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MAUKE, MITIARO AND ATIU: GEOMORPHOLOGY OF MAKATEA ISLANDS IN THE SOUTHERN COOKS

BY

D. R. STODDART, C. D. WOODROFFE AND T. SPENCER

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MAUKE, MITIARO AND ATIU: GEOMORPHOLOGY OF MAKATEA ISLANDS IN THE SOUTHERN COOKS

BY

D. R. STODDART[1], C. D. WOODROFFE[2] AND T. SPENCER[3]

ABSTRACT

Mauke, Mitiaro and Atiu are deeply eroded volcanic islands in the southern Cook Islands, south Pacific, each surrounded by a rim of elevated Cenozoic reef limestone (makatea). This paper presents the results of instrumental topographic surveys of each island. The maximum elevation of the volcanics is 24.4, 8.9 and 71.0 m on Mauke, Mitiaro and Atiu, respectively, and of the makatea 14.7, 10.9 and 22.1 m. The makatea is fringed on its seaward side and in places partially overlain by a sequence of late Pleistocene reef limestones which reach maximum elevations of 12.7, 7.8 and 12.2 m respectively. These exhibit varied reef facies as well as emergent reef topographies, especially groove-and-spur systems. Elevated notches, cliff-foot benches and emergent reef flats indicate higher Holocene relative sea-levels at up to at least 3 m above present. These data are compared with similar features on Mangaia, also in the southern Cooks, and the very different topographic and stratigraphic records on Rarotonga and Aitutaki, and the implications of the independent island histories thus revealed for previous discussions of lithospheric flexure and Pleistocene sea-level change are reviewed.

INTRODUCTION

The islands of Mauke, Mitiaro and Atiu in the Southern Cook Islands rarely enter into the scientific literature. Atiu was discovered during the voyage of the *Resolution* and *Discovery* —Cook's last voyage—on 31 March 1777. Lieutenant Gore, at Cook's request, 'examined all the west side of the island without finding a place where a boat could land or the Ships could anchor, the shore being every where bounded by a steep corral rock against which the sea broke in a dreadfull surf' (Beaglehole, ed., 1967, I, 83). A landing was effected from boats at Oravaru on the west coast on 3 April, when William Anderson made the first geological and geomorphological observations:

> 'Whatever the island itself may be further in we could not tell, but towards the sea it is nothing more than a bank of coral ten or twelve feet high, steep and rugged except where there are small sandy beaches at some clefts where the ascent is graduall. The coral, though it has probably been expos'd to the

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[1]Department of Geography, University of California at Berkeley, Berkeley, California 94720

[2]Department of Geography, University of Wollongong, Wollongong, N.S.W., Australia

[3]Department of Geography, University of Cambridge, Downing Place, Cambridge, England CB2 3EN

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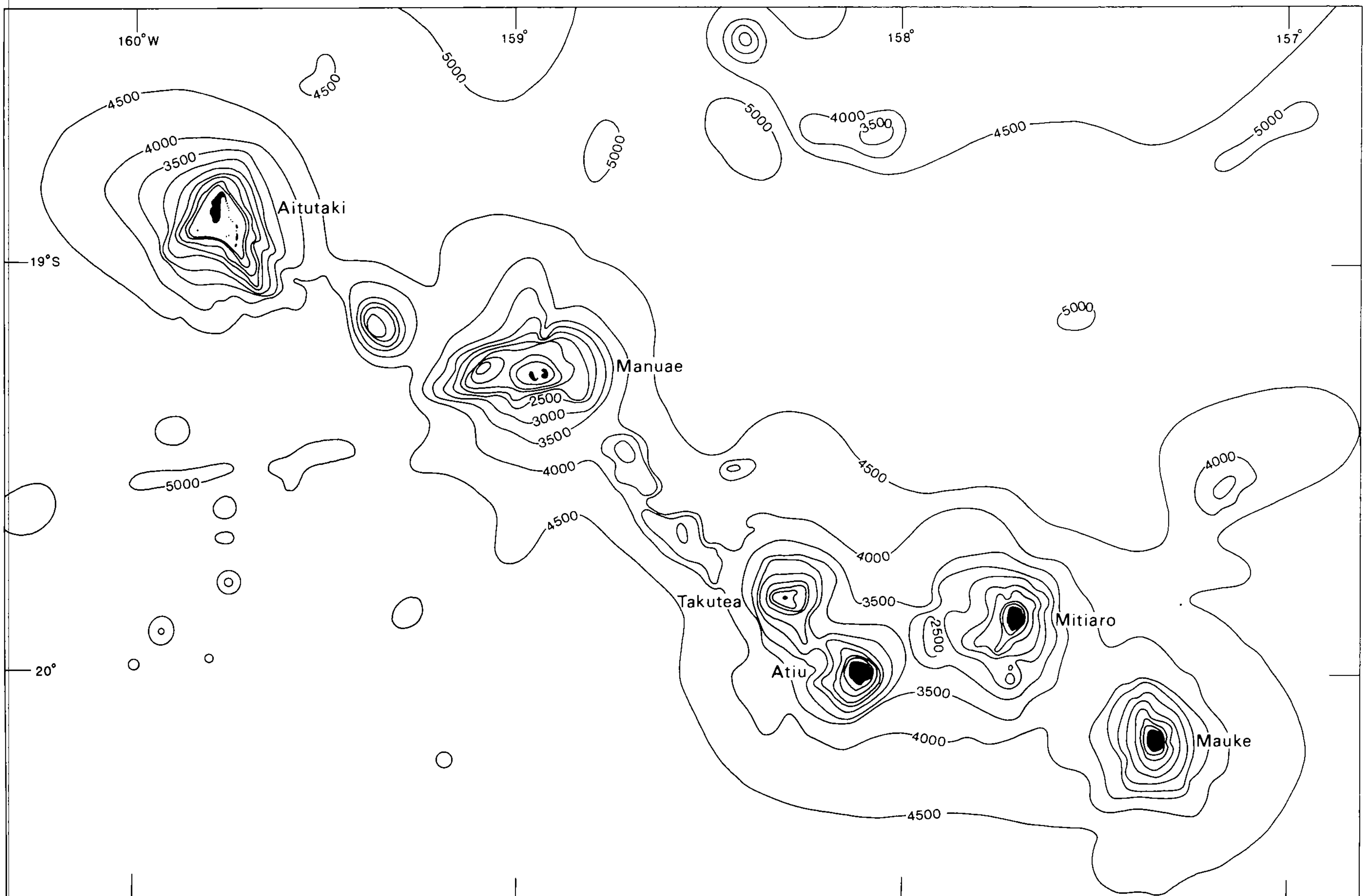


Figure 1. Bathymetry of the southern Cook Islands

> weather for centurys, has undergone no further change than becoming black on the surface, which from its irregularity makes it appear not unlike large Masses of some burnt substance; but on breaking some pieces off we found that at the depth of two or three inches it was just as fresh as the pieces that had been lately thrown on the beach by the sea. The excavations towards the sea mention'd at Mang'ya nooe nainaiwa [Mangaia] were likewise seen here, but it does not seem that they are the effects of the waves dashing violently against the shore; for it is entirely lin'd by a reef or rock running to different breadths into the sea, where it ends all at once and becomes like a high steep wall. It is nearly even with the surface of the water & of a brown or brick colour, but the texture is rather porous though sufficient to withstand the washing of the surf which breaks continually upon it. The soil where we were is light & sandy but within it may differ, as we saw from the ship a reddish cast upon the rising grounds as at Mang'ya ...' (Beaglehole, ed., 1967, III, 841-842).

But Cook stood off for Takutea the following day and the observations were not pursued. Anderson's may be the first description in the literature of an algal ridge, as well as of cyanobacterial darkening of reef limestones.

John Williams called at Mauke and Mitiaro as well as Atiu fortyfive years later, during his missionary voyages in 1822, when he described the karst caves for the first time (Williams 1838). Others, including Byron in H.M.S. *Blonde* and W. W. Gill, visited the islands later in the century, but added little of geomorphological significance.

The geology of Atiu was the subject of a report by Marshall in 1930 during the New Zealand geologist's more substantial investigations of Mangaia (1927) and Rarotonga (1930). Marshall and his contemporaries (e.g. Chubb 1927a) realized that the distinctive island types found in the southern Cook and Austral Islands in the central South Pacific posed particular problems of interpretation, with important consequences for the theory of coral reef development, island evolution, and sea level change. These islands, notably Mangaia, Mauke, Mitiaro and Atiu in the Cooks, and Rurutu and Rimatara in the Australs, consist of eroded volcanoes of Cenozoic age, wholly or partially surrounded by uplifted, karst-eroded Cenozoic reef limestones (*makatea* in local usage). Between the central volcanics and the often vertical inner walls of the makatea there is frequently a depression close to sea-level, with swamps, occasional streams, and standing water.

Marshall (1927, 1929) believed that these features represented an uplifted barrier reef and former lagoon surrounding the volcanic island. Chubb (1927b) and Hoffmeister (1930) believed the depression between volcanics and makatea to be of solutional origin and the gross topography of these islands to be therefore secondary. In our previous studies of Mangaia (Stoddart et al. 1985) and Rurutu (Stoddart and Spencer 1987) we have shown that in these two cases the second of these views is correct.

Nevertheless, two interesting questions remain. The first concerns the degree of uplift of the islands as shown by the maximum elevation of the makatea. This varies from ca 10 m on Mitiaro and Rimatara to 73 m on Mangaia and 100 m on Rurutu. McNutt and Menard (1978) in a remarkable pioneering paper hypothesized that uplift resulted from crustal loading through the formation of nearby younger volcanoes and consequent elastic deformation of the crust. Thus the formation of Rarotonga in the Pleistocene could account for the elevation of islands in the southern Cooks such as Mangaia and Atiu, and of Tahiti the elevation of Makatea; they gave many more examples. The degree of uplift in each case would be a function of distance from the load and the magnitude of the lithospheric flexure. Calculations of uplift by McNutt and Menard (1978) and others (e.g. Lambeck 1981a, 1981b) showed apparently close relationships between theoretical predictions and actual island topography, though in the case of many islands the elevations of both volcanics and makatea were in fact very inadequately known (Spencer et al. 1987). The more precise determination of the altitudes of geomorphic features on these islands thus has important consequences for the interpretation of island development and crustal behaviour in the Pacific.

Second, and particularly after the classic paper by Veeh (1966), it was realized that Pleistocene fluctuations of sea level must have had stratigraphic and geomorphic consequences on these emergent islands, and that these fluctuations could be calibrated using radiometric dating techniques. Many workers, especially in the southern Cooks, had already drawn attention to the presence of more or less well-marked terraces and notches apparently indicative of high sea level stands (Grange and Fox 1955, Schofield 1967, Wood and Hay 1967, Campbell 1982), but the elevations, extent and significance of many of the features to which they drew attention were only weakly established. In our earlier work on Mangaia we identified reef deposits and geomorphic features related to a sea level of last interglacial age (and perhaps earlier) (Stoddart et al. 1985) and calibrated these with uranium series ages (Spencer et al. 1988).

The present study concerns three further islands in the southern Cooks. Mauke, Mitiaro and Atiu were visited by us in June 1985. All three authors were responsible for the surveys on the first two islands. Woodroffe was primarily responsible for the surveys on Atiu, though Stoddart and Spencer also visited the island and inspected the profile sites. The aim of this paper is to present a detailed descriptive geomorphology of each of these islands, with particular reference to the limestones, derived from instrumental levelling of profiles transverse to the coasts. We have determined the elevations of both volcanics and makatea on Mauke and Mitiaro, though on the larger islands of Atiu our surveys were limited to coastal sequences. On all three islands we have found diverse evidence, both morphological and stratigraphic, of late Pleistocene sea level fluctuations. Sequences of radiocarbon and uranium-series dates for Holocene and Pleistocene deposits are available and will be reported elsewhere (Woodroffe *et al.*, in press; Woodroffe *et al.*, in preparation), but they confirm the complexity of the record established in the field and also show that the features we describe are not confined in age to Last Interglacial times.

STUDY AREA

Geomorphology

The southern Cook and Austral Islands comprise two parallel chains of islands extending over some 22° of longitude or ca 2600 km. The southernmost extends from Macdonald Seamount in the southeast to Rarotonga in the northwest, and the northernmost from Rapa and Marotiri in the southeast to Palmerston in the northwest. The existence of these clear linearities, however, disguises the complexity of geomorphic evolution within and between them, and it is clear both from the geomorphic features of the islands themselves and our knowledge of the age of volcanism at each (Jarrard and Clague 1977) that the chains have not developed in simple linear manner from a fixed hotspot (as, for example, the Hawaiian Islands), in which island age and degree of geomorphic development are a simple linear function of distance from the hotspot.

In the southern Cooks, especially, only the volcanics of Mangaia fit the model of age and distance predictions from the Macdonald hotspot: Mauke, Mitiaro and Atiu, as well as Aitutaki and Rarotonga, are all substantially too young. Indeed it has been commented that in spite of such clear island-chain linearity, 'the Austral-Cook chain is clearly the least convincing example of age-distance correlation' among the island chains of the Pacific (Okal and Batiza 1987, 4). Furthermore, the recent detection of ten uncharted or mislocated seamounts in this region reinforces the impression of a complex geological history for the archipelago (Lambeck and Coleman 1982, Diament and Baudry 1987, Baudry et al. 1987, 1988).

The islands studied here comprise a sector of the northern chain extending between Mauke and Aitutaki, contiguous at the 4.5 km isobath (figure 1). Of the six islands in this group Aitutaki is an almost-atoll with a substantial residual volcano 124 m high, but with no elevated Pleistocene or Holocene reef limestones (Stoddart 1975); Manuae and Takutea are reefs and reef islands close to present sea level (though there is no recent account of either, other than Summerhayes's (1971) on the sediments of Manuae) and we rely for most of our information on their geomorphology on the reports of Cook's second voyage in 1777); and Atiu, Mitiaro and Mauke are makatea-encircled volcanic islands, with the components of central volcanics, makatea and swamps, though of very different individual characteristics.

K-Ar dates of volcanics give ages in excess of 8.1 Ma for Aitutaki, though with renewed volcanism at 0.7-1.9 Ma. Atiu volcanics, reaching 72 m above sea level, date at 8-10 Ma; Mitiaro volcanics, reaching 8.9 m, date in excess of 12.3 Ma; and Mauke volcanics, reaching 24.4 m, are in excess of 6.0 Ma (Jarrard and Clague 1977). The three western volcanic islands lack elevated limestones, whereas on Atiu, Mauke and Mitiaro the makatea reaches elevations of 22.1, 14.7 and 10.9 m, respectively (data from this survey). We will also show in this paper that there is evidence of late Pleistocene sea levels up to 12.2 m on Atiu, 10.0 m on Mauke, and 9.8 m on Mitiaro.

Climate

All these islands lie in the Southeast Trades and have tropical climates (see Thompson 1986, from which this summary is mainly derived). Mean annual temperatures are in the range 24-26°C with absolute extremes at Mauke over the period of record (1968-1988) of 34.8°C (in October) and 13.1°C (in July). Seasonality is determined by the latitudinal shift of the South Pacific Convergence Zone, which forms the boundary between the equatorial easterlies and the Southeast Trades. This boundary moves south over the islands, giving wet weather (yielding two-thirds of the annual precipitation) during November to April, and retreats north, giving dry weather during the Trades, from May to October (Table 1).

Table 1. Rainfall of Mauke, Mitiaro and Atiu

	Mean annual rainfall, mm	Wet season rainfall Mean, mm	%	Dry season rainfall Mean, mm	%
Mauke	1773	1156	65	617	35
Mitiaro	1826	1185	65	641	35
Atiu	1970	1336	68	634	32

Source: Thompson (1986, 29, and personal communication)

At Mauke during 1967-1971 easterlies and southeasterlies occurred 58% of the time (the Trades), and winds from the northwest, north and northeast 24% of the time (the wet season). On the same island mean monthly wind speeds averaged 3.1 m/sec during February-April, and 4.1 m/sec during August-November. The annual average of 3.6 m/sec compares with 6.7 m/sec over the adjacent open ocean, though island figures are much affected by aspect and topography.

Mean annual rainfalls are 1773 mm at Mauke (1929-1987), 1828 mm at Mitiaro, and 1970 mm at Atiu (records since 1958). These figures are subject to local topographic control on each island, though this effect is likely to be least on Mitiaro. Inter-annual variability in rainfall is considerable, both in annual and in monthly totals. Table 2 gives mean and extreme figures for the islands. The greatest monthly range at Mauke is between 689 and 5 mm in the month of November, at Mitiaro between 931 and 3 mm in the month of June, and at Atiu between 752 and 0 mm in the month of May. To some extent this variability is explained by irregular movements of the South Pacific Convergence Zone, which themselves correlate with the Southern Oscillation (the longitudinal variation in atmospheric pressure between east and west tropical Pacific). When the SPCZ is unusually far north, rainfall in the southern Cooks may be only 30-40% of the mean.

Hurricanes, defined as low-pressure circular storms with winds in excess of 32 m/sec, are common in this sector of the Pacific and are often of great violence; for a catalogue of more extreme storms in the southern Cooks, see Stoddart (1975, 8). Since 1969, when satellite surveillance began, hurricane frequency has averaged 1.4 per annum in the area.

METHODS

Elevations were determined using a Kern automatic level. The tidal range on these islands has not been established, but it is probably about 80 cm. Because of exposure of the shorelines and rough state of the sea an acceptable survey datum can only be established at low water. We attempted where possible to use the ordinary crest of the algal ridge at the reef edge as the datum for the profile surveys. This usually coincides with the tops of living microatolls in reef flat pools, and also with the lower limit of sand in coastal pocket beaches. Where the algal ridge was inaccessible because of sea conditions, the lower limit

Table 2. Monthly mean and extreme rainfalls (mm) at Mauke, Mitiaro and Atiu

MAUKE (1929-1987)													
Monthly mean	203	226	199	146	151	84	79	100	93	110	166	216	1773
Absolute maximum	549	570	594	415	499	243	269	414	341	380	689	581	3294
Absolute minimum	9	11	1	4	3	6	0	2	3	4	5	7	150
MITIARO (1959-1982)													
Monthly mean	273	204	196	183	138	130	83	88	115	89	149	180	1828
Absolute maximum	554	403	473	495	550	931	201	288	303	201	280	418	2770
Absolute minimum	72	46	0	21	6	3	7	14	19	10	19	9	1079
Mean number raindays	10	9	7	7	5	5	5	5	6	5	8	5	77
ATIU (1959-1982)													
Monthly mean	209	229	223	206	177	84	81	101	81	110	162	307	1970
Absolute maximum	490	732	525	396	752	210	227	488	251	471	479	621	3746
Absolute minimum	5	49	65	7	0	9	0	0	0	0	33	0	690
Mean number raindays	7	9	9	9	6	5	4	3	4	5	6	7	74

Source: Thompson (1986, 30, and personal communication) of sand, which is sharply defined, was used to establish a datum. This datum approximates mean low water, as we have established by precise levelling to benchmarks during earlier work at Rarotonga. Yonekura et al. (1986, 52; 1988) also use the tops of reef flat microatolls as their datum for surveys on Mangaia, and they too believe that this approximates mean low water. In our earlier surveys at Mangaia we used the same algal ridge datum as in this paper (Stoddart et al. 1985). On Mauke we established a benchmark on the base of the white monument at Taunganui (corner nearest the Meteorological Station), at 8.11 m. A second benchmark at 23.55 m was established at the end of profile F, on the metal grid supporting two water tanks adjacent to the pumping shed. On Mitiaro a benchmark was established at 8.73 m at the foot of the water tank steps adjacent to the Cook Islands Christian Church at Mangarei. These benchmarks were used to coordinate the trans-island profiles, and can be redetermined whenever tidal records become available at Mauke and Mitiaro. At Atiu all except E and F of the surveyed profiles were independently calibrated, and no single island datum therefore exists. A level of 10.09 m above mean sea level was determined on the concrete base of the main shed at Taunganui Landing, and elevations on profiles E and F relate to this. Datums of mean sea level on other Atiu profiles were derived from still-water levels and the tidal predictions for Rarotonga (assuming the latter to be lagged two hours relative to Atiu). The datums so established are generally less than 10 cm different from an algal ridge datum.

MAUKE

The island of Mauke (figures 2 and 3) is located in latitude 20°08'S., 157°21'W., 190 km northeast of Rarotonga. It forms the summit of a 4 km high conical volcano that is approximately 35 km in diameter at its base (Summerhayes and Kibblewhite 1969). The island itself has maximum dimensions of 6.4 km N-S and 4 km E-W. Previous workers cite the total area as 18.4 sq km or equivalent (Grange and Fox 1955, 22; Wood and Hay 1970, 36; Wilson 1982, 7). Planimetry of the 1:12,500 topographic map produced photogrammetrically by the New Zealand Department of Lands and Survey (1975) yields an area of 20.3 sq km, of which 5.4 sq km represents the central volcanic area and 14.9 sq km peripheral limestones. Valley-floor swamplands on the volcanics and between the volcanics and the limestones are smaller than on other similar islands in the southern Cooks. Similarly, the makatea cliff topography at the seaward margin of the swamp areas is subdued. This cliff is generally only 4-5 m high and only locally reaches 7-8 m, and exceptionally 10 m, in height.

Volcanics

The central volcanics form a bevelled plateau at heights variously estimated at ca 100 ft [30 m] (Grange and Fox 1953, 22), 30 m (Schofield 1967, 119), 27 m (Wood and Hay 1970, 36), and 25-30 m (Wilson 1982, 9). The 1:12,500 topographic map shows spot heights on the plateau of 22-28 m, with valley floors descending to 2-12 m above sea level. Our levelling in 1985 yielded a maximum elevation of 24.4 m on profile BD (figure 4), with other peaks on the same profile of 23.0 and 23.9 m. The greatest elevation on profile BF is 23.6 m. Valley floor marsh levels in profile BF stand at 5.3 and 9.2 m.

