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GEOLOGY AND GEOMORPHOLOGY OF HENDERSON ISLAND

BY

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ABSTRACT

The 1987 expedition to the Pitcairn group was able to perform a spatially-limited reconnaissance of the structure and topography of Henderson Island and of the more common elements of its fossil fauna; this paper presents a number of observations and hypotheses which need to be tested by further work. Henderson is an uplifted atoll with a large fossil lagoon that preserves many depositional features. The entire lagoon basin surveyed iscovered with pebble sized or larger coral debris, finer sediments being largely absent. The fossil coral fauna is well preserved and diverse, and the old lagoon probably had excellent communication with the surrounding ocean. The rate of uplift, excellent preservation and predominance of recent species among the fossils, abundant depositional features in the interior basin, and limited extent of erosional features all point to the recency of uplift, supporting the hypothesis that hotspot volcanism at Pitcairn Island has been responsible for the regional flexure of the Pacific plate with up-arching and uplift at Henderson. We provisionally assign a Pleistocene age to all exposed deposits. Embayments within the 30m cliffs which encircle Henderson are characterised by core reef buttresses and two apron reefs: an upper fossiliferous reef unit and a lower low limestone unit which we tentatively assign to the Penultimate and Last Interglacial periods respectively.

INTRODUCTION

Raised reef limestone islands provide, generally, an indication of the thermal processes associated with oceanic lithosphere (e.g. Detrick and Crough 1978, Crough 1984, Menard 1986) and, specifically, important observational data to test models of crustal loading by relatively young (<2 m.y.) mid-plate volcanoes (e.g. McNutt and Menard 1978, Lambeck 1981a, 1981b, Pirazzoli and Montaggioni 1985). A comparison of theoretical models and field observations in the south Pacific has demonstrated the need for both the careful determination of raised reef altitudes and the geomorphological evaluation of the significance of such features (Spencer et al. 1987). Raised limestone sequences also provide important locations for the study of carbonate diagenesis (e.g. Schroeder and Purser 1986), including dolomitization (Schlanger 1981, Schofield and Nelson 1978, Bourrouilh-Le Jan 1982), and the genesis of island phosphorites (Hutchinson 1950). Related to these studies, the radiometric dating of emergent fossil corals, allied to a knowledge of the environment of

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deposition from diagnostic coral and molluscan assemblages, allows for the reconstruction of regional sea level histories and the determination of rates of tectonically-determined uplift in varied settings (e.g. plate margin: Huon Peninsula, New Guinea, Chappell and Veeh 1978; mid-plate: Bourrouilh-Le Jan 1985). Raised reef islands thus provide the opportunity to study the interplay between these tectonic, geochemical and environmental processes; they supply input for modelling and simulation exercises (Chappell 1980, Paulay and McEdward in prep.) on reef growth and island morphology; and they occupy an important position in the establishment of general theory on volcanic island development and attendant reef construction.

Of the raised limestone islands found on the Pacific plate (for distribution: Bourrouilh-Le Jan 1977) Henderson Island (Figure 1) falls within the category of raised atoll with preserved lagoon (Fosberg 1985; for the range of island-atoll types: Scott and Rotondo 1983). As such it can be broadly compared, at least in terms of gross appearance, to Nauru and Banaba in the Central Pacific, to Rennell (Taylor 1973), the Loyalty Islands (Bourrouilh-Le Jan 1977) and islands of the Lau Ridge, eastern Fiji (Nunn 1987) in the western Pacific and to Makatea (Montaggioni et al. 1985a, 1985b) and Niue (Schofield 1959) in the south-west Pacific. Some comparisons can also be made with the 'makatea' islands of the Southern Cook Islands (Marshall 1927, Wood and Hay 1970, Stoddart et al. 1985, Stoddart and Spencer 1987, Spencer et al. 1989).

In this paper we consider first, the contemporary sedimentary environments of Henderson Island; secondly, the environmental record preserved in the littoral margin and cliff face sequences; and thirdly, the topography and palaeo-environments of the central depression. These descriptions allow for a preliminary reconstruction of the island's genesis and history.

METHODS

The 1987 expedition concentrated upon (i) topographic levelling, (ii) observations of the morphology and stratigraphy of limestones with sampling for subsequent petrological examination and (iii) collections of fossil corals for both environmental reconstruction and dating purposes. Fieldwork, which was largely restricted to the north-west and north beaches and the areas inland from these coasts, was supplemented by the study of available aerial photographic cover (flown 3 May 1985).

The geomorphological data are summarized in a series of topographic profiles (Figures 2-8) surveyed by 'Abney' clinometer and graduated tape from sea level. Unfortunately, the tidal regime at Henderson has yet to be accurately determined. It is clear, however, that the island experiences a semidiurnal tidal rhythm, as at Ducie Atoll, 360 km to the east (Rehder and Randall 1975). Field observations would seem to agree with Fosberg et al.'s (1983) statement that Henderson's tidal range is probably similar to that of the Gambier Islands and the eastern Tuamotu Archipelago where the range at spring tide is 1.0m. With a knowledge of tidal stage at time of survey, individual profiles were adjusted to a common datum of mean sea level. It is important to stress that local micro-topography on Henderson is often severe, with the amplitude of upstanding pinnacles and erosional clefts often in excess of 1.0m. The compromises which such terrain introduces into field survey are further exacerbated by the density of vegetation cover. This not only impedes forward progress but also dangerously hides from view deeply dissected substrates. We estimate that errors involved in the establishment of a common datum and in ground survey require established altitudes to carry error terms of ±70 cm. Horizontal survey errors were not determined.

Exhaustive sampling for fossil corals and molluscs was undertaken at known locations on the surveyed profiles and also within the central depression along trails mapped by compass bearing and ground distance measurements. These sample locations were supplemented by collections from near the seaward margins of the cliff limestones.

CONTEMPORARY ENVIRONMENTS

The plan form of Henderson Island is shown in Figure 1. According to Fosberg et al. (1983), Henderson has a greatest length of 9.6 km, a maximum width of 5.1 km and an area of 36 km^2. Comparison of the Admiralty Chart, on which these measurements were based, with recent aerial photographyconfirms these general statistics. The only region where there appears to be a potential discrepancy between the chart and the photographic cover is in the area of the North-east Point but, most unfortunately, the Point itself was obscured by cloud cover when the aerial photographs were taken.

The island's perimeter has been calculated at 26.4 km; of this, 16.5km (63 per cent) is encircled by a fringing reef, principally along the entire length of the east coast (and not just the east beach: compare with the Admiralty chart), the north coast, and to just south of the north-west cove. The south-west coast and the south point area of the island are characterised by vertical cliffs undercut at sea level to give a cavernous coastline. Wave attack, even under moderate sea conditions, frequently throws spray to over 30m, above the height of the cliff margin (Plate 1). Fallen blocks, some of considerable dimensions, attest to the process of cliff retreat by undermining marine erosion. Indeed, a comparison of Figure 3 in St. John and Philipson (1962) with Plate 4 in Paulay and Spencer (this volume), photographs of the northern section of the north-west coast taken 53 years apart, shows an additional blockfall over this period.

There is no algal ridge margin to the reef edge at Henderson Island; rather the reef is a gently-sloping limestone platform that remains shallowly submerged and constantly inundated by the surf, even at low tide. The reef platform was investigated at the north beach. It consists of a smoothed reef plate, runnelled and dotted by small (<1cm) holes and covered by a thin algal turf. The seaward end of the platform has many large, deep (0.5m), well-scoured potholes that frequently coalesce to form shallow channels. A few loose or slightly cemented rocks on the reef lie near the landward margin with the limited loose sand found on the reef flat concentrated under them. The reef platform at Henderson varies in width from 20-50m at the north-west beach to 40-75m at the north beach. Estimates from aerial photography suggest maximum lagoon widths of closer to 100m offshore from the east beach.

The reef platform terminates seaward at a line of breakers in a rugged, dissected reef front of vertical to undercut reef promontories separated by a maze of channels. Due to the lack of a protecting algal ridge, water is continuously piled onto the reef flat by surf and drains through larger grooves that extend onto, rather than through, the reef. These grooves provide the best landing sites, and are better developed on the the north-west rather than the north beach. Field observations, including by SCUBA, by the 1987 expedition showed that the jagged reef front gives way to a typical spur-and-groove topography at 3-5m water depth. Thereafter, the fore-reef slopes rapidly and without interruption to at least 50m off the north-west shore. The north-west fore-reef is dominated by reef spurs to 15m, but in deeper water the widening sand and rubble chanels that separate the spurs become dominant, and by 40m coalesce to form a wasting slope. The north beach outer slope has only limited sand channels dissecting the reef front and slopes gently to ~ 30m where it steepens and continues uninterrupted to at least 75m. An algal turf with trapped sand dominates the fore-reef surface and living corals usually account for less than 10 per cent of the cover (measured at 6% at 10.5m off the north shore).

Millepora dominates the coral fauna to a depth of 5-10m, while *Pocillopora* species (especially *Pocillopora* sp. 1 and *P. woodjonesi*) are the most common corals in deeper water. The rarity of *Acropora* on the present reef contrasts markedly with its abundance in the ancient fossil lagoon, as well as on nearby Ducie.

Both the fore-reef and reef platform are wider off the north than off the north-west beach, correlating with the pronounced embayment on the north coast. Shallow but wide embayments, as off the north of Henderson, are often associated with wider reefs on other Polynesian islands e.g. on Niue or Rurutu (Austral Islands).

THE MARGINAL CLIFFS: STRUCTURE, STRATIGRAPHY AND ENVIRONMENTAL HISTORY

The cavernous and undermined cliffs of the south coast are impossible of access from the sea. Furthermore, it seems likely that depositional units of relatively young age accreted to the island core will have been, at best, severely modified and, at worst, removed by wave attack and cliff collapse. The most complete stratigraphic sequences on Henderson are, therefore, preserved in the broad embayments within the main marginal cliffs. In this paper we consider the north-west (Figures 9, 13, Plate 2) and north beach (Figures 10, 14, Plate 3) areas but it seems likely that a similar stratigraphy is preserved in the eastern embayment; reconnaissance shows the presence of limestone units and abundant caves (Plate 4).

Ground survey has established that the marginal cliffs on the northern and north-western shores reach heights of 30.7m and 30.2m respectively. Whereas the cliffs of the south-west coast and the south point appear to be relatively unbroken, the north-western and, particularly, the northern embayments are backed by cliffs which are composed of a series of discrete limestone buttresses, with vertical or even overhanging slopes, separated by slopes of 25-30^{o}. Where buttresses are encountered the cliff margin lies at between 26 and 27m above present sea level (Plate 5). The prominent buttress above the central north beach contains large colonies of *Lobophyllia corymbosa*, *Montastrea curta*, *Favia rotumana*, *Leptoria phrygia*, *Pocillopora eydouxi* (Plate 6), an abundant plate coral (likely *Montipora aequituberculata*), *Fungia scutaria* and a large (3m+) massive *Porites* colony (coral sample: FHEN-23).

Multiple levels of former sea level notches are preserved within the buttresses. The highest of these features is best seen at profile 4, north-west beach where a prominent notch is preserved at 24.8m above present sea level (Figure 5). This notch may correspond to a small bench at 24.5-25.1m on profile 5 (Figure 6) and to notches seen at the tops of limestone buttresses between the north and north-western embayments and at Awahou Point. On profile 4, this notch is a well-developed, laterally extensive feature, 1.44m high and 0.6m deep with a sand fill to the rear of the notch (Figure 5). The notch (coral collecting station FHEN-3) is filled with coarse sand and well rounded cobbles of coralline origin, suggestive of a high energy, beach deposit. Shells of two gastropods, the intertidal limpet *Patella flexuosa* and the intertidal to shallow subtidal *Turbo argyrostomus*, are commonly cemented in the notch, together with large, intact branches of *Pocillopora eydouxi* and *Acropora* colonies (Plate 7). The excellent preservation of the branching corals contrasts strongly with the polished, rounded coral cobbles and worn intertidal shells, and suggests that they were deposited during a second, low energy phase that post-dated notch formation. A much more pronounced notch characterises the limestone buttress in the central section of the north beach (profile 1, Figure 2). The broad notch floor commences at 19.7m above sea level and slopes upwards over ~4m to the rear of the notch; over a 35m-long section this varies in height between 21.0 and 21.6m. The notch roof intersects the buttress at 2.5-3.0m above the notch floor. It is surprising, however, that this well-developed and unambiguous sea level feature is not found elsewhere on the north and north-western coasts (except perhaps at 21.2m on profile 7: Figure 8) and even appears restricted to the central section of the north beach. It would be interesting to know whether or not this level is represented on the east coast.

Below the major constructional buttresses, and forming a veneer on the outer slope of the island, is a fossiliferous reef unit of generally limited width but considerable vertical extent (Figures 13, 14). The contact of this unit with the main cliff face is marked by a break of slope at 16.0m (profile 3: Figure 4) to 16.9m (profile 1: Figure 2) or, in the case of profile 7 (Figure 8) a notch at 16.2m above present sea level. Associated with this contact are caves (cave entrance, profile 2: 18.0m (Figure 3) cave floor, profile 3: 17.3m (Figure 4) and, possibly, a cliff shelf (base of shelf, profile 4: 17.9m (Figure 5)). The cave on profile 2 is ~20m in length behind a hemispherical entrance 2.2m in height. The main passageway varies in width from 1.4-4.1m but a low chamber to the north of the main conduit increases the overall cave width to over 9m (Figure 11; and see Schubel this volume for cave floor sediment characteristics). It is suggested that the cave/shelf level (Plate 9) relates to a sea level stillstand and erosion level associated with the deposition of the fossiliferous reef unit. At 9.6-11.4m on profile 2 (Figure 3; coral collecting station FHEN-11) the fossiliferous reef unit is exposed as a rich coral conglomerate, terminated to the south by a mostly featureless limestone. The deposit is dominated by *Pocillopora* sp(p)., *Astreopora* cf. *moretonensis*, massive *Porites* sp(p)., *Porites* cf. *mordax*, *Psammocora* ?*obtusangula*, *Coscinaraea columna*, *Acropora* sp., and *Plesiastrea* cf. *versipora*. About 50m to the south, the fossiliferous reef unit is well exposed between 7.6-11.1m on profile 7 (Figure 8; HW4-11) and contains a similar fossil assemblage: *Pocillopora eydouxi*, *Pocillopora* sp(p)., *Pavona* sp. 1 and *Montastrea* sp. 1. Additional exposures are found at the eastern end of the central section of the north beach. Here the fossiliferous reef unit is exposed in a 3-5m high cliff, its base at ~ 2.0m above mean sea level (Figure 10; coral collecting stations FHEN-20/22). At this locality the unit is composed of two facies. The lower facies (FHEN-20/21) exhibits abundant *Pavona* sp. 1, *Astreopora moretonensis* and *Pocillopora* sp(p)., as well as specimens of ?*Pocillopora eydouxi*, *Fungia scutaria*, *Plesiastrea* cf. *versipora* and massive *Porites* sp(p). The upper facies is ~1m in thickness and composed of coral stick rubble (Plate 9) in a poorly cemented sand matrix (FHEN-22). Embedded corals include *Pocillopora* sp. 1, *Astreopora* cf. *moretonensis*, massive *Porites* sp(p). and *Porites* cf. *mordax*.

