further information on long-term beach changes and characteristics of waves, tides, and currents. Boats were occasionally available through the co-operation of local fishermen.

Mechanical and mineralogical analyses of beach sediments were carried out by the following methods.

Grain Size

A stratified sampling method was used for sample selection (Krumbein 1954). A sampling line traversing the successive morphological zones (coast, backshore, foreshore, and nearshore) was selected as close as possible to the middle of the beach. One sample collected at random from each zone (or sampling stratum) gave a set of random samples for each beach. A uniform sample, approximately 3 in. diameter and 2 in. deep (75 by 50 mm) was obtained by pressing a small plastic container into the sand. The standard dry sieving procedures (*see* Folk 1965, Krumbein & Pettijohn 1938) were followed. Samples were washed, dried, and approximately 100g shaken for 20 minutes in a sieve shaker. Results were expressed in phi (ϕ) units for computation of statistical parameters and the Wentworth classification was used to define sediment size. Cumulative curves of grain size distribution were plotted for each sample on linear probability paper (frequency against grain size in phi (ϕ) units) and from this, statistical parameters (Folk & Ward 1957) were calculated.

Roundness

A small subsample from the coarsest fraction common to all beach sands (0.210 mm to 0.300 mm) was used to study roundness. Each subsample was spread on a tray and examined under a binocular microscope: 50–100 quartz grains were counted and assigned to one of six classes by comparison with a photographic chart (Powers 1953). The average roundness coefficient of each sample was calculated by multiplying the number of grains in each class by the geometric mean of that class. The sum of the products was divided by the total number of grains counted.

Carbonate content

Fifty grams of sand was treated with dilute hydrochloric acid, filtered, washed, dried, and reweighed. The loss of weight, as a percentage of the original weight, was taken as the carbonate content.

Mineralogy

A small subsample from the mid-tide reference point was subjected to heavy-mineral separation in bromoform. The heavy minerals were further subdivided with a Frantz magnetic separator and the grains mounted in Canada balsam for identification on a petrographic microscope.

Magnetite percentage was assessed by searching 10 g of sand with a magnet and the weight of material removed was expressed as a percentage of the original sample weight.

The quartz content was assessed by counting several hundred mineral grains per sample and expressing the number of quartz grains as a percentage of the total.

Changes in beach level during tidal cycles were measured as follows:
A control-grid of wire rods in rows normal to the shore line was established on the foreshore (*table 2*). Rods were initially established with 18 in (0.5 m) projecting above the sand surface. Changes in sand level were assessed by measuring the difference in height of each rod above the surface relative to the original height. The effects of four successive spring tide cycles on two beaches were assessed in this way.

Hydrographic Charts NZ63 Kaikoura to Banks Peninsula 1 : 200 000 (1953), NZ6321 Lyttelton Harbour 1 : 25 000 (1952); NZ6324 Akaroa Harbour 1 : 30 000 (1954) published by the Hydrographic Branch, Navy Office, Department of Defence, Wellington, allowed an analysis of offshore conditions to be made. Information regarding offshore sediments was available from the chart by Cullen and Gibb (1966). Reference was made to detailed charts of the echo-sounding surveys by HMNZS *Lachlan* (1952–3) and to the Hydrographic Chart based on the survey of HMS *Acheron* (Sheet L9831, 1857 – in NZOI records) to establish differences in coastal conditions from those existing at the present time. Lands and Survey Department aerial photographs and mosaics were available for all of the beaches studied.

	Okains Bay	*Goughs Bay*
no. of rows of rods in grid	3	3
interval between rows	50 ft (15 m)	700 ft (213 m)
no. of rods in each row	18	12
interval between rods	25 ft (8 m)	20 ft (6 m)
wave approach	NE	SE
wave period	10 sec	9-10 sec
wave height at breakpoint	3-4 ft (0.9-1.2 m)	8-10 ft (2.4-3.0 m)
breaker type	spilling	plunging
wind direction	onshore	offshore
wind speed	5-10 mph	10-15 mph
average foreshore gradient	1 in 45	1 in 15
mean grain size	0.13 mm	0.26 mm

Table 2 Layout of control-grid for measurement of sand levels and wave energy conditions during successive tidal cycles

PART I BEACH MORPHOLOGY

CLASSIFICATION OF BEACH PROFILES

Configuration of the beach profile, indicates the peninsula's bay-head sand beaches may be grouped into three classes (*table 3*).

A Beaches with berm development and short, comparatively steep foreshores – Ikoraki*, Goughs, Taylors Mistake, and Long bays.

The berm surface is often almost horizontal or may slope slightly landward (*figures 5, 6*). It varies in size throughout the year, but may be as much as 45 m wide with a prominent seaward berm edge just above the mean high water mark. This edge is the boundary between the backshore and foreshore zone.

Because the foreshore is moderately steep it has a limited areal extent. It is distinctly concave in profile, with the upper foreshore often attaining a slope of eight degrees.

Shape modification occurs by construction of secondary berms, especially at times of calm seas or neap tides, and development of cusps. These were present only at Taylors Mistake, Ikoraki, and Goughs bays where the sand is coarser and less uniform in texture than elsewhere (*figures 5, 6*). Cusps were found only during moderate summer wave action being regular in shape and apical spacing, e.g., at Goughs Bay all nine cusps were spaced at intervals of 95 to 105 ft (29 to 32 m) and at Ikoraki Bay eight of 11 cusps were 60 to 70 ft (18 to 21 m) apart. Where double berms existed cusps often serrated the edges of both, although on

	mean grain size mm	*backshore width* m	*average backshore gradient*	*foreshore width* m	*average foreshore gradient*
(A)					
Ikoraki	0.47	46	1:300*	30	1:17
Goughs	0.28	14	1:25	64	1:20
Taylors Mistake	0.25	23	1:300	76	1:20
Long	0.21	30	1:51	73	1:20
(B)					
Hickory	0.18	23	1:24	78	1:32
Lavericks	0.18	30	1:30	91	1:40
Tumbledown	0.13	46	1:120	137	1:51
Le Bons	0.14	21	1:24	125	1:60
Okains	0.13	18	1:90	137	1:60
Raupo	0.13	38	1:120	145	1:120
(C)					
Flea	0.14	-	-	46	1:30
Te Oka	0.14	-	-	76	1:40
Peraki	0.10	11	1:36	96	1:40

*landward gradient

Table 3 Classification of beaches according to configuration of beach profile (summer conditions)

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*The name Ikoraki Bay is in common usage in the area. Other names for this bay are: Hikuraki Bay (NZMS1, Sheet S94, Akaroa) and Ikirangi Bay (Geological Map of N.Z. Sheet 21).

Figure 5 Beach profile at Taylors Mistake. Staffs mark cusp horns.

Figure 6 Beach profile at Goughs Bay. Cusps serrate the berm edge.

Figure 7 Beach profile at Okains Bay. Foreshore surface modified by development of backwash ripples.

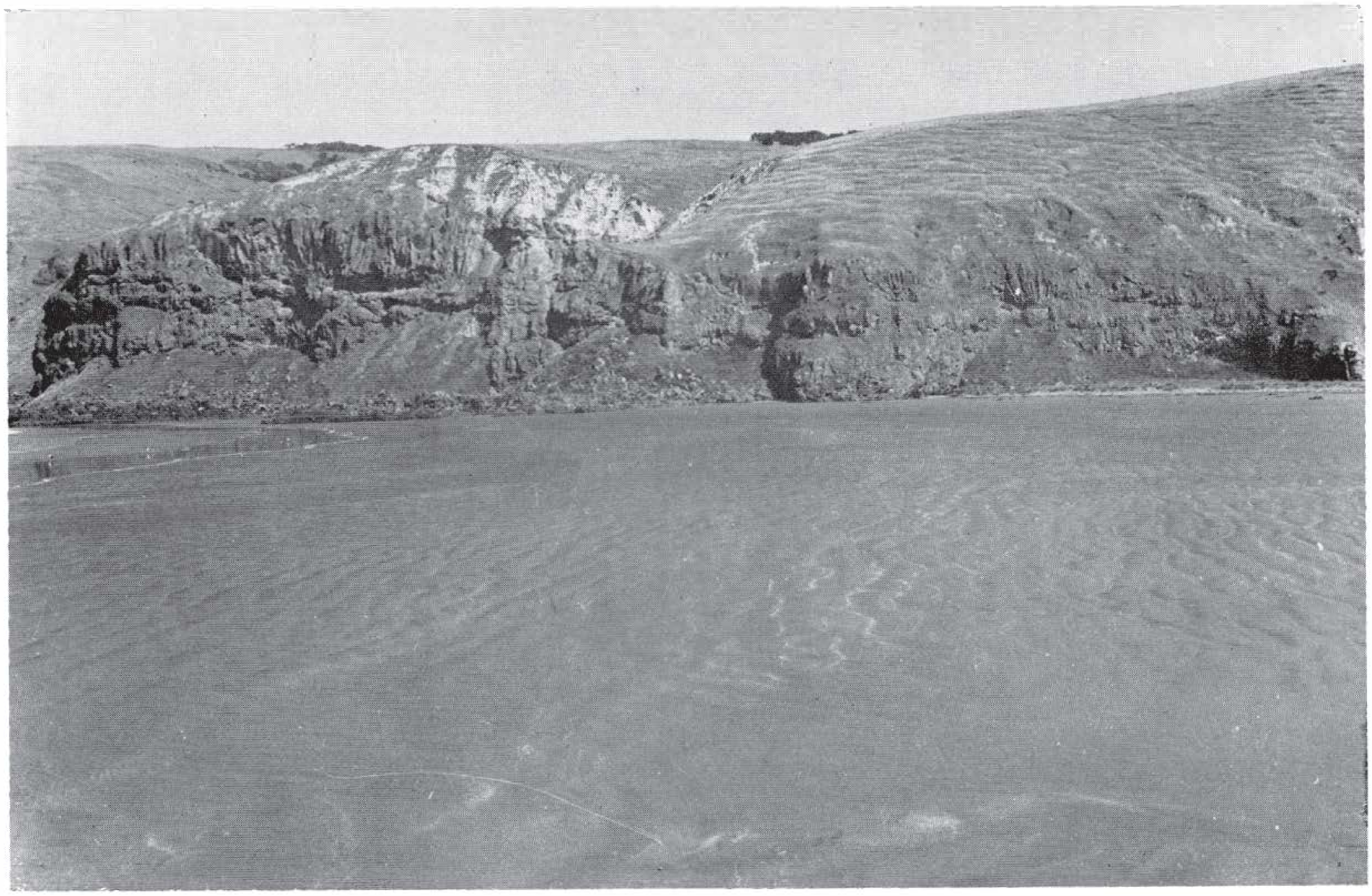

Figure 8 Beach profile at Raupo Bay. Foreshore approximately 140 m wide.

the lower berm they were more closely spaced than on the upper one.

B Beaches with gently-sloping, smooth profiles and extensive foreshores – on the fine sands of Raupo, Okains, Lavericks, Le Bons, Hickory, and Tumbledown bays (*figures 7, 8*).

The dominant zone is the foreshore, which at Okains and Le Bons bays is 275 m wide. The foreshore surface may be modified by development of broad, flat backwash ripples characteristically 18 in (0.5 m) wide. These are separated by narrow troughs approximately 25 mm deep in which fine shells, shell fragments, sponge spicules, and plant material accumulates.

The gradient of the backshore differs little from that of the adjacent foreshore. The transition area between backshore and foreshore is therefore broad and accurate delimitation of the two zones is difficult. Only at Le Bons Bay is there an irregular foreshore slope. Near the stream outlet sand has been built up by waves into a low ridge on the lower foreshore separated from the backshore by a shallow runnel (*figures 9, 10*).

C Beaches with gently-sloping, smooth, sand profiles, backed by steep banks of boulders and cobbles – Flea, Peraki, and Te Oka bays.

At these beaches the sand profile terminates on its landward side at the base of a bank of storm-tossed, basalt cobbles and boulders, rising 7 to 8 ft (2.1 to 2.4 m) and sloping at an angle of 7 to 10 degrees (*figures 11, 12*). The sand deposit has a gently-sloping, smooth, and firm surface extending seaward for a distance of up to 105 m. All of the sand at Flea and Te Oka bays is influenced by swash-backwash and surf action, the profile is therefore remarkably straight. At Peraki Bay the upper foreshore is only affected by swash-backwash, which permits some build-up of the beach in this area, and makes the sand profile slightly concave upwards.

RELATIONSHIP BETWEEN BEACH GRADIENT AND GRAIN SIZE

On exposed beaches the size of material plays a major role in determining the gradient of the foreshore, steeper gradients being associated with coarser material. When a sample is taken on the foreshore in the mid-tide zone and the slope is measured at the same place, there is a consistent relationship between grain size and gradient (Bascom 1951). On the peninsula's less exposed bay-head beaches a similar close relationship exists between grain size and foreshore slope (*table 3*). As mean grain size increases (i.e., as phi (ϕ) decreases) mid-tide slope increases. The correlation coefficient between the two variables was —0.93 (*figure 13*).

SORTING OF BEACH SANDS

The characteristics of beach materials vary both across and along the beach as a result of selective sorting by waves, tides, and wind (Bascom 1951, Inman 1953).

SORTING NORMAL TO THE SHORE

Sand on the lower foreshore is coarser than on the upper foreshore, though the difference between their mean diameters is only 0.01 to 0.06 mm. Furthermore, the finer, upper foreshore sand is better sorted than the coarser sand on the lower foreshore (*table 4*).

Sands are coarser on the backshore than on the adjacent foreshore but are not less well sorted than foreshore sands (*table 5*).

Distinction between dune and beach sands on the basis of size and degree of sorting is not marked. In seven beaches showing dune development, dune sands are finer at Taylors Mistake, Okains, Le Bons, and Ikoraki bays, but at Taylors Mistake, Raupo, Okains, Le Bons, and Goughs bays they are better sorted than adjacent backshore sands. It is not possible to distinguish beach and dune sands from their skewness, except for the dune sands at Taylors Mistake which were positively skewed (*table 6*).

SORTING PARALLEL TO THE SHORE

Particle size was found to vary with change in the distribution of wave energy along the beach (*table 7*).

SEASONAL VARIATION IN GRAIN SIZE

Grain size is largest where wave energy is greatest. Increased expenditure of wave energy on the beach during winter is accompanied by an increase in grain size. As most of the peninsula's beaches are composed of fine sand with uniform texture, seasonal variation in grain size is not marked. Generally, mean grain size increases by 0.01 to 0.05 mm during the winter, but at Hickory Bay the increase was 0.12 mm (*table 8*). Only at Taylors

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Figure 9 Ridge and runnel at Le Bons Bay exposed during low tide.

Figure 10 Spilling breakers marking the position of the ridge at Le Bons Bay during high tide.

Figure 11 Beach profile at Peraki Bay.

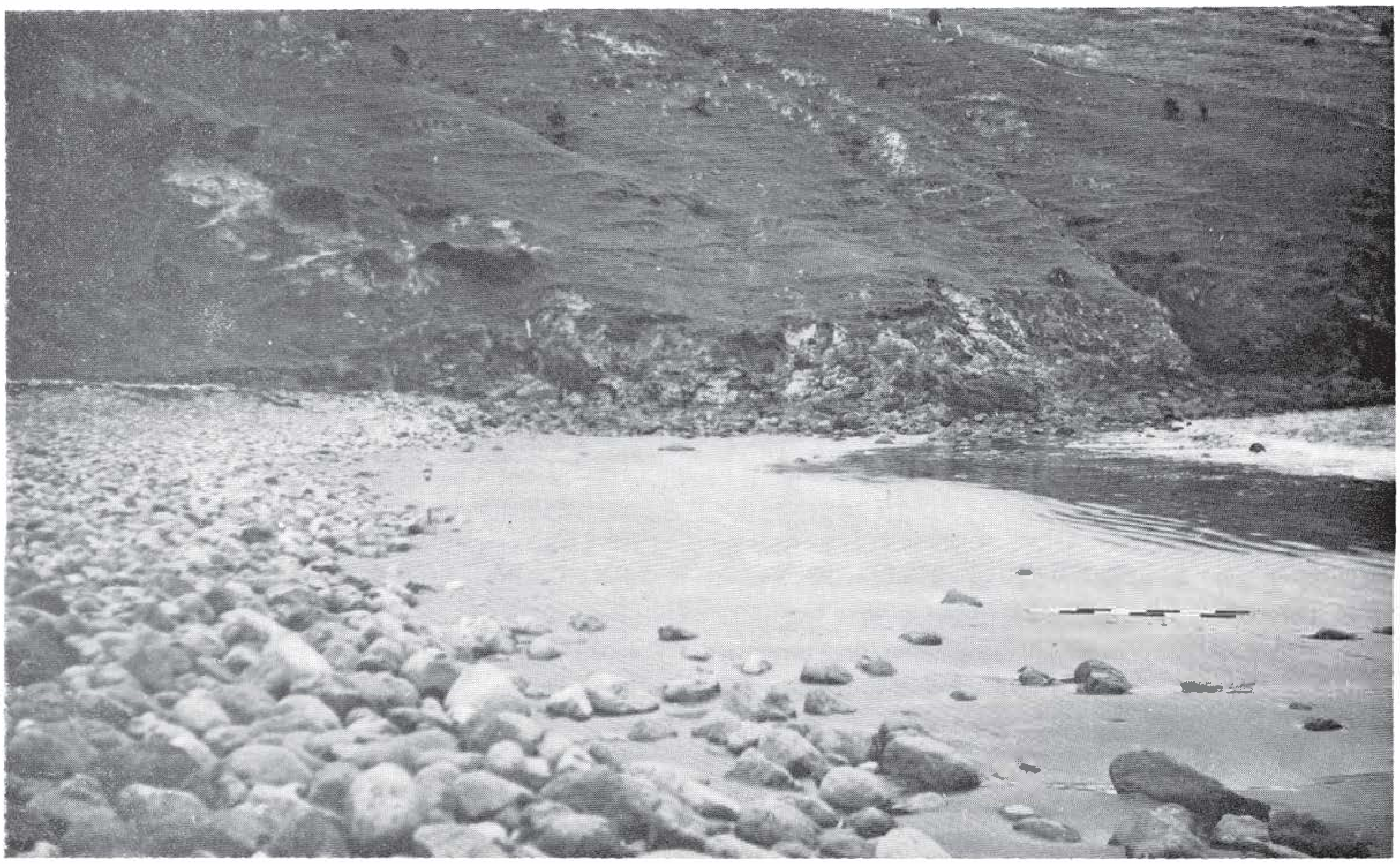


Figure 12 Beach profile at Flea Bay.