Note that in modelling the uplift of Mauke, McNutt and Menard (1978, 1208) assumed a maximum elevation of 30.0 m and calculated uplift at 28.8 m; and Lambeck a maximum elevation of 30 m.

No volcanic bedrock is exposed on Mauke: the slopes are covered by deep brown and red soils described by Wilson (1982). Turner and Jarrard (1982, 193) give 11 K-Ar dates on olivine basalt cobbles from three localities, ranging from 4.64±0.14 to 6.30±0.20 million years. They quote (1982, 203) a weighted mean of six samples of 5.99±0.19 million years. These ages must be considered minimal estimates because of weathering.

Limestones: makatea

The makatea peripheral to the volcanics forms a zone 0.8-1.6 km wide. It consists mainly of presumably Cenozoic limestones, with a narrow seaward fringe of late Pleistocene reef limestones: the difference between these formations and the stratigraphic variability within the Pleistocene limestones have not been previously recognised. The elevation of the makatea has been variously estimated. Grange and Fox (1953, 22) give a height range for the upper surface of 30-70 ft [9.1-21.3 m], and comment that 'the makatea differs from most others [in the southern Cooks] in that the surface deposit is not a red heavy volcanic soil, this no doubt being due to the fact that the uplift of the makatea is of more recent date'. Schofield (1967, 119) quotes elevations for the outer makatea of about 9 m and for the inner makatea 21 m. Wood and Hay (1970, 36) give a maximum elevation for the makatea of 18 m, and refer to 'vague benches' at 4.6 and 12 m. Wilson (1982, 9) gives a height range of 5 to 12-15 m and notes that 'large ... pinnacles are absent'. The 1:12,500 topographic map gives spot elevations on the makatea of 6-19 m.

The greatest elevation found in our profiling was 14.65 m in profile BD, followed by 14.6 m in AB, 13.1 m in BC, and 12.2 m in J (Figures 4 and 6). The maximum makatea elevations in other profiles were between 8.4 and 9.7 m. It is possible that previous height estimates have been exaggerated, though there are many areas we did not penetrate. The contact between the inner edge of the makatea and the underlying volcanics was determined in four profiles, at 8.3 m in E, at 10.4 m with an isolated block of makatea at 11.8 m in BC, at 11.95 m in AB, and at 10.8 m in BD.

Limestones: Pleistocene

Pleistocene reef limestones form a narrow zone round the shores of the island. They are identified and distinguished from the makatea limestones by their abundant corals, especially massive *Porites*; by subhorizontal stratigraphic discontinuities (termed by us 'contacts') of the kind we have previously described at Mangaia (Stoddart et al. 1985, 134), though apparently without terrestrial paleosols; and by characteristic topographic features such as grooves, residual pillars, and horizontal notches indicative of former sea levels. Unfortunately the contact between the Pleistocene limestones and the makatea against which they have been deposited is generally mantled by recent perched beach deposits and hence the Pleistocene unit cannot readily be precisely defined. We believe that the complex of depositional and erosional features identified in these limestones represents a sequence of events during the later Pleistocene, and this is confirmed by the wide range of four uranium age determinations now available and which are reported elsewhere (Woodroffe et al. in preparation). The understanding of the unit is made problematic by the way in which depositional sequences are controlled by pre-existing erosional topography and are in their turn erosionally modified and overlapped by later deposits. Many of the topographic features on these limestones we believe to be of marine origin (horizontal notches indicative of intertidal processes; transverse grooves derived from former groove-and-spur formation, possibly with subsequent karst modification); others may be subaerial karst features.

Maximum elevations on surfaces interpreted at Pleistocene are generally 8-10 m (9.45 m on profile A, 8.11 m on B, 8.67 m on C, 10.03 m on D, 9.6 m on E, 9.41 m on G, 8.50 m on J), with a minimum of 5.97 m on H and a maximum of 12.71 m on F. The elevation of the outermost makatea on each profile (in most cases where it passes beneath the perched beach) is at equivalent elevations or slightly lower: 7.63 m on profile A, 7.61 m on B, 7.98 m on C, 9.39 m on D, 10.78 m on F, 8.91 m on G, 8.97 m on H, 11.89 m on J, and 8.48 m on L (Figures 4-6). Leaving aside the anomalously high elevation on profile J, these figures suggest an upper limit for late Pleistocene reef limestone deposition of ca 10 m. A sea level at this height would have inundated much of the lower makatea, and it is possible that marine erosion at and near this elevation accounts for the extensive areas of makatea at 8-10 m. Under such conditions the higher parts of the makatea would have formed low islands rising 2-5 m above this high sea level. The probability of the deposition of thin, patchy but laterally extensive Pleistocene reef limestones on shallowly submerged flat-lying makatea surfaces increases the difficulty of readily distinguishing units in the field.

Cliff sections in the unit here identified as Pleistocene frequently show a basal discontinuity. Where measured this stands at 1.5-2.75 m above present sea level. It is variable in elevation both laterally and transversely. In profile B it varies in elevation northwards from 1.8 to 2.1 m and southwards from 2.2 to 2.4 m. At C it stands at 2.7 m, at J at 1.5 m, and at L at 2.75 m. The surface of the underlying unit at this discontinuity is smooth rather than pinnacled.

Coastal morphology

There is a continuous reef flat around the island. It has an average width of 150-160 m, reaches a maximum of 190 m, and is only 75-110 m wide along the northeast coast between Angataura and Uriaata: the flat is thus the narrowest in the southern Cooks. It terminates landward in a cliff, usually notched, with occasional pocket beaches. The seaward edge of the flat is rimmed by an algal ridge, the presence of which means that there are no surf benches at the cliff itself.

Intertidal notches are characteristically 4-5 m in horizontal extent; the largest measured was 7 m deep in profile D. The elevation of the deepest part of the notch varies from 0.6 m (profile A) to 1.5 m (profile F). The height of the visor is more variable, doubtless in response to differences in exposure, ranging from 0.9 m (profile D) to 5.7 m (profile E). At any given locality the visor may be a double or even multiple feature. For example there are pronounced levels at 2.6 and 5.7 m near profile E and at 0.9, 1.4, 3.5 and 4.4 m near profile D.

In places where the notch does not exist there are indications of a terrace or bench at the foot of the cliff. This spur-end bench is best developed at Anaraura, south of profile C, where it is a conspicuous feature at an elevation of 2.7 m.

Deep narrow transverse grooves intersect the cliffs around the entire coastline of the island (figures 7 and 8). These resemble the grooves near Oneroa on Mangaia which we have interpreted as elevated fossil groove-and-spur features (Stoddart et al. 1985, 134). A sample groove on profile A is 3-4 m wide, and its floor rises from 3.8 to 7.0 m over a distance of 32 m. Floors of grooves have been measured at elevations of up to 7.5 m (profile D).

In the northwestern part of the island, south of Taunganui, the cliff line is conspicuously castellated, with limestone towers rising above the general level near the crest line. The base of these towers (profile L) stands at 4.6-4.7 m. Each is surrounded by a discontinuous notch with its floor at 5.5-6.5 m. In one case the deepest part of the notch stands at an elevation of 6.7 m and the visor at 7.3 m. The irregularly eroded summits of the towers reach elevations of 8.1-8.59 m. Seaward, on this profile, there are well developed transverse grooves with floors at up to 3 m above sea level.

Holocene coastal features

Perched beaches in the form of wide expanses of cover sands overlying the limestones are found around the coast at distances of 50-150 m from the cliff top; the mean distance in the profiles measured is 85 m. Interpreted as contemporary storm deposits, these perched beaches are 50-150 m wide (mean 90 m), and their inner edges lie at 125-230 m (mean 175 m) from the cliff edge. Maximum elevations on the sand surface range from 9.1 m (profile C) to 12.7 m (profile F). These perched beaches have not been trenched, but are presumably no more than 1-2 m thick at a maximum. As noted above, they effectively mask the contact between the Cenozoic makatea and the Pleistocene limestones.

Massive perched boulders on the surface of the limestones inland from the cliff edge are common close to the shore. On profile A there are two, 1.8 and 1.4 m in height respectively, standing at elevations of 9.2 and 8.7 m above sea level, at distances of 170 and 200 m from the cliff edge (figure 10). On profile C there are three, with dimensions of 3.5x2.0x1.2, 2.8x2.6x1.2, and 5.4x2.3x1.5 m, and volumes of 8-15 m^3, at an elevation of 6.9 m above sea level, and 75 m inland from the shore. Another on profile J is 1.1 m high and stands 11.5 m from the sea. We have no data on the age of these boulders, but they are not conspicuously eroded and none of them stands on erosional pedestals. They have presumably been entrained and carried inland by storm waves during hurricanes or other extreme events: Moore and Moore (1984) have recorded boulders of coral up to 1 m in maximum dimension at elevations up to 326 m on Lanai, Hawaii, which they suggest were deposited by giant waves generated by submarine landslides. Blocks up to 6 m high on the reef flat at Rangiroa Atoll, Tuamotus, described by Stoddart (1969), have been ascribed by him to hurricanes, and by Bourrouilh-Le Jan and Talandier (1985) to either hurricanes or tsunamis. The extreme hurricanes of 1903, 1905 and 1906 are known to have deposited storm blocks at Rangiroa and Raroia of the same magnitude as those on Mauke, though at sea level rather than on cliff tops (Bourrouilh-Le Jan 1985, 315).

Blocks formed by cliff collapse consequent on intertidal undercutting are also common on the inner part of the reef flat adjacent to the cliffs (figure 11). Frequently these can be related to cliff-face scars whence they originated.

Pocket beaches of carbonate sands occur at intervals around the island. In some places beachrock formed on these beaches appears to stand at anomalously high levels. The highest elevation measured on beachrock was 1.96 m on profile F.

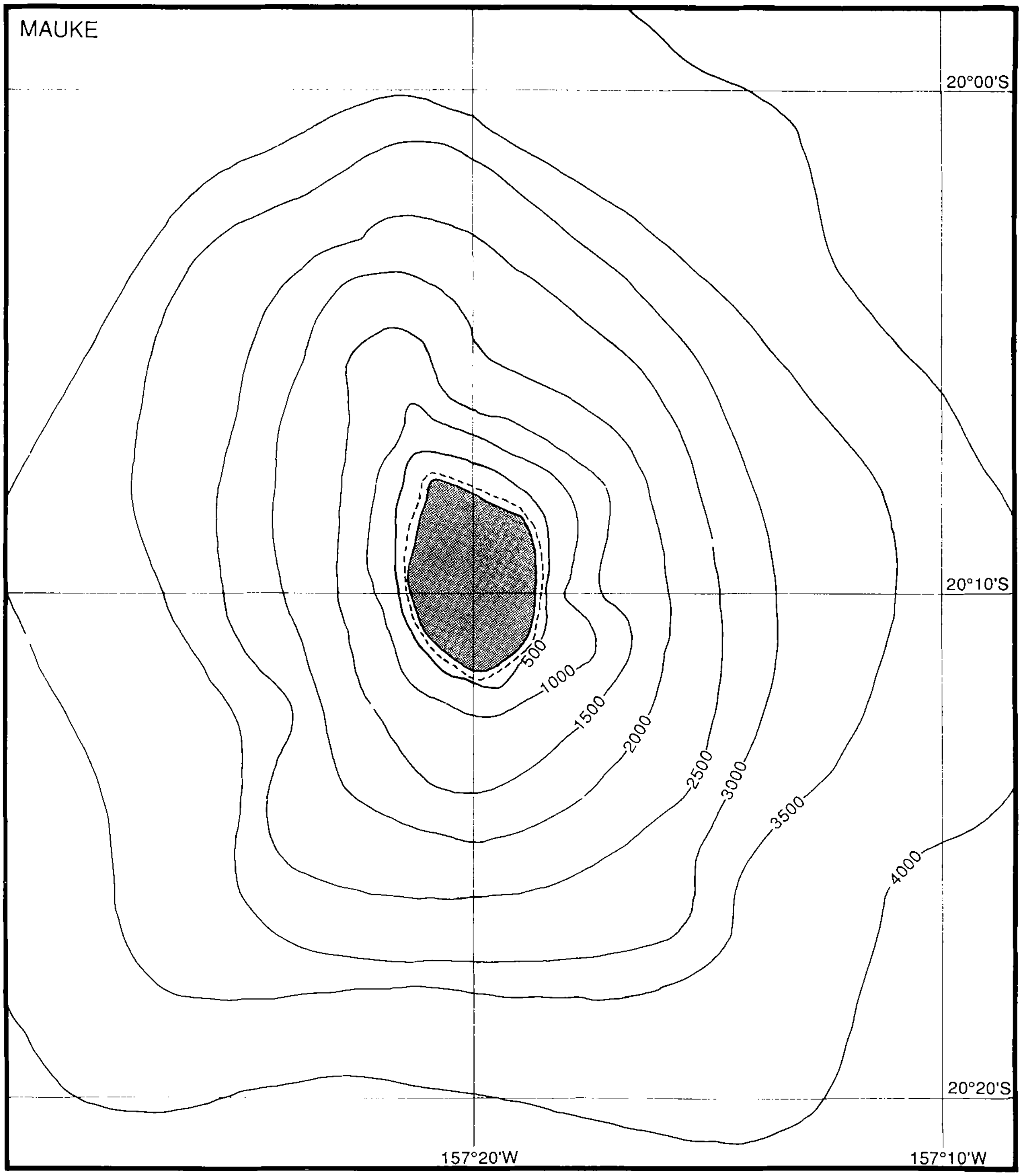


Figure 2. Bathymetry of Mauke (after Summerhayes and Kibblewhite 1969)

