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MARINE BIOLOGY

Geomorphology of the Solomon Islands coral reefs

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[Plates 54 to 59]

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1. Introduction

The opportunity to study the coral reefs of the Solomon Islands was valuable for two reasons. First, the Melanesian region has been remarkably neglected by reef workers. To the south-west, the Great Barrier Reef Expedition of 1928–9 provided a basis for understanding Australian reefs; the *Snellius* Expedition explored those of Indonesia; the Japanese and more recently the Americans have studied the high islands of Micronesia, especially Guam and Saipan; and much recent work has been carried out on the atolls of the Carolines and Marshalls. Within Melanesia itself, the Catala Aquarium in Nouméa and the Singer–Polignac Expedition have begun work on the New Caledonian reefs; the *Noona Dan* Expedition visited the Bismarck Archipelago and Rennell Island; and some prewar studies were made in Fiji and the New Hebrides. Almost no work at all had been done in the Solomon Islands before 1965, with one notable exception.

The second reason is historical. The only previous reef investigations in the Solomons were carried out by H. B. Guppy, surgeon-naturalist on H.M.S. *Lark* in 1882–3, and his results added to growing criticism of Darwin's theory of coral-reef formation (Darwin 1842). Darwin's model called for the transformation of fringing reefs into barrier reefs and atolls by the progressive subsidence of a non-coral basement, and it received considerable support from the reefs of the open Pacific. Semper, however, described reefs of all three types from the Palau Islands, an area of tectonic uplift, and Murray, following his discovery of the importance of pelagic organisms in deep-sea sedimentation during the *Challenger* Expedition, argued that these deposits could themselves form reef foundations

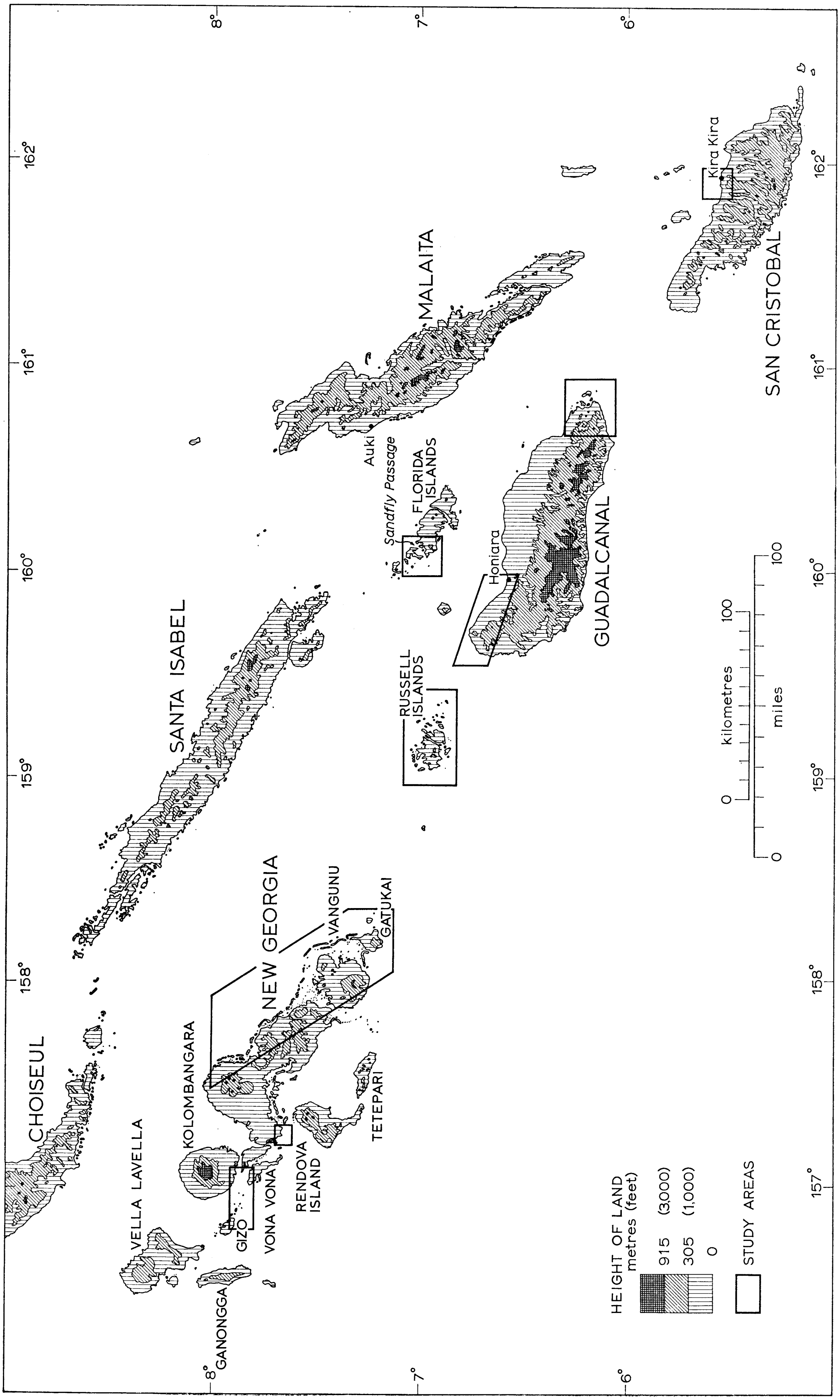

FIGURE 48. Topography of the Solomon Islands, showing Marine Party study areas.

without the necessity of subsidence (Semper 1869, 1880; Murray 1880). Guppy in the Solomons found abundant evidence of uplift, and described from Ugi thin coral overlying deep-sea sediments, evidence which apparently confirmed Murray's model. Guppy thus gave powerful support to Darwin's critics (Guppy 1884, 1885, 1887*a*, *b*, 1888, 1890; Mill 1887). While recent deep drilling on atolls (Bikini, Eniwetok, Mururoa, Turneffe, Glover's Reef) has supported Darwin, it does not follow that tectonically mobile belts are at all comparable in reef growth to open-ocean atolls, and re-examination of the Solomon Islands was therefore needed.

The Marine Party of the Royal Society Expedition to the British Solomon Islands Protectorate, under the leadership of Professor J. E. Morton, spent the period June to December 1965 investigating coral coasts of the southern Solomon Islands. Studies were carried out at the following stations (figure 48); Tetel Island, Sandfly Passage, Florida Group; Kira Kira, San Cristobal; Marau Sound, east Guadalcanal; Cape Esperance to Marovovo, north-west Guadalcanal; Honiara, Guadalcanal; Banika Island, Russell Group; Marovo, Gerasi and Togavai Lagoons, New Georgia; Gizo Island and Kolombangara, New Georgia Group. Geomorphological work here described was carried out either from m.v. *Maroro*, Captain S. B. Brown, or from shore camps, in collaboration with Dr S. A. Wainwright at Tetel Island and Marovo Lagoon and with Dr P. E. Gibbs at Marau Sound and at New Georgia.

Place-name usage in this report follows that on Directorate of Overseas Surveys 1:1 000 000 and 1:50 000 maps so far as possible; local names are introduced where necessary, and the spelling of these must be provisional.

2. Geological background

The Solomons consist of a double chain of islands extending for 950 km from the Bismarck Archipelago in the west towards the Santa Cruz Islands and the New Hebrides in the east. They form part of the western continental margin of the Pacific basin, and though they differ considerably from the simple island arcs of which the margin is elsewhere composed, they can be interpreted as comparable structures (Coleman 1966). The northern line of islands (Choiseul, Santa Isabel, Malaita) have no recent volcanics and consist of folded and faulted older volcanics and sedimentary rocks of late Mesozoic and Tertiary age. The southern islands consist either of recent volcanics (Bougainville, New Georgia), or of more complex block-faulted volcanic and sedimentary structures (Guadalcanal, San Cristobal). According to Thompson & Hackman (1969; see also Richards, Cooper, Webb & Coleman 1966), the oldest rocks in the Solomons are marine sediments of Cretaceous age; present land appeared only in the Oligocene.

Reef deposits are known from the Miocene of Guadalcanal and Choiseul, and younger reef limestones are prominent in coastal locations on most islands (Grover 1957). The Geological Survey maps these younger reef limestones as Pliocene, Pleistocene or Recent, but there is no absolute dating control. Thus at Honiara, on Guadalcanal, terraces of clastic debris with reef material are found at 145 to 135, 80, 60, 44 and 27·5 m above sea level, and the coast itself is formed of recently uplifted reef limestone. The lack of any absolute standard for dating either recent volcanoes, as in New Georgia, or recent reef-growth makes geomorphological interpretation difficult and often speculative, and tends to lead to an over-simplified picture of Pleistocene events. Apart from the problem of Pleistocene climatic changes in low latitudes, and their geomorphic effects, the Melanesian area has certainly been subject to eustatic fluctuations of sea level with amplitude not less than 150 m during a period now recognized to be 1 to 2×10^6 y; and these may have been superimposed on a general Quaternary regression of about 200 m. In the Solomons these sea-level shifts have been contemporaneous with continuing tectonic movements and active vulcanicity since the late Tertiary, making the period when present coasts were formed one of extraordinary complexity. Only in New Georgia is there any immediate prospect of this complexity being reduced to order.

3. Contemporary reefs and reef-flats

Contemporary reef flats at or close to present sea level were investigated at Tetel Island, Floridas; Gizo Island, New Georgia Group; and Marau Sound, Guadalcanal.

3·1. *Tetel Island, Florida Group*

The Florida Group consists of block-faulted and tilted volcanics and later sedimentaries, with areas of limestone of Pliocene to Quaternary age (Thompson 1958; Coleman 1965, p. 24). Drowning has produced a crenulate coastline with many small islets offshore. Tetel (or Gaskell) Island is located in a protected inlet in Sandfly Passage, where Lieut. Bowers and his party were eaten during the first hydrographic survey in 1880. It is a basalt hill 73 m high and 0·17 km^2 in area, separated from the Florida mainland by narrow channels less than 50 m deep. Figure 49 is based on echo-sounding profiles in these channels and on a traverse of the island. The north side of Tetel has a fringing reef up to 150 m wide, which extends eastwards as a narrow ridge to the Florida mainland. On the south side the surface topography is steeper, and there is a narrow mangrove-fringed shelf less than 10 m wide.

A tide-pole was erected in the north-west inlet, and read at half-hourly intervals for 7 days, 22–29 July 1965. Tides were diurnal, with amplitude ranging from 0·48 to 0·87 m. Maximum range at springs is probably about 1 m. Mean sea level derived from this short record was used as datum for a series of eight profiles instrumentally surveyed along reef-flat transects used in the biological surveys; these profiles were continued down the seaward slopes of the reefs by Dr S. A. Wainwright using a sounding lead. Profiles are given in figure 50. The reef flats are generally between lowest sea level recorded and mean sea level, except for occasional pools or moats, but some parts are appreciably above mean sea level. At low tides the flats are completely emergent. Coral growth is almost entirely lacking on the flats except in holes and crevices, where occasional *Acropora*, *Porites*, *Seriatopora*, *Goniastrea* and *Montipora* are found. The flats support a fairly diverse algal flora, and on the lower outer parts there are conspicuous areas of *Sarcophyton* and *Lobophytum*. There is no elevated reef limestone. Angles of fore-reef slopes range from 20 to 35°.

The bathymetric survey makes it possible to estimate the thickness of the Tetel Island reefs from geometrical considerations. The reefs form a prism on the drowned submarine slopes of the island, with thickness at the present reef edge of 15 to 34 m. Basalt probably

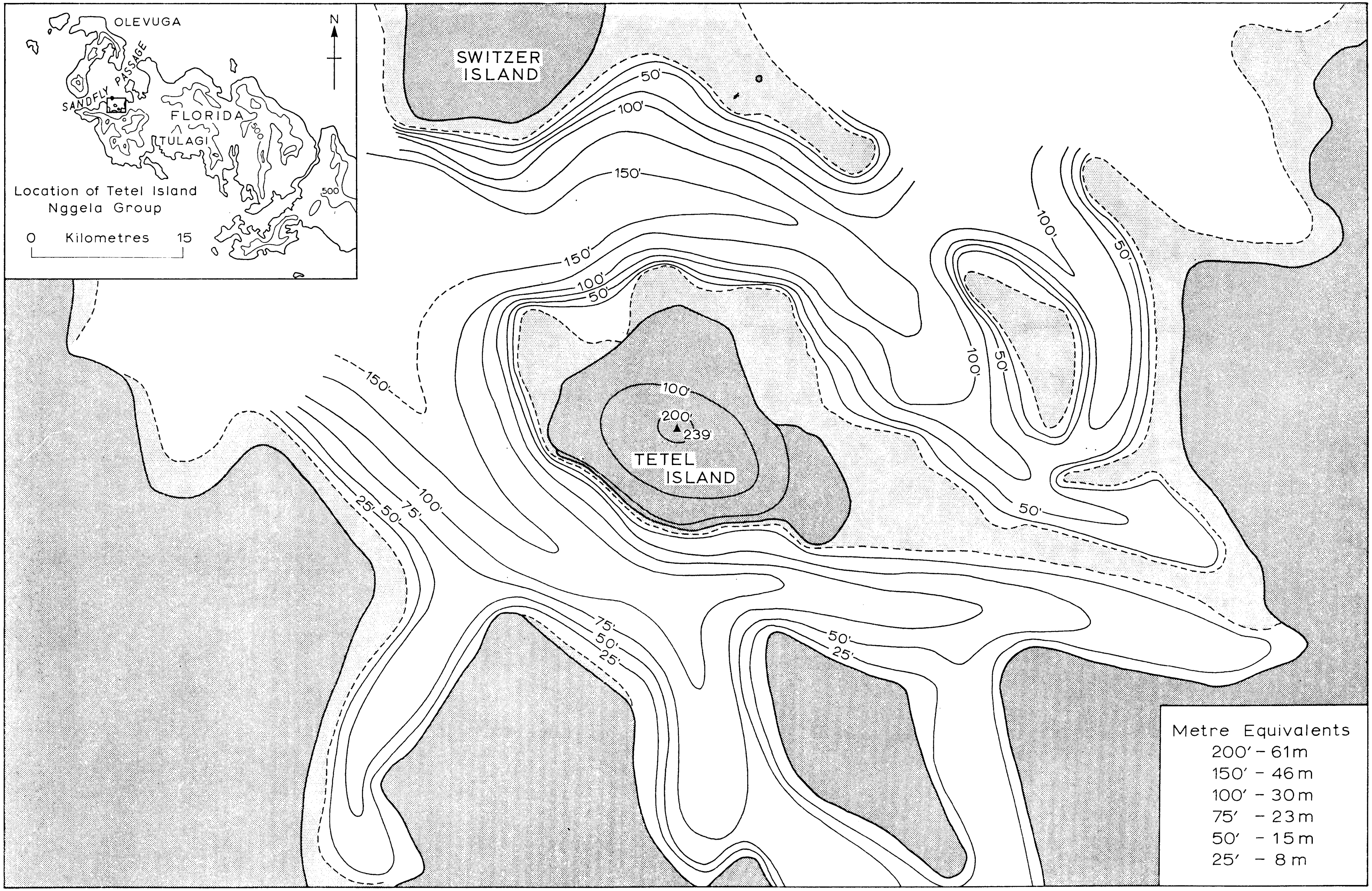

FIGURE 49. Tetel Island, Florida Group: bathymetry and location of profiles.