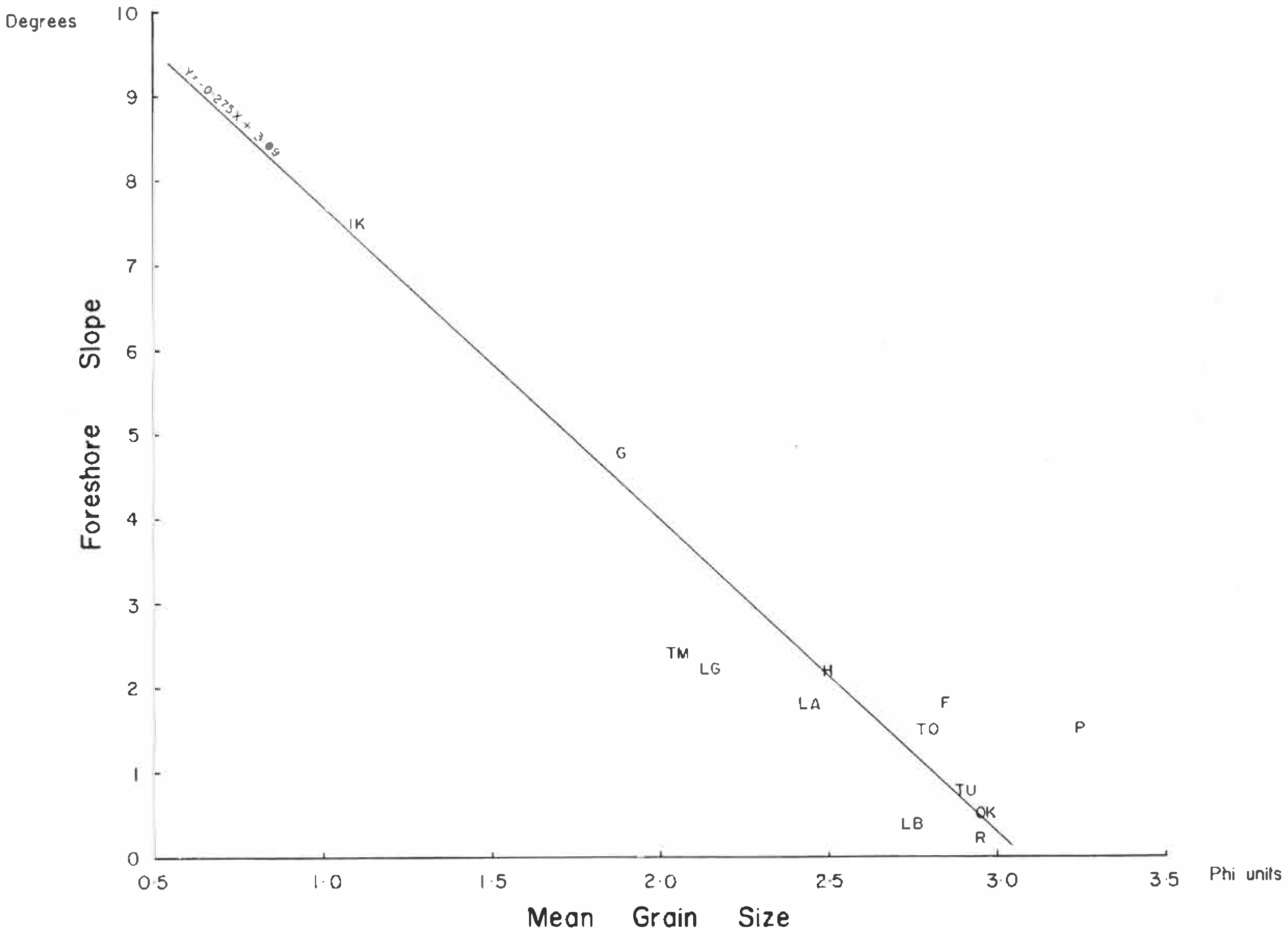


Figure 13 Relationship between foreshore slope and grain size at mid-tide zone.

beach	upper foreshore		lower foreshore	
	Mz mm	$\sigma_I \phi$	Mz mm	$\sigma_I \phi$
Taylors Mistake	0.24	0.41	0.30	0.45
Hickory	0.17	0.23	0.22	0.35
Lavericks	0.15	0.20	0.18	0.34
Tumbledown	0.13	0.22	0.17	0.48
Le Bons	0.14	0.23	0.15	0.33
Te Oka	0.14	0.23	0.15	0.31
Peraki	0.10	0.36	0.11	0.40

Table 4 Mean grain size and sorting of upper and lower foreshore sands

beach	backshore		foreshore	
	Mz mm	$\sigma_I \phi$	Mz mm	$\sigma_I \phi$
Taylors Mistake	0.26	0.38	0.24	0.41
Tumbledown	0.16	0.38	0.13	0.22
Hickory	0.19	0.36	0.17	0.23
Long	0.22	0.35	0.31	0.46
Le Bons	0.15	0.23	0.14	0.23

Table 5 Mean grain size and sorting of backshore and foreshore sands

	beach sand			*dune sand*		
	Mz mm	$\sigma_I \phi$	Sk_I	*Mz* mm	$\sigma_I \phi$	Sk_I
Ikoraki	0.36	0.34	-0.02	0.25	0.35	-0.02
Goughs	0.27	0.36	-0.03	0.31	0.35	-0.05
Taylors Mistake	0.26	0.38	-0.02	0.22	0.33	+0.09
Le Bons	0.15	0.23	-0.06	0.13	0.22	-0.18
Okains	0.13	0.25	-0.23	0.12	0.20	-0.13
Tumbledown	0.16	0.38	-0.23	0.18	0.46	-0.10
Raupo	0.13	0.19	-0.07	0.13	0.17	-0.28

Table 6 Mean grain size, sorting and skewness of beach and dune sands.

	mean grain size mm		
position on beach	*Le Bons*	*Taylors Mistake*	*Hickory*
northern	0.13	0.27	0.28
central	0.15	0.24	-
southern	0.17	0.25	0.22

Table 7 Sorting of beach sediments parallel to the shore

	cusp horn		*cusp bay*	
beach	*Mz* mm	$\sigma_I \phi$	*Mz* mm	$\sigma_I \phi$
Ikoraki	0.60	1.49	0.19	0.54
Goughs	0.26	0.32	0.23	0.30
Taylors Mistake	0.24	0.31	0.22	0.30

Table 9 Mean grain size and sorting in cusp horns and cusp bays

Mistake, Lavericks, and Ikoraki bays did the sand decrease in size over the same period. In each case the decrease accompanied the flattening of the foreshore in the mid-tide zone. The sand at Ikoraki proved to be more variable than on any other beach, its mean diameter ranging from 0.23 to 0.47 mm. A similar change was found at Point Reyes, California, on a highly variable, medium sand beach, fully exposed to the Pacific Ocean (Trask 1956).

SORTING IN CUSPS

The material on cusp horns is coarser than in cusp bays and at Ikoraki Bay the sediment is also significantly less well sorted (*table 9*).

	mean grain size mm	
beach	*February*	*August*
Taylors Mistake	0.250	0.223
Raupo	0.130	0.142
Okains	0.130	0.146
Lavericks	0.180	0.169
Le Bons	0.148	0.170
Hickory	0.186	0.295
Goughs	0.289	0.307
Long	0.219	0.248
Peraki	0.102	0.104
Te Oka	0.145	0.157
Tumbledown	0.135	0.181
Ikoraki	0.476	0.235

Table 8 Seasonal change in grain size at mid-tide zone

SAND LAMINATION

Beach sand was found to be sorted not only areally but also to various depths. This was especially noticeable where sand was composed of grains of different sizes and contrasting specific gravities, e.g., Tumbledown Bay where coarser, heavy mineral grains formed laminae 2 in. (50 mm) thick, alternating with finer, light mineral grains in laminae 5 in. (125 mm) thick.

The coarser sand had a mean diameter of 0.19 mm and the fine sand a mean diameter of 0.14 mm but the coarser sand was not as well sorted (*table 10*). Lamination was also conspicuous in sand possessing a large size range and high carbonate percentage, e.g., at Ikoraki Bay coarse heavy

laminae	Mz mm	$\sigma_I \phi$
coarse	0.19	0.42
fine	0.14	0.24

Table 10 Mean grain size and sorting of laminated beach sand at Tumbledown Bay

minerals, fine light minerals and shell fragments were segregated into separate laminae (*figure 14*). Segregation of shell fragments was revealed by analysis of individual laminae which showed some had 59 percent acid-soluble material, but others contained only 15 percent.

Lamination of sand was never observed on beaches such as Raupo, Okains, and Le Bons bays where sands were remarkably uniform in size and possessed a very small percentage of shell fragments.

DISCUSSION

The investigation revealed variations in the characteristics of beach materials and their arrangement on the beach in response to variations in the action of waves. The middle and upper foreshore, least subject to vigorous wave action, has slightly finer grains, while coarser grains accumulate on the lower foreshore under vigorous wave action. The coarser grains on the backshore probably result from winnowing of the fine material by wind and deposition of coarser material on the backshore by exceptional swash where the higher rate of percolation and the flatter gradient stops backwash from returning it to the foreshore.

It is usually possible to differentiate foreshore and backshore environments on the basis of grain size, but not in beach and dune environments. It appears that valley winds have sufficient velocity and turbulence to transport both fine and coarse fractions from the beach sands to the dunes. Dune and beach sands in some cases can be distinguished by skewness (Mason & Folk 1958, Friedman 1961). Dune sands, composed predominantly of finer grains removed from beach sands, are commonly positively skewed (toward the finer sizes). However, all the dune sands of the peninsula with the exception of those at Taylors Mistake, are negatively skewed. This supports the indication, given by mean grain size and sorting, that winds are capable of removing all size fractions to the dunes.

Variation in the grain size is less marked parallel to the shore than normal to the shore. At Taylors Mistake and Hickory Bay, after a period of southerly swell conditions, coarser grains accumulate at the more exposed northern end of the beach, while at Le Bons Bay, after north-easterly winds have built up higher waves at the southern end of the beach, an increase in grain size is found from the sheltered to the exposed sites.

Though the development of cusps is found to have modified the normal pattern of sorting of material parallel to the shore, the difference in size of material on cusp horns and in cusp bays is only pronounced at Ikoraki where pebbles and shell fragments accumulate on the cusp horns (*figure 15*).

CHANGES IN BEACH MORPHOLOGY

The beaches of the peninsula vary considerably in their relative rate and magnitude of morphological change.

LONG-TERM CHANGES

The total amount of material in some bay-heads is approximately constant. In others excessive deposition of sediment on the beaches is extending them seaward.

Shallowing of bay floors, and beach progradation have their greatest development in the north-eastern bays. Comparison of depths recorded by HMS *Acheron's* survey (1849–51) and the *Lachlan* survey (1952–3) indicates shoaling of up to one fathom (2 m) in Raupo and Okains bays. Influx of fine sand into Okains and Le Bons bays has built out their beaches by constructing extensive systems of beach and dune ridges. At Okains Bay a succession of sub-parallel ridges can be traced 2.4 km inland from the present beach (*figure 16*, page 27). Most ridges are 6 in. to 4 ft (0.15 to 1.2 m) in height though two are 5 ft (1.5 m) high and another rises just over 10 ft (3.0 m). Their crests usually extend across the full width of the valley floor, and they stand from 10 to 65 m apart. At Le Bons Bay, where a system of ridges and swales extends approximately 1.2 km inland, the pattern is different. Ridges are usually higher and of two different types; within 320 m of the shore line they are 2 to 7 ft (0.6 to 2.0 m) high and spaced at intervals of 50 to 150 ft (15 to 45 m); those further inland are 12 to 25 ft (3.5 to 7.5 m) in height with their crests 250 to 400 ft (75 to 122 m) apart. The ridges are more irregular in shape and the system lacks the parallelism which is a feature at Okains Bay.

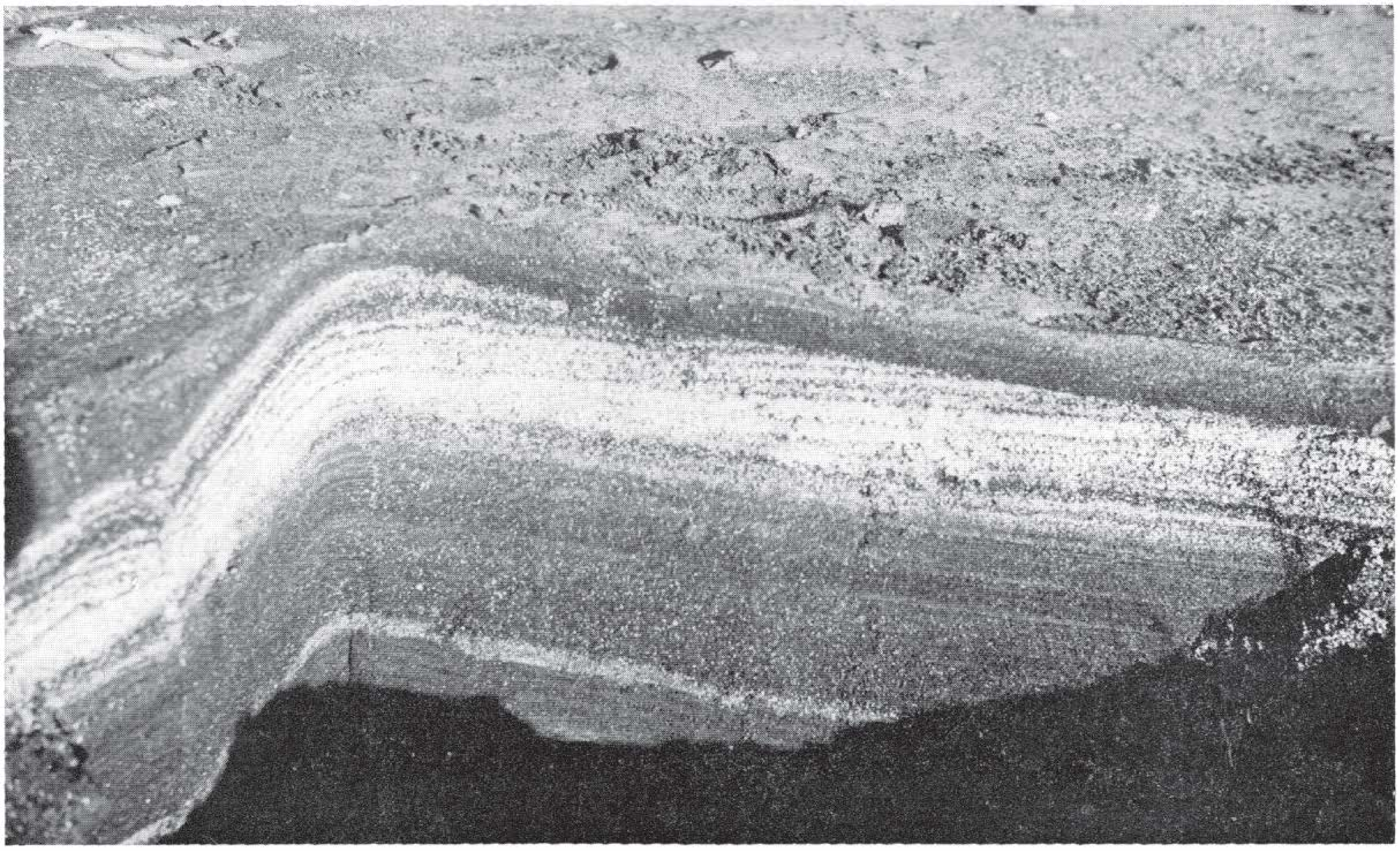


Figure 14 Lamination of beach sand at Ikoraki Bay. Shell fragments, coarser heavy minerals, and finer light minerals segregated into separate laminae.

Figure 15 Cusp development at Ikoraki Bay accentuated by concentration of pebbles and shell fragments on cusp horns and light mineral grains in cusp bays.

4

Comparison of the size and form of the ridges suggests Okains Bay receives sediment at a considerably faster rate than Le Bons Bay. Beach ridges at Okains Bay are rarely more than 1 m high and retain symmetry of form indicating they have been moulded essentially by wave action and colonised rapidly by stabilising vegetation. Data from local residents suggest that the high water mark in Okains Bay has shifted seaward approximately 230 m during the last century. Comparative regularity in ridge height and spacing at Okains Bay further suggests that the rate of progradation has been fairly uniform. Only at three points has the shore line been stable for longer periods and allowed ridges to build up above general levels. A slower and more variable rate of accumulation in Le Bons Bay has favoured development of higher and wider dune ridges through a greater build-up of wind-blown sand.

The shore line at Tumbledown Bay also shows evidence of active progradation and the accumulation of wind-blown sand points to over-nourishment of the beach. Dune development is greater here than in any other bay except Okains and Le Bons bays. A dune complex extends almost 90 m inland, rising 36 ft (11 m) above the backshore. Excess net supply of material is indicated on all other fine sand beaches investigated, but nowhere else has this attained significant proportions.

The medium sand beaches at Taylors Mistake, Goughs, Long, and Ikoraki bays do not exhibit any conspicuous net change in quantity of material. Although sand may be deposited and removed from the beach throughout the year, there is no addition of new material from either local or extraneous sources. Local underfit streams appear to contribute little fresh material for beach construction, under present conditions, and the plunging headland cliffs are not being eroded at a sufficient rate to be significant suppliers of beach sediments.

The shore line only progrades where material is available from extraneous sources and the beach is in a "shifting" state. On beaches supplied largely from local sources the shore line is more stable, and a regular quantity of material is reworked on the beach each year.

SHORT-TERM CHANGES

Seasonal changes

Movements of beach sand occur in response to seasonal changes in wave action. Steep winter waves plane down summer profiles by eroding sand from the upper foreshore and backshore. This is subsequently redeposited at a lower level.

In summer and winter the peninsula's beaches differed markedly as revealed by profiles surveyed in February and August (*figure 17*).

High-energy winter waves cause recession and frequent steepening of upper foreshores (*table 11*). The most outstanding example was at Goughs Bay where the summer upper foreshore slope of 4°20′ was steepened to 9° during winter months (*figures 18 & 19*).

In most beaches the beach face retreated at an even slope, but at Le Bons Bay the concentration of surf action at the base of the small berm formed a vertical scarp approximately 0.6 m high (*figure 20*).

However, not all upper foreshores were steepened. At Peraki Bay winter waves stripped sufficient sand from the upper foreshore to expose cobbles and boulders of the beach foundation (*figure 21*). At Long and Ikoraki bays the beach faces assumed more moderate slopes as a result of the combing-down effect of increased winter wave action (*figures 22 & 23*).

Sand eroded from the upper profile during berm retreat was deposited below mean sea level, causing a marked decrease in lower foreshore gradients (*table 11*). The rarity of winter slopes of more than 1° shows the gently-sloping nature of lower foreshores. In some beaches parts of the lower foreshore were perfectly flat, and in Goughs and Hickory bays winter cutting of the beach profiles extended below mean sea level, with sand removed to the nearshore and offshore zones.

Sequence of changes in successive profiles

Although magnitudes of change differ, all beaches exhibit a similar sequence of responses to changing wave conditions.

The initial surveys in February, which established summer conditions of beach profiles, revealed the presence (especially on medium sands) of sizeable berms, prominent berm edges, and relatively steep, smooth foreshores.

Subsequent surveys in March showed that constructive wave action had built out berms with material eroded from lower foreshores thereby steepening beach gradients. The greatest alterations to beach profiles were caused by the first autumn storm waves. Surveys during April and May showed beaches had been cut back and sand removed to the offshore zone.

During winter months profiles remained relatively stable around the levels established in autumn (these were commonly below the levels of summer profiles). Retreat of beach faces and removal of berms were accentuated by winter wave action and accompanied by a lessening of beach gradients. In late winter accretion on the lower foreshore at Okains and Le Bons bays reached excessive proportions. The fill consisted mainly of sand washed from the estuaries, but probably

(Text continues on *page 33*)

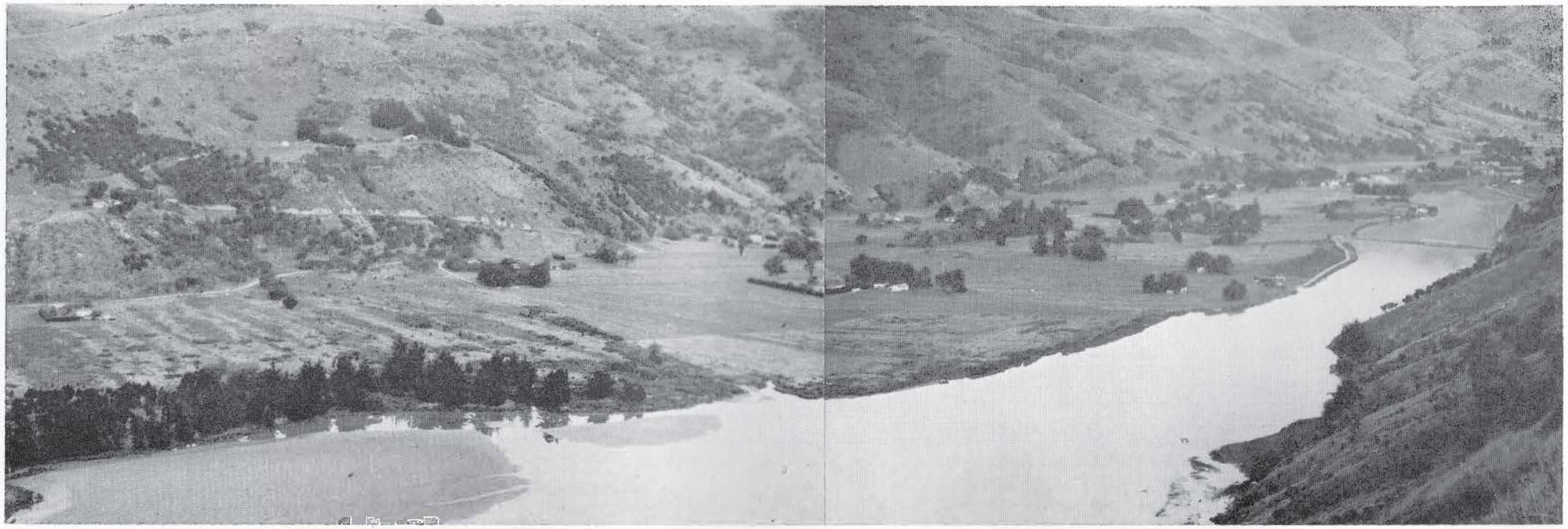


Figure 16 Accretionary series of beach ridges at Okains Bay. Stream is tidal for 2.4 km inland.

