III. GEOMORPHOLOGY OF ADDU ATOLL

by

D. R. Stoddart, P. Spencer Davies and A. C. Keith

A. General description

Addu Atoll, latitude 0°38' South, longitude 73°10' East, is the southernmost atoll in the Maldive Islands, separated from the next nearest atoll to the north, Huvadu or Suvadiva Atoll, by the 45 mile wide Equatorial Channel. The next nearest atoll to the south is Salomon Atoll, Chagos Arthipelago, 320 miles distant. Addu itself (Fig. 2) is one of the smallest of the Maldive atolls, measuring 28.4 km (17.6 miles) in maximum dimension (NW to NE points), and 16.5 km (10.2 miles) in the transverse direction. The atoll may be termed semi-circular or triangular: the south-facing reefs are broadly convex, the northern reef concave. The shape may be approximated to that of a triangle, apex southwards, with a base of 28 km between the northwest and northeast points, and sides of 25 km. Shape measurements by several methods give values for Horton's F number of 0,604, for Miller's Circularity Ratio of 0.754, for Schumm's Elongation Ratio E of 0.895, for Boyce and Clark's Radial Line Index of 28.54, and for the Ellipticity Index of 1.3 (Stoddart, in press).

The total area of the atoll is approximately 60 square nautical miles, or 6.5 on Haggett's G scale (Haggett et al. 1965). Of this, no less than 41% consists of reef flat and islands. The peripheral reefs of the atoll are broad, ranging from 700 metres on the north side to 1900 metres on the southwest; maximum widths of up to 2900 metres are found on the northwest projection. The reefs are continuous except for two gaps in the centre of the southern reef (Gan Channel, Wilingili Channel) and two in the centre of the northern reef (Kudu Kanda Channel, Man Kanda Channel). Gan Channel, which is buoyed, is 950 metres wide with a sill depth of 9-10 fathoms; Wilingili Channel, 750 metres wide, has a sill depth of 21-31 fathoms. In the north the channels are narrower: Man Kanda, which is buoyed, is 350 metres wide with a 13-18 fathom sill; Kudu Kanda is 250 metres wide, with a 13-19 fathom sill. All the peripheral reefs are of simple linear form, and lack the ring-shaped faros so well developed in the northern Maldives. Little is known of the detailed topography of the atoll slopes. The John Murray Expedition ran a profile from the northeast corner of the atoll, recording a depth of 1000 fathoms within 4.5 miles in the easterly direction (mean slope 14°10') and within 5 miles to the northeast. Their soundings also indicated a ridge extending northeastwards towards Fua Mulaku, shown by soundings of 590 and 654 fathoms (Farquharson 1936, Plate 6). H.M.S. Modesta, sounding out of Gan Channel in 1956, recorded 1069 fathoms 1.5 nautical miles southeast of the Wilingili reef edge, giving a mean slope of 35°.

The atoll lagoon is elliptical, with its axis trending ENE-WSW. It has a maximum length of 11.7 km and breadth of 9 km. Unlike the northern Maldive atolls, such as North Male and Ari, there are few knolls or patch reefs in Addu lagoon. The two most conspicuous patch reefs are near the lagoon centre, named Medagala and Aruhal, on which waves break even in calm weather. Medagala and two smaller patches near the west side of the lagoon are buoyed. Small reef patches and knolls are more profusely developed in the extreme northwest and northeast corners of the lagoon, but elsewhere the lagoon reef slope falls steeply to the lagoon floor. The maximum lagoon depth is 43 fathoms, comparable to that of the much larger Huvadu Atoll and considerably deeper than that of the larger atolls in the northern Maldives (cf. Biewald 1964, 354).

Islands occupy approximately 20% of the peripheral reef flat of the atoll by area, and no less than 65% of the seaward reef edge is backed by land. The only extensive reef sector without land is the concave northern reef. There are large villages on two of the islands, Midu and Hitaddu, and the settlement formerly located on Gan Island has been relocated on Fedu following the 1960 Agreement between Britain and the Maldivian Government. An airstrip was operational on Gan Island during the Second World War, when the deep channels and lagoon of Addu proved of naval value (the Queen Mary has anchored here). Following the Agreements of 1953 and 1960 the Maldivian Government has made certain scheduled territories (Gan Island and part of Hitaddu Island) available for use as a Royal Air Force Staging Post. Development of this Staging Post has involved the construction of a new runway and facilities, with personnel quarters on the northwest side of the island.

The population of the atoll was 4664 in 1931 and 5686 in 1946 (Didi 1949); in 1963 it was 8235. For a fairly detailed general account, see the *West Coast of India Pilot*, tenth edition (1961, p. 57-62), together with the more scientific papers cited in this report.

To aid in location an arbitrary 1000 metre grid was laid down on the Admiralty Chart (No. 2067) of Addu, related to the earth graticule in that the 0°40' S latitude line and the 12 km S grid line, and the 73°10' E longitude line and the 12 km E grid line are coincident. This basic 1000 metre grid shown in the figures in this report may then be subdivided to give locations to the nearest 10 metres, easting before northing in each point reference. The grid, with a 100 metre interval, was also superimposed on an enlarged vertical air photograph of Gan to aid location referencing in the field. All reef flat and lagoon locations were obtained by horizontal sextant angles on fixed island points, and then reduced to grid coordinates.

B. Peripheral reefs

The most detailed descriptions of the Addu reefs are those of Sewell (1936a, 69-72, 87-92), who divided the reef area into reef platform, outer reef and inner reef. Gardiner (1903, 317-321, 416) briefly comments on the reefs, stating that "the coral growth, taken as a whole, in Addu lagoon is most extraordinary, and in vigour quite surpasses anything in my experience elsewhere either in the Maldives or in the Pacific Ocean" (1903, 319). Most of his remarks on reef characteristics, however, are phrased in general terms. Agassiz (1903, 148) doubted whether the coral growth on the lagoon reef slopes of Gan was as vigorous as Gardiner implied. Kohn (1964a) gives a brief description of the reef flat and reefs at Hitaddu and Gan. Eibl-Eibesfeldt (1964, 38-39) gives a schematic section of the reefs of a Maldivian atoll, and his zonation is followed here (Fig. 7). Figure 8 gives in diagrammatic form cross-sections of the peripheral reefs at Gan (B) and Hitaddu (A) Islands, to show contrasting conditions at these two locations. Peripheral reef characteristics are treated under the following headings: (i) seaward reefs and slope, (ii) seaward reef edge (algal platform), (iii) seaward reef flat, (iv) northern reefs--Midu side, (v) lagoon reef flat, reef and slope.

(i) Seaward reefs and slope

Little is known of the seaward reefs of Addu, except from air photographs, though Davies and Keith inspected the seaward reef slope by diving at Gan and Bushy Island. The 1958 aerial photography shows spur-groove formation well-developed along the reef front along the whole of the convex southern reefs from Hitaddu to Midu, but not along the northern reefs, the lagoon reefs, or in the channels. Along most of the southwest reefs the lineations are approximately 100 metres long, or less; but off Wilingili they reach 250 metres, and off Mulikadu, north of Wilingili Channel, they reach a maximum length of 300 metres. The depth to which the lineations extend is unknown; Davies and Keith report no apparent trace of lineations on the seaward slope off Gan in depths of 7-16 fathoms. They also report a fairly gentle bottom slope, suggesting that at some point, perhaps 400-500 metres outside the breakers at Gan, the bottom slope increases rapidly and falls to great depths. Air photographs indicate that the reef front outside the breakers is steeper or the reef front terrace narrower round most of the rest of the atoll perimeter than at Gan. There is no data on the area immediately outside the breakers, which Wells (1957, 618) terms the innominate zone.

Hass (1961, 60) and Eibl-Eibesfeldt (1964, 37) describe an abrupt increase in bottom slope to form a "reef wall" at the foot of the more gentle reef slope outside the breakers on the seaward sides of Maldivian atolls. Undercutting at the base of this reef wall forms "Grotte" or "Höhle" at depths of 25-135 metres (14-19 fathoms). Hass ascribes this undercutting to low-level marine erosion during a Würm glacial low sea level at -30 metres (16.4 fathoms). Main Würm sea levels, however, were probably in excess of -100 metres (Donn, Farrand and Ewing 1962), and stillstands at the -30 metre level may be connected with the Allerød or similar oscillations. Whether these brief Holocene stillstands (Fairbridge 1961) were long enough to cut Hass's features is debatable. Similar undercutting was unfortunately not observed during the 1964 expedition.

An attempt was made by Davies and Keith to investigate the structure of the seaward reef slope at Gan at a distance of approximately 150 metres from the reef edge, using SCUBA apparatus, but the high bottom surge made working conditions too dangerous for more than a brief examination. Here the depth was approximately 35-40 feet and the seaward beginnings of the surge channels were discernible. Corals, particularly massive palmate Acroporas were present on the areas corresponding to the base of the spurs and reached a height of no more than 4 feet above the general level of the bottoms of the groove areas. In the bases of the groove channels there was a continuous back and fore surge corresponding to the passage of each wave above, of approximately 15-20 feet. Coarse sand and fine gravel are kept in suspension in these areas, often rising to heights of 4-5 feet above the level of the floor of the surge channel. The backwards and forward motion of the bottom water was discernible to depths of approximately 70 feet on the seaward terrace.

At a distance of 200-250 metres from the reef edge a more thorough examination of the structure of the seaward reef slope was made. At this point the seaward terrace had a depth of 40 feet and sloped gradually seawards at about 10°. At a depth of 70 feet there is a slight increase in the steepness of the slope to 30-40°, extending to a depth of 130 feet and the bottom then appears to flatten out again. At 200-250 metres from the reef edge, there is little trace of the groove and spur system. The corals nevertheless appear to be in bands of approximately 10 feet wide, normal to the reef edge. Between the bands are areas of dead coral fragments, rounded and largely covered with calcareous algae though still mobile. Sand is present in places amongst the dead coral. The living coral is of three dominant types 1) a much branched twig like <u>Acropora</u> similar to that growing on the lagoon reef slope at Gan, 2) <u>Echinopora</u> and 3) a massive palmate <u>Acropora</u> whose growing points all pointed in the direction of the reef edge. Occasional small colonies of <u>Pocillopora</u> were present but there were few encrusting corals. This was in marked contrast to that seen at equivalent depths on the lagoon reef where encrusting corals were common. The calcareous alga <u>Halimeda</u> was to be found, particularly amongst the first mentioned type of <u>Acropora</u>.

At 60 feet coral growth gave way to a zone of Alcyonarians often forming masses of up to 4 x 5 feet in area. There was no sign of any banding of corals and the few small coral colonies present were randomly dispersed amongst the Alcyonarians, with areas of sand and small coral fragments between. There was no evidence here of any cementing action by calcareous algae. At a depth of 120-130 feet the bottom flattens out and is comprised largely of gravel and sand.

(ii) Seaward reef edge

Seaward reef edge features at Gan are comparable to those described in the Marshall Islands (Ladd and others 1950). The outermost zone, between the reef flat and the breakers, is formed by a platform of encrusting and nodular red and purple calcareous algae, forming a rough and irregular surface. Unlike some areas in the Marshall Islands, where the algal zone forms a high ridge, at Gan it is less distinctive topographically, forming a zone 30-50 metres wide, rising 0.5-1 ft above the level of the reef flat immediately to landward, and drying at extreme low water but not at other low tide stages. Between islands, where the level of the reef flat is lower, the relative height of the algal platform is correspondingly greater. At low tide stages, waves break outside the algal platform, where its crest begins to curve down towards the reef slope, and each breaker sends a sheet of water over the platform, the higher parts of which remain emerged. At higher tides the platform may be covered with 3-4 ft of water, and breaking of waves takes place over a wider area on the platform itself.

In places the seaward slope lineations extend through the breaker zone into the algal platform. At Gan, long sectors of the reef edge lack algal-platform channels, and often poorly and irregularly developed channels can only be seen where the platform descends beneath the breakers at low tide. At certain points, however, as at 093150 and particularly 115161, the channels cut back into the platform for 25-35 metres, forming deep, steep-sided gullies, with vertical or overhanging sides and floors 6 ft or more below the level of the intervening ridges. The channels are narrow, often less than 2 metres wide, and the ridges are wider. The sides of the channels and the intervening areas are covered with encrusting nodular and papillose brownish-red algae and other non-calcareous colonial organisms. Small colonies of Acropora are found on the channel walls and are exposed at low tide during backwash, when water level in the channels may vary vertically 3-5 ft with each wave advance. During backwash the channels act as drainage lines for water on the reef flat, which cascades over the channel lips and attached small corals; during swash, water surges up the channels and spills over the brim onto the flat, where it joins with the slower water flow over the platform surface to form a translating wave 1-2 ft deep. No signs of channel roofing or tunnel formation were seen, and no observations were made on the channels during higher tidal stages.

The Gan reef edge may be compared with that in the Northern Marshalls described by Emery, Tracey and Ladd (1954, 24-26), except that reef blocks lodged by extreme storm action are not found. At Gan the reef edge falls into the Northern Marshalls Class I, strongly grooved, Sub-type A, ridge low and uncut by grooves. In this type the algal zone is described as forming "a broad arch, sloping gently seaward and rising only 6 inches to 1 foot above the main reef flat. With rare exceptions, the grooves, though well developed, are limited to the seaward slope beyond low-tide level" (Emery, Tracey and Ladd (1954, 25). Their Type I-B, with an algal ridge 2-3½ feet above the reef flat and deeply cut by surge channels, is apparently absent at Addu. The northern reefs at Addu, not investigated in detail, appear to belong to their Class II, grooves weak or absent, Sub-type A, reef edge straight or smoothly scalloped.

(iii) Seaward reef flat

Precise levelling was carried out on the seaward reef flat, from Fedu to Gan Channel, a distance of 5 kms. Landward of the algal platform is a deeper area, or moat, 20-70 metres wide, and generally 9-12 inches lower than the highest part of the algal platform. It lacks encrusting red algae of the reef-edge type, is floored with rubble coated with filamentous algae and occasional massive Halimeda, with occasional flattened coral colonies. This moat carries a few inches of water even at lowest low tides. Landward it is succeeded by a rubble zone of small boulders, usually less than 1 ft in diameter but exceptionally up to 3 ft, and smaller rubble. This zone is as high as the reef edge platform and is exposed at lowest low water. Gravel and cobbles form irregular tongues extending lagoonward from the rubble zone across the reef flat, with maximum lengths off the southeast shore of Gan of 250 metres. Generally these debris tongues are about 50 metres long and only a few inches thick, fingering out lagoonward; there is some indication in vegetation patterns on the flat of the existence of tongues of several ages, suggesting that they may be mainly formed periodically during storms.

The reef flat itself (Fig. 9) is a rock platform thinly veneered with sand and some coarser debris, partly in transport and partly held by vegetation. The width of the reef flat varies widely round the atoll, and the width of the seaward flat depends largely on the relative location of islands on it. At Gan the total width of the reef flat is 1500-2000 metres, and of the seaward flat 600-750 metres. Most of the islands are situated closer to the seaward reef, and between Hitaddu and Hankada and Mahera and Mulikadu the seaward flat is 50-300 metres wide; the mean width of the whole reef flat round the atoll is approximately 1000 metres (cf. Section E below). The flat also varies in height. Off the central part of Gan (115-120 easting), where the flat is 750 metres wide, it stands at a relatively high level, is thickly covered with marine grasses, and dries completely from the shore to the algal platform at lowest low tides. Between Gan and Fedu, by contrast, the flat is at a lower level, carries 1-3 ft of water even at lowest tides, lacks a vegetation mat, and is covered with sand in transport. These reef flats on the southern side of the atoll differ considerably from those on the north side, and may be distinguished as windward reef flat types. They differ from many described elsewhere in the Pacific and the Caribbean chiefly in the lack of coral growth on the seaward flat itself (cf. Emery and others 1954, 27; Wells 1954, 396-398). This apparently results from the high level of the flat and its regular drying. Where the level is lower on the Gan flat, growing corals are found. This occurs in three main areas: (a) the Gan-Fedu channel, (b) the lobe-shaped inlet of deeper water at the reef edge at 106158, and

(c) on the flat near the Gan channel (130153). A few very small and scattered corals are also found in the moat and in deeper parts of the algal platform round the reef edge. These consist mainly of corymbose Acropora and small nodular Porites, tightly cemented to the flat, together with small patches of Heliopora. In the three deeper areas, carrying at least 1 foot of water at lowest tides, the dominant corals are widely scattered colonies of Heliopora and Porites, the latter forming "micro-atolls" the top surface of which often supports a growing mass of Turbinaria. In the Gan-Fedu channel, where coral growth is scattered in spite of adequate water depth, coral growth is probably restricted by the amount of sediment in transport across the flat into the lagoon: in the case of many Porites colonies this is indicated by scouring on the upstream face and construction of a sand tail on the lee side, which creeps up the face of the colony killing the polyps which it buries.

At Hitaddu where the seaward flat is narrower and thus more characteristic, the seaward edge is also formed by an algal platform, but the seaward flat itself is rocky, 100-200 metres wide, and 18-24 inches deeper than at Gan (precise comparison is difficult in the absence of a common datum). No part of the seaward flat dries at any time. From the algal platform to within a few metres of the shore the flat is covered with coral rubble and blocks, with scattered small colonies of Heliopora, Porites and Acropora. Heliopora nowhere reaches the importance described at Funafuti and Onotoa Atolls (Cloud 1952), but it is certainly one of the more successful colonisers on shallow seaward flats at Addu.

(iv) Northern reefs - Midu side

The northern reef flat at Addu is quite different from those described above. It is likely that it carries 1-2 feet of water over almost its whole extent at lowest tides, and circulation of water is not inhibited by the presence of islands. Considerable coral growth is found both along the seaward edge of the flat, and on the lagoon side, and the sand-floored area between is patterned by growing corals. Similar conditions are found on the flats at the northwest and northeast corners of the atoll lagoon. The patterns of coral growth on these flats resemble at a small scale those described by Kornicker and Boyd (1962, 643) at Arrecife Alacran, Gulf of Mexico. This reef flat type may be termed the leeward type.

Lagoon reefs (approximate grid ref. 045130)

The northern reefs are considerably narrower than those at the south end of the atoll and differ in morphology and species composition of the corals. The lagoon reef slope is less steep and has an estimated angle of approximately 40°, merging with the lagoon floor at a depth of approximately 80 feet. The cessation of coral growth is not so distinct and patches of coral growth are found to depths of 100 feet on the gradual slope of the lagoon floor. Chute formations were not observed. The reef edge does not form a distinct zone and the outermost area of the reef top merges with the upper area of the lagoon slope, being dominated by palmate Acroporas, although some Pavia, Galaxea and Porites are also present.