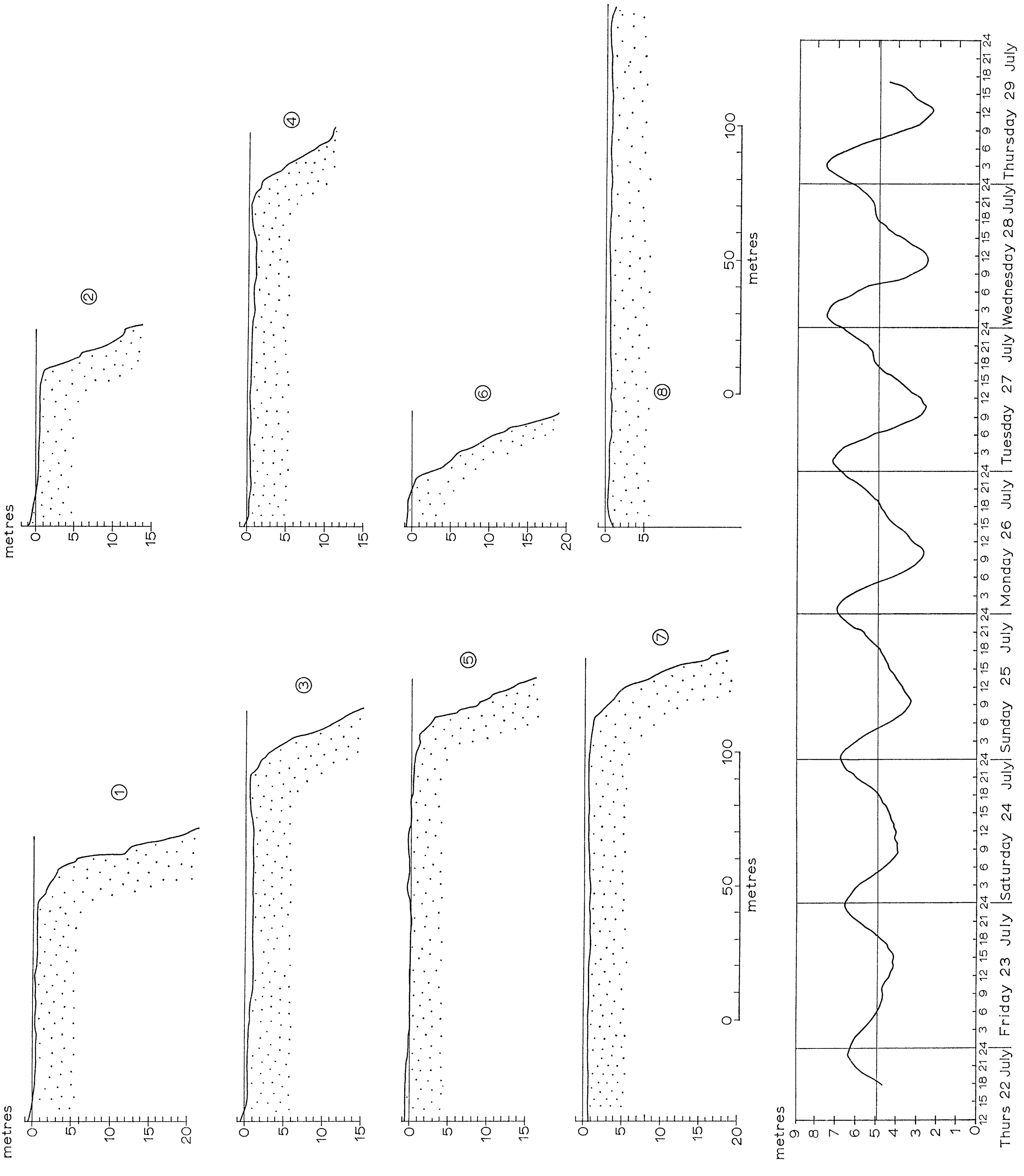

FIGURE 50. Reef profiles, Tetel Island, and tidal record for 22 to 29 July 1965.

outcrops on the sea floor at about −45 m. Some of the narrow southern reefs are probably thinner. Reefs of this magnitude could have formed entirely in the Holocene. Though vigorous coral growth would not be expected in these protected waters, the high level of the flats and the importance of dead coral and rubble on their surfaces requires explanation. Elevated reef limestones are reported elsewhere in the Florida Islands, for example at the north end of Sandfly Passage, but there is no evidence of recent elevation at Tetel.

3·2. *Gizo Island, New Georgia Group*

Gizo Island is a faulted block of Pliocene volcanics to the west of the New Georgia group. Pleistocene calcarenites are reported to have been raised to heights of 180 m (Coleman 1965, p. 25), and the island appears to be tilted northwards, giving a drowned north coast with barrier reef and a steeper south coast with fringing reef (Pudsey-Dawson 1960*b*). Fringing reefs were investigated for a distance of 4 km at Titiana Point, on the south coast (figure 51).

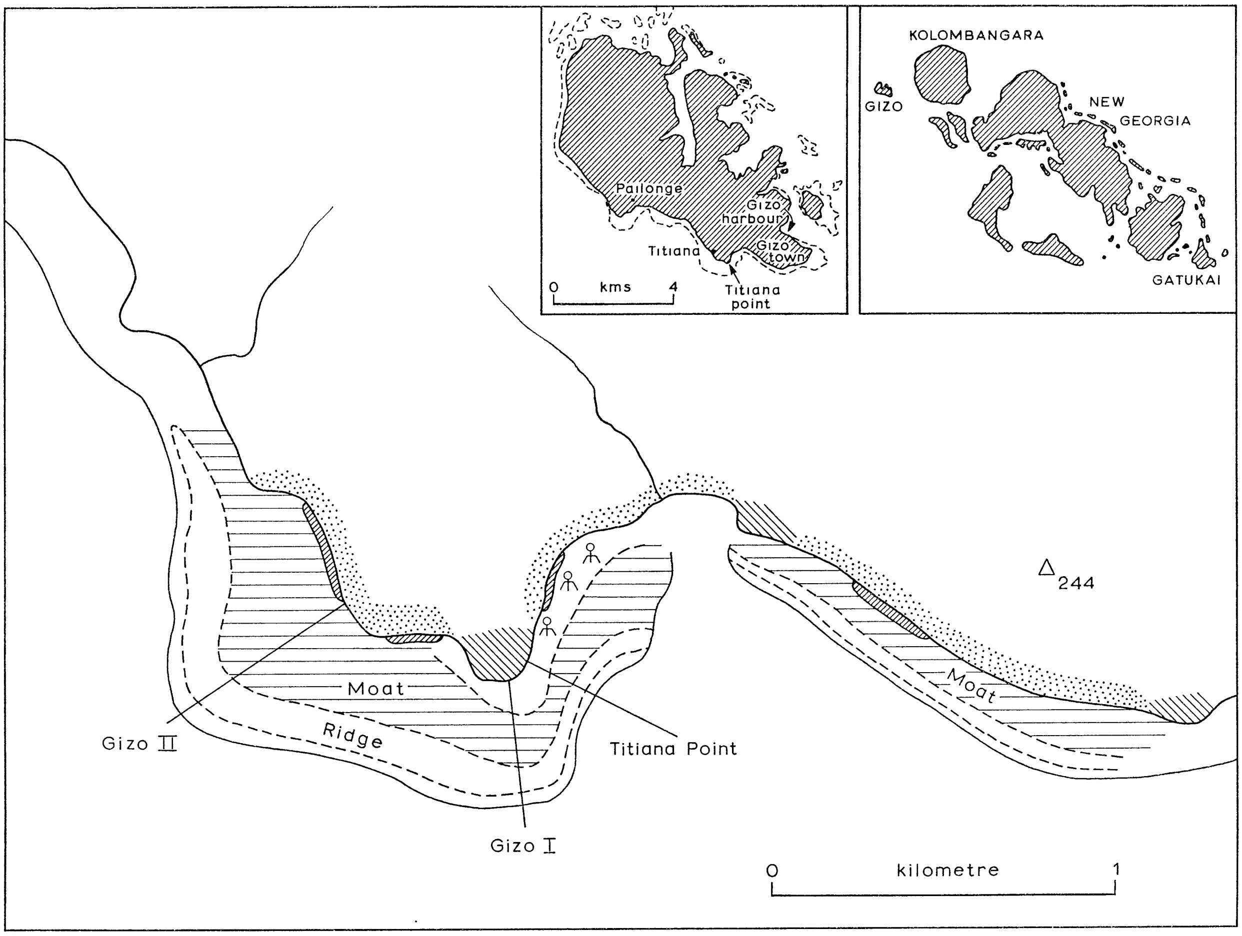

FIGURE 51. Fringing reef at Titiana Point, Gizo Island.

The Titiana fringing reef is widest on headlands (up to 600 m), and is interrupted at river mouths; its mean width is about 250 m. The shoreline at headlands is formed by undercut volcanic bluffs, separated by stretches of dominantly carbonate-sand beaches in the intervening bays. Beachrock is patchily developed at mid-beach in the bays: west of Titiana Point one uneroded outcrop, 1 to 3 m wide and 0·2 m thick, is continuous for 90 m. To the east of Titiana Point, beachrock plates up to 8 m wide are more eroded and contain much volcanic material; some outcrops are located behind a fringe of *Avicennia* mangrove.

The reef flat (figure 52) can be divided into three zones: (*a*) an inner carbonate mud-flat with mangroves, which is only discontinuously developed; (*b*) a moat, up to 1 m deep and reaching 180 m in width, with scattered small colonies of *Acropora* and *Porites*, mostly dead, on a rock floor; (*c*) an outer rim, consisting partly of jaggedly eroding reefrock up to 0·2 m above high water, and partly of a seaward rim of smoother reefrock coated with the calcareous algae *Porolithon onkodes* and *Neogoniolithon myriocarpon*. Grooves in this algal zone include living *Pocillopora*, *Acropora* and faviids, together with *Millepora*. The high eroded coral of the rim may correlate with the basal notch of the volcanic headlands, at 2m above low water, but slumping in weak agglomerates has largely destroyed the form of the notch and it is difficult to be precise about its altitude.

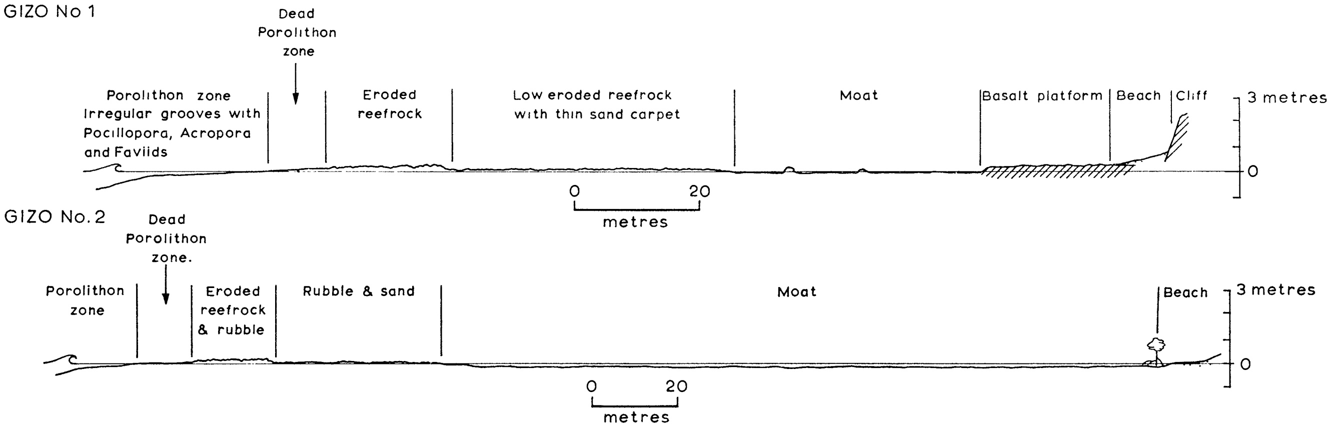

FIGURE 52. Reef-flat profiles, south coast of Gizo Island.

3·3. *Marau Sound, East Guadalcanal*

The shores of Guadalcanal lack sea-level reef flats, except for weak development at the north-west end and the Marau Sound reef province of eastern Guadalcanal. At Marau, basement basalts of the mainland plunge eastwards and are submerged to form a drowned coastline of inlets and crenulate high islands such as Beagle, Komachu and Malapa (Grover & Pudsey-Dawson 1958). Several of these high islands are surrounded by reef flats up to 0·5 km wide, and Marau Sound itself is enclosed by a crescentic, partially drowned barrier reef. The sound has an area of 1000 km^2 and depths of 20 to more than 65 m (figure 53; figure 64, plate 54).

The topography of the reefs is complex, but there is some evidence of recent (and continuing ?) tilting from west to east. The Marau barrier becomes a fringing reef to north-west and south-west, where it joins the Guadalcanal mainland, and here it is clearly elevated. Outlying reef patches (Pari, Symons and North) have high, planed-rock surfaces, and are also elevated. Towards the east the flats are lower, and Taunu Shoal, outside the barrier, does not reach the surface.

Eroded slightly elevated reefs are found along the south coast of Guadalcanal from Conflict Bay to Kopiu Bay and beyond. These form intertidal shelves 45 to 370 m wide at the foot of plunging basalt slopes. Since this is a weather coast, with sea level dependent on both tides and local weather conditions, precise relationships between the benches and tidal levels could not be established. In places, as at Untava (figure 54), the flat is slightly above mean sea level, slopes gently from land to sea, and has few living corals except for goniastreid microatolls on its seaward part. Its surface of bare rock, thin sand deposits, and *Thalassia* beds is not obviously elevated. At Vavau Point, Karipaupapa, however, the flat terminates landward in a vertical limestone cliff 2·15 m high, and is clearly erosional. At Purikiki, the elevated reefrock is lower but more extensive. The outer intertidal flat is subject to considerable wave action and is covered with dead calcareous algae; landward there is a wide zone of gullied and fretted reefrock 0·6 to 0·75 m above the flat, with small

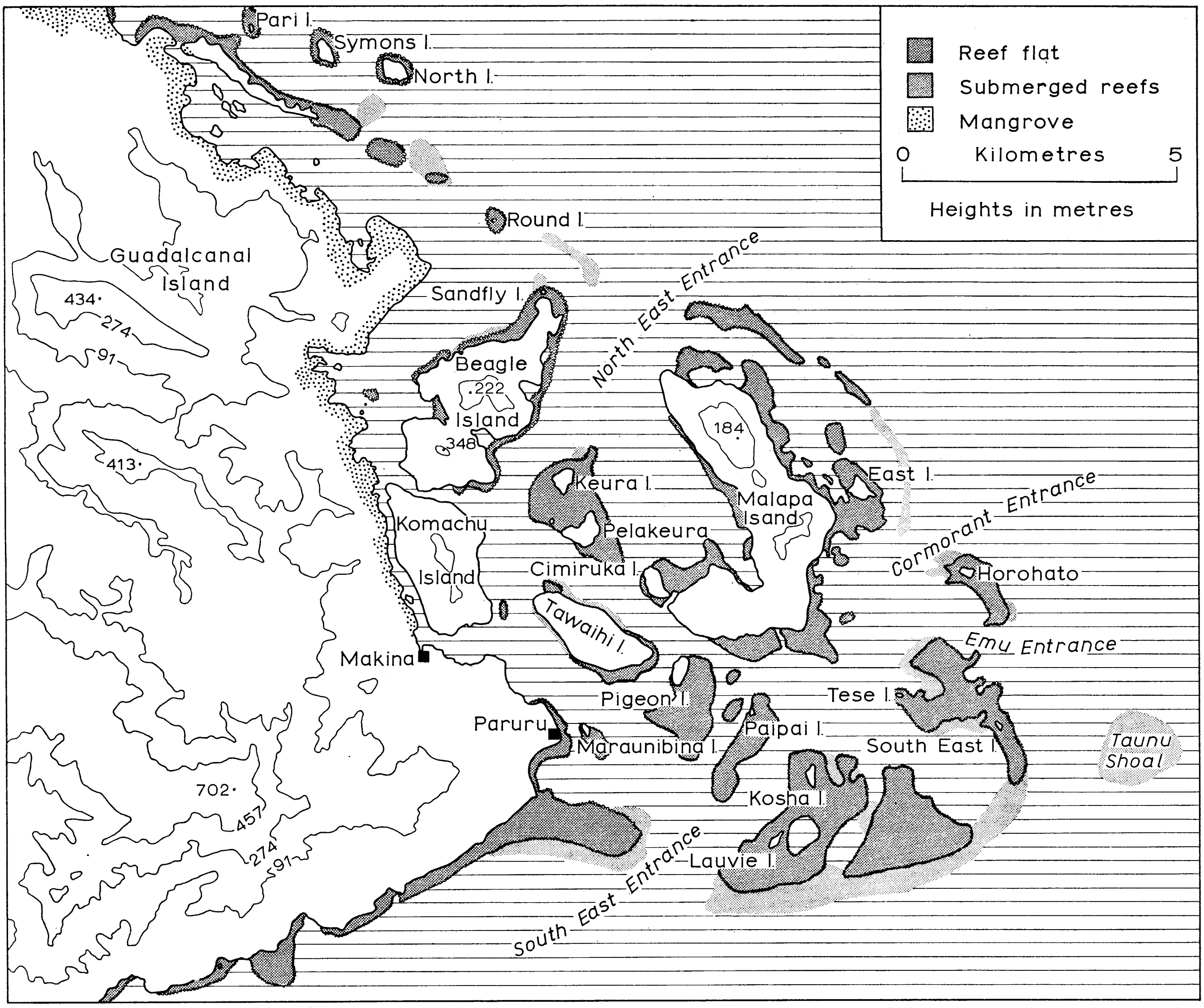

FIGURE 53. Reefs of Marau Sound, east Guadalcanal.

Goniastrea on the floors of some gullies. The reefrock is covered landward by a terrigenous cobble beach.

At Kopiu Bay, the limit of the reconnaissance, the shelf is narrower (55 m) but higher (figure 65, plate 54). Its outermost point, under heavy wave action, is covered with pink *Porolithon* and non-calcareous algae such as *Sargassum binderi* and *Turbinaria conoides*. Nestling *Pocillopora* are present but rare. Landward the algae are replaced by a zone of rimmed pools 18 to 23 m wide. The inner part of the flat, 18 m wide, stands 1 m or more above the mean flat surface: it consists of pools with serrate and irregular rims passing upward into a jagged erosional surface. The limestone is a conglomerate of largely algal deposits with some coral and secondary brown limestone; it contains cobbles of basalt from the cliffs. The contact between the basalt and the reefrock is clearly exposed (figure 66, plate 55), but the reefrock is so eroded that nothing can be said about the contact except to note its unconformability. Elevated reef limestones were formerly more extensive within Marau Sound itself, for on the north side of Pelakauro Island, behind fringing mangrove, there is a limestone residual 3·7 m high, cliffed and basally notched.