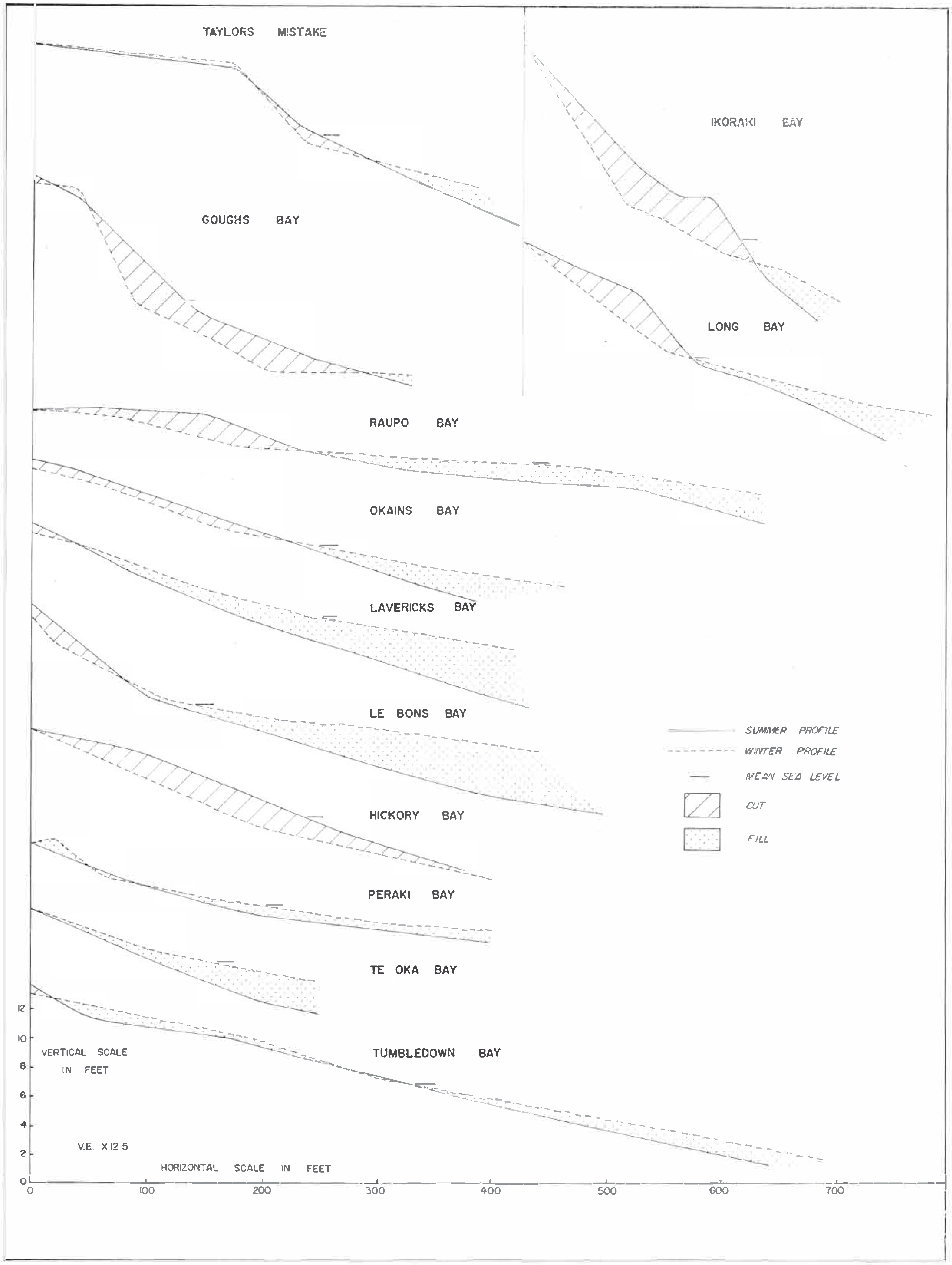


Figure 17 Seasonal changes in beach profiles.

beach	upper foreshore		lower foreshore	
	summer	winter	summer	winter
	° '	° '	° '	° '
Taylors Mistake	4 10	5 00	2 10	1 20
Raupo	1 40	1 20	0 30	0 10
Okains	1 40	1 40	1 40	0 50
Lavericks	2 00	1 40	1 20	0 50
Le Bons	3 40	2 20	1 20	0 40
Hickory	2 20	2 00	1 40	1 00
Goughs	4 20	9 00	1 50	1 10
Long	5 40	3 30	2 00	1 00
Peraki	1 40	3 20	1 10	0 30
Te Oka	2 10	1 10	1 10	0 50
Tumbledown	0 50	1 20	1 10	0 50
Ikoraki	7 00	3 00	3 10	2 00

Table 11 Seasonal changes in upper and lower foreshore slopes

Figure 18 Summer beach profile at Goughs Bay.

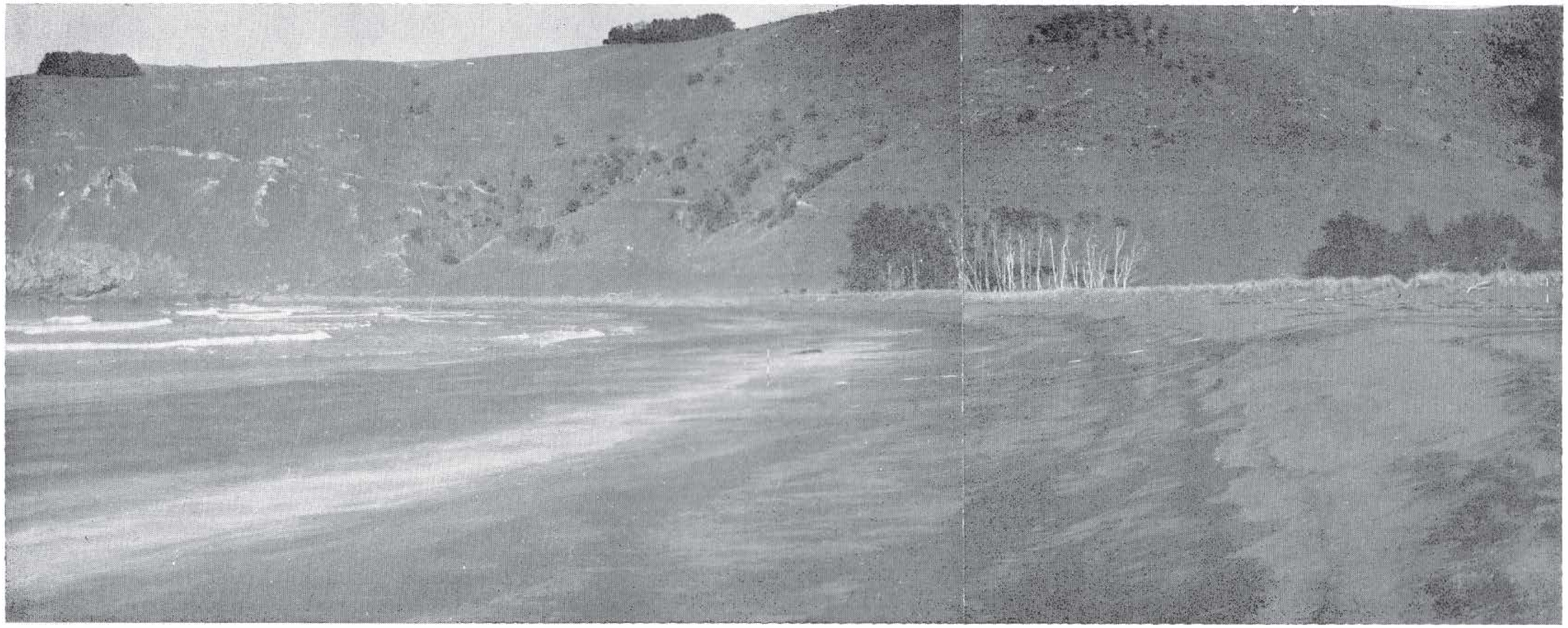


Figure 19 Winter beach profile at Goughs Bay. Steep upper foreshore contrasts with gently-sloping surface of berm and lower foreshore.

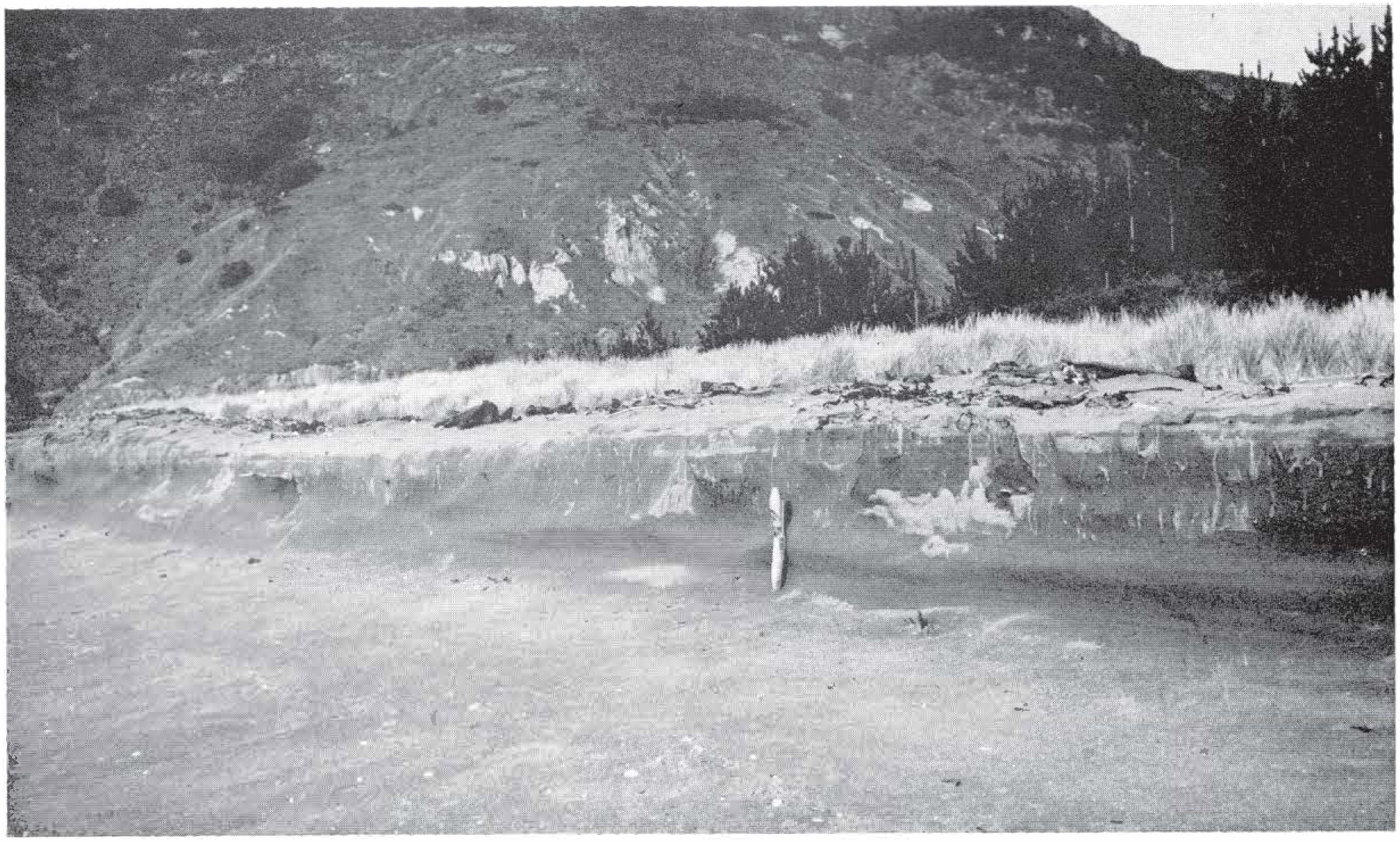


Figure 20 Vertical scarp at Le Bons Bay. Trowel is 305 mm long.

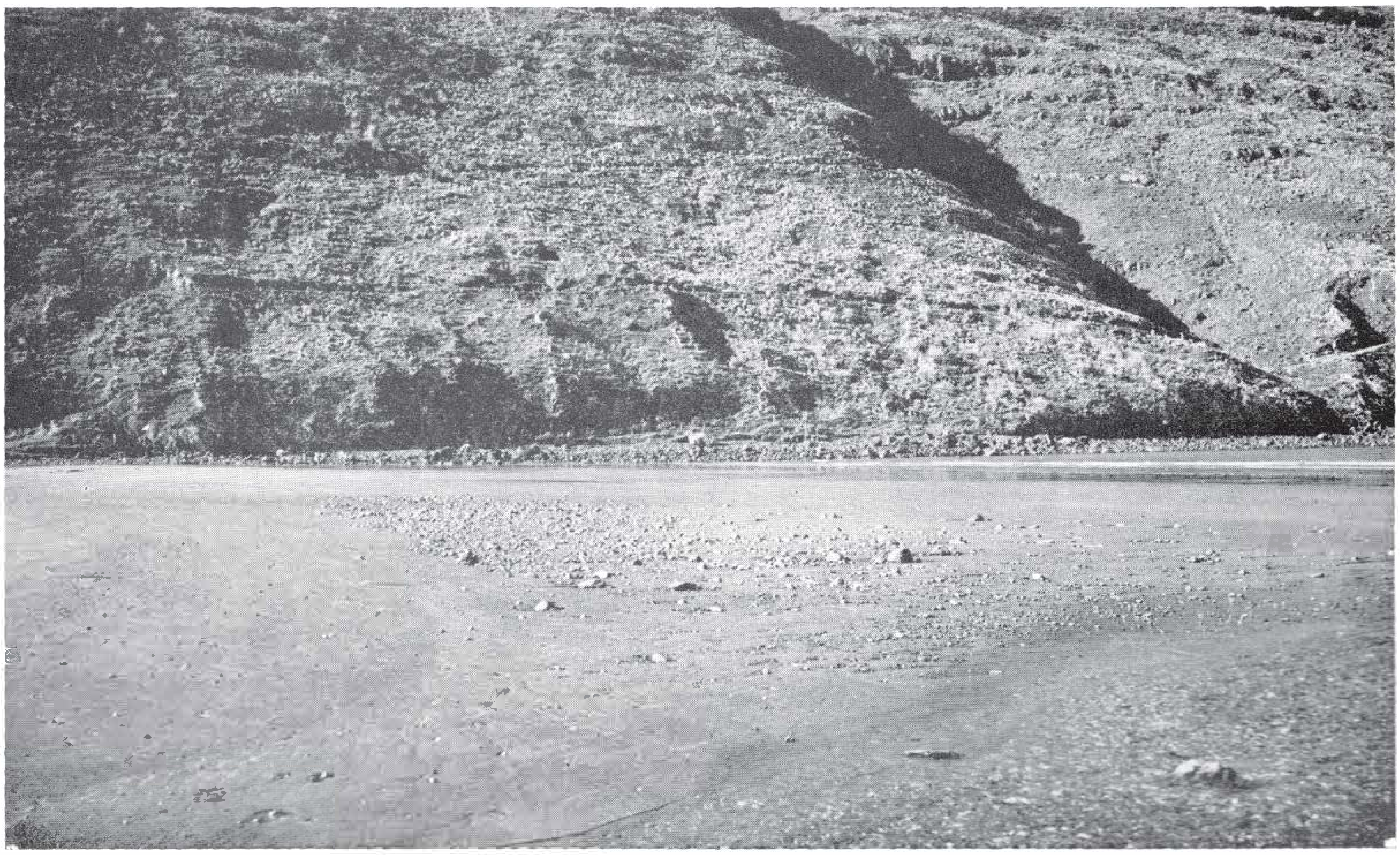


Figure 21 Beach foundation exposed by winter wave action at Peraki Bay.

Figure 22 Summer beach profile at Ikoraki Bay, viewed at low tide.

Figure 23 Winter beach profile at Ikoraki Bay, viewed at low tide. Widening of foreshore due to accretion of material eroded from the upper part of the profile.

included material stirred up from the bay floor and driven landward by vigorous winter waves. As early as August the beaches at Taylors Mistake and Tumbledown Bay were building out again. This was the final stage in the seasonal cycle.

Changes in berm widths provide a good indication of seasonal beach variation. An abrupt cutback in late March and April was followed by comparative stability during mid-winter and, in some cases, rebuilding in August (*figure 24*).

Changes associated with storms

The most spectacular modification of beach profiles is caused by steep storm waves. During the last days of March, Taylors Mistake was subjected to heavy swell from the north-east which produced plunging breakers up to 3.5 m in height on the beach. At Hickory Bay storm waves approached from the south-east in late April, producing breakers similar in type and height to those at Taylors Mistake.

The berm at Taylors Mistake was lowered by 1 ft (0.3 m) and the beach face cut back by 25 to 30 ft (7.5 to 9.0 m) (*figure 25*). The waves at Hickory Bay completely removed the berm and combed down the foreshore by as much as 1 m. In both cases the effects of storm waves were entirely destructive. Material was eroded from the full length of the profile and removed well beyond the low water mark. This contrasts with the usual situation produced by winter waves in which erosion on the upper portion of the beach is accompanied by redeposition on the lower foreshore.

Although storms produced marked changes within a few days their effects were evident over a much longer period. The levels they established remained relatively unchanged during the following winter season.

Changes related to wave approach

As well as moving normal to the shore, beach sediments may be shifted along the beach. Surveys at Goughs and Tumbledown bays revealed cutting at one end of the beach and contemporaneous filling at the other, the shift of sand being related to the direction of wave approach. In the more exposed Goughs Bay incompletely refracted swell from the north- and south-east retains a longshore component. A period of north-easterly swell in April caused the removal of 2 ft (0.6 m) of sand from the northern end of the beach and built up the southern end by a similar amount (*figure 26*). It is more difficult to account for cut at the eastern end of the beach at Tumbledown Bay and fill at the western end (*figure 26*). However, large waves are often reflected from the eastern wall, which is more exposed to the bay entrance. They then approach the beach at an angle which could cause such transport of sand.

Changes associated with tidal regimes

Sand levels are shifted not only by unpredictable changes in the nature of wave action but also by regular changes in the tides. On several occasions short-term cycles of cut and fill related to differences in spring and neap tide water heights were observed on the peninsula's beaches. This phenomenon was especially noticeable during summer months, on both fine and medium sand beaches (*figures 27*, *28*). Four examples of neap tide berm construction are recorded in *figure 29*. Constructive wave action during spring tides built out berms at the highest point reached by waves. Because similar wave conditions prevailed during the ensuing succession of neap ties, smaller, secondary berms were constructed in front of, and 2 to 3 ft (0.6 to 1.0 m) below, older berms. Seaward-sloping faces of lower berms regularly have steeper gradients than those of higher berms. Neap-tide berms were very transient features, being completely removed by the next spring tides (*figure 29*). Their development, however, may play a vital role in beach construction especially on a prograding shore line such as at Okains Bay. If secondary berms are large and stable enough they may impede wave advance sufficiently to allow vegetation to colonise the upper berm thus, forming an incipient foredune.

Changes during tidal cycles

Beach profiles fluctuate with the daily change of tide which shifts the active zone of breakers up and down the beach effecting a constant redistribution of wave energy. Successive tidal cycles resort the fine sands of Okains Bay and medium sands at Goughs Bay, causing continual modification of beach profiles. The magnitude of change is governed closely by size of material and intensity of wave action.

Fluctuations in sand level at Okains Bay are illustrated in *figure 30*. The pattern shows the sand level is remarkably stable during individual tidal cycles. The greatest vertical change in any single cycle was 25 mm but frequently no change was recorded on the lower foreshore. Even after four high tides no significant modification of sand level was recorded on any part of the profile. The greatest change from original levels was only 38 mm. Most measurements showed total changes of less than 25 mm. However, changes in upper foreshore level reached greater proportions than on the lower foreshore.

At Goughs Bay three separate profiles were surveyed (*figure 30B*) to compare sand level changes at the centre and at each end of the beach. During individual tidal cycles the sand level on the lower

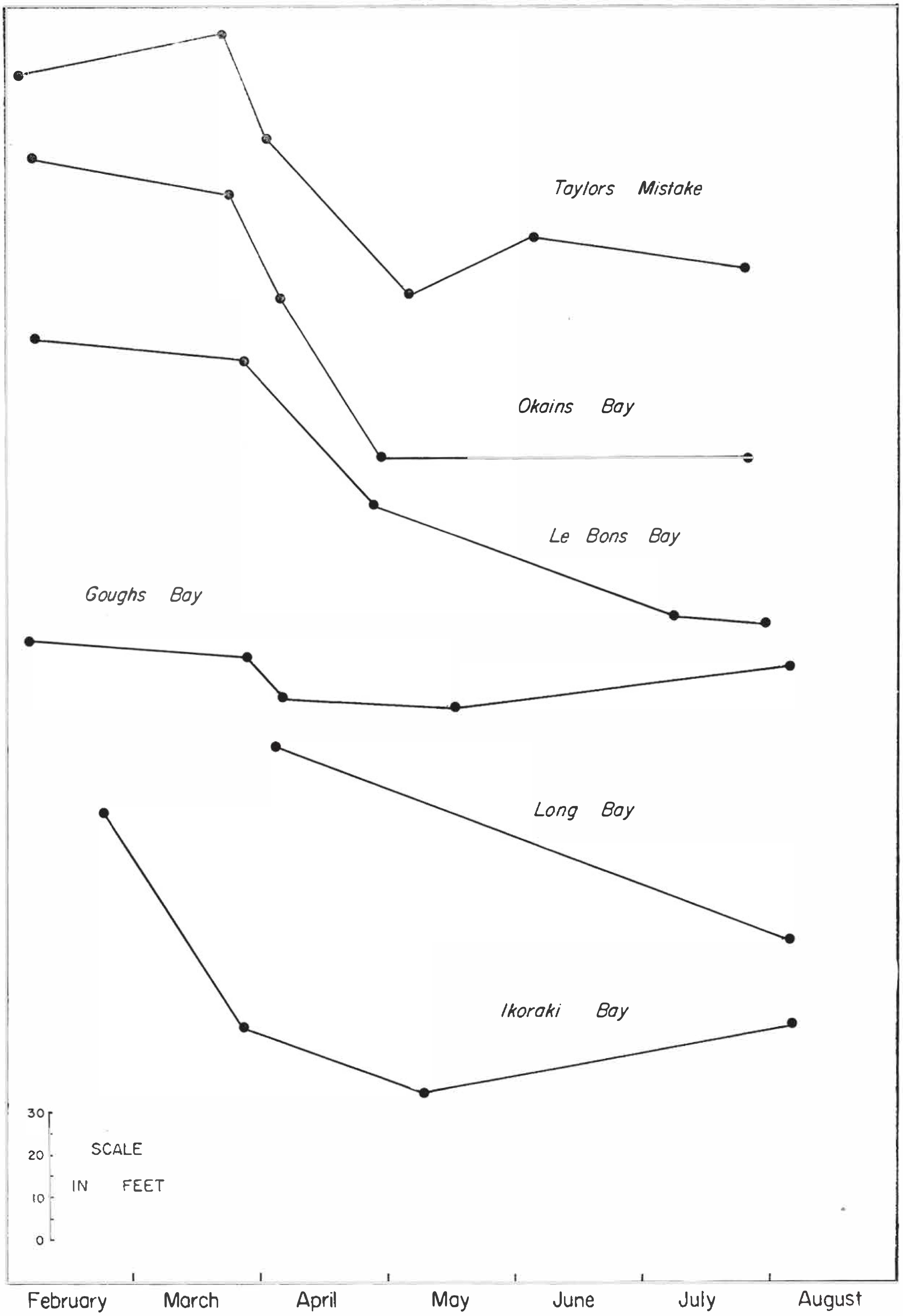


Figure 24 Monthly variation in berm widths.