The reef flat or reef top is characterized by the very low growths of coral which rise no more than 1-1.5 feet above the level of the surrounding sand. The area between corals is typically composed of a coarse sand rather than of coral fragments. The area occupied by living coral decreases towards the centre of the reef top and in some areas 90% of the surface of the reef is covered by the sand. Corals of the genus Acropora are dominant and comprise an estimated 95% of the total coral population. There are probably five or six species of this genus present, all tending towards a rather heavy, massive growth form. Other corals observed included Millepora, Pocillopora but Echinopora and Goniastrea did not appear to be present and massive cerioid and meandroid corals were not found.

Seaward reefs (approximate grid ref. 037133)

The centre of the reef top was not observed directly but aerial photographs indicate that there is little or no coral growth and that this area is carpeted with a layer of sand. Towards the reef edge, coral growth increases in abundance. Acropora spp. are again the dominant corals, particularly A. palifera and a branching species resembling A. formosa. Altogether there appears to be about six or seven species of Acropora composing this community but occasional colonies of Millepora and Pocillopora eydouxi are also present. The only common alga is a species of Halimeda. There are very few massive or cerioid corals. The area between corals is again filled by sand which here shows evidence of sorting and is typically of large flake-like form, from 1 to several millimeters in diameter and probably derived from the breakdown of Halimeda. Towards the edge of the reef the corals form a very close community with very little non-living areas between the colonies. Where these are present they are filled by small Acropora fragments cemented together with encrusting calcareous algae. The dominant corals here are A. palifera and a massive bracket type of Acropora. These corals are actively growing and probably do not break surface at low water spring tide.

The reef edge is not distinct, but at a depth of approximately 10 feet the zone of luxuriant growth gives way to a barren zone which is characterized by the lack of vigorous coral growth. Here, instead is an area of broken coral fragments cemented into a stable structure by the growth of encrusting red calcareous algae. Very small colonies of Acropora and Pocillopora of 6-9 inches diameter make up 10-15% of the bottom cover. This zone slopes gradually seawards to a depth of approximately 20 feet and then gives way to a steeper sloping zone (slope approximately 30°) of very luxuriant coral growth. Acropora species are again dominant but Favia spp., Seriatopora, Millepora and occasional fungiids are also found. Occasional massive upgrowths, rising up to 20 feet above the general surface of coral growth were observed and these provided ecological niches for the establishment of several encrusting and nodular form corals which were not otherwise in evidence.

At a depth of approximately 80 feet a break occurs in the slope, forming a fairly distinct edge and from here the reef falls away at a slope of about 50-60° to the depths of the Equatorial Channel. Beginning at depths of 40 feet in the zone above, the area between corals is filled by a coarse sand similar to that on the seaward region of the reef flat above. The relative area occupied by the sand increases with increasing depth as the number of corals and coral species decreases. At a depth of 150 feet there are very few corals still present but small Porites colonies are of sporadic occurrence. The hermatypic corals are gradually replaced by large branching colonies of Dendrophyllia and by large gorgonian sea fans and sea whips. Algae are still present at depths of 150 feet, attached to the larger coral fragments.

The northern reefs were visited at a time of year when the predominant wind is from the southeast so that the seaward reefs were therefore in the lee of the atoll. At midday, depths in excess of 150 feet were visible from the surface and water clarity was greater than that experienced in any part of the lagoon or on the seaward reef at Gan. Morphologically the seaward reef of the northern reef system differs from that of the southern reef in:

a) the absence of a distinct reef edge breaking surface at low tides

b) absence of a groove and spur system

c) the absence of a 10-fathom terrace although it is possible that the barren calcareous algae zone is the morphological equivalent of this

d) the presence of delicate weak-framed corals and gorgonians

e) the almost total domination of the surface reef by species of Acropora, including species which were not observed at the south of the atoll.

The windward reef flats at Addu are further distinguished by the presence of areas of relict "reefrock" standing (at Gan) up to 4 feet above the general level of the reef flat. In the Gan-Fedu channel the largest of these patches are found 300 and 400 metres respectively from the reef edge, and measure 140 x 30 and 140 x 60 metres. Smaller patches are found up to 700 metres from the reef edge near the Fedu shore. At Hitaddu similar rock platforms outcrop at the foot of the seaward beach, at a distance of 100-200 metres from the reef edge. The distribution of this rock and its origin are discussed under Section G below.

At Gan there has been considerable human interference with the condition of the seaward flat. Several of the areas of exposed reef-rock have been damaged by military vehicles and by excavation, and areas of the reef flat near the Gan shore have been used as a source of reef-rock for construction purposes, particularly in the construction of the runway, leaving a pattern of excavation hollows; the approximate extent of these is given in Figure 9.

(v) Lagoon reef flat and slope

Like the seaward flat, the lagoon reef flat varies widely in character in different parts of Addu. At Gan it is narrow (100-140 metres wide) and slopes from the shore to the lagoon reef edge. Most of the flat carries more than 1 ft of water at low tide, and except for the tips of some corals none of it dries. It is divisible into an inshore sandy zone with breaking waves, a zone of rubble and dead coral from 25-60 metres from the shore, and a zone of living reef from 60 metres to the edge and down the lagoon slope. The break of slope marking the edge of the flat has depths, between coral heads, of 10-15 ft at Gan. At Hitaddu the leeward flat is much wider (reaching 1000 metres), has a depth of 1-2 fathoms, and for most of its width is sandy, covered with marine grasses, and lacking in growing corals. The reef itself appears to be similar to that at Gan. It is possible, especially at Gan, that military activity has led to increased sediment disturbance on the lagoon reef flat, with the death of nearshore corals; certainly the extent of coral growth, while comparable to that on Caribbean reefs, falls short of Gardiner's description. Detailed transects were made on the lagoon reef at Gan, and some geological aspects of these are discussed in Section D below.

The lagoon slope at Gan has a gradient of 60^{o} from the reef edge to a depth of 14 fathoms, and is coated with growing corals. At 14 fathoms the slope angle decreases to less than 10^{o}, and begins to merge with the lagoon floor. Coral growth in this zone is restricted to patches of Leptoseris, together with scattered Alcyonarians.

The nature of the lagoonward reefs is subject to modification between islands, where water flowing across the reef flat carries a considerable load of debris. Thus between Gan and Fedu, Fedu and Maradu, Maradu and Hankada, and elsewhere, through-flowing currents have incised deep channels into the upper part of the lagoon reef edge and slope, concentrating flow across the reef flat into narrow streams with speeds of 2-3 knots, and resulting in the growth of sand deltas at the foot of the lagoon slope.

C. Addu Lagoon

Lagoon topography

Information on lagoon topography is derived almost entirely from Dalgleish's 1923 survey, in which the density of soundings exceeds even that at Eniwetok (Table 1). Since location-finding methods were less refined in 1923, however, and since the soundings were all lead-line soundings corrected for tide and not reduced from echosoundings, the accuracy at Addu may be less than in the Marshall Islands.

Table 1. Sounding density in selected atolls

Atoll	Lagoon area[1] sq.miles	Number of soundings[1]	Soundings per sq.mile
Addu	30	18,000	600
Eniwetok	360	180,000	500
Bikini	259	38,000	146.7
Rongelap	396	14,550	36.7
Rongerik	57	1,640	28.8

1. Emery, Tracey and Ladd 1954.
2. Estimated from sample counts.

The Daugleish chart has been supplemented by ten echo-sounding profiles made with a Marconi Ferrograph Offshore 500 echosounder in 1964; these have been replotted on rectangular coordinates in Figures 12-15 and the location of the echo-sounding tracks is shown in Figure 11. The Daugleish chart has been contoured and redrawn to include land topography derived from aerial photography and included on Admiralty Chart 2067 of 1964; it is included here as Figure 10.

Addu lagoon is deepest in the east and northeast, and shoals towards the north and southwest. The 30 fathom isobath delimits a basin of irregular outline, which includes a number of isolated deeper basins and a few upstanding knolls. The lagoon reef slopes are steep (Profiles 1-4, 6-7, 9-10) and extend from the lagoon reef edge at 5-15 ft to the lagoon floor at depths of 85-100 ft, where the slope angle decreases and the slope becomes a flatter apron. Chart inspection suggests that much of the lagoon floor is fairly flat at depths of 25-29 fathoms, particularly in the south and northwest parts of the lagoon, and this is also suggested by several of the profiles. Profile 1, between Gan and Man Kanda Channel, shows a distinct level at 20-25 fathoms, with deeper central areas down to 33 fathoms below this level. Similar features are shown in Profile 9. The deepest parts of the lagoon (more than 40 fathoms) lie in the south-central sector, where nine small areas fall below this level. Most of these are narrow and aligned east-west on Daugleish's chart, in the direction of sounding, suggesting systematic variation in sounding accuracy between successive lines of soundings. Hence the absolute depths of these basins may be unreliable. The maximum charted depth is 43 fathoms (258 ft).

To determine the reality of the apparent floor flattening between 20 and 30 fathoms, Daugleish's chart at 1:18,360 was contoured, and the areas between successive contours were measured using a Stanley Precision Disc Planimeter. The areas of reef flats and islands were obtained in the same way from the published Admiralty chart at 1:25,000, in which these features are plotted from aerial photography. The results of these measurements are given in Table 2.

Table 2

Depth fathoms	Area sq. yds	Cumulative area shallower	Per cent shallower	Cumulative area deeper	Per cent deeper
Islands	13,419,197				
Reef flat, 0-1 fathom, inc. islands	65,987,766				
Reef flat, 0-1 fathom, exc. islands	52,568,569				
1 - 14	12,110,207	12,110,207	13.20	91,750,231	100.00
15 - 20	11,815,554	23,925,761	26.08	79,640,024	86.80
21 - 24	19,085,942	43,011,703	46.88	67,824,470	73.92
25 - 29	22,353,011	65,364,714	71.24	48,738,528	53.12
30 - 34	14,153,743	79,518,457	86.67	26,385,517	28.76
35 - 39	11,553,133	91,071,590	99.26	12,231,774	13.33
40 - 43	678,641	91,750,231	100.00	678,641	0.74
Total lagoon area, inc. gaps	91,750,231				
Total atoll area	157,737,997				

The data in Table 2 are plotted as a histogram in Figure 16, which shows the large area of reef flat and also the dominant lagoon floor area at 25-30 fathoms. The hypsometric curve for the whole atoll (bounded by the outer reef edge) in Figure 17 gives a graphic idea of the wide shallow reef flats, the steep lagoon floor slopes between 1 and 15 fathoms, the slope foot apron at 15-21 fathoms, the wide flatter area between 21 and 30 fathoms, and the smaller extent of deeper holes in the main lagoon floor level. A percentage hypsometric curve may be constructed for the lagoon data only, and directly compared with percentage hypsometric curves constructed for the better sounded lagoons of the Northern Marshall Islands (Fig. 18), where the curves were obtained by cutting out and weighing depth zones on contour maps. The similarity between the curves for Eniwetok, Rongelap and Bikini Atolls and Addu Atoll is striking, at depths shallower than 28 fathoms, though Addu lagoon floor reaches greater depths than those in the Marshalls. The curve for Rongerik is of different form, and a curve for Johnston Island published by Emery is not really comparable because of the absence there of an enclosed lagoon (see Emery, Tracey and Ladd 1954,55; Emery 1956).

<u>The infilling controversy</u>

Using Daugleish's chart it is also possible to resolve the controversy between Agassiz, Gardiner and Sewell over possible aggradation or degradation of the lagoon floor. Gardiner (1903, 317-321), comparing Moresby's 1836 chart with the soundings made by his colleague Forster Cooper, argued for "a decrease in depth of from 1 to 8 fathoms, the general reduction being 2 or 3 fathoms" on the lagoon floor proper, at the same time as the encircling reefs were growing rapidly into the lagoon. He concluded that "in the 65 years between Moresby's visit and my own there has been <u>at the least</u> a decrease in depth of 2 fathoms over the whole area of <u>the lagoon proper</u>, i.e. about 15 square miles....To suppose, therefore, for the 60 odd years since the survey, a deposit or filling in by coral growth of $2\frac{1}{4}$ inches a year over an area of 22 square miles does not seem to me to be excessive" (Gardiner 1903, 320). Lagoon infilling was the reverse of the process which Gardiner thought was general in the Maldive Islands lagoons: in the case of Addu he attributed lack of solutional deepening to the landlocked nature of the lagoon, its small size, supposed lessened rate of water circulation through the reef gaps, and high rates of coral growth. Agassiz (1903, 148) questioned whether Forster Cooper's soundings were close enough to Moresby's to allow Gardiner to draw any conclusions, and emphasized the difficulty of accurate location within the lagoon. Subsequently Sewell made several more soundings (Sewell 1936a, 64), and calculated that while the "average depth" of the lagoon, excluding shoal areas, was on Moresby's chart 24.4 fathoms and on Cooper's 21.5 fathoms, Cooper's and Sewell's soundings together made it 24.5 fathoms. He hence concluded that no change had taken place. Sewell's contoured chart bears a tolerable resemblance to Daugleish's, from which the median depth read from the hypsometric curve (including shoal patches) is found to be 25.5 fathoms. The maximum depths in the lagoon were charted by Moresby as 36 fathoms, by Cooper as 32 fathoms, and by Daugleish as 43 fathoms. Subsequently Gardiner (1931, 141)ceased to stress the supposed infilling of Addu lagoon. As Sewell observed and Daugleish demonstrated, the bottom topography of the lagoon is sufficiently complex to require precise sounding location before conclusions on depth changes can be made.

Lagoon reef patches and knolls

By comparison with other atoll groups, and with the northern Maldive atolls, there are few reef structures within the Addu lagoon. Arbitrarily defining a patch reef as a structure rising more than 10 fathoms above its base and capped with wave-breaking corals, Addu lagoon patch reefs total 3. Defining knolls as structures rising 10 fathoms or more above the floor, denoted by two or more closed contours on the bathymetric chart, but failing to reach the surface, Addu lagoon knolls total 22. The total of 25 lagoon reef structures may be compared with nearly 2300 at Eniwetok, over 900 at Bikini, and 700 at Glover's Reef, British Honduras. Daugleish's density of sounding was such that it is unlikely that any major structures were unrecorded.

The knolls and patch reefs are located and given index numbers in Figure 19. Two in the centre of the lagoon, Aruhal (13, at 137084) and Medagala (14, at 136094), have living reef caps, and are normally marked by breakers, peaking up to 6 ft in height even in calm water. Of the rest, numbers 3, 23 and 24, on the west side of the lagoon, have growing coral on their summits and reach to within 2½ fathoms of the surface; number 4, reaching 4 3/4 fathoms, also has growing coral, but Davies and Keith report much dead coral also. Whether any other knolls support growing coral is not known.

Chart inspection suggests that of the knolls which fail to reach the surface there is a dominant summit level at 15-25 fathoms. The Stanley Precision Disc Planimeter was used to measure the basal area (lowest closed contour) and summit area (highest closed contour) of all 25 knolls and patches: their depth-area distribution is shown in Figure 21. Apart from Aruhal (13) and Medagala (14) all of the patches which reach within 10 fathoms of the surface are small and steep sided: the mean ratio of basal area and summit area is 7.6 and the median 4.6. None of the other knolls rises above 12.5 fathoms; six reach to between 12.5 and 17.5 fathoms; and five to between 20 and 25 fathoms. With one exception (21) the knolls rising to 12.5-17.5 fathoms all lie in the northeast part of the lagoon (numbers 7, 9-12). Those rising to 20-25 fathoms all lie in the centre of the lagoon. The mean ratio of basal to summit area of knolls rising to 12.5-25 fathoms is 24.4 and the median 9.1; the mean ratio for Aruhal and Medagala is 14.6. Of the knolls rising above 20 fathoms some show apparent terracing at the 20-25 or 25-30 fathom levels, as in numbers 12 and 21.

Comparison may again be made with the Marshalls. At Eniwetok the greatest frequency of knoll summits is at 16-20 fathoms, with few rising to 0-8 fathoms. At Bikini the greatest frequency of summits is at 4-12 and 20-24 fathoms (Emery, Tracey and Ladd 1954, 96). The concentration of the larger Addu knolls at similar depths, and the contrast between these and the smaller, steeper surface patches, suggests that the deep knolls have not been formed by reef growth in the Holocene. The echo-sounding profiles of two different types of knoll may be compared in Figure 15 (number 24) and Figure 12 (number 20). The apparent bevelling of the lower knoll summits may possibly be correlated with the apparent lagoon floor flattening shown by the depth-area histogram, and with the reported erosional undercutting of the seaward reef wall described by Hass and Eibl-Eibesfeldt, both at 25-30 fathoms. It is possible, as shown by the distribution diagram, Figure 20, that the knolls fall into two groups, one rising to about 12.5 and the other to about 20 fathoms. If these knolls are indeed older features, then they may have lost both height and steepness during karst erosion at the time of glacial low sea levels: it would be extremely valuable to have data on the nature of the knoll surfaces, and whether coral growth occurs on them. The small size of the sea-level patches (numbers 1-4, 6, 22-24) may indicate that they are wholly Holocene reef constructions. Of the larger knolls only Aruhal and Medagala reach the surface, and it is possible that they have been the only older knolls on which Holocene reef growth was established, and that the fairly small area of surface reef growing on much larger foundations represents an amount of Holocene reef growth comparable to that of the other near-surface patches. Such interpretations must be speculative until more data are available on the knolls themselves.

Notes on the structure of "Five Fathom Shoal" (095095)

Underwater observations were made on the leeward, northwestern side of this structure (no. 4, fig. 19) to a depth of 140 feet. The surface of the knoll lies at a depth of approximately 30 feet, is flat topped and is characterised by almost complete lack of coral growth. There are occasional small colonies of *Pocillopora*, *Porites*, *Galaxea* and *Acropora* but most of the surface comprises loose, uncemented skeletons of a branched *Acropora* with individual pieces of up to 2 feet in length and of plate-like fragments probably derived from *Echinopora*. The whole is carpeted with a fine leafy alga.

Below approximately 45-50 feet on the northwest side, the dead coral is replaced by fine sand and the slope is very steep to a depth of 80 feet. The sand is very tightly packed, cannot be scooped into with the hands and superficially resembles a soft sandstone. Occasional coral colonies are found in this area, with a density which rarely exceeds one per 10 square metres. A loosely branching bracket form of *Acropora* is the most common of these but *Favia* and *Porites* were also observed.