There are several topographic breaks and sea level features within the fossiliferous reef unit. These include a notch at 14.3-15.1m (profile 2; Figure 3), which is also reflected in a shelf at 15.0m on profile 7 (Figure 8), and a range of cliffed sections and slope inflections, with breaks of slope at between 12.5-14.0m for the top, and 11.6-11.9m for the base, of these slope elements. Erosion within this height band may have been related to the deposition of the low limestone unit which fronts the fossiliferous reef unit. On profile 7, north-west beach (Figure 8) an erosional embayment reveals the fossiliferous reef unit behind the low limestone unit (and see Figure 13). The contact between these two units, marked variously by either a change in slope angle, or a notch or a small cliff, has been established at 8.7m on profile 2 (Figure 3) and at between 9.4 and 10.6m on profiles 2-6 (Figures 3-7). This contact is marked, easily seen and shows considerable lateral continuity. It is possible to trace the junction between the north beach and the north-west embayment (Plates 11, 12); estimates from ship survey and photographic record suggest that in this region the contact varies in height between 7.6-11.9m, with an average altitude of 10.0m. The low limestone unit is also well seen at the southern end of the north-west beach (Plate 12) where the upper limit appears to fall between 8.4-10.5m, with a mean height of 9.7m above sea level.

The low limestone unit is represented by a thin deposit plastered onto the cliffed headlands; this extends to form a low fringing terrace, up to 40m in width, in the embayments of the north and north-west beaches. This terrace is divided into two sections. The upper section slopes downward to terminate at a well-defined margin (seen on five of the seven profiles) at 7.3-8.3m. This forms the top of a small cliff whose base is found at 6.3-7.0m above sea level. Below this cliff, the lower section of the terrace forms a highly dissected and often stepped profile, either composed of a series of joint-controlled blocks or characterised by a number of deep (>1m) clefts in a pitted surface topography, ending in a marginal cliff whose upper surface varies in height between 2.6 and 3.7m above sea level. These heights , however, have no significance but merely indicate the degree of shoreward retreat within a unit which slopes upwards onshore. Fallen blocks in front of the seaward margin of the terrace, and remnants of blocks offshore, show that marine erosion is currently active. On the north-west beach, for example, at high tide waves break not on the reef edge but at the terrace margin.

At the eastern end of the central section of the north beach the low limestone unit is divided by a series of steep (>30^{o}), narrow (~1.5m) gullies which exit on the terrace surface (e.g. profile 5, Figure 6; Plate 13). These features may represent the grooves of a groove-and-spur fore-reef topography. Fossil groove-and-spur features of a similar scale have been described from Last Interglacial reef limestones on Mangaia, Southern Cook Islands (Stoddart et al. 1985). Some of the grooves on Henderson Island are roofed over at their seaward margins in a manner reminiscent of similar fossil grooves on Mauke and Mitiaro, Southern Cook Islands. Although the exits of the grooves and the lower groove walls are characterised by large colonies of *Montastrea* sp. 1, the Henderson grooves (Plate 13), unlike the groove-and-spur features of the Southern Cooks, are not lined with a wide range of well-preserved encrusting corals. The low limestone unit is, in fact, very poor in preserved corals with only the occasional colony of *Montastrea* sp. 1 and, uniquely, a large colony of *Porites* sp. at 1.8m above present sea level near the seaward margin of profile 6 (Figure 7).

At the north-west beach, the low limestone unit terrace is characterised not by narrow grooves but by broader embayments which widen seawards. The embayments are floored by a bevelled bedrock ramp (Figure 13) which slopes upwards from the beach foot within the intertidal zone to a small cliff, 20cm in height and with a base at 2.2m above present sea level, which marks the ramp's erosional contact with the cliffed margin of the low limestone unit. In some places, there is clear evidence for the bevelling of *Montastrea* sp. 1 in growth position within the ramp (Plate 15). On profile 4 (Figure 5) the ramp includes a smooth dome at 1.9m above sea level which resembles the exfoliating coralline algal crusts described from Vahitahi, eastern Tuamotu Archipelago by Pirazzoli et al. (1987b). Locally at its seaward margin the ramp is overlain by beachrock; individual plates may be 0.35m in thickness and extend up the ramp to a height of 0.8m above present sea level (Figure 13). The upper plates of this beachrock are frequently composed of cemented coral sticks. Similar agglomerations of coral rubble, with typical acroporid branch diameters of 0.5-0.8cm, plaster the contemporary notch, related to present sea level, in the cliffed margin to the terrace. In addition, on the north-west beach, coral debris on the bevelled ramp forms cemented blocks or pillars up to 0.8m above mean sea level. It seems likely that these deposits are the product of storm wave attack and subsequent transport from the coral ledges offshore. Accumulation and ensuing cementation has clearly been locally variable, and we ascribe no significance to the height of these deposits.

THE CENTRAL DEPRESSION: TOPOGRAPHY AND PALAEO-ENVIRONMENTS

Although many of the early descriptions of Henderson, made from the sea, stressed the apparent flatness of the top of the island, the 1934 Mangarevan Expedition recorded the presence of a shallow depression in the island's interior (St. John and Philipson 1962, Fosberg et al. 1983). This they interpreted as a former lagoon, thus adding weight to the explanation of the Henderson topography as being that of an elevated former atoll. The 1987 expedition was able to confirm the presence of both an interior depression and lagoonal deposits on Henderson Island.

On the north-west coast inland from the immediate cliff top margin the island limestones reach 31.3m, and generally exceed 29.0m, above sea level (Figure 12). In this area the surface topography is characterised by both joint-bounded limestone blocks 0.2-0.5m in height and pinnacles with an amplitude in excess of 1.0m. At a larger scale the limestones also exhibit straight-sided basins 0.5m deep and 2.0m in diameter and solution holes with vertical walls up to 2.5m high and flat floors 3m in width. The top of this surface is, however, covered by patches of loose, uncemented coral rubble, composed of both small coral sticks (*Acropora* spp., *Pocillopora eydouxi*, *Pavona* sp. 1), as well as small coral colonies (massive *Porites* sp(p)., *Montastrea* sp. 1, branching *Acropora* spp.) and frequent *Turbo argyrostomus* and *Tridacna maxima* shells, even on the cliff margin at 30.7m above sea level. The abundance of *Pocillopora eydouxi* and *Turbo* indicates that this area, as expected from its physiography, was probably part of the outer reef flat of the original atoll (coral collecting station FHEN-4).

Although the surface topography is irregular, there is clearly a regional slope downwards into the island's interior (Figure 12). However, no continuous slope profiling was undertaken by the 1987 expedition across this area and, therefore, the heights which follow with regard to the central depression should be seen as rough first estimates only.

The contact between the island rim limestones and the central depression is marked, first, by an area of pinnacle-pitted limestone ~26m above sea level and 220m from the cliff-top margin (Plate 15). It is not clear from our field surveys and available aerial photography whether this landform forms a band encircling the central depression or is only present in more localised patches. The pinnacle-pitted limestone is a landscape of sharp, recrystallised limestone pinnacles and deep solution pits with a vertical relief of ~2m, and lacks the coral rubble that characterises the plateau surface elsewhere. While fossils of *Montastrea* sp. 1 are commonly visible in cross-section, branching corals that form most of the coral rubble elsewhere were not seen, although this could be due to excessive remineralisation of their finer structure. *Turbo* shells were also noted embedded in this landscape. The pinnacle-pitted limestone is followed by a rugged yet marked slope, of 3m vertical fall over 15-20m horizontal distance, down to the interior depression at an estimated 22m above sea level and 300-350m inland (Figures 12, 15). Over the next 300m (i.e.to the end of our trail) the level floor of this depression is characterised by a largely uniform cover of coral sticks, dominated by branches of *Acropora* spp. but with *Pavona* sp. 1 and less commonly *Porites* cf. *mordax* also ubiquitous and locally dominant. Scattered amongst this rubble are entire colonies of these branching species as well as massive *Montastrea* sp. 1, *Favia rotumana*, *Favia stelligera*, *Montastrea curta*, *Plesiastrea* cf. *versipora*, plates of *Astreopora* cf. moretonensis and small *Fungia* spp. Although these corals lie uncemented to each other, many appear to be in growth position, perfectly preserved, often allowing identification to the species level (Plates 16, 17). However, the branching skeletons fracture easily on contact and *in situ* diagenesis has altered the original aragonitic skeletons to low magnesium calcite. While coral rubble forms most of the substrate, other fossils (molluscs, echinoderms, crustaceans) are rare. An essentially identical community was encountered in the north shore interior (see below); and it is possible that most of the central lagoon has similar cover (coral collecting stations: FHEN-6/9).

The topography of the central depression as reached from the north coast is rather different. (Figure 12). Unlike the narrow transition zone from limestone bedrock to coral-covered depression on the north-west coast interior, and although lagoonal deposits appear to be first encountered 300m inland from the cliff top, pinnacled limestone outcrops are present over 1 km from the island margin (Figures 12, 16). On the north coast the island rim reaches, in a pinnacled zone, a maximum height of 33.6m above sea level 250m from the cliff edge (Figure 12). The wide expanse of makatea seaward of the highest point could represent a former outer reef flat backed by an atoll rim. *Motu* on this rim might have been characterised by emergent limestone (e.g. cf. *feo* limestones, N W Tuamotu archipelago). However, it is likely that the solid limestone that outcrops at, and dominates, the present cliff-top margin both here and on the north-west shore corresponds to the cemented reef flat that surrounded the atoll lagoon.The clear presence of a cliff-top ridge topography from aerial photography further suggests that a similar palaeo reef flat is present above the south-west cliffs (Figure 1). Inland from this makatea zone on the north coast, a series of basins are encountered between well-defined limestone outcrops. The basin floors are 30-31m above sea level and are generally characterised by *Montastrea* sp. 1 and valves of *Tridacna* . There does appear, however, to be a greater diversity of corals near the limestone outcrops as coral rubble is often banked up around the basin margins. We suggest that these basins represent a very shallow lagoon margin. Beyond this zone of alternating basins and limestone outcrops, a much more diverse lagoonal assemblage is encountered. It comprises the following genera and species:-

Very common	*Acropora* group 3 *Pavona* sp. 1 *Porites* cf. *mordax* *Favia stelligera*
Common	*Montastrea* sp. 1 *Acropora* groups 1+ 2 *Montastrea curta* *Astreopora* cf. *moretonensis*
Occasional	*Favia rotumana* *Plesiastrea* cf. *versipora* *Fungia scutaria* ?Fungiid sp(p). *Pocillopora damicornis* *Pocillopora* sp(p). *Leptoria phrygia* *Scolymia vitiensis* *Psammocora ?obtusangula* *Montipora* spp.

The fossil lagoon appears to have had considerable interchange with the surrounding ocean. This is indicated by the following features:

1) Great coral diversity. That faunal diversity of atoll lagoons is directly related to the extent of water exchange with the surrounding ocean is especially well documented for corals (Salvat 1967, Chevalier 1979). Thus in the Tuamotu archipelago, closed Taiaro atoll has only one coral living in the lagoon whereas Takapoto atoll, where two shallow passages break the island rim, has 21 lagoonal species in a total fauna of 63 species (Chevalier 1976, Kuhlmann and Chevalier 1986). At Aitutaki (S.Cook Islands), an almost-atoll where one large and many small passages allow water exchange between ocean and lagoon, 60 of the total count of 68 non-acroporid scleractinians are found within the lagoon

(Paulay 1988). On Henderson 22 of the 26 fossil coral species (15 of 17 genera) encountered were found in lagoonal deposits (Table 1).

2) Prodigious coral growth, such that the whole laggon thus far investigated is filled with coral rubble and

3) the concomitant lack of sediments finer than coral rubble, indicating either rapid coral growth filling the lagoon with coral rubble faster than fine sediments could be produced, or loss of such sediments to the surrounding ocean through vigourous water exchange.We are not aware of any contemporary atolls that exhibit such uniformly coarse bottom sediments.

4) The presence of corals requiring oceanic water conditions, such as *Pocillopora eydouxi* and *Pavona maldivensis*, and the rarity of species that are usually common under more stagnant conditions, such as *Pocillopora damicornis* or massive *Porites* spp. (cf. Paulay, 1988).

There are few differences in species composition between the north and north-west fossil communities, the most notable being *Leptoria phrygia*, a species occasionally encountered both on the north coast fossil fore-reef and lagoon but not on the north-west coast. Interestingly, *Leptoria* is currently only known from southern, subtropical localities within French Polynesia: the Austral, Rapa and Gambier Islands (Chevalier 1974, 1980, Faure 1985). It has not been recorded living in the Tuamotu Archipelago or Society Islands (Chevalier 1979, 1981) or the Pitcairn group (Paulay, this volume). *Leptoria* has been recovered, however, from cores into Pleistocene limestones on Fangataufa atoll, southern Tuamotus (Chevalier and Repellin 1978) which together with the present find suggests considerable range constriction of this species since the Pleistocene. Further into the northern areas of the lagoonal depression, local topographic highs, with a distinctive non-forest vegetation cover (see Paulay and Spencer, this volume) consist of large accumulations of *Acropora* sticks (A. group 3; Plate 18) with only a few other corals present. These include *Montastrea* sp. 1 (Plate 17), *Favia stelligera*, *Porites* cf. *mordax*, *Acropora* group 2, *Pocillopora* sp(p). and *Pavona* sp. 1. We interpret these areas as large lagoonal patch reefs. Additional distinct reef complexes up to 15m across are found both in the north and north-west interior, composed of associations dominated by massively branching (5cm + branch diameter) *Acropora* (A. group 2; Plate 16) and large tabloid *Acropora* (A. group 1).

INTERPRETATION

Reconstructions of the plate-tectonic history of the south-east Pacific (see Spencer, this volume) suggest that initial island-building at Henderson took place at ~13 m.y. BP; thereafter, with the cessation of volcanism, island subsidence and the development of a carbonate cap followed. Fosberg et al. (1983) have suggested that Henderson Island stands comparison with the makatea islands of the central and southern Pacific and, therefore, that the limestones which comprise the core of the island are of mid-Tertiary age. By extension, the central depression has been interpreted by these authors as a karst erosion feature and, as such, characterised by residual pinnacles and columns of limestone rather than a depositional topography of lagoonal patch reefs. Such a history requires a period of emergence; presumably this would have taken place in the late Tertiary (Miocene-Pliocene) and would have been accompanied by the severe meteoric alteration of emergent carbonates and the commencement of dolomitization (e.g. Schlanger 1981). The degree of emergence of Henderson is in the range of Tertiary makatea islands: intermediate between Makatea Island (113m, N.W.Tuamotu Archipelago), Rurutu(100m, Austral Islands) and Mangaia (73m, S. Cook Islands) on the one hand, and Atiu (22m), Mauke (15m) and Mitiaro (11m; all S. Cook Islands) on the other (Montaggioni et al. 1985a, Stoddart et al. 1985, Stoddart and Spencer 1987, Spencer et al. 1987, 1989). The physiography and sediments of the central depression on Henderson, however, suggest a young age. Although field observations clearly show that on the north coast near the depression margin lagoonal deposits drape an older, erosional topography, the rest of the plateau surface is covered by very well preserved, unconsolidated coral skeletons. Moreover, putative depositional patch reefs are encountered further inland and it seems probable that more original depositional structures might be encountered as the centre of the island is approached. Indeed, no unambiguous erosional features were seen within the central lagoonal deposits. In addition, the cliff-top of the island on both the north and north-west coasts shows the presence of well-preserved, framework-building corals in original depositional features. None of the uplifted islands in French Polynesia or the S. Cook Islands have such clearly depositional, lagoonal features, or as well preserved coral fossils that lack advanced diagenesis on their core reefs. Henderson also lacks an accumulation of phosphorites (Fosberg et al., pers. obs.), unless they have been buried beneath the lagoonal deposits. Their absence could otherwise be explained by 1) a lack of upwelling areas and large sea bird rookeries (at least at the present time) and 2) a lack of time for accumulation of such deposits. Thus although it seems possible that Pleistocene deposits fringe an older (?Tertiary-?early Pleistocene) core on Henderson, it is likely that the entire surface structure of the island is of Pleistocene age. It is to be hoped that petrological studies of limestone samples collected on the shore to central depression transect on the north-west coast will test between these two competing hypotheses. A Pleistocene age would lend support to the hypothesis that uplift at Henderson has been the product of lithospheric flexure consequent upon the formation of Pitcairn Island within the last million years (see below, and Spencer, this volume).