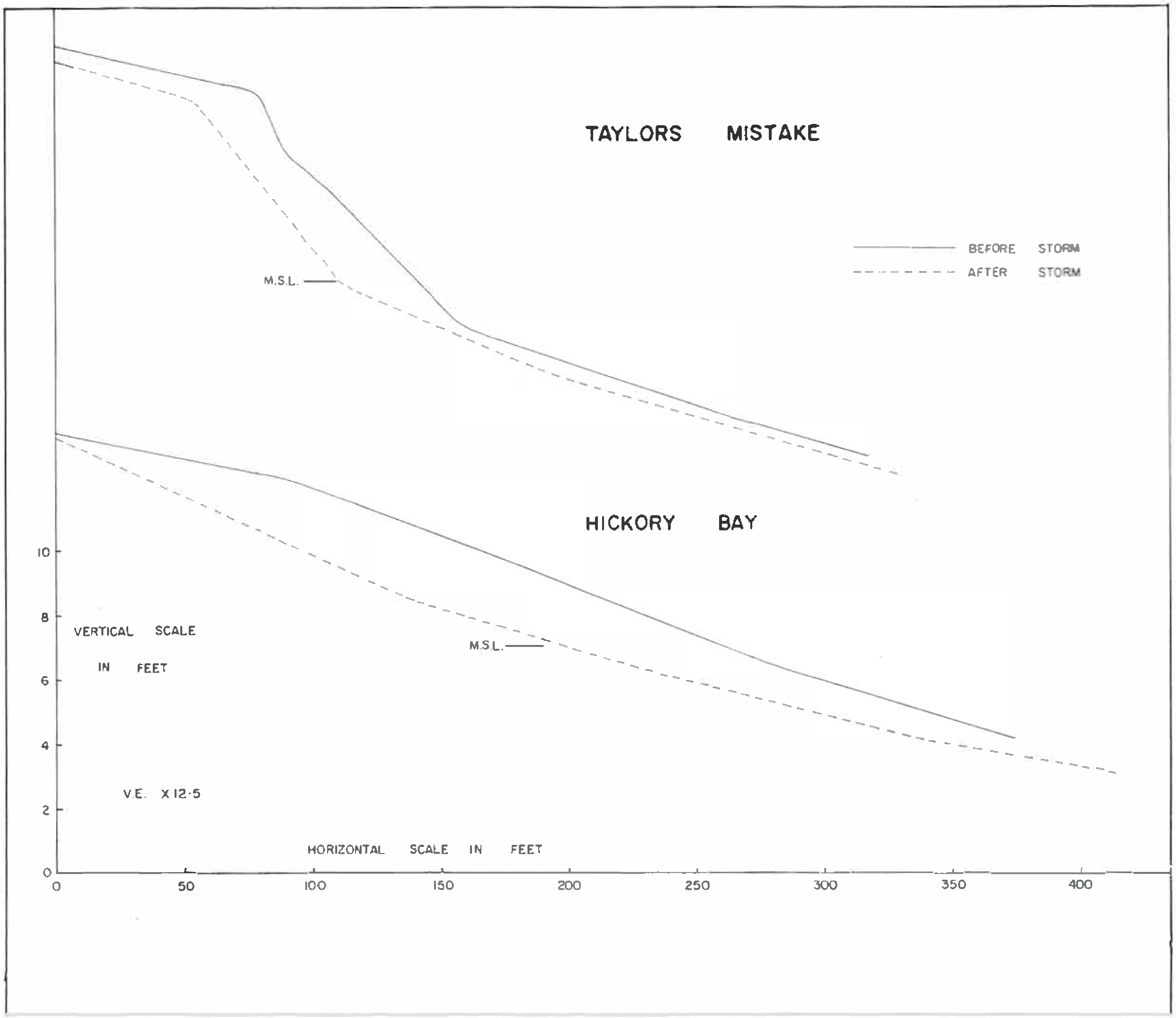


Figure 25 Effects of storm waves on beach profiles at Taylors Mistake and Hickory Bay.

foreshore frequently fell by 229 mm to 305 mm. A maximum cut of 0.5 m was recorded in the central profile. The sand on the upper foreshore was least disturbed, changes in level after one high tide generally being less than 150 mm. Overall changes in level were greater on the lower than on the upper foreshore. The vertical range of lower foreshore fluctuations averaged 0.6 m, while the upper foreshore range was 203 mm. The greatest vertical range was 1.0 m. The mid-tide zone was fairly stable especially in the central profile.

Disturbance of sand was not uniform along the beach. The central and northern sections of the beach, more exposed to south-easterly waves, exhibited greater mobility than the southern end.

Discussion

A close relationship exists between profile changes and size of material. Surface level changes are far greater on medium sands than on fine sand. Changes recorded at Okains Bay correspond closely with those on the fine sands of Rhossili Bay, South Wales (King 1959, p. 249) and single tidal cycles changes at Goughs Bay are similar in magnitude to those on medium sands at Sandy Hook, New Jersey (Strahler 1966). However, the actual changes at Goughs Bay (75 to 150 mm) are higher than at Sandy Hook, New Jersey (63 mm) but it must be borne in mind that these occurred during mid-winter, while Strahler's observations were made in late summer.

The site of maximum disturbance is different on Okains and Goughs bay beaches. At Okains Bay the lower foreshore is the most stable part of the profile, whereas at Goughs Bay it is the most mobile. This is due to differences in foreshore slopes which, in turn, are related to grain size. The steeper profile on the medium sands at Goughs Bay allows waves to break close inshore, and induces plunging breakers whose energy is absorbed over a relatively narrow zone of the beach. Because the lower foreshore is directly beneath the breakpoint

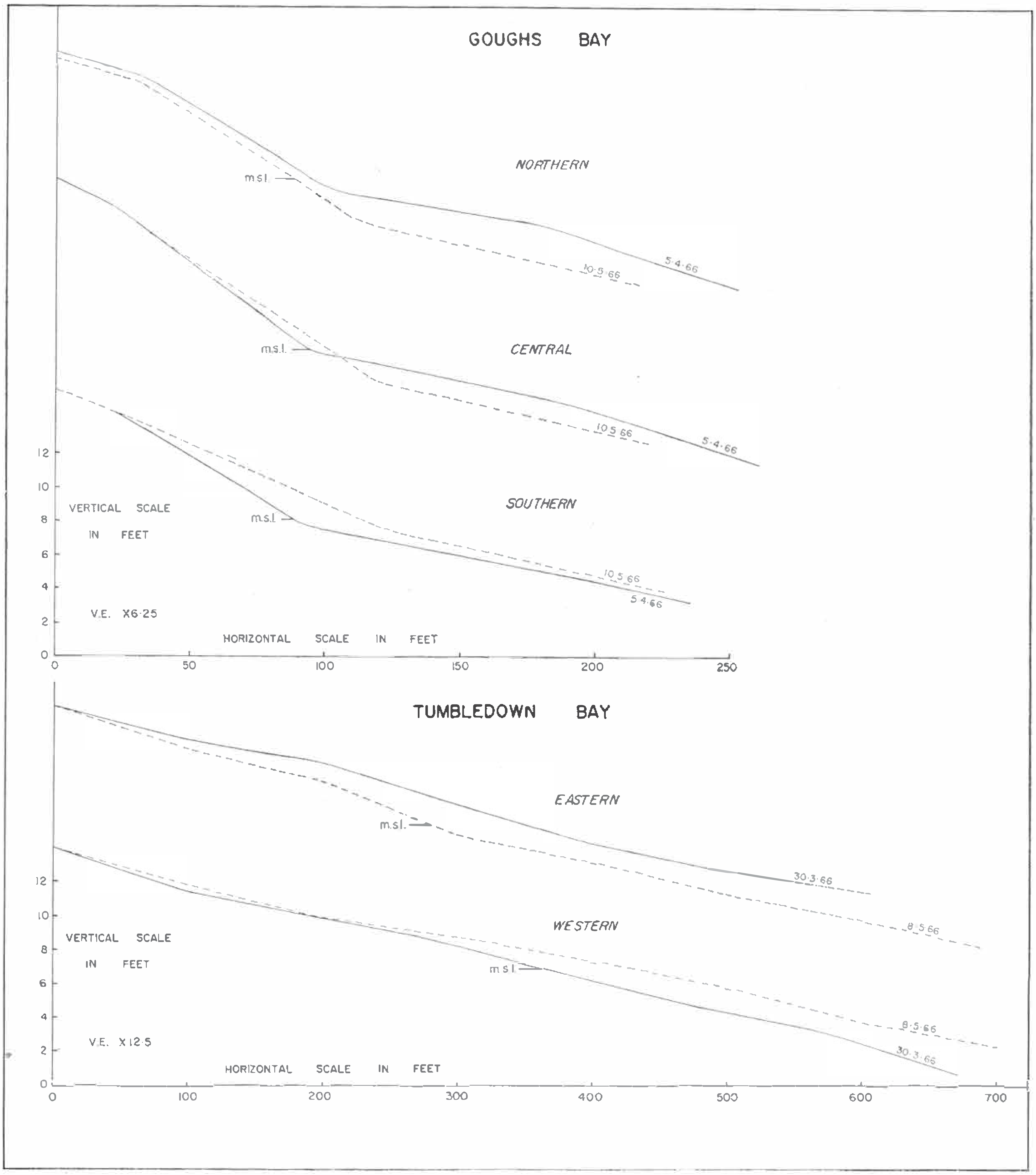


Figure 26 Short-term lateral shifts of sand at Goughs and Tumbledown bays.

of waves at high tide, it experiences the greatest disturbance. The longer still-stand of water around the high- and low-water levels produces greater changes at these positions, but the waves are less effective in modifying the middle section of the swash-backwash zone. At Okains Bay the influence of spilling breakers is spread more uniformly over the gently-sloping foreshore. However, the drier, less compact and coarser upper foreshore sands are more vulnerable to wave action. They therefore experience greater changes than the more consolidated lower foreshore sands.

Variation in degree of mobility also reflects the differences in intensity of wave action on the beaches. Greater turbulence in the surf zone, and more vigorous action of swash-backwash at Goughs Bay, induces greater changes in sand levels. There is less difference between the velocities of swash and backwash on the steeper beach. At Goughs Bay the ratio of swash to backwash is 5:3, while at Okains Bay it is 7:3. The backwash gathers more momentum on the steeper beach than on the gentle slope of the fine sand beach, thus it may have a greater influence on the sand level.

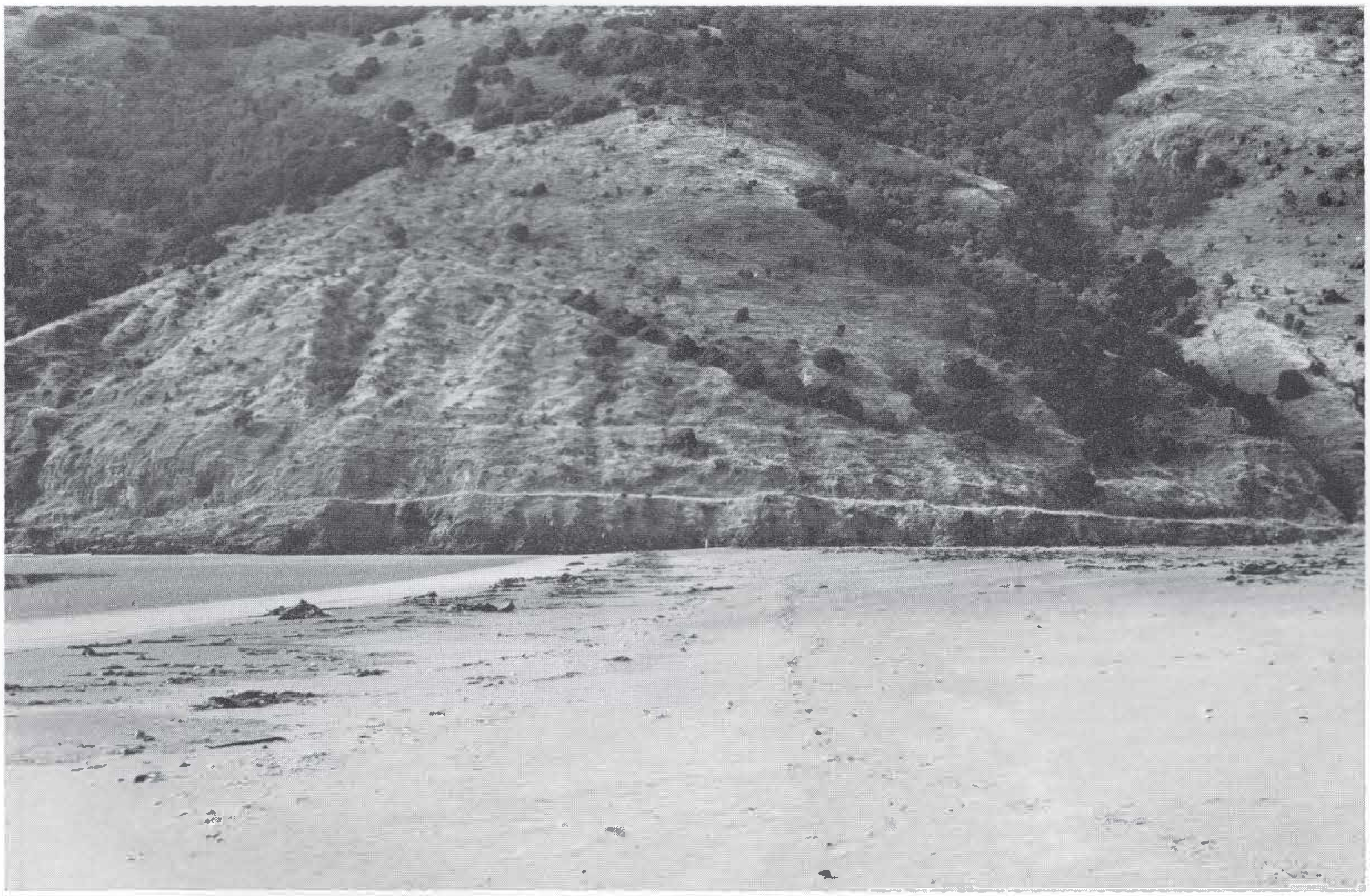


Figure 27 Neap-tide berm at Le Bons Bay. View looking along surface of secondary berm, with upper berm on right.

Figure 28 Neap-tide berm at Goughs Bay. Upper berm on right. Staffs mark cusp horns on edge of lower berm.

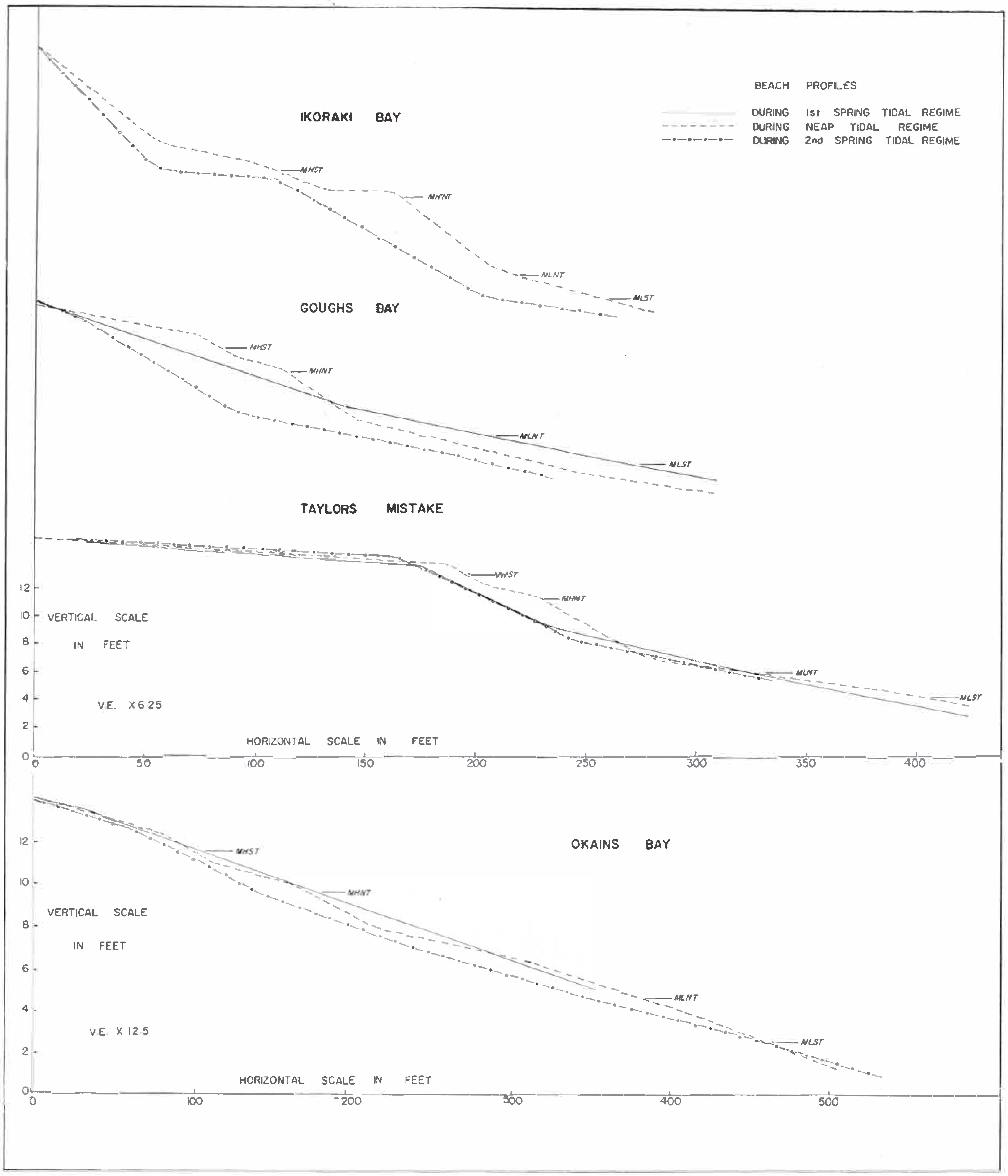


Figure 29 Changes in beach profiles during tidal regimes.

MOBILITY OF BEACH MATERIAL

The beaches vary appreciably in their relative mobility. Sweep zone profiles (*figure 31*) indicate the maximum and minimum levels attained by beach profiles during the period of study.