Below a depth of approximately 80 feet the slope begins to level off and at a depth of 140 feet the bottom is almost flat. Between these two depths reef building corals are very infrequent although one large colony of *Porites* was present. Small colonies of *Dendrophyllia* and occasional gorgonian sea whips were observed.

D. General Reef Characteristics

The main reef work of the expedition was concentrated on two lagoon reef transects at Gan (locations: 108140, between the jetties, and 113143, east of the oil jetty). Recording and collection of corals and algae in 10 feet quadrats from the shore to the foot of the lagoon slope was carried out continuously along a steel chain laid on the sea floor. Within each quadrat an effort was made to collect a specimen of every species of corals and marine algae present, and estimates were made of total percentage cover and of relative importance of particular species. Details of these transects will be published when all the determinations are available, but certain features are of geological interest and are discussed here. Figure 21 shows relative abundance of corals across each transect in terms of total number of species per quadrat; the species themselves were separated in the field and their identity will be subject to revision. Figure 22 shows the distribution of these species roughly classified by growth form. In both transects coral growth begins at about 30 metres from the shore, though scattered small colonies may be found closer, and rapidly increases to form a rich reef association at about 70 metres from the shore. From here to the reef edge at 112 metres, the abundance of species increases (Figure 21), from about 10 species per 100 sq. ft. to about 20 species per 100 sq. ft. From the reef edge to the foot of the lagoon slope the number of species remains approximately constant (10-17 per 100 sq. ft. in Transect I, 12-29 per 100 sq. ft. in Transect II). Abundance of species itself is not necessarily of geological importance, however, for many are small and often insignificant reef builders. A rough division was therefore made into species of the genus Acropora, those of the family Fungiidae, and the cerioid corals (those with adjoining polygonal calices such as Favites). Both transects show regularity in the distribution of these admittedly rather diffuse groups. The cerioid corals are important on the reef flat, forming 25-35% of the species present, but are less so on the reef slope, particularly with increasing depth. The fungiid corals are not important on the flat, but form a minor constituent on the slope. The Acropora spp. form one of the most important and cosmopolitan groups, generally accounting for 25-50% of the species present on the flat, and continuing to the base of the reef slope.

A rough classification of species was also made into growth form (Fig. 22), distinguishing foliaceous corals (e.g. Pachyseris and Echinopora), meandroid corals, branching corals (e.g. Acropora, Pocillopora, Euphyllia, and the superficially meandroid Lobophyllia), and the non-meandroid massive corals, many of cerioid form (e.g. Astreopora, Favites, Hydnophora, Porites, and many others). The contribution of the massive corals appears exaggerated, for many of the species represented form only small colonies. Attention may be drawn (a) to the importance of branching corals over the whole transect, and (b) to the importance of foliaceous corals on the outermost flat and particularly on the reef slope. Estimates of cover of different corals give a similar picture, particularly reinforcing the importance of reef flat Acroporas: on the outer part of the flat many quadrats show 50% of the area of living coral to be Acropora, and one shows 85%.

By comparison with Caribbean reefs there are certain major differences, with geological implications, in these reef assemblages. These may be summarized as:

(a) the virtual absence in the Maldives of the massive meandroid frame-building corals, such as the Diploria spp., and the greatly reduced significance of other massive frame-builders corresponding to the Caribbean Montastrea and Siderastrea species.

(b) the greater diversity in species and the greater area covered by Acropora. Branching and plate-like Acropora spp. are the most important corals on the Addu lagoon reefs, and most of the species present are of light and open growth form, rather than heavy and massive. On lagoon patch reef 24 the diversity and luxuriance of the Acropora, especially the flat, plate-like species, is remarkable, compared to the abundance of other species and to the Atlantic Acropora. Massive Acropora, comparable to the Atlantic A. palmata, are less common.

(c) the importance of foliaceous corals, particularly Echinopora on the slope, and of other open-branched, weak-framed, and often unattached corals (such as Fungia, Herpolitha and Halomitra) in similar situations.

It is probably reasonable to conclude from this that the Maldivian lagoon reefs are formed of much faster growing species than the Caribbean reefs, but that the reef framework formed is less rigid and more unstable than that in the Caribbean. There is, as a result, evidence of reef instability at Gan. The lagoon slope is exceptionally steep, and must approach the limits of cohesion of weak-structured corals. On the Gan lagoon slope coral growth is frequently interrupted by dead areas of broken coral and rubble, often extending from the top of the slope to the bottom, which are clearly slide scars. At times small scale sliding was seen taking place down the slope, raising turbid clouds of finer material. The reef structure, as Hass (1962) observed, is certainly a fragile and delicate one, at least near the surface, but the conclusions which Hass drew from this on the question of atoll origins misconceive the space and time scales involved. It is also possible that some at least of the larger slides have been triggered by military activities at the Gan Staging Post. Nevertheless, the evidence indicates major differences in the nature of reef growth between the Maldives and the Caribbean, and the implications of this might well be explored further.

E. Islands

Types of islands

Twenty per cent of the reef flat area at Addu is covered by islands, and the proportion would be higher if it were not for the almost island-less northern reef. The three largest islands are Hitaddu, Gan and Midu: six other islands have areas in excess of 100,000 sq. yds. The planimetric area of the islands is given in the following table:

Table 3. Areas of Addu Islands

Island	Area, sq. miles
Hitaddu	1.3943
Gan	0.8711
Midu	0.7913
Maradu	0.3118
Heratera	0.2965
Wilingili	0.1989
Fedu	0.1588
Abuhera	0.1399
Mahira	0.0464
15 small islands	0.1132
Total	4.3222

Many of the islands have only been sketchily studied, but fairly full accounts exist for Midu, Hitaddu, and particularly Heratera (Putali), and Gan and Hitaddu were visited during the 1964 expedition. The characteristics of the islands vary with size and with position on the reef flat. There are two extreme cases of island types: those formed close to the seaward reef edge, and those formed close to the lagoon reef edge (Fig. 8).

(a) Seaward-edge islands.

The seaward beach of these islands characteristically lies 45-180 metres from the algal platform, and may adjoin the rubble zone. The seaward beach is steep and high, and generally built of coral debris coarser than gravel, though in more protected areas it may be largely or wholly sand. According to Gardiner (1903, 146) raised reef-rock outcrops on the seaward beach, underlying beach sediments, whereever the shore lies within 230 metres of the reef edge, though this is by no means a general rule (Section G below). At Wilingili the seaward beach lies only 90 metres from the reef edge, is built of shingle, and was reported by Agassiz (1903, 146) to be "the highest in the Maldives". At Hitaddu the seaward beach is sandy with patches of shingle at a distance of 180 metres from the reef edge, and rises 10-12 ft above the flat; but at Abuhera, 45 metres from the edge, the beach is built of shingle and is steeper. The lagoonward beach on these islands may be 450-1000 metres from the lagoon reef edge, and is usually low and sandy, with vegetation reaching close to high tide level.

(b) Lagoon-edge islands.

In this class the island lies close to the lagoon reef edge, and correspondingly farther from the seaward reef. The distance between the lagoon reef edge and the lagoon beach ranges from 45-180 metres, and between the seaward reef edge and seaward beach from 180-1000 metres. Beaches facing the wide and often high-standing seaward reef flat are thus relatively more protected than those facing the narrow lagoon reef flat. At Gan, which falls in this class, the seaward beach is flat and narrow, and the lagoon beach high, steep and wide. Gravel and coarser debris is rare on both seaward and lagoon beaches, which are mostly sandy.

The characteristics of the larger islands thus depend to a considerable extent on relative location on the reef flat, and this varies in a fairly systematic fashion round the atoll rim. Smaller islands such as Bushy and Mulikadu are simple ridges of coral shingle and sand lodged on the reef flat by waves, and they do not show the more complex features of the larger islands. The following table classifies the Addu islands into three types: A, seaward-edge islands, B, lagoon-edge islands, and C, intermediate islands, and gives distances measured from air photographs between the seaward and lagoon reef edges and beaches.

Table 4

Island	total width of reef flat, metres	width seaward flat, metres	width lagoon flat, metres	Island type
Hitaddu	900-1350	90-180	900 +	A
Abuhera	820	45	640-900	A
Maradu	1040	600-690	180-320	C
Fedu	1130-1350	600-1350	160-180	B
Gan	1350-1800	550-690	70-90	B
Wilingili	730	90	460-550	A
Midu	300-400	90-180	-	A
Heratera	820-1260	70-90	550-900	A
Firhidu Hera	900-1000	90	730-820	A
Kalu Hera	1130	90	1000	A
Mulikadu	450	135-275	90-180	C

Island beaches

151 beach profiles were surveyed at Gan Island and 30 at Hitaddu, using a tripod quickset level and staff. Profiles were carried from the beach crest (or where vegetated the outer edge of the vegetation hedge) to a point 15-30 metres seaward of the foot of the beach. The foot of the beach is defined on most profiles by a sharp concave break of slope where the beach face meets the horizontal reef flat. In the field it is delimited by a more or less abrupt transition between white beach sands and the rocky, vegetated flat. Beach profiles may be slightly convex or concave, but most are straight with a summit convexity, except where erosion has led to scarp formation at the beach crest. A distinction may be made between (a) rough water beaches, where the foot of the beach forms a step up to 1 ft in height immediately below low tide level, often with an area of strongly rippled sand to seaward, and (b) calmer water beaches, where this step is absent. Beach profiles were measured over a period of weeks, but always at similar tidal stages, i.e. during the 4-5 days of exceptionally low low tides occurring at fortnightly intervals. Gan profiles 1-5 were also repeated at a medium high tide (profiles 6-10).

Considerable differences were found in beach angle in areas with different exposure to wave activity. At Gan the profiles were grouped into beach sectors (Fig. 23), separated by areas unsurveyed because of human interference or other reasons. Within each sector, beach angles tend to be tightly clustered about a mean value (except on the east shore, where values are more widely scattered), but there are considerable differences between beach sectors. Mean beach angles for Gan beach sectors are as follows:

Table 5

Beach sector	Number of profiles	Mean angle
East shore	10	5.75°
North shore (east)	10	7.95
North shore (centre)	56	8.30
North shore (west)	15	8.07
West shore	14	4.18
Southwest shore	36	5.77
Total and Mean	151	7.01

These beach angles correlate directly with exposure. Wave activity is most intense on the lagoon shore between the two jetties; it is high along the whole lagoon shore, and much less on the east and west shores where the reef flat is wider and shallower. On the southwest shore the beach is rather more exposed to waves in the wide and deeper Gan-Fedu channel, and beach angles are correspondingly higher. The steepest beach angle recorded at Gan is 11.5° in profile 58. The south shore of Gan, facing the exceptionally wide seaward flat, is most protected from wave action: the beaches are low and flat, and vegetated almost to high tide level; this, together with the fact that this shore has been used since World War II as a rubbish dump for military debris, made profiling impossible.

At Hitaddu similar contrasts are found in beach angles, again co-relating with wave energy, but whereas at Gan the steepest beaches are on the northern lagoon shore, at Hitaddu they face the narrow seaward reef flat, and the more protected lagoon beaches are lower and flatter.

Table 6

Beach sector	Number of profiles	Mean angle
Seaward shore	19	9.5°
Lagoon shore	11	5.2

The steepest beach angle measured at Hitaddu was 13° on seaward shore profile B9.

Inspection of the Gan profiles shows that the width of the beach tends to be fairly constant between the sectors measured (not including the south shore): width averages 14-16 metres, and varies extremely from 7 to 23 metres. The height of the beach above the immediate offshore flat (i.e. above the concave break of slope at the beach foot) is more variable, and is directly related to beach angle. On beaches with a mean angle of 5° or less, the height of the beach is 5 ft or less. On steeper beaches (angle greater than 8°) beach heights are greater than 5 ft and range up to 10.5 ft. Steep, high beaches are built in exposed areas where rapid swash builds the beach face above still high-water level. The most sheltered beaches have heights approximately equal to the tidal range. Median beach heights for different beach angles at Gan are as follows:

Table 7

Beach angle, deg.	3	4	5	6	7	8	9	10
Median height, ft.	3	4	5	4	5	6	7	8

Similarly at Hitaddu, the width of the seaward beach averages 15 metres, varying from 13 to 20 metres, and that of the lagoon beaches averages 13-14 metres, varying from 10-15 metres. Main variability is in beach height, which again directly correlates with angle:

Table 8

Beach angle, deg.	5	5.5	8	9	10	11	13
Median height, ft.	4	4	7*	7	7	8*	10*

(* single cases only)

Plotting median height and height range against beach angle in Figure 24 indicates the range and variability of these beach characteristics; the regression line is fitted by eye.

Interior topography

Most of the Addu islands consist of seaward and lagoonward ridges, separated by a lower area, in places occupied by water. The eastern islands consist of a rocky seaward ridge and sandy lagoon ridge, separated by freshwater lakes or kuli (Willis and Gardiner 1901, 78). Air photographs show a large interior lagoon at Hitaddu, but this could not be visited. Much of the central part of southern Hitaddu was covered with standing water 6-24 inches deep in August 1964, under a vegetation of sedges and *Pandanus* thicket. At Gan the interior topography has been considerably altered by construction work, but in the centre of the island the soil is black and mucky, with the water table at or within an inch or two of the surface. Excavation at several places showed a clear distinction between soils derived from peripheral sand ridge sediments, and those formed under high water table conditions in the centre of the island. Unlike many Pacific and Caribbean islands, mantles of coarse sediments ("rampart wash") in the interiors of islands, resulting from exceptional storm activity, seem to be absent at Addu.

The height of the water table is such that after heavy rain fresh water may stand on the island surfaces for several days, and in places permanently. This is the case at Gan, where levelling of the surface has added to drainage difficulties, but also at Hitaddu. Gardiner described similar conditions at Maradu (Willis and Gardiner 1901, 80). Rainwater replenishment of the Gan freshwater lens is sufficient to supply all freshwater requirements for the R.A.F. Staging Post established there.

Minor changes in Addu island topography

The records of 1836, 1900, 1934 and 1964 show that some features of the Addu islands are subject to minor alteration, particularly where gaps between islands are narrow and shallow. Islands charted as separate by Moresby and even by Gardiner may now be joined; and some small islands may have disappeared. Sewell has chronicled the changing numbers of small islands off northwest Midu: 6 in 1836, 7 in 1900, 5 in 1934 (Sewell 1936a, 73-74); in 1964 there were three, two small, and one (Mahira) long and narrow. Heratera and Firhidu Hera were separate in 1836, joined in 1900 (Gardiner 1903, 318), separate in 1934 (Sewell 1936, 74), and joined in 1964. Wilingili, charted as two islands in 1836, had become one by 1900 (Gardiner 1903, 418), and remains so. In 1836 Abuhera was continuous with Hitaddu, and remained so in 1900 (Gardiner 1903, 415). By 1934 the two were separated (Sewell 1936a, 84), but were again joined in 1964, by a sandy area with continuous vegetation cover, standing 3.5-4 ft above the level of the reef flat immediately to seaward, with a seaward sand and shingle ridge 2.5 ft higher (Profile B19). The series of small islands on the seaward side of Fedu and Maradu, uncharted in 1836 but recorded by Gardiner, were probably omitted in error by Moresby; they are discussed by Gardiner (1903, 419) and Sewell (1936a, 80-81). The scrub vegetation described by Sewell has now been replaced by coconut thicket with trees 45-50 ft tall.

According to Agassiz (1903, 147-8) and Kohn (1964b) the lagoon and southwest shores of Gan are being eroded, while Sewell (1936a, 80) inferred aggradation. Evidence for beach retreat is given by the beachrock at the northwest point, which is now being actively undercut by throughflowing water in the Gan-Fedu channel; by the exposure of cay sandstone on the beach face on the southwest, west, and to a lesser extent the northern shore; and occasional undermining of trees at the eastern end of the north shore. Retaining walls have been built to stabilise the shore on parts of the west and north shores. For details of the beachrock and cay sandstone exposures, see Section G(iii) and (iv). Local aggradation is taking place at the northeast point of Gan, where a fresh sand spit extends 60 metres from the main beach crest.

F. Sedimentary environments

The main aim of the geomorphic work was the sampling of sediments in a variety of atoll environments, to demonstrate (a) how sediment characteristics varied between environments within the depositional framework of the atoll, and (b) how sediment characteristics (mechanical and organic composition) vary on the beach face and the immediate nearshore area in a number of beach sectors subject to differing wave intensities at Gan and Hitaddu Islands. The main sedimentary environments sampled were (1) island beaches, (2) reef flat, (3) lagoon reef slope, and (4) lagoon floor. On beaches sampling was carried out at the same time as beach profiling, on a total of 250 beach profiles. Samples were collected at 5 metre intervals on each profile, measured from the beach crest, and the profiles were generally spaced at 25 metre intervals along the beach. Generally 5-6 samples are available per profile: the profiles are located in Figure 23. The total number of beach face and immediate nearshore samples collected at Gan numbered 950, and at Hitaddu 99. Sampling of reef flat environments was carried out on the seaward flat at Gan, and in the Gan-Fedu channel, concurrently with levelling. Location of the reef flat samples, totalling 127, is shown in Figure 25. On both beaches and reef flat sampling was carried out with a simple scoop sampler holding approximately 300 grams. On the lagoon reef slope 5 samples were collected by Keith using SCUBA apparatus. On the lagoon floor sampling was carried out using a bronze grab sampler which closed automatically on striking the bottom. Recovery of samples was poor because of frequent malfunction of the release, and the total number of samples collected was 42; their location is given in Figure 26. Processing of these samples for machine computation of mechanical characteristics is continuing, and this section simply records some gross characteristics of reef flat, beach and lagoon floor sediments, on the basis of preliminary data for 350 samples. As measures of sediment characteristics, cumulative percentage curves were drawn from sieve data and used to derive phi median diameter (ϕM_d) and sigma phi ($\sigma\phi$), the latter giving a simple measure of sorting (ϕ $[\phi 84 - \phi 16] / 2$).