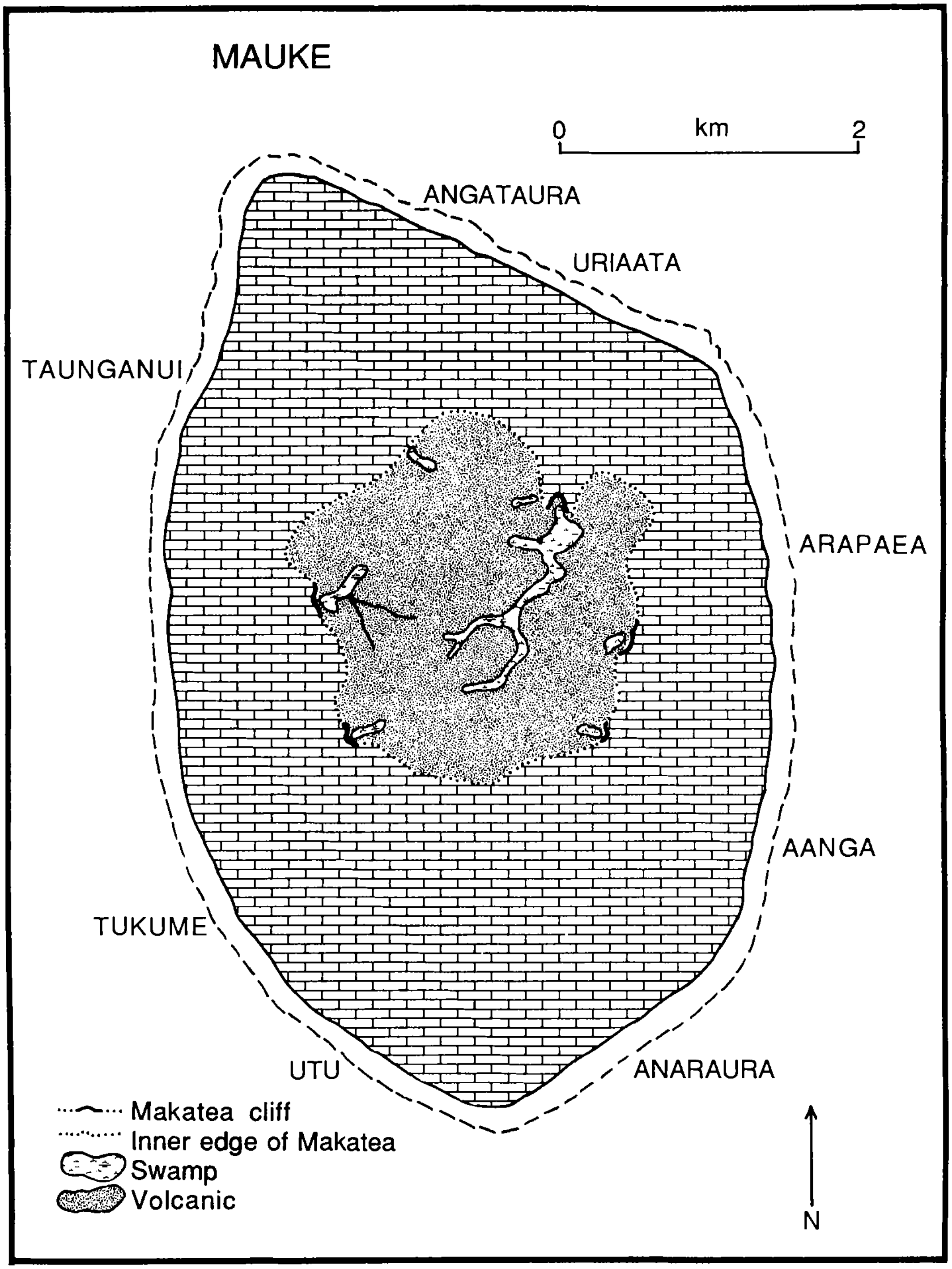


Figure 3. Geology of Mauke

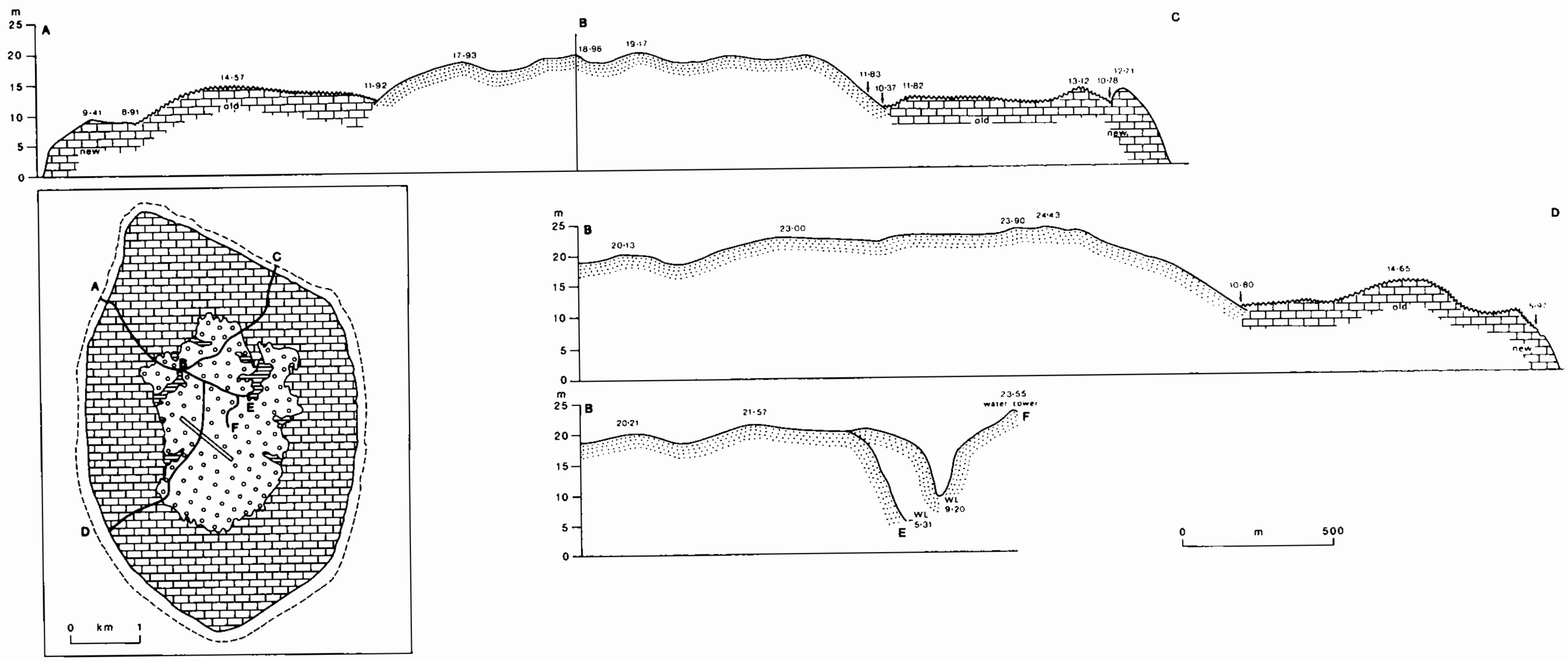


Figure 4. Mauke: topographic profiles AB, BC, BE, BF and BD

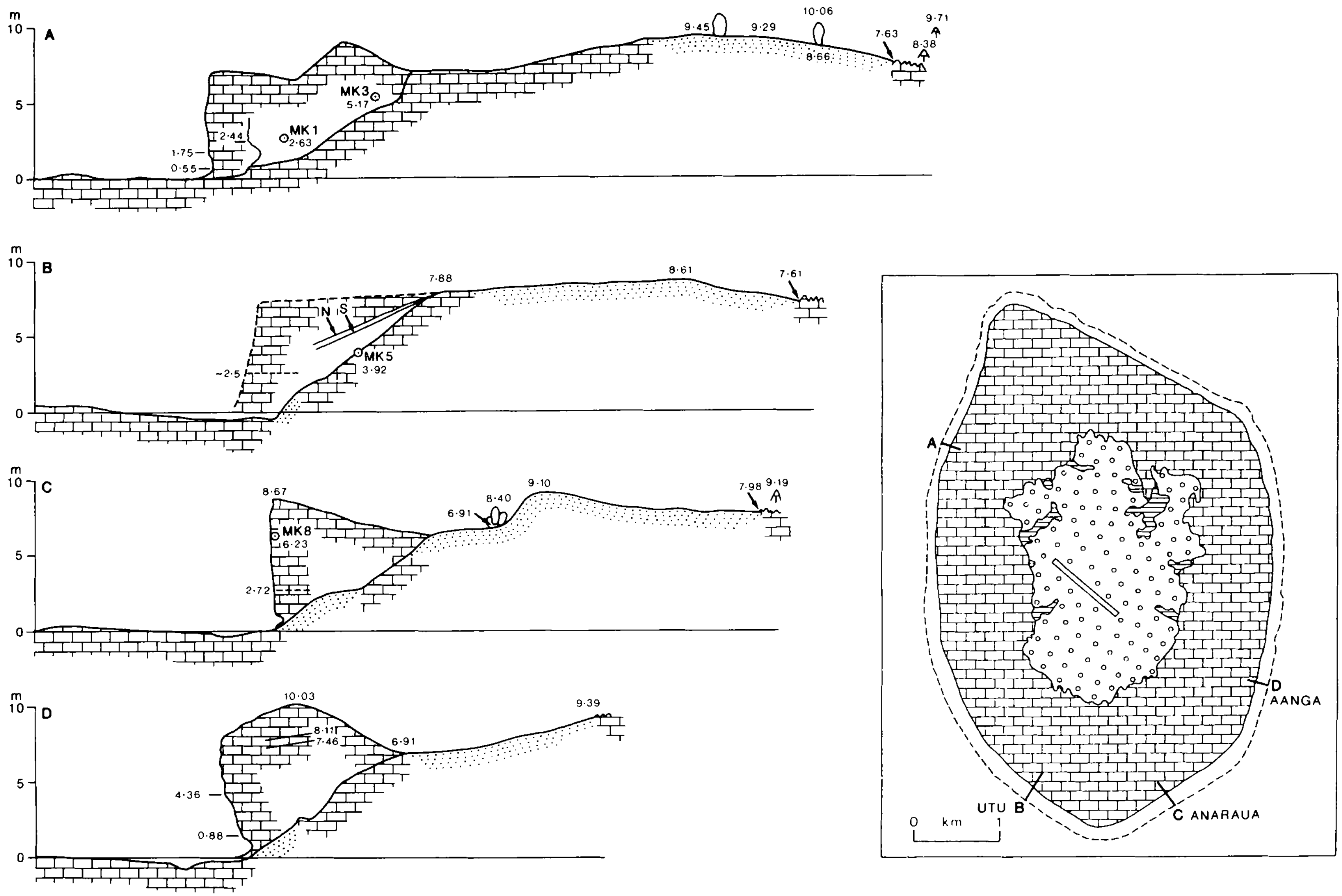


Figure 5. Mauke: topographic profiles A, B, C and D

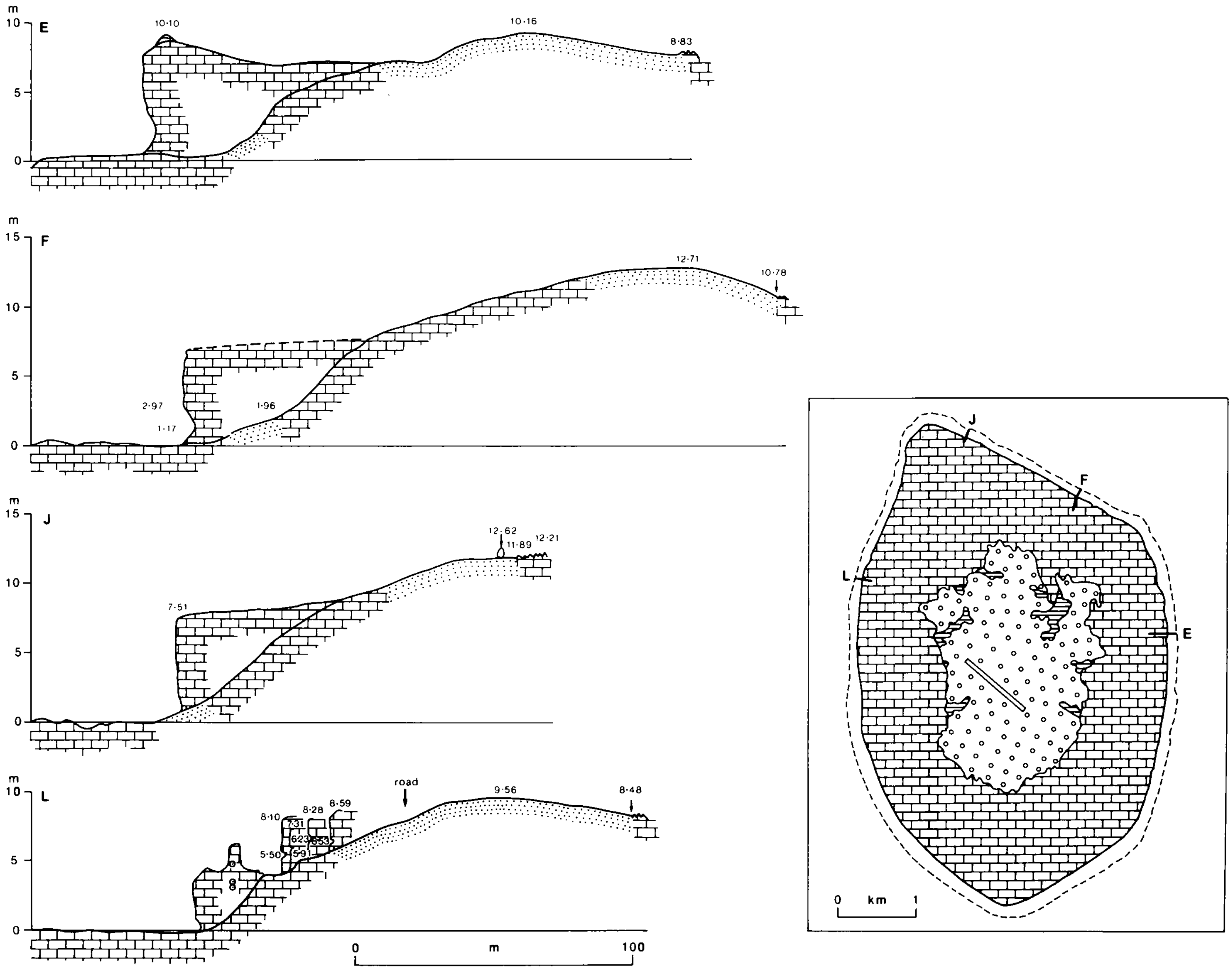


Figure 6. Mauke: topographic profiles E, F, J and L

Figure 7. Emerged groove-and-spur coastline at Taunganui, Mauke

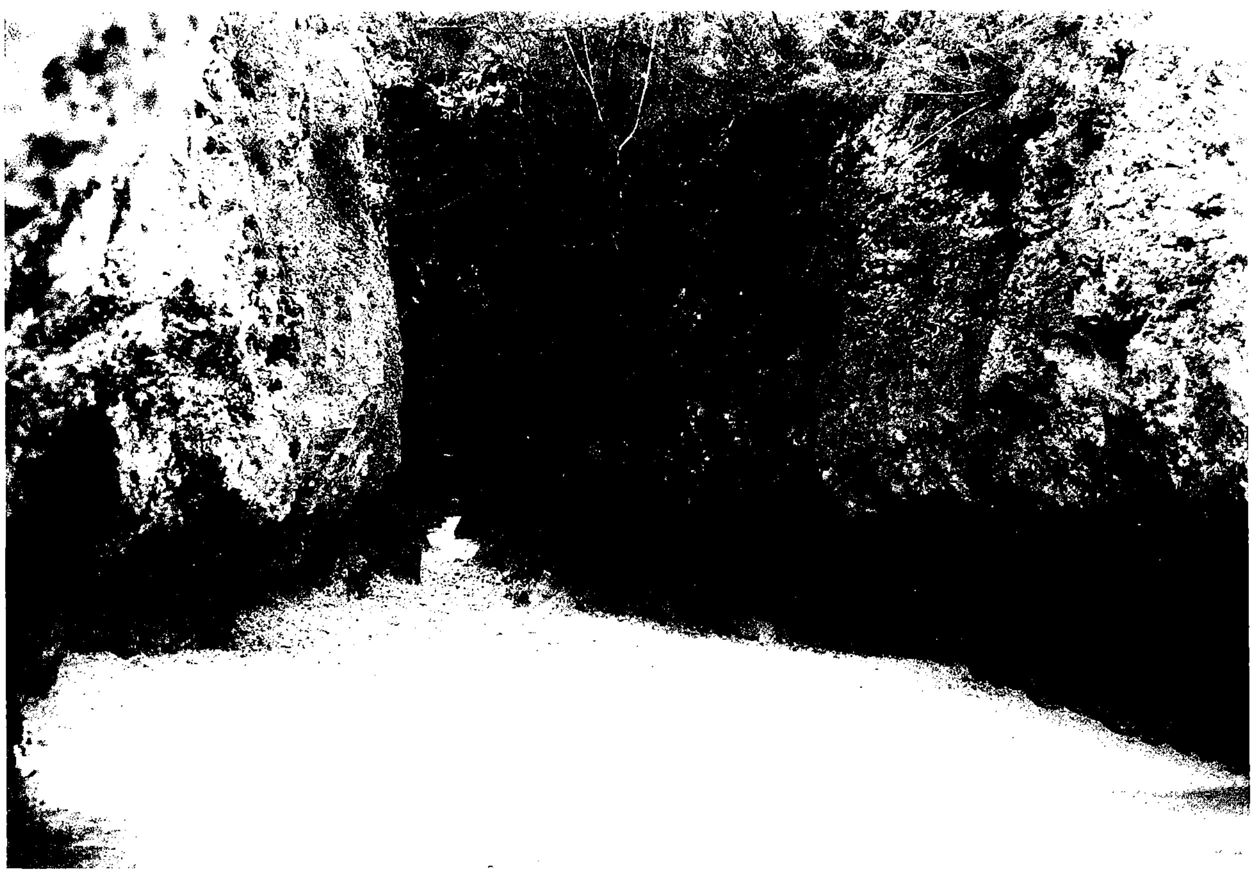


Figure 8. Groove in profile A at Taunganui, Mauke

Figure 9. Erosional embayment in coastal cliffs at Taunganui, Mauke

Figure 10. Perched boulder on profile A, Mauke

Figure 11. Detached coastal block, east coast of Mauke

Figure 12. Elevated reef flat near Aanga, Mauke

MITIARO

The island of Mitiaro (figures 13 and 14) is located at latitude 19°01'S., longitude 157°03'W., 225 km northeast of Rarotonga. It has maximum dimensions of 6.3 x 4.4 km. It stands on the summit of a conical volcano 4.25 km high, and approximately 25 km in diameter at its base (Summerhayes and Kibblewhite 1969). Grange and Fox (1955, 25) and Wilde (1981, 5) give its total surface area as 10.25 and 10.12 sq km, respectively, but planimetry of the New Zealand Department of Lands and Surveys 1:25,000 topographic map (1983) gives a total area of 29.56 sq km, comprising 22.47 sq km of elevated limestones, 1.27 sq km of volcanics, and 5.8 sq km of swamp and lake.

Volcanics

There are four discrete areas of low volcanic topography in the centre of the island. Three of these (the Atai and Auta foodland, the Taurangi foodland, and the Mangarei foodland) are completely encircled by marsh deposits in the centre of the island. The fourth, the Takuae foodland, is partly encircled by raised limestones, except on its northern side where it abuts the swamp. The maximum height of these volcanic residuals is quoted by Wood and Hay (1970, 35), Wilde (1981), and Turner and Jarrard (1982, 202) as 12 m; Grange and Fox (1955, 25) place it 'at or a little above the height of the makatea'.

Our topographic profiles (Figures 15 and 16) suggest that some of these elevations are exaggerated. Table 3 summarises available height information (which on the Lands and Surveys 1:25,000 map is photogrammetrically derived).

Table 3. Maximum heights of volcanics on Mitiaro

Area	Wood and Hay (1970)	1:25,000 map	this survey
Atai and Auta	3.0 m [10 ft]	4.0 m	3.9 m
Taurangi	-	5.0 m	5.7 m
Mangarei	9.1 m [30 ft]	3.0 m	6.9 m
Takuae	12.2 m [40 ft]	6.0 m	8.9 m

There are no outcrops of unweathered basalt on the volcanic residuals, which are covered with deeply weathered red and brown clays (Wilde 1981). Turner and Jarrard (1982, 193, 202) obtained a K-Ar age of 12.3±0.42 million years on a cobble of olivine basalt from the weathered material; because of alteration this must be considered a minimum age.

Interior depression

The extensive interior depression consists of a sedge marsh (Punavai) with *Cladium jamaicense* and a shallow open lake, Te Rotonui (figure 22). The water level in the lake stood at 0 m at the time of our survey, and in the sedge marsh at up to +0.4 m. Wood and Hay (1970, 35) refer to the marshes as 'a few feet above sea level', but this must be exaggerated. We have no information, however, on water-level variation.

Limestones: makatea

The greater part of the peripheral raised limestone of Mitiaro comprises deeply dissected makatea, presumably Cenozoic in age. There is some variability in existing estimates of the maximum elevation of this makatea. Grange and Fox (1955, 25) estimate it as less than 20 ft [6.1 m]. Wood and Hay (1970, 35) give the greatest elevation as 30 ft [9.1 m] but also give spot heights of up to 40 ft [12.2 m] on their accompanying map. The 1:25,000 Lands and Surveys topographic map gives spot heights of 15 m in the southeast, 11 m in the southwest, 12 m in the northeast, and 9-10 m elsewhere. McNutt and Menard (1978, 1208) in their theoretical analysis of island uplift use a figure of 27 m for the uplift of the limestones on Mitiaro. Jarrard and Turner (1979, 5693) and Turner and Jarrard (1982, 202) cite 15 m, and Lambeck (1981, 485) 12 m.

In our surveyed profiles across the makatea the greatest measured elevations are 10.9 m between Omutu and Atai (figure 16), 8.9 m between Omutu and Mangarei (figure 15), and 8.8 at Parava (figure 17). There is, however, a considerable area on the south side of the island in which we have no surveyed elevations and which is very difficult of access. Our data do, however, confirm the fact that the highest makatea is at the same level or higher than the maximum height of the volcanics. Grange and Fox (1955, 26) drew attention to the presence of 'large blocks of limestone on the margin of the Mangarei "island"' and suggested that the makatea formerly covered the whole of the centre of Mitiaro and was eroded during a period of lower sea level, thus unroofing and exposing the volcanics. Wood and Hay (1970, 35) likewise note the presence of 'coral blocks ... upon the highest parts of these [volcanic] "islands" and also around the margins of the swamplands surrounding them', and they reach a similar conclusion.

We have determined the elevation of the makatea-volcanics contact on the Mangarei and Takuae floodlands. On the north side of Mangarei it stands at 2.93 m and on the south side at 0.92 m above sea level. On Takuae there are elevations of 6.48 m (6.22 m for isolated scattered blocks) on profile F, section C-D, and of 5.10 and 4.79 m on profile F, section C-E. These heights are consistent with the solutional formation of the interior depression.

The surface morphology of the Mitiaro makatea is less pinnacled and rugged than on other islands, with more rounded terrain (Wood and Hay 1970, 35; Wilde 1981).

Limestones: Pleistocene

The coastal margins of the raised limestones are formed of much younger limestones, probably of late Pleistocene age. The peripheral cliffs are highest in the east (6.04 m in profile C, 6.67 m in profile D) and southwest (7.01 m in profile J), and lowest in the north (3.51 m in profile G) and west (2.73 m in profile H); we have not seen the cliffs along the south coast. Inland from the cliff top the surface increases in height, usually to a maximum of 6-7.5 m (6.17 m in profile C, 7.40 m in profile D, 5.89 m in profile H, 7.73 m in profile J, 6.16 m in profile L), before passing beneath modern cover sands. The sequence from the cliff top to the cover sands consists of a complex microtopography of hummocks, gullies and broader depressions which contains abundant, well-preserved corals in the position of growth (e.g. Vaikoura). Uranium-series ages to be reported elsewhere indicate ages older than the last interglacial (ca 125,000 yr). Unfortunately the cover sands generally obscure the contact between the clearly Pleistocene coastal sequence and the makatea which it abuts and overlies. The relationship between the Pleistocene sequence and the underlying makatea is further obscured by the fact that the upper surface of the makatea lies close in many areas to the maximum height of the late Pleistocene deposits. This is well seen both on the transect from sea to lagoon at Parava (figure 17), where there are fields of late Pleistocene acroporid corals (figure 28), deeply weathered with apparent recrystallization of skeletal aragonite to calcite, but in the position of growth, at elevations of 6.77-7.81 m above sea level, especially on flat-lying areas and in depressions on the makatea surface, with older ridges and pinnacles of makatea reaching higher levels. Similarly, on the northwest coast (profile H), corals are abundant in grooves in the makatea surface but are absent from the highest areas between (corals in grooves stand at 3.65 m above sea level, compared with 4.09 m between).

Elevated subhorizontal transverse grooves are well developed above the cliff top in profile C (figures 26 and 27). Individual grooves begin at an elevation of 4.6 m at the cliff top and rise inland until they coalesce into a continuous rocky ramp parallel to the cliff edge at a height of 5-5.6 m. The grooves are margined by an undercut notch with a visor at 5.0 m above sea level. Between these flat-floored grooves there are irregular ridges rising to 6-6.2 m.

Similarly, in profile L, there is a sequence of groove-and-spur features on the cliff top, with coral growth within the grooves. Some of the grooves are roofed-over and closed at their seaward exit; others are open with undercut, smoothed walls (figure 24). There is a pronounced discontinuity in the cliff face at this point between a lower and an upper limestone unit. This discontinuity rises from 2.62 m above sea level in the north to 4.45 m in the south, over a distance of 50 m. The discontinuity forms the flat floors of the grooves. The floor elevations also rise inland: in one sample groove, with the floor at 3.81 m above sea level at the cliff line, the floor rises to 5.68 m inland over a distance of 20 m. The upper unit forms the spurs between the grooves. At the cliff line this unit is 1.24-2.10 m thick. The upper surface of this unit also rises inland: at the same location it stands at 4.69 m at the cliff line and rises inland to 6.27 m over 20 m. Grooves at other localities have floors at 4.8-5.0 m above sea level in profile B and at 3.65 m in profile E.

Comparable discontinuities between upper and lower limestone units are found at varying heights around the coast: at 5.6-6.0 m in profile B, 4.1-4.75 m in C, and 5.0-5.1 m in D.

Coastal morphology

There is a continuous reef flat around the island, averaging 100 m in width and reaching a maximum of 120 m. It is edged by a prominent algal ridge, with deep surge channels. The datum used in this study is the lowest elevation of an identifiable algal ridge; the maximum elevation of the highest algal ridge we have measured rises 0.83 m above this datum (profile K; figure 21). Contemporary reef flat surfaces, all of eroded limestone with little sediment cover, lie at or close to datum, with two exceptions. The first is that all along the west coast there are extensive residuals on the reef flat of a higher surface. In profile K these stand up to 1.23 m above datum, as steep-sided platforms with pitted and eroded upper surfaces (figures 31 and 32). These residuals may represent a fossil algal ridge, similar to those described from Mangaia, southern Cooks (Yonekura et al. 1986, 1988) and Suwarrow, northern Cooks (Scoffin et al. 1985), indicating the former position of the reef margin prior to the Holocene sea level highstand of ca 1.0 m between ca 6000-2000 a B.P. in this part of the Pacific (Pirazzoli and Montaggioni 1988). Second, in most profiles the reef flat is more deeply scoured at the foot of the cliffs, often forming pools which retain water even at low tide and which is some cases contain massive living microatolls, especially of *Porites*. In profile K these pools are scoured down to -1.34 m below datum, and the tops of the microatolls (figure 33) stand at +0.10 and +0.13 m.

The cliffs are generally conspicuously notched at or slightly above the present reef flat level. Most notch floors stand close to this level, with the deepest part of the notch at elevations of 0.5-1.0 m above it (0.56 m in profile J, 0.63 m in G, 0.83 m in K, and 0.97 m in H). Visor elevations range more widely, doubtless reflecting local exposure (e.g. 1.97 m in profile H, 2.23 m in G, 3.16 m in J, and 3.23 m in K). Most notches are 2-3 m deep.

In profile D there is a comparable but higher notch (figure 25), with its floor at 1.77 m, its deepest part at 2.27 m, and its visor at 4.07 m; this notch has a horizontal extent of 5.0 m.

There are occasional pocket beaches of carbonate sands and gravels in indentations in the cliffs. The foot of these beaches lies at survey datum (e.g. +0.05 m in profile K).

Holocene coastal features

The cover sands above the cliffs, already noted, form a perched beach back from the cliff edge round most of the island (figures 29 and 30). They form some of the highest ground of the island. Elevations on the cover sands reach 9.76 m in profile D, 10.10 m in E, 10.2 m in G, and 10.9 m in B. The sands have not been trenched but are probably 1-2 m thick. They are usually 100 m wide but in places exceed 200 m and exceptionally reach 500 m.

Large perched boulders of reef rock, undoubtedly of storm origin, are common round the entire coast of the island. The biggest recorded, 2.2 m high, stands 100 m back from the cliff top in profile H at an elevation of 4.85 m. Another in profile B is 1.67 m high and lies 47 m from the cliff top at an elevation of 6.75 m. Two in profile C are respectively 1.3 and 1.7 m high, at 9 and 35.5 m from the cliff top, at elevations of 6.17 and 5.11 m above sea level. In some cases they show inverted coral colonies. They appear to be relatively recent: they are not deeply eroded on their upper surfaces, and they do not stand on protected pedestals of underlying limestone. W. M. Gill noted that the hurricane of 1865 brought wave action up to 30 ft [9 m] above present sea level (Grange and Fox 1955, 26), and such events, though not necessarily that particular one, have doubtless been responsible both for the deposition of the perched beach sands and for these storm blocks.