A Pleistocene age for the island is further supported by palaeontological estimates. Since the proportion of extant species in a fossil assemblage decreases with increasing age, one may use the percent extant species (Lyellian percentage) in a fossil deposit as a crude indicator of its time of formation. Stanley et al. (1980) and Stanley and Campbell (1981) present Lyellian curves for bivalve and gastropod faunas from Japan, California and the Western Atlantic where early Pleistocene mollusc assemblages have Lyellian percentages of 70-90%. Similarly, Wells (1954) provides estimates of Lyellian proportions for Oligocene to Recent corals from Indonesia with the separation of Pliocene to Pleistocene occuring at ~70% living species. Preliminary identification of fossil corals from Henderson (Table 1) indicates that 95% of the 21 corals identified to species level are still extant. Similarly, all fossil molluscs identified to date are known to be living (Paulay, in prep.).

If, as suggested by the lithospheric flexure model of McNutt and Menard (1978), uplift at Henderson has been the product of crustal loading by the volcano of Pitcairn Island 200 km to the west-southwest, then this emergence probably dates from the mid-Pleistocene. Potassium-argon (K-Ar) dating of exposed volcanics on Pitcairn has identified two phases of volcanism, at 0.46-0.63 and 0.76-0.93 m.y. BP. Petrological studies and palaeo-magnetic chronologies suggest that the older of these two phases represents the main island-building stage and that island construction could have been rapidly achieved between 0.85-0.93 m.y. BP (Duncan et al. 1974). Rapid shield-building has been characteristic of many mid-plate Pacific volcanoes (Jarrard and Clague 1977). Assuming an average age of 0.90 m.y. for Pitcairn Island then the average rate of tectonically-induced uplift at Henderson since this time has been ~1m $25kyr^{-1}$ (4cm kyr^{-1}). This is comparable to the rate of island uplift calculated for Mangaia, Southern Cook Islands under crustal loading from the Pleistocene volcano of Rarotonga (Stoddart et al. 1985). The sea level features within the coral buttresses at 24-25m and 21-22m above present sea level may represent stillstands during island emergence. Once sea level fell below these levels the lagoon became a subaerial feature and subject to terrestrial weathering processes, including the commencement of diagenesis within the stranded and emergent coral communities. Subsequent sea level fluctuations were not of a sufficient magnitude to re-flood the lagoon. The two main reef units preserved below the reef buttresses represent the interaction between tectonic uplift and glacio-eustatic sea level fluctuations. We suggest that the fossiliferous reef unit which reaches 16.9m (profile l; Figure 2) represents coral growth associated with the high sea level stand of the Penultimate Interglacial (>200-400 kyr BP) and that the low limestone unit and terrace, averaging 10.0m above present sea level at its contact with the fossiliferous unit, dates from the Last Interglacial (100-140 kyr BP) sea level high stand. Fossil corals from known altitudes have been collected from both units and it is hoped that uranium-series and electron-spin resonance (ESR) dating of these samples will establish a firm chronology for reef growth and sea level change during the late Pleistocene at Henderson.

The Henderson reef limestones can be compared to other coralline islands in Polynesia which are widely believed to have been affected by lithospheric flexure. At Makatea Island the Penultimate Interglacial and Last Interglacial deposits form cliff-veneering apron reefs reaching altitudes of 20-25m and 5-8m respectively (Veeh 1966, Montaggioni 1985). On Mangaia, Southern Cook Islands, Last Interglacial reef limestones (uranium-series dates: 101-135 kyr BP, Spencer et al. 1989) contact Tertiary makatea, and perhaps older Pleistocene limestones, at 14.5m above sea level. Both these islands, like Henderson, are regarded as falling on the crest of the arch in the moat-and-arch response to lithosphere loading and thus should show the greatest degree of tectonic uplift. These predictions appear to be validated by the degree of uplift on islands beyond the radius of the crest of the arch: thus in the atolls of the N.W. Tuamotus Pleistocene *feo* limestones are found at 2-10m above sea level (Delesalle 1985, Pirazzoli 1985, Harmelin-Vivien 1985) and in the Southern Cook Islands deposits as yet undated but provisionally identified as of Late Pleistocene age reach elevations of 12.2m on Atiu, 10.0m on Mauke and 9.8m on Mitiaro (Spencer et al. 1987, 1989). These heights compare with the height of presumed Last Interglacial reefs on Rarotonga, Southern Cook Islands, assumed to be unaffected by tectonic uplift, which reach a maximum altitude of 3.5m above present sea level (Stoddart et al. 1985). Assuming the Last Interglacial limestones on Henderson Island were formed under a sea level at ~13.0m above present sea level at ~120 kyr BP yields an average uplift rate since that time of 9-4 cm kyr^{-1}.

Surprisingly, there is little evidence on Henderson Island for the higher-than-present Holocene sea level of ca. +1.0m between 6,000 and 2,000 yr BP which is so prevalent throughout Polynesia (see Spencer, this volume). The reasons for this may relate to the lack of full reef development around Henderson for there is no sheltered lagoon or intertidal reef flats within which micro-atolls might have developed at, and subsequently reflected, a raised Holocene sea level. In addition, the lack of a modern algal ridge around the island makes the preservation of a fossil algal ridge, as on Suwarrow, Northern Cook Islands (Scoffin et al. 1985), Mangaia, Southern Cook Islands (Yonekura et al. 1986), Reao, eastern Tuamotu Archipelago (Pirazzoli et al. 1987a) and Makatea Island (Montaggioni et al. 1985b), unlikely. Finally, unlike many Polynesian barrier reefs and atolls, there are no obvious sites for the accumulation of conglomerate deposits which may record high sea level stands (Montaggioni and Pirazzoli 1984). It is perhaps to be expected, therefore, that the possible evidence that is present on Henderson for a Holocene high sea level is erosional in nature, in the form of the bevelled ramps which terminate at 2.2-2.4m above present sea level.

CONCLUDING REMARKS

Henderson Island, like many raised reef islands, clearly preserves an important record of climatic, oceanographic and biogeographic change in the south Pacific. What is also clear is that the 1987 expedition was only able to perform a spatially-limited reconnaissance of the structure and topography of the island. It can only be hoped that the geology and geomorphology described here provides a context and a basis for more detailed studies which should be undertaken on Henderson in the coming years.

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Table 1. Fossil corals of Henderson Island

Species	Lo	Fo	Bu	Or	La	Loc
Pocillopora eydouxi		X	X	X	X	H
Pocillopora damicornis					X	P
Pocillopora sp. 1		X				H
Pocillopora sp(p).	X	X	X	X	X	?
Acropora group 1 =						
Acropora hyacinthus					X	T
+*Acropora cytherea*					X	P
+*A.* sp(p).					X	?
Acropora group 2		?		X	X	?
(= *A.robusta* spp. group)						
Acropora group 3				X	X	?
(= *A.valida* and/or *A. nasuta*, *A.* spp.)						
Montipora spp.			?	?	X	?
Astreopora cf. *moretonensis*		X		X	X	H
Porites cf. *mordax*		X		X	X	T
Porites massive	X	X	X	X	X	?
Psammocora ?obtusangula		X			X	H?
Coscinarea columna		X		X		G
Pavona sp. 1		X		X	X	H
Pavona maldivensis		X			X	H
Fungia scutaria		X	X		X?	P
Fungiid sp(p). other					X	?
Scolymia vitiensis					X	H
Acanthastrea ?echinata				?	X	G
Lobophyllia corymbosa				X		G
Favia stelligera				X	X	P
Favia rotumana			X	X	X	H
Leptoria phrygia			X		X	G
Montastrea curta				X	X	H
Montastrea sp. 1	X	X		X	X	E
Plesiastrea cf. *versipora*		X		X	X	H?
TOTAL: 26	3	14	7	17	23	

Lo: low limestone unit; Fo: fossiliferous reef unit; Bu: core reef buttresses; Or: outer island slope fossils not *in situ*, thus not definitely located stratigraphically; La: central lagoon; Loc: The closest locality from where this species is known today: H: Henderson Island; P: other islands in the Pitcairn Group; T: Tuamotu Archipelago; G: Gambier Islands; E: species presumed globally extinct.

Taxonomic notes:
Pocillopora sp. 1 (= *P.* cf. *verrucosa* of Paulay and Spencer 1989): see Paulay (this volume) for a discussion of this species. *Pocillopora* sp(p). : other *Pocillopora* spp. than listed above, likely includes *P.meandrina*. *Acropora* group 1: large tabloid *A.* species, many not identified to species, includes *A. hyacinthus* and *A. cytherea* listed above, as well as at least 1 additional species. *Acropora* group 2: species with very massive branches, often 5cm+ diameter, most or all in *A. robusta* group. *Acropora* group 3: other *Acropora* species, mostly of corymbose growth form, many not identified to species, includes *A. nasuta* and/or *A.. valida* listed above as well

as other species. *Montipora* spp. : unidentifiable due to poor preservation. *Astreopora* cf. *moretonensis* (= *A.* sp. 1 of Paulay and Spencer 1989): a plate forming *Astreopora*, kindly identified by J E N Veron as *A.* cf. *moretonensis*. *Psammocora ?obtusangula* (= *P.* sp. 1 of Paulay and Spencer 1989): a subarborescent *Psammocora* that appears to be conspecific with *P. obtusangula* collected alive on Henderson; however,it is not sufficiently well preserved to allow for a definite identification. *Pavona* sp. 1 (= *P.* cf. *clavus* of Paulay and Spencer 1989): see Paulay (this volume) for a discussion of this apparently undescribed species. ?Fungiid sp(p): poorly preserved, small specimens of *Fungia* and/or *Cycloseris*. *Montastrea* sp. 1: an apparently extinct species, with second order septo-costae greatly reduced or aborted. *Plesiastrea* cf. *versipora*: fossils have consistently 12 septo-costae while recent specimens are more variable.

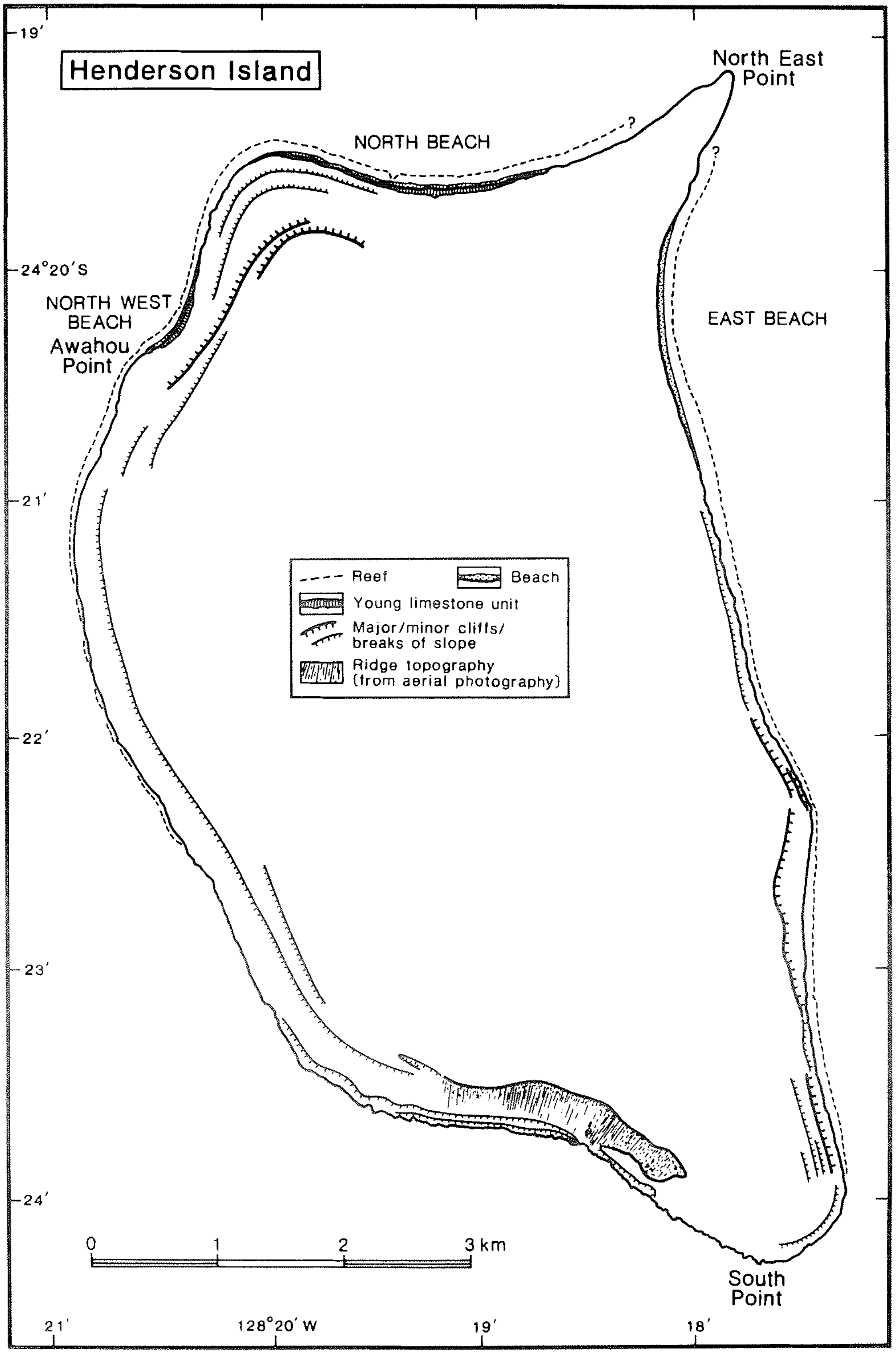

Figure 1. Henderson Island (from aerial photography sortie 035/85 and Admiralty Chart 987 (1953)).