The sand surface fluctuates through a greater vertical range on beaches composed of medium sand than on those of fine sand. At Taylors Mistake, Goughs, and Ikoraki bays the difference between maximum and minimum elevations of beach profiles ranged from 2 to 4 ft (0.6 to 1.2 m). Also, uniform mobility of sand at all points on the foreshore is indicated. It is notable at Goughs Bay that changes in foreshore levels were as great during only four high tides as throughout the year. The fine sand beaches are more stable. At Peraki Bay, for example, envelope curves were only 0.3 m apart, and upper foreshores on the other beaches fluctuated through a vertical range of no

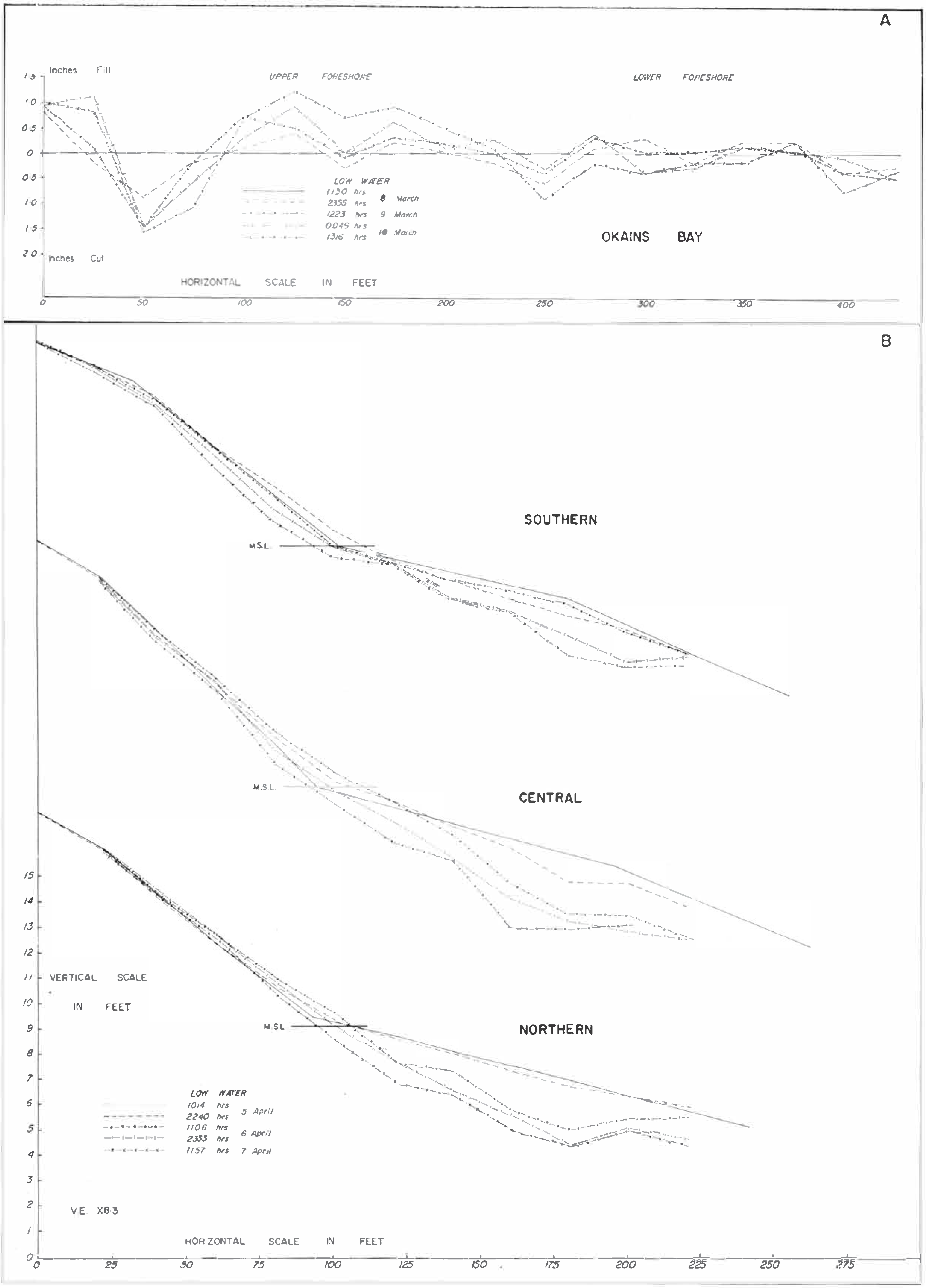


Figure 30 A Changes in sand levels during single tidal cycles at Okains Bay.
B Changes in sand levels during single tidal cycles at Goughs Bay.

more than 1 m. However, vertical changes of up to 1.2 m on the lower foreshore at Tumbledown, Okains, and Le Bons bays were similar to those on the coarser sands. These were attributed to excessive filling during the latter winter months.

Only in one instance, at Peraki Bay, did the lower sweep zone profile coincide with the foundation of the beach. In all other cases, where the beach deposit was thicker, it lay entirely within mobile beach material.

Sweep zones were established on separate profiles on some beaches in order to compare the degree of mobility at different positions along the shore. Generally the change in profile was of similar magnitude along the whole beach, and sweep zones were of approximately equal sizes. Sweep zones at Taylors Mistake and Goughs Bay (*figure 32*) indicate a uniform distribution of wave energy in the bay head, with no one section of the beach experiencing abnormal degrees of cut or fill. However, at Okains and Le Bons bays, larger sweep zones on profiles nearest the streams resulted from excessive accretion of sand on the lower foreshore during late winter (*figure 32*). Moreover, presence of a variable ridge and runnel at Le Bons Bay meant that the southern sweep zone covered a wider vertical range than on the central and northern profiles.

Variables affecting mobility and gradients

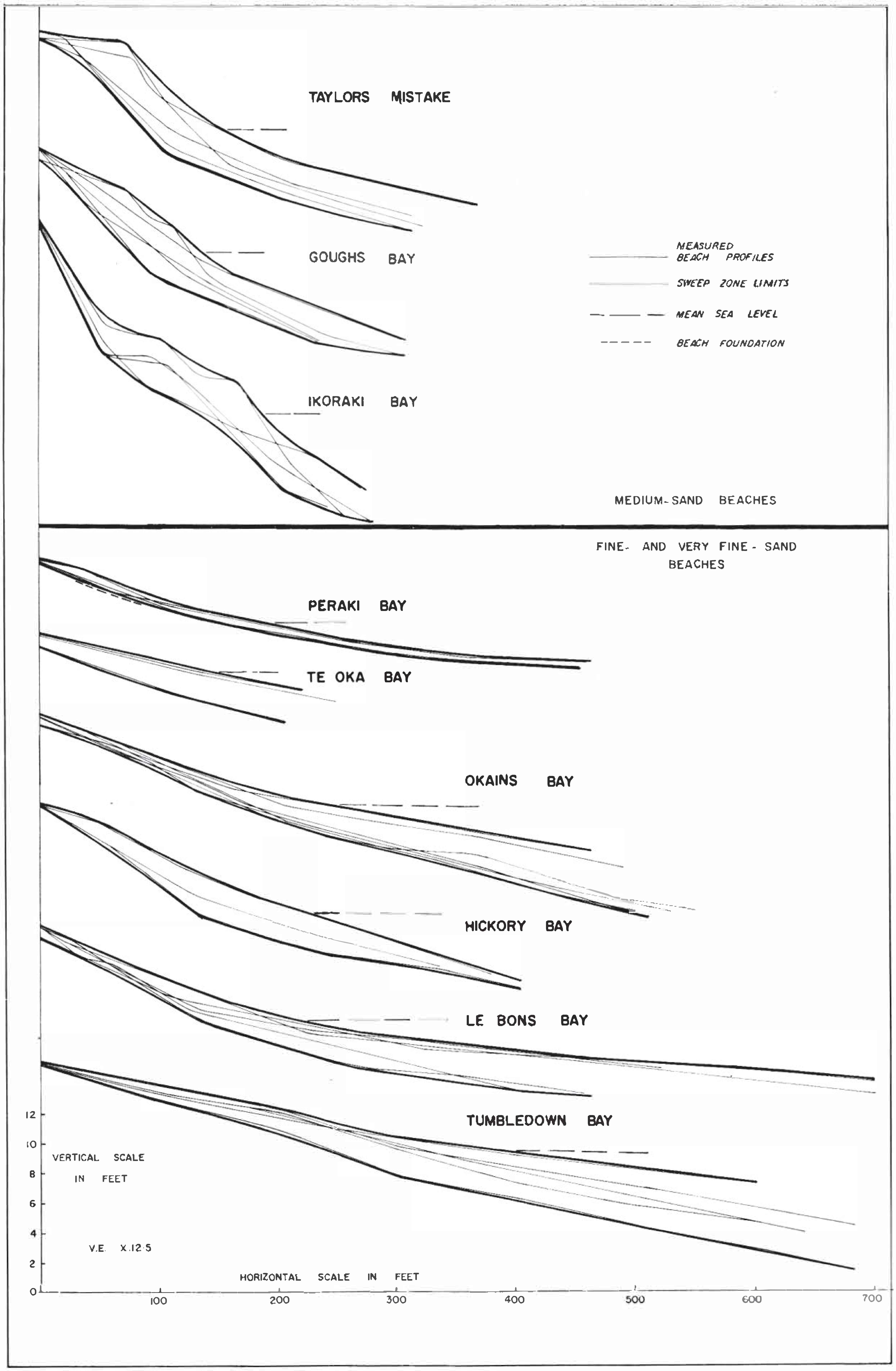
Changes in profiles on peninsula beaches emphasise the interrelationship between wave action, textural characteristics of beach material, beach morphology (especially foreshore gradient), and the mobility of beach material.

It is difficult, without detailed information on circumstances at the onset of beach development, to assess the dominant causal factors governing this interrelation. For any one beach, however, degree of exposure, hydrological regime and original texture seem to be the more obvious parameters that control the equilibrium between the various characteristics. These act within well defined limits, although even here a mutual influence is present. In Banks Peninsula the distributional pattern of sands appears to be more related to the geomorphic setting of the beach than to the bedrock geology of the hinterland. Therefore, the vital factors determining the nature of beach materials are the orientation of the bay entrance and its exposure to wave action. Vigorous wave action will result in accumulation of relatively poorly sorted, subangular medium sands with relatively steep slopes, because of a greater angle of repose, berm development, and greater mobility, due to a lesser degree of packing, as a secondary effect. The steeper beach will in turn maintain a greater turbulence in the surf zone and a smaller difference between swash and backwash velocities.

In contrast, moderate to weak wave action will produce better sorted, subrounded fine sand beaches with more gentle gradients and relatively low mobility.

Within the limits of long-and short-term changes in the external parameters (i.e., waves), textural characteristics and beach profiles will oscillate about an equilibrium, attaining in time a lower energy level. Abrupt changes in the external regime, such as those caused by storms, may upset the equilibrium for short or long periods, restarting the process at a higher energy level, but the general tendency is maintained. The process is controlled by an internal feed-back system incorporated in the close interrelation of external and internal parameters.

Figure 31 Sweep zone profiles. These allow a comparison of the range between the boundaries of maximum and minimum beach profile elevation occurring on the steeper medium sand beaches and the gently sloping fine and very fine sand beaches.


TAYLORS MISTAKE
GOUGHS BAY
IKORAKI BAY
MEASURED BEACH PROFILES
SWEEP ZONE LIMITS
MEAN SEA LEVEL
BEACH FOUNDATION
MEDIUM- SAND BEACHES
FINE- AND VERY FINE - SAND BEACHES
PERAKI BAY
TE OKA BAY
OKAINS BAY
HICKORY BAY
LE BONS BAY
TUMBLEDOWN BAY
12
10
8
6
4
2
0
VERTICAL SCALE IN FEET
V.E. X 12.5
HORIZONTAL SCALE IN FEET
100
200
300
400
500
600
700

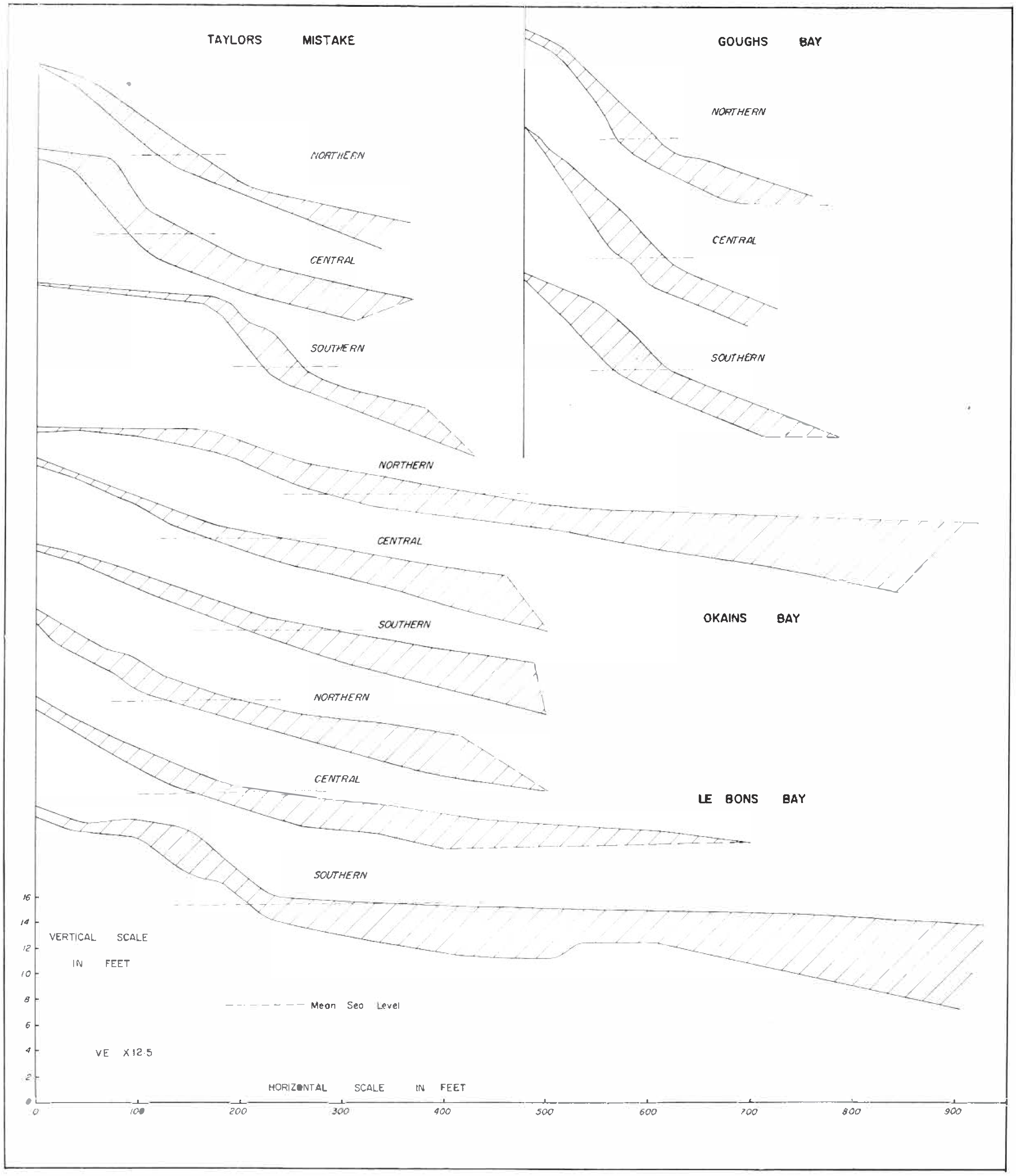


Figure 32 Comparison of sweep zones at three positions (northern, central, and southern) on each of four selected beaches.

PART II CHARACTERISTICS, TRANSPORT, AND ORIGIN OF BEACH SEDIMENTS

MECHANISMS OF TRANSPORT

CURRENTS

Coastal Currents The principal coastal current is the Southland Current which flows northwards past the peninsula (Brodie 1960, Heath 1973).

Wind-generated Currents Many currents are surface streams determined by prevailing winds (*figure 33C,D*). Dawson (1953) reported transient currents from the north-east in Pegasus Bay, generated and controlled by wind. Hydrographic charts record a set towards Canterbury Bight after strong south-east winds.

Littoral Currents Wave-generated littoral currents, travelling north along the Canterbury Bight shore line, transport large quantities of sediment to the peninsula's southern margin (Speight 1930). Along the shore line of Pegasus Bay the direction of littoral drift is more variable, although net transport appears to be from north to south. This bay is sheltered from south-easterly waves, but exposed to waves from the north-east which generate currents along the shore. The basic form of the South Brighton Spit and the infilling of Sumner Bay and beach suggest considerable southward movement of sand.

Tidal Currents The strongest currents off the peninsula are generated by tides. The tides are semi-diurnal with high water occuring twice daily. Tidal streams change direction four times daily. The tidal range at Lyttelton is 6.2 ft (2 m) at springs, and 5.4 ft (1.6 m) at neaps, but at Akaroa both springs and neaps are slightly less (Hydrographic Chart NZ63, 1953).

Flood streams set to the north and ebb streams to the south. The current off East Head flows northwards from 3 hours before high water until 2 hours after high water. It then flows southwards for the balance of time with no prolonged slack water (Hydrographic Chart NZ63). However, tidal currents vary continuously, even over short periods, according to weather and water conditions. This causes difficulties in applying general rules to directions of flow and times of slack water. During southerly winds the north flowing (flood) stream may prevail all day, but with the return of calm weather the south flowing (ebb) stream predominates. Occasionally, streams set normal to, rather than along the shore.

Current velocities also vary. The Hydrographic Chart (NZ63) records an average velocity of 0.35 knots for both north and south flowing streams, but local fishermen report north flowing streams prevail, in duration and rate of flow, probably because of the influence of the Southland Current.

The projection of the peninsula from the Canterbury coastline distorts the tidal current causing streams to attain greater velocities off the eastern extremity of the peninsula than along its northern and southern margin. Maximum rates of flow are encountered when the flood stream of spring tides is reinforced by southerly winds. At such times extremely turbulent flows of up to 5 knots occur.

Schofield (1967) has shown that tidal currents can be effective in transporting shelf sediments down to depths of 20 fm (37 m).

WAVES

Waves in the vicinity of the peninsula are wind-modified swell rather than dominantly generated directly by the wind. The shore line is perennially subject to heavy swell emanating from storm centres in the South Pacific. This swell approaches predominantly from the south-east, east, and north-east across long fetch distances (*figure 33B*). Consequently, swell is largely independent of local weather, and waves of considerable amplitude and energy may occur in the absence of local wind. The characteristic period of waves before breaking is 10 sec (*figure 33A*) giving a theoretical deep-water wavelength of 512 ft (156 m).* The pattern of wave attack on the coastline may be visualised from the refraction diagrams for waves of 10 sec period from the south-east and north-east (*figures 34, 35*). An outstanding feature is the lack of refraction, as waves approach the peninsula. This is due to the flat and the uniform offshore bottom relief. A wave with a period of 10 sec will first "feel" the bottom at 256 ft (88 m) yet refraction diagrams show that the wave crests are not appreciably modified until they meet depths of approximately 60 ft (18 m). Waves from the south-east proceed essentially unhindered into the south-eastern bays, but close inshore are refracted considerably around the southern and northern margins of the peninsula. On entering the expanse of shallow water off Okains and Raupo bays such waves are refracted and sweep straight into Lyttelton Harbour and

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*Calculated from the formula $L=5.12\ T^2$, where L = wave length in feet and T = wave period in seconds (King 1959, p. 8).

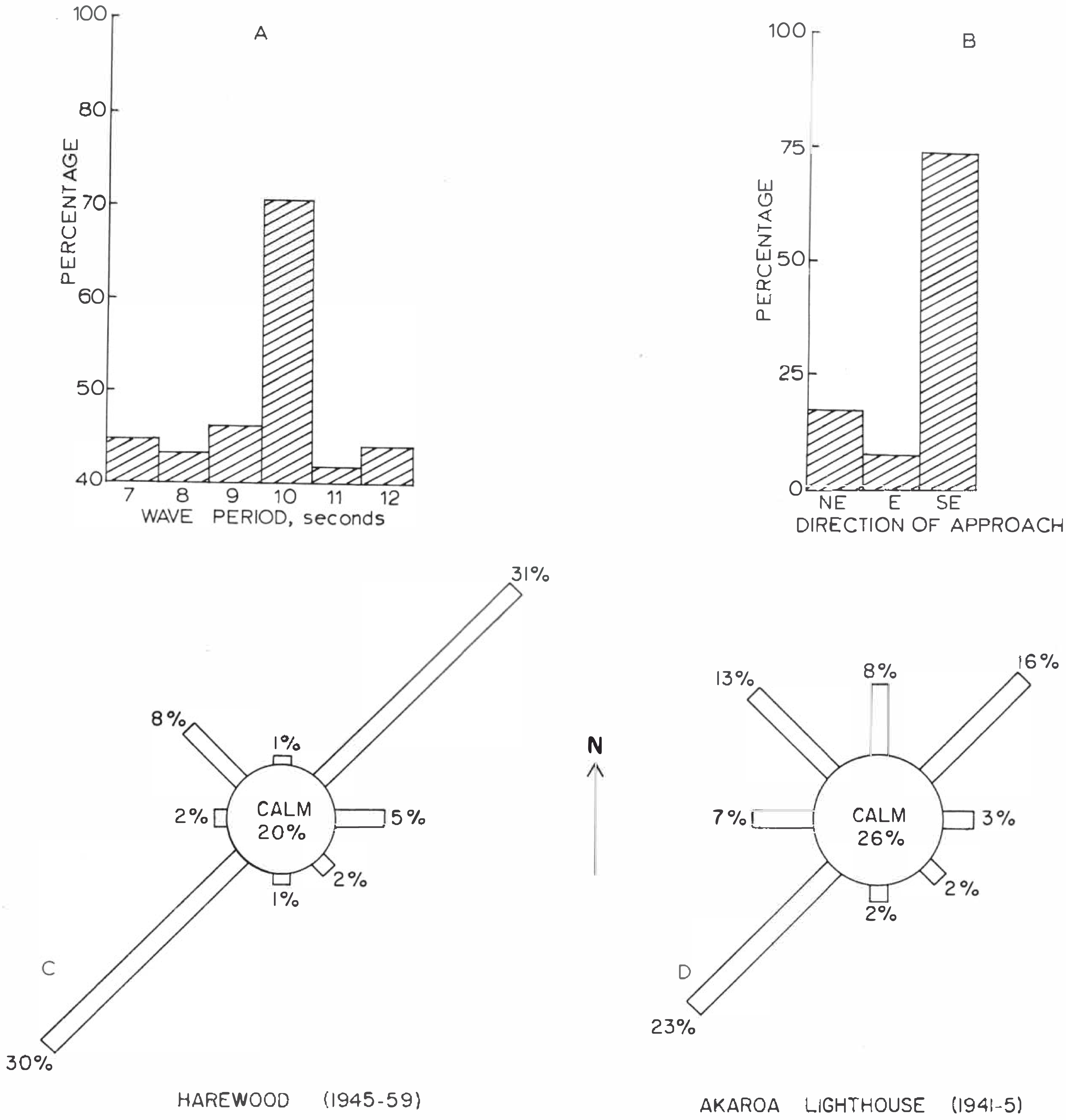

Figure 33 A Percent occurrence of observed wave periods.
B Observed direction of approach of swell.
C Annual wind distribution at Harewood (1945–59).
D Annual wind distribution at Akaroa Lighthouse (1941–45).

