

The Snellius-II Expedition

Progress Report

Theme I

Geology and Geophysics of the Banda Arc and adjacent areas

Cruise G 4

Banda, Seram, Halmahera and Maluku Sea

Kau Bay

April 14 – April 29 1985



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1. Introduction

Cruise G4 had two objectives: 1. establish the Late Cenozoic paleoenvironments of Kau Bay, Halmahera and 2. establish the origin and extent of Mn encrustations West of Misool. Both objectives were based on observations made during the first Snellius expedition in 1929-1930. A third task was to recover a string of current meters that was moored in Lifamatola Strait in January 1985 during theme II operations.

Figure 1 shows the overall ships track and along track the underway geophysical measurements are marked.

2. Scientific and technical crew

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ECN Energie Onderzoek Centrum Nederland, Petten
 Netherlands Energy Research Center, Petten

TNI-AL Tentera Nasional Indonesia-Angkatalan Laut
 Indonesian National Armed Forces-Navy Department

3. Cruise narrative

All sites mentioned and all operations carried out underway can be located on figure 1 (overall track chart), figure 2 (tracks and stations off Misool), figure 3 (track chart inner Kau Bay), figure 4 (airgun, KSA and sparker, KSS lines in Kau Bay), figure 5 (box core and piston core casts in Kau Bay) and figure 6 (CTD casts in Kau Bay). All times mentioned are in local time (i.e. GMT + 9 hrs.).

Sunday April 14 1985

The rv Tyro departed from Ambon at 09.20 hrs (i.e. 00.20 GMT), 20 minutes late and proceeded toward our first objective, the investigation of the origin and extent of Mn encrustations west off the island of Misool. A course was set negotiating the passage between the islands of Buru and Ceram, to later alter to a northeasterly course to site M 1. At 11.15 the magnetometer was streamed, recording the total magnetic field and about 16.00, after reducing speed to 6 knots, the airgun seismic reflection system was deployed.

Monday April 15

Stopped seismic and magnetic survey after breakfast and started MB 1 (boxcore nr. 1 off Misool). Completed 6 stations that day on an W - E transect (MB 1 to MB 6). Took 1000 l of surface water which was centrifuged to concentrate suspended particulate matter (SPM).

Tuesday April 16

Continued the Misool reconnaissance survey and sampling program and recovered boxcores MB 7 to MB 9 on a S - N transect. After some searching we occupied station M 10, ENE of M 9, to recover MB 10 shortly before lunch. Set a course for station K 1 outside Kau Bay collecting airgun and magnetometer data.

Wednesday April 17

Crossed the equator at 05.38 in the morning at 129° 07¹.5 min E. Finished airgun run at 11.19 to then spend time on a test run with the Indonesian sparker system. After three hours we proceeded full speed to the vicinity of site K 1 which we located (away from the originally planned site) on a relatively shallow spur, a little distance E of the southern end of the Philippine trench. Recovered boxcore K 1 B 1. Corer P 1 did not penetrate what appeared to be basalt outcrop as testified by fragments of a heavily weathered vesicular dark rock which we retrieved from a badly damaged core cutter. Decided to head for Kau Bay without loosing more time to hopefully recover an oceanic core later, on our way out of Kau Bay, somewhere off the northern tip of Halmahera.

Thursday April 18

Occupied station K 2 at or near the 500 m line just north of the sill that separates the inner Bay from the outer Bay. Lowered a (normal) boxcorer, the Scripps boxcorer and twice the piston corer on site K 2 to top it off with a third boxcorer. Station completed at about 14.00 hrs. Began the passage of the western shipping channel through a minefield (a protection for the Imperial Japanese fleet in World War II) to enter Kau Bay proper at 16.55. There, we began a reconnaissance survey deploying the sparker system together with a four section hydrophone eel. One line was run W - E to gather information for the positioning of an anchored current meter later in the program, the other line was run in a SW direction through the centre of the Bay. Finished the survey at 22.30 and set course to station KC 1 (1st CTD station in Kau Bay). KC 1 started shortly before midnight.

Friday April 19

Completed CTD stations KC 1 to KC 18, the last station providing also an opportunity to pump 700 l of bottom water from the Bay for PSM analysis.

A five man land party left for shore after breakfast to sample the Kau River. This group came back in time to start station K 3 at 16.25. As a matter of routine from each site in the Bay henceforth we recovered two boxcores and two piston cores, the length of the piston corer to be decided on 3.5 kHz information and results of the boxcorer. Station K 3 completed at 21.19 to then start an airgun survey covering the Bay on a number of NW- SE runs and their tielines (KSA 3 to KSA 10).

Saturday April 20

Airgun survey completed at 08.00. Resumed CTD work, covering the SE half of the Bay stations KC 19-33. Oxygen probe posing problems.

Station KC 33 completed at about 19.00 hrs. Headed for station K 4 in waterdepth 437 m, occupying a position we had taken from the airgun and 3.5 kHz records obtained earlier this morning. K 4 B 1 on the bottom at 20.42. K 4 P 1 hit a hard subbottom layer resulting in a damaged core cutter. The corer did not fully penetrate and as a result the piston sucked in the lower-most section, (about 1 m length), whereas the upper 2 - 2.5 m of the core liner had collapsed on vacuum. Opening of corer and freeing core took considerable time (almost 5 hours operation on P1).

Sunday April 21

Recovered two more cores, K 4 P 2 and K 4 P 3, and a boxcore K 4 B 2. We finished station K 4 at about 07.30. Lack of sleep during the last few days because of heavy working load started to take its toll. Set course for anchor station KC 34 in valley just S of the sill ($01^{\circ} 06^{1.7} N - 127^{\circ} 56^{1.8} E$) where we stayed for the next 25 hrs. Arrived on site at 09.45. At the anchor station a current meter was positioned 10 m above the bottom and a CTD cast made every hour on the hour. 1000 l of surface water pumped aboard for PSM analysis. Both rubber boats and a sloop were used to ferry several parties ashore during the day. A small river about 3 km NE of Wasile was sampled.

Monday April 22

Shortly before lunch we took a boxcore in the channel while still anchored (K 5 B 1). After lunch we weighed anchor and steamed to a position at the edge of the valley, dredging for sample from what appeared hard bottom on the 3.5 kHz (K 6 D 1). Upon completion moved to stations K 7 and K 8, respectively which we sampled by boxcores to test the best site for subsequent piston coring (K 7 B 1 and K 8 B 1). K 8 was deemed the best site and K 8 P 1 and K 8 P 2 were recovered. In between the two sections of core liner there was quite a bit of water and although P 1 appeared to have penetrated to full depth (i.e. 9 m) we do not yet know what disturbances to expect. The station was topped off with a box core which emptied itself, however, on deck upon recovery.

All together a promising site which we decided to reoccupy later if sufficient time available. At 23.07 started a sparker survey recovering lines KSS 3 to KSS 9 using only one section of the NIOZ eel, which was in better tune with the sparker signal.

Tuesday April 23

Finished KSS 9 at 07.00 after which we set course for station KC 35 (i.e. reoccupying station KC 18) to take in 800 l of water from a depth of 200 m below the surface for PSM analysis. Station completed at 10.55. We then ran a CTD line, reoccupying stations KC 20, 24, 25, 31 and 32 along a SE - NW course through the middle of the Bay, now with a functioning oxygen probe. Those stations were relabelled respectively KC 36, 37, 38, 39 and 40. We then headed for station K 9 located in the eastern part of the Bay just off Roni Island. Manoeuvring the ship on target was difficult because of abrupt and dramatic changes in bottom morphology. K 9 B 1 went down at 17.58. We also recovered two piston cores K 9 P 1 and K 9 P 2.

Good recoveries, but some disturbance of cores by dissolved gas. Finished station K 9 with a last boxcore. End of station at 22.48. We then resumed the CTD program recovering stations KC 41 to 43 in the NE part of the Bay.

Wednesday April 24

Station KC 43 completed at 00.30 to then start sparker profiling. Line KSS 1 was partly rerun now in a westerly direction (line KSS 1 A), followed by a rectangular survey along lines KSS 10 (Hdg SW), KSS 11 (Hdg SE), KSS 12 (Hdg NE) and KSS 13 (Hdg NW). Survey successfully completed at 08.43. We then went back to site K 8 of last Monday to recover K 10 B 1 and K 10 P 1, a smoothly run operation this time, even though we penetrated a sandy layer with some rather coarse shell fragments. Station finished at 09.30. We then started a circumnavigation of the Bay close under the shore to recover information on the 3.5 kHz sounder about the bottom conditions near shore. These appeared to change dramatically in shallow water and - not unexpectedly - hardly at all in the deeper parts of the basin. One deviation in course had to be made rather abruptly because of the presence of uncharted shoals near Tanjung Tolawi off the eastern shore. At Wp 3 of this survey in the NW part of the Bay we occupied CTD station 44 to pump 1000 l of surface water for PSM analysis. We then headed for position K 11 to start search for a suitable coring site. Target identified at about 19.00 and K 11 B 1 hit bottom at 19.24. Due to relatively strong drift we had to reposition the ship for K 11 P 1 and P 2, the target area being small. Box K 11 B 2 slightly of target at 23.43 on a gentle slope above the chosen sites.