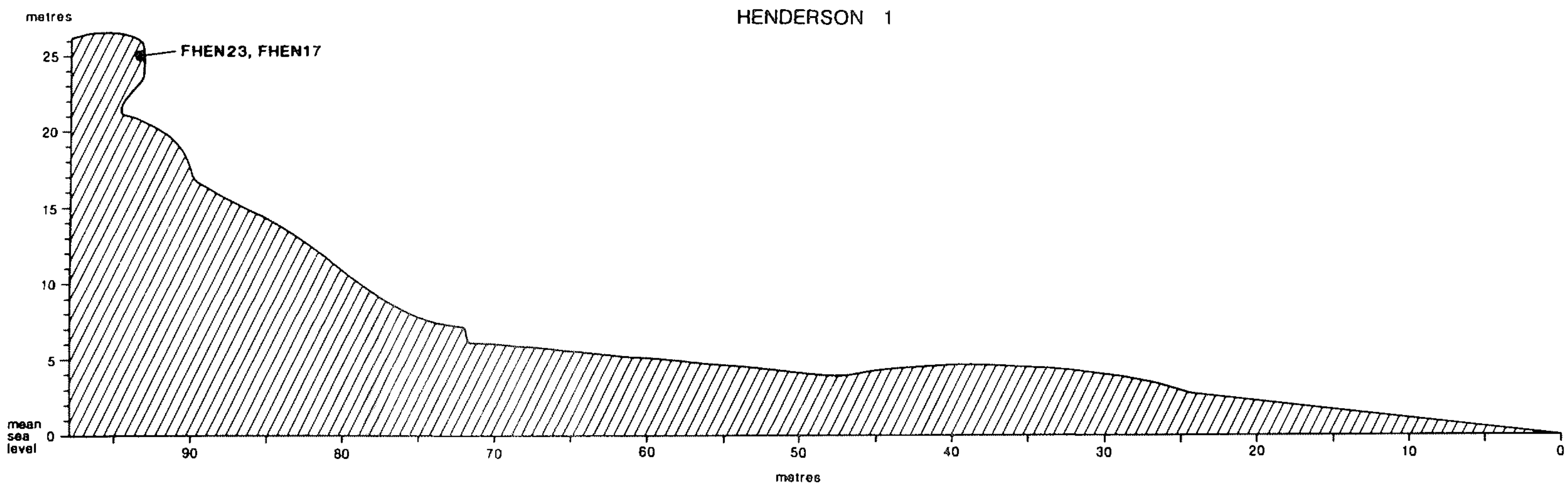

Figure 2. Profile 1, North Beach, Henderson Island (location: see Figure 10).

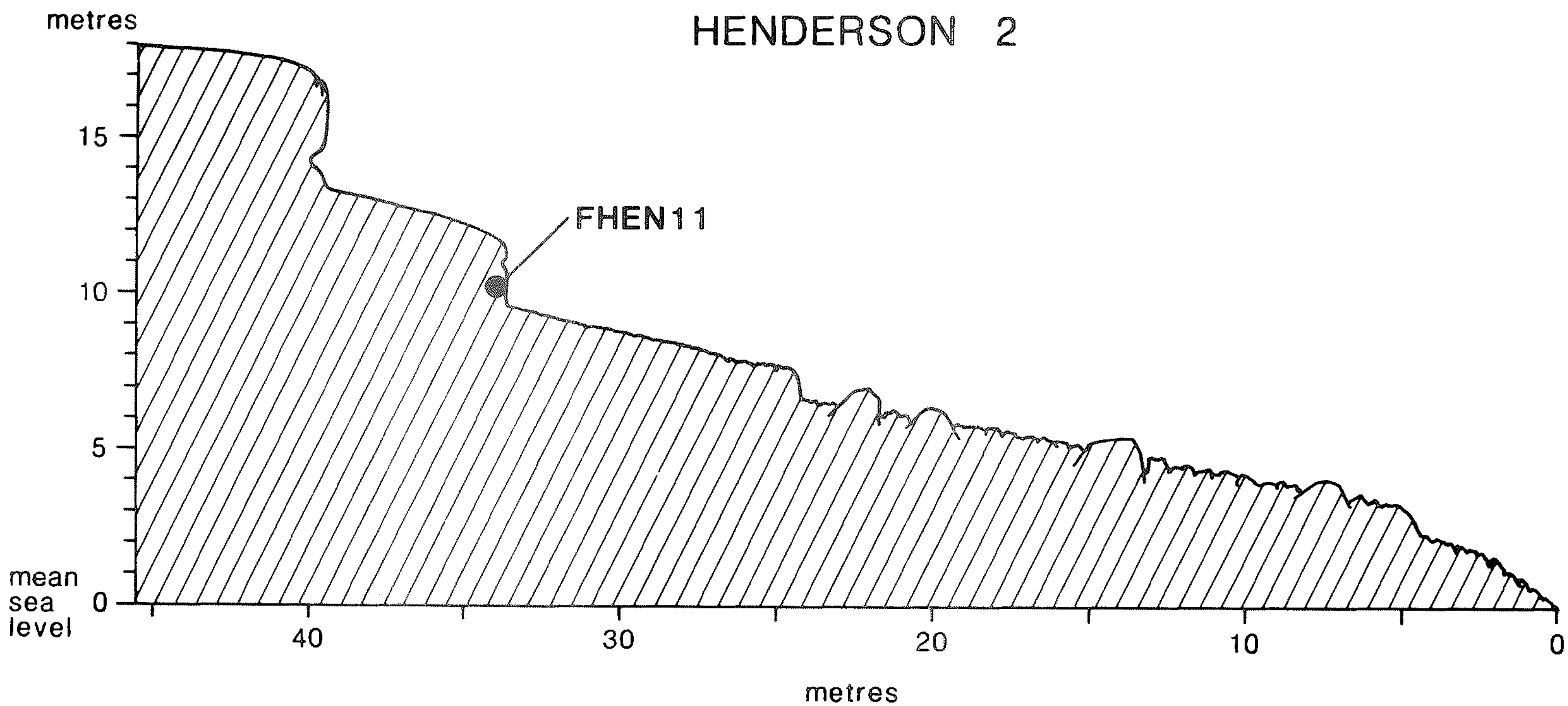

Figure 3. Profile 2, North-west Beach, Henderson Island (location: see Figure 9)

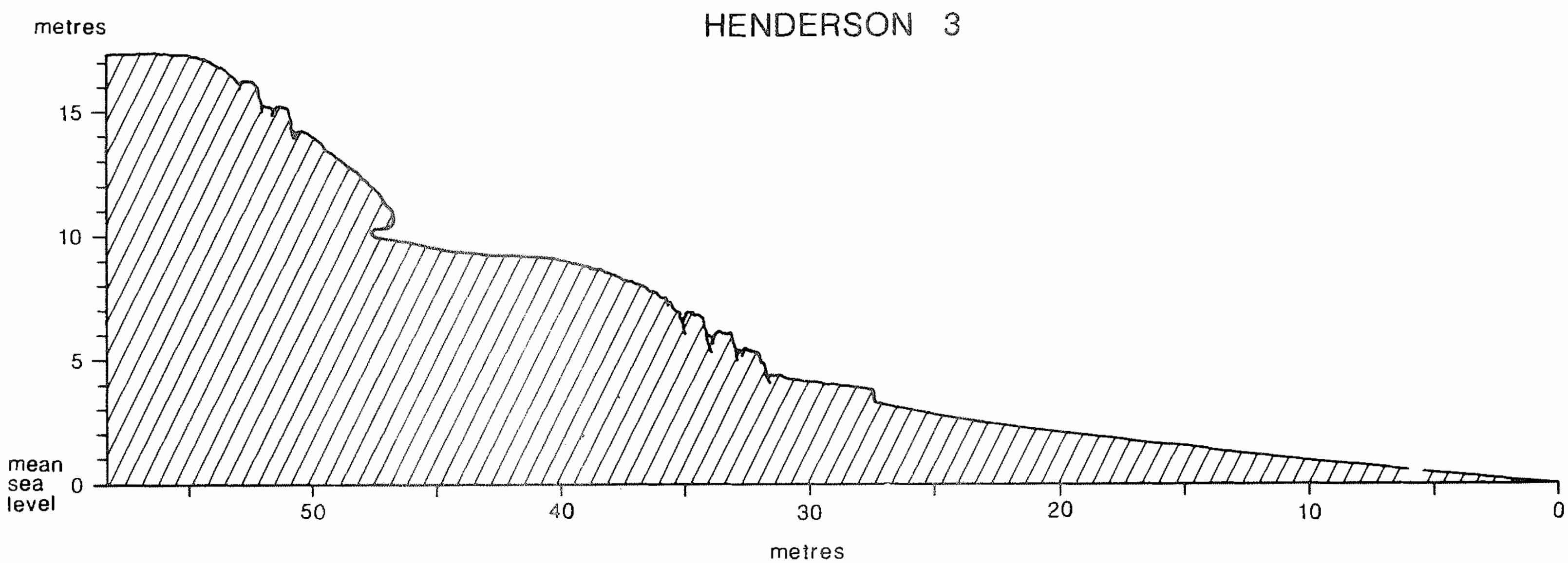

Figure 4. Profile 3, North Beach, Henderson Island (location: see Figure 10).

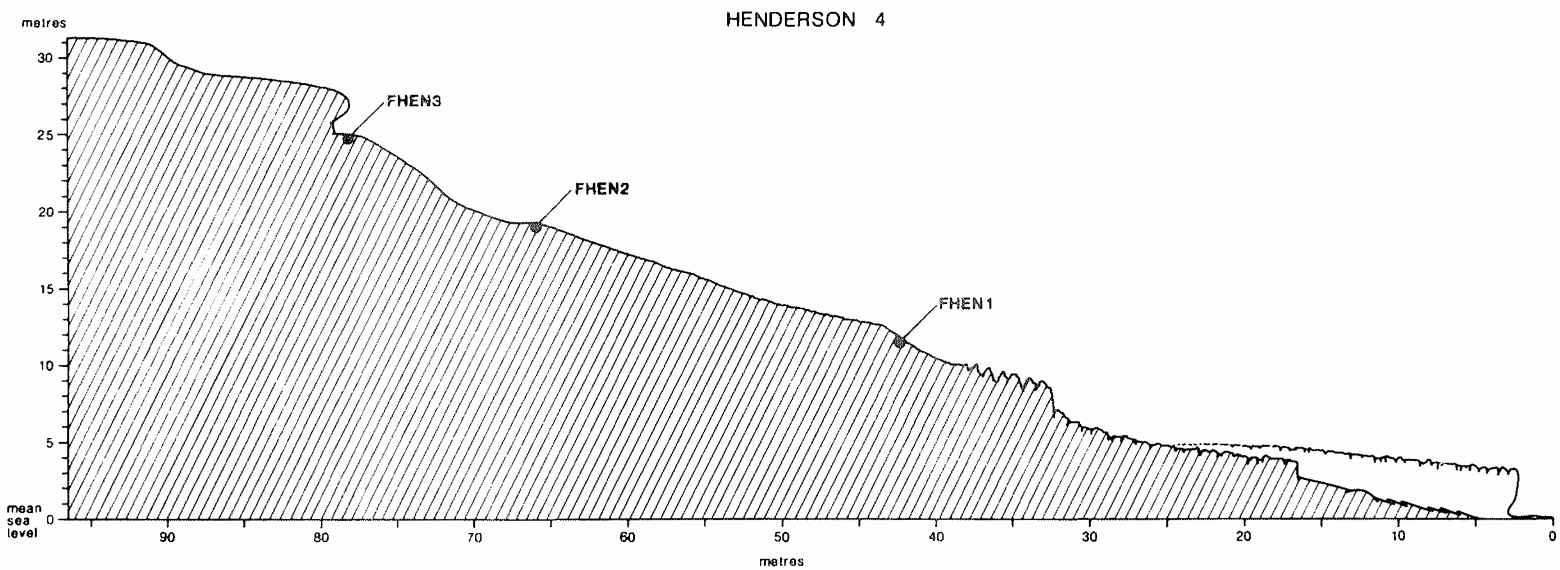

Figure 5. Profile 4, North-west Beach, Henderson Island (location: see Figure 9).

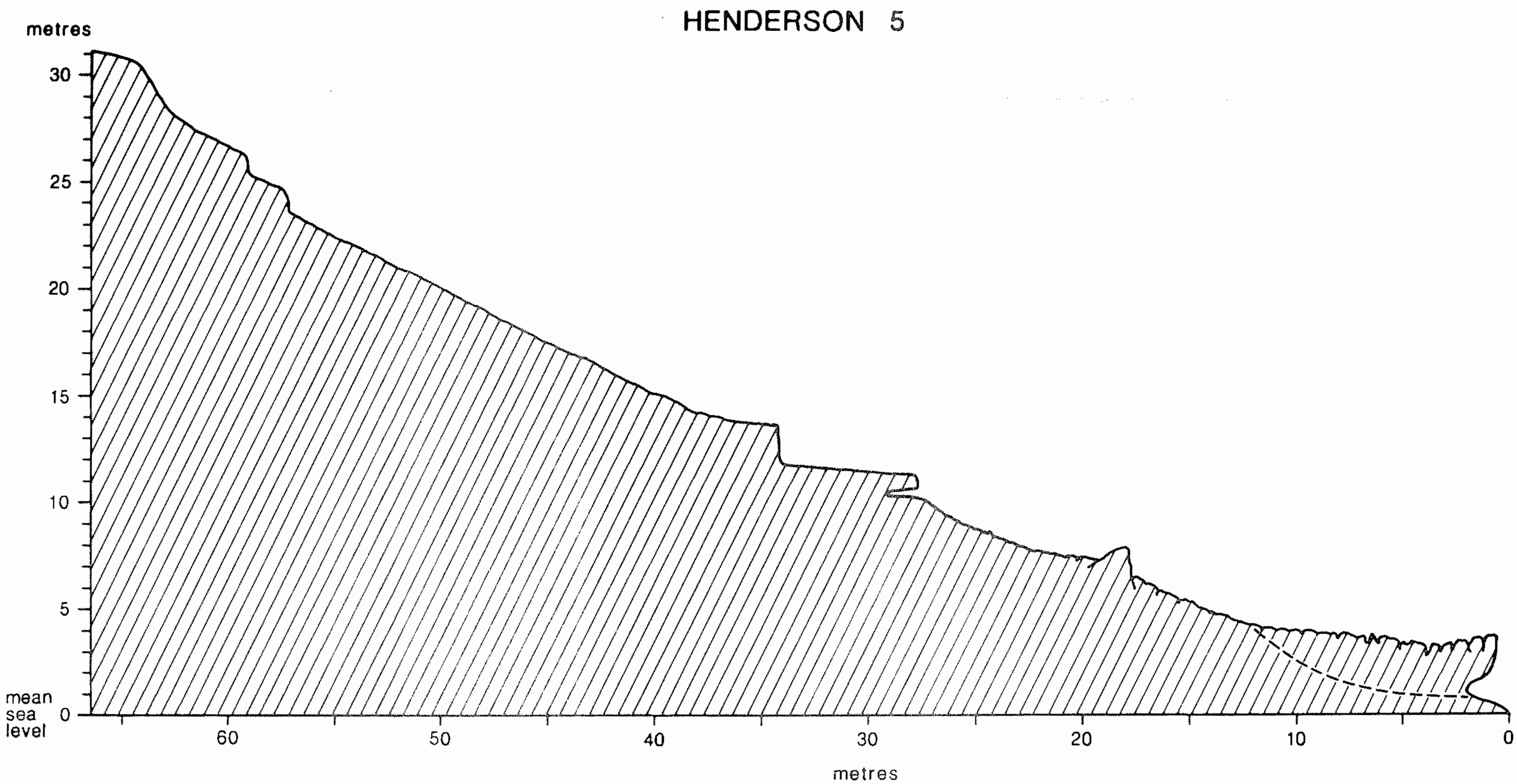

Figure 6. Profile 5, North Beach, Henderson Island (location: see Figure 10).