Taylors Mistake from the east. North-easterly waves remain largely unaltered crossing the plane floor of Pegasus Bay but, like those from the south-east, turn abruptly shoreward on reaching the critical zone of shallow water off the peninsula's north-eastern extremity. Orthogonals spread out markedly south of the peninsula, so that while Taylors Mistake experiences storm waves 10 ft (3 m) high, the beaches at Peraki, Te Oka, and Tumbledown bays may have no surf whatsoever.

Wave energy is not expended in the same way or at a uniform rate on all of the peninsula's beaches, a fact that assists in explaining differing rates of supply of material to the beaches and movement of material on the beaches.

Incomplete refraction of waves within the bays is important in the supply of sediment to the beaches and the nature of wave attack on the shore. The offshore bottom relief differs from that of most embayed coastlines. Similar depths of water off

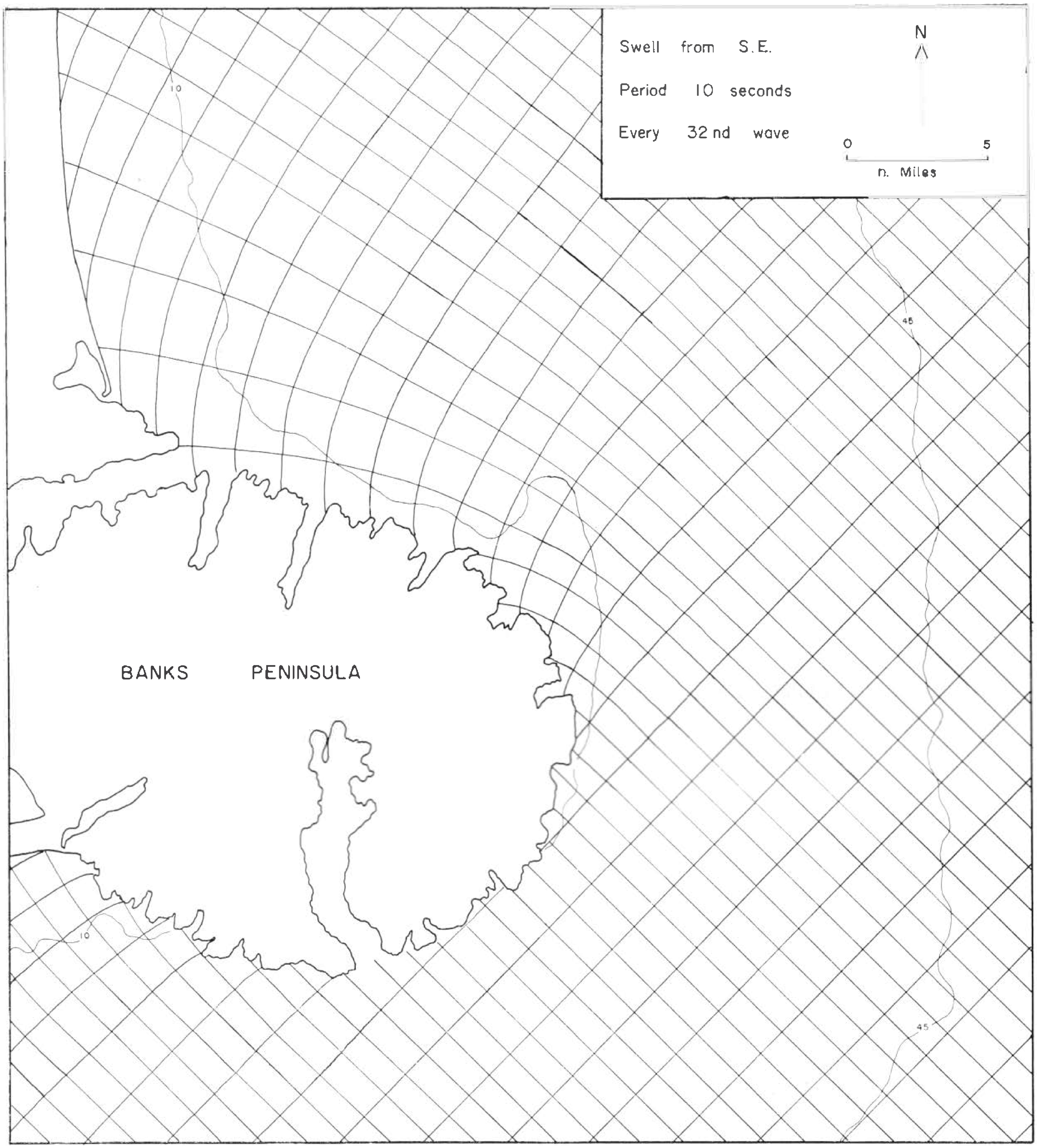

Figure 34 Refraction pattern for south-easterly swell of 10 sec period for Banks Peninsula.

both the plunging headlands and the re-entrants, coupled with the absence of shelving sides on the bay floors prevents wave energy being concentrated on the headlands and dissipated along the bay sides. Instead, high energy waves approach the peninsula over plane sea floors, undergo little refraction as they enter the bays, and run through the channels without greatly diminishing in energy until they break on the bay-head beaches. This makes the peninsula an exception to the general rule that even imperfectly "landlocked" bays are little influenced by ocean swell. Prolonged occurrences of 3 to 4 ft (1 to 1.2 m) breakers on beaches more than 1.6 km from the open ocean stress that wave action on these bay-head beaches is more like that on exposed beaches than on beaches at the head of most bays elsewhere.

The distribution of wave energy within the beach area itself is determined by the type of breaker. This in turn, is a function of offshore bottom slope. On the more exposed, steeper beaches and Long and Flea bays, breakers are

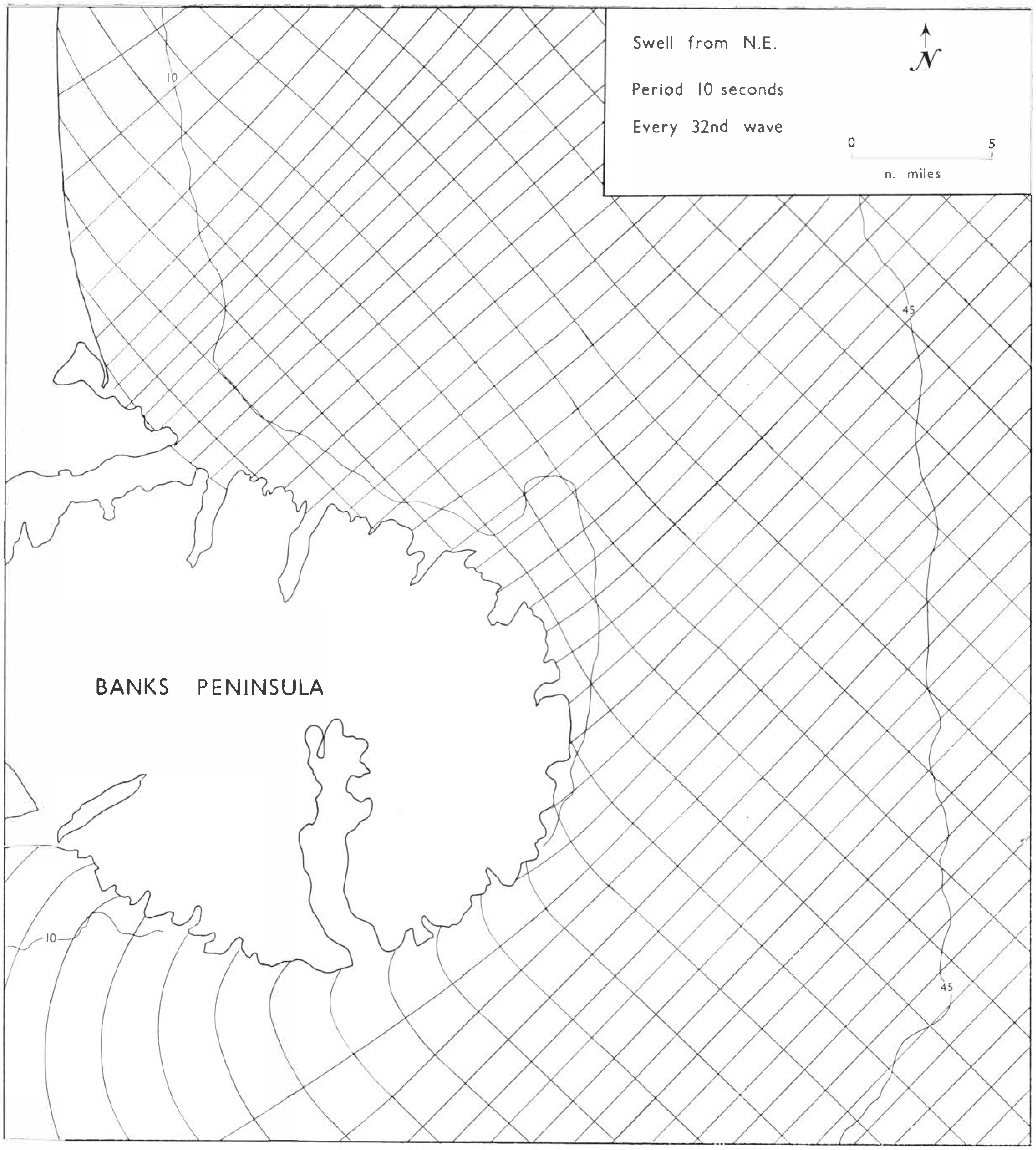

Figure 35 Refraction pattern for north-easterly swell of 10 sec period for Banks Peninsula.

characteristically the plunging type, with surf zones less than 50 m wide; breakers up to 10 ft (3 m) in height occur. On beaches such as at Goughs, Hickory, and Ikoraki bays wave action is usually vigorous. However, on the gently sloping beaches several rows of spilling breakers advance shoreward simultaneously across a surf zone up to 150 m wide.

WINDS

Conditions at Akaroa Lighthouse are representative of the southern areas of the peninsula, and those at Harewood of the northern area. The prevailing winds are from the south-west and north-east, with north-westerlies next in importance (*figure 33*). The dominant wind is south-westerly in the southern bays and north-easterly in the northern bays; both winds commonly reaching force 4 to 6 on the Beaufort Scale. An orographic influence is exerted on winds in the vicinity of the peninsula. Winds from all directions are channelled into valleys so that they blow directly onshore or offshore at the beaches. This channelling effect also increases the velocity and turbulence of winds, making them more effective in removing sand from the beach to the dunes or the offshore zone.

Wind has been important in providing a probable source of beach sand on the peninsula–the loess which mantles the volcanics. The ubiquity of the deposit and thicknesses in excess of 25 ft (7.5 m) on the seaward margin suggest it has been derived both from the plains to the west and, when exposed by low sea levels, the continental shelf to the east (Raeside 1964).

CHARACTERISTICS OF BEACH SANDS

TEXTURAL CHARACTERISTICS

Grain size

The values of mean grain size, sorting, skewness, and kurtosis and for samples from the mid-tide zone* of each locality have been plotted (*figures 36, 37*). Values of mean grain size (M_z) and sorting (δ_1) are similar (*figure 38*) in the backshore, foreshore, and nearshore zones on all beaches. This permits the choice of the mid-tide zone as a reference to characterise and compare the beach sands.

The bay-head sand beaches consist of medium, fine, and very fine sands, though the total size range (0.47 mm at Ikoraki to 0.10 mm at Peraki Bay) is not large. The more exposed beaches at Taylors Mistake, Goughs, and Ikoraki bays are medium sands. The fine sand beaches are within longer and more sheltered inlets. The very fine sands at Peraki Bay have a mean size close to the minimum expected in a beach environment (Folk 1965). This is the only beach with a measurable quantity of silt-sized material (9 percent of sample less than 0.075 mm in diameter).

Sorting

The sand is very well sorted on seven beaches, well sorted on five and moderately well sorted on one other (*figure 36* and *Appendix 1B*). Sorting and grain size are closely interdependent, sorting decreasing with increase in grain size (*figure 39*).

Some fine sands are remarkably well sorted. The sorting coefficients for sand at Okains, Le Bons, Te Oka, and Tumbledown bays are among the lowest found in natural sediments, and at Raupo Bay sand is sorted to a degree rarely encountered (Folk 1965), 80 percent being within the 0.104 to 0.150 mm size fraction.

Skewness

Although all sands (with the exception of Hickory Bay) have negative skewness values, there are no significant departures from normal symmetrical distributions (*figure 38*). The predominance of negative skewness, suggests an excess of coarse material. This can result from the action of swash-backwash, winnowing out the fines and causing the lack of a "tail" at the fine-grain end of the curve.

Finer sands are more deficient in fines than coarser sands (*figure 40*) suggesting that much of the material smaller than the mean size of the fine sands is too fine to accumulate on the beach.

Kurtosis

As expected for unimodal sediments, the sands have normal or near-normal values for kurtosis (*figure 36*). The sand on eight of the beaches showed normal distribution curves, while sands from the other five beaches had curves indicating better sorting in their central portions than in their "tails".

Roundness

The sands are subangular to subrounded (*table 1*). Although the range of roundness means is not large (0.30 to 0.39), the finer sands are generally more rounded than the coarser sands. This may be due to the particular mineral composition of the finer grains and their having been transported over greater distances thereby being subjected to greater abrasion. On the shelf and bay floors, the finer (and more readily moved) grains may be transported over considerable distances by being washed to and fro by tides and currents.

MINERALOGY

Carbonate content

Coarse sands contain most carbonate, the shell fragments in some sands being sufficient to prevent

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*Position on foreshore approximating the water level half-way between the previous high tide and the succeeding low (Bascom 1951).

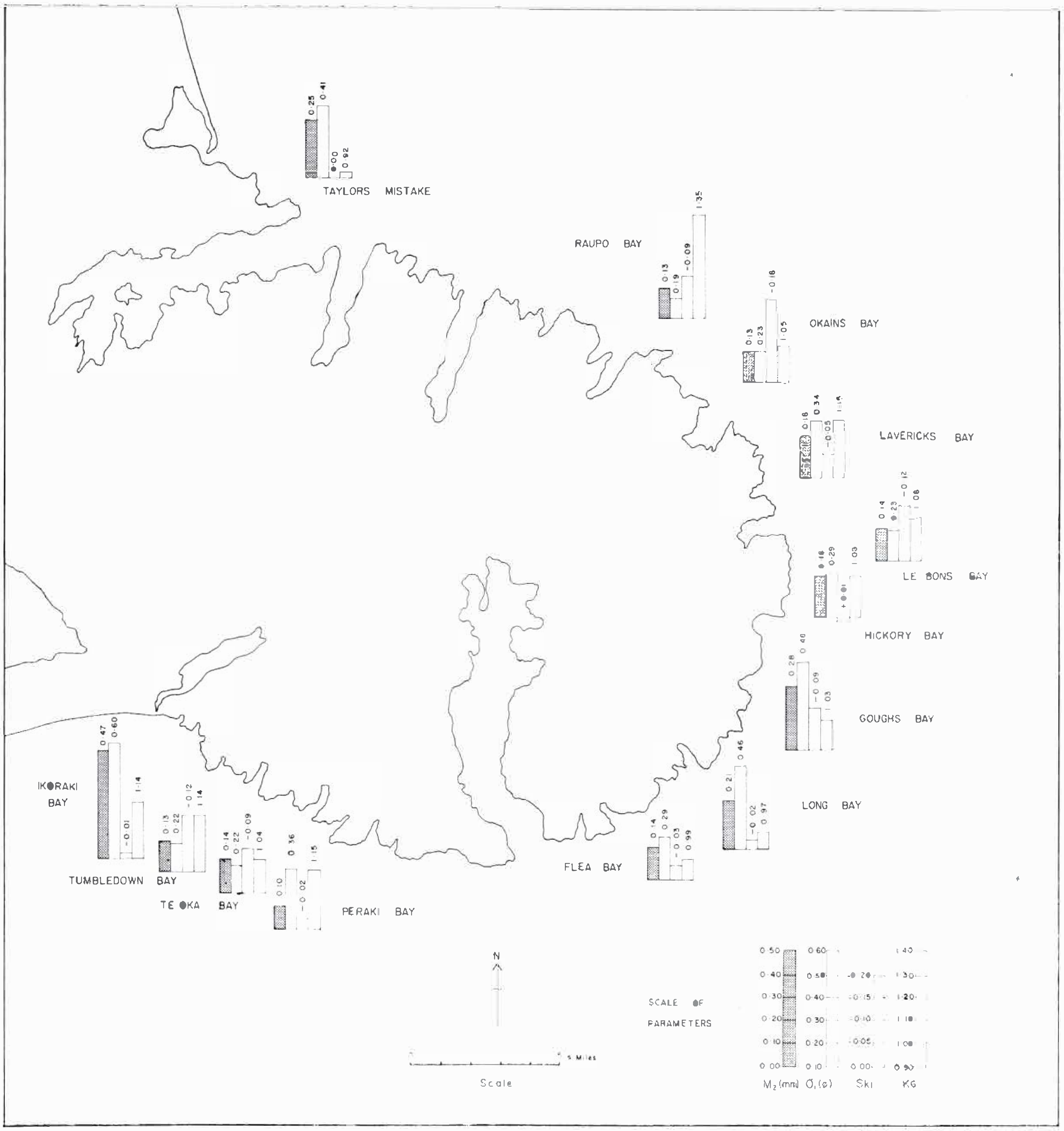

Figure 36 Grain size parameters for sand from the mid-tide zone of each beach.

firm packing. This plays an important role in determining the mobility of sand under wave action. Shell fragments were commonly segregated into distinct laminae. Analysis of individual laminae at Ikoraki Bay, where this phenomenon was most pronounced, showed some laminae contain up to 79 percent acid-soluble material as compared with only 15 percent in others.