Using these parameters clear distinctions may be made between reef flat, beaches and lagoon floor environments (Fig. 27). In the reef flat sediments as a whole the mean ϕM_d is about 0.5, a coarse sand, with a range from -1.3 to +1.7 ϕ (very fine gravel to medium sand). Taking the Gan beach sediments as a whole, mean ϕM_d size is about 0.85, a less coarse sand, with a range from -0.2 to +2.1 ϕ (very coarse sand to fine sand). The lagoon floor sediments are highly variable in size composition, ranging from less than 1.0 to more than 4.0 ϕM_d (coarse sand to coarse silt). There is therefore some distinctiveness in size range between the three environments (note that no attempt was made to sample beach sediments coarser than fine gravel, such as the shingle or rubble sediments on the seaward beach of Hitaddu). Taking median size characteristics alone, however, there is considerable overlap, particularly between reef flat and beach sediments. Sorting is more discriminatory. Although the sorting measure used here is rather inefficient and was chosen for ease in calculating, it is clear that considerable differences in sorting exist between environments. Beach sorting values are almost all less than 1.0, except where the sediment sampled is obviously bimodal; the peak frequency of beach sorting values is 0.5-0.6, i.e. beach sediments are very well sorted. By contrast, reef flat sediment sorting values range from 0.7 to 2.1, with a mean value of about 1.5, i.e. sorting is much poorer. Lagoon floor samples have similar or higher sorting values than those on the reef flat. Plotting of median size against sigma phi in Figure 28 shows that reef flat and beach sediments are clearly distinguishable in terms of size and sorting; data are too few to accurately define the range of lagoon floor characteristics. In summary:

(1) beach sediments are moderately fine sands and very well sorted;
(2) reef flat sediments are coarser and poorly sorted;
(3) lagoon floor sediments are coarse to very fine, and poorly sorted.

There is in addition considerable variation within the major environments. The beach sampling programme was designed to assess changing sediment characteristics normal to the shore, particularly in the light of Miller and Zeigler's (1958) model of beach sediment characteristics. Preliminary results indicate that sediments are coarsest at the foot of the beach, at the "step" on rough-water beaches, and become finer in median diameter both to seaward of the beach foot and up the beach face. Sorting is also best in the lower part of the beach, and decreases to seaward of the beach foot and up the beach face. Much work needs to be done on the data, however, before conclusions can be drawn. Similarly on the reef flat, a distinction can be made between flats backed by islands and channels, since considerable sediment transport and sorting occurs through the Gan-Fedu channel, by comparison with more stable conditions on the vegetated flat south of Gan.

G. Lithified sediments

Lithified sediments of various types have been described from the Maldive Islands by Moresby, Gardiner, Agassiz and Sewell, and Gardiner in particular has used the present distribution and height of lithified sediments on the atolls as evidence for considerable shifts of sea level in Recent times. In many discussions of lithified sediments, genesis has been deduced only from the gross topographic characteristics of the outcrop, and it has then been assumed that similar outcrops have a similar composition. Few discussions of atoll rocks consider lithology and mineralogy as well as topography and distribution, and many of the earlier deductions on rock origin and its implications in terms of geomorphic history are purely speculative.

Gardiner (1903) and Sewell (1935a, 500-512) distinguished three main types of rock on atolls: reef rock, beach sandstone or beachrock, and cay sandstone. All these types are found at Addu Atoll, but a further distinction must be made between reef rock underlying the modern reef flat, and raised or relict presumed "reefrock" of uncertain status. This account is purely descriptive, and no attempt is made to describe the mineralogy or origin of the rocks, or their bearing on atoll history at this stage.

(i) Reef rock

Wherever investigated the reef flats of Addu atoll consist of a more or less regular rock platform, veneered with loose sediment. This is particularly so south of Gan, on the wide seaward reef flat, which is wholly a rocky feature, lacking any considerable relief, and giving no indication of subsurface structure in the form of either curvilinear fracturing or of truncated and relict coral heads described from such flats elsewhere. Samples of reef rock were obtained by blasting on the seaward reef at Gan, location 115159, through the courtesy of Mr. J. Woodward. The rock is a toughly cemented rock of coral fragments in a limestone matrix, with abundant Heliopora fragments which have lost their blue colour and turned brown. The constituents indicate a reef community similar to that now found on deeper flats than the present Gan flat. It is difficult to see how such rock could form at the present level of the flat off central Gan.

(ii) Relict "reef rock"

Several of the seaward-edge islands have low rock platforms at the foot of their seaward shores. Gardiner (1903, 416) described this as occurring wherever part of the island lies within 230 metres of the seaward reef edge; at Hera, north of Midu, he described emerged reef-flat rock masses standing up to 6 ft above high water and 10 ft above the flat. At Midu, rock is described along the east shore, reaching 5 ft above high water (Gardiner 1903, 417; Sewell 1936a, 73, Plate 1ii). Seaward-beach rock masses are also described at Heratera (Sewell 1936a, 75, Plate 3ii), Firhidu Hera and Kalu Hera (Sewell 1936a, 79), Mulikadu (Sewell 1936a, 79), and Maradu (Sewell 1936a, 82). Sewell also describes it between the seaward shore and the reef edge at Maradu, forming "coral horses" (Sewell 1936a, 83, Plate 3i), and in the small islands between Fedu and Maradu (Sewell 1936a, 81).

"Reef rock" of similar type is present on the seaward shore of Hitaddu, where it was surveyed in beach profiles B1, B12, B14 and B15.

In profile B1 the highest point of the reef rock outcrop, which is 4 metres wide, reaches 4.3 ft above the general level of the reef flat, but only 3 ft above the level of the flat immediately seaward of the rock. It outcrops at the foot of the beach, which here rises 6 ft above lowest low water, and the rock itself dries at least 1.5 ft at this stage. Other profiles show similar characteristics, except that the beach face above the rock is only 3-4 ft high. In places the upper surface of the rock shows a distinct seaward gradient (4.5° in B1, 3° in B12), but this is clearly erosional: elsewhere the surface is rough but horizontal. The structure of this relict rock is not easily discernible, but at places on the southernmost part of the Hitaddu seaward shore and the northernmost part of Abuhera the coral slabs forming the rock are clearly imbricated, dipping seawards, which might indicate a subtidal reef flat rather than a beach environment.

Several patches of rock, mentioned by Gardiner and Sewell, are found in the reef flat embayment between Gan and Fedu Islands, and on the wide reef flat to the south of Gan. The patches are as follows: (1) A rock platform marked on charts as Addu Island, south of Gan, location 1048/1536-1550, measuring 140 x 30 metres, the highest part rising 5.1 ft above the deepest part of the seaward flat between it and the reef edge, and 3.45 ft above the level of the reef edge algal platform. (2) A large patch 800 metres to the northwest, 220 metres from the seaward reef edge, location 0958-0966/1486-1500, rising at its highest 4.3 ft above the surrounding reef flat. (3) Two small patches of rock, the largest 35 x 23 metres, approximately the same distance from the reef edge, with a similar height, location 091143. (4) A small patch of rock standing 3 ft above the reef flat approximately 30 metres to the northwest. (5) A much larger patch, the first of a series, location 089142, which continue towards the northwest and form the basis of several of the small islands on the seaward side of Fedu, as described by Sewell. (6) Two small patches, location 095139, close to the southeast shore of Fedu, drying up to 2 ft at low water, marked on the Admiralty chart as "drying 4 ft." In all these cases the rock surface is deeply pitted and eroded, and in cases 1 and 2 it has also been damaged by military activity. The rock is formed of coral fragments in a coral sand matrix, and in places is dominantly sandy.

(iii) Cay sandstone

The Maldive Islands form a classic area for the description of cay sandstone. Moresby (1835, 398) described subsurface induration of sands at a depth of 3-4 ft, forming a layer 2 ft thick overlying unconsolidated sands, at the freshwater table, at Miladumadulu Atoll. Sewell (1935a, 502-3) described a similar occurrence at Maradu Island, Addu Atoll, and also figured a section at Fehendu Island, Goifurfehendu Atoll (cf. Sewell 1936b), where a layer of sandstone 1½ ft thick underlies 2-3 ft of surface sands and soil, well above high water level.

Cay sandstone is well exposed on the west and southwest shores of Gan, where it forms a nearly horizontal ledge or platform several feet wide on the upper part of the beach. The rock is generally 1-2 ft thick:

its base is dry at low water, but its upper surface is covered by swash at high tide. Its seaward edge forms a vertical or overhanging scarplet, which is being eroded by transverse gullying, by local undermining and wave action, and by the dislodgment of sections several metres long because of longitudinal fracturing. Inland the rock passes under the beach, and at one point outcrops in the eroded beach face to a height [illegible] inches higher than the platform, suggesting that the upper surface of the rock may itself be erosional. The rock is poorly bonded and may generally be crumbled in the fingers at fresh sections; at the outcrop it is casehardened and tougher. It lacks internal structures in bedding or grain size sorting, and is essentially horizontal.

Cay sandstone outcrops on the west shore, as recorded in beach profiles 76, 77, 78 and 79. These are all low-angle beaches (gradients 1 in 10 to 1 in 15), the beach crest rising 5 ft above the immediate offshore flat. Cay sandstone outcrops 1.3-2.5 ft below the beach crest, forming a platform 2.3-5.6 metres wide, and 1-1.5 ft thick. On the southwest shore, cay sandstone outcrops are shown in beach profiles 92, 95, 96, 98, 99 and 100. Beach gradients here range from 1 in 5 (where there has been considerable steepening as a result of erosion) to 1 in 16. The height of beach crests above the flat ranges from 5 to 9 ft. The sandstone outcrop is 1-6.4 metres wide; it passes landward beneath unconsolidated beach sands which form a vertical scarplet up to 2.5 ft high. The outer edge of the rock platform forms a scarplet 0.5-2 ft high. The height difference between the sandstone platform and the beach crest depends on the amount of human interference with the latter: at its greatest, where the erosional sand scarp is highest, the platform is 3.3-4 ft below the beach crest. Elsewhere it may be only 1-2 ft. Profile 99 shows the rock with a maximum thickness of 3.4 ft; generally it is 0.5-2 ft. The surface of the platform is often tilted slightly seawards, but at a very much smaller angle than intertidal beachrock.

No outcrops of cay sandstone were seen at Hitaddu, but Sewell describes outcrops of similar rock on the lagoon beach at Heratera (Sewell 1936a, 76, Plate 4iii).

(iv) Beachrock

Intertidal beachrock has been classically described from the Maldive Islands by Gardiner (1903, 341-346, Plate 16), and its characteristics are now well known. Gardiner insisted on its intertidal character (1903, 343), and this appears to be a useful field criterion for beachrock identification. Beachrock is uncommon on Addu beaches, where it must not be confused with outcropping beach sandstone on the upper beach face, exposed by beach retreat. Outcrops of beachrock are found in two places on the Gan beaches, the largest being at the northwest point (1014/1367). Three lines of beachrock continue the trend of the north shore towards the deeply scoured Gan Channel. The rock is eroded and discoloured by algae, the outer line blackened, the inner lines grey and brown, but by contrast with the Caribbean, larger algae such as *Turbinaria* are absent, doubtless because of the high tidal range. The beachrock is shown in beach profiles 72 and 73. The lowest seaward part of the beachrock stands 1.5 ft above the level of the lagoon reef flat, at this point a hard planed rock floor; the highest landward part of the beachrock stands 4 ft above the flat and 3.5 ft below the beach crest. Low tide level approximates to its lowest extent, and the rock is submerged at high tide. The three lines of beachrock all dip seawards: the innermost at 3°40', the second at 5°36', and the outermost at 6°30'. They are separated by scarps 1-1.4 ft high. At its westernmost extent the beachrock is being undermined by current scouring in the Gan channel, and several slabs have been broken transversely and have fallen into scour holes. At the end of the beachrock the channel floor lies 4 ft below the beachrock surface, and as a result of this scouring there is a secondary longitudinal tilt in the exposure.

Possible massive beachrock outcrops on the north shore of Gan, (a) immediately west of the marine jetty (1060/1394), where it has been much altered by man, and (b) in four small patches at the eastern end of the north shore (124144), where it is difficult, however, to distinguish it from possible cay sandstone on morphologic grounds. Similar difficulty is also experienced with some of the outcropping rocks figured by Sewell at Goifurfehendu Atoll (Sewell 1936b). Unmistakable beachrock was not seen at Hitaddu, though a lagoon beach exposure south of the jetty may be so classed. Gardiner also reports beachrock on the seaward beach at Midu (Gardiner 1903, 417).

The Gan beachrock consists of sedimentary particles similar to those of the adjacent beach, showing vertical sorting into distinctive layers dipping seawards, which helps to differentiate it from cay sandstone. The constituent particles show evidence of solution, and the rock has been secondarily cemented to an extremely tough and hard character.

Problems

The problems posed by the Addu lithified sediments may be briefly stated. The nature of the relict "reef rock" is of critical importance in the geomorphic history of the atoll. Gardiner and Sewell supposed it to be a true submarine reef rock exposed by relative elevation, but it is also possible that it has been formed by lithification of coarse island clastic sediments at its present elevation and exposed by beach retreat, as Newell suggests in the Tuamotus (Newell 1961). Bearing on this problem is the generally unsorted nature of the constituents and the imbrication of coral slabs at Hitaddu. Even though there is no evidence of corals being found in the rock "in the position of growth", as Gardiner observed at Minikoi and elsewhere, this seems to indicate a subtidal origin, implying a relative shift of sea level. The widespread nature of similar exposures elsewhere in the Maldives and in the Indian Ocean generally (Sewell 1935a, 474-479; 1932, 1928) would also lend support to a negative eustatic shift in explanation of these raised features. It is interesting in this connection that Shepard (1963, 5) has obtained a radiocarbon date of 2990 ± 220 yrs B.P. from a raised reef 2-3 ft above low tide level in Ceylon, although comparable Pacific and Australian features have yielded considerably older dates. At Gan the rock has been subject to considerable alteration by erosion, and is probably undatable. However, samples of reefrock underlying the present flat should give significant results: if near-surface samples are very old, they may indicate antiquity and subsequent planation of the flat, from which the higher fragments of reefrock rise as erosional remnants; but if young, it will be difficult to attribute the relict rock to any major eustatic shift of sea level.

The nature of the cement in the cay sandstone and the intertidal beachrock is of interest. If, as seems likely, the cay sandstone is a freshwater rock and the beachrock marine, the primary cements should be calcite and aragonite respectively (Stoddart and Cann 1965). In the case of the Gan beachrock, however, solution may have gone too far for the primary cement to be determined. Alternatively, if the beachrock cement is calcite, this will add further evidence to Russell's theory of beachrock origin at the freshwater table under beaches (Russell 1962). A major problem is why rock of one sort is developed on a particular island, rather than another. At Gan, cay sandstone is the dominant lithified material, whereas at Cocos-Keeling Russell and McIntire (1965) report massive beachrock.

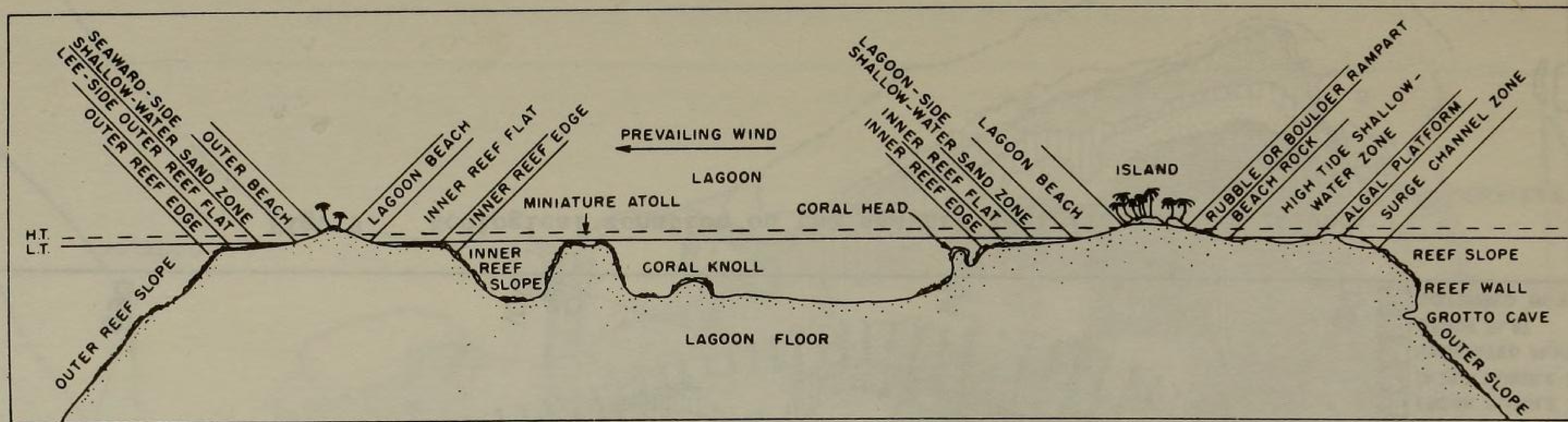

Fig. 7. Zonation of Maldivian reefs, after Eibl-Eibesfeldt (1964).

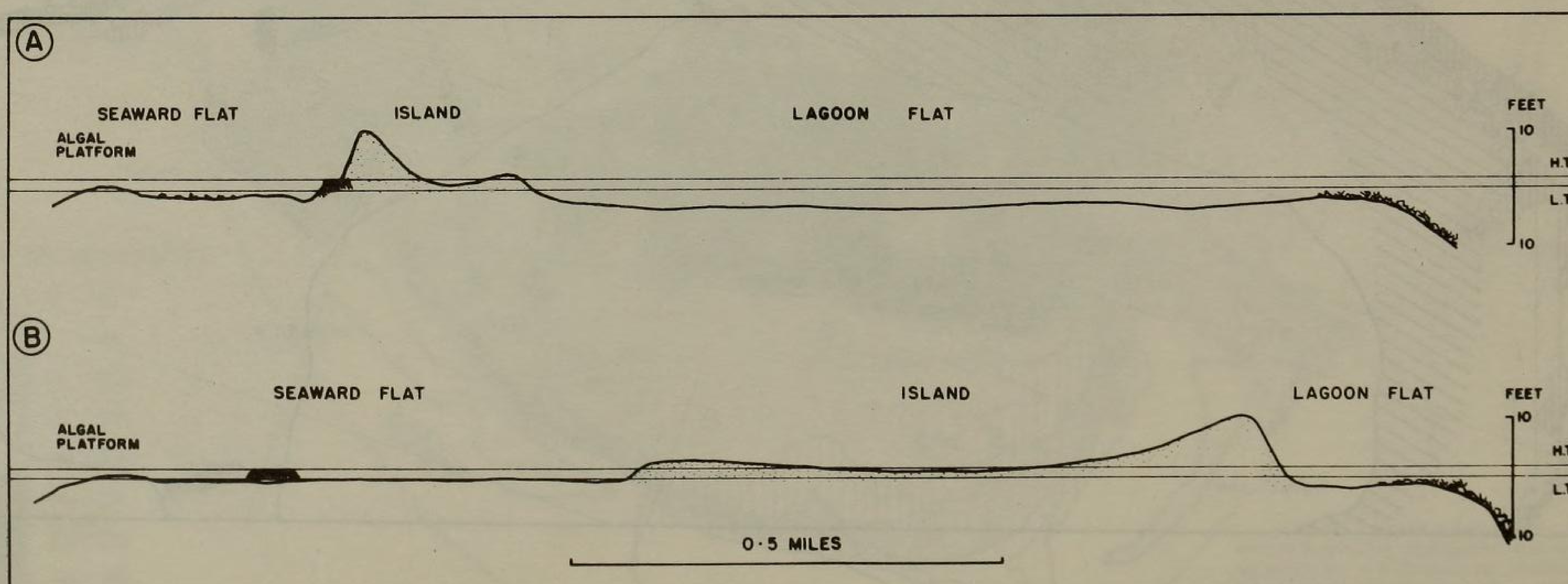

Fig. 8. Diagrammatic cross-section of peripheral atoll reefs at (A) Hitaddu and (B) Gan Islands, Addu Atoll.