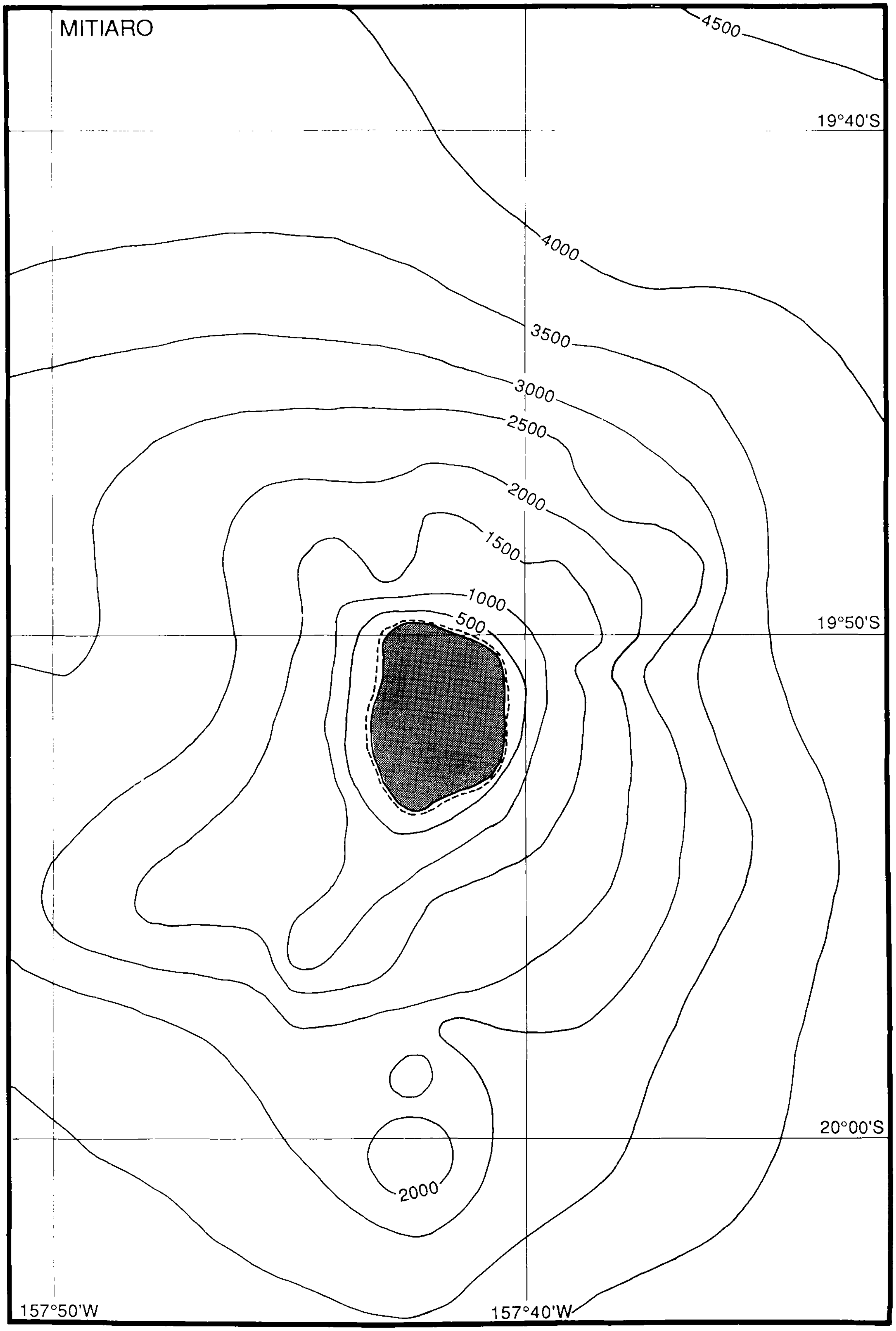


Figure 13. Bathymetry of Mitiaro (after Summerhayes and Kibblewhite 1968)

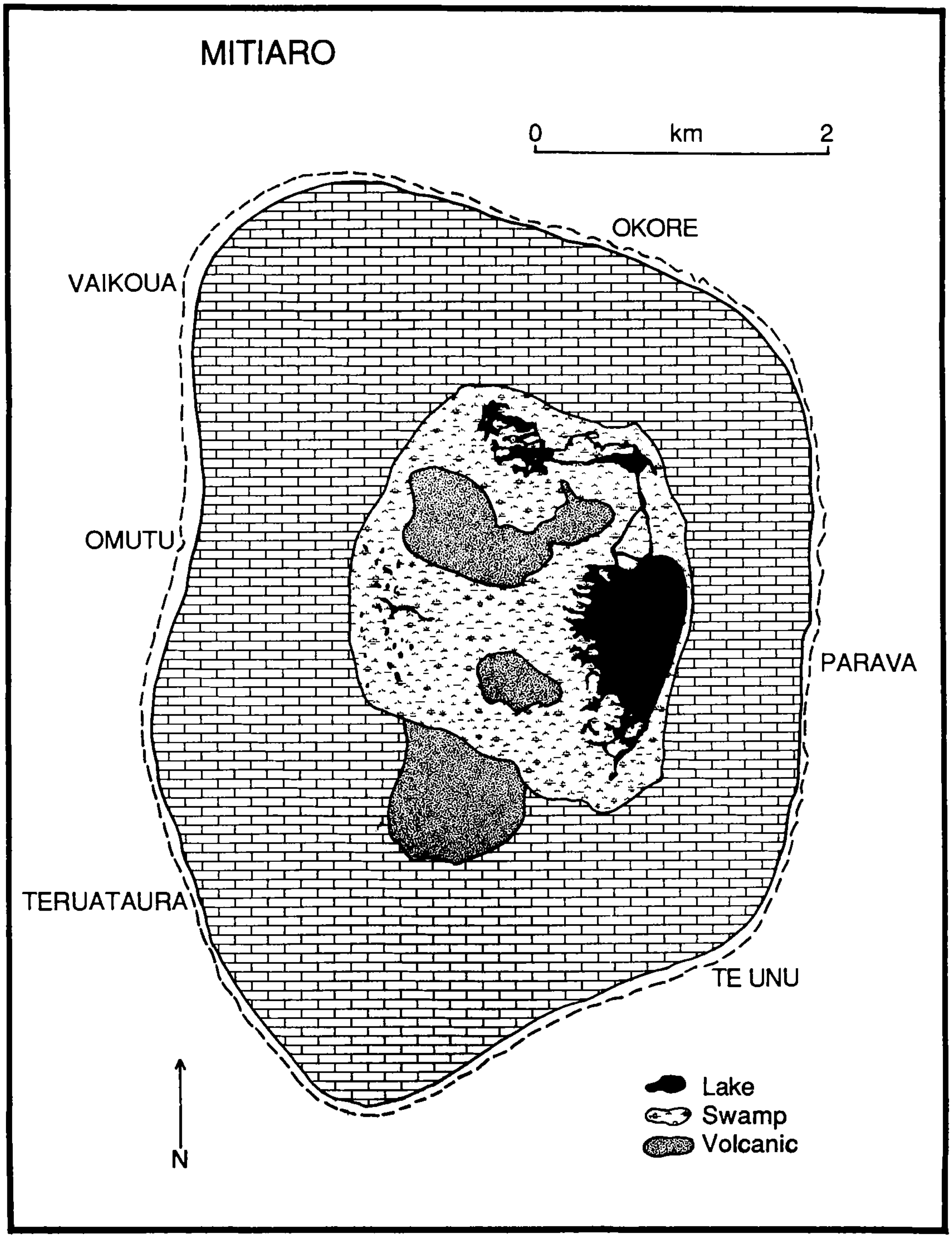


Figure 14. Geology of Mitiaro

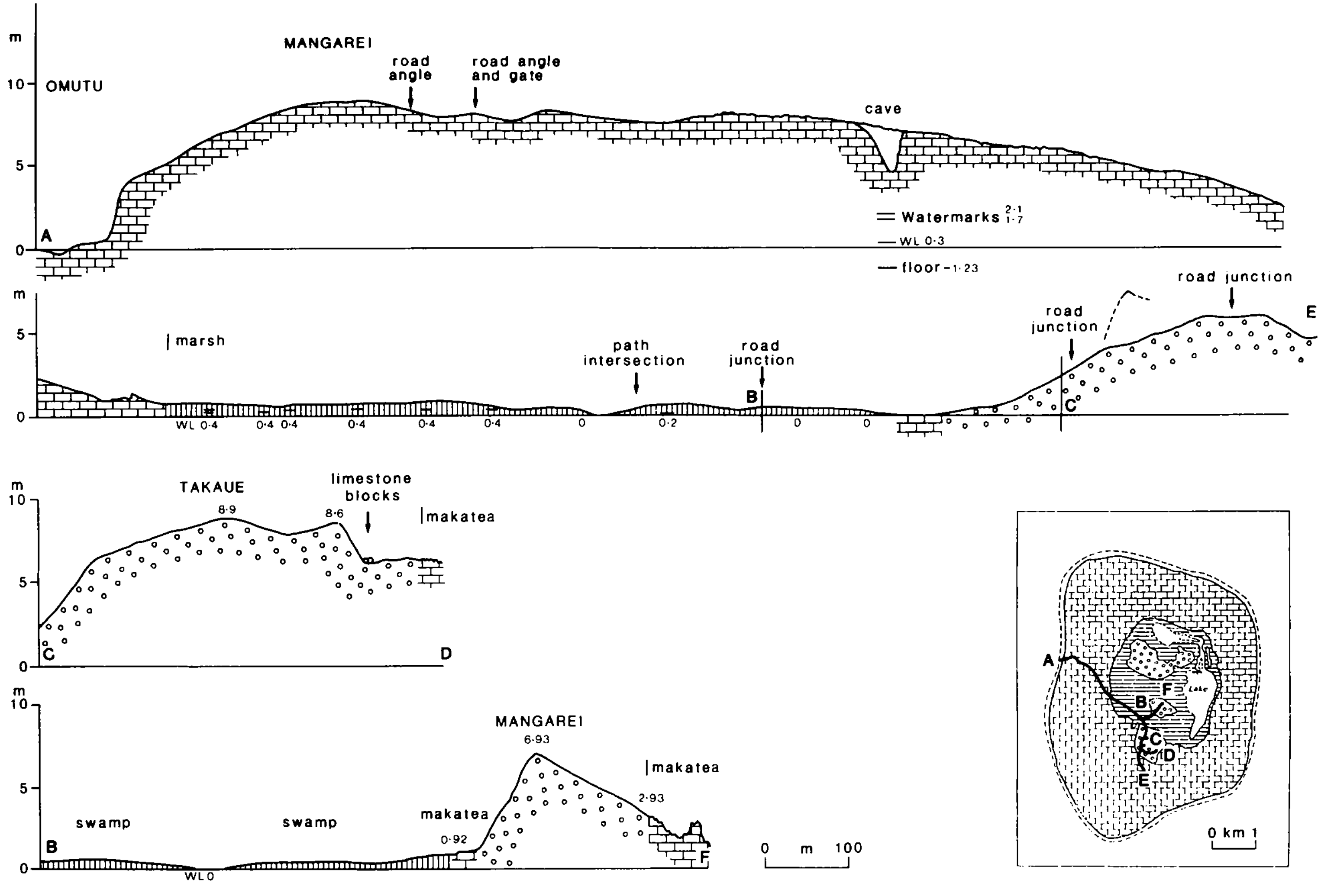
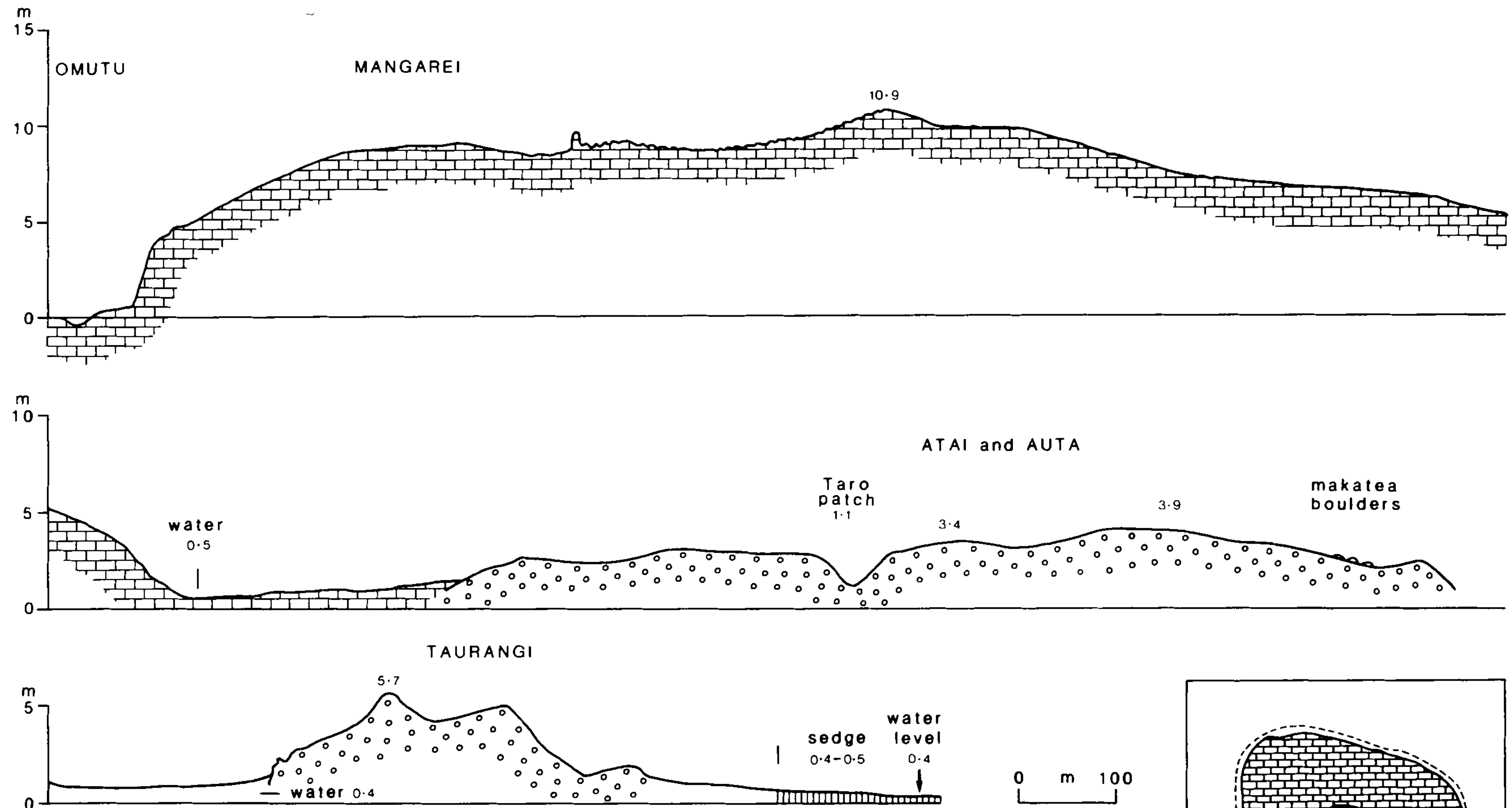


Figure 15. Mitiaro: topographic profiles AB, BD, BE and BF from the coast to Takuae and Mangarei



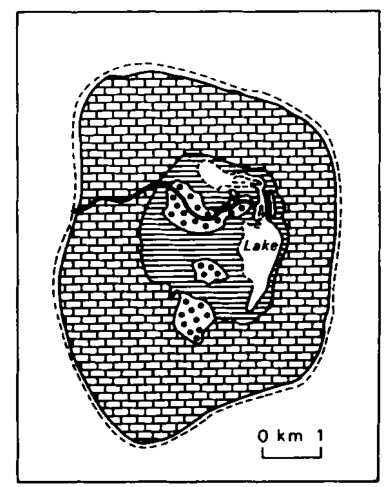


Figure 16. Mitiaro: topographic profiles from the coast to Atai, Auta and Taurangi

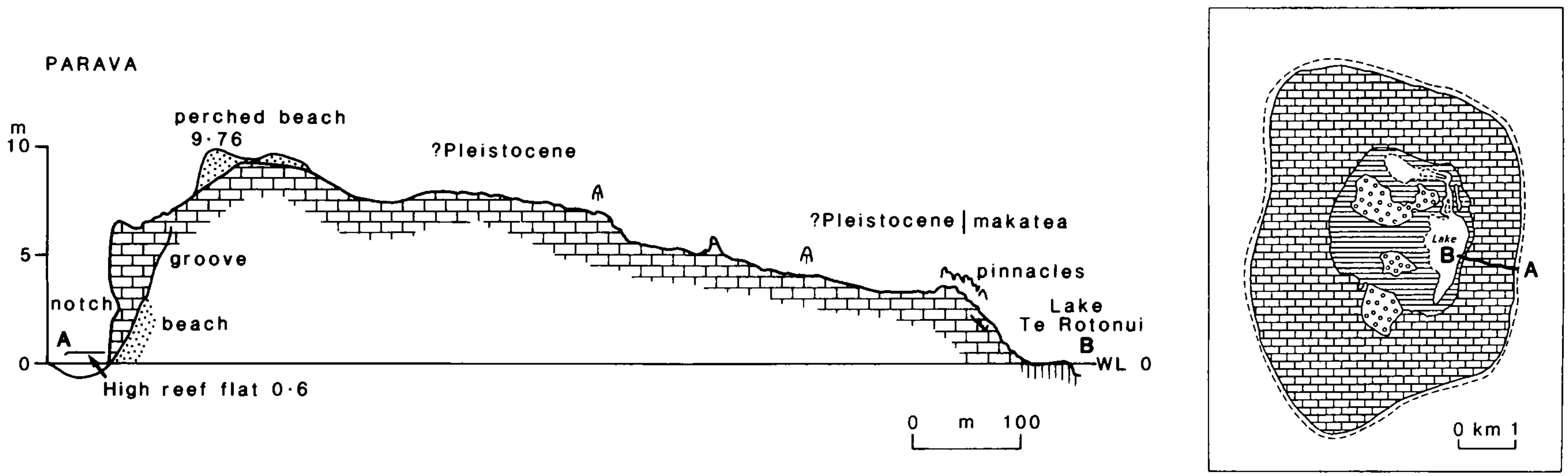


Figure 17. Mitiaro: topographic profile across the makatea rim at Parava

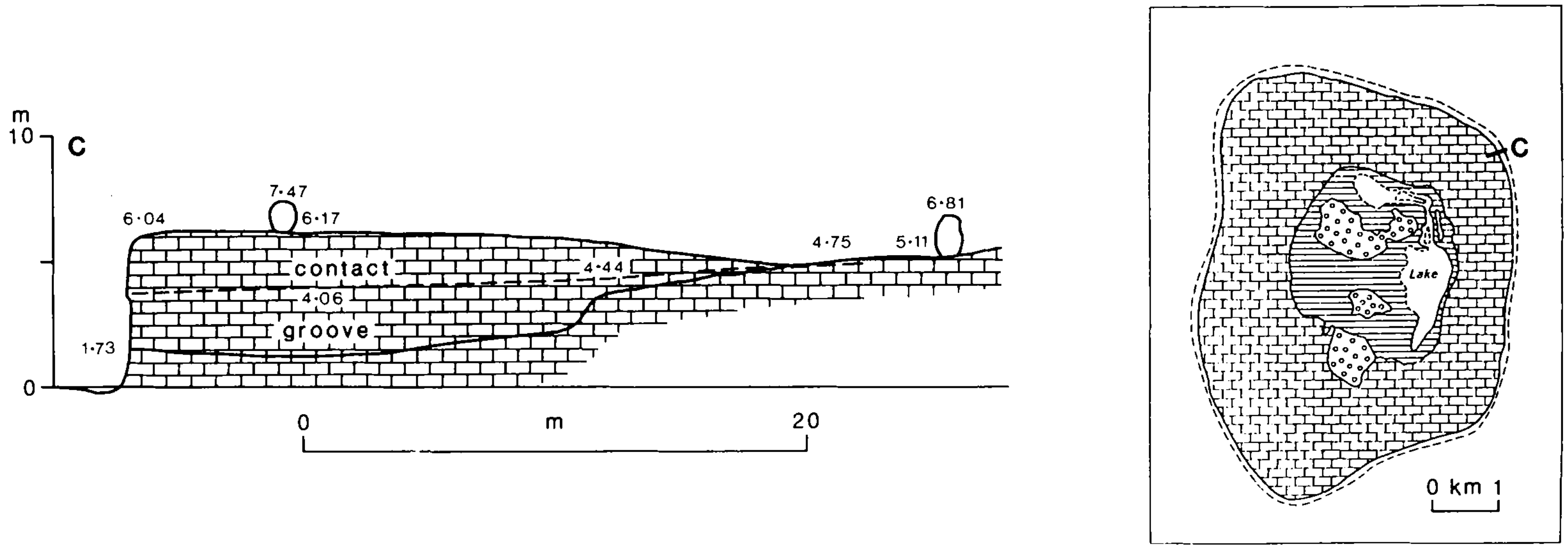


Figure 18. Mitiaro: topographic profile C (groove-and-spur)