Heavy minerals

The contrasting sands from Ikoraki and Raupo bays were analysed for heavy mineral assemblages. Ikoraki Bay heavy mineral separations consist predominantly of angular basalt rock fragments, and grains of plagioclase feldspar with inclusions of magnetite, occasional grains of pure magnetite, clinopyroxene (augite) and garnet. Rock fragments also dominate the heavy mineral separation from Raupo Bay, but are weakly magnetic and contain small amounts of light minerals such as quartz and feldspar and fragments of argillite. The remainder of the heavy mineral suite includes plagioclase feldspar with magnetite inclusions, titaniferous pyroxene, and conspicuous amounts of biotite and

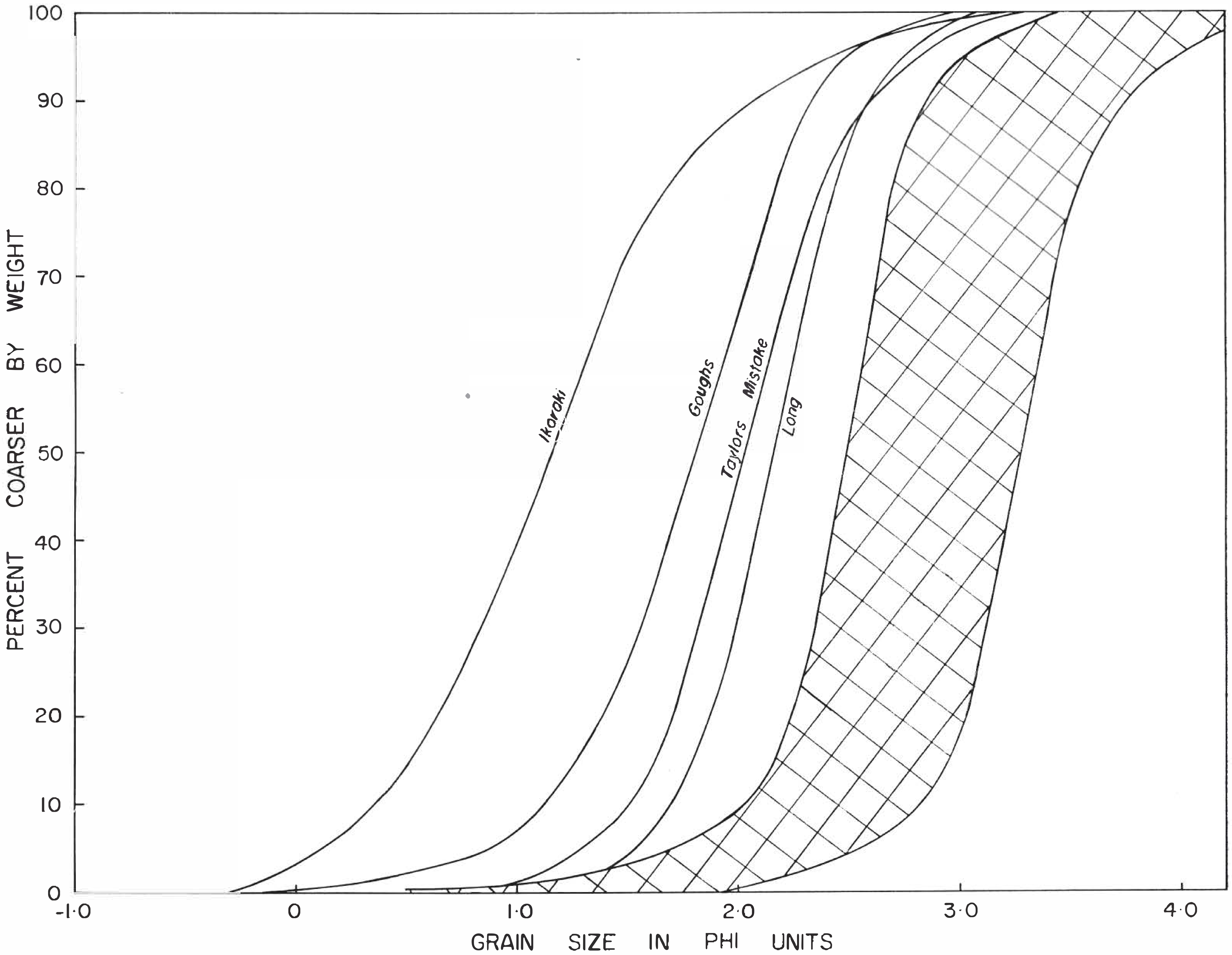

Figure 37 Cumulative curves of grain size distribution for samples from the mid-tide zone. Curves for the fine and very fine sand beaches lie within the hatched area

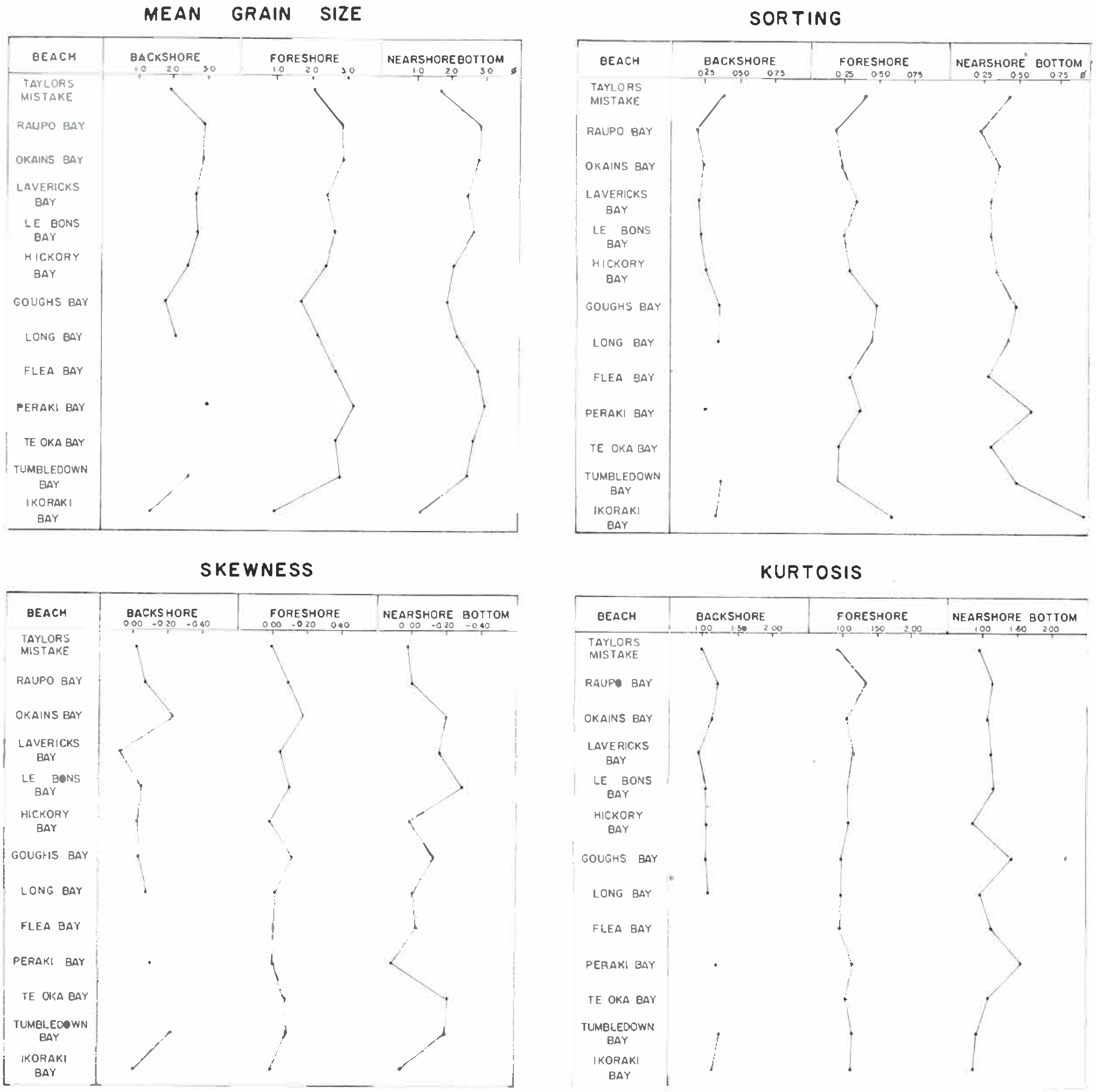

Figure 38 Comparison of grain size parameters of backshore, foreshore, and nearshore bottom sands.

chlorite. The heavy minerals at Ikoraki Bay suggest derivation from the volcanic rocks of the peninsula, but the biotite, chlorite, and nature of the other rock fragments at Raupo Bay suggest derivation from greywacke rocks.

The greatest portion of heavy minerals on the beaches would be expected to be derived from the peninsula's igneous rocks (high heavy mineral content), whereas greywackes would supply comparatively minor amounts of detrital heavy minerals. Medium-grained sands contain a significant amount of heavy minerals but the finer sands, especially at Peraki, Raupo, Okains, and Le Bons bays, contain predominantly light minerals (*figure 41*).

Magnetite

Magnetite, or plagioclase feldspar with magnetite inclusions can indicate sediment derived from volcanic rocks. The magnetite content in the beach sands (*figure 41*) varies considerably: the medium sands at Goughs and Ikoraki Bays contain 50 percent or more, but several of the fine, light mineral sands have only a very small percentage of magnetite.

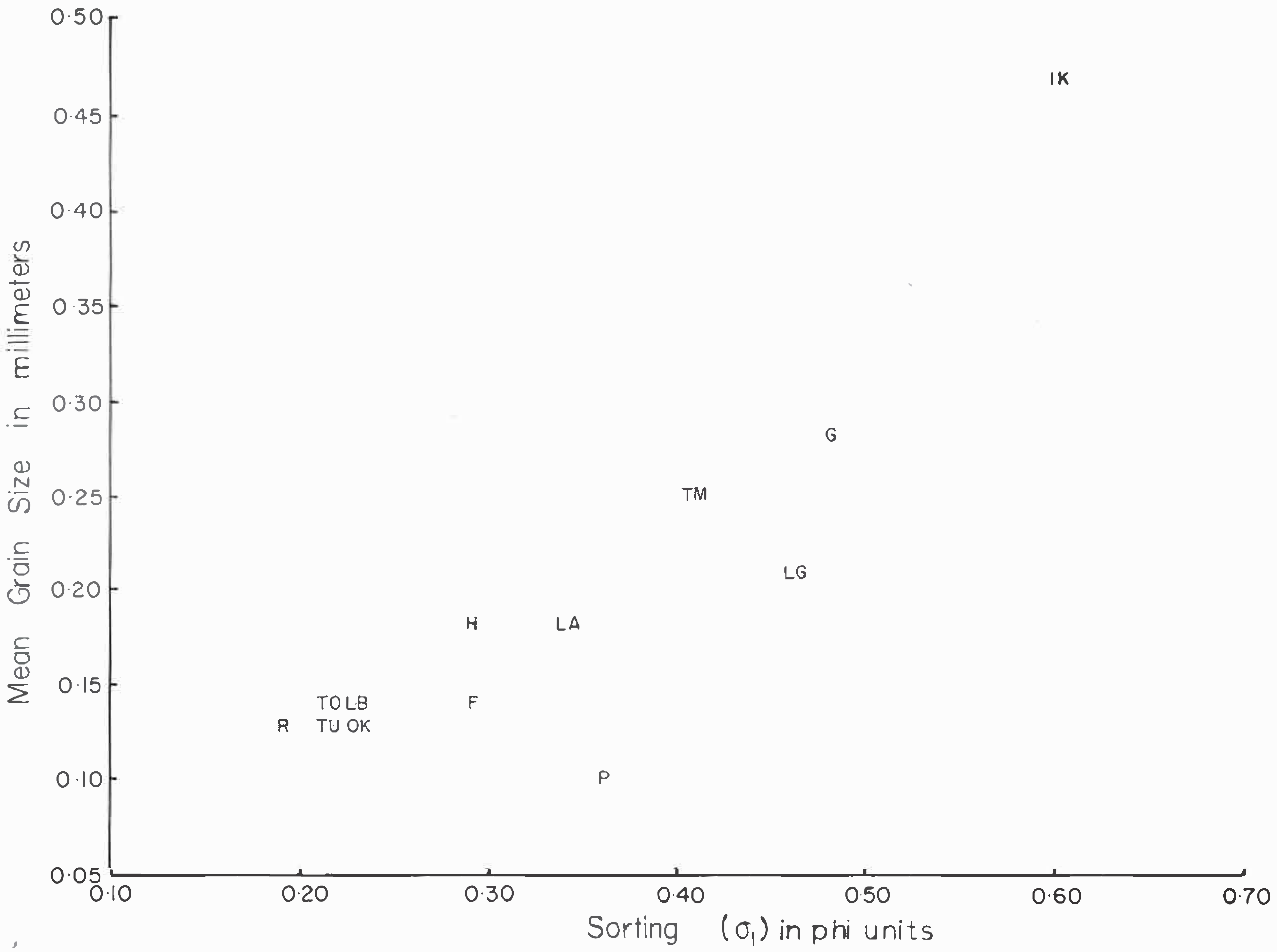

Figure 39 Relationship between mean grain size and sorting at the mid-tide zone.

Quartz

In contrast to basic igneous rocks greywackes produce sands with high quartz contents. Sand transported over long distances by waves and currents will be largely reduced to quartz through the elimination of less resistant mineral constituents. Quartz content is thus a good indicator of the proportion of material from greywacke-derived detritus.

Ikoraki and Goughs bays sands contain abnormally small amounts of quartz. However, four fine sand beaches contain 50 percent of quartz (*figure 41*).

CLASSIFICATION OF BEACH SANDS

The beaches of Banks Peninsula can be arranged into three groups according to the mineralogical and physical characteristics of their sands (*table 1*).

Group I–*Predominantly medium-grained heavy-mineral sands*–Ikoraki Bay, Taylors Mistake, and Goughs Bay.

These three beaches are at the head of inlets well exposed to waves and their offshore bottom slopes are comparatively steep. Wave energy is abruptly dissipated on the shore, and surf zones are characteristically turbulent. Fine sand, the largest fraction involved in longshore transport, is not deposited on the beach under such high-energy conditions, and medium-grade sand predominates on the beach. In each case the degree of roundness is low (0.30–subangular) and the sands are well sorted or moderately well sorted. The magnetite percentages are the highest of all the beaches examined, 37 to 54 percent, the quartz percentage is low (7 to 12) and the other heavy minerals are present in the highest proportions encountered (28 to 35 percent).

Group II–*Fine light-mineral sands derived from greywacke detritus*–Raupo, Okains, Le Bons, and Peraki bays.

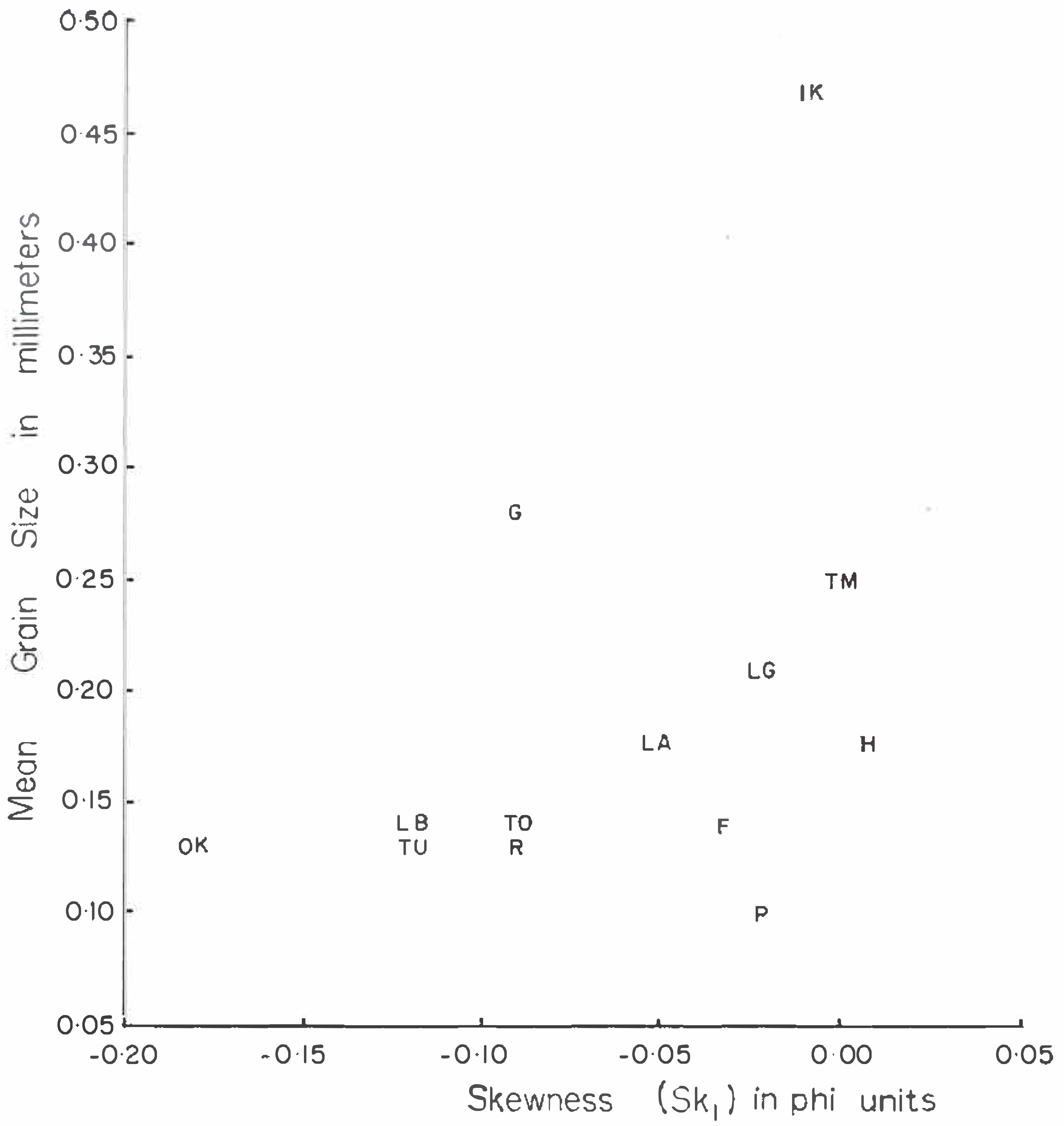

Figure 40 Relationship between mean grain size and skewness at the mid-tide zone.

These sands contain very small proportions of magnetite (3 to 6 percent) and other heavy minerals (1 to 3 percent). Although the exposure of the bays varies from "well-exposed" to "least exposed", the beaches are all sheltered. Three are composed of fine sands and one (Peraki) of very fine sand and silt. Three beaches have sands that are "very well sorted" and one (Peraki) "well sorted". The values for roundness are the highest (0.34 to 0.39—subangular to subrounded) measured. A detailed analysis of Raupo beach sand indicated dominant quartz, feldspar, argillite fragments, biotite, and chlorite.

Beach progradation in Raupo, Okains, and Le Bons bays exceeds that of all other bay-head beaches and the heads of the two harbours. The alluvial flats at the heads of Okains and Le Bons bays, (537 and 377 acres, 217 and 152 hectares respectively), have extensive beach and dune ridge systems. All the ridges consist of sand with remarkably uniform textural characteristics throughout the accretionary series.

Group III—*Intermediate percentages of quartz, heavy minerals, and magnetite in fine sands*—Lavericks, Hickory, Long, Flea, Te Oka, and Tumbledown bays.

All the bays except Hickory are in the category least exposed to waves. All the beaches are sheltered, all have dominant fine sand; four of the sands are "very well sorted" and two "well sorted". The sands are in the middle range of roundness measured (0.32 to 0.35). The percentage of quartz grains varies from 12 to 18 in the well sorted sands (at Long and Hickory bays) and from 30 to 41 in the very well sorted sands. Quartz is the dominant measured mineral in the very well sorted examples and magnetite and other heavy minerals are high and dominant in the well sorted sands.

SUPPLY OF SAND FROM SOURCE AREAS

The shelf sediments were for the most part deposited by aggrading rivers at times of low stands of Pleistocene sea levels. The reworking of this material by waves and currents would have been facilitated by lower sea levels resulting in higher rates of transport and a greater accumulation of sediment on the peninsula's margin than under present conditions. The build-up of sediment is

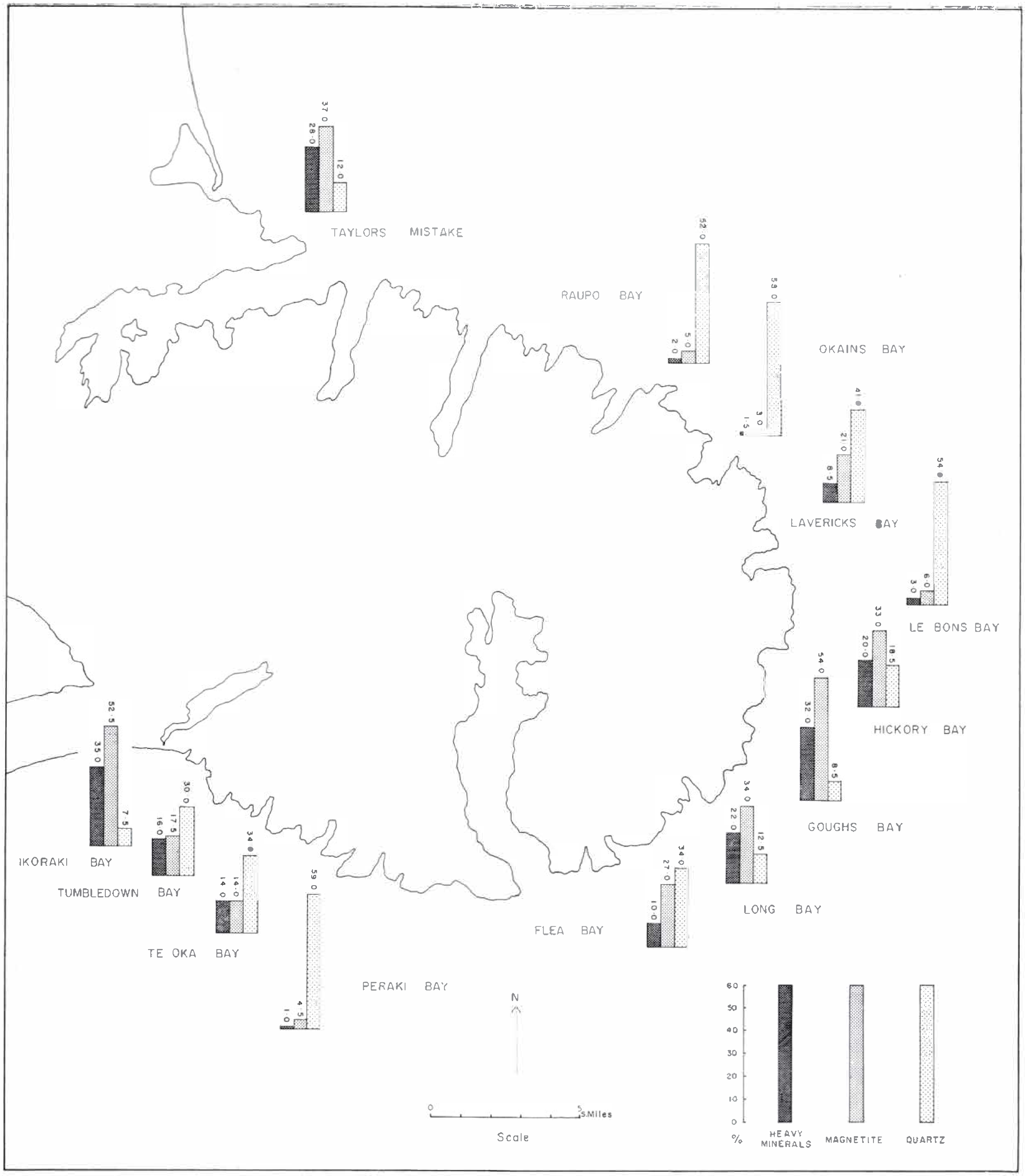

Figure 41 Distribution of heavy minerals, magnetite, and quartz in mid-tide beach samples.

continuing at the present time. The shelf sediments contain an abundant supply of fine sands whose transport is facilitated by the offshore planar surfaces. The high postglacial sea-levels have not produced depths great enough to prevent disturbance of shelf sands immediately offshore, but it is nevertheless difficult to determine the relative importance of waves and currents in sediment transport. Recent studies indicate that wave action does not substantially shift sand at more than 10 fm (18 m). Detailed investigations by Inman and Rusnak (1956) off the Californian coast revealed little change in the level of the sea bed below five to seven fathoms (9 to 13 m) and Trask (1955) noted from his study of sediment transport around promontories that sediments below 10 fm (18 m) were rarely disturbed by waves. Depths more than 10 fms adjacent to headlands are found only on the south-eastern portion of the peninsula's coastline. All bay floors are therefore within easy reach of even moderate wave action. The most important role of waves is probably in moving material from the seabed into suspension to be transported by currents.