Thursday April 25

Operations at station K 11 stopped at 00.05 hrs. which completed the mission in the Kau Bay proper. Waited for daylight and drifted in the Bay until 04.30 in the morning, when we headed for the passage through

the mine field. Transit began at 06.18. During the passage we occupied CTD stations KC 45 and 46, to continue CTD work once outside the Bay north of the sill, recovering stations KC 47 to 53. Left the survey area at 12.30 and headed for a core position yet to be located north of Halmahera in the deeper part of the Molucca Sea. On our way we pumped 1000 l of surface water for PSM analysis some distance E of the northern arm of Halmahera (posn. $01^{\circ} 54^{1.5} \text{ N} - 128^{\circ} 06^{1.5} \text{ E}$).

Thanks to a speedy passage, running at times at more than 11 knots we reached the target area for site K 12 at about 20.30, starting a survey for a suitable site. Bottom of the basin in about 3500 m extremely rough (deformed) and we decided on a relatively small but smooth sediment-covered seamount or ledge at the base of the slope. K 12 P 1 took some time to be readied and 30 minutes to reach bottom, enough time to almost drift off target. Recovered an excellent core for comparison with Kau Bay results and we left station at 23.30, setting a course for Lifamatola Strait to recover mooring Saturday morning.

Friday April 26

Passage between the west coast of Halmahera and a string of volcanic islands (a.o. Ternate and Tidore), making this part of the voyage an impressive scenic happening. On the 3.5 kHz record we noticed a peculiar feature south of the volcanics (almost exactly on the equator) which had every appearance of a gas concentration (fig. 7). The likelihood of a volcanic gas accumulation must be considered. During passage the last geochemical analyses were done and containers were cleared for the next leg, packing equipment and samples to be stored below decks on the ship.

Saturday April 27

By slowing the ship we arrived at the mooring site in Lifamatola Strait at 08.00. The operation to search the mooring and subsequent recovery went like clockwork. Searching and triggering release mechanism was done

from a rubber boat some distance of the ship to reduce acoustic disturbances. An excellent satellite fix put ship and boat within a few kms on target. Recovery of mooring, current meters and thermistor over the stern was completed at 11.00 hrs which gave us an extra 7 hours, enabling us to make for Ambon at a comfortable and easy speed. In the afternoon a telex message changed our plans. Because of the difficulty to transport the Sealion probe to Ambon (to be used on Leg G5) the apparatus was sent to Ujung Pandang and the ship therefore changed course for a first ETA on Monday at 22.00 hrs local time (GMT + 8). Decided to stream magnetometer and keep a 3.5 kHz watch on our passage through the northern Banda Sea.

Sunday April 28

Passage through the northern Banda Sea running at a fast clip, recovering good magnetometer and reasonable 3.5 kHz information. Altered course to 270° south of Sulawesi heading for Strait Makassar at 19.30. Clocks retarted 1 hr during the night. Working on initial report and data inventory forms.

Monday April 29

Passage south of Sulawesi. Thanks to favourable conditions ETA advanced to 19.00 hrs. Working on initial report and data inventory forms. Pilot aboard shortly after 19.00 hrs. Vessel alongside at berth Ujung Pandang at 19.55 hrs. End of cruise G4.

4. Preliminary results

I Manganese encrustations W off Misool

A. Shipboard results

In this area earlier expeditions (SIBOGA and Snellius I) have reported the occurrence of manganese crusts. In order to verify these earlier findings and to investigate their mode of formation 10 boxcores were taken in the area west of Misool (for positions see fig. 2), in waterdepths ranging from 500 to 3000 m.

Boxcore-recovery was poor due to the coarseness and the indurated nature of the sediments. Therefore, piston coring has not been attempted. Submarine topography consists of E-W trending ridges and troughs, the morphological expression of a shear zone between Sula and Irian Jaya.

Trough infilling consists of coarse biogenic sediments (ranging from medium sand to gravel) almost entirely made up of pelagic calcareous skeletons. Additional biogenic components consist of pelecypods, coral fragments, and bryozoa. Black-coloured grains to boulders (up to 10 cm) are frequently present. The black colour originates from a thin coating of manganese oxide covering calcareous mudstone and packstone grains and pebbles. Trough sediments are well-sorted and homogenized.

Along the line of stations M 1 to M 6, i.e. from deep to shallow water, the grain-size changes from clay/silt (hemipelagites) to medium/coarse sands (planktonic foram sands and pteropod sands). At station M 7 hemipelagites contain several blackish interbeds probably representing turbidite tails. At station M 6 two layers of distinctly different grain-size are present: a lower unit made up of pteropods, the upper one consisting mainly of planktonic forams. At station M 4 clay pebbles occur in a sandy matrix.

Altogether the evidence seems to indicate that sediment-flows are trapped in the troughs. The source area of these sediment-flows most likely is the area off Misool. Preliminary results on the pore water geochemistry show that the concentration of nitrate in the boxcores approaches zero within 2 cm of sediment depth. This would mean that reduction of manganese oxide occurs at very shallow depths.

The black-coloured grains and pebbles recovered at stations M 3, M 4, M 5, and M 6 (especially at station M 3) float randomly in a sandy matrix indicating their mass-transported origin. Pebble-size does not vary systematically from west to east. The preliminary results indicate a nearby source-area for the black-coloured pebbles (at least for the larger fragments). It is possible that the source-area is located on adjacent ridges.

At one ridge station (M 9) we recovered a huge fragment of a cavernous, biogenic packstone coated with manganese oxide. Biogenic components in the packstone are poorly preserved due to dissolution/reprecipitation processes. Planktonic forams indicate a Neogene age, possibly Pliocene. The calcareous packstone has been deposited in a relatively shallow marine environment. The packstone contains dispersed grains of manganese oxide that tend to be concentrated in cavities. Comparable packstones may be exposed on Misool as well (information from the Indonesian geological map), although sediment samples subsequently sampled and kindly made available by Dr. H. Wensink did not show significantly enhanced manganese concentrations.

The surface of the packstone is rough, due to numerous approximately 1 cm deep borings. These borings indicate a long submarine exposure. The manganese coating post-dates the borings which might indicate that manganese oxide-formation started after the ridge subsided to its present depth, which may be beyond the depth at which epibiotic borings occur.

At ridge station M 8 a dark-grey claystone has been recovered. The claystone broke easily apart along smooth planes, obliquely to the bottom and these planes were grooved by slicken-sides. Again the exposed surface is covered with borings, but, contrary to station M 9, there is no obvious manganese coating. The claystone is of a late Pliocene age and has been formed on a muddy shelf-area with high food supply. Pyritic grains and the black colour indicate that reducing conditions prevailed below the sediment water interface. The depositional environment of the claystone may be best compared with the present-day Orinoco shelf or the modern mud-platform south of Irian Jaya.

The ridge stations contain little recent sediments: they consist of (winnowed) biogenic sands which seem to occur as a thin veneer on top of ancient (pre-Recent) rocks indicating (almost) non-depositional conditions on the ridge-crests.

The ridges thus appear to be non-depositional highs, consisting of an indurated substrate (i.e. limestone instead of claystone) on top of which manganese-crusts are formed. The amount of manganese crusts that has been found does not seem very promising for future exploration. The mode of the manganese-crusts formation in this area is presently unknown and has to be elucidated by future research.

The troughs channel sediment-flows and trap relatively coarse-grained, pelagic, sediments. The main (biogenic) sediment transport route is longitudinal, whereas manganese-coated pebbles and gravels are supplied by the ridges in a direction perpendicular to the axis of the troughs. In the distal western parts of the troughs fine grained sediments (hemipelagites) accumulate.

B. Post-cruise analyses and findings.

First laboratory analyses of the dark encrustations not only confirm the enhanced concentration of manganese they also indicate enhancement of

trace element levels such as cobalt, nickel and phosphorus.

All shipboard lithological descriptions of boxcores have been collected in tables and diagrams. Subsamples have been analyzed to establish the planktonic foraminiferal distribution. Quantitative analyses on the > 150 micron planktonic foraminifera have been made.

II Late Cenozoic paleoenvironments of Kau Bay

A. Preamble

Kau Bay, in between the northern and northeastern arms of Halmahera, can be characterized as a mini Black Sea. The exchange of water between Kau Bay and the open Pacific Ocean is restricted by the presence of a shallow dam or sill in the narrow entrance to the Bay.

Ventilation of the Bay waters is therefore poor and Snellius I depicted a deep-water layer without oxygen (c.f. fig. 8A) and with a high concentration of dissolved H_2S (hydrogen sulfide). Under those conditions all organic material collected on the bottom of the Bay may be expected to decay under anoxic (anaerobic) conditions, giving rise to the accumulation of "sapropels", which may eventually become important as source rock for hydrocarbons, oil and gas. Furthermore, due to the lack of oxygen, the bottom sediments once deposited would not be disturbed by burrowing organisms - who need oxygen - and this would give a very detailed record of the sedimentary column and of the processes that led to its accumulation. If we would core deep enough we expected to reach into the Pleistocene, a period when, thanks to the accumulation of huge masses of ice in high latitudes, sea level stood considerably lower (100 - 150 m) than at present. Because of the sill Kau Bay during that time would have been a lake and that should show up in the sediments (fig. 9).

B. Ship-board results

A total of 53 CTD stations were occupied in Kau Bay, 44 in the Bay proper, 2 on the sill - i.e. in the passage through the mined area -, and 7 north of the sill (see fig. 6). On these stations a total of 86 CTD-casts were made. An oxygen sensor was added to the CTD system, but only from station 35 to 53 the oxygen results were reliable. Malfunction of the oxygen sensor on the first 34 stations was caused by a damaged membrane due to an accumulation of very small air bubbles behind the

membrane. To try and recover the early oxygen measurement stations 20, 24, 25, 31 and 32 were reoccupied at a later stage, numbered sequentially station 36, 37, 39 and 40. The positions of all stations are marked in figure 6.