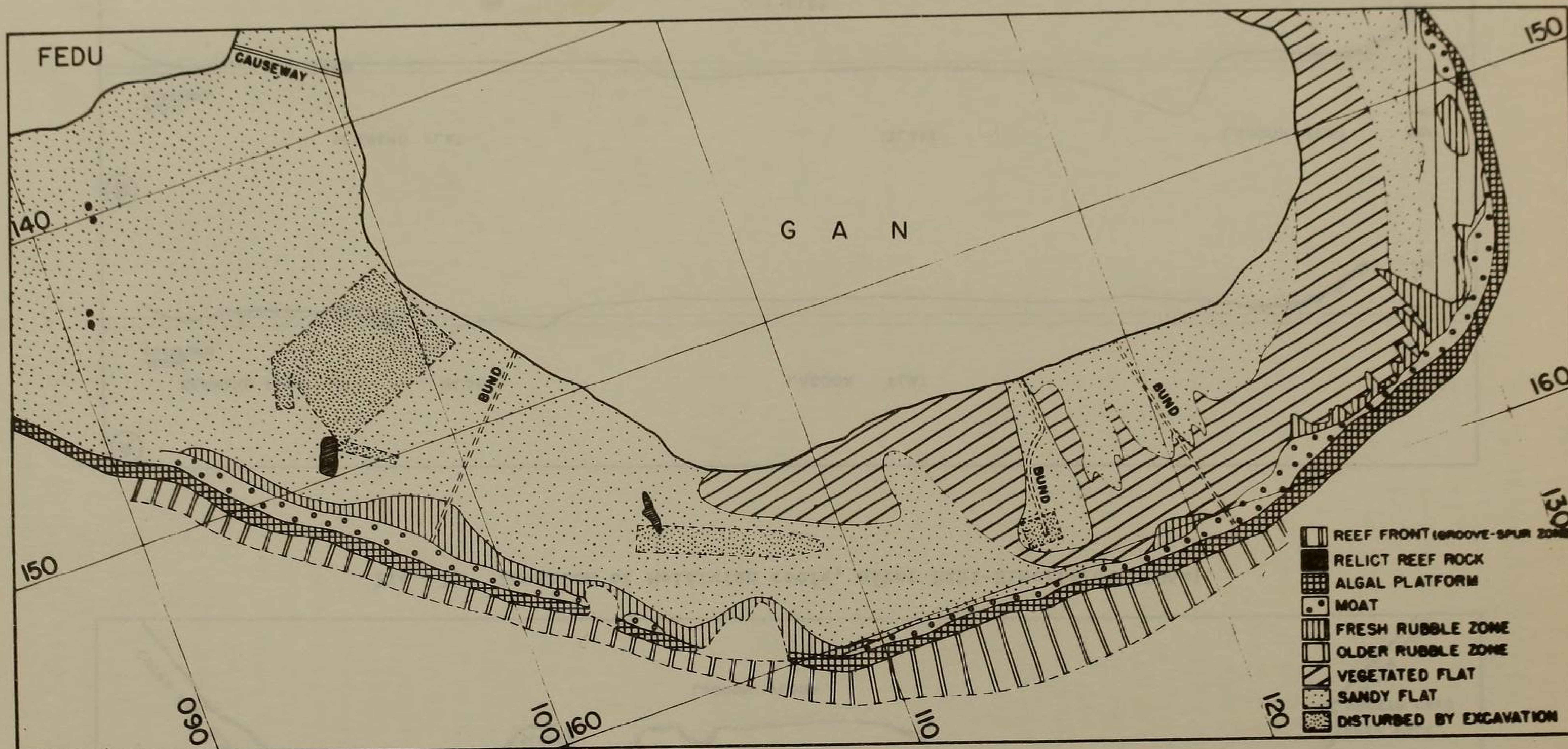

Fig. 9. Ecological zonation on the seaward reef flat at Gan Island

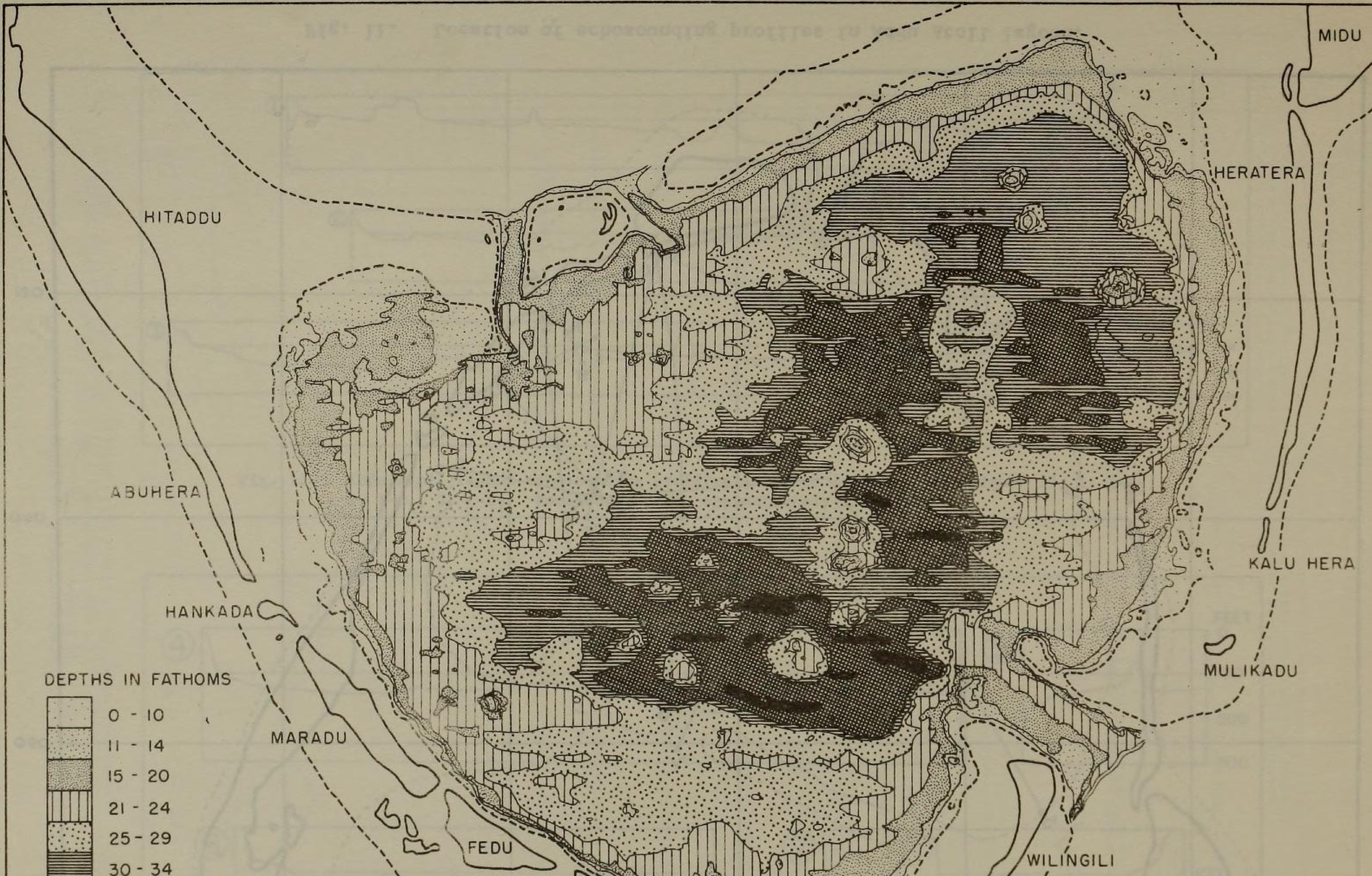

FIG. 10. LAGOON FLOOR OF ADDU ATOLL. BOTTOM TOPOGRAPHY REPRODUCED FROM ORIGINAL DOCUMENT No. C.9155 WITH THE PERMISSION OF THE HYDROGRAPHER OF THE NAVY, BASED ON 18,000 SOUNDINGS BY COMMANDER E.H.DAUGLEISH, R.I.M.S. INVESTIGATOR, 1923; CONTOURED BY D.R. STODDART, 1964. REEF AND ISLAND TOPOGRAPHY FROM AIR PHOTOGRAPHY OF 1958 AND 1960 AS PLOTTED ON CHART No. 2067(1964), REPRODUCED WITH THE PERMISSION OF THE CONTROLLER OF H.M.STATIONERY OFFICE AND OF THE HYDROGRAPHER OF THE NAVY.

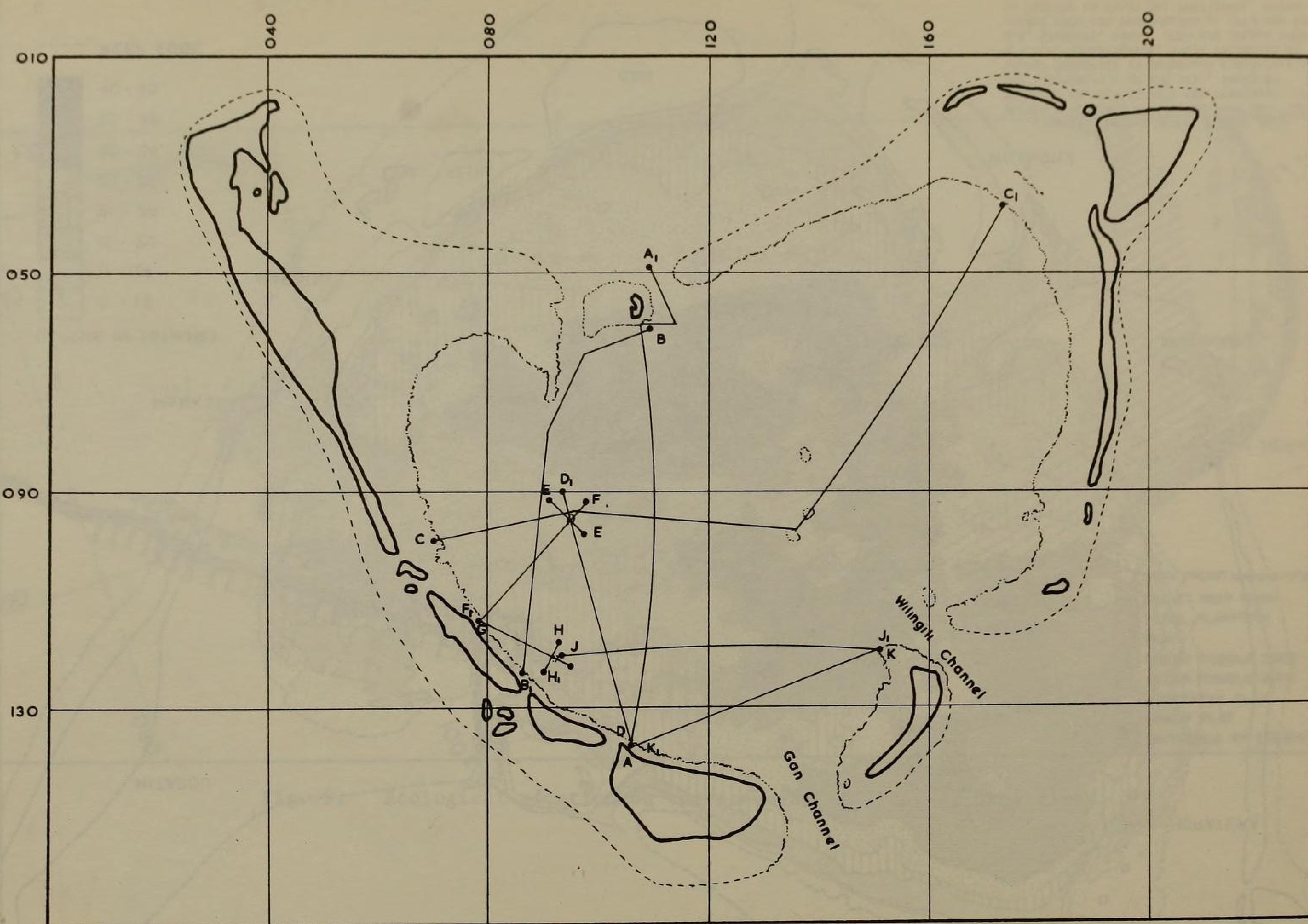

Fig. 11. Location of echosounding profiles in Addu Atoll lagoon.

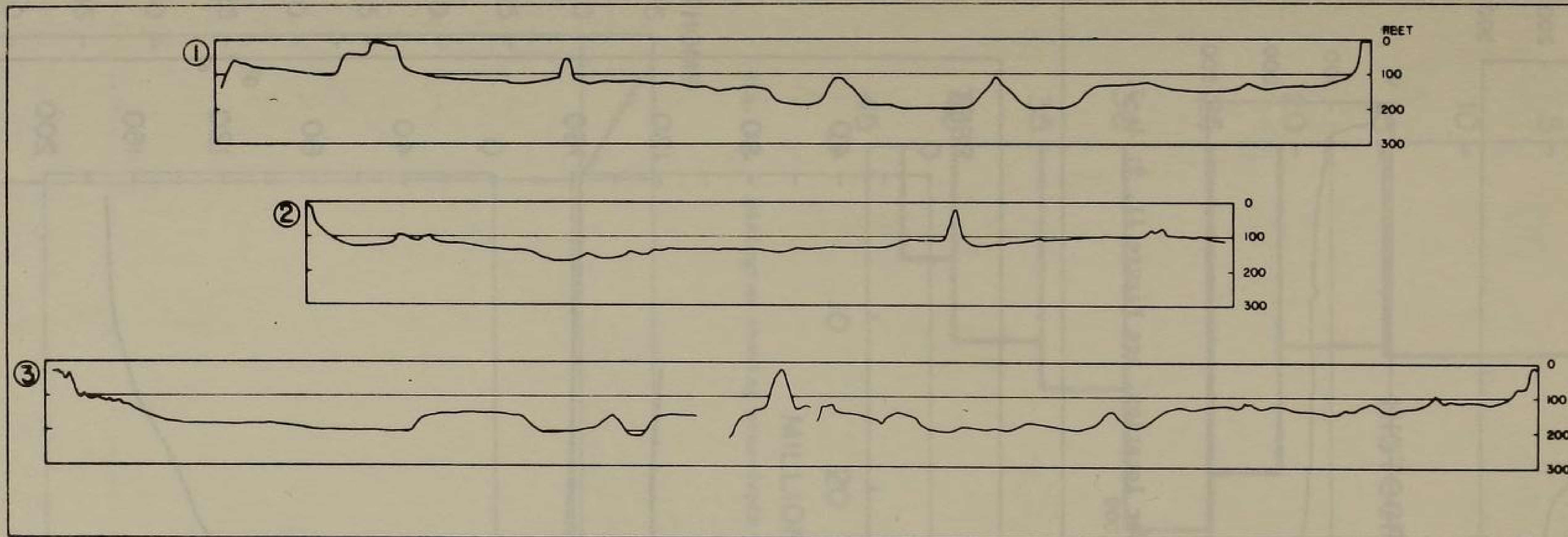

Fig. 12. Addu Atoll lagoon echosounding profiles 1-3; for location, see Figure 11, 1: $A-A_1$; 2, $B-B_1$; 3, $C-C_1$. Horizontal scale approximately 1:55,000

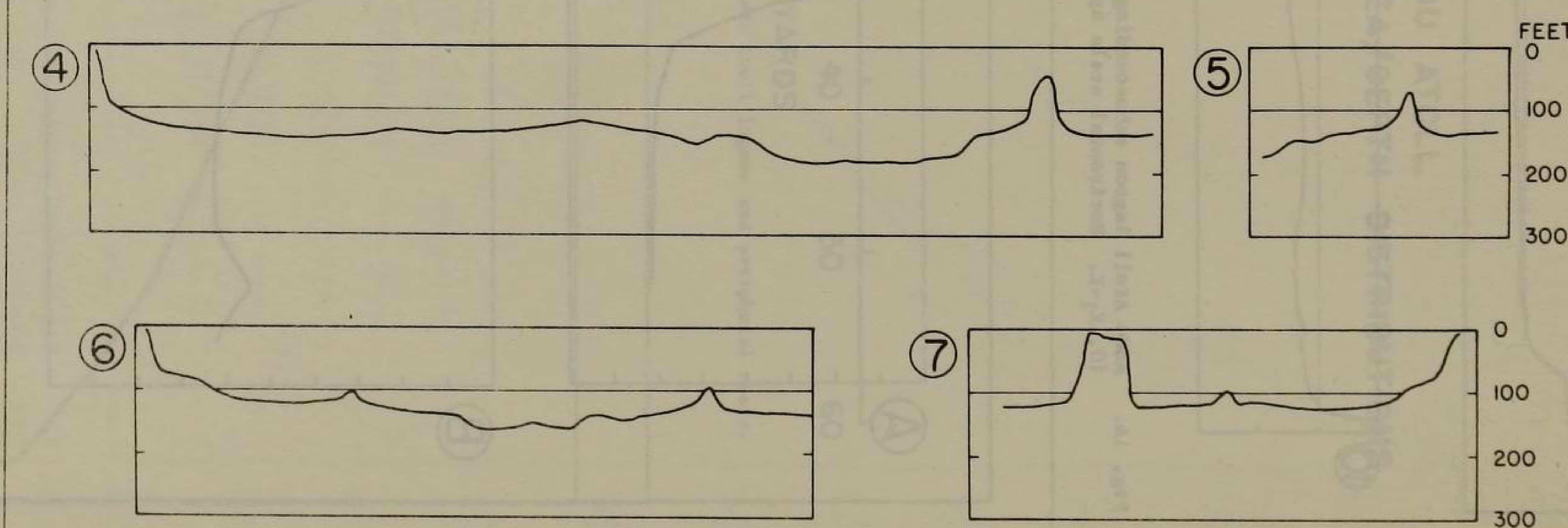

Fig. 13. Addu Atoll lagoon echosounding profiles 4-7; for location, see Figure 11, 4: $D-D_1$; 5: $E-E_1$; 6: F_1-F; 7: G_1-G. Horizontal scale approximately 1:28,000