Large-scale movements at depths more than 10 fm (18 m) must be achieved by means other than wave action. The action of currents (King 1959) especially of tidal currents (Shepard 1963) extends to greater depths than wave action (Schofield 1967). The permanent coastal current (velocities up to two knots) flows close enough to the eastern extremity of the peninsula to be a significant contributor of sediment to the coastal margin. However, tidal currents are probably the most important transporters of material in the immediate vicinity of the peninsula. The tidal streams forced to flow around the headlands, and thereby increased in velocity and turbulence are thus rendered more capable of disturbing and moving bottom sediments. Such transport parallel to the shore is frequently seen as "suspension clouds" which travel around the peninsula's headlands.

Fine sands, swept northwards from the shelf south of the peninsula by the permanent coastal current, the predominating south-easterly swell and the flood tidal stream, accumulate in comparatively undisturbed water on the peninsula's leeward margin. Additional material may be supplied from the eddy current which occasionally sweeps southwards from Pegasus Bay (Dawson 1953) and the site of deposition may mark the vortex between this eddy and the major coastal current.

TRANSPORT OF SEDIMENTS TO BEACHES

Bay-head beach sands may have been transported in two ways. They may be derived directly from the sand-laden currents that flow close to the headlands when these are swept into re-entrants either by wave transport or flood tidal streams.

Deposition can also take place from the sediment in shallow water on the north side of the Peninsula. From this depositional site sand is driven shorewards towards the north-eastern bays by wave action. The bottom-relief is such that waves from all directions are refracted and sweep into the bays. Incomplete refraction of waves as they run towards the bay head allows them to retain sufficient forward impulse to transport sand along the full length of the bay and on to the beaches at the bay head. The sand on the beaches represents the fraction of the longshore-drifted material that is sufficiently large to be moved shoreward by the swash, without being returned by the backwash.

PETROLOGICAL ORIGIN OF SEDIMENTS

THE ROLE OF LOESS

It seems likely that a certain proportion of the fine beach sand is the coarsest fraction of the loess eroded from surrounding slopes. Loess forms an extensive mantle on the volcanic rocks and has been severely eroded over much of its area. Its mineralogy and texture are similar to that of the fine beach sands. Subequal proportions of quartz and feldspars make up 90 percent of the primary minerals in loess (Raeside 1964) and fine sand constitutes almost 70 percent, by weight, of some loess samples from the peninsula (Birrell & Packard 1953). Reworking of the loess on the shelf could selectively sort out the fine sand making it available for deposition on the beaches, while silt, clay and that portion chemically altered by the sea water remain as a superficial cover for bay-fillings.

Elucidation of the relative importance of loess and alluvial shelf sediments as sources of beach sand is a matter awaiting further research. It initially requires reconstruction of the former thickness and extent of the loess cover, and calculation of the volume eroded. Since both shelf sediments and loess stem ultimately from the same greywacke source (Reed 1951, Raeside 1964) they have similar mineralogical and physical properties. Indeed, Raeside (1964) suggests that the toes of the Canterbury alluvial fans, now submerged on the shelf, may have been the richest source of the peninsula's loess at times of lower Pleistocene sea levels.

GREYWACKE-DERIVED SEDIMENTS

The bulk of sediments mantling the shelf are derived ultimately from the greywacke rocks of the Southern Alps. Some sediments will have been emplaced subaerially as river deposited alluvium; some are being brought down by present-day rivers or eroded from sea-cliffs and distributed by present-day marine processes. Some will consist of loess eroded from Banks Peninsula hills and redeposited in the marine environment.

BANKS PENINSULA VOLCANICS

At earlier stages of its geological history the Banks Peninsula volcanic complex has contributed a large volume of erosion products to the surrounding sea. However, in late Pleistocene and Holocene times erosion of cliffs has been minimal because of their steep sub-aerial and submerged form and bay-heads have been protected by aggradation. The present streams on the peninsula are small, often underfit and contribute relatively small amounts of eroded volcanic material to the bay heads.

ORIGIN OF BEACH GROUPS

BEACHES OF GROUP I

Ikoraki, Taylors Mistake, Goughs Bay

The medium sands from all these beaches have a low mean roundness coefficient suggesting that they have been transported over only short distances. The predominance of magnetite and other heavy minerals and the low quartz content indicate a substantial component derived from the erosion of local andesitic and basaltic rocks. The exposure to waves and the high energy environment at the beaches minimises the deposition of finer-grained sediments (available from greywacke sources) that would otherwise mask the locally derived material.

BEACHES OF GROUP II

Raupo, Okains, Le Bons, and Peraki bays

The higher mean roundness coefficient indicates a longer transport time and the extensive progradation and development of dune systems suggests emplacement in these sheltered bay-heads from an extensive sediment supply. The high quartz content, significant biotite and chlorite, and low heavy mineral content indicate a predominant greywacke origin for these fine-grained sands.

Similarity in sand mineralogy and grain size at Raupo, Okains, and Le Bons bays suggests a common origin of beach material. The textural uniformity within the ridge systems and similarity with properties of sand on the present beaches show the sediments have had an identical origin throughout the depositional histories of these particular bays.

Differences in degree of exposure to the shallow water depositional site on the north side of the peninsula probably account for the differences in the rate of build-up of material in Okains and Le Bons bays and the extent of progradation of their beaches.

Peraki Bay acts as a trap for fine, light detrital sand swept northwards from the shelf and shore line further south. This small transient deposit is laid down and removed from the shore in accordance with changing wave conditions.

BEACHES OF GROUP III

Lavericks, Hickory, Long, Flea, Te Oka, and Tumbledown bays

The mean roundness coefficient of the fine sands from these sheltered beaches indicates an intermediate length of transport. The intermediate mineralogical characteristics suggest that although the greywacke-derived minerals form a large proportion of the beach materials there can have been a significant contribution from erosion of the local volcanics.

CONCLUSIONS

Compositional differences in beach sediments produce differences in beach morphology. Steeper equilibrium gradients on medium sands contrast with gently-sloping gradients on fine sands. A close relationship exists, also, between the character of material, and beach morphology. The fine sand beaches are rather stable, but medium sand beaches are dynamic. The beaches are in a constant state of flux. Modification of beach profile configuration may be rhythmic or cyclic when caused by the systematic repetition of tidal regimes or seasonal variation in wave conditions. It may alternatively be irregular, when related to storms or changes in orientation of wave approach.

The magnitude of change exhibited by beach profiles is greater than would be expected on beaches located deep within a land mass and set between confining headlands. It results from the unusual nature of the coastal sea floor, whose planar surfaces cause a concentration of wave energy in the bay head, rather than on headlands or bay sides. This renders beach characteristics and processes on the peninsula's bay-head beaches analogous to those on beaches fully exposed to the open ocean.

Variations in the physical and mineralogical characters of nearshore sands on Banks Peninsula indicate that its bay-head beaches are influenced by an influx of longshore-drifted sand from the continental shelf. Most individual bays do not constitute isolated and complete physiographic units with respect to supply and transport of beach sediments. This is strongly supported by the transporting potential of waves and currents in the vicinity of the peninsula. Perennially heavy swells appear capable of disturbing shelf sediments of fine sand grade over a wide area and thereby bringing material of this grade into suspension. Tidal currents, which are increased in velocity and turbulence by the peninsula's irregular coastline, have the potential to move at least fine sands around headlands.

Although the greywacke-derived detritus mantling the continental shelf has been deposited by both past and present fluvial processes, its final resting place is determined by marine processes. It is most likely that the net transport of sediment is from south to north. The greatest rates of transport take place when the northerly-flowing coastal current, flood tidal streams, and south-easterly swells operate in unison. Coarser fractions are progressively sorted out on the shelf and beaches to the south, while finer fractions are swept northwards around the peninsula's margin. The bays act as traps for this transported material. The fine sands migrate between promontories under the influence of wave action, shallowing the bay floors and ultimately adding to material on the beaches. The variation of sand characteristics on the peninsula's beaches indicates that the pattern of sand distribution is related principally to geographic and geomorphic setting of the beach; the location with respect to sediment source; and orientation of the bay entrance and its consequent exposure to wave action.

On individual beaches the relative proportion of sand derived from the shelf and directly from the peninsula's volcanic rocks is determined by the exposure of the beach to marine processes which control the strength of water movement in the bay head. Wave energy is expended at too high a rate on beaches at the head of shorter, more exposed inlets for fine sands to be deposited. Consequently, such beaches are composed of medium sands and coarser fractions derived mainly from igneous rock. Moreover, the process of linking the peninsula to the mainland by sediment accretion is still very much in progress. Just as west-facing valleys have been filled with coarse greywacke-derived alluvium by aggrading rivers of the plains, so the valleys on the seaward periphery are being filled dominantly with fine greywacke-derived sands, that have been reworked by currents and waves on the shelf. However, shallowing of bays and simplification of the initial, embayed coastal outline have not reached such a mature stage as on the Otago Peninsula, where the growth of spits is actively bridging bay mouths.

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Appendix IA Formulae and verbal scales for sedimentary grain size parameters

I GRAPHIC MEAN :

$$M_Z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

II INCLUSIVE GRAPHIC STANDARD DEVIATION :

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

<0.35ϕ	very well sorted
0.35 to 0.50ϕ	well sorted
0.50 to 0.71ϕ	moderately well sorted
0.71 to 1.0ϕ	moderately sorted
1.0 to 2.0ϕ	poorly sorted
2.0 to 4.0ϕ	very poorly sorted
>4.0ϕ	extremely poorly sorted

III INCLUSIVE GRAPHIC SKEWNESS :

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

+1.0 to +0.3	strongly fine skewed
+0.3 to +0.1	fine skewed
+0.1 to -0.1	near symmetrical
-0.1 to -0.3	coarse skewed
-0.3 to -1.0	strongly coarse skewed

IV GRAPHIC KURTOSIS :

$$K_G = \frac{\phi 95 - \phi 5}{2.44\ (\phi 75 - \phi 25)}$$

<0.67	very platykurtic
0.67 to 0.90	platykurtic
0.90 to 1.11	mesokurtic
1.11 to 1.50	leptokurtic
1.50 to 3.00	very leptokurtic
>3.00	extremely leptokurtic

Appendix IB Grain size distribution in each beach sample, Summer 1966

BEACH		ZONE	Md ϕ	Mz ϕ	$\sigma_I\phi$	Sk_I	K_G
Taylors Mistake	TM1	dunes	2.14	2.16	0.33	+0.09	0.93
	TM2	backshore	1.93	1.92	0.38	-0.02	0.97
	TM3	foreshore	2.00	2.00	0.41	0.00	0.92
	TM4	nearshore bottom	1.71	1.73	0.45	+0.02	0.95
Raupo Bay	R1	dunes	2.89	2.89	0.15	-0.13	1.30
	R2	backshore	2.94	2.94	0.19	-0.07	1.20
	R3	foreshore	2.93	2.93	0.19	-0.09	1.35
	R4	nearshore bottom	2.89	2.89	0.18	0.00	1.16
Okains Bay	OK1	dunes	2.97	2.96	0.20	-0.13	0.87
	OK2	backshore	2.96	2.94	0.25	-0.23	1.14
	OK3	foreshore	2.96	2.94	0.23	-0.18	1.05
	OK4	nearshore bottom	2.88	2.84	0.36	-0.21	1.08
Lavericks Bay	LA1	hinterland	2.69	2.68	0.22	-0.07	1.40
	LA2	backshore	2.68	2.69	0.20	+0.06	0.92
	LA3	foreshore	2.48	2.47	0.34	-0.05	1.15
	LA4	nearshore bottom	2.57	2.54	0.31	-0.16	1.13
Le Bons Bay	LB1	dunes	2.89	2.87	0.22	-0.18	1.18
	LB2	backshore	2.73	2.72	0.23	-0.06	1.02
	LB3	foreshore	2.76	2.75	0.23	-0.12	1.08
	LB4	nearshore bottom	2.81	2.79	0.39	-0.30	1.13
Hickory Bay	HK1	hinterland	2.40	2.35	0.36	-0.20	1.14
	HK2	backshore	2.48	2.48	0.26	-0.03	1.05
	HK3	upper foreshore	2.51	2.52	0.23	+0.02	1.13
	HK4	lower foreshore	2.34	2.33	0.35	0.00	1.04
	HK5	nearshore bottom	2.15	2.15	0.36	0.00	0.88

(continued on *page 60*)

BEACH		ZONE	Md ϕ	Mz ϕ	$\sigma_I \phi$	Sk $_I$	K $_G$
Goughs Bay	G1	dunes	1.66	1.65	0.35	-0.05	1.02
	G2	backshore	1.89	1.88	0.36	-0.03	1.02
	G3	foreshore	1.81	1.79	0.48	-0.09	1.03
	G4	nearshore bottom	1.98	1.95	0.49	-0.13	1.41
Long Bay	LG1	hinterland	2.23	2.21	0.39	-0.04	1.10
	LG2	backshore	2.19	2.16	0.35	-0.09	1.07
	LG3	upper foreshore	2.20	2.19	0.47	-0.03	0.98
	LG4	lower foreshore	2.24	2.24	0.46	0.00	0.97
	LG5	nearshore bottom	2.23	2.22	0.44	-0.02	0.97
Flea Bay	F1	upper foreshore	2.74	2.73	0.30	-0.02	0.97
	F2	lower foreshore	2.82	2.81	0.28	-0.03	1.00
	F3	nearshore bottom	2.83	2.83	0.30	-0.04	1.12
Peraki Bay	P1	backshore	3.13	3.10	0.27	-0.11	1.20
	P2	foreshore	3.27	3.27	0.36	-0.02	1.15
	P3	nearshore bottom	3.11	3.13	0.40	+0.11	1.54
Te Oka Bay	TO1	upper foreshore	2.77	2.76	0.21	-0.08	1.00
	TO2	lower foreshore	2.80	2.78	0.23	-0.10	1.09
	TO3	nearshore bottom	2.73	2.71	0.31	-0.21	1.09
Tumbledown Bay	TU1	dunes	2.32	2.29	0.55	-0.06	0.80
	TU2	dunes	2.46	2.42	0.46	-0.10	0.65
	TU3	backshore	2.64	2.58	0.38	-0.23	1.24
	TU4	foreshore	2.89	2.87	0.22	-0.12	1.14
	TU5	nearshore bottom	2.59	2.53	0.48	-0.21	0.92
Ikoraki Bay	IK1	dunes	2.02	2.00	0.35	-0.02	1.14
	IK2	backshore	1.48	1.46	0.34	-0.02	1.14
	IK3	foreshore	1.11	1.07	0.60	-0.01	1.14
	IK4	nearshore bottom	1.20	1.23	0.97	+0.05	0.89

Appendix IC Grain size distribution in samples from mid-tide zone, May 1966

BEACH	POSITION ON BEACH	Md ϕ	Mz ϕ	$\sigma_I \phi$	Sk_I	K_G
Taylors Mistake	southern	1.99	1.97	0.37	-0.07	1.19
	central	2.04	2.03	0.40	-0.02	1.14
	northern	1.90	1.87	0.41	-0.13	1.19
Okains Bay	northern	2.88	2.86	0.21	-0.20	1.34
	central	2.96	2.92	0.21	-0.19	1.41
	southern	3.04	3.04	0.15	-0.22	1.48
Le Bons Bay	northern	2.85	2.84	0.16	-0.11	1.66
	central	2.74	2.70	0.22	-0.23	1.14
	southern	2.62	2.50	0.44	-0.45	1.31
Hickory Bay	northern	1.82	1.85	0.51	+0.12	0.90
	southern	2.15	2.17	0.29	+0.12	0.90
Goughs Bay	northern	1.90	1.89	0.34	-0.02	1.10
	central	1.84	1.82	0.37	-0.10	1.03
	southern	1.95	1.94	0.31	-0.02	1.05
Tumbledown Bay	western	2.57	2.52	0.49	-0.21	0.73
	eastern	2.36	2.30	0.60	-0.45	0.90
Ikoraki Bay	northern	1.56	1.57	0.58	+0.03	1.11
	central	1.89	1.92	0.43	+0.12	1.04
	southern	1.58	1.62	0.72	+0.04	0.94

Appendix ID Grain size distribution in samples from mid-tide zone, Winter 1966

BEACH	Md ϕ	Mz ϕ	$\sigma_I \phi$	Sk_I	K_G
Taylors Mistake	2.14	2.16	0.32	+0.08	1.00
Raupo Bay	2.81	2.80	0.19	-0.09	1.25
Okains Bay	2.78	2.77	0.18	-0.06	1.30
Lavericks Bay	2.59	2.56	0.32	-0.05	1.00
Le Bons Bay	2.64	2.55	0.40	-0.38	1.16
Hickory Bay	1.75	1.76	0.50	+0.04	0.94
Goughs Bay	1.75	1.70	0.50	-0.16	1.08
Long Bay	2.02	2.01	0.41	-0.01	1.03
Peraki Bay	3.27	3.26	0.36	-0.01	1.14
Te Oka Bay	2.68	2.67	0.23	-0.09	1.08
Tumbledown Bay	2.58	2.46	0.45	-0.28	0.81
Ikoraki Bay	1.98	2.06	0.51	+0.14	0.72

Appendix IE Grain size distribution in samples from cusps

BEACH	POSITION	Md ϕ	Mz ϕ	$\sigma_I \phi$	Sk_I	K_G
Taylors Mistake	horns	2.05	2.04	0.31	-0.01	1.16
	depressions	2.12	2.13	0.30	+0.03	1.23
Goughs	horns	1.92	1.90	0.32	-0.03	1.04
	depressions	2.14	2.12	0.30	-0.07	1.20
Ikoraki	horns	0.75	0.73	1.49	0.00	1.02
	depressions	2.43	2.36	0.54	-0.18	0.78

Appendix II Scale of roundness (Powers 1953)

ROUNDNESS GRADES	CLASS INTERVALS	GEOMETRIC MEANS
very angular	0.12 - 0.17	0.14
angular	0.17 - 0.25	0.21
sub-angular	0.25 - 0.35	0.30
sub-rounded	0.35 - 0.49	0.41
rounded	0.49 - 0.70	0.59
well-rounded	0.70 - 1.00	0.84

Appendix III Wave observations

BEACH	DATE	T sec	H ft*	TYPE **	DIRECTION OF DEEP WATER APPROACH
Taylors Mistake	10-2-66	8	4	S	SE
	21-3-66	10	3	S	E
	1-4-66	8	7	PS	NE
	3-5-66	10	4	P	SE
	29-7-66	10	5	P	NE
Raupo	9-3-66	9	4	S	SE
	30-7-66	10	3	S	SE
Okains	7-2-66	7	3	PS	-
	8-3-66	10	3	S	-
	22-3-66	10	1.5	S	E
	4-4-66	7	4	S	NE
	25-4-66	10	2	S	SE
	26-4-66	10	2	S	SE
	27-4-66	10	2	S	NE
	30-7-66	10	2	S	SE
Lavericks	11-5-66	10	3	S	SE
	31-7-66	10	3	PS	SE
Le Bons	8-2-66	12	4	S	-
	23-3-66	8	2	S	E
	27-4-66	10	2	S	NE
	31-7-66	10	3	PS	SE
Hickory	6-4-66	9	9	P	SE
	26-5-66	10	8	P	SE
	1-8-66	10	4	PS	SE
Goughs	9-2-66	10	6	P	SE
	24-3-66	10	5	P	E
	5-4-66	10	6	P	NE
	6-4-66	9	10	P	SE
	7-4-66	10	10	P	SE
	10-5-66	9	6	P	SE
	2-8-66	12	4	P	SE
Long	7-4-66	9	3	P	SE
	3-8-66	12	5	P	SE
Flea	2-6-66	9	2	P	SE
Peraki	3-2-66	7	3	S	-
	28-6-66	11	2	PS	SE
	4-8-66	12	2	S	SE
Te Oka	24-2-66	10	3	S	-
	26-6-66	10	4	PS	SE
	5-8-66	10	3	S	SE
Tumbledown	1-2-66	7	2	S	SE
	3-2-66	7.5	2	S	SE
	30-3-66	10	0.5	S	-
	8-5-66	10	3	S	SE
	26-6-66	10	4	S	SE
	5-8-66	10	3	PS	-
Ikoraki	24-2-66	10	4	P	-
	30-3-66	10	2	P	-
	8-5-66	10	4	P	SE
	5-8-66	10	4	PS	SE

* 1 ft = 0.30 m

** P = plunging
S = spilling