The CTD results indicate that Kau Bay is a multi-layered basin in which at least 12 different layers can be distinguished, each layer being characterized by a different combination of temperature, salinity and oxygen content. In the deepest part of the Bay an anoxic layer with a maximum thickness of only 15 m was found near the bottom. The temperature of that level was about 28.2°C and the salinity about 34.5‰.

At a position in the NE part of the Bay 01° 06^{1.6} N - 127° 56^{1.8} E an anchor station was occupied during 25 hours. Current measurements were made with a direct-reading current meter, situated at 10 m from the bottom.

Tides and highly non-linear internal waves were observed. There was no indication of inflow of oceanic water from outside the Bay. At a large number of CTD stations water samples from different depths have been analyzed for oxygen, nitrate, nitrite, ammonia, phosphate, sulphide and pH. Nutrients are almost always depleted, except for the samples close to the bottom. The surface water of the Kau Basin contains a substantial amount of brown-coloured suspended matter. Present day bottom water is oxygen deficient, whereas during the Snellius I expedition true depletion of oxygen and the presence of dissolved hydrogen sulphide has been shown at water depths of more than 300 m (cf. fig. 8). This difference in bottom water composition indicates a 'turn-over' during which oxygen-deficient bottom water mixed with oxygen-rich surface water. According to Ir. Wenno from LIPI, Ambon, a red bloom followed by mass mortality of molluscs has been reported in 1965. This event could be the biological response to a 'turn-over' of the water column.

Due to the limited amount of time only two rivers could be sampled for sediment and water: the Kau river and a smaller river approximately 3 km NE of Wasile.

The Kau river seems to be the largest one with an estimated flow of 20 m³/s. There seems to be a large compositional difference between the transported material from both rivers. The coast-line of the Kau Bay is either rocky (exposed volcanic rocks) or sandy/muddy (sandy beaches, alternating with mud flats, passing into mangrove swamps). Parts of the shallow water sediments are exposed during low tide. The shelf area has been poorly studied in the northeastern part of the basin (i.e. southwestern part of the narrows). Sea floor topography and sediment distribution in this area are strongly governed by tidal currents. The overall setting closely resembles that of the modern Wadden Sea. The broad shelf areas fringing the deep basin may trap dominantly fine-grained bioturbated sediments. In the deeper parts of the Kau Basin predominantly fine-grained hemi-pelagic muds are deposited with interbedded turbidites.

The seismic record (e.g. KSS2 + KSS9, fig. 10) shows that the physiographic setting of the Kau Basin is defined by steep basin slopes, hanging ledges, and a flat basin floor. Several parallel sub-bottom reflectors occur in the deep basin, whereas truncated sub-bottom reflectors are shown to be frequent in the shallow northeastern area adjacent to the sill. The truncated structures may represent ancient submarine channels and their subsequent infillings. One of the present day submarine channels (station K 5) contains soft coarse-grained (winnowed) sediments. Channel walls instead appear to exist of lithified sands with attached recent corals, hydrozoans, etc. (K 6). Laterally, these lithified sands are buried under finer grained sediment (stations K 7 and K 8).

Apparently sub-bottom reflectors in this shallow marine area represent buried coarse-grained sediment, lithified during periods of erosion and non-deposition. Non-marine sub-bottom reflectors are registered in the deeper part of the basin. Differences in the seismic facies in the

deep basin may be attributed to compositional and textural differences in fine-grained sediments. The top-most transparent seismic facies at station K 4 consists of water-soaked hemipelagic mud underlain by very stiff solid clay. The depth of this lithological change corresponds approximately with the depth of the youngest sub-bottom reflector on the seismic profile.

Altogether 12 piston and 13 box cores were collected in the bay. In addition 2 piston and 3 box cores were taken on site K 2 seaward from the narrows that separate Kau Bay from the East Pacific Ocean, and one single core, K 12, was taken from a sediment-covered isolated high in the deeper part of the Moluccasea, immediately N of Halmahera. Sediments recovered from the deep part of Kau basin invariably consist of two types: 1. hemipelagic muds, which are interbedded with 2. silt and sands, representing various turbidite facies. The hemipelagic muds are greenish and smell strongly of H₂S, indicating anoxic conditions. Macroscopically the hemipelagic muds can be observed to contain pteropods throughout, although their concentrations may vary rapidly. Wood fragments occur at all depths. The coarse grained turbidites are blackish (in case of sands) or grey-blueish (in case of silts) and mostly contain pteropods and molluscs in augmented abundance.

The pore water in the deep water sediments probably contains high concentrations of dissolved organic matter. In all the cores the concentration of nitrate and nitrite is close to zero, whereas the alkalinity is very high. Measured concentrations of sulphide in the pore water show some very interesting profiles; they seem to indicate alternating reducing and weakly reducing conditions in the sedimentary column, which must be accompanied by a very high sedimentation rate. The pH and Eh of the sediment are both low, indicating reducing conditions.

Varves are remarkably absent, i.e. the hemipelagic mud is macroscopically structureless and - unlike midlatitudinal anoxic environments - does not contain seasonally generated laminations. Microscopic examination of a

few samples shows high abundances of diatom frustules, common radiolarians and calcareous pelagic organisms such as pteropods and planktonic forams. In addition relatively rare empty shells of benthic forams have been noticed and faecal pellets are numerous. The coarse-grained sediments in the deep basin and on ledges on the slope must originate from point and line sources somewhere on the shelf. These coarse-grained interbeds are transported by turbidity currents which could have been generated by incidental floods and/or by tectonic activities.

The structureless nature of the hemipelagic muds could be explained 1. by resuspension and transport of fine-grained sediments from the shelf, 2. by mudflows or even coherent sliding of slope sediments through slope-failure processes and 3. by bioturbation.

Biogenic carbonate preservation is excellent, the same holds for biogenic opal preservation. High abundances of diatoms point to highly fertile surface water conditions. Dependent on the origin of the deep water sediment (i.e. allochthonous, autochthonous or both) highly productive surface waters are either restricted to shallow water environments or are basin-wide. High surface water productivity is reflected also in the high numbers of faecal pellets in the deep water sediments.

C. Post cruise analysis and findings.

All 3.5 kHz soundings obtained from inner Kau Bay along the various tracks (see fig. 3), together with soundings taken from available hydrographic charts have been used to construct a bathymetric map of Kau Bay (fig. 11). Although the soundings have not been corrected for sound velocity variations (Matthews tables) and although the track density is highly variable, the chart gives a reasonable presentation of the Bay physiography.

The connection between the open Pacific Ocean and Kau Bay is barred by a shallow sill in which two N-S running channels are cut, down to a depth of about 40 m. South- and southeastwards the sill widens and deepens to 60 m under flat-bottomed Wasile embayment. Deep Kau Bay is surrounded by a shallow ledge, about 4 km wide along the NW shore and only 1 to 2 km wide along the southern and eastern shores. From a depth of about 20 m (40 m in the west) the waterdepth increases rapidly to about 400 m, to then gently bottom out to 470 m. The slope is cut by numerous canyons and especially the steep - in places more than 10° sloping - margin is dissected by narrow troughs and rilles that drain the surrounding high country. The drainage pattern that is superimposed on the geological map of northern Halmahera (fig. 12) shows that the runoff is mainly channeled through short steep creeks and brooks, while volcanic northern Halmahera is drained predominantly through the Kau River and tributaries.

The two interpreted seismic sections (KSS2 and KSS9, fig. 10) show generally flat lying sediments that cover and smoothen an irregular subsurface. Although the almost vertical dislocations are far less steep than shown (note the vertical exaggeration) it appears that the subsurface is divided into a number of highs and lows, the result presumably of active blockfaulting. This would be in agreement with the structure of eastern Halmahera (cf fig. 12) which, unlike northern Halmahera, is dissected by NE-SW running westerly dipping thrusts and N-S to NNW-SSE oriented normal and reversed faults.

Lithological descriptions of boxcores and of opened piston cores from Kau Bay (i.e. K4P3; K3P2; K4P1; K10P1, K9P1 and K9P2) have been collected in tables and diagrams. X-radiographs are available from piston cores K4P3, K3P2, K4P1, K10P1, and K9P2).

Cores K4P3, K9P1 and K3P2 have been subsampled in the mean time for micropaleontology, clay mineralogy, palynology and geochemistry.

Quantitative analyses on the >150 micron planktonic foraminifera have been made on all boxcores. The data show that the planktonic foraminiferal association in Kau Bay deviates significantly from the adjacent oceanic environment.

Quantitative analyses of the >63 micron benthic foraminiferal associations in boxcores from Kau Bay also strongly deviate from normal oceanic environments. A cluster analysis on the benthic foraminiferal data illustrates the presence of three major associations in Kau Bay. Their distribution is related to depth and to oxygen content of the water.

Quantitative analyses on planktonic and benthic foraminifera in cores K9P1 and K4P3 show fairly uniform downcore compositional patterns for the planktonic foraminifera and strongly fluctuating ones for the benthic foraminifera. Surprisingly, benthic foraminifera are continuously present downcore which suggest that the structureless nature of the hemipelagic muds in Kau Bay can, at least partly, be attributed to bioturbation.

Low to zero numbers of foraminifera and highly deviating benthic foraminiferal associations in the lowermost part of core K4P3 coincide with strongly deviating patterns in chemical parameters and may point to fresh to brackish water environments.