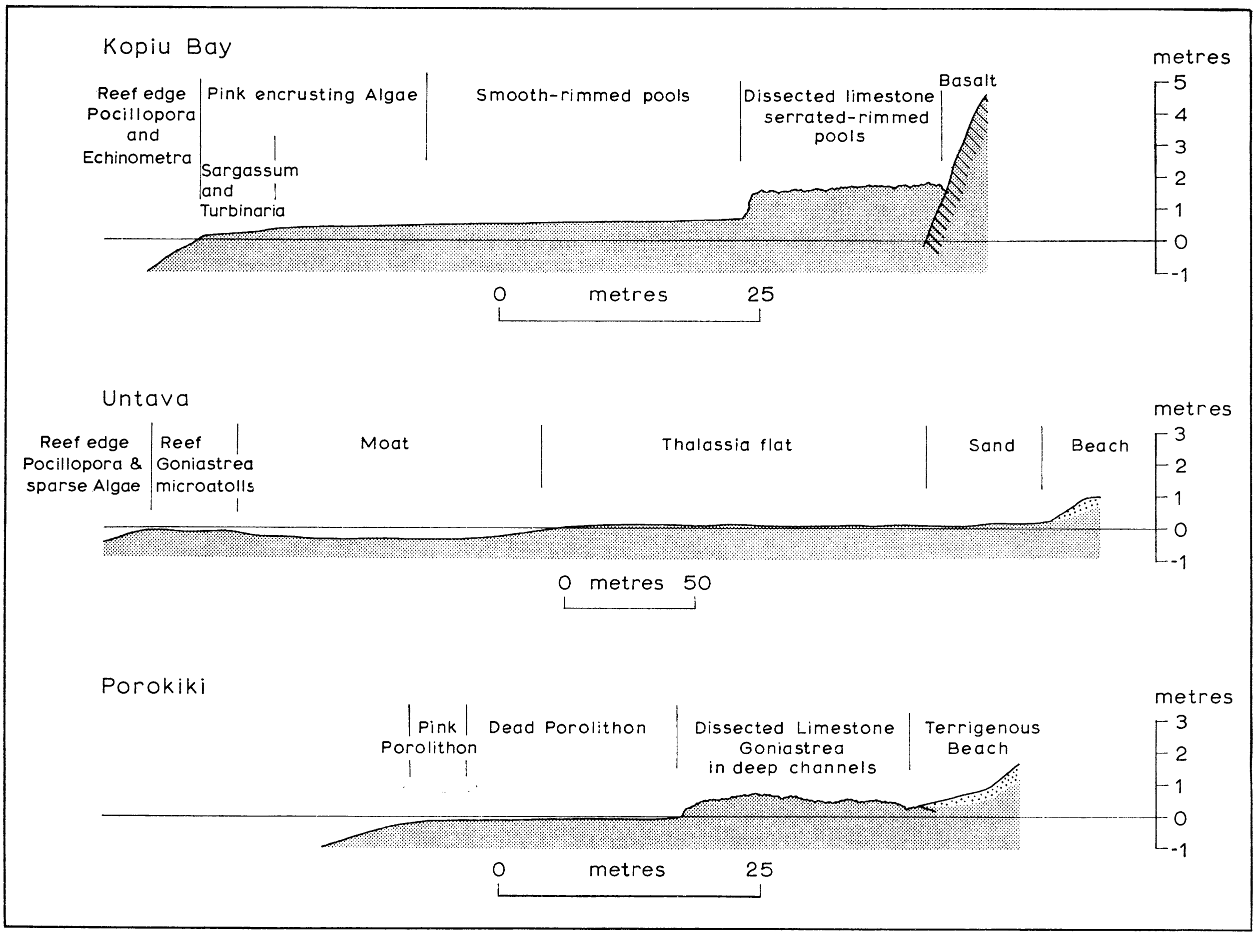

FIGURE 54. Reef-flat profiles, south coast of Guadalcanal.

Reef flats at intertidal levels, on which the Marau Sound cays stand, have characteristically dead surfaces, drying at low water, and often covered with reef rubble and coral cobbles. Almost all the Marau Sound reef flats are devoid of growing coral: only one flourishing reef was seen, 0·8 km north-west of Paruru on the mainland coast. None of the flats showed high residuals of reefrock, except at North Island (where the residuals may be a beach-rock); but evidence of erosional origin, such as polished, grooved and potholed surfaces, was common. At North and Niu Islands, large corals up to 2 m in diameter have been smoothly bevelled by this erosion.

A further feature of the Marau reefs is that contemporary coral colonies on the flats are invariably dead. Figure 67, plate 55 shows an area of *Acropora* in the position of growth on Harbour Reef flat: the colony is entirely dead.

The low islands of Marau Sound all consist of clastic reef sediments accumulated on these erosional flats: they were studied in greater detail and are discussed in another paper (Stoddart 1969*a*).

4. Elevated fringing reefs

4·1. *Kira Kira, San Cristobal*

At Kira Kira the shoreline is formed by a low terrace of reef limestone 100 m wide (figure 68, plate 56). This consists of three main zones: (1) an outer zone of smooth, *Porolithon*-encrusted rock pavement, intersected by deep narrow channels normal to the reef edge; (2) a zone of rimmed pools up to 10 m diameters in which the deep channels end (figure 64, plate 54); and (3) an inner zone of dissected reef limestone up to 2 m above the main terrace level (figure 55). The dissected reef limestone is above high tide level, and is colonized by strand vegetation; the innermost rimmed pools are partly filled with salt water and are reached by spray, and probably by the sea at springs. The pools themselves are primarily erosional (though in some cases with secondary deposits of limestone on the floors), for old coral colonies are bevelled and etched on the floors; the walls are of reef-rock, though much eroded by polychaetes. Some of the pools contain occasional hardy corals, mainly *Pocillopora*, at anomalously high levels. The lower terrace is almost devoid of living corals, except on the walls of the deep channels, which support small corymbose *Acropora* and *Pocillopora*. The channels are interpreted as elevated surge channels of the

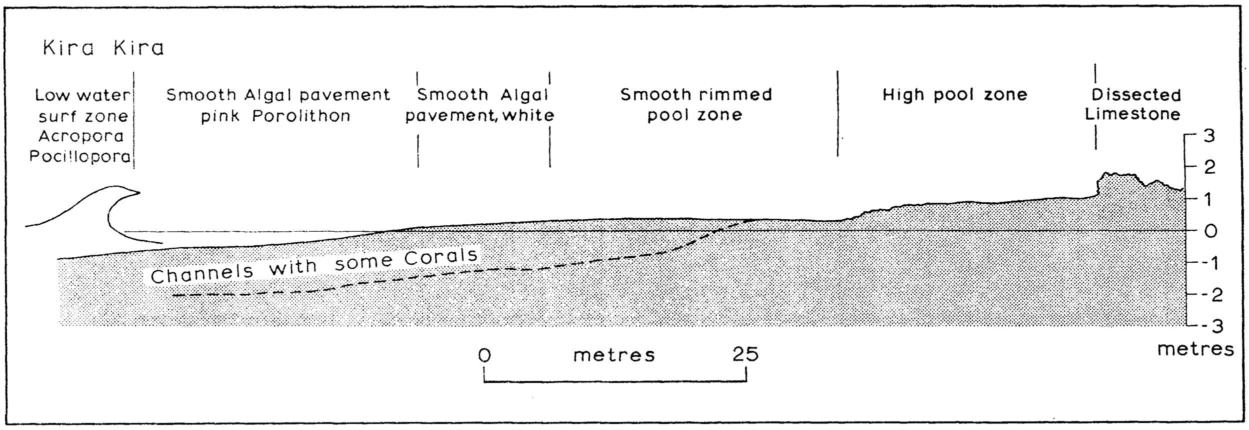

FIGURE 55. Reef-flat profile, Kira Kira, San Cristobal.

kind characteristic of living reef edges. Water movement is concentrated in these channels, and cobbles and potholes are rare. This profile at Kira Kira is characteristic of many Solomon Island shores, in the importance of its slightly elevated and eroding fringing reef, and the lack of active coral growth.

4·2. *Banika Island, Russell Group*

The Russell Group consists of the two main islands of Pavuvu and Banika, and a number of smaller outlying islands. Pavuvu and Banika consist of volcanics dipping northwards from a faulted south coast; Sunlight Channel between the two islands is probably fault-alined. The volcanics rise to 520 m on Pavuvu and to 206 m on Banika; they are surrounded by fringes of raised reef limestones, and the drowned northern coasts are rimmed by an intermittent barrier reef (Pudsey-Dawson 1960*a*) (figure 56).

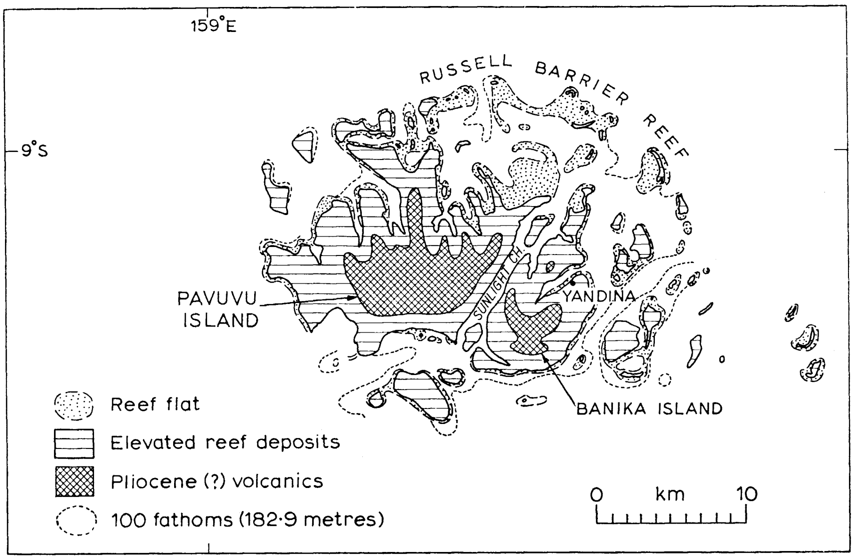

FIGURE 56. Topography of the Russell Islands.

The coastal platforms and elevated reefs of Banika (figure 57), particularly on the east coast between Menmui Point and Lever Point, were studied. The sea-level reef flats are similar to those recorded on Gizo and Guadalcanal (figure 58). At Sifola, the shoreline itself is formed by a 2 m shelf of elevated reef limestone, fronted by a platform 60 m wide (figures 70 and 71, plate 57). This platform consists of a wide inner moat, up to 0·3 m deep at low water, a shallow outer moat, and a medial ridge of eroded reefrock up to 0·6 m above low water level. The outermost part of the platform consists of a low ridge of *Porolithon onkodes*, with some small corals in the breaker zone. Living corals are concentrated in the outer moat, where low colonies of *Goniastrea* coalesce to form a reticulated pattern of microatolls with white dead crowns. The deeper inner moat has some colonies of *Montipora*, almost all dead, and is carpeted with coral rubble and the calcareous alga *Neogoniolithon myriocarpon*. The relict reefrock near the edge of the platform is clearly being eroded from both seaward and landward: erosion on the seaward side is limited by contemporary algal and coral growth, and that on the landward side is probably more rapid. Solution at low water in the inner moat is probably followed by flushing out of dissolved carbonates at high tide (Mayor 1924).

A second profile was measured on the south side of the Lingatu Peninsula. This is comparable in width to that at Sifola, and also possesses an outer moat with corals, an inner moat, and a higher medial ridge, though in this case smoothly but deeply dissected and encrusted with *Porolithon*. The Lingatu coast is rougher, and a wide cobble beach overlies the eroded reefrock at its shoreward end. This beach partly fills an elevated tidal notch cut in a limestone cliff 5 m high. At the south point of Lingatu, the intertidal platform is largely absent, and the shore is formed by this notched cliff of elevated limestone (figures 71, 72 and 74, plates 57 to 59). At the point itself wave action is considerable (scend 2 m), and it is difficult to determine a datum. Two profiles were measured (Lingatu nos. 2 and 3: figure 59), and it was assumed that the raised notch bears the same relation to mean sea level as the beach-filled notch in Lingatu no. 1. The base of the cliff is formed by a narrow

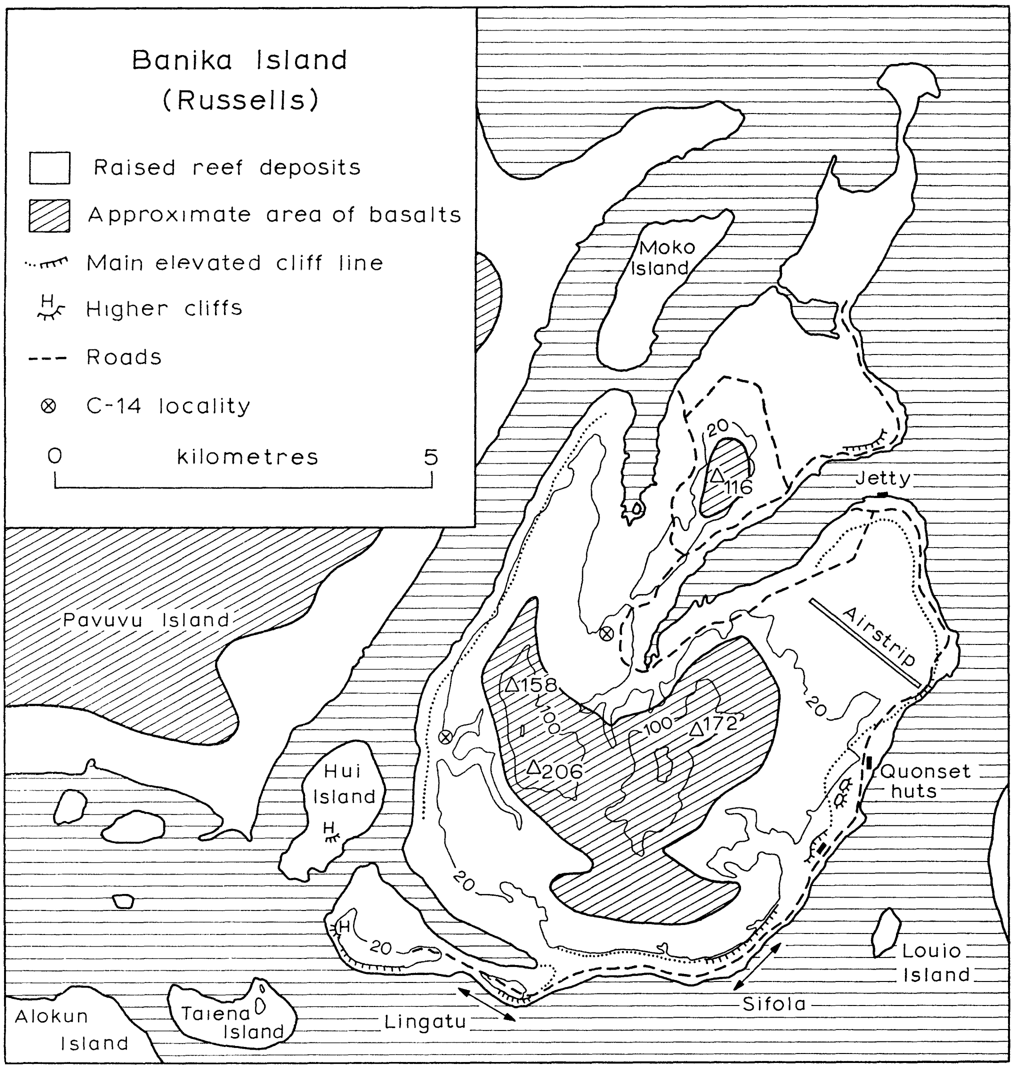

FIGURE 57. Reefs of Banika Island, Russell Group.

platform of *Porolithon onkodes* with *Turbinaria ornata*, deeply channelled to seaward but horizontal with rimmed pools and small corals towards the cliff. The foot of the cliff is a vertical step 3 m high, with chitons, leading into the elevated notch at 3·5 ± 1 m. The floor of the notch is pitted with oblique solution holes, and there is no trace of a double notch.