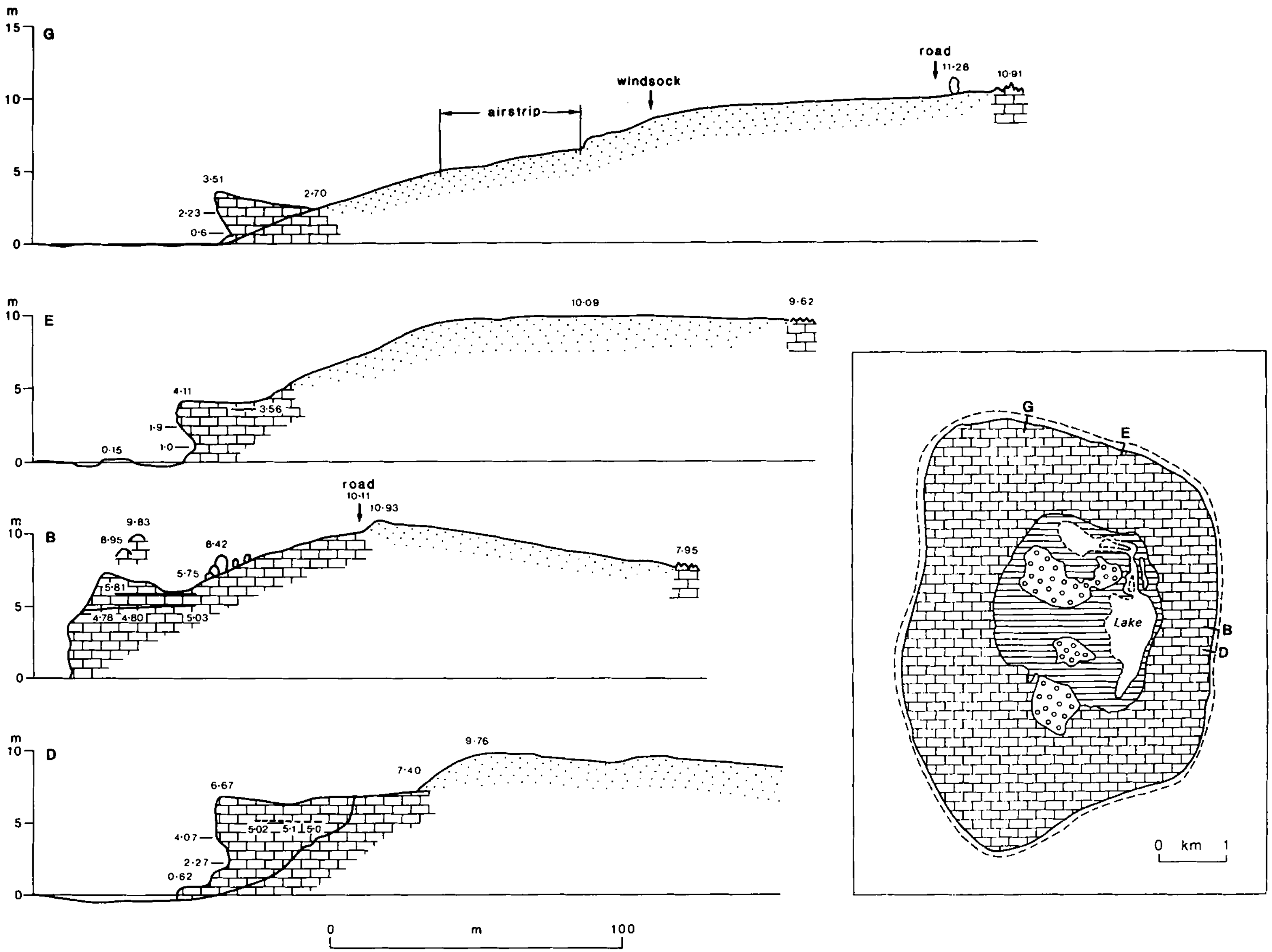


Figure 19. Mitiaro: topographic profile G, E, B and D on the north and east coasts

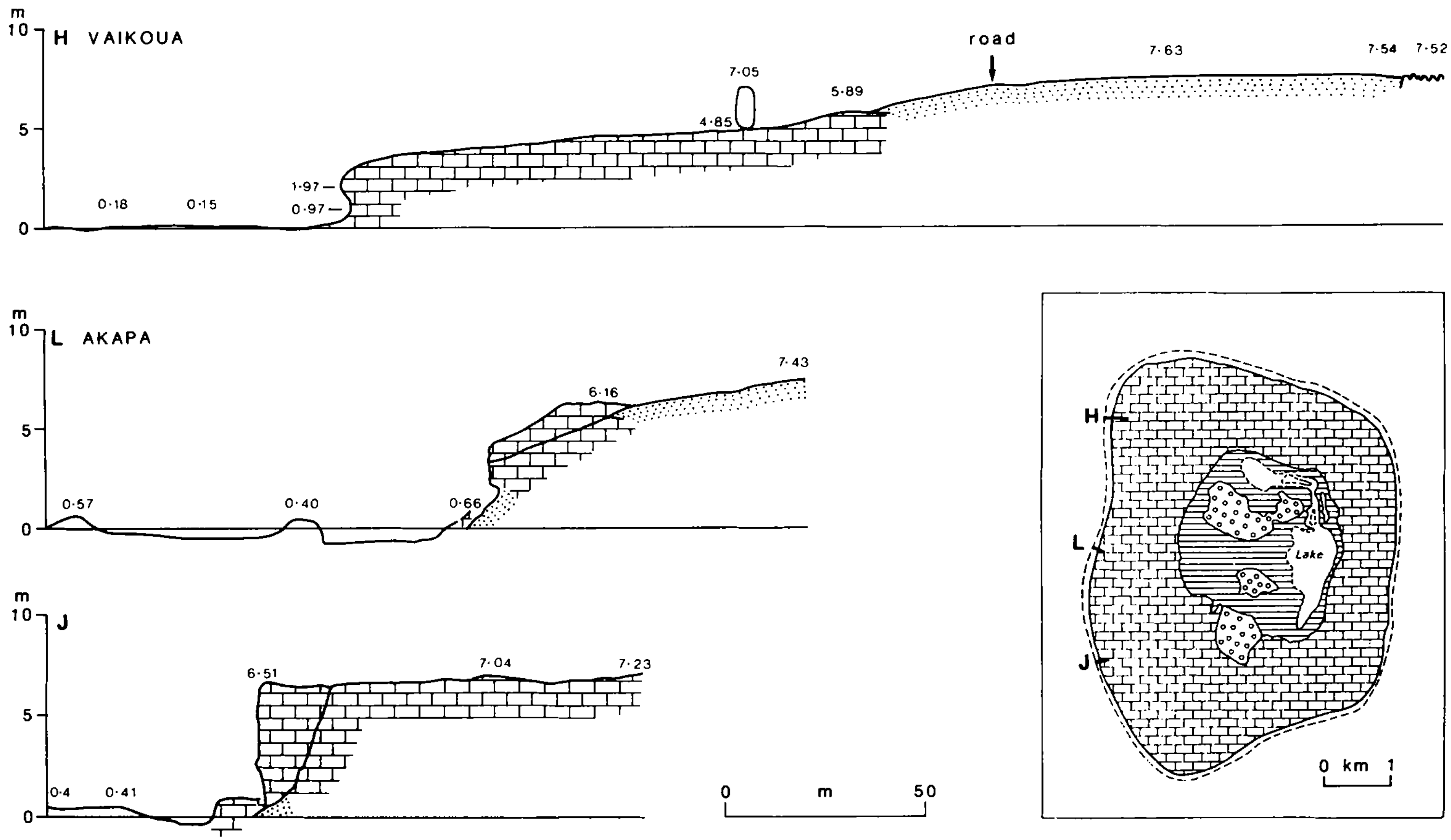


Figure 20. Mitiaro: topographic profiles H, L and J on the west coast

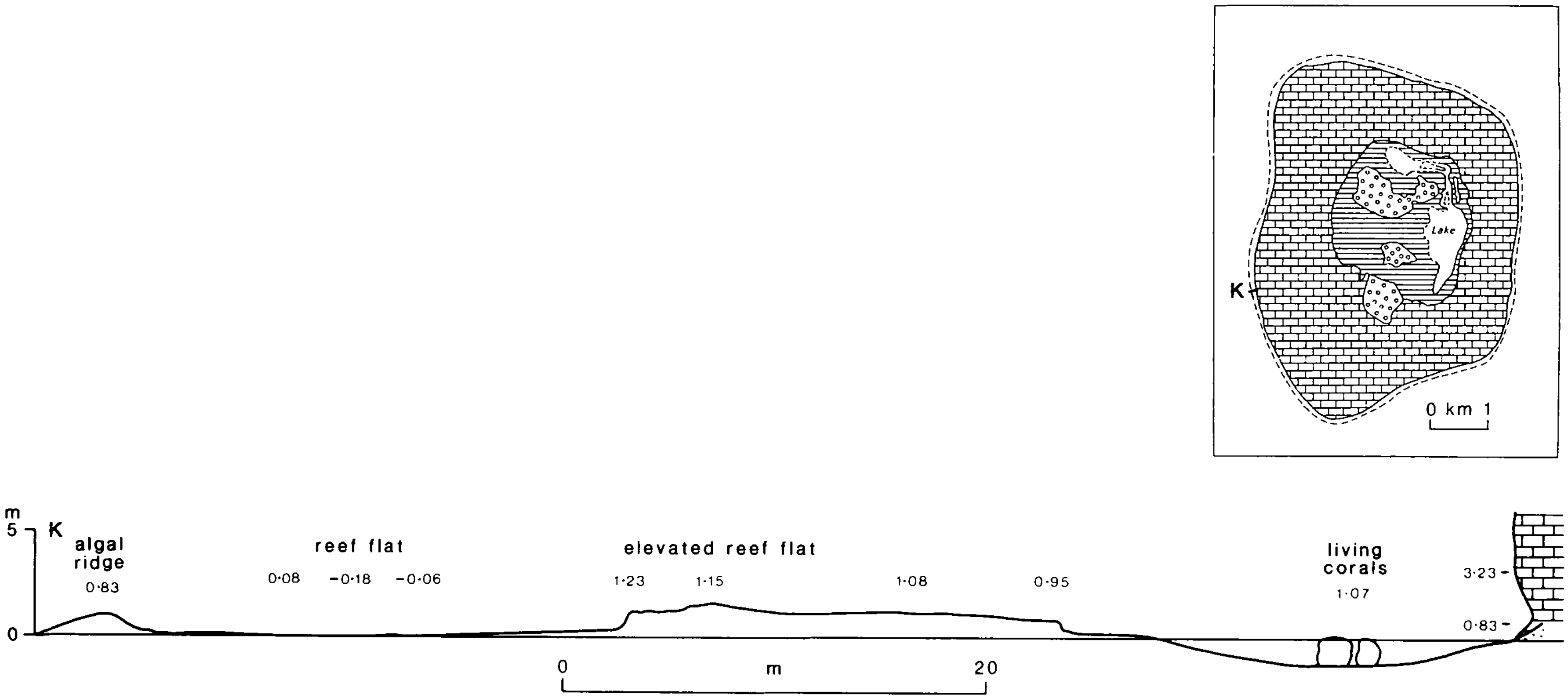


Figure 21. Mitiaro: topographic profile K on the reef flat at Tukume

Figure 22. Te Rotonui and the central volcanics at Mitiaro, from the west end of profile AB

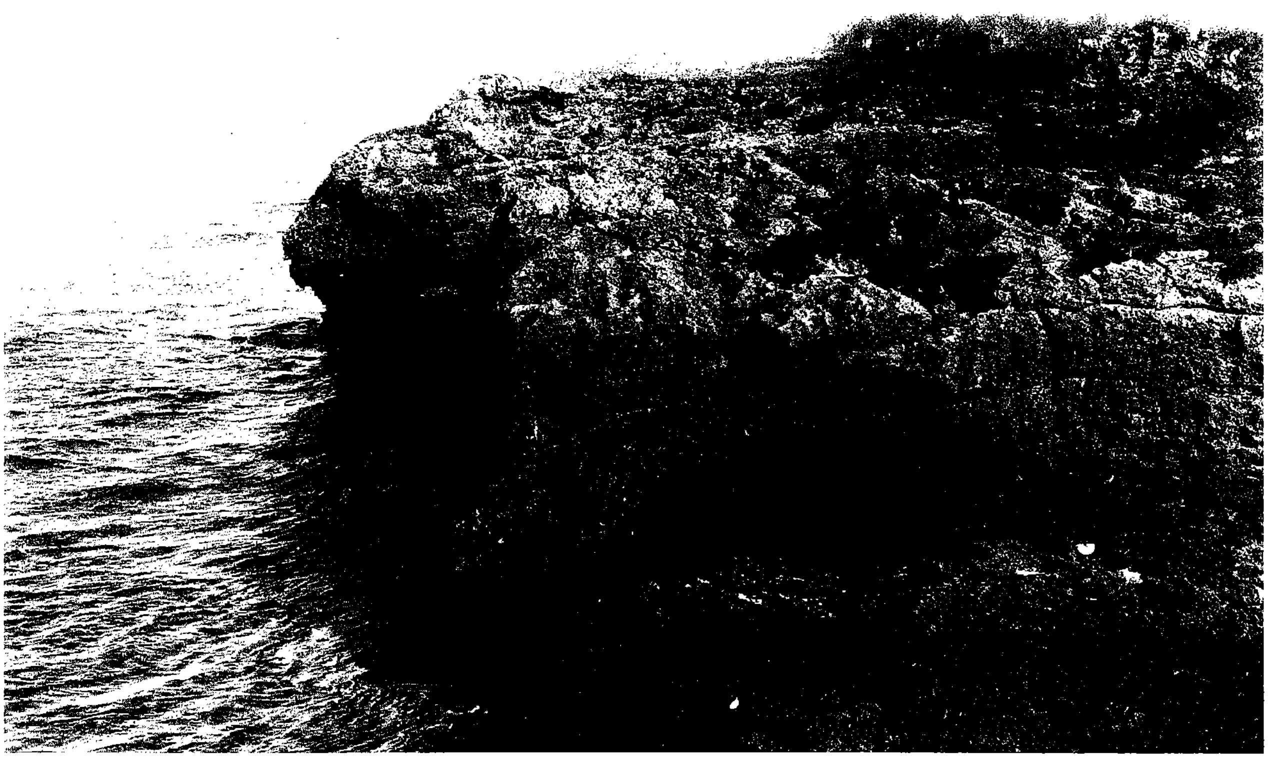


Figure 23. Coastal cliffs near Omapere, Mitiaro

Figure 24. Emerged groove in coastal cliffs at Teruataura, northeast coast of Mitiaro

Figure 25. Elevated notch at Parava, Mitiaro, at profile D. The deepest part of the notch stands at 2.27 m and the visor at 4.07 m.

Figure 26. Cliff-top grooves with basally-notched walls, profile B, Mitiaro. The floor of the grooves stands at 4.78-5.03 m.

Figure 27. Cliff-top abrasion platform at 5.75 m with cover of storm blocks on its landward side, profile B, Parava, Mitiaro

Figure 28. Emerged *Acropora* on the makatea surface at Parava, Mitiaro

Figure 29. Storm block on profile C, Mitiaro. The base of the block is at 6.17 m.

Figure 30. Storm block on profile H, at Vaikoua, Mitiaro. The base of the block is at 4.85 m.

Figure 31. Raised reef flat at Oponui, Mitiaro

Figure 32. Raised reef flat at Vaikoua, Mitiaro

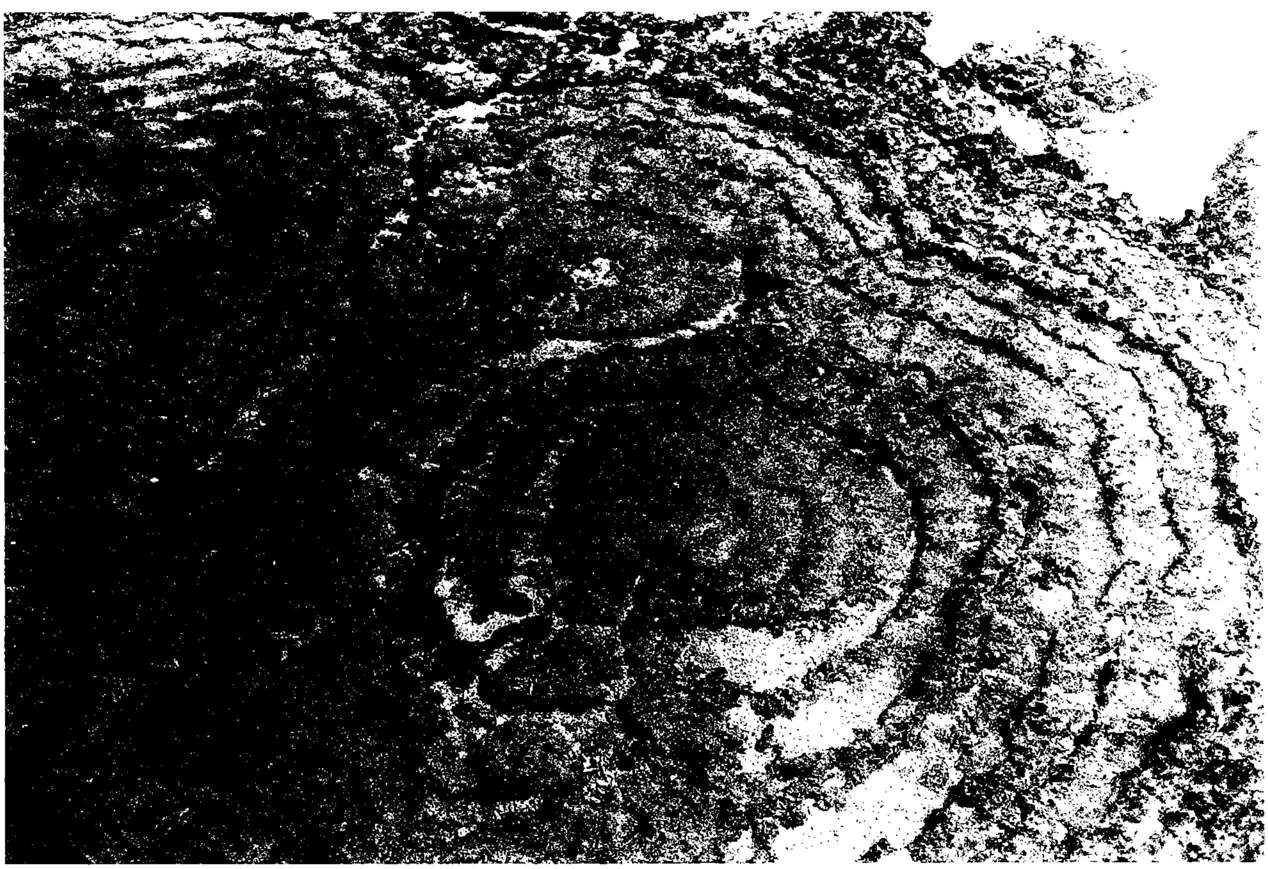


Figure 33. Microatolls in cliff-foot pool, seen from the cliff top, at Vaikoua (profile K), Mitiaro

Figure 34. Reef edge surge channel at Teruataura, west coast of Mitiaro

ATIU

Atiu, the largest and highest of the islands considered in this paper, is located in latitude 20°S., longitude 158°10'W., 187 km northeast of Rarotonga. It has been mapped photogrammetrically at 1:7920 by the Department of Survey, University of Otago (Hunt 1969). From this map the greatest dimensions of the island are 7.25 km N-S and 6.3 km E-W, compared with the 6.4 km [4 miles] and 6 km [3.75 miles] quoted by Grange and Fox (1955, 19). Its total area according to Grange and Fox (1955, 19) is 6654 acres [26.9 sq km] and from the topographic map 29.0 sq km. Like the other islands Mitiaro and Mauke, Atiu consists of an eroded central volcanic area surrounded by an elevated limestone rim. Unlike the other islands, however, Atiu was the subject of an extensive early account of its geology by Marshall (1930).

Volcanics

Atiu (figures 35 and 36) is the summit of a subconical asymmetric volcano some 25 km in diameter at the 3 km isobath (Summerhayes and Kibblewhite 1968). It is contiguous with Takutea to the northwest at the 3 km isobath, and with Mitiaro to the northeast at the 3.5 km level. The slopes of the Atiu cone are steepest to northeast and southeast.

The central volcanic area of the island comprises a flat-topped plateau, dissected by steep-sided, flat-floored radial valleys, well outlined by the 50 m contour (figure 39). Estimates of the height of the plateau vary. According to Schofield (1967, 119) it ranges from 65 to 82 m, the latter figure presumably deriving from Grange and Fox (1955). Wood and Hay (1970, 33) give a maximum figure of 235 ft [71 m], which is accepted by Turner and Jarrard (1982). Campbell (1982) quotes 72 m. The University of Otago topographic map gives a spot height of 70.97 m. We were unable during our time on Atiu to carry traverses from the coast through to the volcanics.

The basalts were first described by Marshall (1930, 7) and subsequently by Wood and Hay (1970, 33) and C. P. Wood (1978). Jarrard and Clague (1977) cite ages of 3.5-5 million years for these rocks, but these determinations have been superceded by those of Turner and Jarrard (1982). They report two group of dates: an older group of three, from 9.1±1.5 to 10.0±0.4 million years, and a younger group of four, from 8.0±0.2 to 8.4±0.3 million years. They infer two periods of volcanism at approximately 10 and 8-8.5 million years. Deep weathering has led to the formation of a red clay with limonitic nodules and black manganiferous veins (Wood and Hay 1970).

Since the time of Marshall (1930) many workers have drawn attention to the presence of terraces on the volcanic slopes, in addition to the bevelled summit. Marshall himself (1930, 70) identified a terrace at 70 ft [21 m] and a less pronounced terrace at 40 ft [12.2 m], which he considered to be of marine origin. Schofield (1967, 119) found 'terrace remnants' at 21, 12 and 4.6 m [70, 40 and 15 ft], which he also interpreted as 'marine platform levels'. Campbell et al. (1978, 231-232) describe a highest terrace, 700 m wide, rising to a height of 45 m with a 5° slope, bounded at its outer edge by a scarp 8-10 m high, followed by a second terrace up to 200 m wide, descending to 20 m above sea level, and finally a third terrace at 7-15 m. Later Campbell (1982) refers to the 'most prominent' terrace at 20-30 m, with 'smaller intermediate and lower terraces', each with distinctive soil assemblages. These features, which are not well supported by locational or altitudinal data, have been used to erect erosional histories for the island based largely on inferred sea-level change. Because of time constraints we could not investigate these features on the volcanics, but it is crucial for the interpretation of the history of Atiu that their status be resolved.