A relatively strong reflector that is visible on the 3.5 kHz records at about 5-10 m below the bottom appears to coincide with a dolomitic layer that was cored in the lowermost part of K4P3. Extrapolation of two radiocarbon datings suggests an age of about 10 Ka for that layer. Dolomitization at that interval is possibly related to oxydation of ascending methane (CH₄).

In the cores we find as yet unexplained substantial variations in the dissolved sulphide content of the porewater.

Profiles of dissolved chloride in pore waters of cores at stations K3, K4 and K11 are shown in figure 13, indicating a decrease with depth. A preliminary explanation is that Kau Bay has been a fresh or brackish water basin during the last glacial period.

One of the exciting findings is the presence in the watercolumn of 3 to 4 micron spheres which consist of manganese oxide. SEM studies of these spheres indicate that manganese-oxidizing bacteria are responsible for their formation.

5. Acknowledgements

Thanks are due to officers and crew of the MV Tyro under the able command and management of Captain L.J. Blok, to Commander (Royal Neth Navy, retd.). Th. G. Loeber for administrative and logistic support, and to Ms M. Rakke for processing the text.

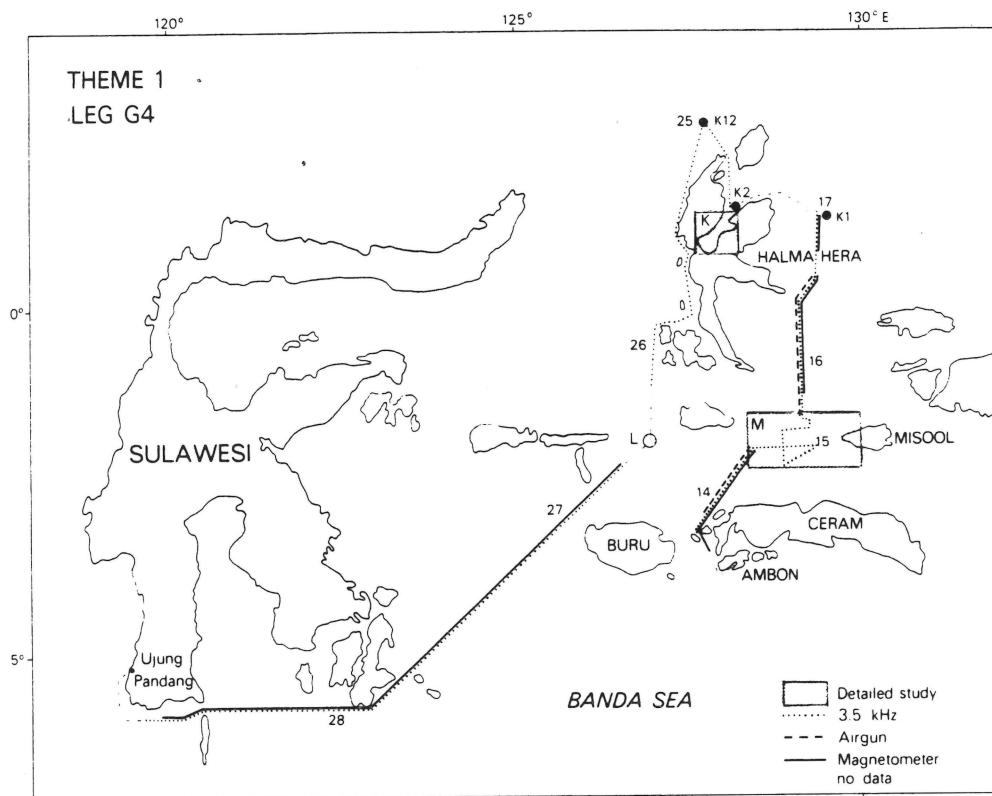


Figure 1
Track chart, areas of detailed study and underway geophysical data coverage. K1, K2 and K12 are sites outside Kau Bay where piston cores were taken. The labels M, K and L mark the areas of detailed study, Misool (cf. fig. 2), Kau Bay (cf. figs. 3 & 11), and the site in Lifamatolo Strait where a string of current meters was recovered. Numbers (14-28) along track mark the 1200 hrs GMT ships positions in April 1985.

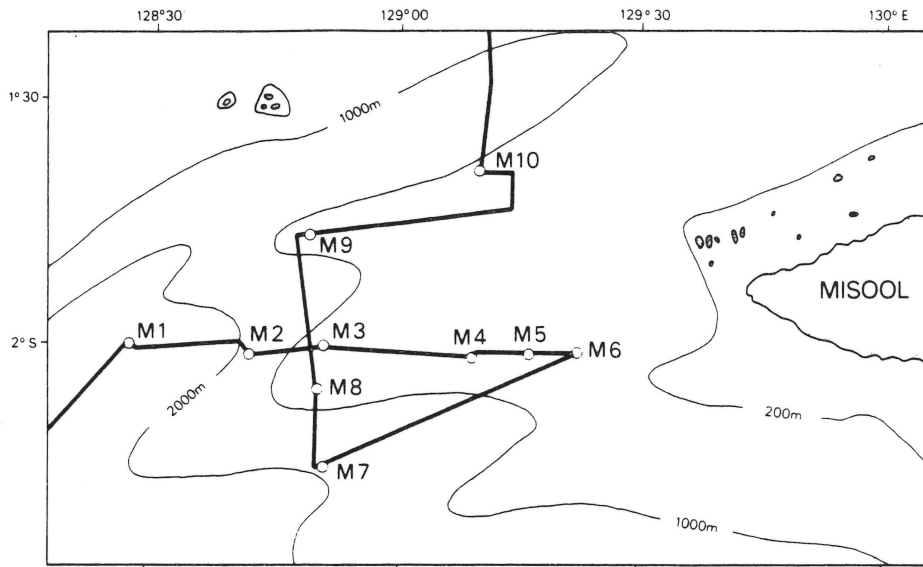


Figure 2
 Track chart and positions of stations M1 - M10, where boxcores MB1 - MB10 were taken in the area of special study west of Misool. Bathymetry based on Dutch and British hydrographic charts.

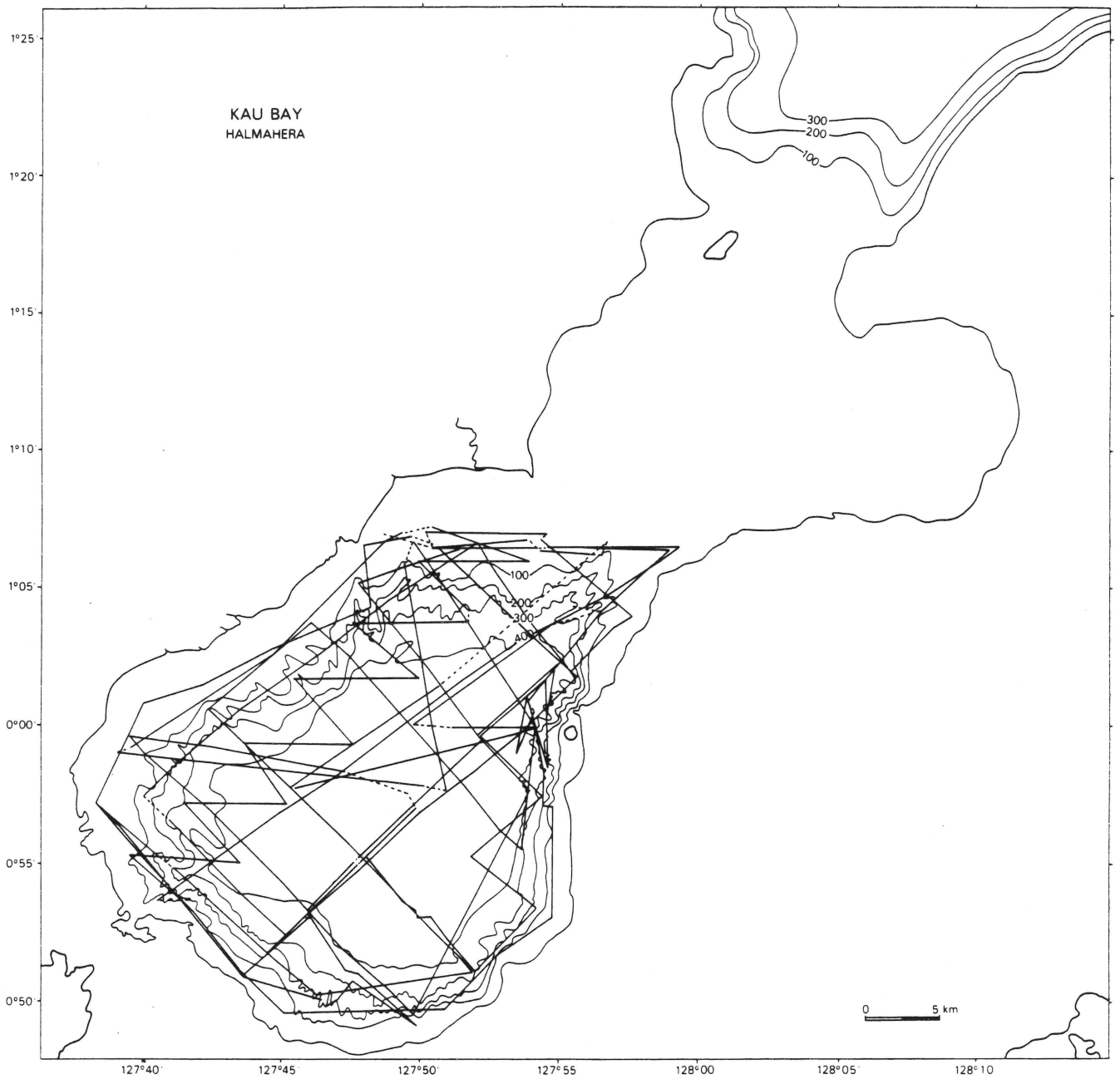


Figure 3
Chart of all tracks sailed in inner Kau Bay. Full lines mark tracks where 3.5 kHz soundings were obtained, dashed lines where no data were recovered.