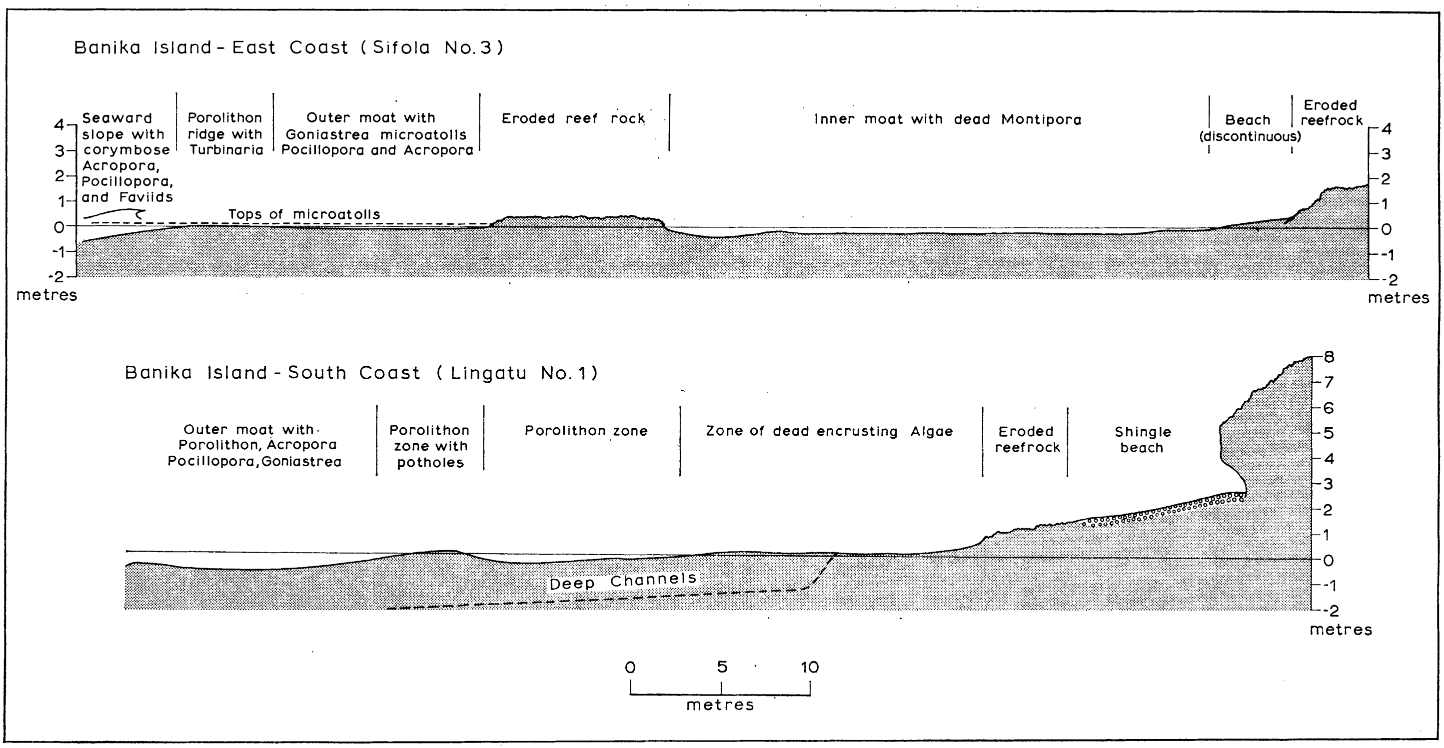

FIGURE 58. Reef-flat profiles, east coast of Banika Island.

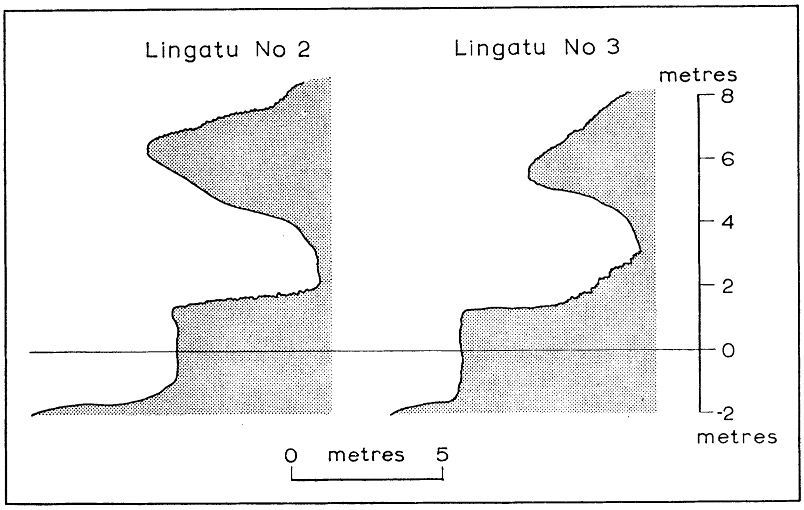

FIGURE 59. Notched cliffs, Lingatu Point, Banika Island.

The elevated notch at Lingatu may be traced round most of the coast of Banika on the landward side of a conspicuous terrace, the level of which varies from 1·5 to 5 m above low water. This terrace is 60 to 450 m wide; the cliff at its inner edge is deeply notched (figure 73, plate 58), and small islands, also basically notched, stand on its surface. The floor of the notch stands at +3 m, with a possible second notch at +4·3 m. Stalactites and stalagmites up to 1 m in diameter have been formed on its roof and floor (figure 73, plate 58). Profiles (Lingatu, no. 1, Sifola nos. 1–3: figure 60) also show conspicuous higher bevels, some of which may be local, at 11–12, 15, 20, 32, 60 and 65 m, though at these higher altitudes the topography is more subdued and no fresh cliff-lines were seen. During circumnavigation of Banika, fresh cliff-lines were seen at about 40 m on Hui Island and Lingatu Peninsula, at the south end of Sunlight Channel. The elevated reef deposits rise to *ca.* 60 to 70 m on Banika. Grover (1958*a*, p. 46) has described elevated notches on Mone Island, north-west of Pavuvu, at 0·76, 3 and 5·5 m on a lower cliff 8·5 m high, and a well-defined notch at 22 m on a higher cliff extending from 16·8 to 29·6 m.

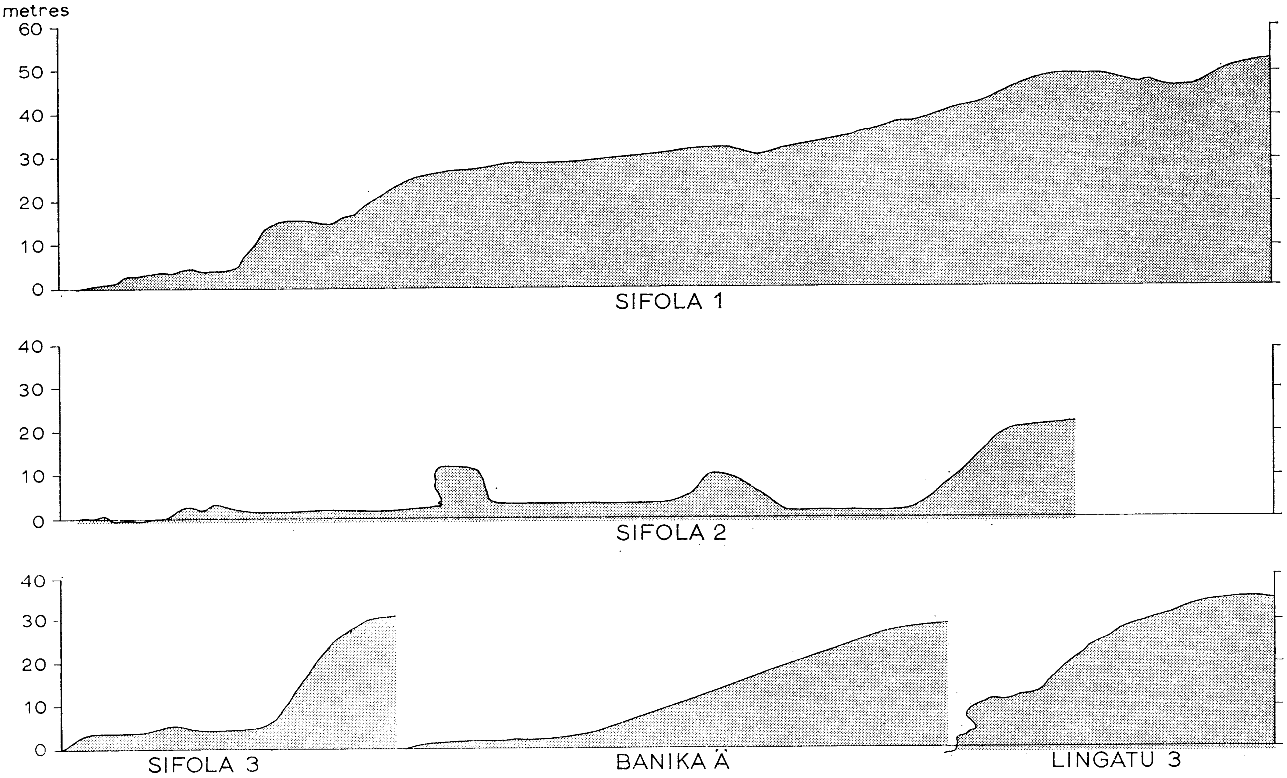

FIGURE 60. Profiles of elevated fringing reefs, Banika Island.

Samples of *Tridacna* shells for ^{14}C dating were taken from quarries on the east side of Sunlight Channel and at the head of Renard Sound (figure 57). The Sunlight Channel sample (Banika A–1), from a quarry cut into the cliff-line behind the 1·5 to 3 m coastal shelf, at a height of 4·6 m, had a ^{14}C age of $33\,200^{+2400}_{-1900}$ B.P. The Sunlight Sound sample (Banika B–1), from a quarry in reef deposits above the 1·5 to 3 m shelf and underlying a terrace at 23 m, at a height of 9 m above sea level, was older than 39 700 y.

The Russell Island reefs have thus grown on a tilted and partially drowned volcanic basement, the barrier reef forming on submergent topography in the north and suites of elevated reef terraces on emergent topography in the south. The most recent terrace at 1·5 to 5 m postdates reef growth which took place during the late Pleistocene at a time of world eustatic low sea levels; higher reefs on Banika are, on topographic grounds, older. The depth of the 3·5 m notch suggests a stillstand of several thousand years. Modern reef growth is restricted by the shallowness of the intertidal platform now being formed by solution of the elevated reefrock.

5. Elevated barrier reefs

New Georgia consists of a series of Pliocene to Recent volcanoes, rising in Kolombangara to a height of 1768 m, and surrounded by elevated reef limestones (Stanton & Bell 1965; Coleman 1965, p. 25). On New Georgia Island itself (figure 61), these form elevated barrier reefs along the north-east coast, enclosing Marovo, Gerasi and Togavai Lagoons, and along the south-west coast, enclosing Roviana Lagoon. South of Vangunu the barrier reef has been downwarped and submerged beneath the sea, and between Panga Bay and the Roviana Lagoon the coast is steeply cliffed and devoid of reefs. West from New Georgia towards Gizo the reefs form a complex series of partly emergent islands, including Vona Vona and Kohinggo, as yet unstudied.

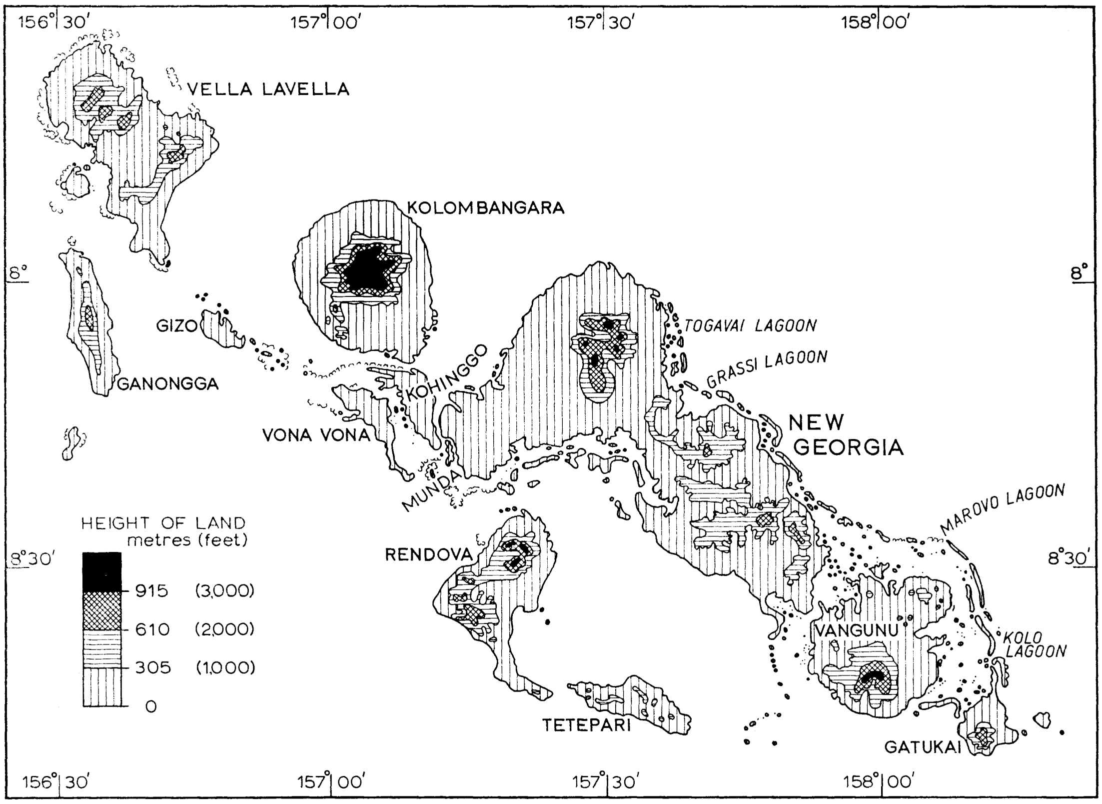

Figure 61. Topography and raised reefs of New Georgia.

The general morphology of the Marovo barrier in relation to New Georgia, Vangunu and Gatukai suggests reef growth during subsidence of volcanoes of differing ages. The reefs of the Marovo barrier may be several hundred metres thick, though it is impossible on morphologic grounds to assess the scale of recent faulting. The barrier itself is raised, with a fairly constant altitude of 15 m except in the south, near Gatukai, where it reaches 25 m. It is prominently notched at +4 m, and in the south at about +12 m, and there is a weakly developed contemporary notch which is well seen on lagoon islands and in protected situations. Diving on the seaward face of Matiu Island showed two further terraces at −10 to −15 m and at −45 m.

Togavai and Gerasi Lagoons are narrow and shallow, with an irregular single raised barrier reef; except in the low level of the elevated barrier, these lagoons resemble Roviana Lagoon. Marovo Lagoon is wider and deeper, with an unusual double barrier, the outer raised reef being higher than the inner. Double barriers are also found on Kohinggo and in the Shortlands, but in these areas the outer raised reef is lower than the inner one.

The differential uplift of the New Georgia barrier reefs has led to the development of a wide series of reef shores, from vertical and overhanging cliffs to horizontal intertidal flats similar to those of Banika Island. Because of their great interest, geomorphic work was concentrated on the Marovo raised barrier and lagoon, and these are considered in a separate paper (Stoddart 1969*b*).

6. Problems of Solomon Islands coral shores

Within the general framework of uplift of fringing and barrier reefs controlling the gross morphology of coral coasts in the Solomon Islands, three problems are of interest in the detailed morphology of the shore. These are: (1) the evidence of recent changes of level, shown by elevated tidal notches or platforms and by drowned terraces; (2) the forms created by solution on both steep and flat shores on elevated reefs; and (3) the problem of the widespread mortality of modern corals growing close to low tide levels. Before considering these in greater detail, three general points must be made.

First, Solomon Islands coral coasts are at present coasts of elevation, with steep and often vertical gradients. Few corals are able to grow under such conditions, especially on rougher shores, and thus modern reefs are not well developed. Secondly, because coasts are steep and in the reef areas exposed rock is generally limestone, clastic sediments are rare and over large areas beaches are almost non-existent. Sedimentary deposits are limited to thin carpets of sand and rubble on reef flats, and to mobile layers in transit down seaward and lagoon slopes. Thirdly, while the geologically most important organisms in the lower eulittoral and sublittoral are the encrusting and cementing algae, no cases were seen of these constructing algal (*Porolithon*) ridges on the edges of reef flats comparable in scale with those of open-Pacific atolls: in this respect the Solomon Islands may be compared with Indonesia. It should, of course, be noted that these generalizations do not apply to non-coral coasts, where, for example on north Guadalcanal, long stretches of coast are lined with beaches of quartz and other terrigenous sands.

6·1. *Elevated shorelines*

Stearns (1945), in an early survey of elevated benches in the south-west Pacific, attempted to correlate levels between the Solomons, New Hebrides and Marianas, with Hawaii and the coast of California. Since then, data have accumulated on benches throughout the

Solomon Islands, and also in the Marianas, the Bismarck Archipelago, and the New Hebrides. Correlation even within this region is extremely hazardous: apart from the Russell Islands* no dates are available for limestones in which the benches are cut, and size, freshness and even elevation are dubious parameters to employ. Reports, for example, rarely indicate whether the features have been instrumentally surveyed, or to what datum. Table 20 lists some of the levels below 30 m reported in the literature for Solomon Island shores. The benches described in this paper from the Russell Islands (main bench at 3·5 m, others at 11 to 12, 15, 20, 32, 60 and 65 m) and from New Georgia (1·5, 4 and 12 m) cannot be correlated with these levels with any confidence, particularly in view of the known tectonic instability of the region.