The volcanics are for the most part covered with deeply weathered red and brown clays, described in detail by Campbell et al. (1978) and Campbell (1982).

Marginal swamps

Between the volcanics and the makatea is a discontinuous lowland, termed a 'moat' by Marshall (1930), where streams flowing from the dissected volcanics are ponded back by the peripheral limestones to form swampy areas. The most extensive of these marshes extends for 3.5 km along the northeast flank of the volcanics. Some have been converted to taro cultivation; others still have massive buttressed trees of *Inocarpus edulis*, the low herb *Ludwigia octovalvis*, or sedges. Marshall (1930) believed the swamps stood at 20-30 ft [6-9 m] above sea level, and these figures have been quoted by Wood and Hay (1970, 33). Campbell (1982) gives an elevation of 6 m, and Campbell et al. (1978, 231-232) 2-4 km. The Otago topographic map, however, gives heights of 6-10 ft [1.8-3 m].

There is one extensive freshwater lake, Tiriroto, in the southwest part of the island (figure 40). The Otago map gives the height of the water surface as 3 ft [0.9 m]. The inner wall of the makatea which bounds it on its west side is deeply notched, with a characteristically horizontal notch roof 1.0-1.5 m above the swamp surface. This notch is generally 1-2 m in horizontal extent, but locally reaches 5 m, and exceptionally 8 m (figures 41 and 52). Marshall (1930) and local informants say that seawater incursions occur through and under the makatea.

Limestones: makatea

Limestones of presumably Cenozoic age (Marshall [1930] dated them as early Pliocene and later) entirely surround the central volcanics. Marshall (1930) described them as 1200 yards [1100 m] wide, terminating seawards in cliffs 10-20 ft [3-6 m] high, rising to a height of 70 ft [21 m] within 300 yards [275 m] of the coast, and then declining to the level of the swamps in a distance of 600-800 yards [550-730 m]. Grange and Fox (1955) likewise describe seaward cliffs 30 ft [9 m] high, a makatea surface rising to a maximum height of 70 ft [21 m], and the limestones having a total width of 0.5-1 mile [0.8-1.6 km]. Campbell et al. (1979, 247) record the presence of 'fresh basalt fragments within the coral limestone at the present inner limestone margin', possibly indicative of reef growth while volcanism still continued. Wood and Hay (1970) quote an average width of 1100 m, seaward cliffs 6 m high, and maximum heights of 70 ft [21 m] in the south and 100 ft [39 m] in the north. Campbell (1982) and Campbell et al. (1978) also refer to cliffs 6 m high, but give a maximum elevation for the makatea of 30 m, in the centre, before the surface declines inland to elevations of 6-15 m.

The Otago topographic map clearly shows the broadly convex transverse profile of the makatea (figure 36). It also shows that the makatea is highest on the northwest and east where its central part exceeds 60 ft [18 m]. Two spot heights of 75 ft [23 m] are marked on the east side. Conversely, on the southwest and south sides, maximum elevations rarely exceed 50 ft [15 m]. There is a similar apparent tilt to the upper surface of the makatea on Mangaia, where the west side is some 20-25 m higher than the east (Stoddart et al. 1985, 123).

In places the inner margin of the makatea grades smoothly into the volcanic slopes (Grange and Fox 1955, 19), but elsewhere, especially adjacent to swamps, it is formed by a vertical cliff 10 or more meters high (Campbell et al. 1978, Campbell 1982), with dripstones and flowstones. At Kurekure these cliffs are 20-25 m high (not 20 ft [6 m] as reported by Marshall [1930, 68]). They are conspicuously notched at their base, with a 1 m high notch extending to a horizontal depth of 10 m in places. There are apparently no outliers of the makatea on the volcanics (Marshall 1930, 69; Campbell et al. 1979, 247), though Jarrard and Turner (1979, 5691) refer to 'a few outcrops ... on the central volcanic hills', apparently at an elevation of 55 m (Jarrard and Turner 1979, 5693). This is 32 m above the present maximum elevation of the makatea proper; until these outcrops are confirmed or properly described, this report must be discounted.

Campbell (1982, 8) states that the makatea surface 'rises inland by a series of gentle steps ... [which are] possibly marine benches'. We did not have the opportunity to investigate these.

On the basis of foraminifera, Marshall (1930) suggested that the inner (older) section of the makatea was equivalent in age to the outer section of the makatea on Mangaia, i.e. early Pliocene. He also (1930, 56-57) found mineralogical differences in the limestones, with the older (inner) limestone being dolomitized. In 1985 Woodroffe found dolomitic crusts up to 3 cm thick on the inner section of the makatea. Other palaeosols have not been found in the makatea limestones.

According to Wood and Hay (1970, 34) the makatea limestones at Taunganui overlie 'a foot or two' of sticky yellow clay, over deep-red volcanic clay. If these clays result from subaerial weathering of the volcanics, then relative subsidence followed by reef upgrowth is indicated.

The surface of the makatea is deeply dissected, taking the form of a joint-controlled labyrinthine karst. Individual karst pinnacles and towers range in height from 3.0 to 4.5 m but locally (e.g. profile H) may exceed 6 m. There is also substantial internal limestone corrosion. We have, for example, surveyed one sinkhole which descends 22.5 m from the pinnacles on the makatea surface, the lower 11 m being a vertical fall to a freshwater pool. Caves in the makatea were first described by Williams (1838). Woodroffe visited Anetaketake cave, 500 m long, which may have been the one described by Williams. Its floor is uneven, with no evidence of either wave-cut features or changed base levels. The cave extends below the present water-level and there are pools of standing water. There are impressive stalactite, stalagmite and flowstone deposits, with sequences of rimmed terracettes. Marshall (1930) suggested that the horizontal caves may have been original reef passages, but there seems to be no evidence of this: they are clearly predominantly solutional. Some of these caves have been used as burial sites, as described by Trotter (1974).

Much of the makatea surface is irregularly covered with red clays, 'especially on the inland side' (Marshall 1930, 55). This material is clearly colluvial, derived by downslope transportation of weathered material from the volcanics, and as at Mangaia (Stoddart et al. 1985, 126) may in places predate the solutional development of the moat between volcanics and the makatea. Bizarrely, as at Mangaia (Marshall 1927, 24), Marshall (1930, 65) interpreted these clays as 'the accumulated excrement of water birds, especially of duck' (which are by no means abundant).

Limestones: Pleistocene

Marshall (1930, 56-57) himself recognised a fundamental distinction in the peripheral limestones, although he did not recognise its true significance. He found that the outer zone of limestone, 46 m wide, consisted of calcite and aragonite, whereas the limestones more than 370 m from the shore were irregularly dolomitized. Campbell (1982, 7), in a schematic section, showed the outer part of the makatea as consisting of 'coral sand and gravel' in contrast to the 'coral limestone' of the main part of the makatea.

As at Mitiaro and Mauke, these differences correspond to a transition between the main mass of makatea, of Cenozoic age, and a peripheral fringe of much younger Pleistocene limestones along the coast. The Pleistocene limestones have been studied in eight profiles around the island (figures 37 and 38). In these figures the full limestone symbol indicates limestones we consider to be Pleistocene, and the broken limestone symbol the older makatea. In general the older makatea outcrops at about 8-9 m in the south, rising to 13-14 m in the north. In several profiles the transition between older makatea and Pleistocene limestones coincides with a pronounced topographic break, at 8.6 m in profile A, 10.6 m in G, 10.1 m in H, and 12.2 m in D. In profiles B, C, E and F, however, such a break is not apparent. It would be tempting, but perhaps simplistic, to interpret the topographic break as a sea-level feature corresponding to the period of Pleistocene reef formation, especially as there is evidence from Mauke of a Pleistocene high sea level of ca 10 m (the limestones on Mitiaro are too low to reach this level). But preliminary uranium dates (to be reported elsewhere) indicate an extended period of late Pleistocene reef formation, and the stratigraphy of the Pleistocene deposits on Atiu is itself complex.

Three units can be distinguished in the Pleistocene deposits:

(a) lower unit. This is a constructional reef unit in which massive corals are dominant, with subsidiary branching corals. Interstices are filled with *Halimeda* plates and molluscan fragments. This unit is found at up to 2.65 m above sea level at Matai (profile A), and in a bench at 1.76 m at Oravaru (profile F).

(b) An intermediate unit of bedded sands, which occurs sporadically, especially at seaward locations. The presence of *Halimeda* plates up to 8 mm long suggests a beach environment. The unit is heavily cemented. At Taunganui (profile E) it contains 3 cm long vertical columnar structures which may be either root casts or burrows. In places the beds may be truncated. It is well seen at Oravaru (profile F), where it overlies *in situ* reef of the lower unit, and north of the Taunganui landing (profile E), where it overlies a boulder deposit; at both sites the sand unit is overlain by the upper unit.

(c) Upper unit. This consists of coral rubble with no corals in the position of growth within it: the only corals associated with it are superficial massive (*Porites*) or platey encrusters on the walls of grooves, and they do not form part of the unit. This may be a forereef rubble, possibly associated with the presumptive 10 m sea-level.

Coastal morphology

The reef flat around Atiu is generally less than 45 m wide, but reaches a maximum of 90 m near Oravaru on the west side (profile F). The reef flat is absent for a distance of about 2 km in the Totika area in the north (profile D). Wave conditions on the flat are rough and erosion has scoured depressions in it in which large and often coalescent microatolls grow. The deepest depression measured was 66 cm below mean sea level. No emergent corals or reef flat was seen, unlike Mauke and Mitiaro, although the microatoll upper surfaces are dead. Marshall (1930) thought the reef flat a constructional rather than an erosional feature, because of what he judged to be the small amount of erosion of the limestones where the flat was absent, but this is unlikely. At Totika (profile D), where the reef flat is absent, there is a well developed surf platform (Focke 1978) of calcareous red algae standing ca 1 m above sea level. This effectively protects the cliff behind it, which is, nevertheless, deeply notched (figures 48-51). The notch, related to present sea-level, is up to 2-3 m in vertical amplitude. On the top of the cliff there is a solutional topography of hummocks and depressions (figure 42) and blind gullies, at an elevation of 6.5 m. Offshore there are well-developed contemporary groove-and-spur features on the reef edge.

The seaward cliffs cut in the limestones are higher in the northeast (more than 10 m) and lowest in the southwest (3-6 m), corresponding to differences in height of the limestones themselves. Along the northwest coast between Totika and Teanapuku (profile C) they reach more than 20 m in height, with a maximum of about 26 m.

Fossil groove and spur features are found in many localities. At Taunganui (profile E) they are 6-8 m wide and several metres deep. As at Mangaia they may be arched over at their seaward ends. Encrustations of platey corals are common on their walls.

Holocene coastal features

Intermittent benches and raised notches on the seaward cliffs may provide evidence of recent high stands of the sea (figures 45 and 46). There are cliff-foot benches at 2.78 m on profile A, a bench (with associated notch) at a 1.8 m on profile F, at 1.78 m on profile G, and at 3.1 m on profile H. In several places the benches are being eroded and merging into the reef flat. There are raised notches in the cliff face above present intertidal levels, for example at 3.27 m on profile C and at 2.8, 3.0 and 3.6 m on profile H, giving complex profiles (figures 44 and 45) indicative of falling sea-levels (Pirazzoli 1986, 373-375). The dominant levels for benches and raised notches are 1.7-1.8 m and 2.8-3.2 m above present sea level. There is some indication of possible older features at ca 6 m in profiles A, B, E, G and H.

There are, however, no extensive areas of emerged reef-flat on Atiu, as there are on Mauke and especially Mitiaro.

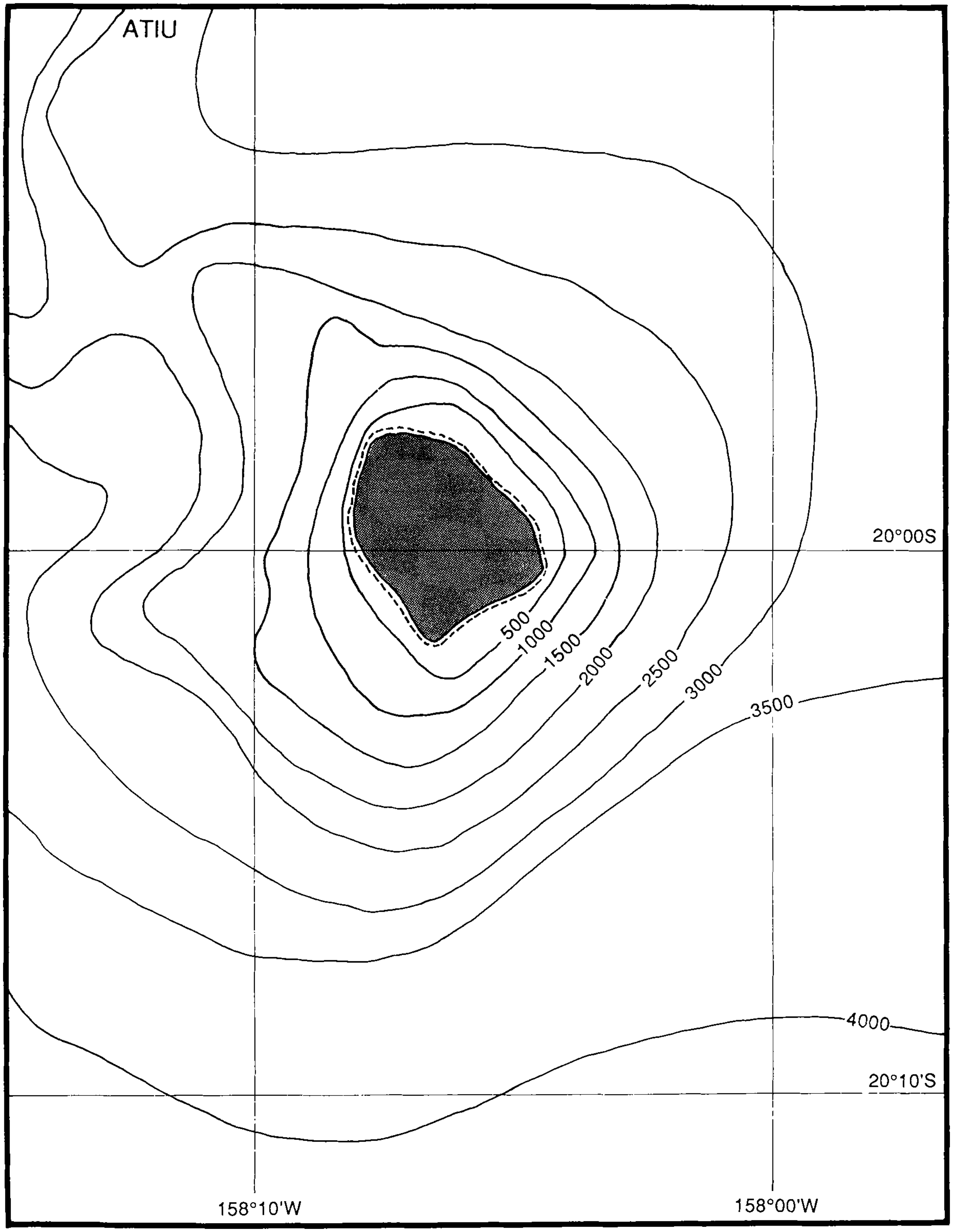


Figure 35. Bathymetry of Atiu (after Summerhayes and Kibblewhite 1968)