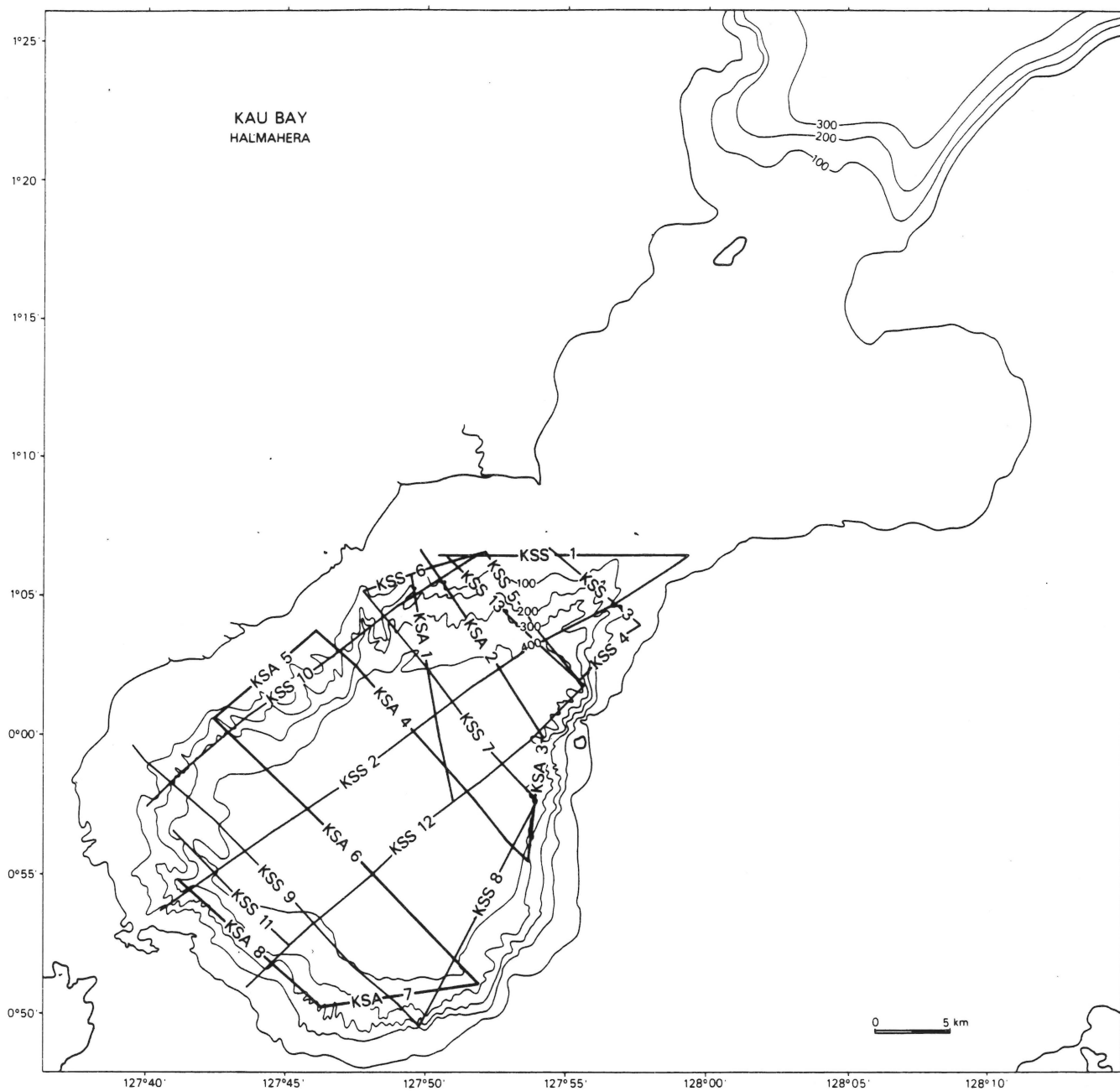


Figure 4
 Chart of tracks in inner Kau Bay along which sparker (KSS) and airgun (KSA) seismic reflection profiles were shot.

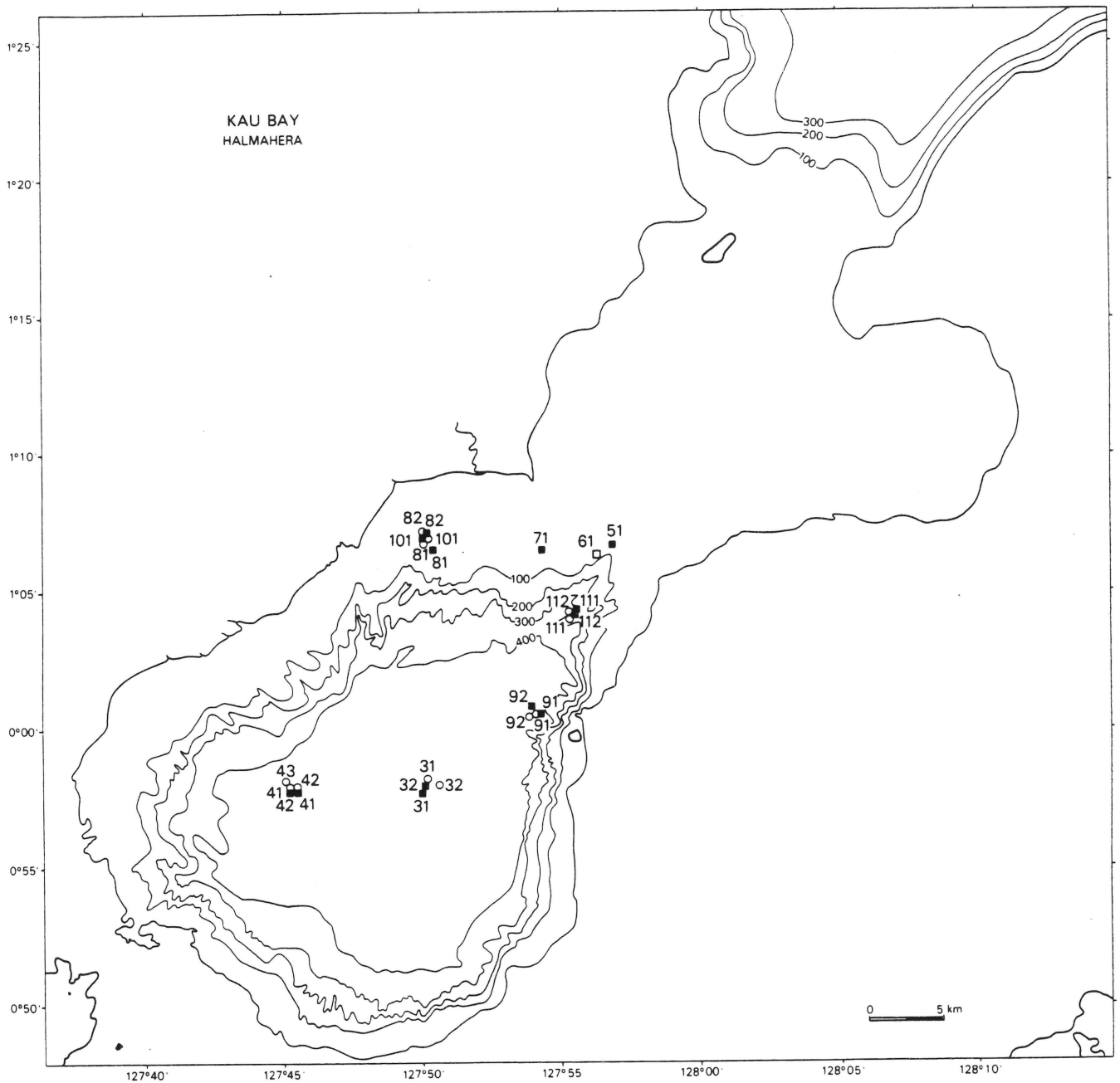


Figure 5

Core and dredge sites in Kau Bay. Full squares mark the positions of boxcore stations, the open square the position of dredge station 61 and the open circles the positions of piston core stations. Two and three digit numbers are made up of two parts: first (one or two) digit(s) give(s) the station number, last digit the cast (e.g. 32: station K3, second cast-piston core or boxcore-; 111: station K11, first cast).