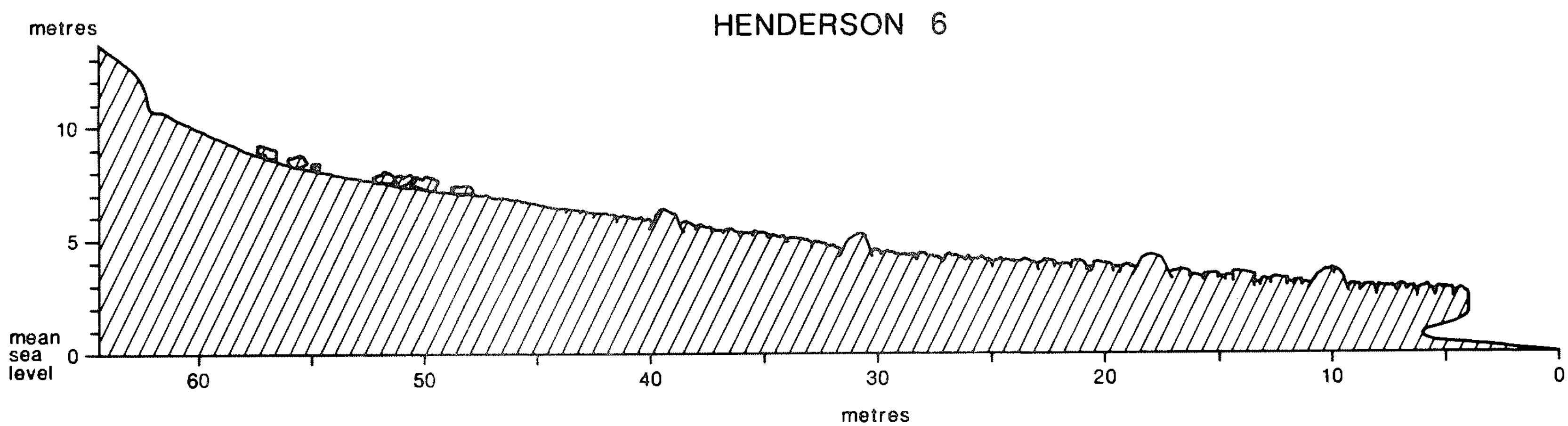

Figure 7. Profile 6, North-west Beach, Henderson Island (location: see Figure 9).

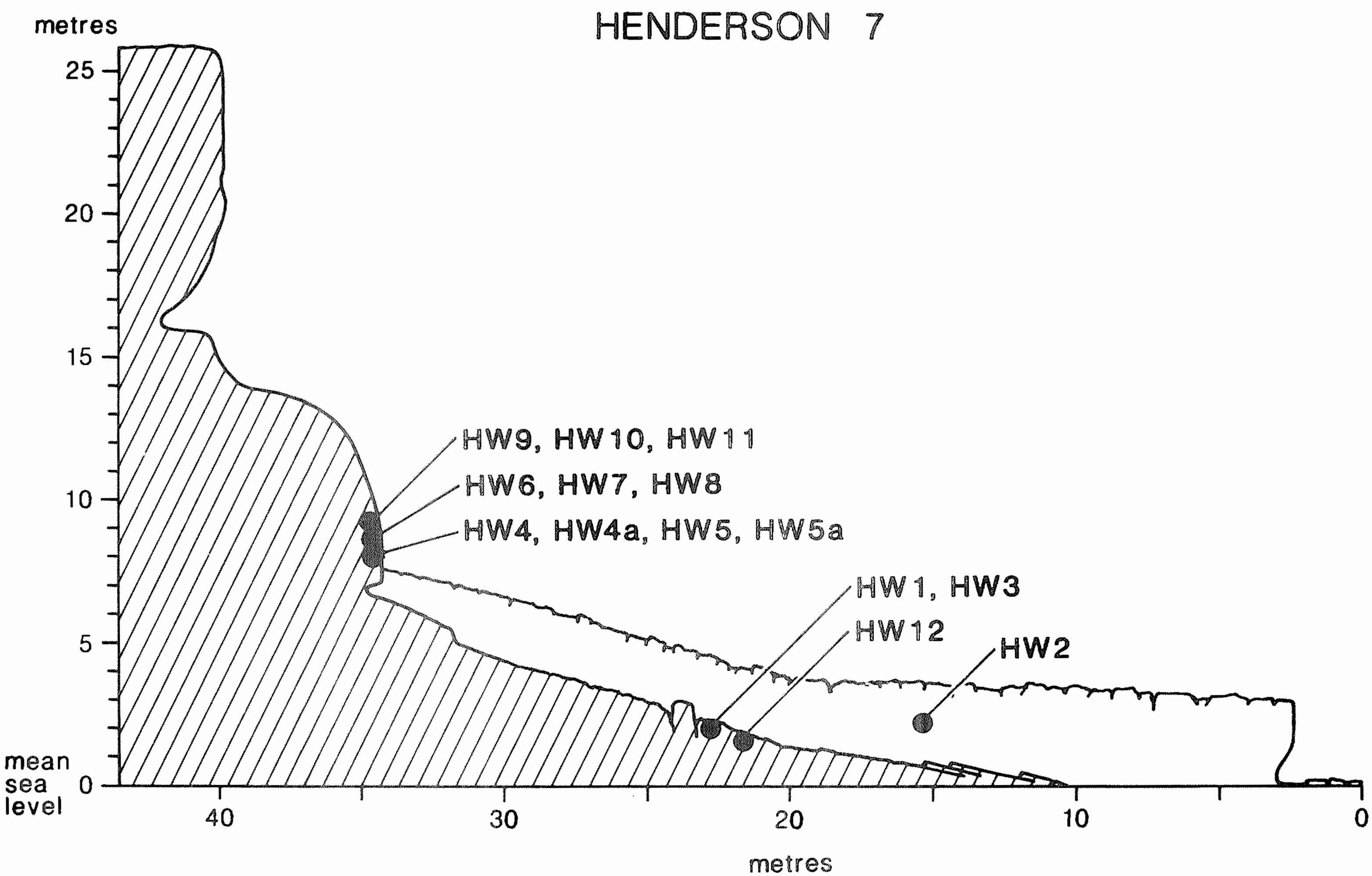

Figure 8. Profile 7, North-west Beach, Henderson Island (location: see Figure 9).

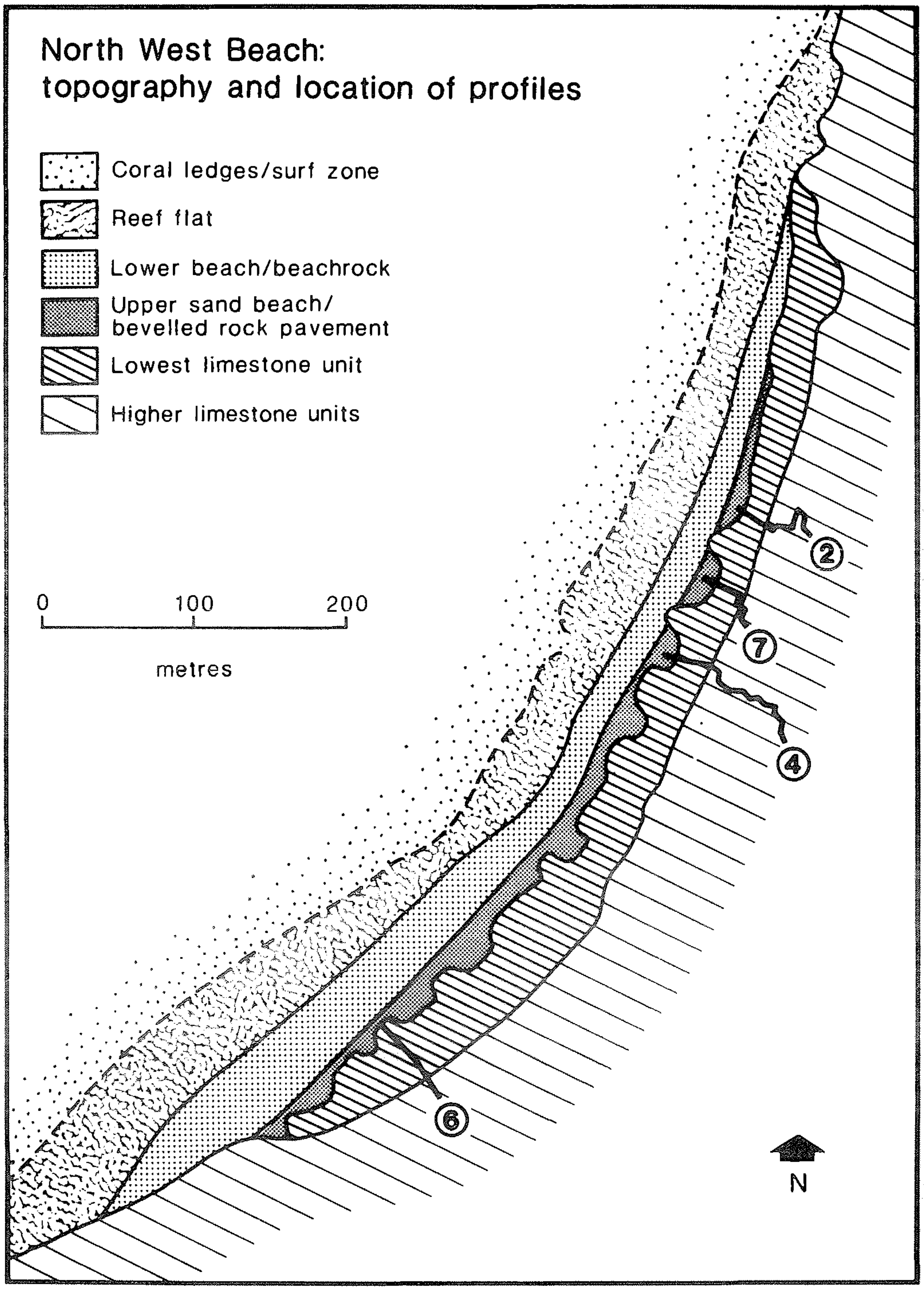

Figure 9. North-west beach: topography and location of profiles.

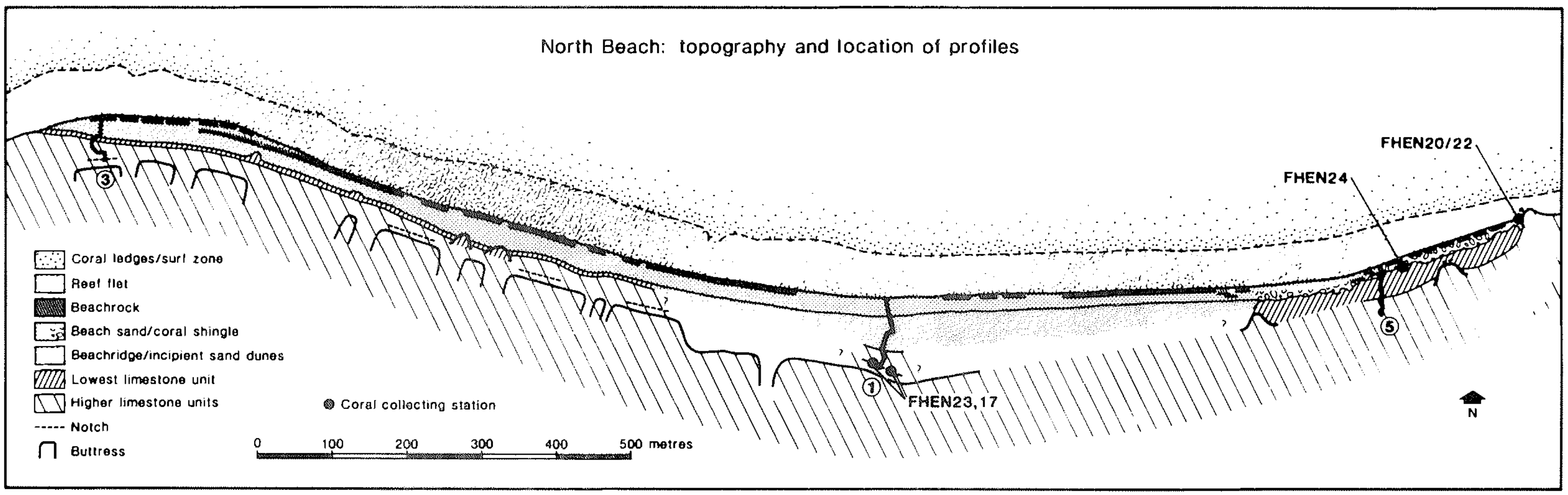

Figure 10. North beach: topography and location of profiles.

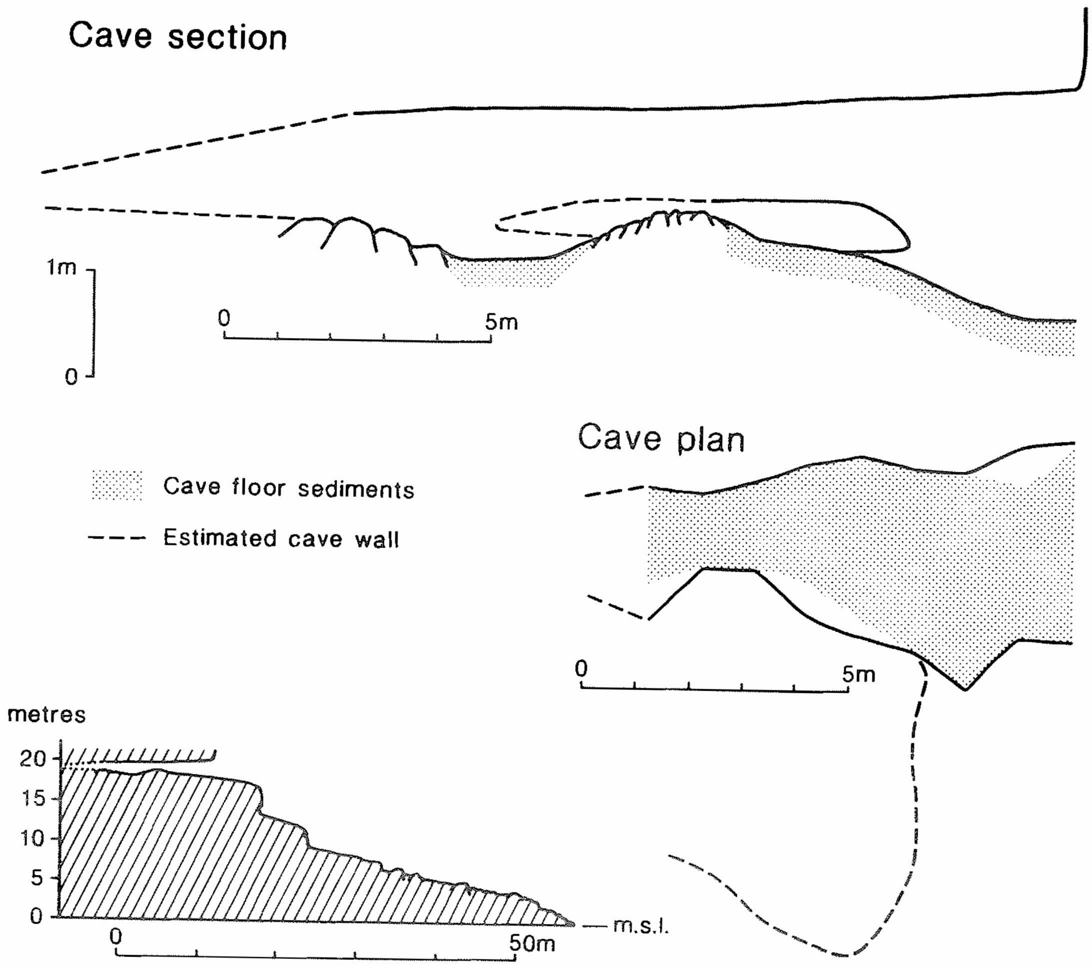

Figure 11. Cave morphometry, profile 2, North-west beach.