Elsewhere in Melanesia, Stearns (1945) has described a series of levels from Espiritu Santo, New Hebrides, at 1·52, 8·23, 13·72 and 30·48 m, and in 1965 I observed benches of raised reef limestone on Vate, New Hebrides, at 2 and 4 m approximately. Christiansen (1963), in the Bismarck Archipelago, described a main notch in cliffs at 1·5 m, with less well-marked features at 3 and 6 m, and he later observed the elevated notches of Rennell Island. Farther north, in Micronesia, benches have been described at a variety of levels on Saipan and Guam in the Marianas: at 2, 5 to 10 and 20 m (Tayama 1952), 1·22 to 2·44 (Emery 1962), and 1·52, 7·62, 13·72, 21·34 and 30·48 m (Stearns 1945).

Elevated tidal notches in reef limestones were classically described from the Red Sea by Macfadyen (1930) and from Indonesia by Kuenen (1933). More recently, Guilcher has re-studied the Banc Farsan, Red Sea. He considers that the heights of benches in the Red Sea, western Australia, and Indonesia are so similar (table 21) that they are probably eustatic, the highest marking the upper limit of the Flandrian Transgression (Guilcher 1955). The sample is small for a conclusion of such importance, and the reality of a Holocene transgression in the reef seas has yet to be demonstrated: if these levels are eustatic, it is unlikely that they would be found undeformed in the Solomons.

Because of the demonstrated variability of levels over short distances, for example on Matiu Island, New Georgia (Stoddart 1969*b*), long-distance correlations should only be attempted on grounds of age and not of height. Apart from the fact that the Russells 3·5 m level is younger than 33000 y, no dates are available. It is thus impossible to relate the Melanesian benches to Pleistocene eustatic sea-level changes. Recent work has suggested slightly higher sea-levels in the last interglacial, when reefs formed which now stand slightly above sea level, as in the Tuamotus; this was followed by a fall to at least −150 m, and a gradual rise over the last 20000 y to the present level. Contrary to earlier views, there seems little evidence for sea levels in the Holocene higher than the present (Shepard & Curray 1967; Shepard *et al.* 1967). Sedimentary sequences under deltas in New Georgia should provide data of the kind now required on sea-level changes and tectonic movements in the Solomons.

There is little point, in the present state of knowledge, in attempting to correlate the submerged terraces found at New Georgia with those elsewhere in the south-west Pacific. Stearns (1945) described a terrace at −18·3 m at Espiritu Santo, New Hebrides, and

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* ^{14}C dates of two *Tridacna* shells from a 100 m elevated reef on Buka Island, near Bougainville, both greater than 33 000 y, have recently been reported by Speight (1967*a*, *b*); Dury & Langford Smith (1968).

Table 20. Elevated shorelines in the Solomon Islands below 30 m

Santa Cruz, Graciosa Bay (Grover 1958*a*, p. 51)	Santa Cruz, Nanambolu, Matema Is. (Grover 1958*a*, p. 55)	Rennell (Grover 1958*b*)	Bellona (Hill 1960)	Ugi (Grover 1958*a*, pp. 43–5)	Guadalcanal, Honiara (Stearns 1945)	Russells (Pudsey-Dawson 1960*a*)	Russells, Mone Is. (Grover 1958*a*, p. 64)	Ranongga (Pudsey-Dawson 1960*c*)
—	—	—	—	1·22	1·52	—	—	—
—	—	2·44	2·44	2·74	—	3·05	3·05	—
4·27	3·81	—	—	—	—	—	—	—
—	5·64	—	—	5·18	—	—	5·49	6·10
7·32	—	9·14	7·62–9·14	—	7·62	9·14	—	—
—	—	—	—	—	—	—	16·76	—
—	—	—	—	—	—	—	21·95	—
30·48	—	—	30·48	—	—	30·48	—	—

Table 21. Levels of presumed eustatic limestone notches

Abulat Red Sea (Guilcher 1955)	Iles Farsan Red Sea (Guilcher 1955)	Indonesia (Kuenen 1933)	West Australia (Fairbridge 1948, 1950*a*, 1950*b*)
—	—	0·5–1·0	0·6–0·9
1·2–1·4	1·35–1·65	1·5–2·0	1·5–1·8
2·4–2·8	2·85–3·15	—	3·0
—	—	4·0–5·0	—

Emery (1962) found a series on Guam at depths of 16·8, 32, 59·4, and 96 m. A terrace at *ca.* −18 m has been described from Oahu (Stearns 1935) and Japan (see Emery 1962, p. 11), which may correlate with the so-called 8-fathom (15 m) terrace first described from atolls in the Marshall Islands, and later from Andros Island, Bahamas, and Raroia Atoll, Tuamotus. The 10 to 15 m terrace at New Georgia is at this time level, but the correlation is probably fortuitous.

6·2. *Limestone erosion features*

A distinction can be made between erosion features of cliffed coasts and those of flat coasts. On cliffed coasts the dominant feature is the intertidal notch and raised intertidal notches, particularly that at +4 m. The modern notch is a shallow feature, deepest between mean sea level and mean high water. The 4 m notch is much deeper, reaching maximum depths of 10 to 15 m on New Georgia. Measurements of the rate of intertidal limestone erosion elsewhere give rates of retreat in the deepest part of the notch of from 0·001 m y^{-1} (Kaye 1959; Hodgkin 1964) to 0·005 m y^{-1} (Verstappen 1960): at such rates, the deeper elevated notches in the Solomons would require a stillstand of from 3000 to 15000 y, and the smaller modern notch a stillstand of about 1000 y. The form of the notches is similar to that described elsewhere, for example in the Bismarcks by Christiansen (1963). Most have a complex upper visor with several distinct concavities. Christiansen has attributed these either to erosion at different levels during seasonal changes of sea level and storm conditions, or to sequential development during changing sea levels, the upper concavities being older than the main notch. The latter seems a more reasonable explanation.

On rough coasts the cliff is fronted by an intertidal ledge or platform covered with encrusting calcareous algae. On Matiu Island the platform varies in width from a few to tens of metres; in places it is absent through recent collapse. The level of this platform at its outer edge is generally below mean low water. On protected coasts, on lagoon shores of barrier islands, on lagoon islets, and in barrier entrances, the platform is absent, and the cliff continues vertically into deep water. Protected cliffy coasts are thus paradoxically often more difficult to traverse than exposed ones. The platform is interpreted as a growth feature, formed mainly by calcareous algae growing in rough water on emergent shores. At Matiu, New Georgia, where it often overhangs by 2 to 4 m, it clearly forms a cornice built on to the cliff face, rather than an erosional bench. Presence of this platform affects the shape of intertidal notches: on rough-water coasts, with the platform present, notches are flat-floored and on protected coasts, with no platform, the floor of the notch slopes markedly to seaward. Kaye (1959, p. 94) has described homologous forms from protected and rough-water coasts in Puerto Rico.

On flat coasts, especially on slightly emergent fringing reefs, rimmed pools are an important feature, often separated by moats. Two types of pool may be distinguished. Reef-edge pools are found on rough-water coasts (south coast of Guadalcanal; south coast of Batuona Island, Wickham Anchorage, New Georgia (figure 75, plate 59), forming shallow stairways of ledges descending from the reef edge towards the flat. These are constructional features, with rims formed by encrusting algae; part of the difference in height between the pools and the moat may result from solution in the latter. The pools are generally shallow, and of crescentic, overlapping outline. They resemble those first described by Lister (1891) from Tonga. The second type of pool, exemplified by those at Kira Kira, San Cristobal, lies at or slightly above high water, but within reach of spray. They are larger (up to 10 m in diameter), with flat floors, and walls up to 0·15 m high. These pools are erosional (coral skeletons are etched out and bevelled on their floors) and the rims are formed of reefrock, much bored by polychaetes and thinly veneered with algae. Several workers have studied the chemistry of sea water in such pools elsewhere, without conclusively demonstrating that changes in pH between day and night are sufficient for solution to take place (Emery 1962; Revelle & Emery 1958; Kaye 1959); boundary-layer effects and biogenic erosion may also be important. Similar rimmed pools were described by Kuenen (1933, pp. 82–3) from Indonesia.

At mid-tide levels on low coasts, moats are formed, again by solution; these are well seen at Banika Island. Solution is demonstrated by the flatness of the moat floor and the undercutting of the moat walls and contained residuals.

In addition to notches, pools and moats, several features of microrelief are worth further study, in particular the intricate fretwork of holes and pinnacles developed in the spray zone above high water. Some of the larger holes develop into small flat-floored pools containing salt water. On open coasts the pinnacles are vertical, but on cliffs and under notch overhangs they are angled towards the sea (cf. Kuenen 1933, p. 32). The rock in the pinnacles is very recrystallized and brittle, and rings under the hammer. These erosion pinnacles are only found on rough-water coats with much salt-spray; they are absent, for example, in the Marovo Lagoon, on protected coasts. Similar solution pinnacles are well developed in the salt-spray zone on cliff-tops at Aldabra Atoll in the Indian Ocean (Stoddart & Wright 1967).

6·3. *Modern corals*

The poverty of modern coral growth is one of the most striking features of reef shores in the Solomon Islands. Few flourishing coral reefs were seen: one at Haroro, Sandfly Passage, Florida Islands; another north of Paruru, Marau Sound, Guadalcanal; a third, 10 to 15 m below sea level on a terrace at Matiu Island, New Georgia. Most of the reef flats identified on air photographs, however, are devoid of living corals, and where corals do occur, they are often dead. Colonies of dead corals, in the position of growth and unfragmented, but emergent at low tide levels, have been seen at Marau Sound and Honiara, Guadalcanal; in the Florida and Russell Islands; at Gizo and Kolombangara; and on New Georgia. Only at Kolombangara was the reason for death apparent (burial by fluvial sediment from an actively eroding cone).

The *regional* problem of poverty in reefs can be explained by the tectonic behaviour and geomorphic history of the region: coral shores are steep and often exposed, and there is no suitable substrate in many areas for large corals to develop. Over a large part of the Solomons the subtidal consists of near-vertical cliffs of old coral limestone, with scattered modern corals; the use of the term 'coral reef' in this situation is misleading.

The problem of recently dead corals at unusually high levels is more difficult. Two major reasons may be considered. First, as Dr H. B. S. Womersley has suggested, mean sea level may vary seasonally, permitting corals to grow at some seasons at levels where they are killed at others. This suggestion has been amplified to include the effect of either high insolation during mid-day low tides, or of high rainfall during low tides, both leading to mortality. Of the two, lowered salinity is probably the most likely cause of death. It is not possible to calculate, in the Solomons, the probability of heavy rainfall coinciding with extremely low tides, but rainfall is so high (Brookfield & Hart 1966) that death is likely from this cause.

Tidal records made during the expedition were too short to bear on the problem of seasonal fluctuation, but two longer periods of record were obtained from the B.S.I.P. Marine Department in Honiara: the first extends from 6 January to 14 July 1962, and the second (with 7 weeks missing) from 10 November 1962 to 7 June 1963, both series recorded automatically at Point Cruz, Honiara. Figure 62 plots, for each week of record, the lowest, highest, and mean weekly tidal levels recorded. The extreme range over the period of record was 1·04 m, the greatest range in any week 0·945 m. Mean sea level over the combined periods of record was at 1·78 m (datum not specified); the standard deviation of weekly means was 0·0555 m. Both periods of record show the weekly mean to be below the over-all mean in January and February, above it in March, April (by up to 0·12 m) and early May, and below it from late May onwards. The trend in level of weekly high waters is less apparent: the mean level is 2·155 m, and the standard deviation of the weekly maxima 0·049 m, with, at least in the 1962 records, higher levels in April and May and lower ones at other times.

The level of weekly low tides is more variable than either the weekly mean or weekly high water levels. The over-all mean low level and the standard deviations of the weekly values are as follows:

	mean	σ
Period I: January to July 1962	1·463	0·116
Period II: November 1962 to June 1963	1·405	0·095
both periods	1·433	0·110

In the most complete record (Period I), actual weekly low tide levels were above the mean low level for 10 consecutive weeks in April and May, by up to 0·168 m. During November to February and from late May to July the lowest levels are below the mean by up to 0·244 m. There are no data for the period late-July to early November.

Thus while high water and mean levels for the period are relatively invariant, on a weekly basis, over at least half the year, the considerable variations in the level of weekly extreme low water, which have an amplitude of 0·412 m, could well be of direct ecological significance. Dr H. B. S. Womersley has also pointed out that in the Solomons low tide occurs during the day in winter and during the night in summer.

The second reason for coral death could be continuing uplift of reef substrates in a tectonically active area. The Solomon Islands form one of the most seismically active areas of the globe, and land displacements are frequent. Grover (1955, 1958*a*, 1960, 1965*b*) has catalogued the distribution of earthquake epicentres in the Solomons for 1952–62 (figure 63). The distribution shows a concentration of deeper focus shocks south of Bougainville and in the Santa Cruz Islands, and a relatively smaller number of mainly shallow focus shocks in the Solomons proper. Solomons earthquakes are concentrated in the Guadalcanal–San Cristobal area, with a much smaller number in New Georgia and along the northern chain of islands.

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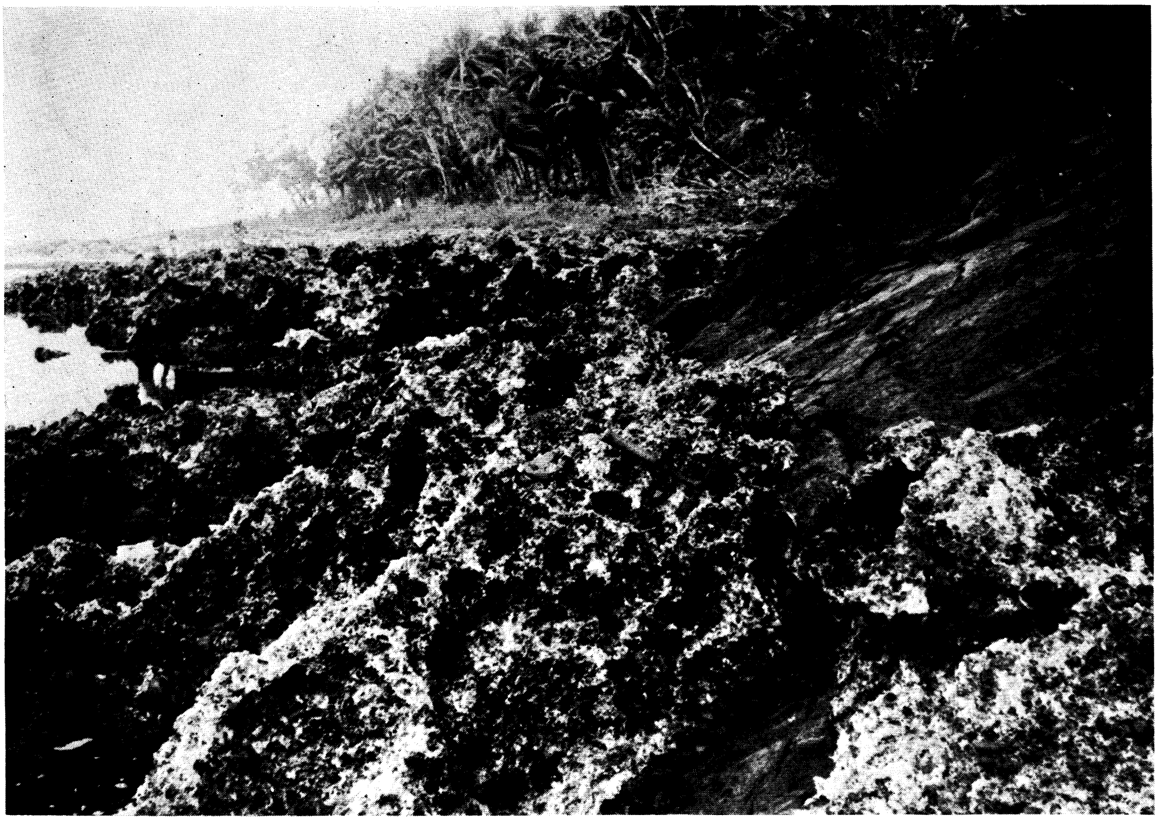
FIGURE 64. Sand cays of Marau Sound, East Guadalcanal, looking westwards from Lauvie Island Massive beachrock in the foreground.

FIGURE 65. Algal-rimmed pools at Kopiu Bay, south coast of Guadalcanal.