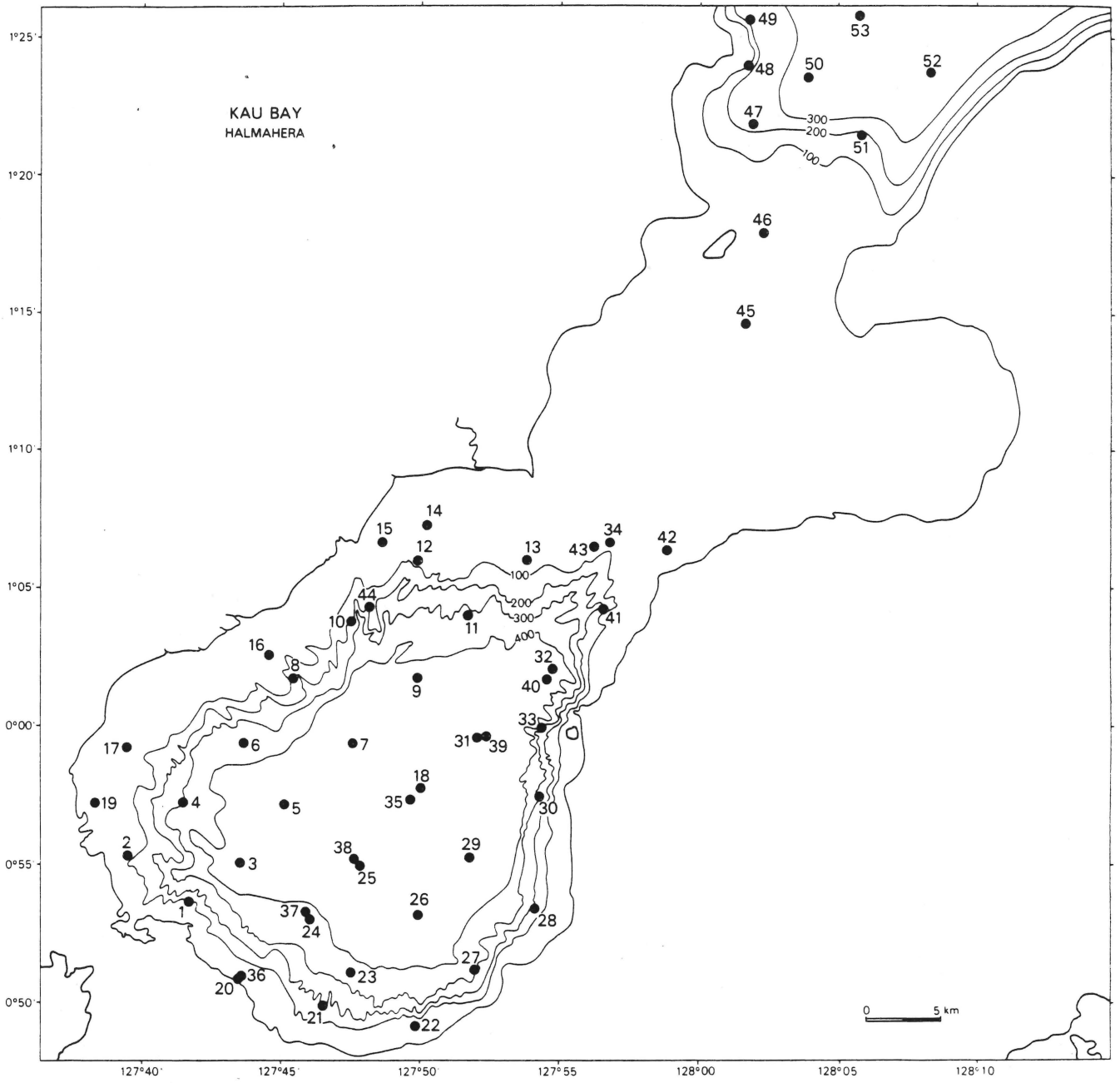


Figure 6
Positions of CTD casts in Kau Bay.

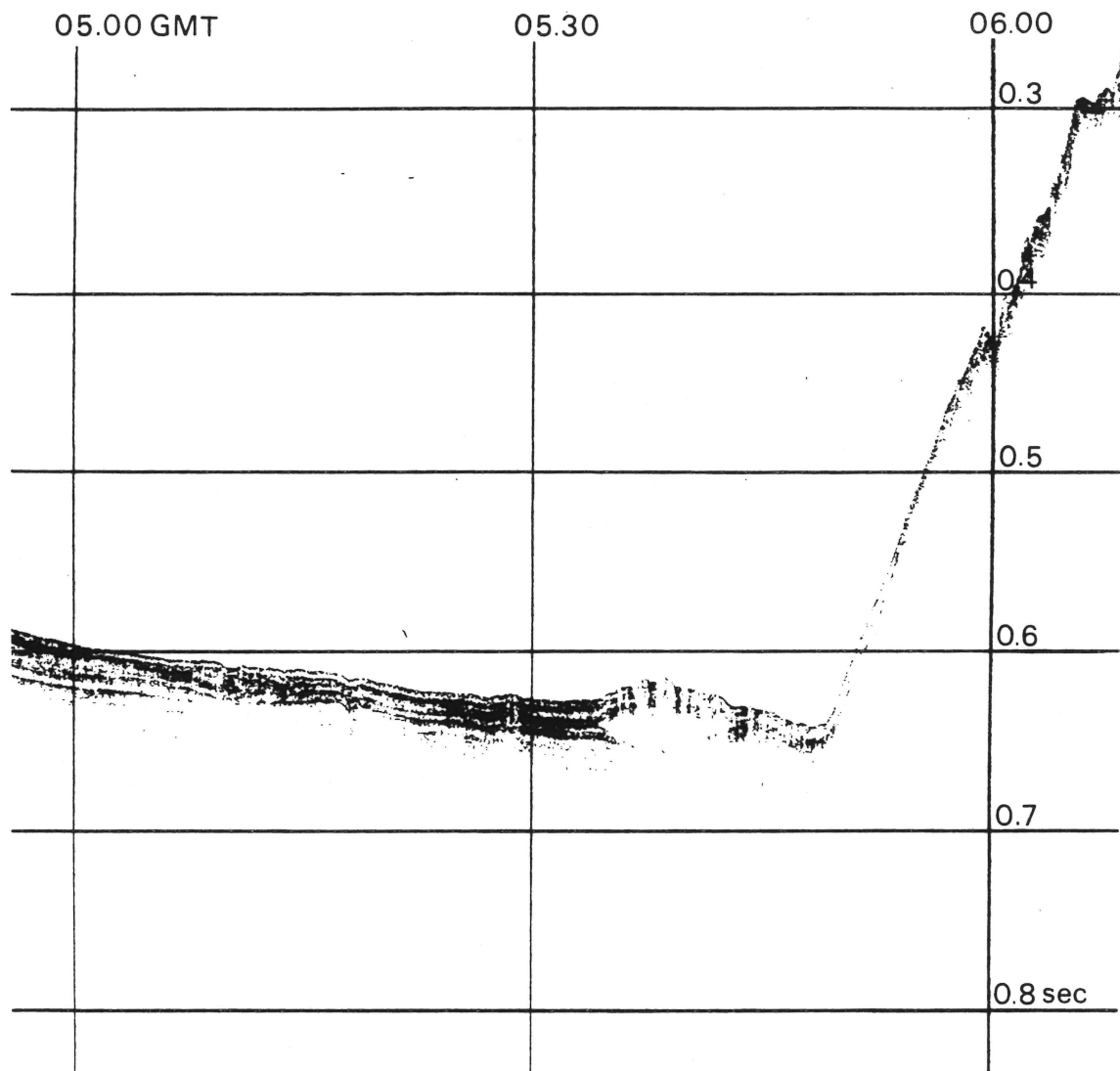


Figure 7
 Part of a 3.5 kHz seismic reflection record obtained during the passage between W. Halmahera and the island of Kayoa (posn. approx. $00^{\circ} 00^1$ S - $127^{\circ} 30^1$ E). The separation of reflectors underneath the elevation at the foot of a steep slope and the presence of a "bright" blister-like feature in between is probably due to the presence of dissolved (volcanic ?) gas. Thanks to the velocity reversal the lower reflectors are pulled down, whereas the upper layers (reflectors) are upheld by gas pressure. Vertical scale in seconds two-way reflection time; horizontal lines are 0.1 s = 75 m apart. The vertical time lines are 30 minutes apart, which at the ship's speed corresponds with a distance of approximately 10 km.

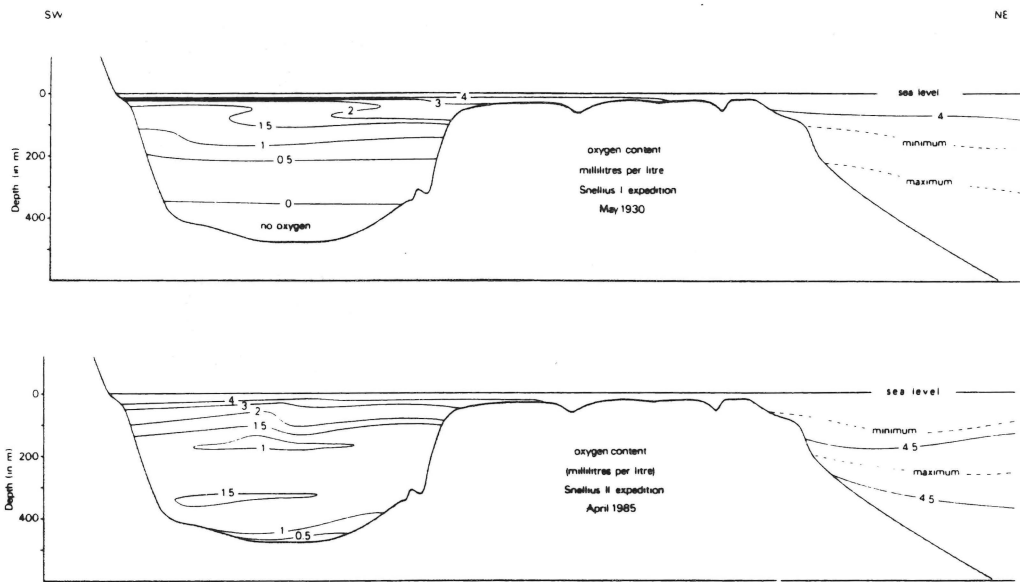


Figure 8
 Comparison between the oxygen content of the waters in Kau Bay and across the sill in May 1930 (Snellius I) and April 1985 (Snellius II).