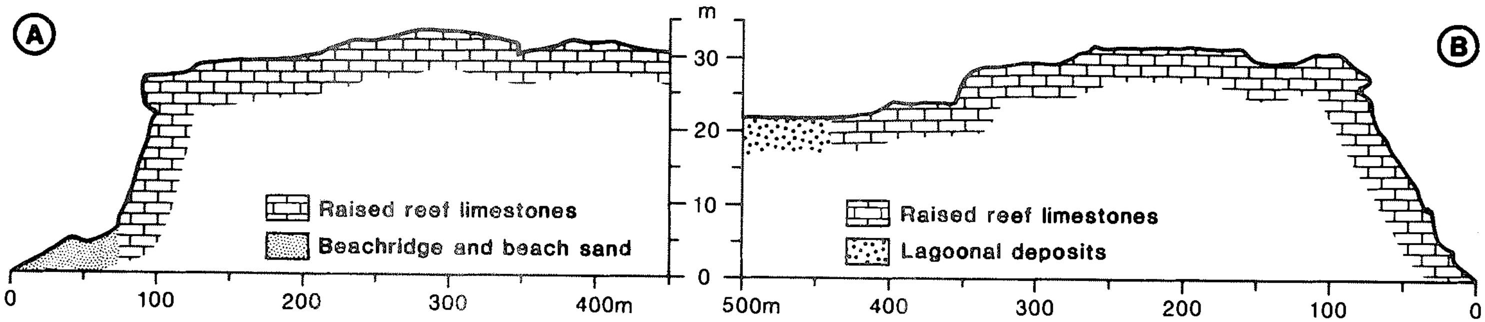

Figure 12. Topographic profiles from island cliff margin to island interior, North (A) and North-west (B) transects.

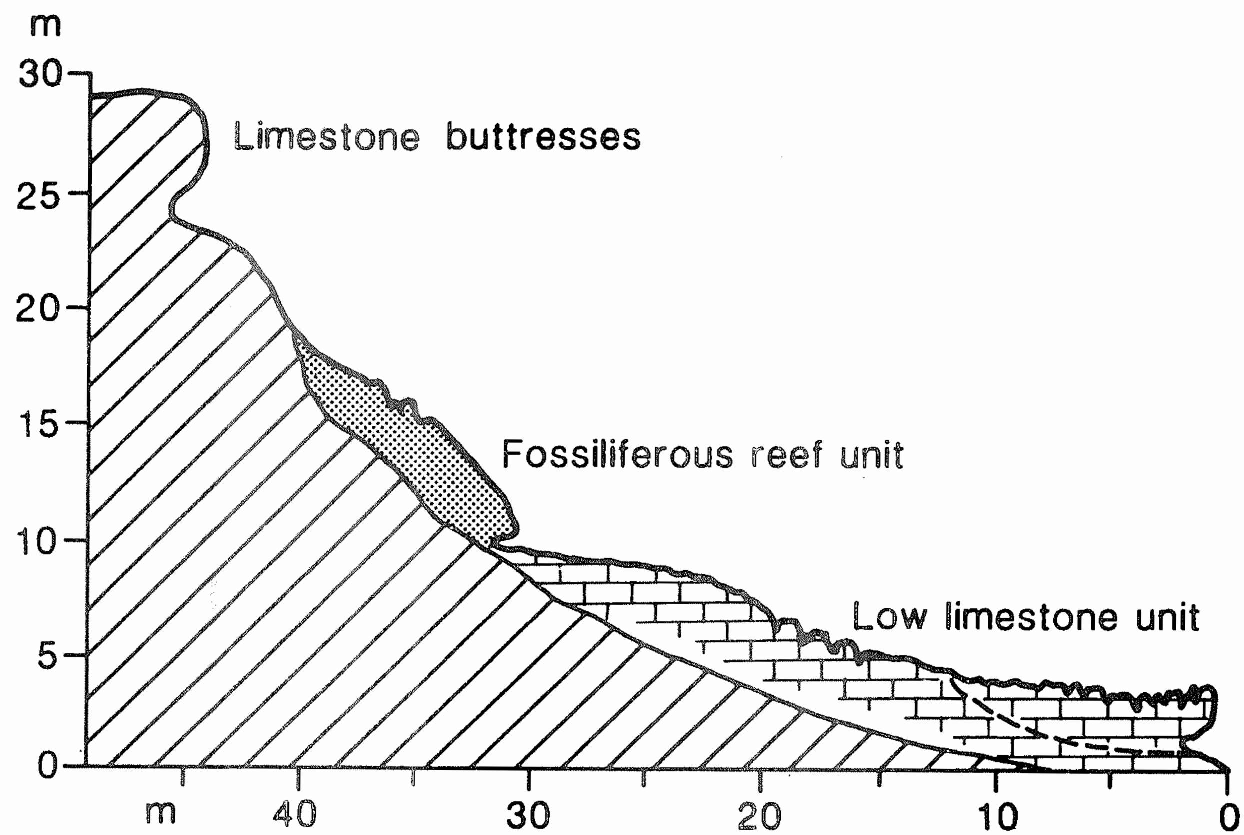

Figure 13. Summary diagram of stratigraphic units and sealevel features in north embayment, Henderson Island.

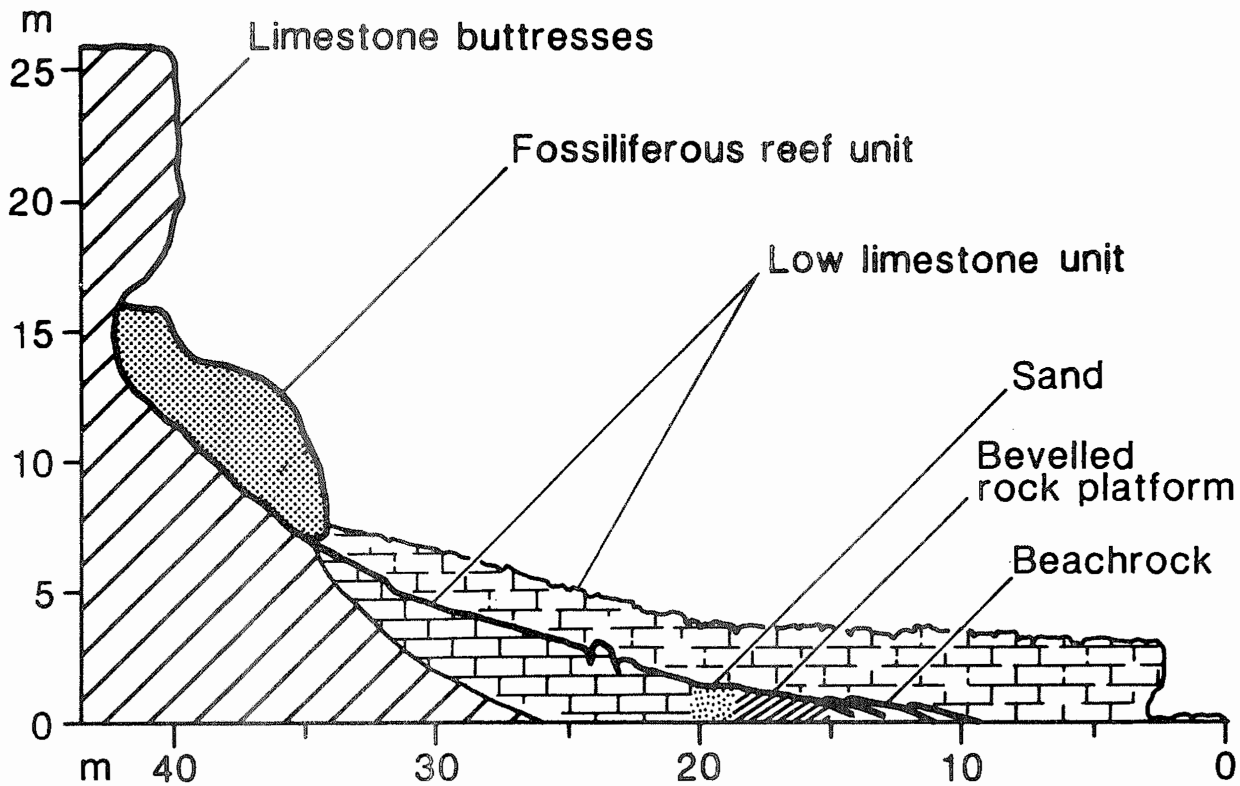

Figure 14. Summary diagram of stratigraphic units and sealevel features in north-west embayment, Henderson Island.

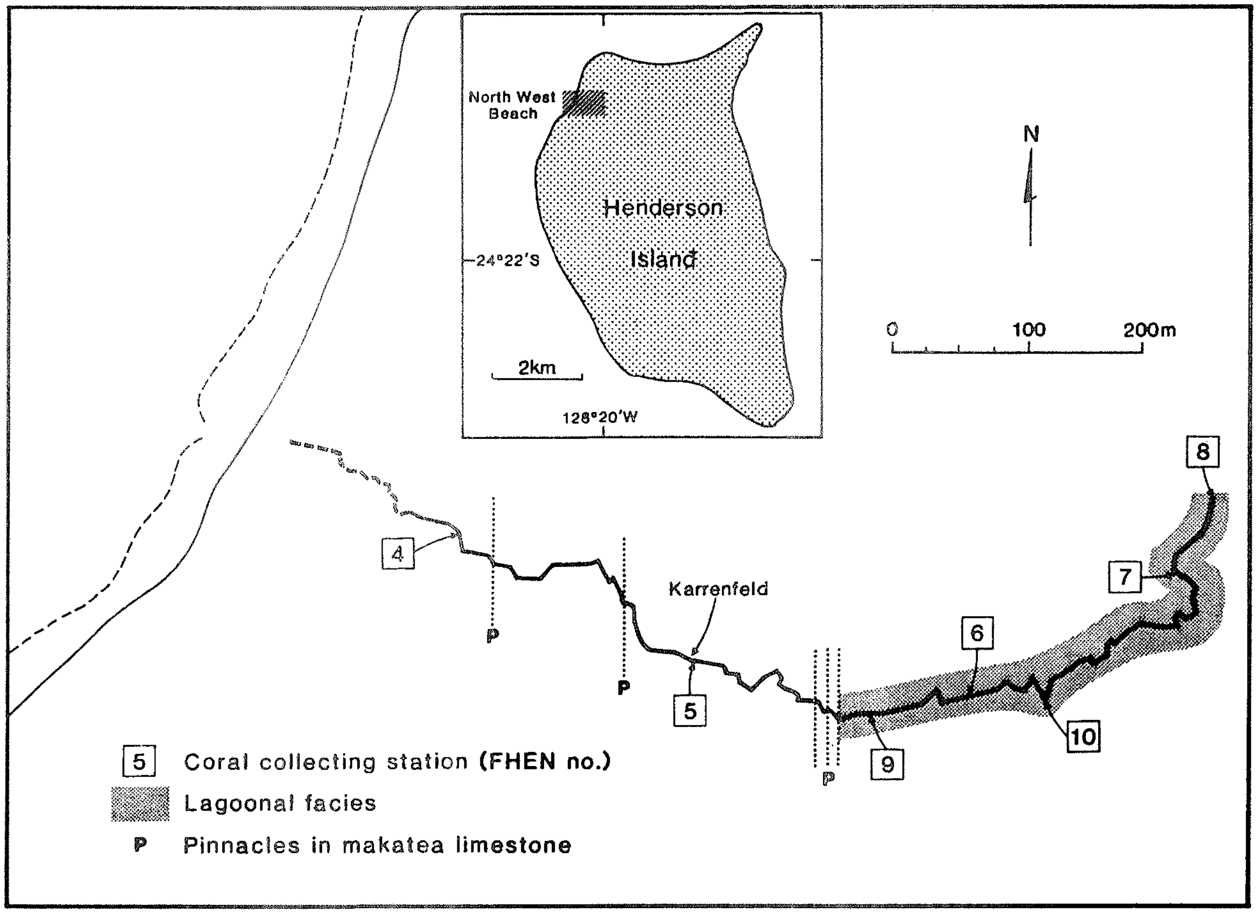

Figure 15. Plan of island cliff margin to island interior transect, North-west beach.