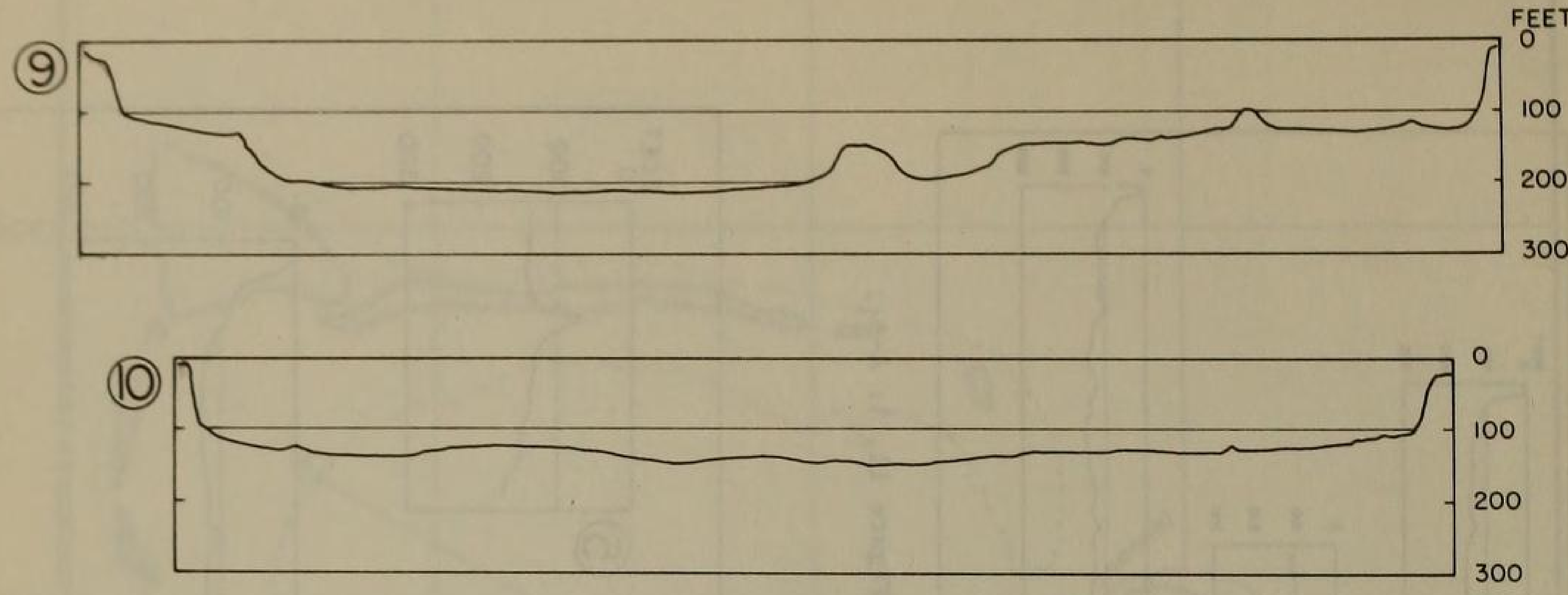

Fig. 14. Addu Atoll lagoon echosounding profiles 9-10; for location, see Figure 11, 9: J_1-J; 10, K_1-K. Horizontal scale approximately 1:27,000

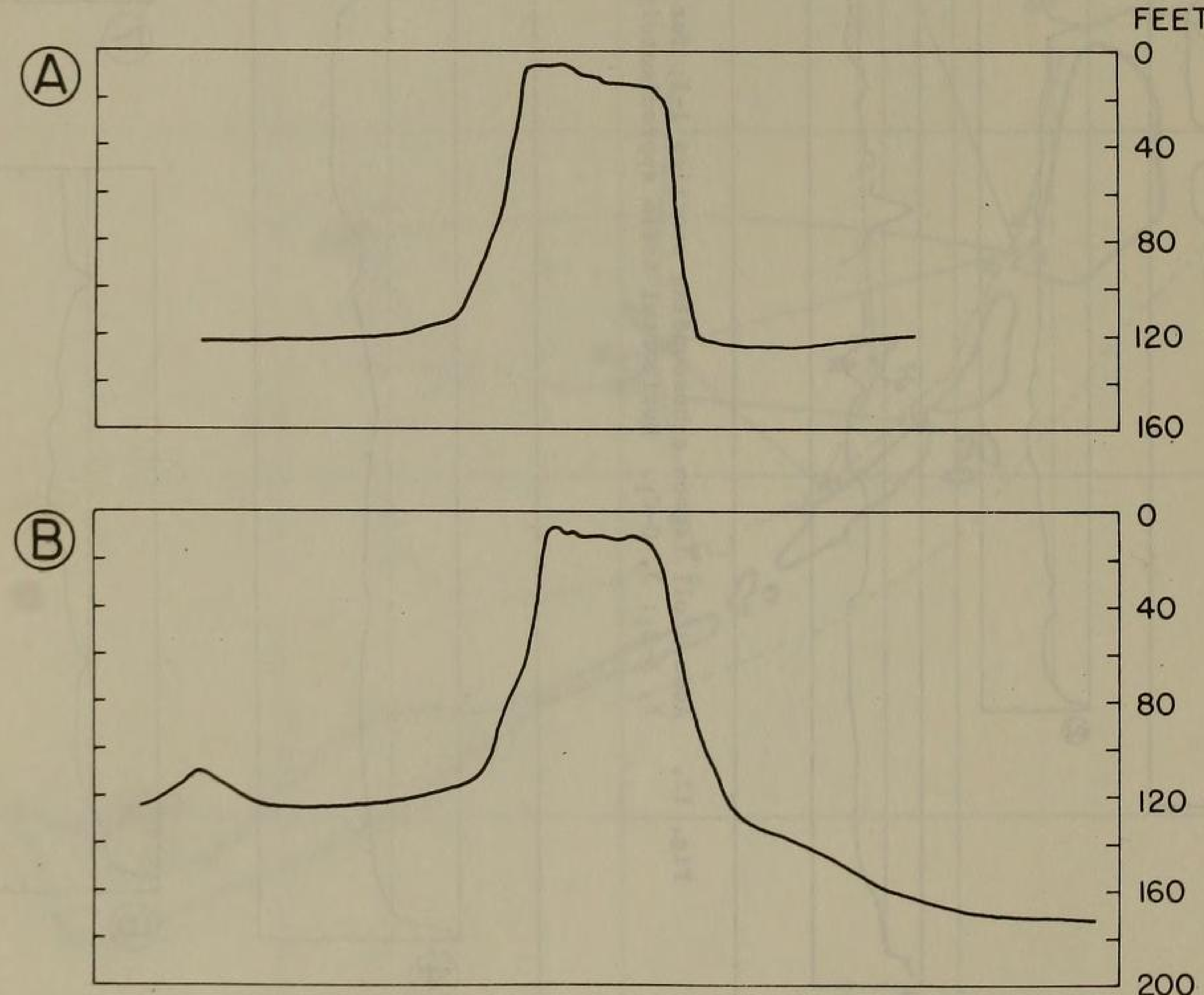

Fig. 15. Echosounding profiles of lagoon patch reef 24: (A) from profile 7, (B) from profile 8. For location, see Figure 11, A: G_1-G; B: H-H_1. The diameter of the summit is approximately 220 metres.

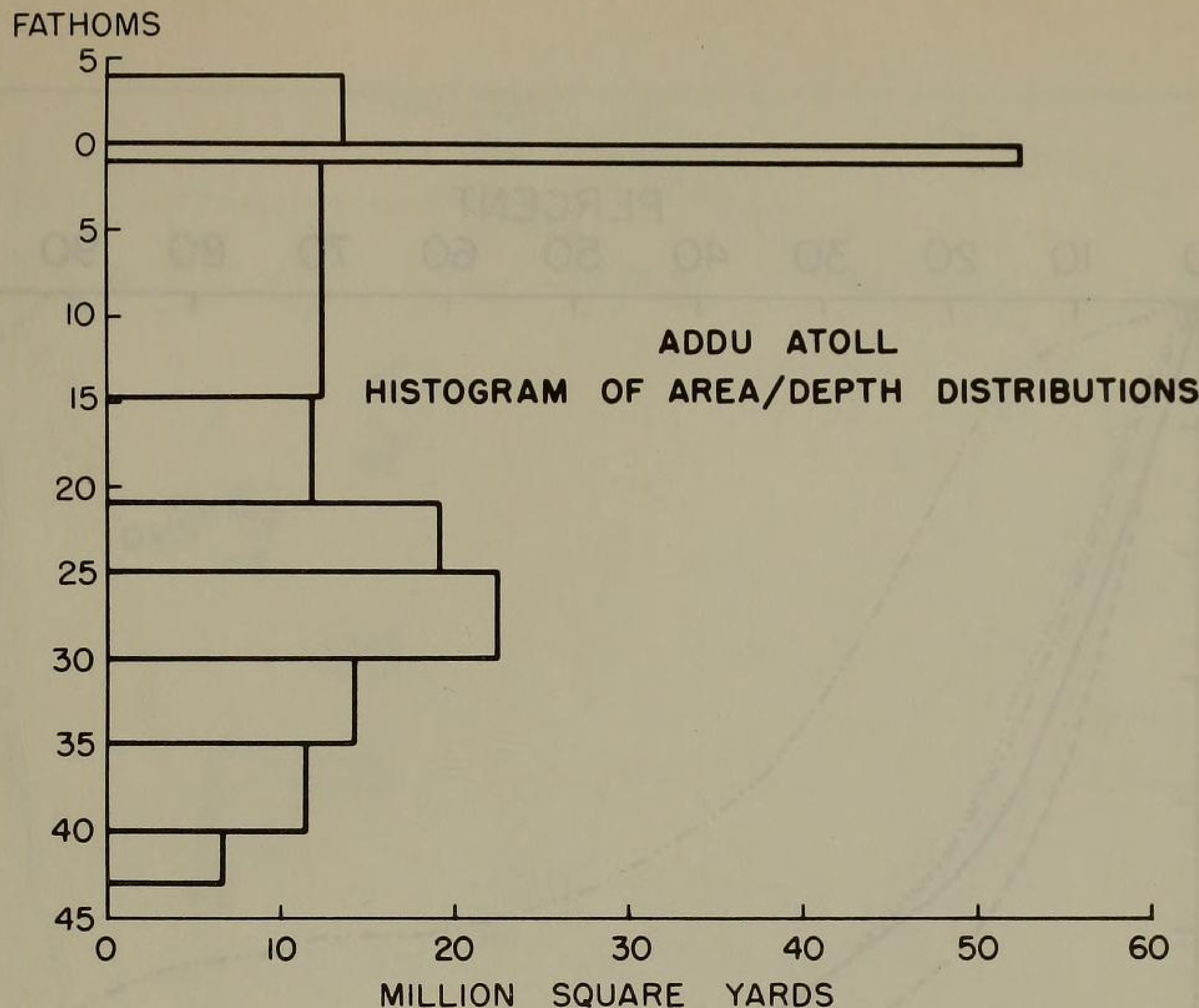

Fig. 16. Histogram showing area-depth distributions in Addu Atoll lagoon and peripheral reefs.

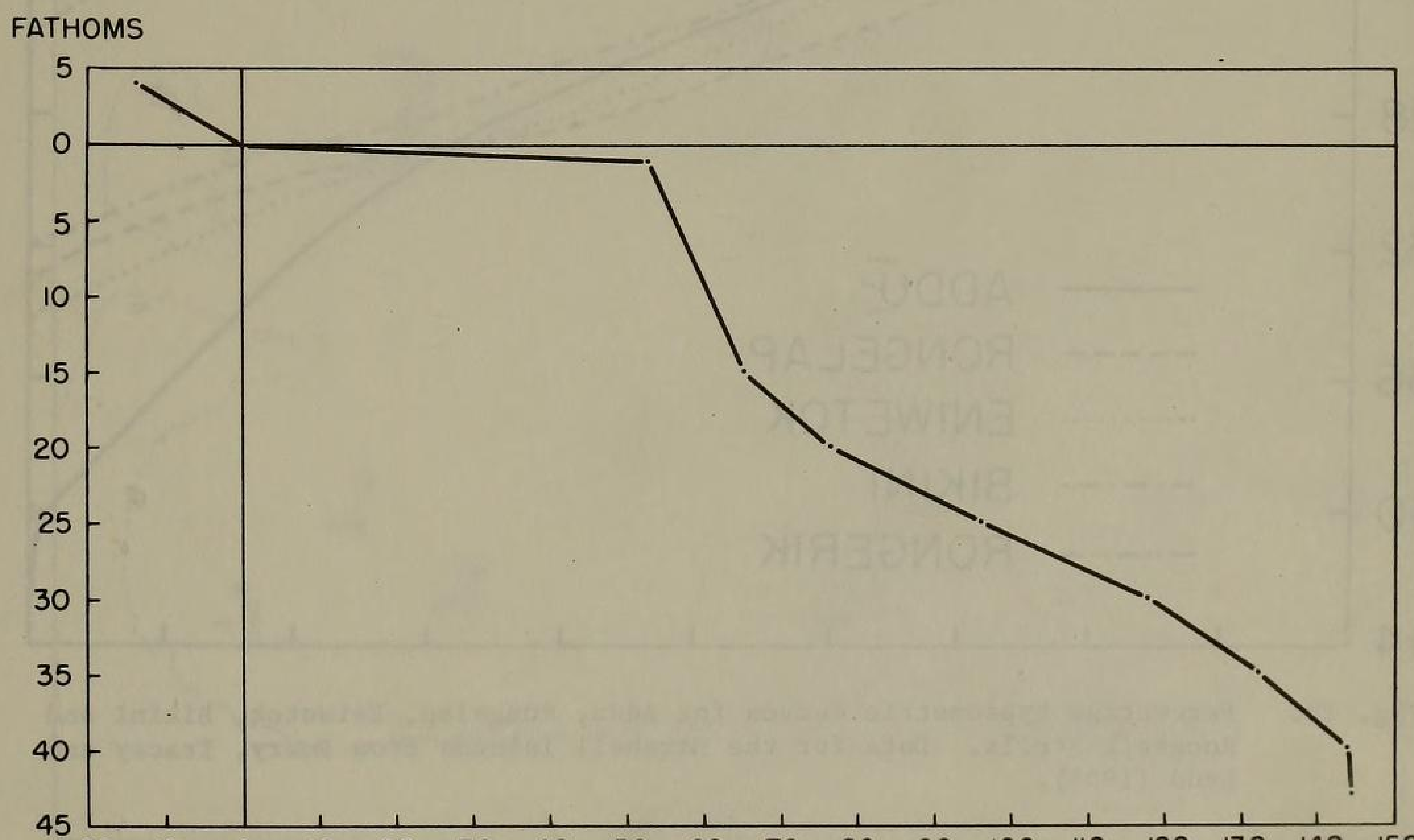

Fig. 17. Hypsometric curve for Addu Atoll lagoon and peripheral reefs.

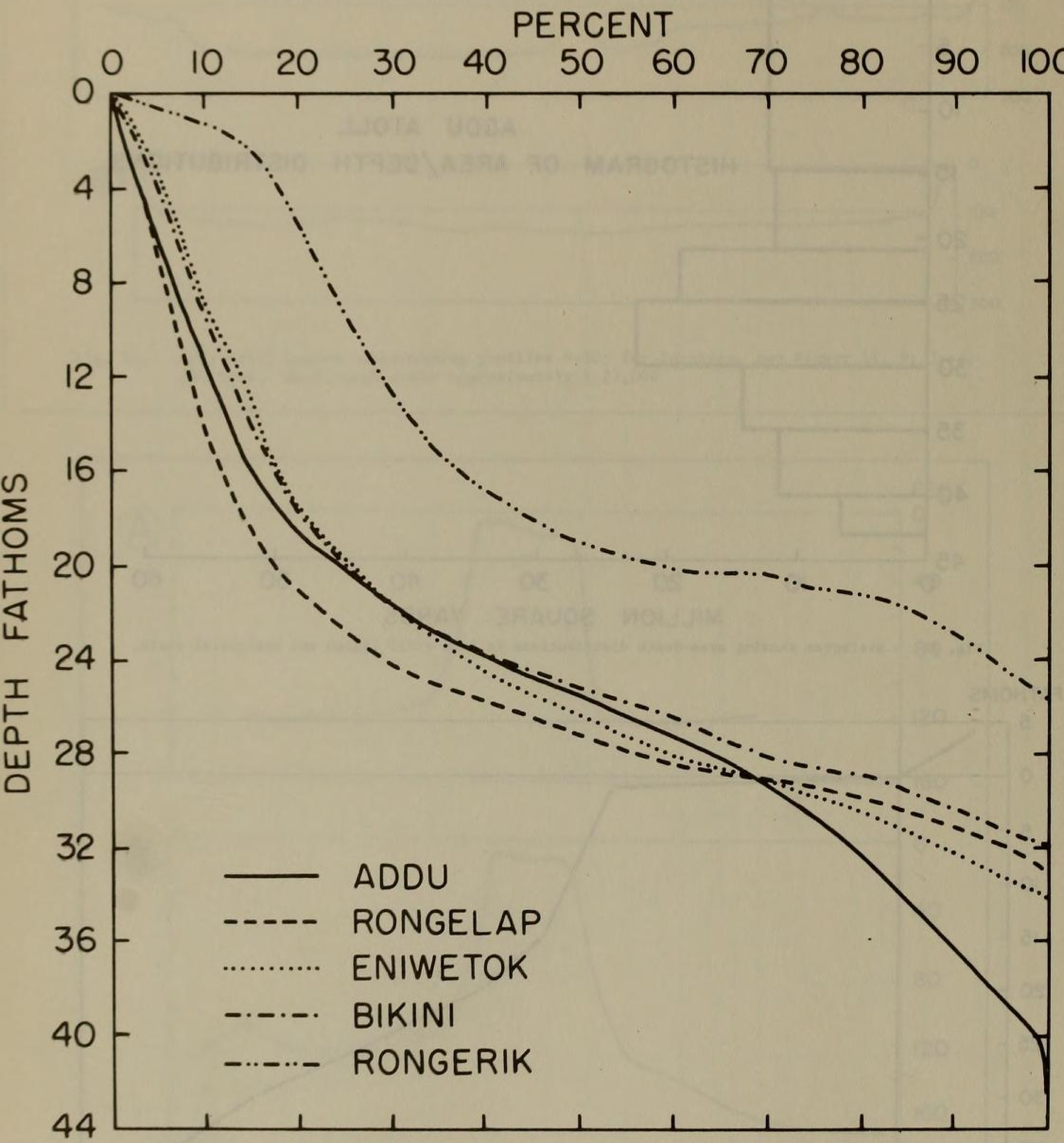

Fig. 18. Percentage hypsometric curves for Addu, Rongelap, Eniwetok, Bikini and Rongerik Atolls. Data for the Marshall Islands from Emery, Tracey and Ladd (1954).