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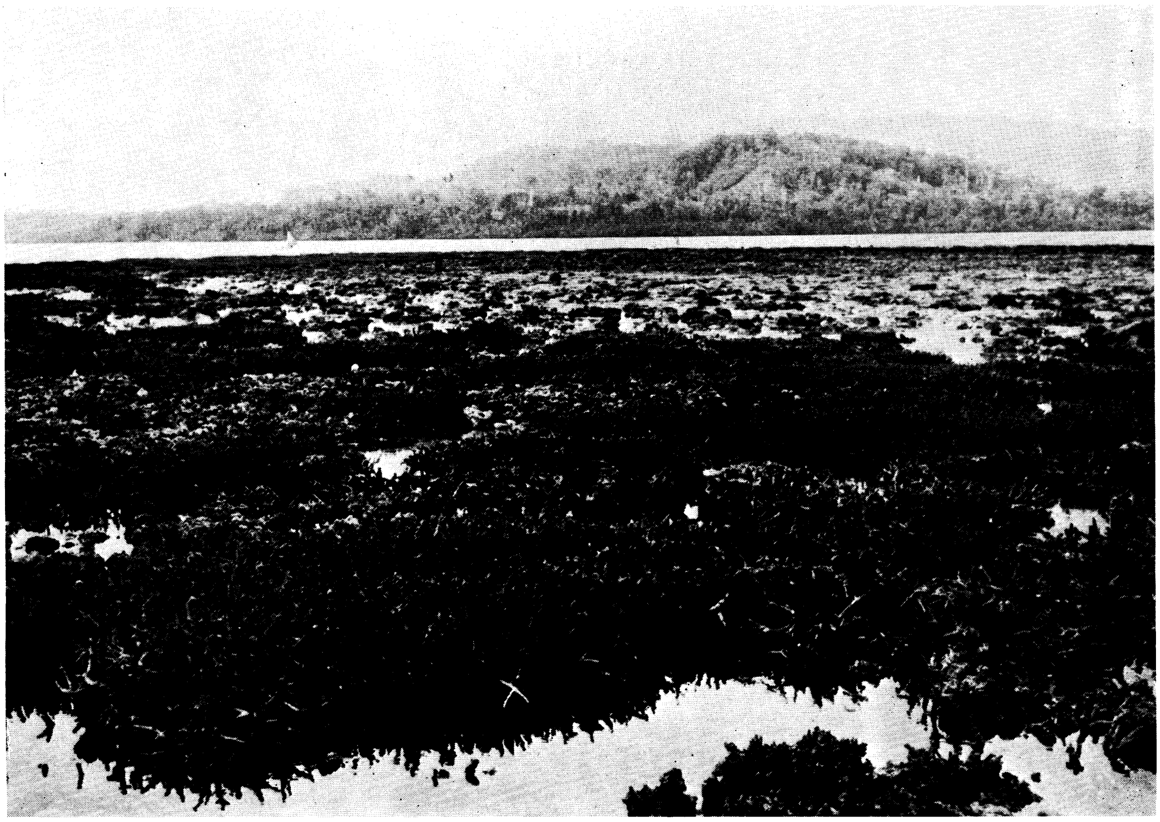

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FIGURE 66. Contact between elevated reefrock and basalt at Kopiu Bay, south coast of Guadalcanal.

FIGURE 67. Thickets of dead *Acropora* exposed on the drying reef-flat surface of Harbour Reef, Marau Sound.

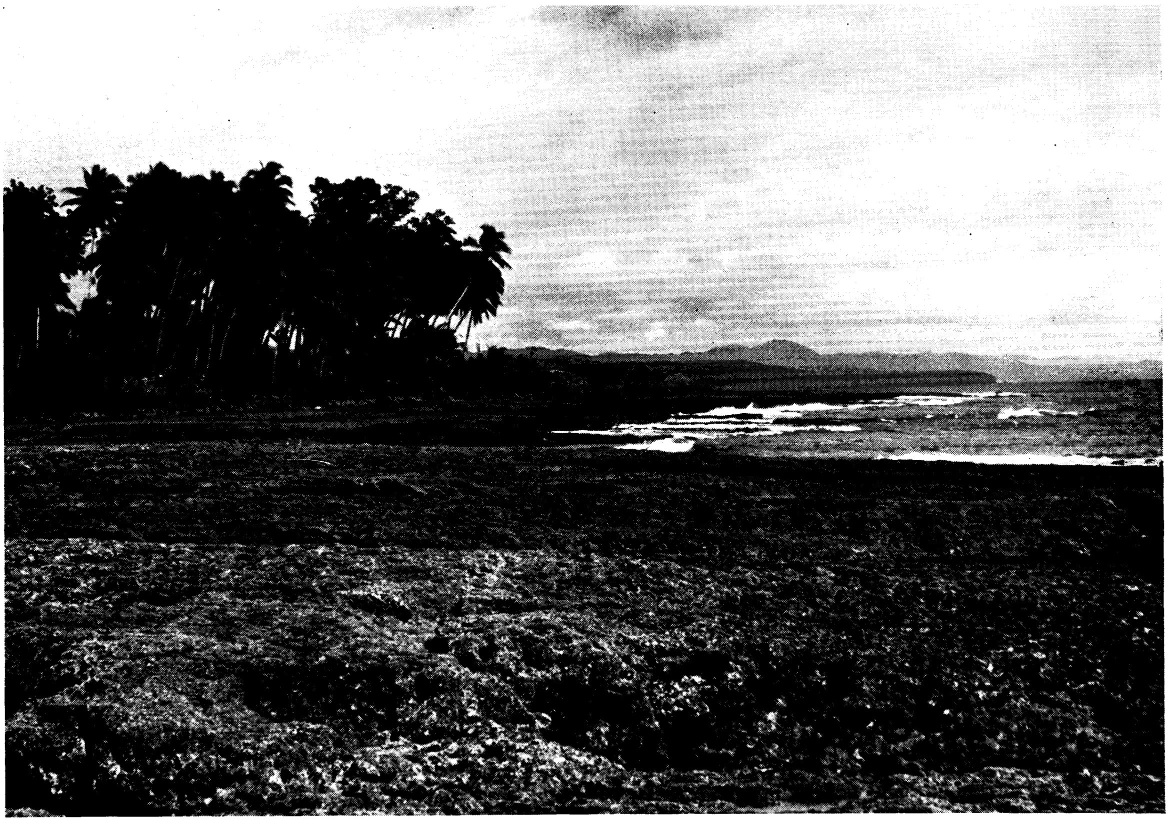

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FIGURE 68. Elevated fringing reef at Kira Kira, San Cristobal.

FIGURE 69. Transverse grooves and high-level rimmed pools, elevated fringing reef at Kira Kira, San Cristobal.

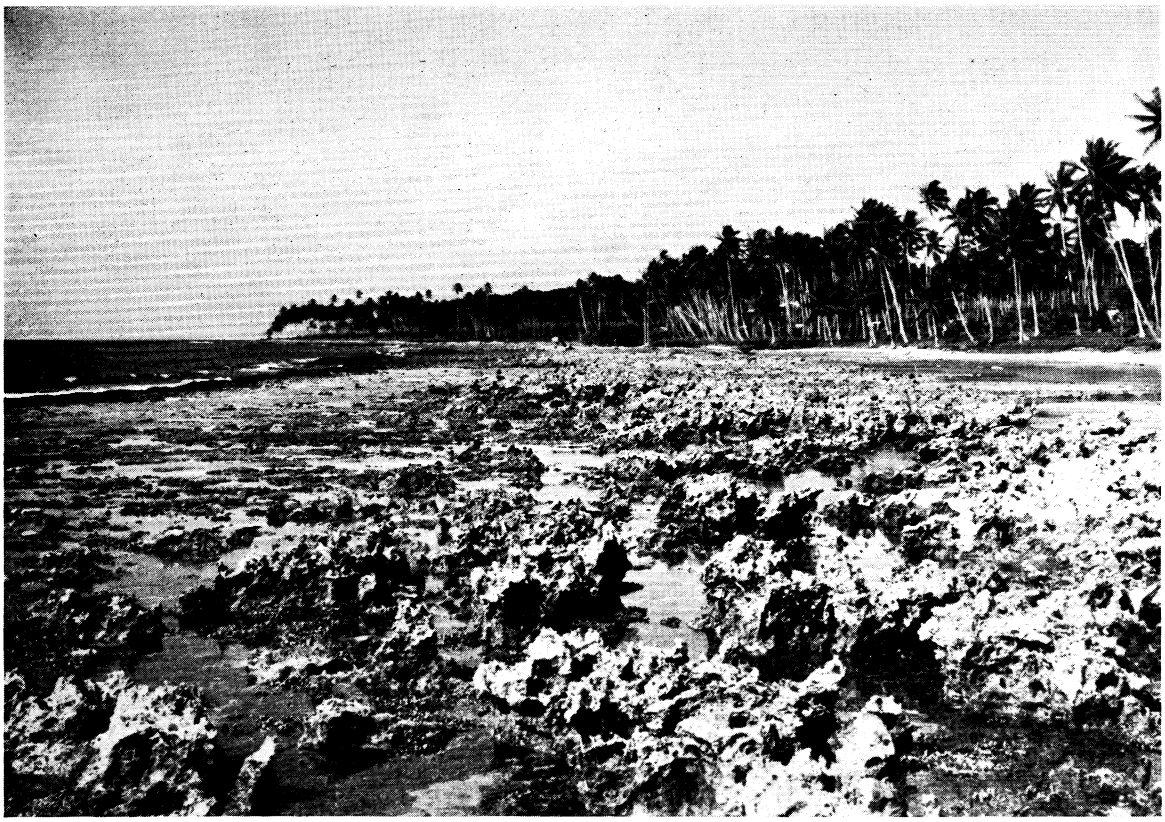

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Figure 70. Reef flat at Banika Island, Russell Group, showing eroded residuals of a higher surface.
Figure 71. Reef flat at Banika Island, Russell Group, showing the inner moat.

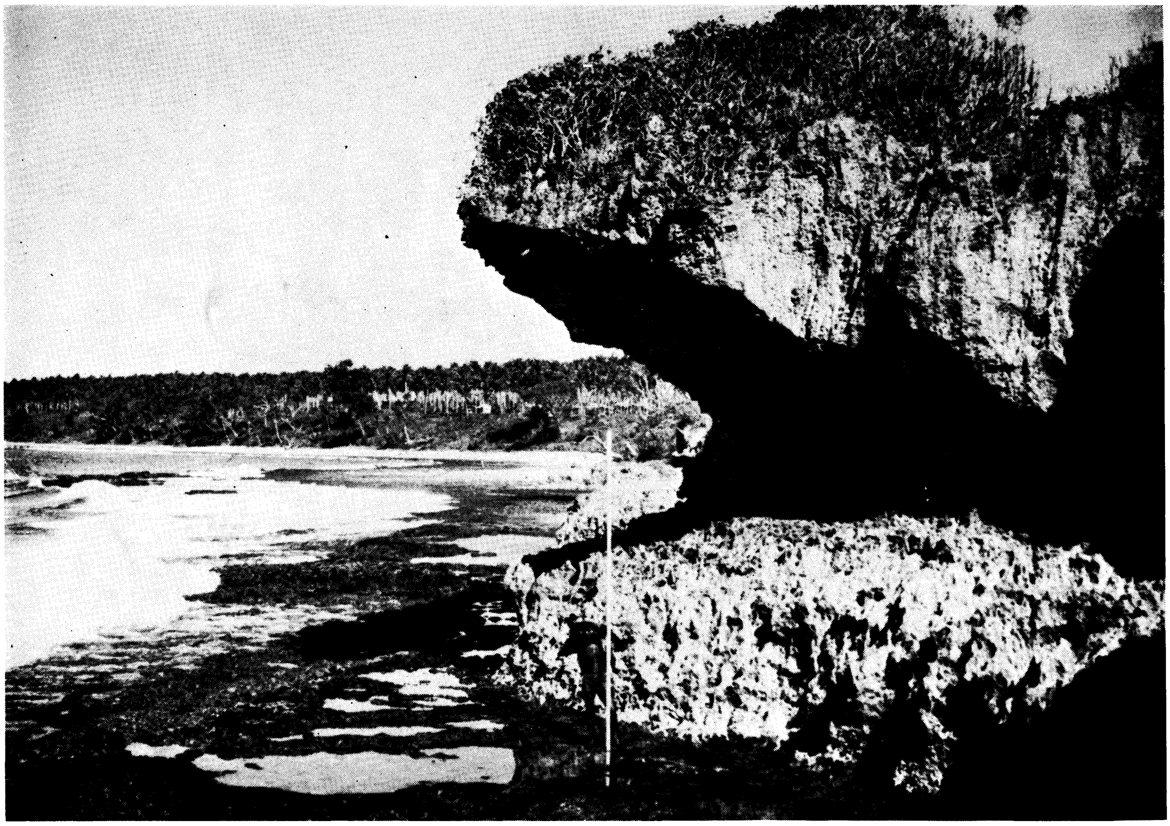

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FIGURE 72. 4 m elevated notch in cliffs at Lingatu Point, Banika Island, Russell Group.

FIGURE 73. Tidal notch of the elevated cliff line, east coast of Banika Island, Russell Group.

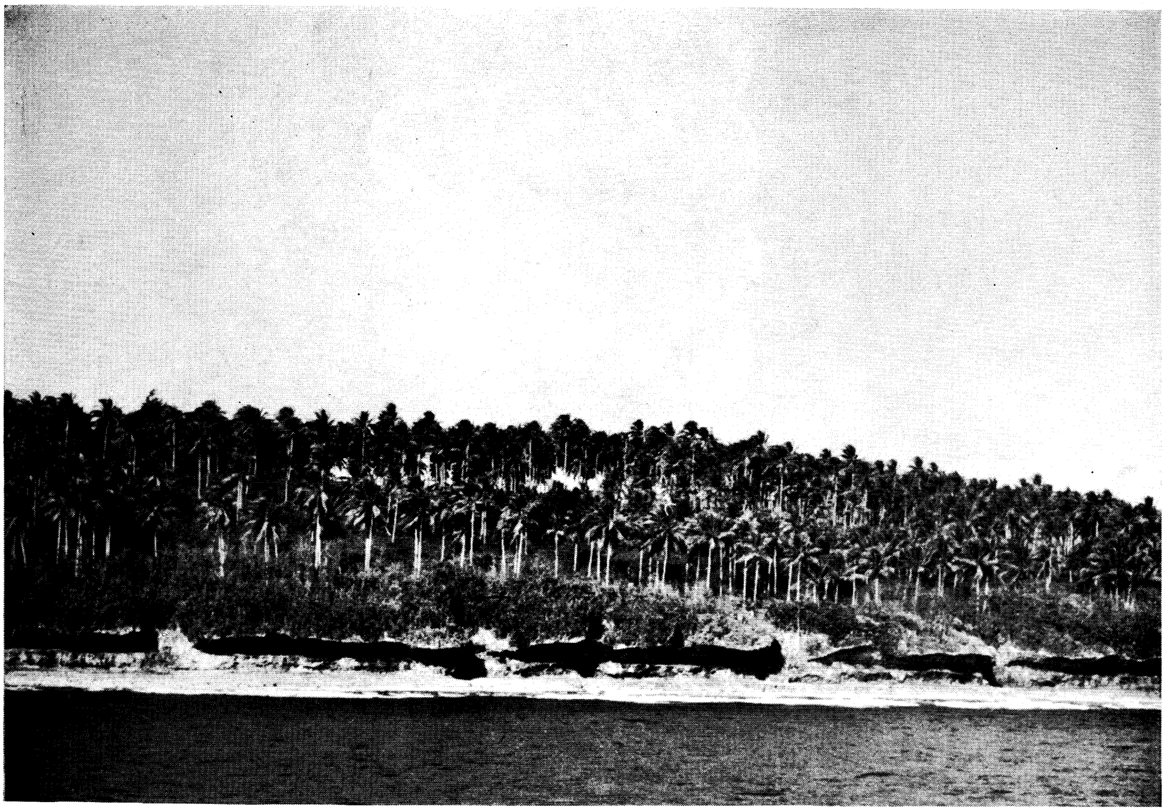

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FIGURE 74. Lingatu Point, Banika Island, Russell Group, from the sea, showing the 4 m and higher levels.

FIGURE 75. High-level rimmed solution pools at Batuona Island, New Georgia.