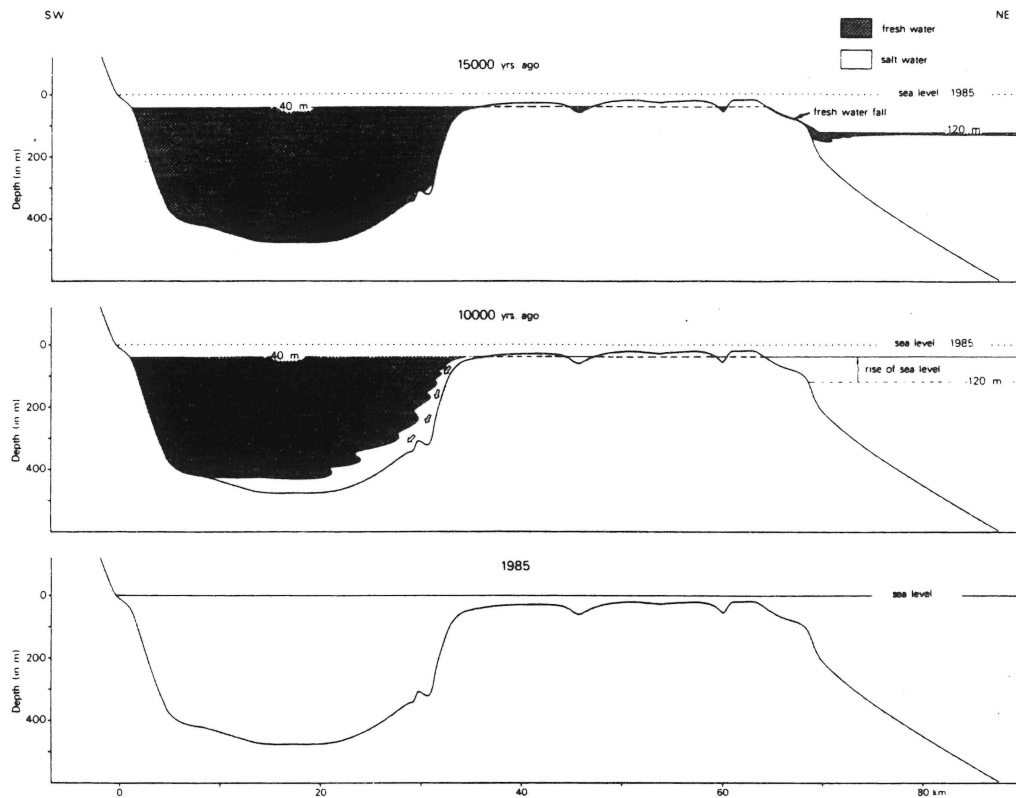


Figure 9
 Comparison of the fresh/salt water balance in Kau Bay at time 15.000 yrs ago (at the end of the last Pleistocene glacial maximum), at (extrapolated time) 10.000 yrs ago (when sea level had reached sill depth), and at present.

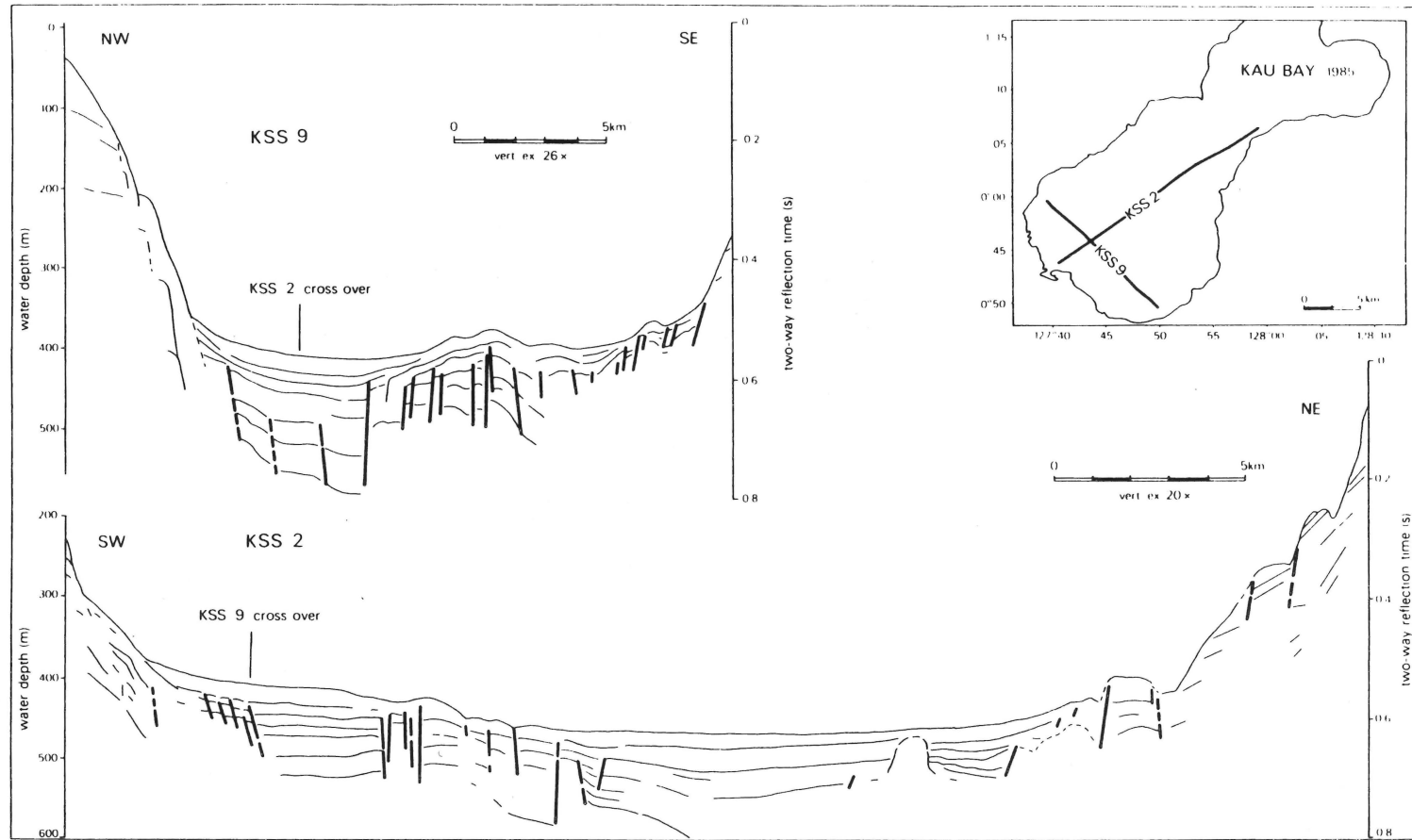


Figure 10
 Interpreted sparker reflection profiles across Kau Bay. Note that the two profiles have different horizontal scales and thus different vertical exaggerations.