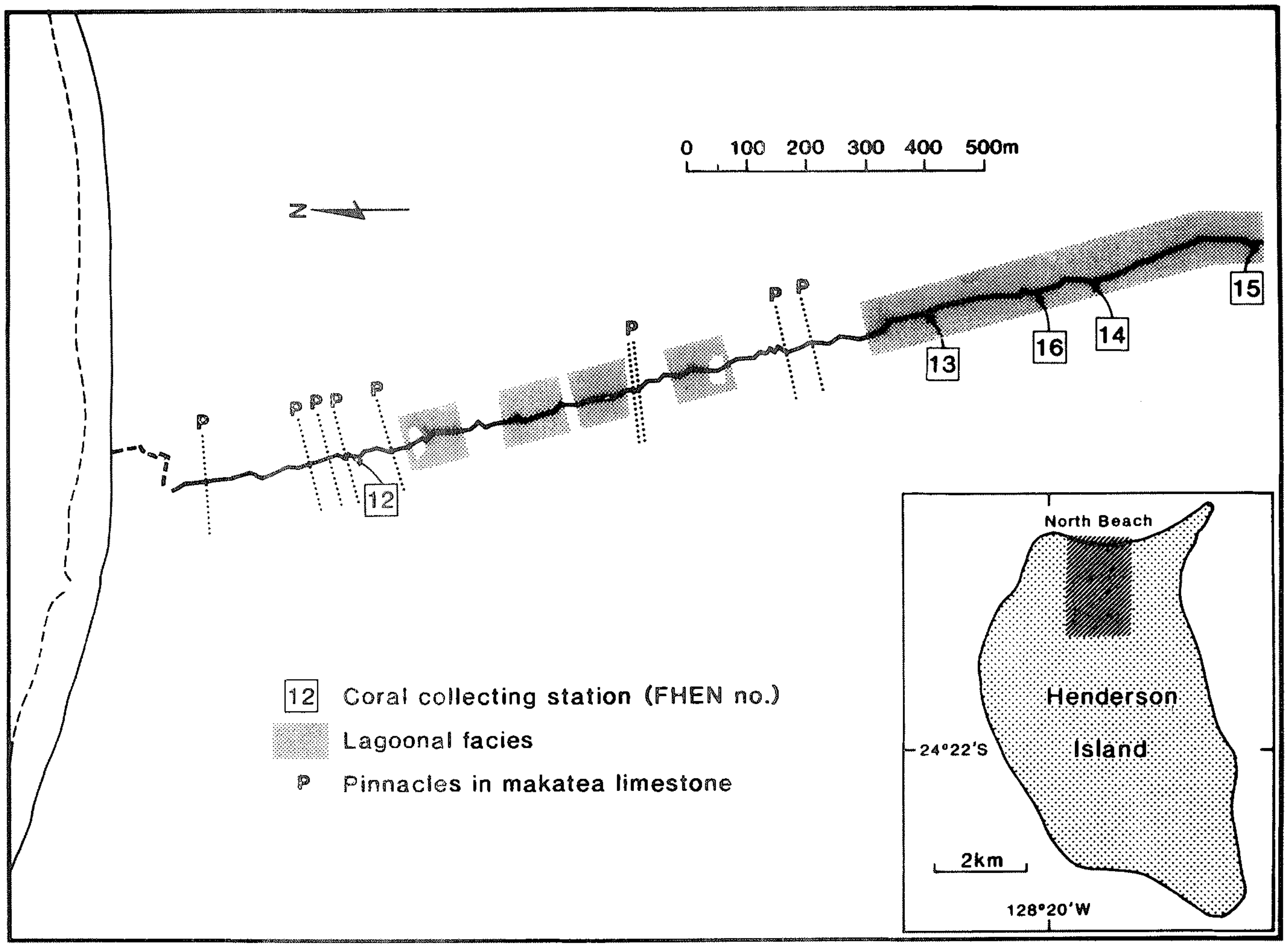

Figure 16. Plan of island cliff margin to island interior transect, North beach.

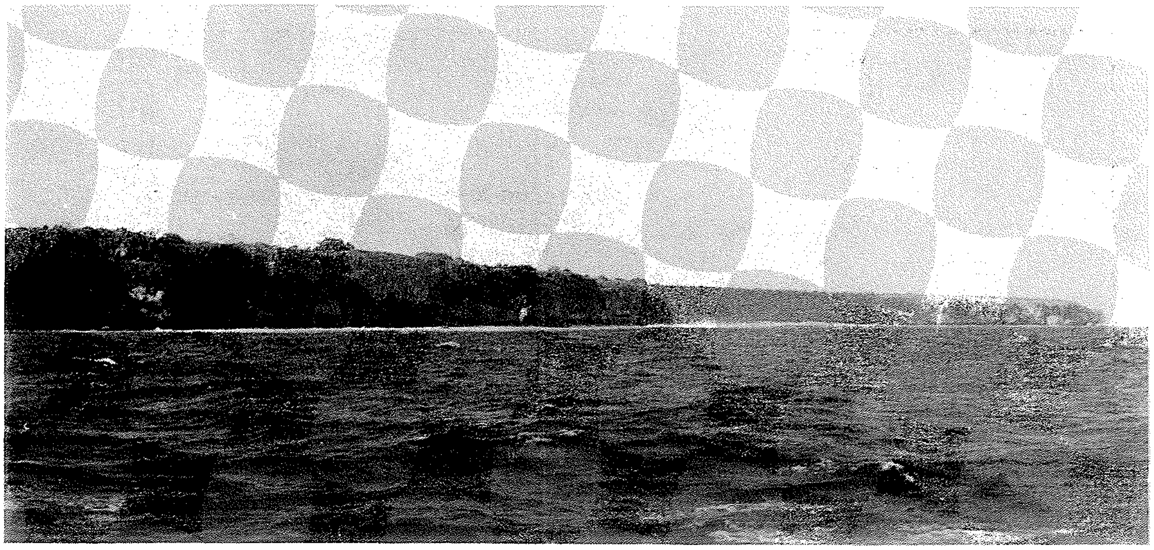

Plate 1. Western cliffs, looking south-southwest towards the south point.

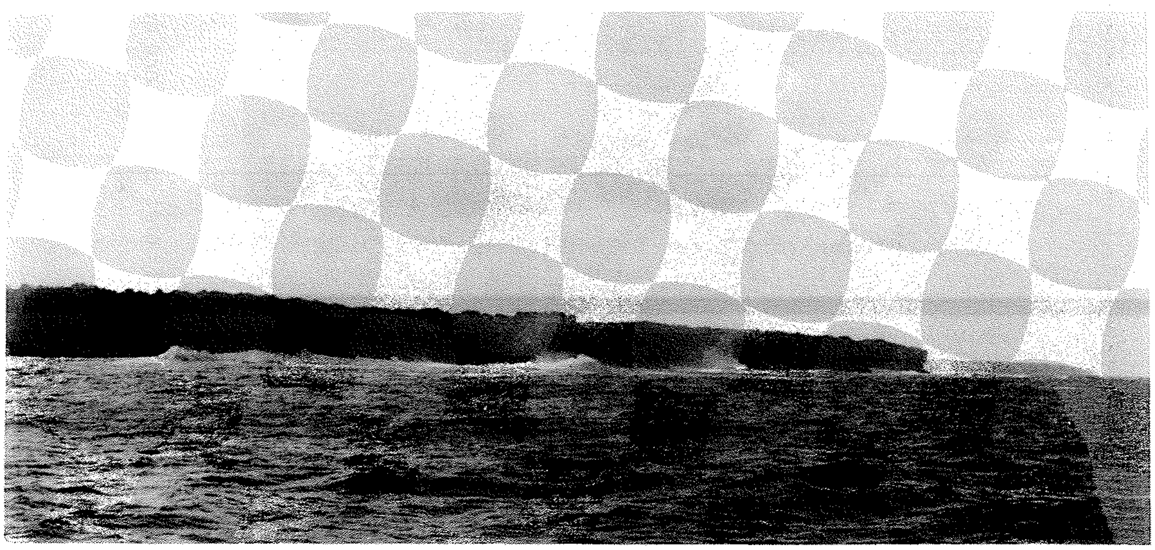

Plate 2. North-west embayment and beach. Awahou Point at far right.

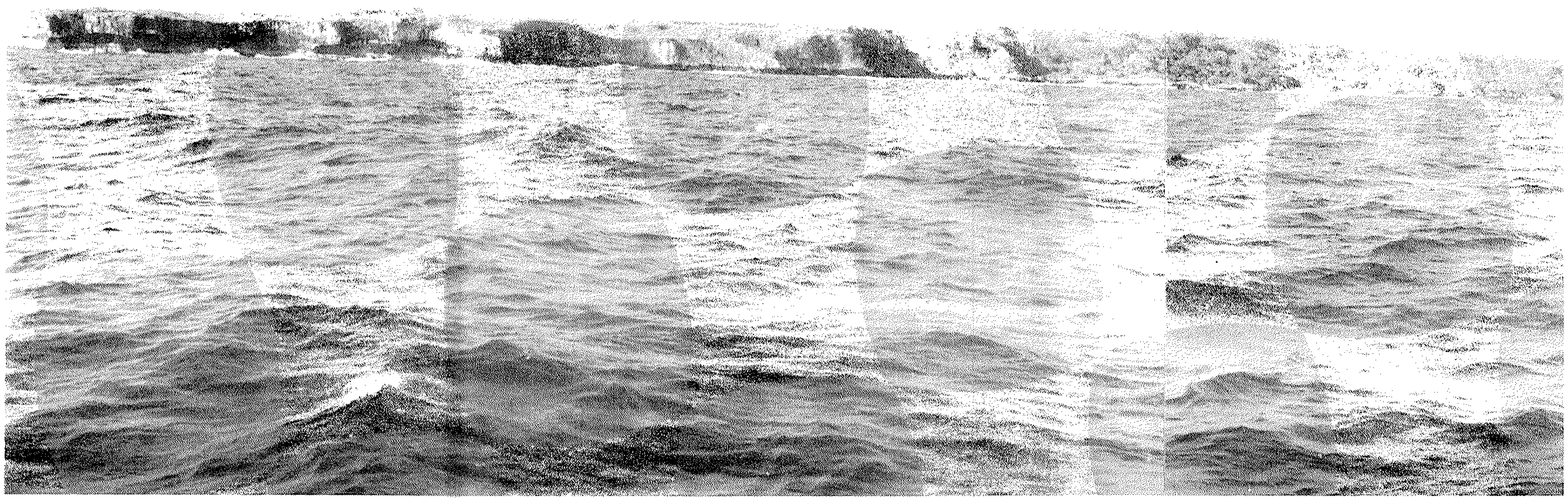

Plate 3. North-east Point and eastern end of North Beach, approaching Henderson from the north.

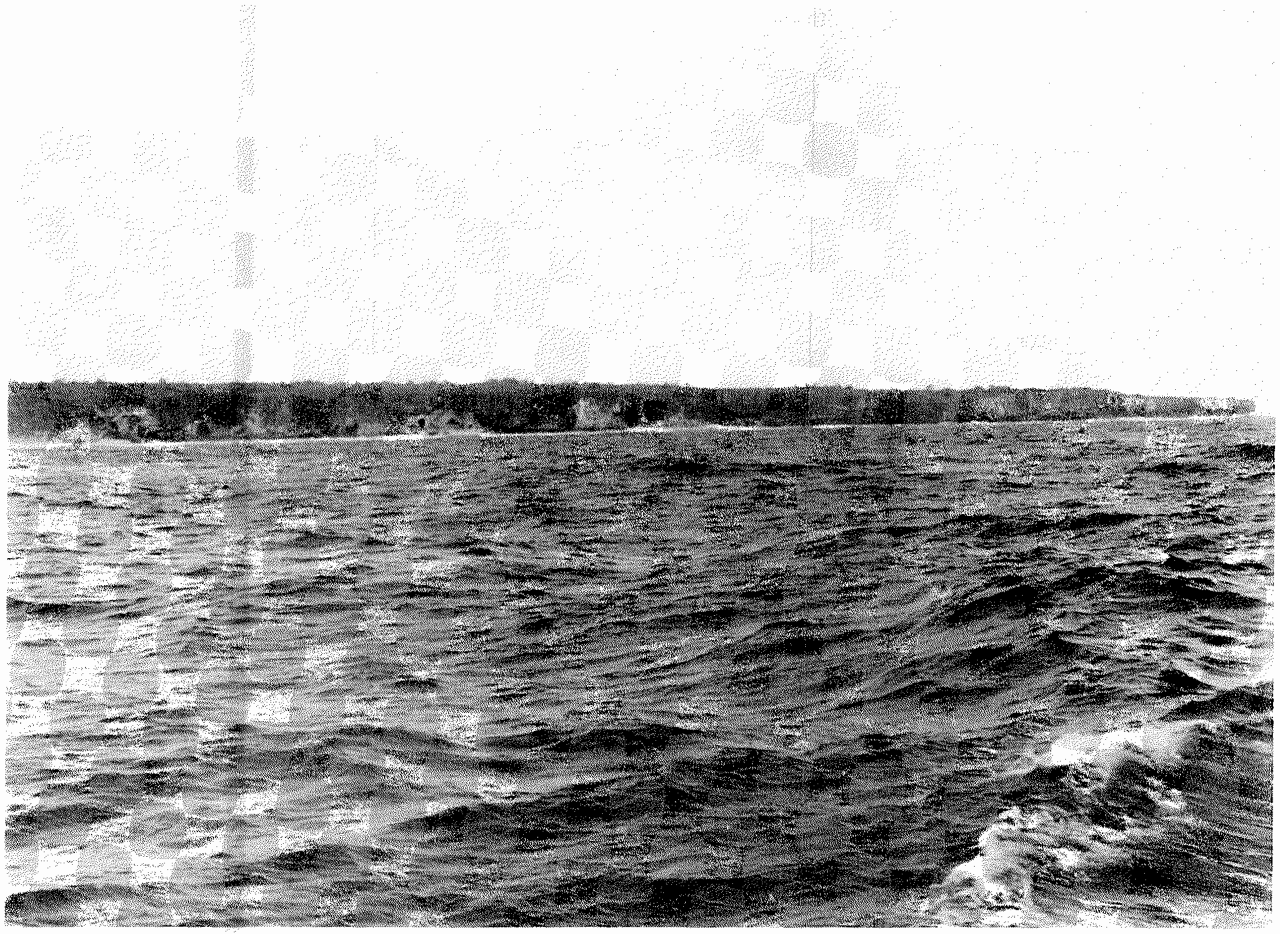

Plate 4. Northern end of East Beach and North-east Point, approaching Henderson from the east.

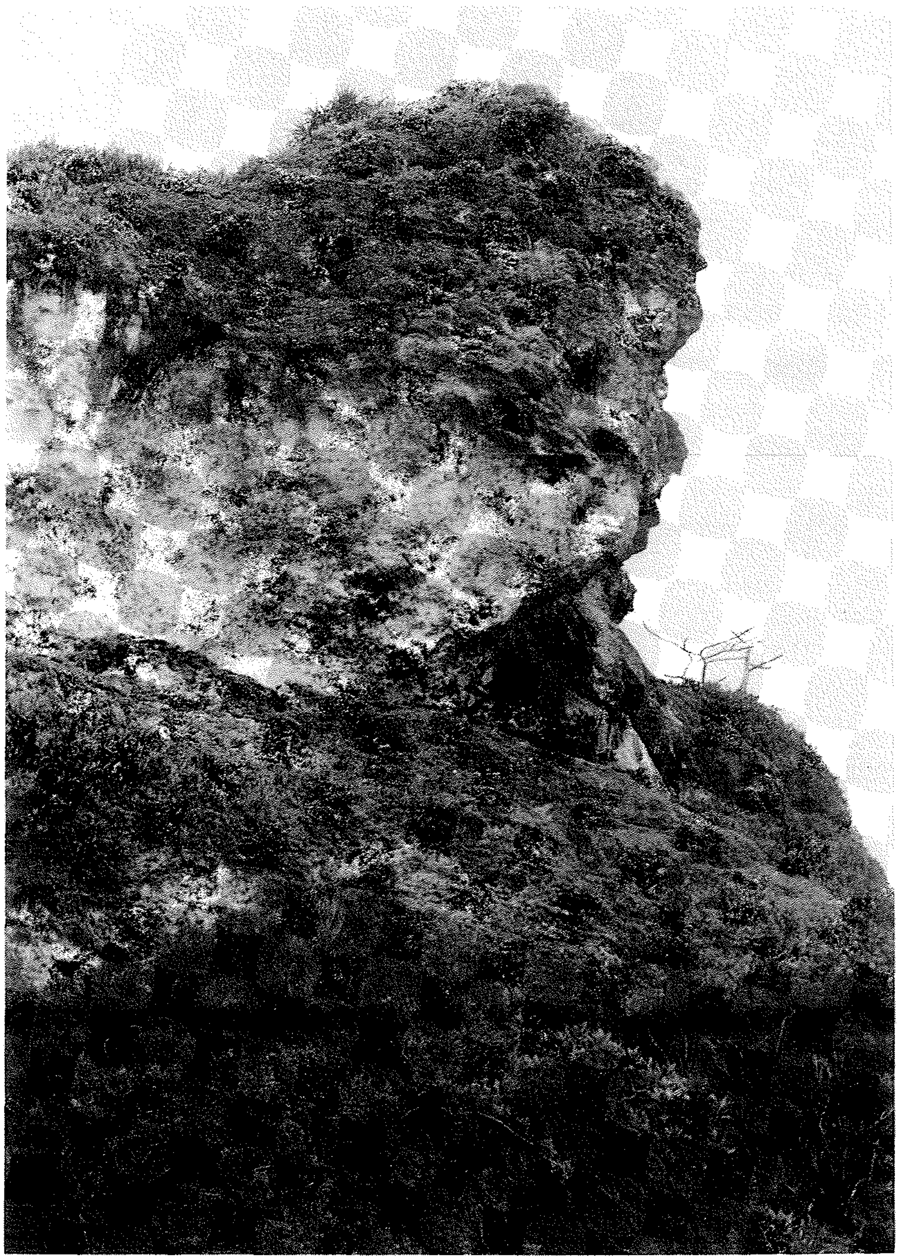

Plate 5. Fore-reef buttress, profile 7, North-west Beach. Notch at 16.2m above mean sea level with fossiliferous reef unit below (in foreground).