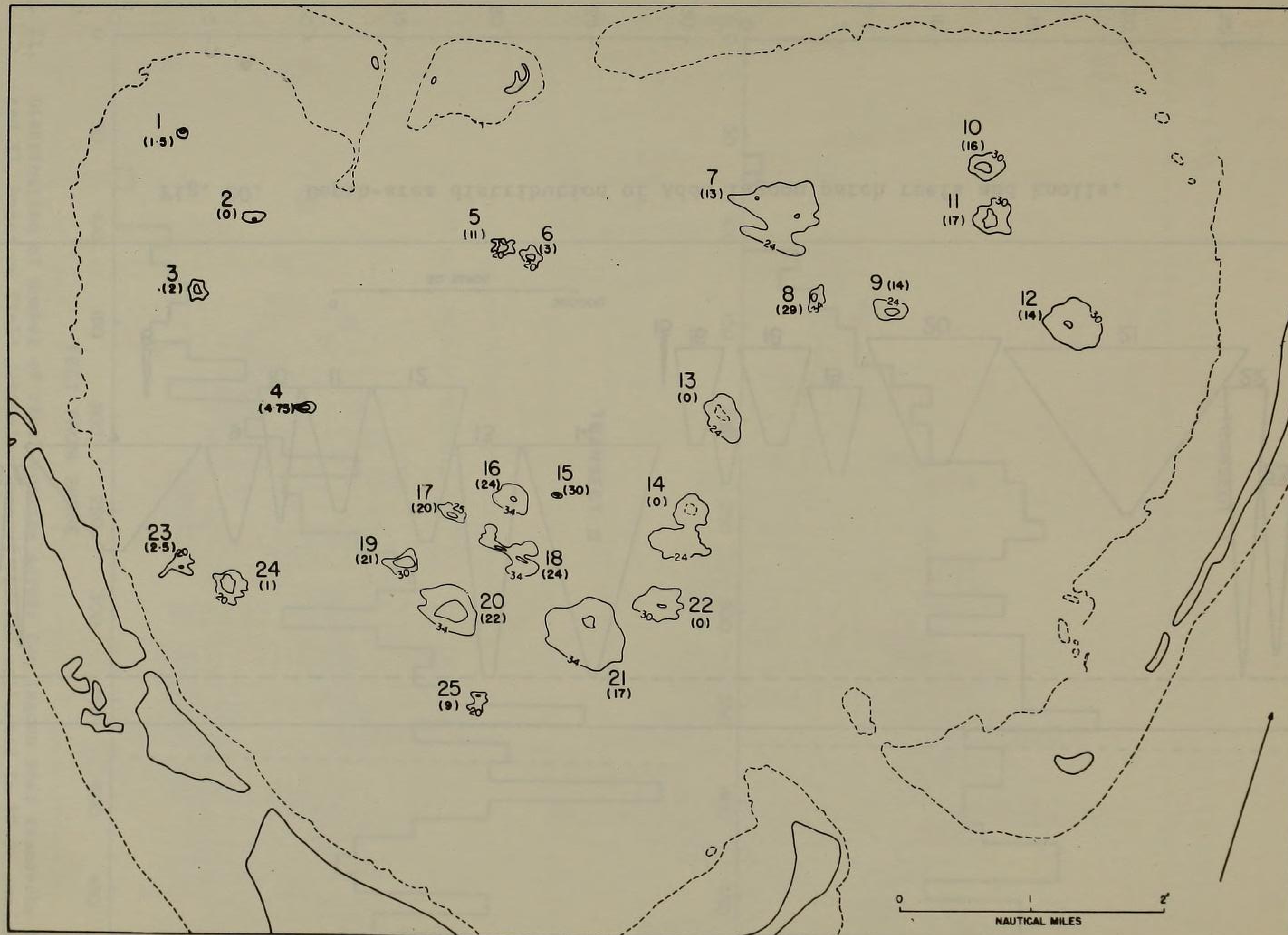

Fig. 19. Location and index numbers of Addu Atoll lagoon patch reefs and knolls, defined by their lowest closed contour. The small figure in brackets is the minimum recorded summit sounding. Based on the chart by Daugleish (1923).

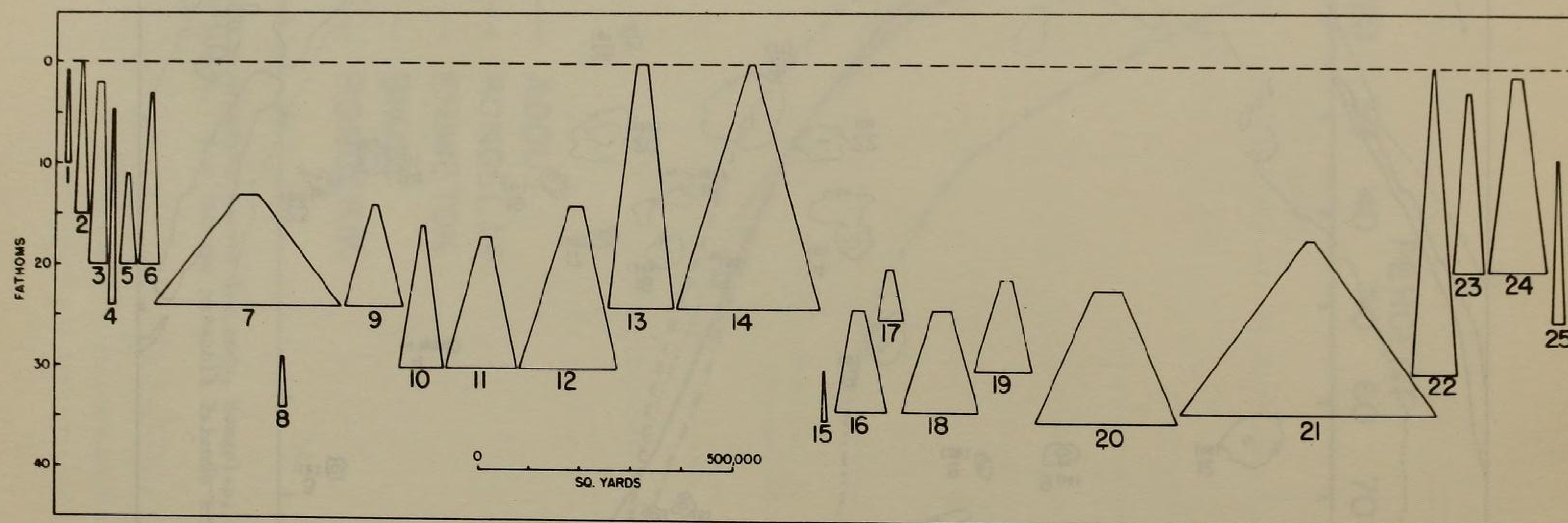

Fig. 20. Depth-area distribution of Addu lagoon patch reefs and knolls.

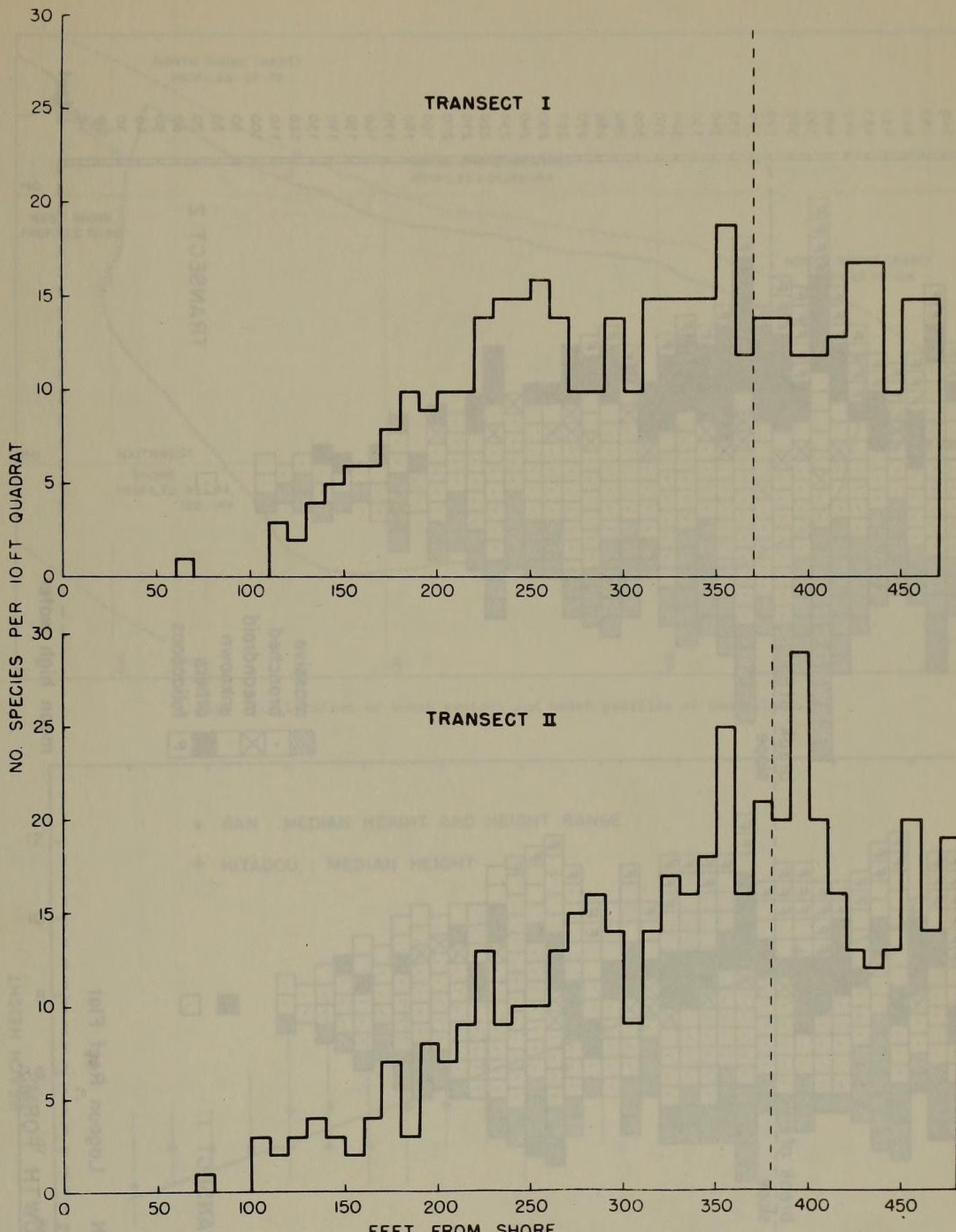

Fig. 21. Distribution of number of coral species across Gan lagoon reef transects I and II, based on field determinations of species collected in 10 ft quadrats.

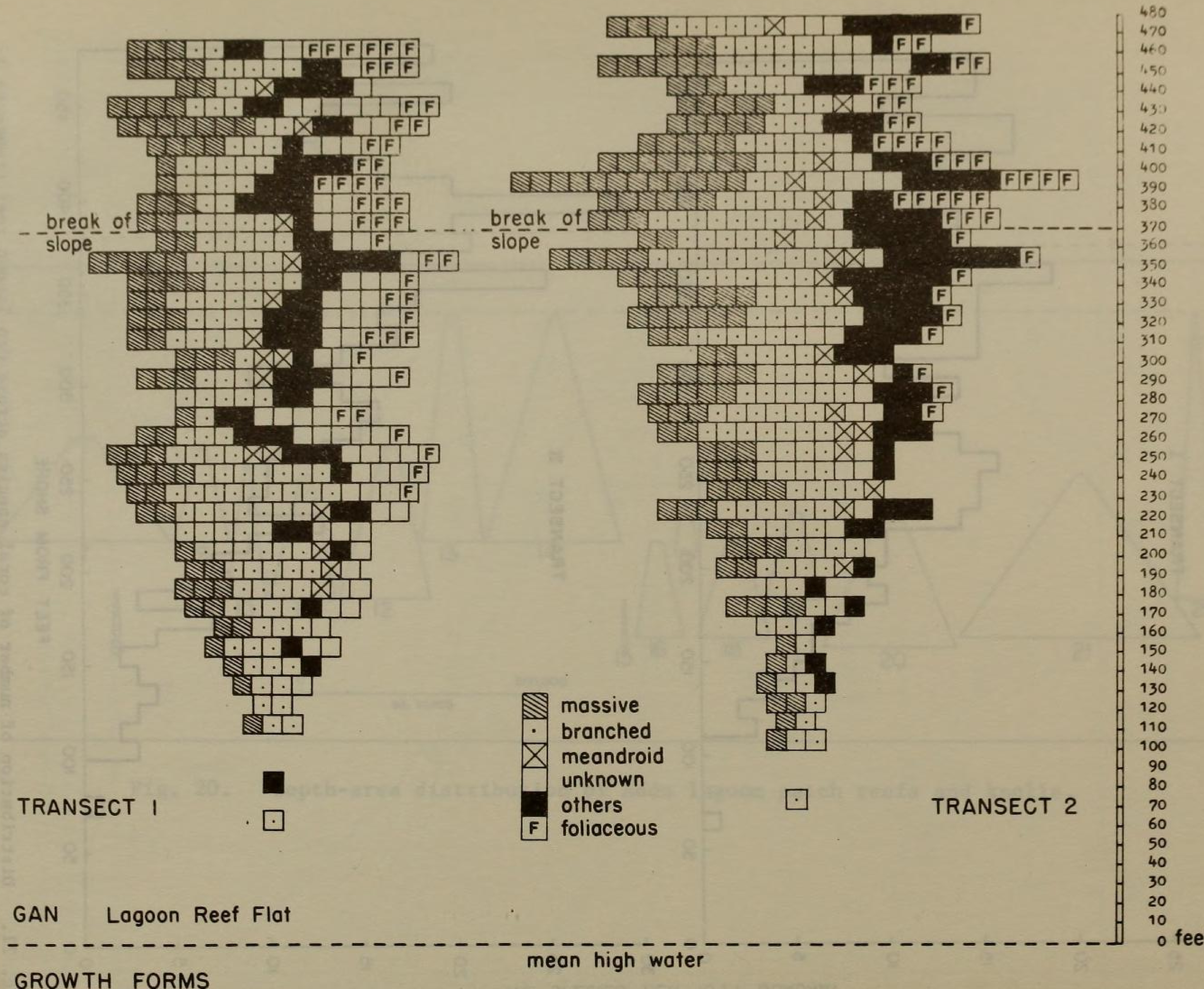

Fig. 22. Distribution of growth form of corals across Gan lagoon reef transects I and II.

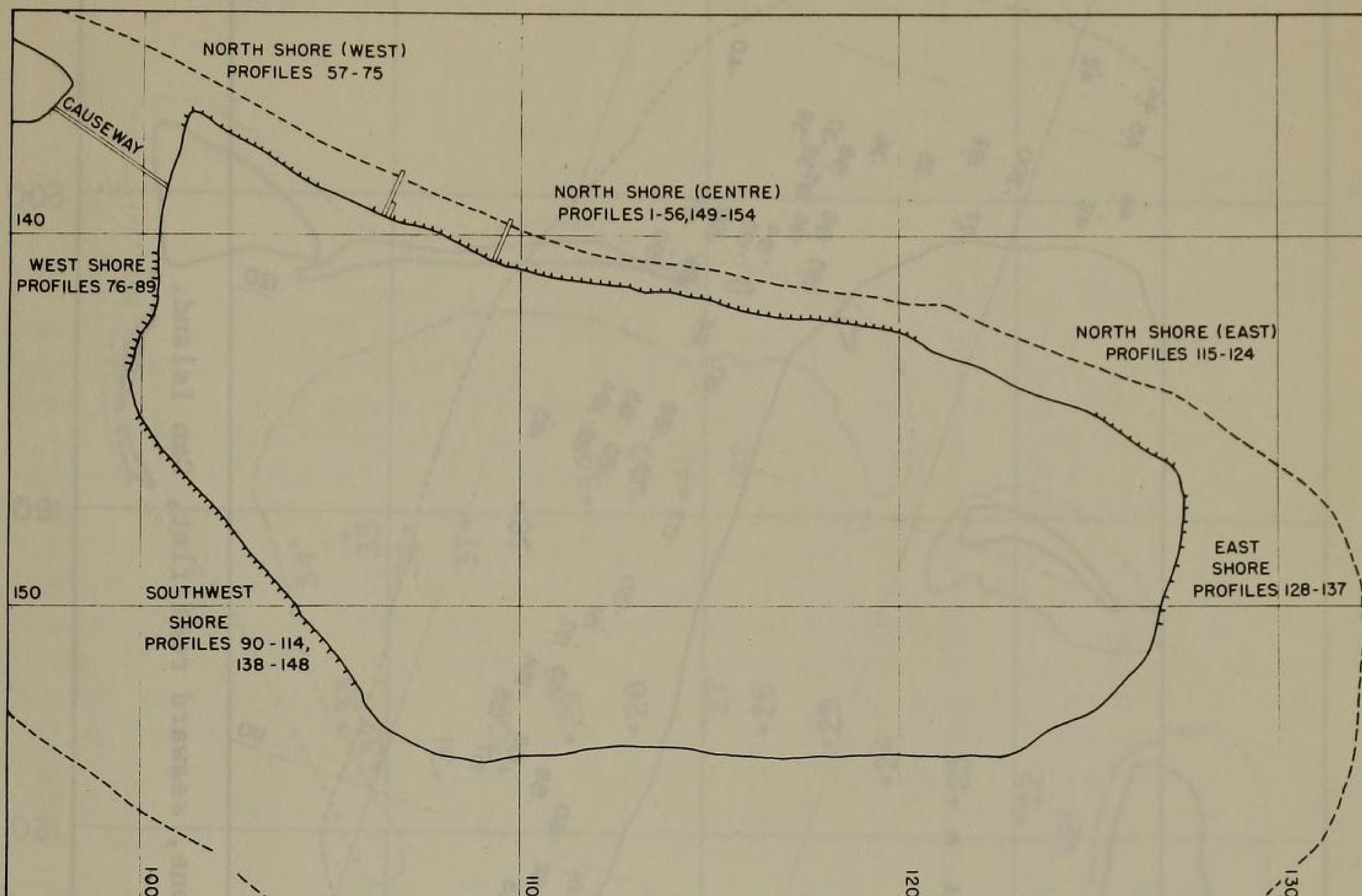

Fig. 23. Location of beach sectors and beach profiles at Gan Island.