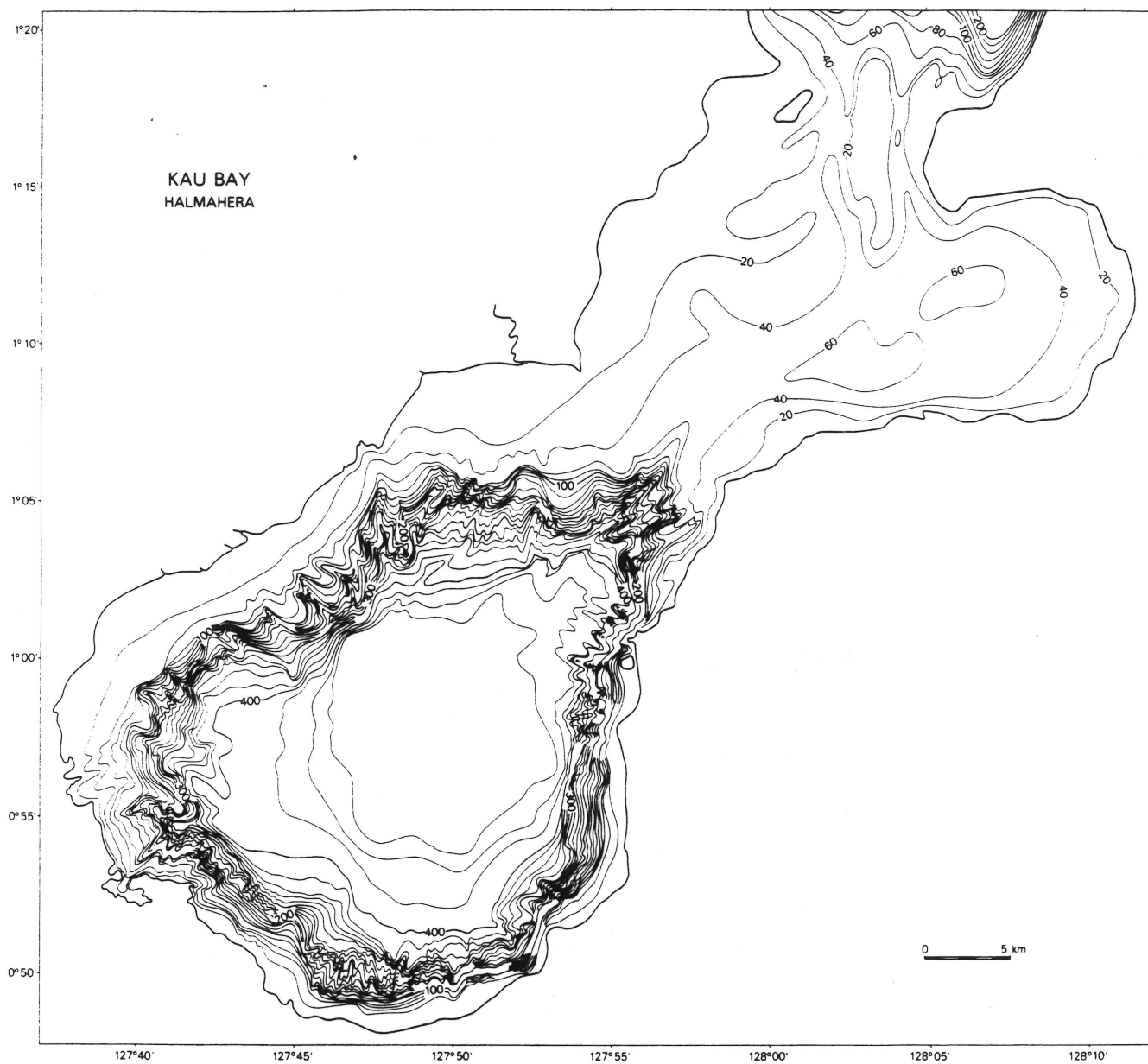


Figure 11
 Bathymetry of Kau Bay, Halmahera based on Tyro 1985 3.5 kHz reflection data and on Dutch and British hydrographic charts. Contour interval 20 m. No corrections made for sound velocity variations with depth. Chart not to be used for navigational purposes.

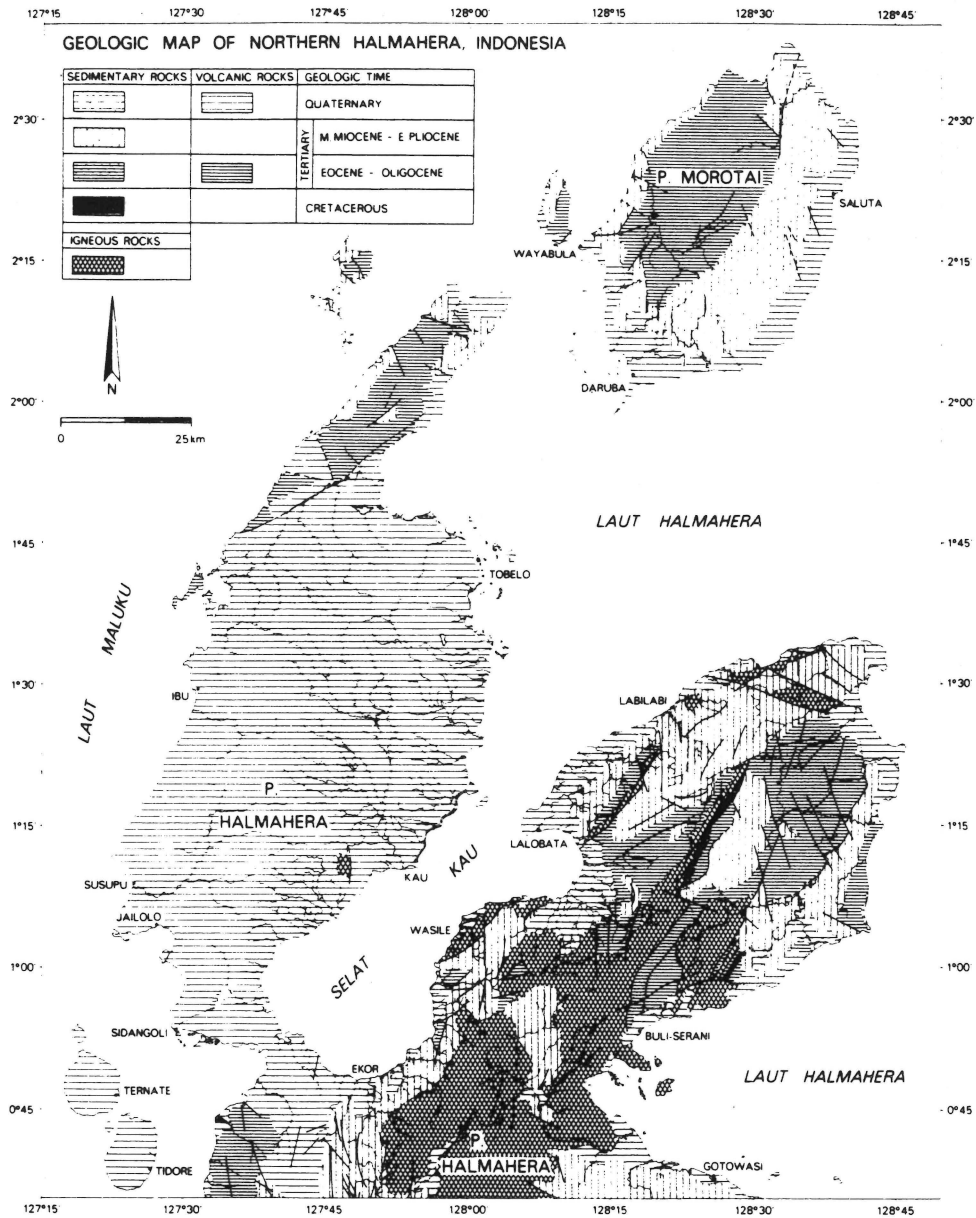


Figure 12
 Geological map of northern Halmahera and Morotai compiled and simplified from the geological maps 1:250 000 of Ternate and Morotai Quadrangles, North Maluku by T. Apandi Dan & D. Sudana (1980) and Sam Supriatna (1980), respectively, Geological Research and Development Centre, Bandung. The northwestern arm of Halmahera and Morotai constitute the volcanic complex, while the northeastern arm of Halmahera forms part of an accretionary wedge. Volcanic arc and accretionary wedge together form a double island arc in the plate that overrides the W to SW subducting Pacific plate.

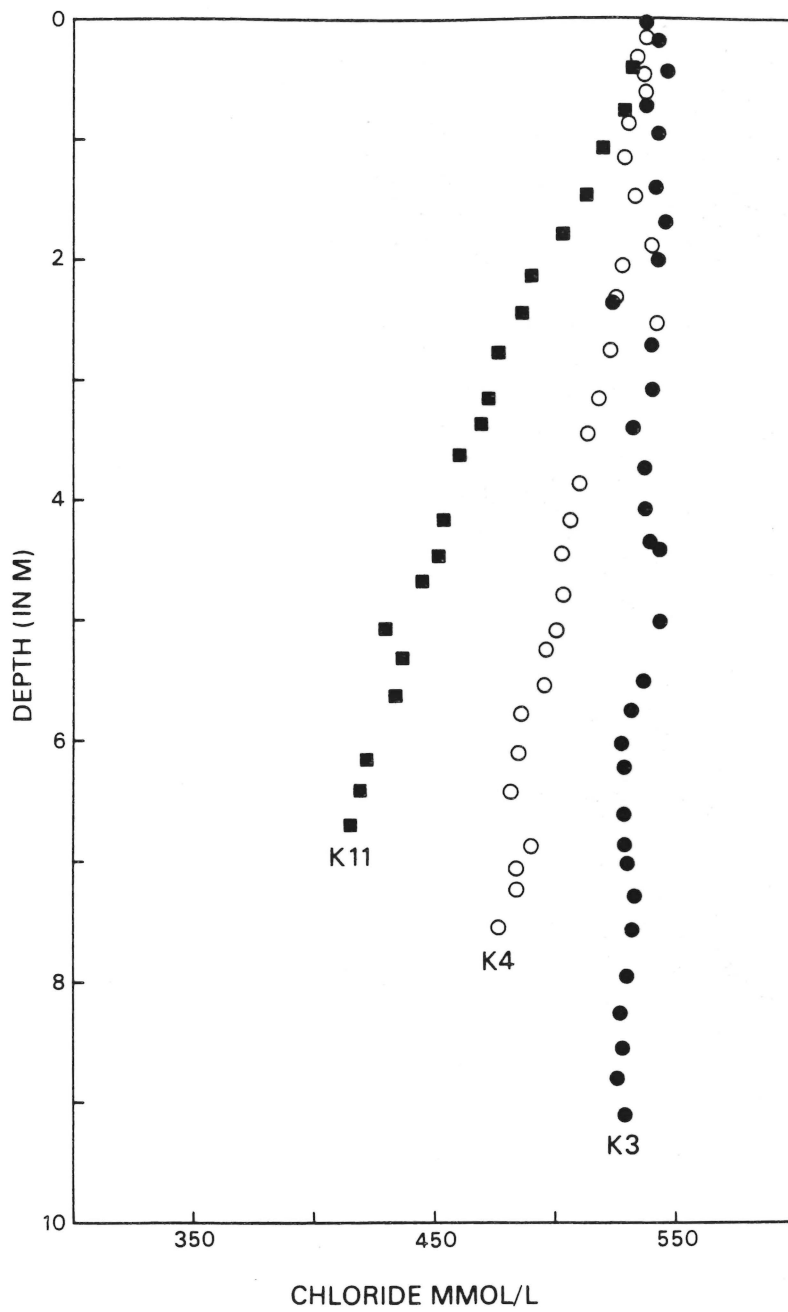


Figure 13
Chloride profiles in porewaters from cores K3P2, K4P3, and K11.