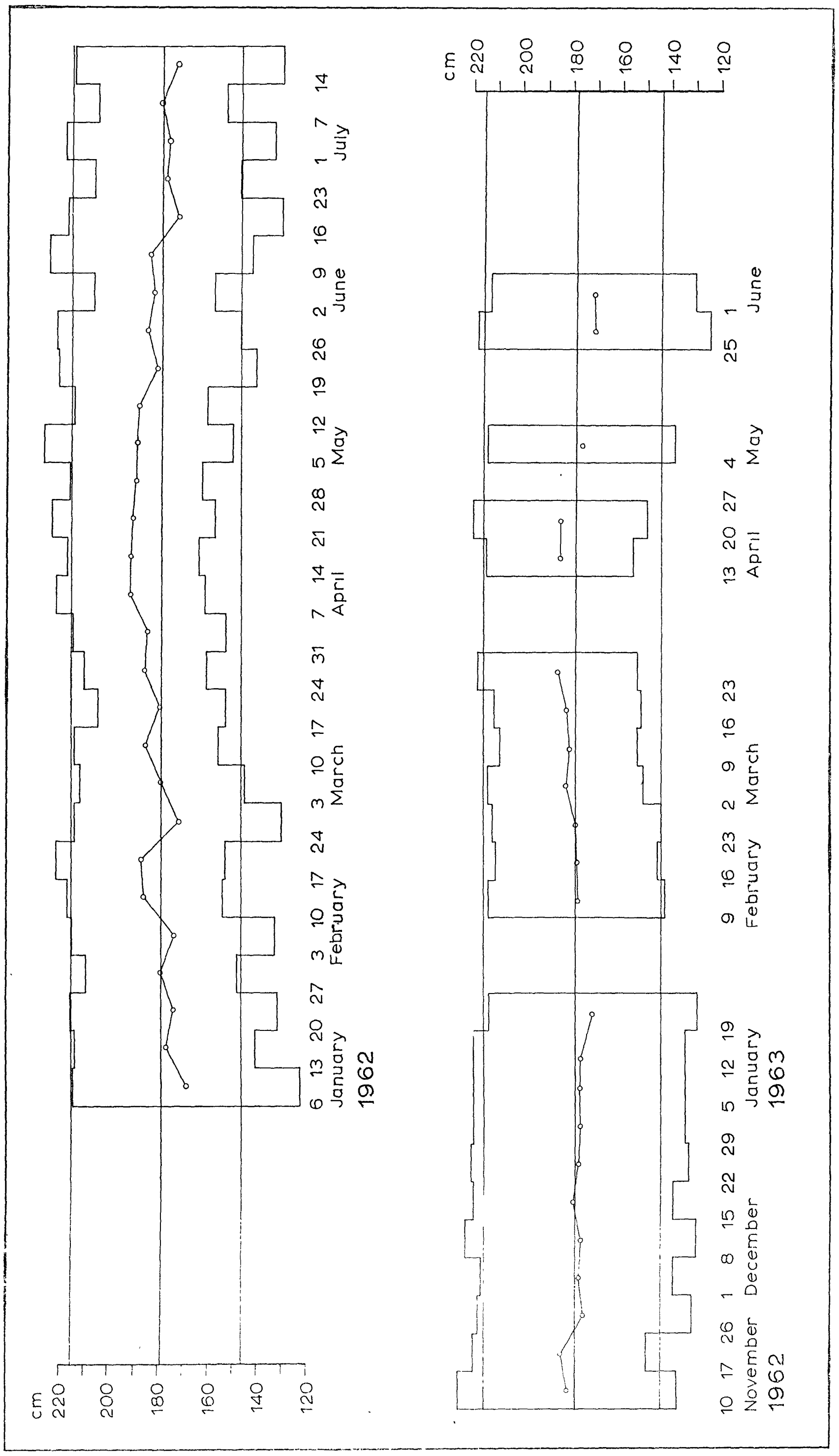

FIGURE 62. Weekly tidal levels, Honiara, Guadalcanal, from records for 6 January to 14 July 1962 and 10 November 1962 to 7 June 1963.

Effects of earthquakes on shorelines are recorded in a number of instances. Thus the 1930 earthquake both elevated and drowned mangroves on eastern San Cristobal (Grover 1955, p. 43; Grover 1958*a*, p. 84), and that of 1959 on Vella Lavella had similar effects (Grover 1965*a*). Trees are reported recently drowned at Poroi, Ranongga, by Pudsey-Dawson (1960*c*) and on Malaita by Dr T. C. Whitmore. There is an eye-witness account of emergence of reef flats and mangroves during an earthquake on 1 August 1961 at Marau Sound, Guadalcanal (Grover 1965*b*, p. 188). Relative movements of 1 to 1·25 m have been described as a result of these disturbances; movements of less than 0·5 m would in many cases have been sufficient to cause the death of corals in observed cases.

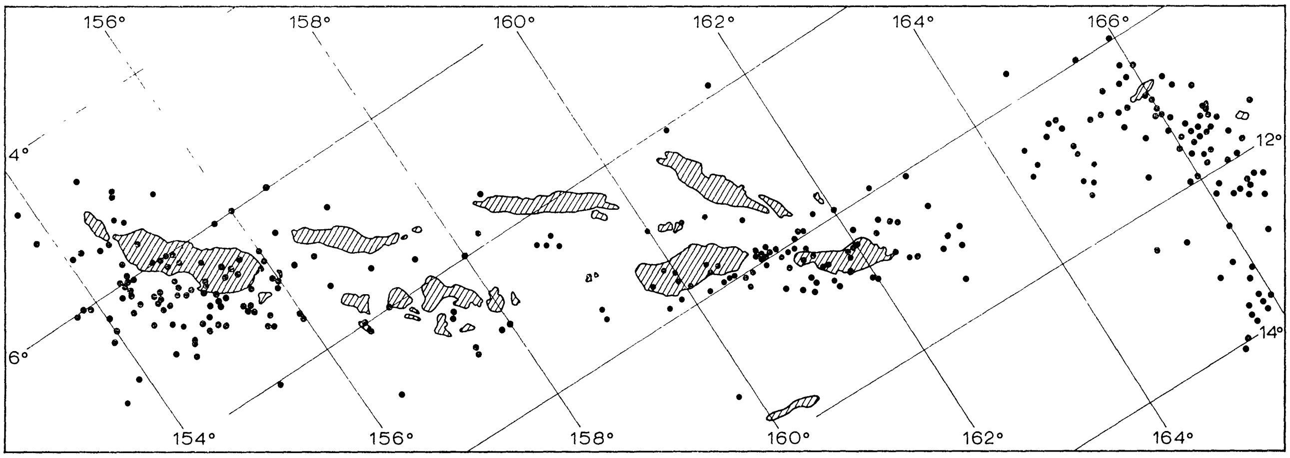

FIGURE 63. Distribution of earthquake epicentres in the Solomon Islands, 1952–62, based on Grover (1958*a*, 1960, 1965*b*).

Such movements are essentially episodic and limited in extent: some areas of the Solomons may have been stable long enough for coral growth to form reefs. Thus when Grover resurveyed in 1951 the benchmark established in 1882 by Guppy in an intertidal notch on Ugi, at 1·98 m above mean sea level, he determined its level to be 1·78 ± 0·1 m and concluded that no significant movement had taken place (Grover 1958*a*, pp. 43–45). Slight movements of elevation would of course reinforce the effects of seasonal variations in tidal levels. The fact that corals are able to grow at lower levels where topography permits rules out such factors as disease as a cause of death.

7. GENERAL CONSIDERATIONS

Geomorphic work during the expedition concentrated on detailed shoreline features rather than on the geological relationships of coastal features, and it was not expected that the expedition would contribute to the wider geological problems of stratigraphy and tectonics. Because the Solomons have been regarded, however, since Guppy, as a type-area for theories of reef development opposed to Darwin's, this paper is concluded with brief observations on more general problems of theoretical importance.

First, while it is undoubtedly true that the Solomons as a whole form a region of reef uplift, with reef limestones carried to heights of at least 300 m on Guadalcanal and

Choiseul, uplift has not been uniform, and many of the first-order reef features of present coasts are clearly related to differential local movements. Thus, to take simple examples, Gizo is a volcanic block tilted to the north, with a steep coast with fringing reef on the south side and a drowned coast with barrier reef to the north. The Russell Islands similarly are tilted to the north: the southern coasts are abrupt and reefless, the northern coasts lower, drowned, and rimmed by a barrier reef. On Malaita the east coast is submergent, with inlets and mangroves, the west coast emergent with a raised barrier reef. The barrier reef of Marau Sound has formed round the foundered eastern end of Guadalcanal, and the reef complex of northwest Santa Isabel round the faulted and foundered end of the island. The great areas of reefs in the New Georgia group appear to be formed round volcanoes of different ages in a classical Darwinian manner. The most recent history of uplift of all of these reefs thus does not disguise their basic structural and topographic relationships, and the picture which emerges is certainly more diverse than that of continuous emergence of small reef-caps of the sort postulated for Ugi and the Shortlands by Guppy.

The complexity of reef forms developed, however, depends largely on the recent history of relative movements of land and sea; most are small-scale features considered in § 6. The double barrier reefs of the Solomons deserve greater attention: that fringing Marovo Lagoon, New Georgia (in part a triple barrier) and that along the north coast of Kohinggo Island, Blackett Strait, are the best defined double barriers in the world. Small and often poorly developed double barriers have been reported from Fiji (Davis 1920; Kuenen 1951), New Caledonia (Guilcher 1965), and the Comoros (Guilcher, Berthois, Le Calvez, Battistini & Crosnier 1965). Double barriers are not easily explained on the Darwinian model, especially when, as in Marovo, the outer is considerably higher than the inner reef: such an arrangement presumably has a tectonic explanation. At Kohinggo, and also in the Shortland Islands (Guppy 1884), the outer barrier is lower than the inner, and may have been developed after the uplift of the inner, before it was itself uplifted. The double barrier problem would repay further study in the Solomons.

The second point of theoretical importance is that because of the ubiquity of elevated reefs the Solomon Islands provides a model of conditions in the coral seas during the low sea levels of the Pleistocene. Daly (1910, 1915, 1919) based his theory of the glacial control of coral reefs and the formation of atolls largely on assumptions about the efficiency of low-level marine abrasion during Pleistocene low stands of the sea: his theory called for widespread truncation of emergent reefs (later less emphasized), to form the bases of post-glacial reef growth and to account for accordant lagoon floors. In the Solomons, marine erosion of emerged coral limestone is a self-regulating process: when an intertidal notch is cut to depths of 10 to 15 m the cliff above becomes unstable and collapses, and the process of erosion must begin again. Rough calculations of the order of magnitude of time required for bevelling an island 0·5 km wide, at known rates of notch-cutting, depending on the amount of reef limestone elevated above the sea, suggest that such bevelling would not occur in the time available in the Pleistocene. Newell's (1960) studies of aeolianite shores in the Bahamas led to a similar conclusion: that Daly's theory was based on untenable assumptions. It is also pertinent to note that in the last glaciation, when Daly argued that reefs were killed by emergence and prevented from growing at lower levels by abrasion, increased turbidity and lowered temperatures, coral reefs were flourishing in the Russell Islands, when world sea levels were presumably *ca.* 100 m below the present and sea temperatures about 6 °C cooler.

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FIGURE 64. Sand cays of Marau Sound, East Guadalcanal, looking westwards from Lauvie Island Massive beachrock in the foreground.

FIGURE 65. Algal-rimmed pools at Kopiu Bay, south coast of Guadalcanal.

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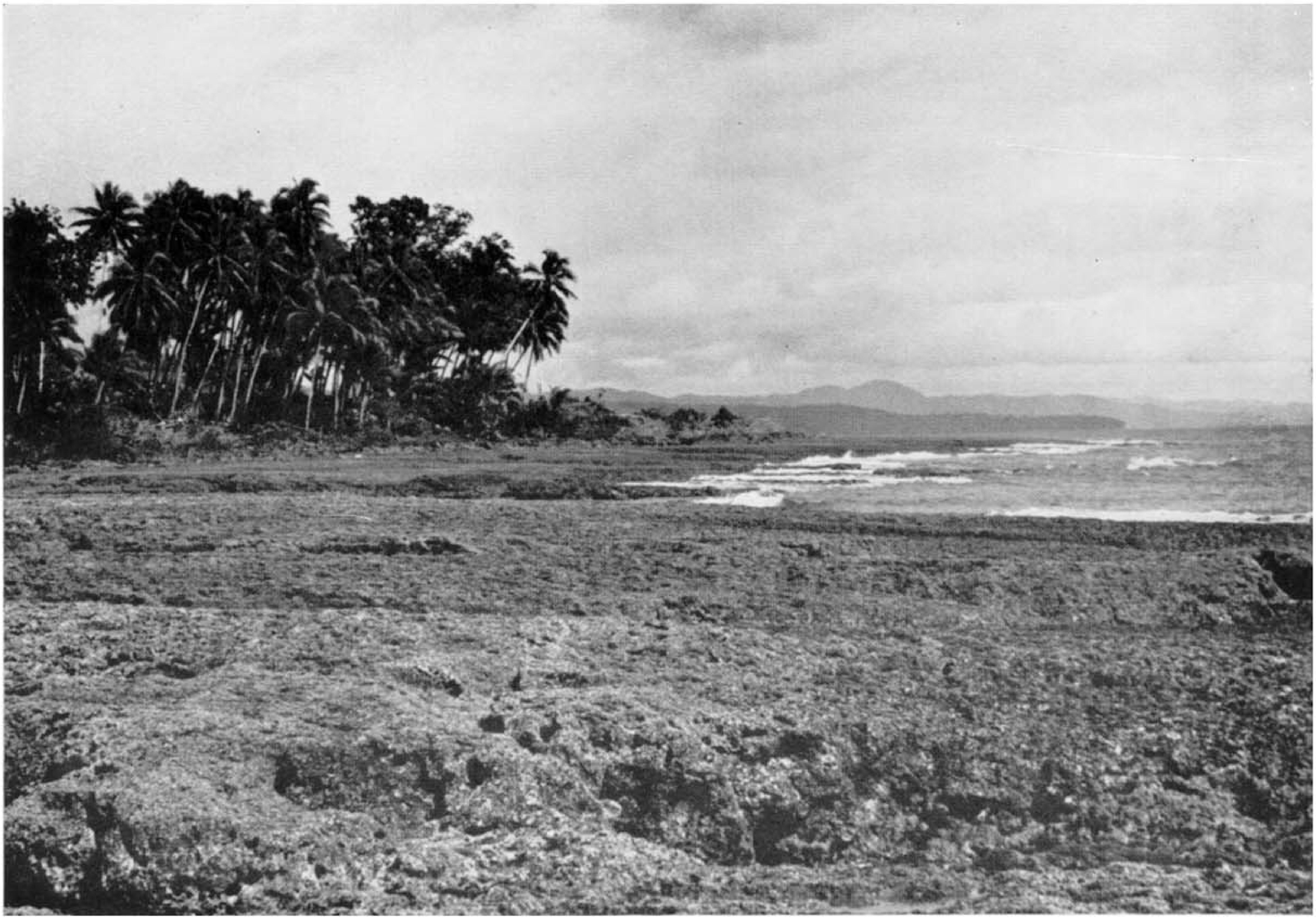
FIGURE 66. Contact between elevated reefrock and basalt at Kopiu Bay, south coast of Guadalcanal.

FIGURE 67. Thickets of dead *Acropora* exposed on the drying reef-flat surface of Harbour Reef, Marau Sound.



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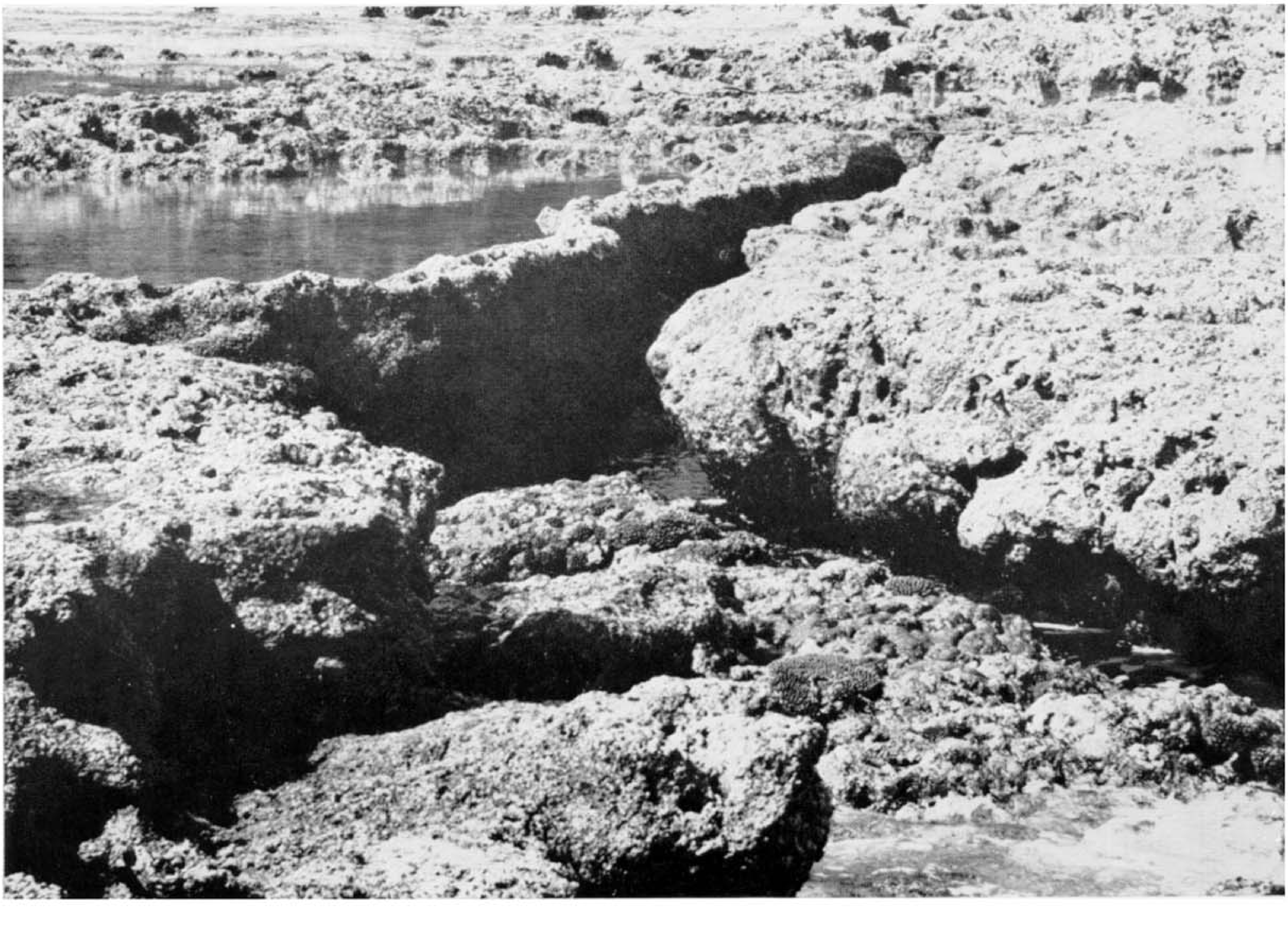

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FIGURE 68. Elevated fringing reef at Kira Kira, San Cristobal.