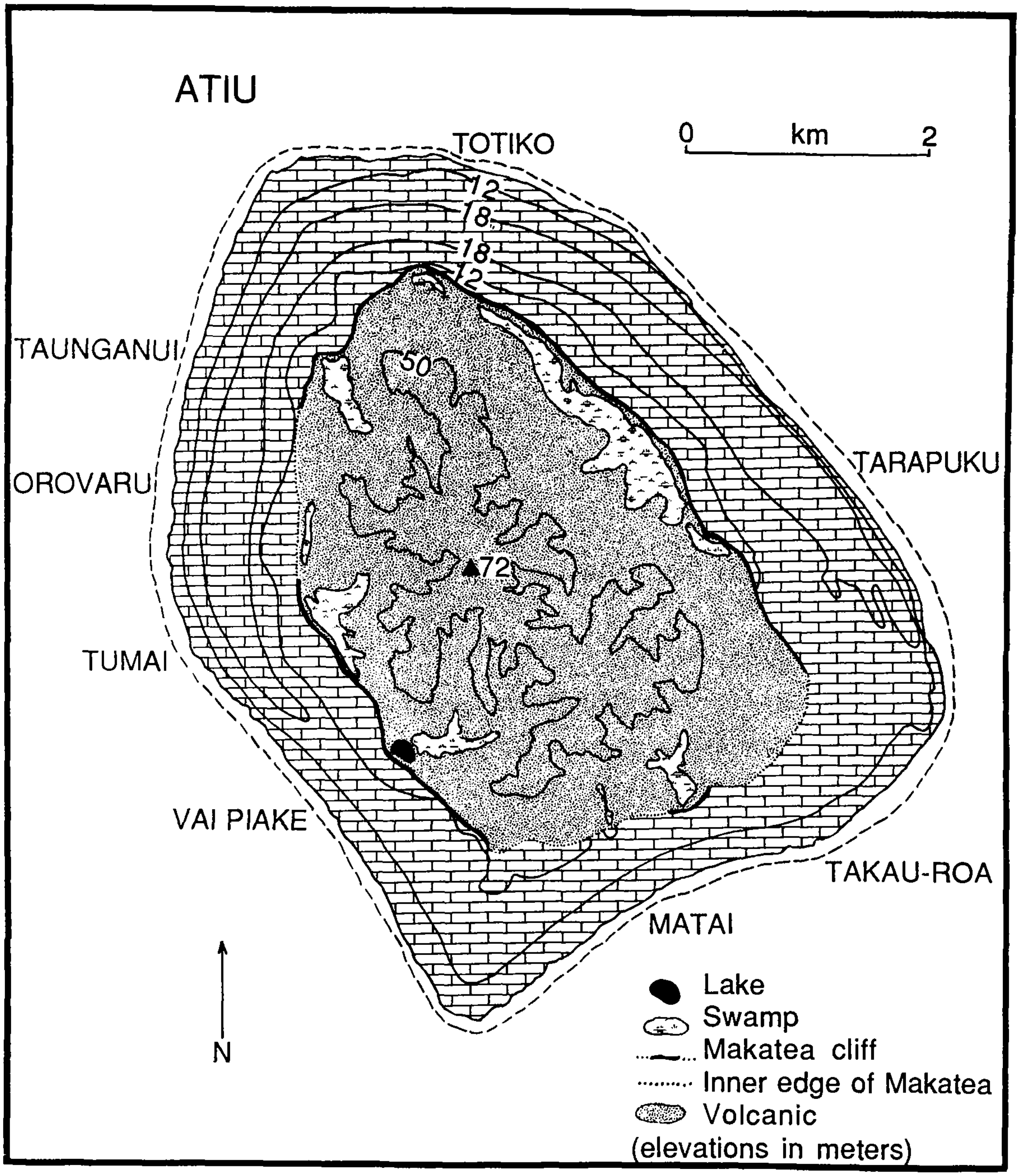


Figure 36. Geology of Atiu

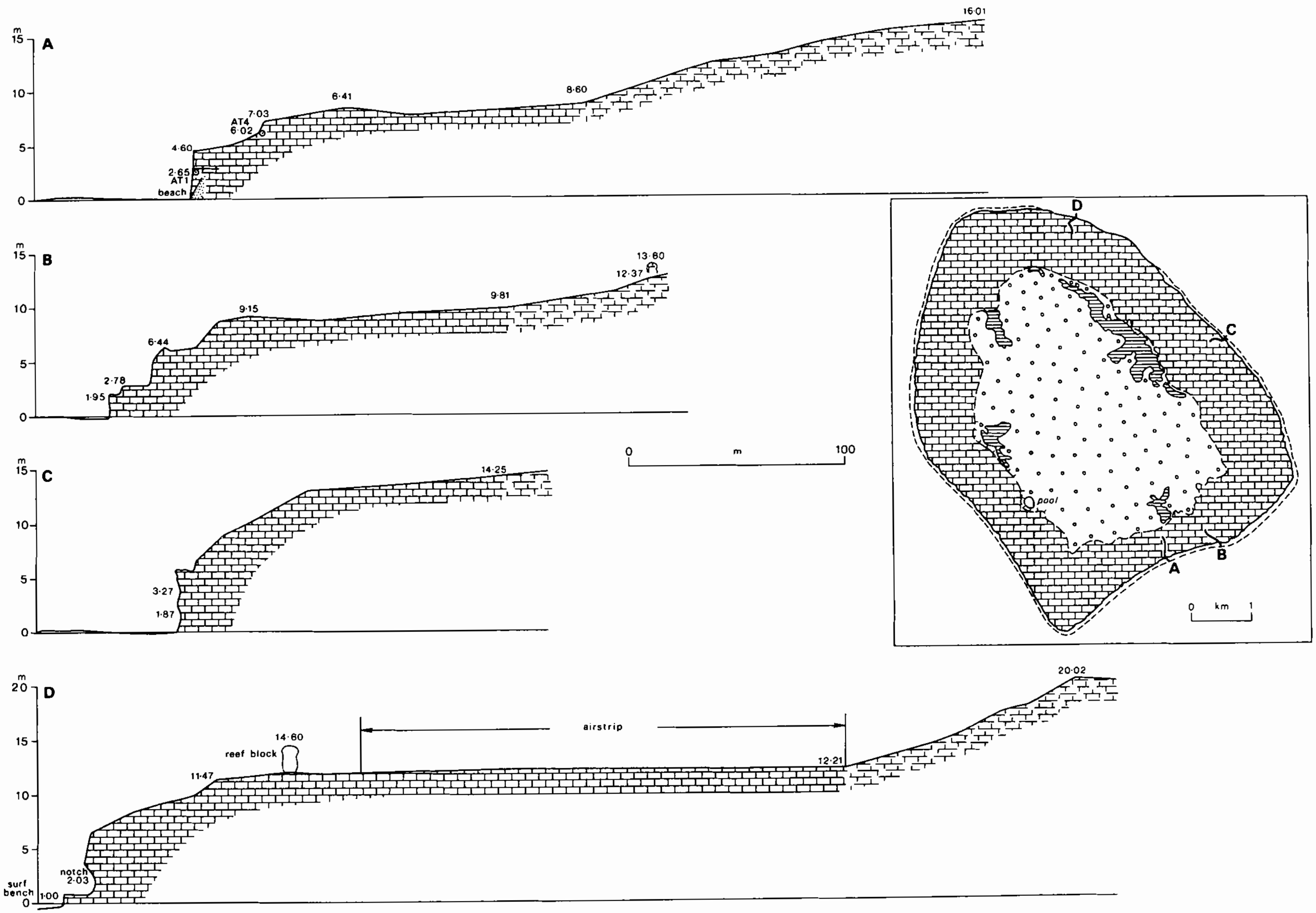


Figure 37. Atiu: topographic profiles A, B, C and D

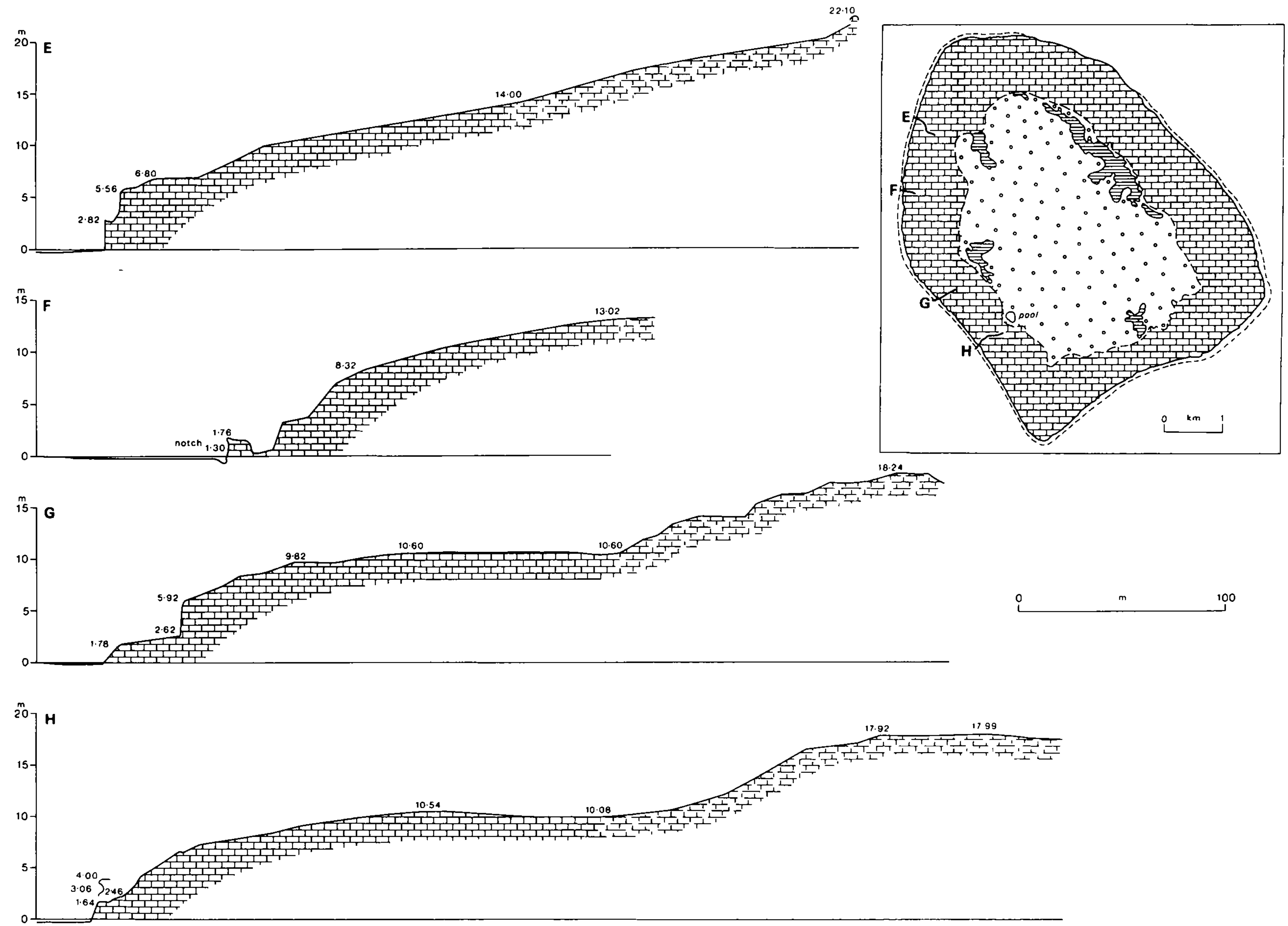


Figure 38. Atiu: topographic profiles E, F, G and H

Figure 39. Bevelled upper surface of the central volcanics on Atiu

Figure 40. Lake Tiriroto on the southwest side of Atiu

Figure 41. Basally notched cliffs on the inner side of the makatea near Lake Tiriroto, Atiu

Figure 42. Mammillated surface of limestones inland from the cliff edge at Totika (profile D), Atiu

Figure 43. Makatea surface at Orovaru, Atiu

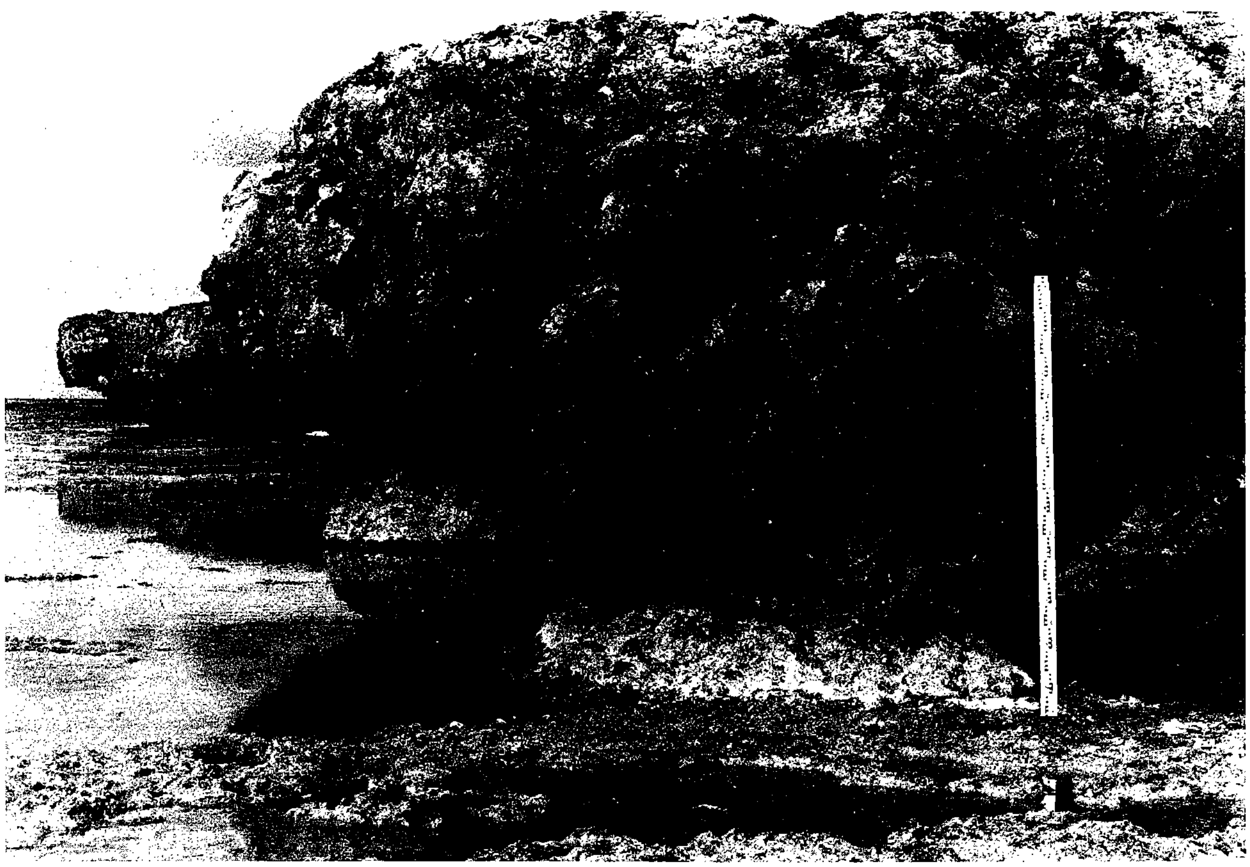


Figure 44. Basally notched coastal cliffs, southwest coast of Atiu

Figure 45. Double-notched cliffs at Teanapuka, east coast of Atiu

Figure 46. Basally-buttressed cliffs at Vaipiake, Atiu

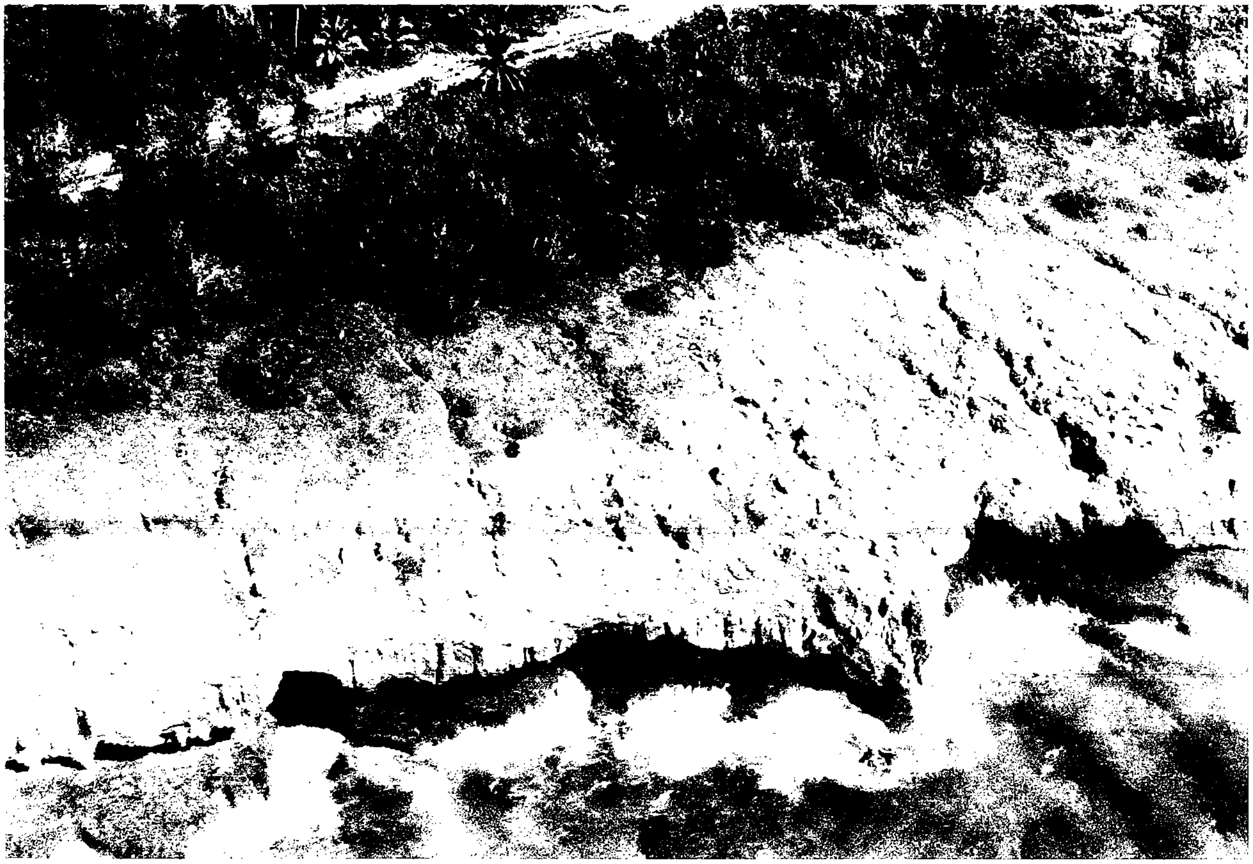


Figure 47. Aerial view of basally notched cliffs at Totika, Atiu

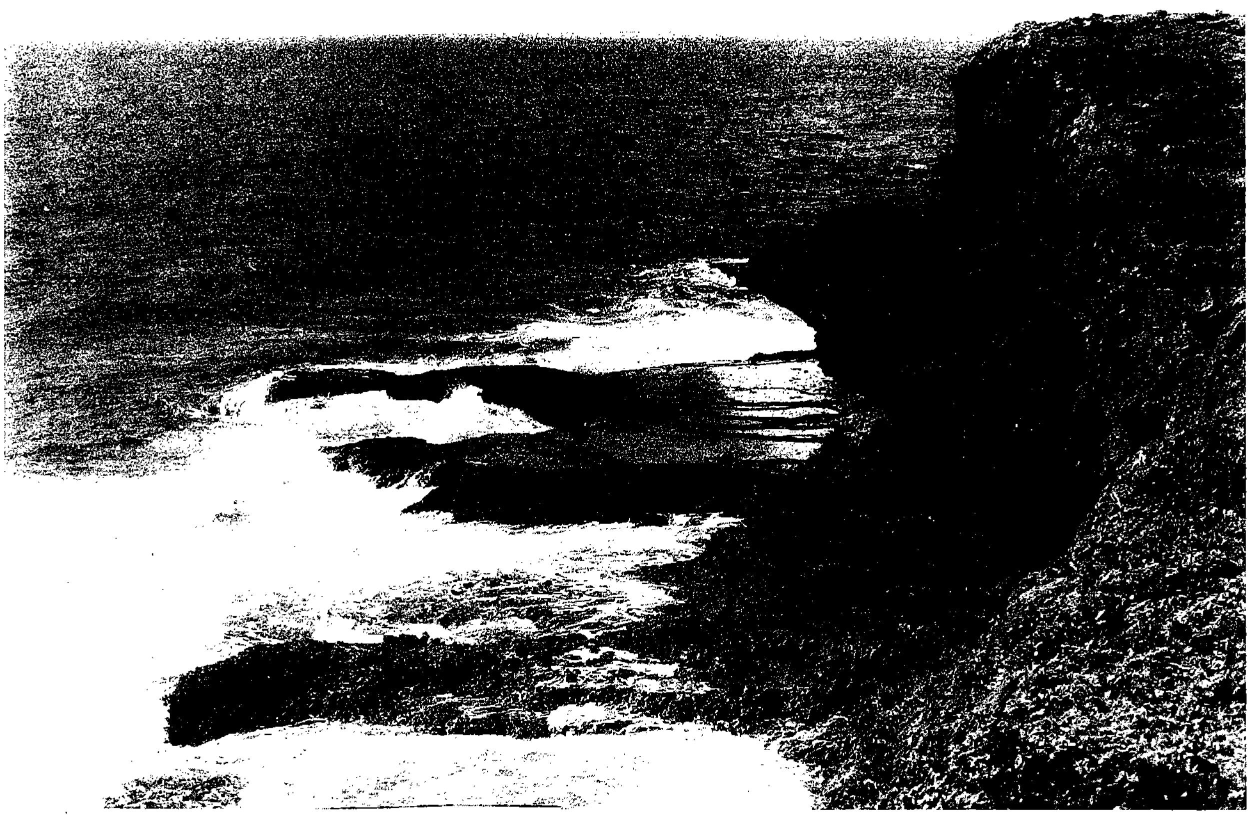
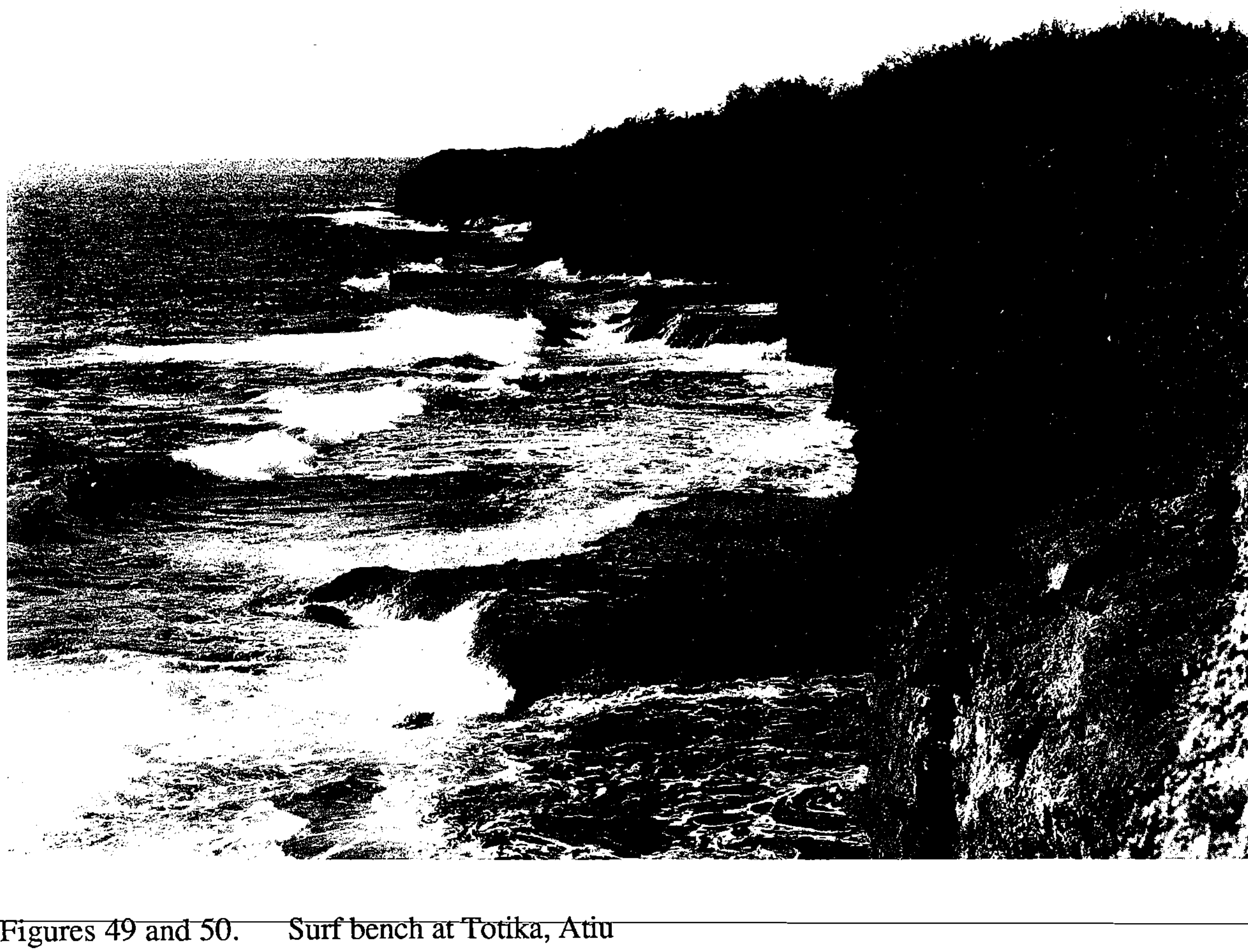


Figure 48. Surf bench at Totika, Atiu



Figures 49 and 50. Surf bench at Totika, Atiu

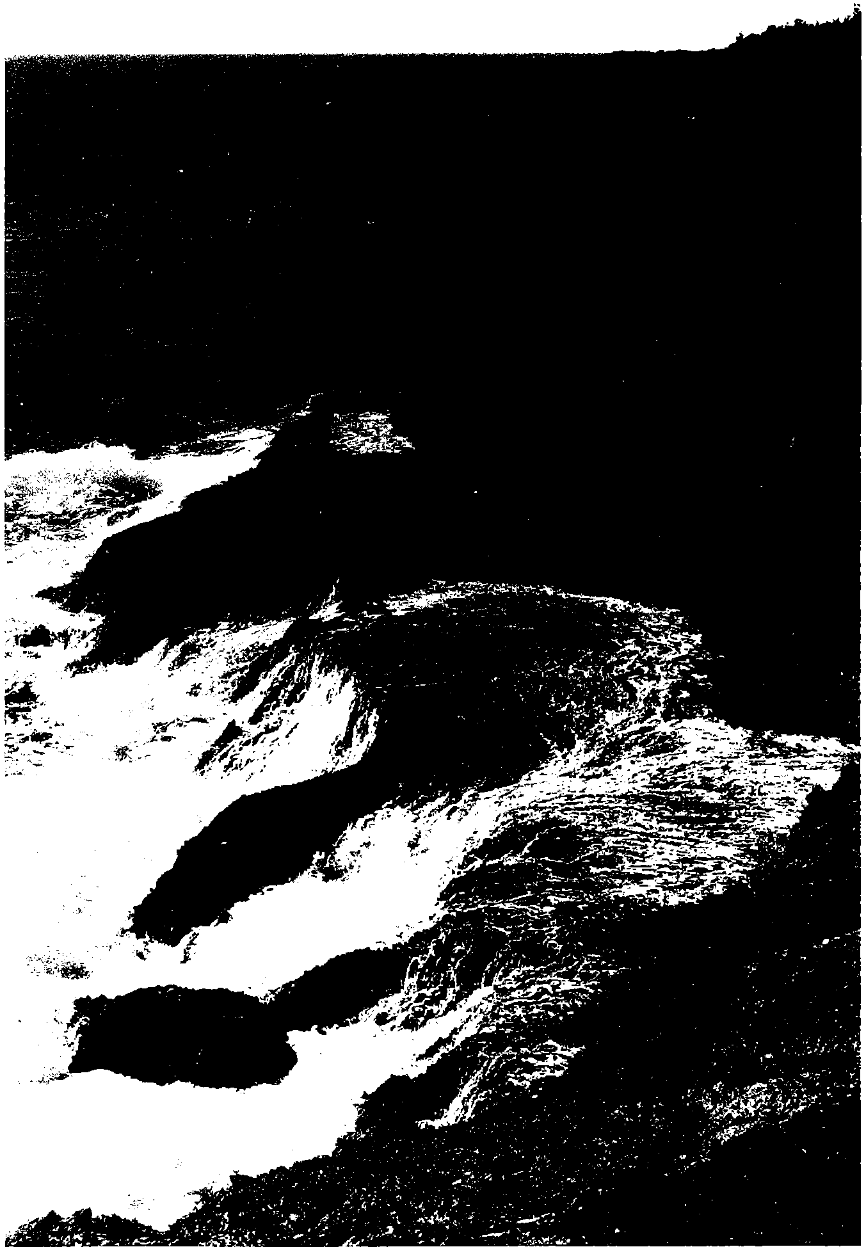


Figure 51. Surf bench at Totika, Atiu

Figure 52. Basal notch in inner makatea cliff on the west coast of Atiu

DISCUSSION

In this section we summarise the salient features of the geomorphology of Mitiaro, Mauke and Atiu, and make some comparisons with other islands in the southern Cooks, notably Mangaia and Aitutaki.