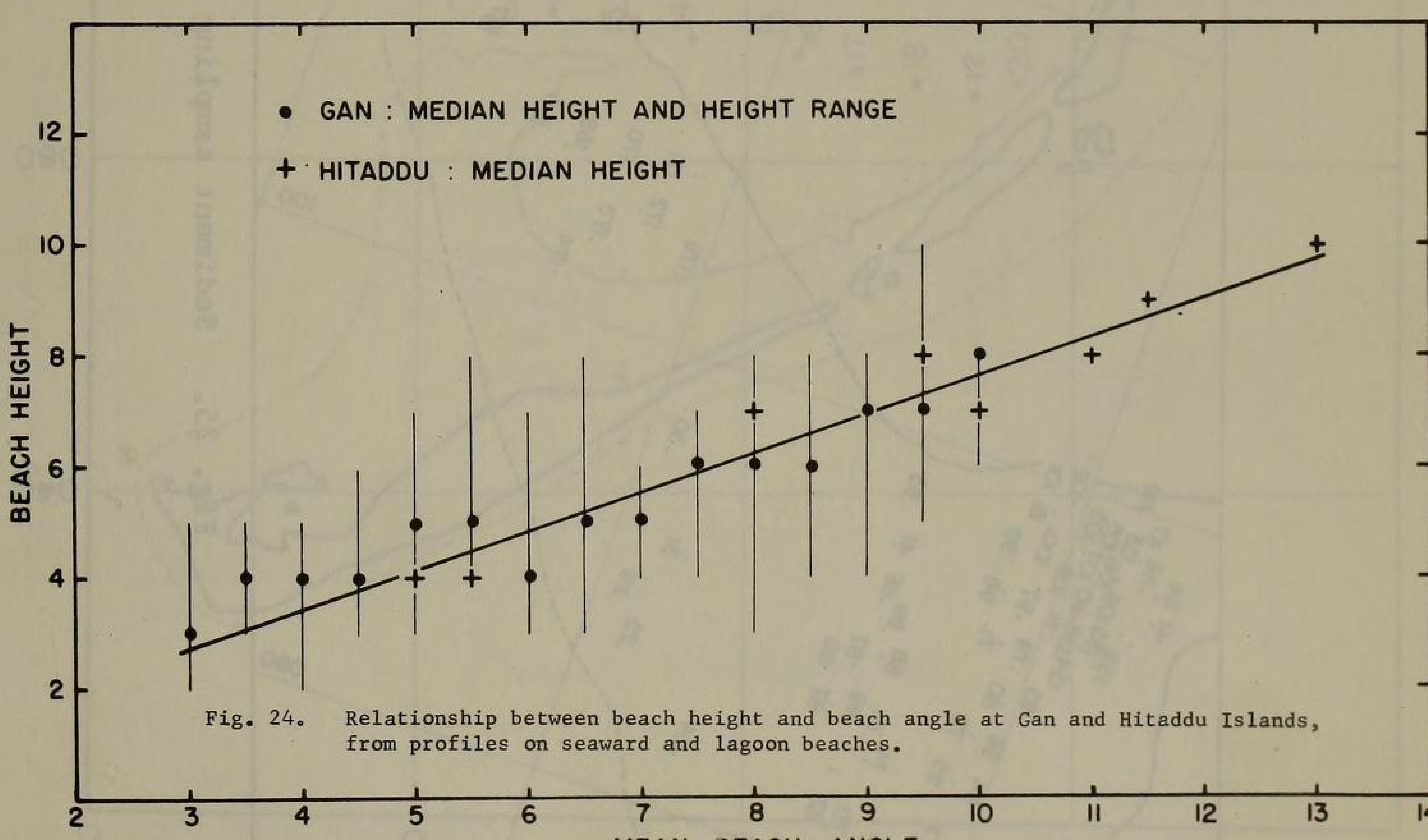

Fig. 24. Relationship between beach height and beach angle at Gan and Hitaddu Islands, from profiles on seaward and lagoon beaches.

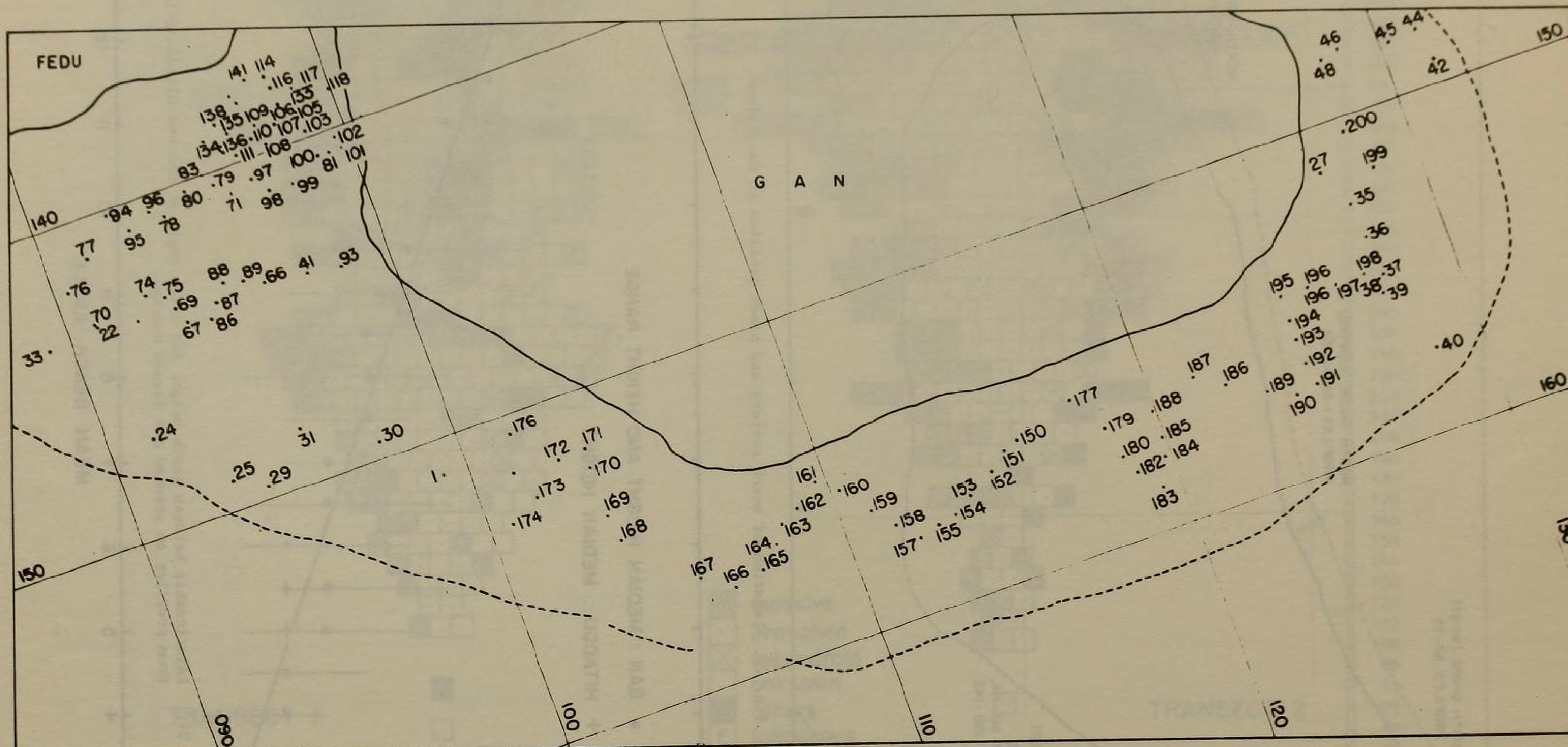

Fig. 25. Sediment sampling stations, seaward reef flat, Gan Island.

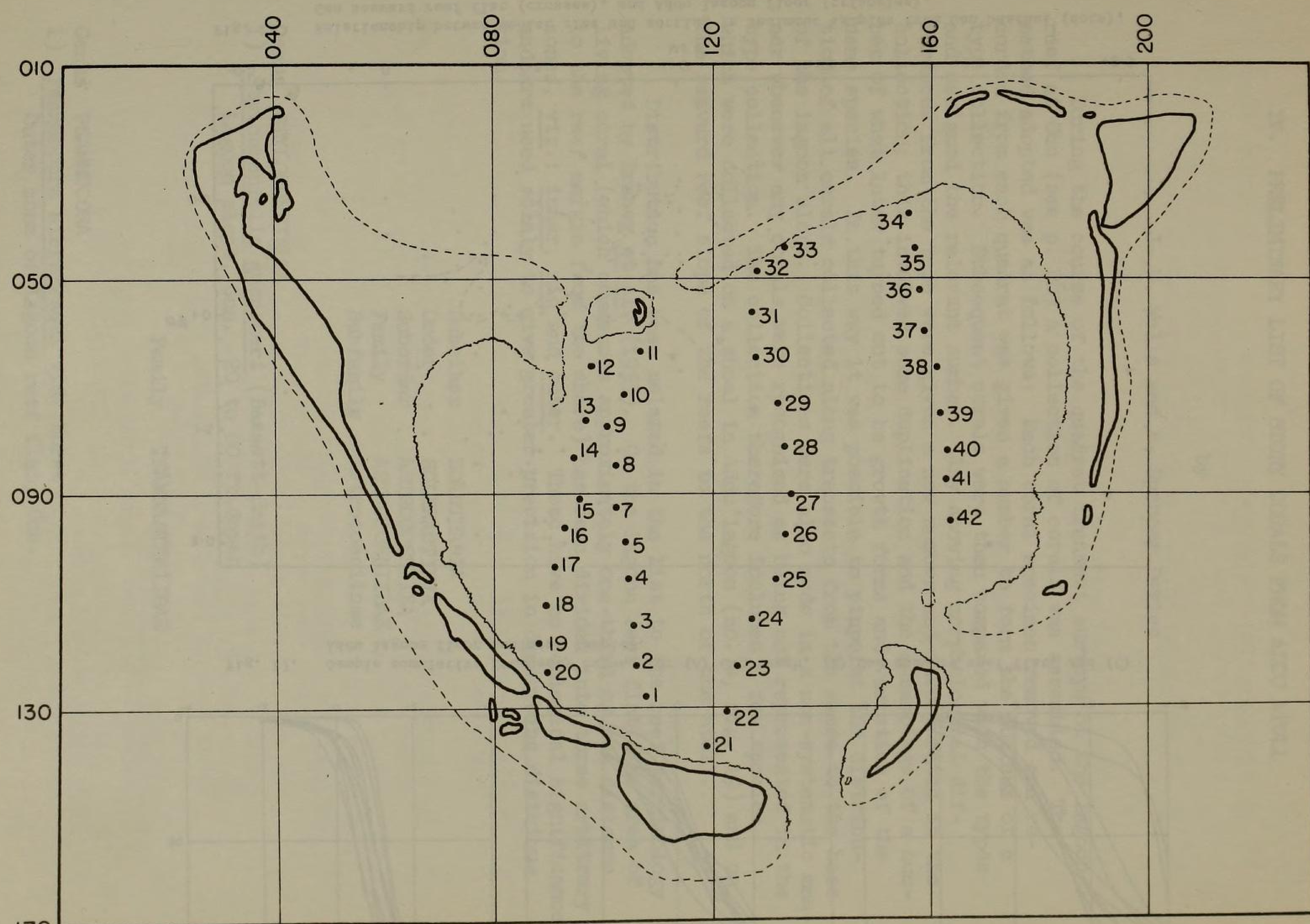

Fig. 26. Sediment sampling stations, lagoon floor, Addu Atoll.

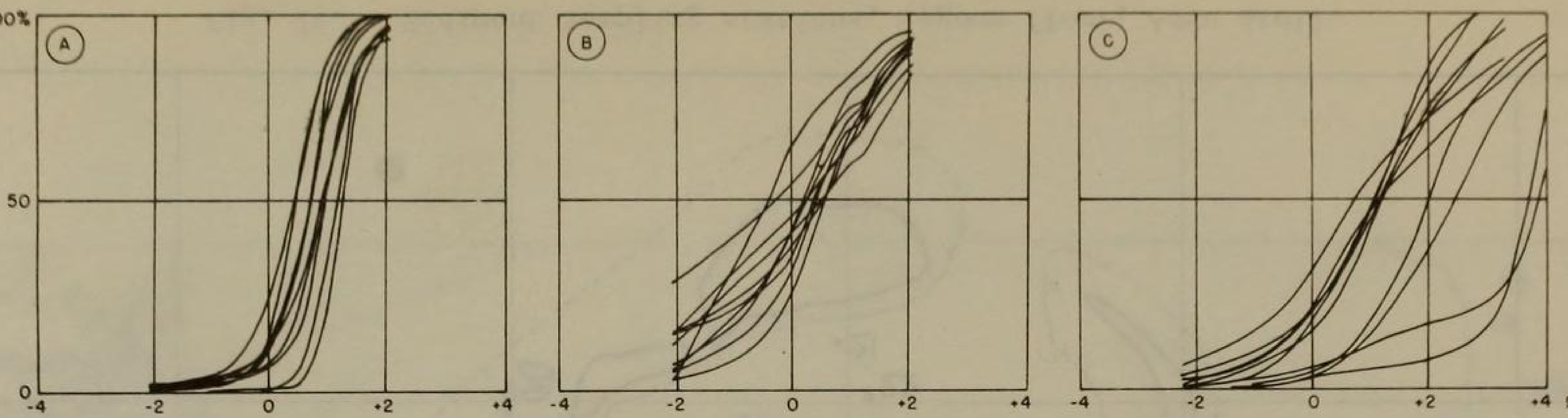

Fig. 27. Sample cumulative frequency curves for (A) Gan beach, (B) Gan seaward reef flat, and (C) Addu lagoon floor sediment samples.

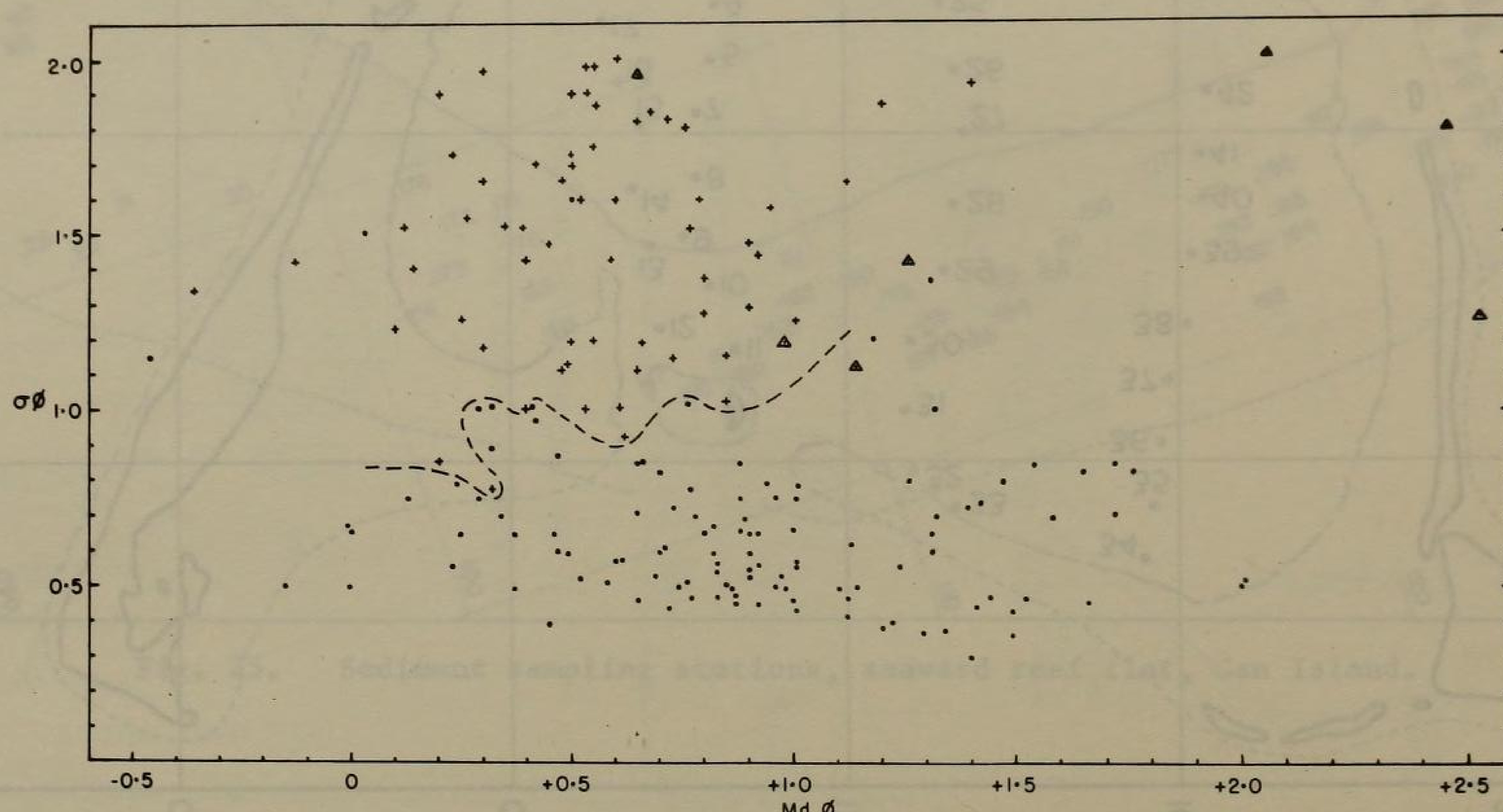

Fig. 28. Relationship betwen median size and sorting in sediment samples from Gan beaches (dots), Gan seaward reef flat (crosses), and Addu lagoon floor (triangles).