FIGURE 69. Transverse grooves and high-level rimmed pools, elevated fringing reef at Kira Kira, San Cristobal.

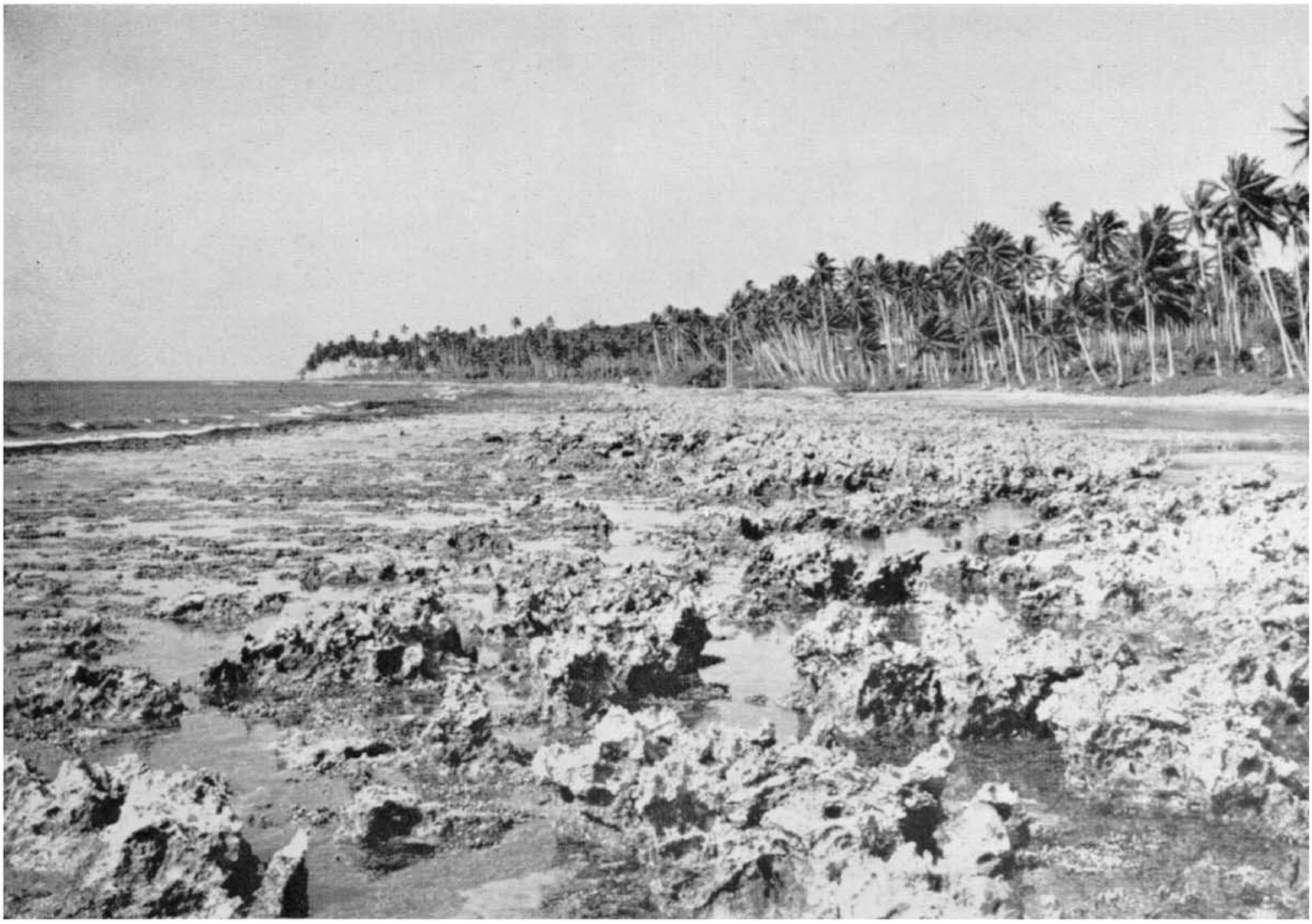

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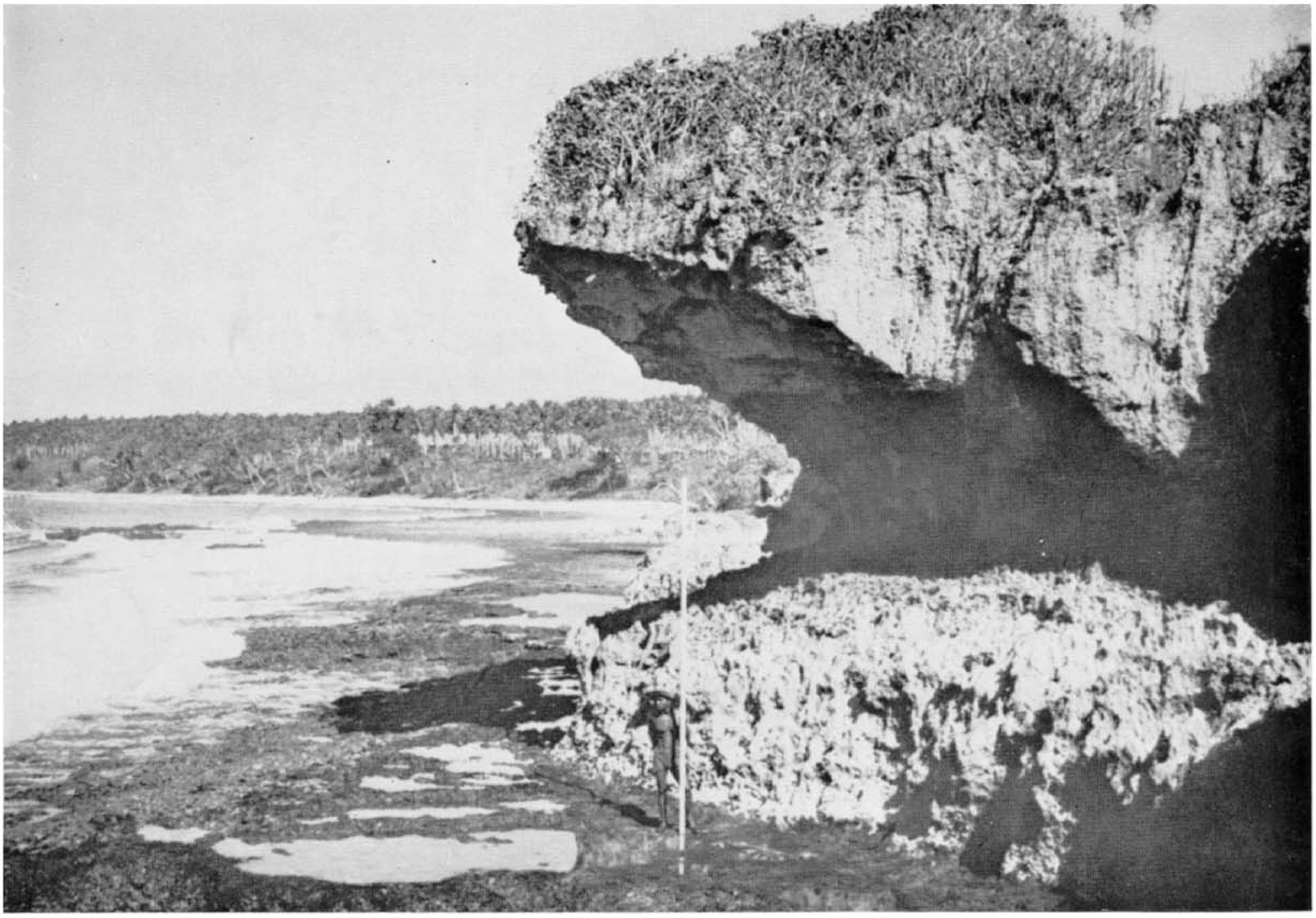
FIGURE 70. Reef flat at Banika Island, Russell Group, showing eroded residuals of a higher surface.

FIGURE 71. Reef flat at Banika Island, Russell Group, showing the inner moat.



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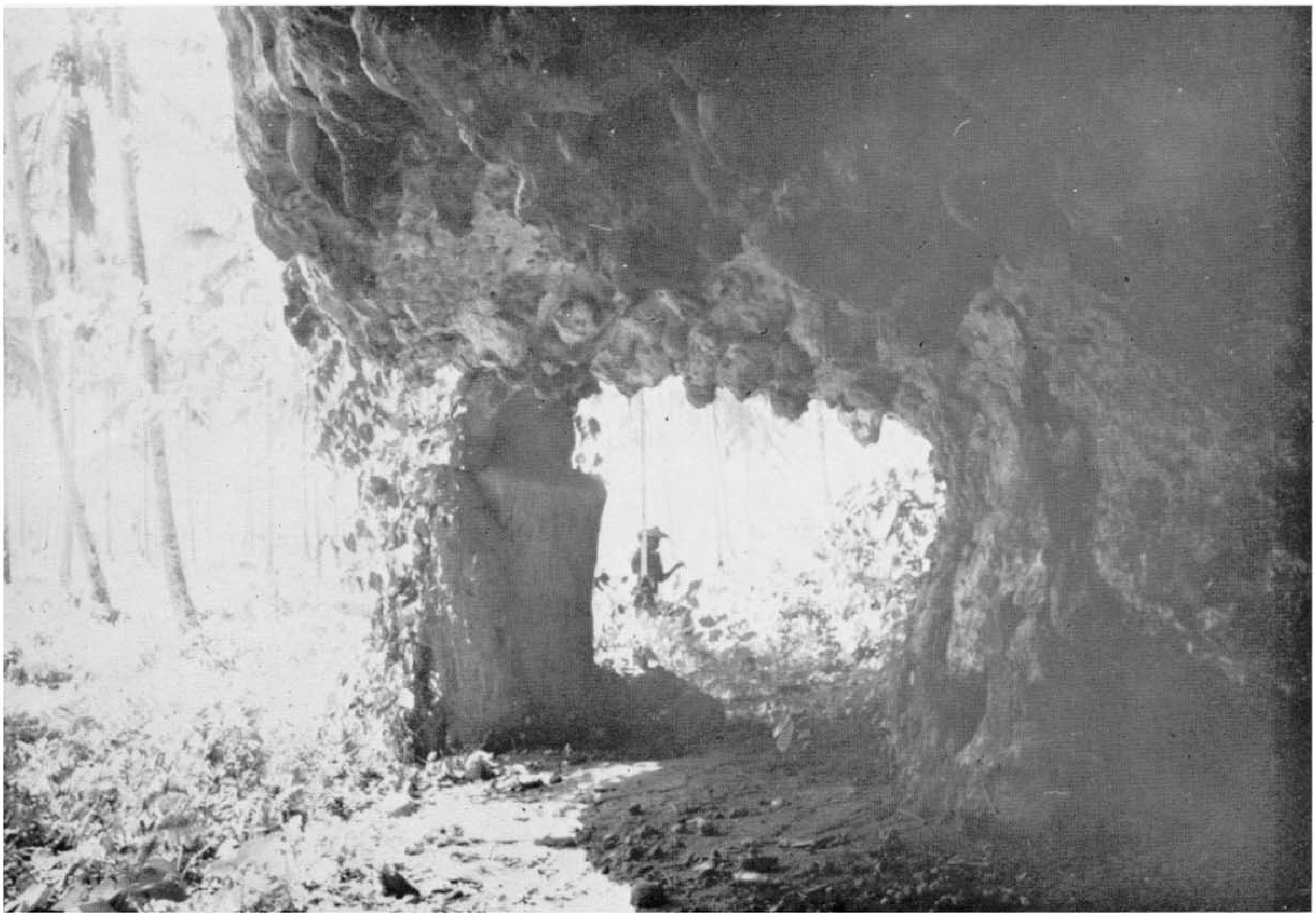

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FIGURE 72. 4 m elevated notch in cliffs at Lingatu Point, Banika Island, Russell Group.

FIGURE 73. Tidal notch of the elevated cliff line, east coast of Banika Island, Russell Group.

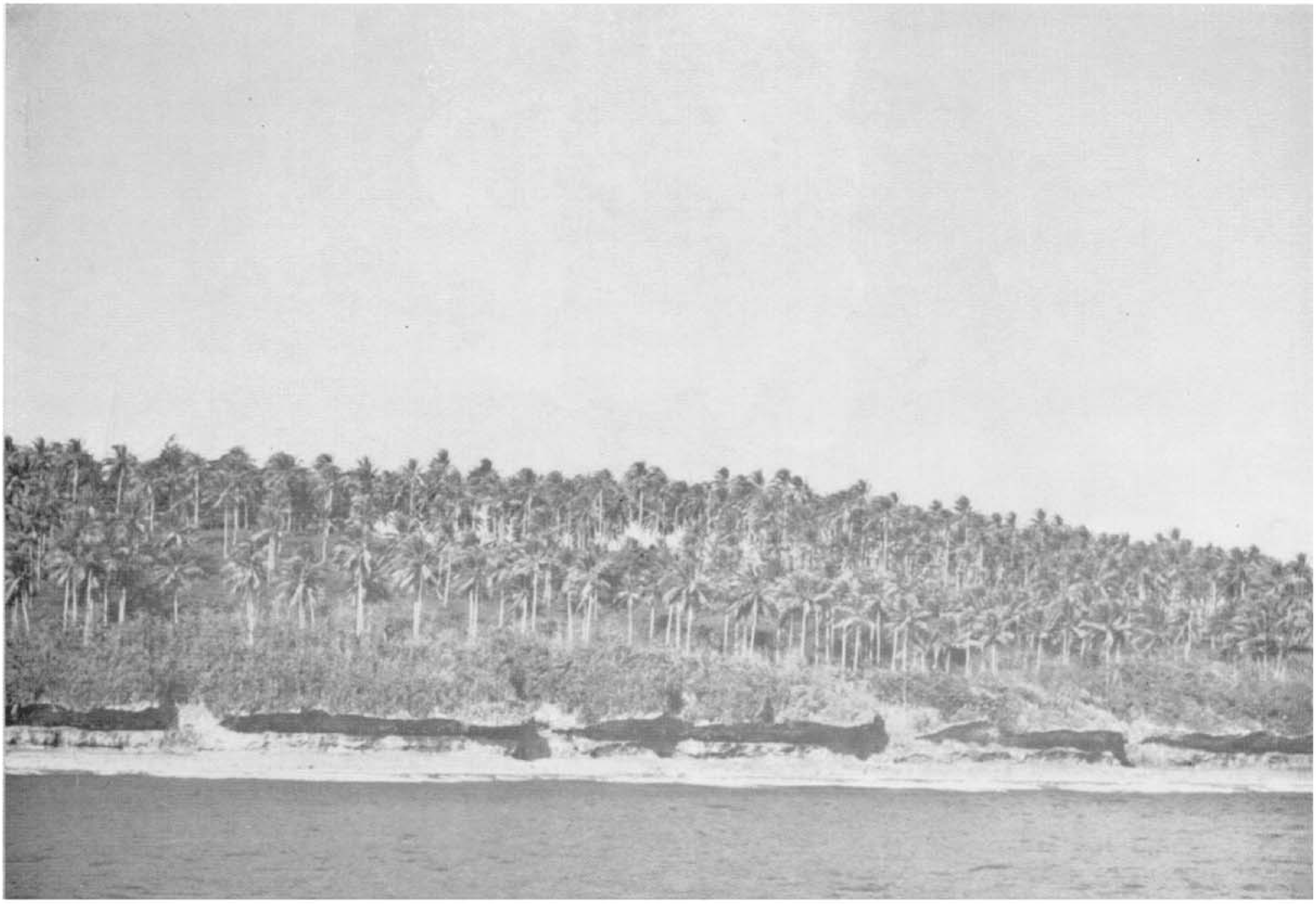

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FIGURE 74. Lingatu Point, Banika Island, Russell Group, from the sea, showing the 4 m and higher levels.

FIGURE 75. High-level rimmed solution pools at Batuona Island, New Georgia.