Volcanics

We have established the maximum elevation of the volcanics on Mitiaro as 8.9 m (previous estimates 6.0-12.2 m) and on Mauke as 24.4 m (previous estimates 25-30 m). The maximum elevation on Atiu from the Otago topographic map is 71 m. These heights compare with 124 m for Aitutaki and 169 m for Mangaia. Mitiaro is the only island in the southern Cooks on which the maximum elevation of the volcanics is less (by 2 m) than the maximum elevation of the makatea, and it seems likely that in this case the makatea formerly completely covered the volcanics which have been unroofed by karst erosion.

The upper surface of the volcanics is conspicuously horizontally bevelled at both Mauke (at 20-24 m) and at Atiu (at ca 65-70 m). The higher parts of both Aitutaki and Mangaia are likewise bevelled, at ca 75 m and 165 m respectively. Previous workers have attributed these bevels to marine erosion and it is difficult to think of any other reasons for such smooth truncation of previously conical topography. Indeed, if one extrapolates the regular submarine volcanic topography of many of the Cook Islands, to which Robertson and Kibblewhite (1966) fitted the expression $y = y_0 e^{-0.10x}$ (where y is depth at distance x from shore and y is mean depth of the surrounding ocean floor, 4.6 km), it is evident that very substantial truncation has taken place on these cones.

Mauke and Mitiaro are too low to display benches or terraces below the summit bevel. Conspicuous terraces have been described for Atiu at 45, 20 and 7-15 m (Campbell et al. 1978); Schofield (1967, 119) gives comparable terrace heights of 21 and 12 m, and adds a further level at 4.6 m. No similar terraces have been described from Mangaia, but at Aitutaki Wood and Hay (1970) refer to wave-cut terraces at 76, 18-21 and 12 m, and Lambeck (1981, 484) mentions 'several marine terraces up to 120 m'. The 76 m level is close to the summit level of Atiu. The Aitutaki 18-21 m level (if real and significant) corresponds altitudinally with the summit level at Mauke (20-24 m) and the 20-21 m terrace at Atiu. The Aitutaki 12 m terrace (again, if real and significant) lies above the Mitiaro summit level (8-9 m), but corresponds to the terrace described by Schofield at 12 m and by Campbell et al. at 7-15 m on Atiu, and it is also close to the maximum height of late Pleistocene shorelines on Mauke, Mitiaro and Atiu. But it should be emphasised that none of these features in the southern Cooks has been rigorously mapped or levelled, and that there is no direct evidence of their marine origin at all.

Makatea

The maximum elevation of Cenozoic limestones is shown by our surveys to be 10.9 m on Mitiaro and 14.7 m on Mauke. The Otago topographic map gives the maximum height on Atiu as 23 m.

The upper surfaces of the makatea at Mitiaro and Mauke are broadly horizontal. The convexity of the surface in cross-profile at Atiu is indicative of considerable post-uplift erosion, however. The horizontality at the former islands could well reflect bevelling by late Pleistocene sea levels. The degree of post-emergence modification at Atiu is unknown, but in the case of Mangaia we have argued that the development of the swamplands by limestone retreat effectively isolates the surface of the makatea from fluvial dissolution as the streams draining the central volcanics exit through the limestones close to present sea level. Thus most of the karst erosion in the makatea is internal to the limestone body and the external geometry of the makatea is relatively resistant to change (Stoddart et al. 1985, 127). Two points need to be considered at Atiu in judging the degree of modification and neither is unambiguous. The first is the unsupported statement by Jarrard and Turner (1979, 5693) that outcrops of makatea are found on the volcanic slopes of the island at an altitude of 55 m, or 32 m above the present maximum height of the makatea. If correct this would indicate a degree of erosional modification of the makatea on a scale hitherto never contemplated. We doubt this record, as we did their reference to makatea outliers at 90 m on the Mangaia volcanics (Stoddart et al. 1985, 136). Second, at both Atiu and Mangaia Wood and Hay (1970) refer to the existence of concentric structures in the makatea, evident in aerial photography, as evidence of the exposure of internal seaward-dipping depositional structures by surficial erosion. It is impossible to quantify the magnitude of this effect, however.

A more specific index of the erosional modification of the limestones is given by the presence at Atiu of colluvial weathered materials from the volcanics on the inner slopes of the makatea. There are no precise data on the distribution of this colluvium, but it can be inferred from Campbell (1978, 231) that it extends to an elevation of ca 20 m above sea level. It was presumably progressively deposited downwards as the 'moat' between the volcanics and the makatea was incised by erosion, though there is also the possibility that the swamp levels were at higher elevations during Pleistocene high stands of the sea and that some of the colluvium may be relict from that time.

A major difficulty in understanding the makatea is that the ages of the formation of the limestones as well as of their emergence is unknown. At Mangaia Marshall (1927) believed the limestones were of Oligocene and lower Miocene age, or younger. Recently Yonekura et al. (1986, 50) have inferred an age of 17 million years from foraminifera collected on the innermost upper surface of the makatea, i.e. very soon after volcanism: the K-Ar ages of Mangaia volcanics range from 16.6 to 19.4 million years, with one young date of 13 million years. Unlike Rurutu in the Austral Islands (Bardintzeff et al. 1985), however, we have seen no exposures where volcanic conglomerates occur near the base of the makatea, which would suggest the contemporaneity of initial reef growth and continuing volcanism. The volcanics on Mitiaro, Mauke and Atiu are apparently substantially younger (12.3, 6.0, and 8-10 million years, respectively). There is therefore a real possibility that the makatea units on the different islands are of different ages and hence their morphologies cannot be directly compared. Marshall (1930) himself believed the Atiu limestones to be early Pliocene and later.

Whatever the age of the limestones, however, it appears reasonable to follow McNutt and Menard (1978) in explaining their emergence by lithospheric flexure consequent on loading by subsequent volcanicity. Two points might be made about their analysis, however. The first is that their calculations of net uplift incorporate loading by the three volcanoes of Rarotonga, Aitutaki and Manuae, of which only the first is known to postdate the formation of Mitiaro, Mauke and Atiu. The second is that their calculations depend on the independent response of each of the volcanoes, and it is by no means clear that this condition would be met with such closely associated cones as the three under discussion. Nevertheless, it is pertinent to use our new elevation data from the makatea to re-examine the goodness of fit of the McNutt and Menard model (Spencer et al. 1987). These data are summarised here in Table 4.

Table 4. Island uplift and lithospheric flexure in the southern Cooks

A Island	B Distance from Rarotonga km	C Maximum elevation of volcanics m *	D Maximum elevation of makatea m *	E Actual uplift according to McNutt & Menard, m **	F Predicted net uplift through loading by Rarotonga, Aitutaki and Manuae, m **	G Predicted uplift through loading by Rarotonga only, m **	H Goodness-of-fit of model (G - D)
MAUKE	281	24.4	14.7	30.0	28.8	17.0	+ 2.3
MITIARO	264	8.9	10.9	27.0	27.4	25.0	+14.1
ATIU	222	71.0	22.1	20.0	17.7	48.0	+25.9
MANGAIA	205	169.0	73.0	70.0	50.5	51.0	-22.0

* This paper

** McNutt and Menard (1978)

Pleistocene events

The maximum elevation of Pleistocene features on the seaward side of the makatea was found to be 7.8 m on Mitiaro, 12.7 m on Mauke, and 12.2 m on Atiu: Mitiaro is anomalously low simply because the makatea on which the Pleistocene reefs formed does not itself rise above 10.9 m. In consequence, whereas on Mauke and Atiu the Pleistocene deposits are banked against the seaward edge of the makatea, on Mitiaro they are spread across its upper-surface in many areas. There are no Pleistocene deposits on Aitutaki; on Mangaia there is a prominent shoreline at 20 m. Prominent stratigraphic discontinuities are found within the Pleistocene at 4.1-6.0 m on Mitiaro, 1.5-2.75 m on Mauke, and 1.75-2.65 m on Atiu. These themselves indicate a fairly complex late Pleistocene history, and this is supported by unpublished uranium-series dates (Woodroffe *et al.*, in preparation), in contrast to Mangaia where the uranium-series dates tie the deposits closely to last interglacial times (Veeh 1966; Spencer et al. 1988).

The floors of raised groove-and-spur features associated with late Pleistocene reef deposits rise inland from the coast to maximum heights of 5.7 m on Mitiaro, 7.5 m on Mauke, and 6.5 m on Atiu. On Mangaia similar features rise to 11 m.

Holocene features

Raised notches and occasional cliff-foot benches also record sea-level fluctuations over a shorter time scale. Notches reach 2.3 m on Mitiaro, 0.6-1.5 and 5.5-6.5 m on Mauke, and 2.8-3.6 m on Atiu. Benches on Mauke reach 2.7 m and on Atiu 1.8-3.1 m. Benches and associated notches are found on Atiu at 1.7-1.8, 2.8-3.2, and possibly 6 m.

Anomalously high sectors of reef flat of possibly Holocene age are found at 1.23 m on Mitiaro. These may correlate with the notches and benches in the height range 2.3-3.6 m.

Apparently anomalously high beachrock is found up to 1.96 m on Mitiaro.

These features taken together resemble the emerged benches, high notches at 2-3 m, uplifted microatolls at 0.95-1.5 m, and raised and eroding reef flats described by Yonekura et al. (1986, 1988) on the northwest coast of Mangaia, except that the Mitiaro, Mauke and Atiu elevations are somewhat greater than those on Mangaia. Yonekura et al. (1986, 1988) show that the features on Mangaia all date from a high stand of the sea at 1.0-1.7 m above present in the interval 5000-ca 3150 years B.P., after which sea level fell to its present level or less, when contemporary reef flats and notches began developing. These differences may result from flexural control.

Modern coastal features

Perched beaches are extensive on the cliff tops of Mitiaro and Mauke, where they reach heights of 10.9 and 12.7 m respectively; the cliffs of Atiu are too high and steep for perched beach formation.

Storm-thrown reef blocks are common on the cliff tops of both Mitiaro and Mauke, at heights of 4.9-6.8 m on the former and 6.9-9.2 m on the latter, at distances of 9-200 m from the cliff edge.

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REFERENCES

Bardintzeff, J.-M., Brousse, R. and Gachon, A. 1985. Conditions of building of coral reefs on a volcano: Mururoa in Tuamotu and Rurutu in Australes (French Polynesia). *Proc. 5th Int. Coral Reef Symp.* 6, 401-405.

Baudry, N., Diament, M. and Albouy, Y. 1987. Precise location of unsurveyed seamounts in the Austral Archipelago area using SEASAT data. *Geophys. J. R. astronom. Soc.* 89, 869-888.

Baudry, N., Von Stacklelburg, U. and Récy, J. 1988. Alignements volcaniques dans les Iles Australes: analyse et interprétation de données SEASAT et Seabeam. *C. r. hebd. Séanc. Acad. Sci., Paris,* 306 (II), 643-648.

Bourrouilh-Le Jan, F. G. and Talandier, J. 1985. Sedimentation et fractionation de haute energie en milieu récifal: tsunamis, ouragans et cyclones et leurs effets sur la sédimentologie et la géomorphologie d'un atoll: motu et hoa, a Rangiroa, Tuamotu, Pacifique SE. *Marine Geology*, 67, 263-333.

Campbell, I. B. 1982. Soils of Atiu, Cook Islands. N.Z. *Soil Survey Report*, 54, 1-38.

Campbell, I. B., Claridge, G. G. C. and Blakemore, L. C. 1978. Pedological study of soils from basaltic parent material on the island of Atiu, Cook Islands. *N.Z. J. Science*, 21, 229-248.

Chubb, L. J. 1927a. The geology of the Austral or Tubuai Islands (southern Pacific). *Q. J. Geol. Soc. London*, 83, 291-316.

Chubb, L. J. 1927b. Mangaia and Rurutu: a comparison between two Pacific islands. *Geol. Mag.* 64, 518-522.

Diament, M. and Baudry, N. 1987. Structural trends in the Southern Cook and Austral Archipelagoes (South Central Pacific) based on an analysis of SEASAT data: geodynamic implications. *Earth Planet. Sci. Lett.* 85, 427-438.

Focke, J. W. 1978. Limestone cliff morphology on Curaçao (Netherlands Antilles), with special attention to the origin of notches and vermetid/coralline algal surf benches ('cornices', 'trottoirs'). *Z. Geomorph.*, N.F., 22, 329-349.

Grange, L. I. and Fox, J. P. 1953. Soils of the lower Cook Group. *N.Z. Soil Bureau Bull.* N.S. 8, 1-56.

Hoffmeister, J. E. 1930. Erosion of elevated fringing reefs. *Geol. Mag.* 57, 549-554.

Hunt, P. J. 1969. Atiu Island 1:7920. University of Otago, Department of Surveying.

Jarrard, R. D. and Clague, D. A. 1977. Implications of Pacific island and seamount ages for the origin of volcanic chains. *Rev. Geophys. Space Physics*, 15, 57-76.

Jarrard, R. D. and Turner, D. L. 1979. Comments on 'Lithospheric flexure and uplifted atolls' by M. McNutt and H. W. Menard. *J. Geophys. Res.* 84, 5691-5697.

Lambeck, K. 1981a. Flexure of the ocean lithosphere from island uplift, bathymetry and geoid height observations. *Geophys. J.* 67, 91-114.

Lambeck, K. 1981b. Lithospheric response to volcanic loading in the southern Cook Islands. *Earth Planet. Sci. Lett.* 55, 482-496.

Lambeck, K. and Coleman, R. 1982. A search for seamounts in the Southern Cook and Austral region. *Geophys. Res. Lett.* 9.

Marshall, P. 1927. Geology of Mangaia (Cook Islands). *Bull. Bernice P. Bishop Mus.* 36, 1-48.

Marshall, P. 1929. Mangaia and Rurutu - a comparison betwen two Pacific islands. *Geol. Mag.* 66, 385-389.

Marshall, P. 1930. Geology of Rarotonga and Atiu. *Bull. Bernice P. Bishop Mus.* 72, 1-75.

McNutt, M. and Menard, H. W. 1978. Lithospheric flexure and uplifted atolls. *J. geophys. Res.* 83, 1206-1212.

Moore, J. G. and Moore, G. W. 1984. Deposit from a giant wave on the island of Lanai, Hawaii. *Science, N.Y.* 226, 1312-1315.

New Zealand Department of Lands and Surveys. 1975. Mauke Island 1:12,500. Aerial plan 1036/8m. Wellington: Department of Lands and Surveys.

New Zealand Department of Lands and Surveys. 1983. Mitiaro, Cook Islands. 1:25,000. Wellington: Department of Lands and Surveys.

New Zealand Oceanographic Institute. 1969. Mauke bathymetry 1:200,000 [includes Mitiaro]. Wellington: Department of Scientific and Industrial Research.

Okal, E. A. and Batiza, R. 1987. Hotspots: the first 25 years. *Geophysical Monographs* (American Geophysical Union), 43, 1-11.

Pirazzoli, P. A. 1986. Marine notches. In O. van de Plassche, ed.: *Sea-level research: a manual for the collection and evaluation of data* (Norwich: Geo Books), 361-400.

Pirazzoli, P. A. and Montaggioni, L. F. 1988. Holocene sea-level changes in French Polynesia. *Palaeogeog. Palaeoclimatol. Palaeoecol.* 68, 153-175.

Robertson, E. I. and Kibblewhite, A. C. 1966. Bathymetry around isolated volcanic islands and atolls in the south Pacific Ocean. *N.Z. J. Geol. Geophys.* 9, 111-121.

Schofield, J. C. 1967. Pleistocene sea-level evidence from the Cook Islands. *J. Geosciences Osaka City Univ.* 10, 118-120.

Scoffin, T. P., Stoddart, D. R., Tudhope, A. W. and Woodroffe, C. D. 1985. Exposed limestones of Suwarrow Atoll (Northern Cook Islands, S. W. Pacific). *Proc. 5th Int. Coral Reef Symp.* 3, 137-140.

Spencer, T., Stoddart, D. R. and Woodroffe, C. D. 1987. Island uplift and lithospheric flexure: observations and cautions from the south Pacific. *Z. Geomorph.*, N.F., supplbd. 63, 87-102.

Spencer, T., Stoddart, D. R., Woodroffe, C. D., and Harmon, R.S. 1988. Lithospheric flexure and raised reef limestones, S. Cooks-Austral Islands. *Proc. 6th Int. Coral Reef Symp.*, 3, 485-489.

Stoddart, D. R. 1969. Reconnaissance geomorphology of Rangiroa. *Atoll Res. Bull.* 125, 1-44.

Stoddart, D. R. 1975. Almost-atoll of Aitutaki: geomorphology of reefs and islands. *Atoll Res. Bull.* 190, 31-57.

Stoddart, D.R. and Spencer, T. 1987. Rurutu reconsidered: the development of makatea topography in the Austral Islands. *Atoll Res. Bull.* 297, 1-19.

Stoddart, D. R., Spencer, T., and Scoffin, T. P. 1985. Reef growth and karst erosion on Mangaia, Cook Islands: a reinterpretation. *Z. Geomorph.*, N.F. Supplbd. 57, 121-140.

Summerhayes, C.P. 1971. Lagoonal sedimentation at Aitutaki and Manuae in the Cook Islands: a reconnaissance survey. *N.Z. J. Geol. Geophys.*, 14, 351-363.

Summerhayes, C. P. and Kibblewhite, A. C. 1968. *Atiu provisional bathymetry.* New Zealand Oceanographic Institute chart, Island Series, 1:200,000 [includes Mitiaro and Takutea].

Summerhayes, C. P. and Kibblewhite, A.C. 1969. *Mauke provisional bathymetry.* New Zealand Oceanographic Institute chart, Island Series, 1:200,000 [includes Mitiaro].

Summerhayes, C. P. 1967. Bathymetry and topographic lineation in the Cook Islands. *N.Z. J. Geol. Geophys.* 10, 1382-1399.

Thompson, C. S. 1986. The climate and weather of the Southern Cook Islands. *New Zealand Meteorol. Serv. Misc. Publ.* 188(2), 1-69.

Trotter, M. M., ed., 1974. Prehistory of the southern Cook Islands. *Canterbury Museum Bull.* 6, 1-155.

Turner, D. L. and Jarrard, R. D. 1982. K-Ar dating of the Cook-Austral chain: a test of the hot-spot hypothesis. *J. volcanol. geothermal Res.* 12, 187-226.

Veeh, H. H. 1966. Th^{230}/U^{238} and U^{234}/U^{238} ages of Pleistocene high sea level stand. *J. geophys. Res.* 71, 3379-3386.

Wilde, R. H. 1981. Soils of Mitiaro, Cook Islands. *N.Z. Soil Survey Rept.* 53, 1-20.

Williams, J. 1837 . A narrative of missionary enterprises in the South Sea Islands; with remarks upon the natural history of the islands, origin, languages, traditions, and usages of the inhabitants. London: J. Snow and J. R. Leifchild. xx, 589 pp.

Wilson, A. D. 1982. Soils of Mauke, Cook Islands. *N.Z. Soil Survey Rept.* 52, 1-59.

Wood, B. L. and Hay, R. F. 1970. Geology of the Cook Islands. *N.Z. Geol. Surv. Bull.* N.S. 82, 1-103.

Wood, C. P. 1978. Petrology of Atiu and Mangaia, Cook Islands. *N.Z. J. Geol. Geophys.* 21, 767-771.

Woodroffe, C. D., Short, A. D., Stoddart, D. R., Spencer, T. and Harmon, R. S. In preparation. Stratigraphy and chronology of late Pleistocene reefs in the southern Cook Islands, South Pacific.

Woodroffe, C. D., Stoddart, D. R., Spencer, T., Scoffin, T. P. and Tudhope, A. W. In press. Holocene emergence in the Cook Islands, South Pacific. *Coral Reefs.*

Yonekura, N., Ishii, T., Saito, Y., Maeda, Y., Matsushima, Y., Matsumoto, E. and Kayanne, H. 1988. Holocene fringing reefs and sea-level change in Mangaia Island, southern Cook Islands. *Palaeogeog. Palaeoclimatol. Palaeoecol.* 68, 177-188.

Yonekura, N., Ishii, T., Saito, Y., Matsumoto, E. and Kanne, H. 1986. Geologic and geomorphic development of Holocene fringing reefs of Mangaia Island, the South Cooks. *Sea-level changes and tectonics in the Middle Pacific: report of the HIPAC Project in 1984 and 1985* (Kode: Department of Earth Sciences, Kobe University), 44-69.