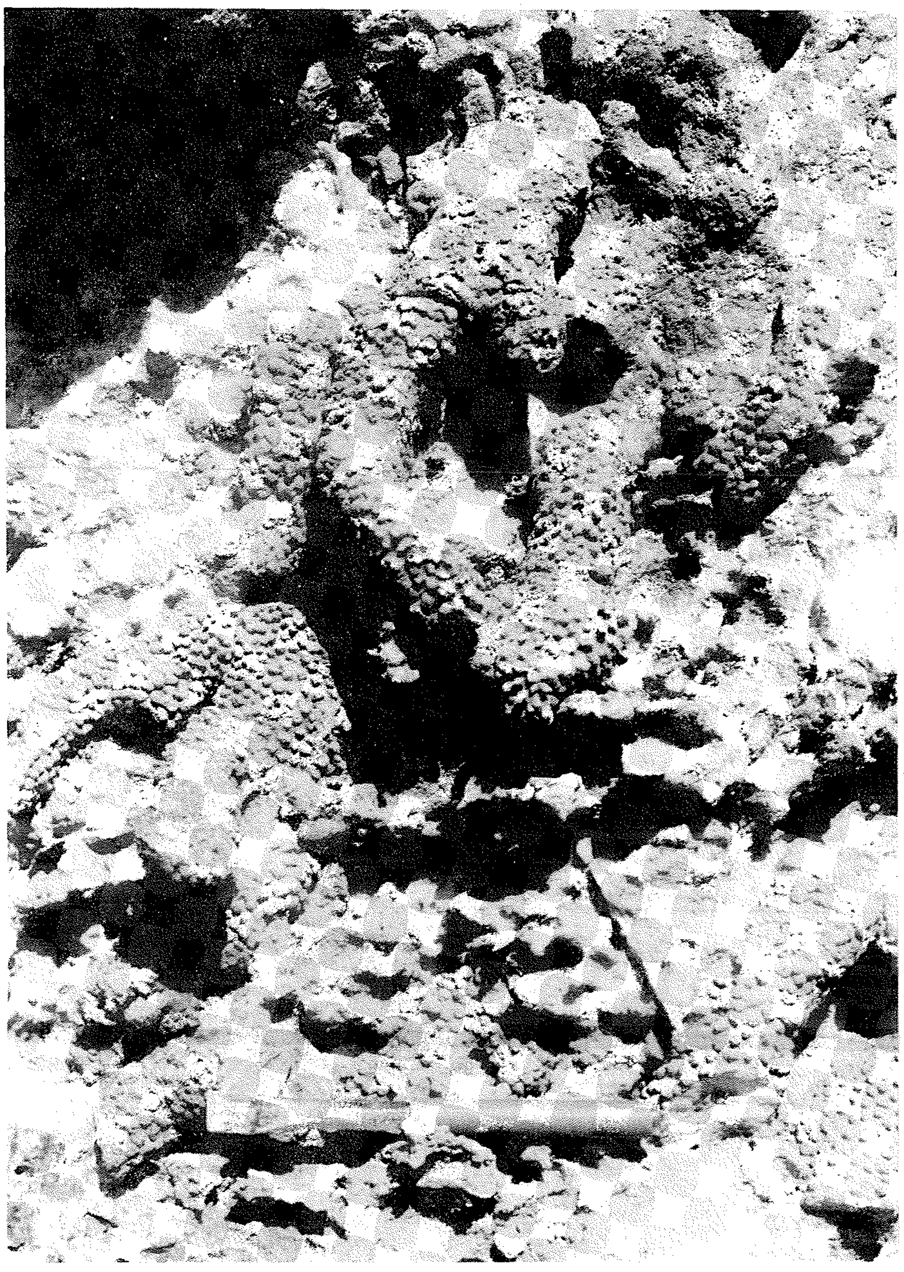

Plate 6. *Pocillopora eydouxi* in cliff face, ~ 24m above sea level, central North Beach.

Plate 7. 25m notch, profile 4, North-west Beach. Well-preserved *Acropora* sp. and sand fill in notch.

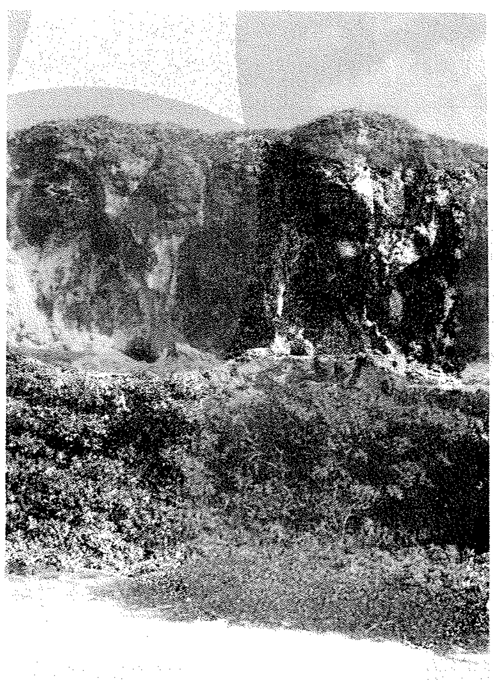

Plate 8. Coral buttress with notch level at 17-18m above sea level, eastern section, North Beach. Note post-erosional flowstone pillars within notch.

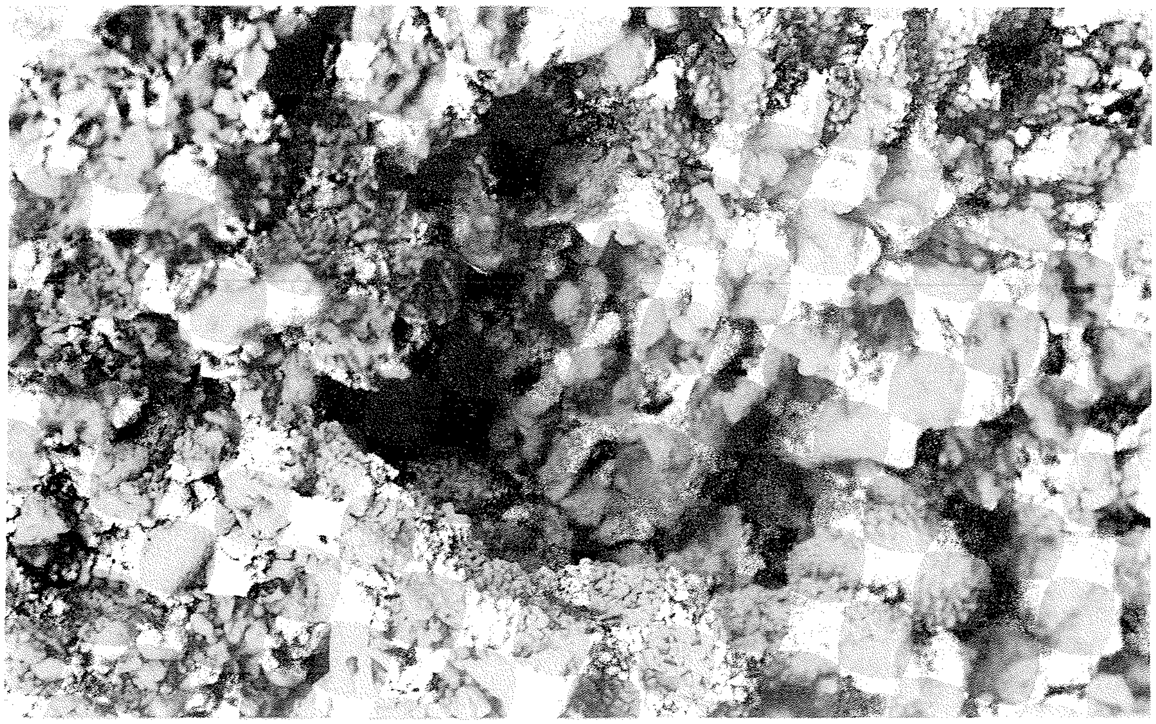

Plate 9. Upper facies, fossiliferous reef unit, eastern end of central section, North Beach.

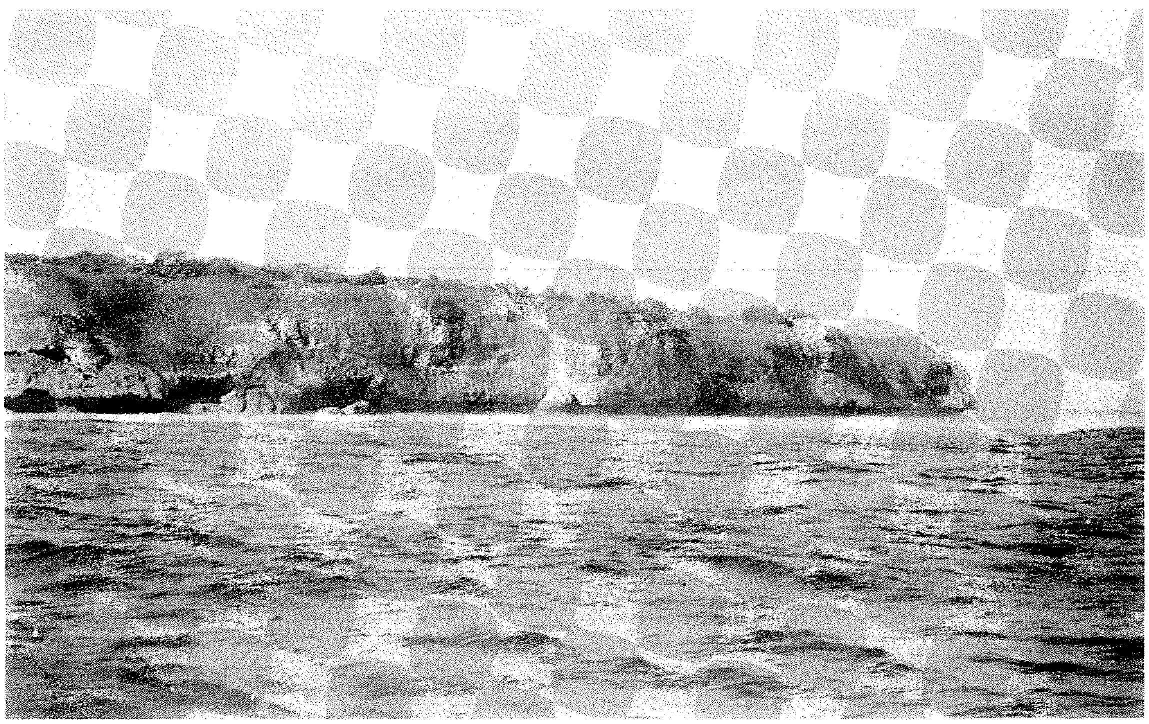

Plate 10. Headland at western end of North Beach. Note contemporary notch and (at centre) upper boundary of low limestone unit at ~ 10m above sea level. Upper, fossiliferous reef unit and low limestone unit well distinguished in headland profile.

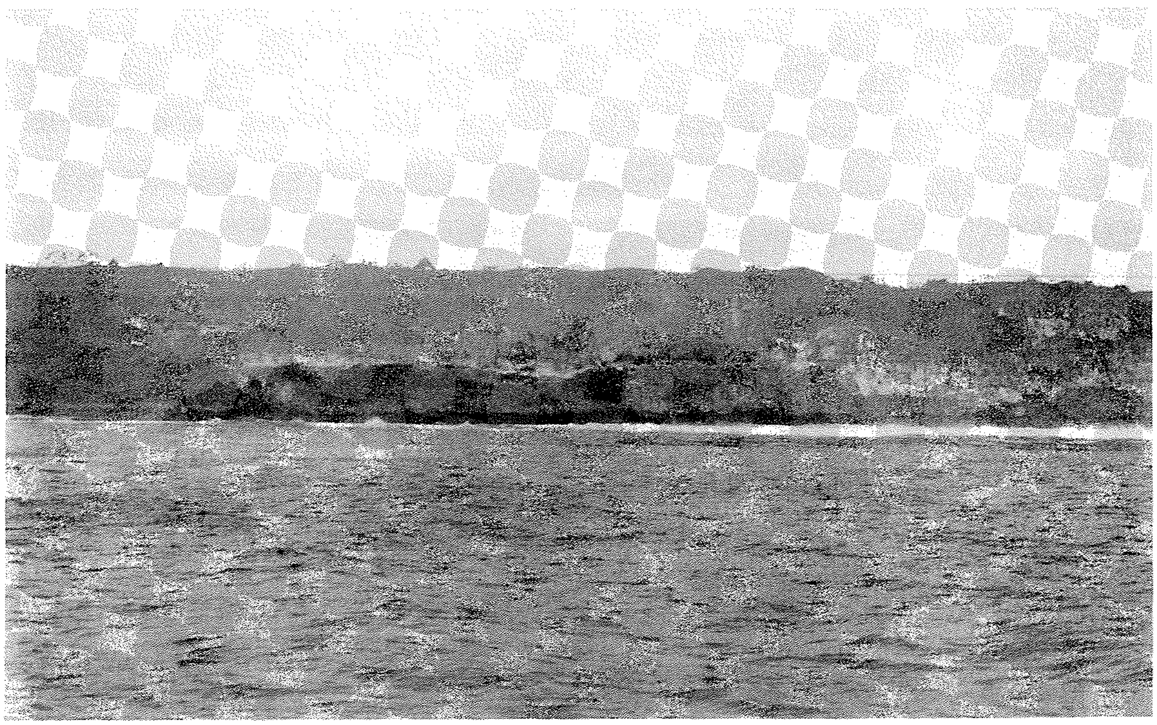

Plate 11. Cliffs to north of North-west Beach. Low limestone unit upper boundary marked by pale contact and large caves/overhangs.

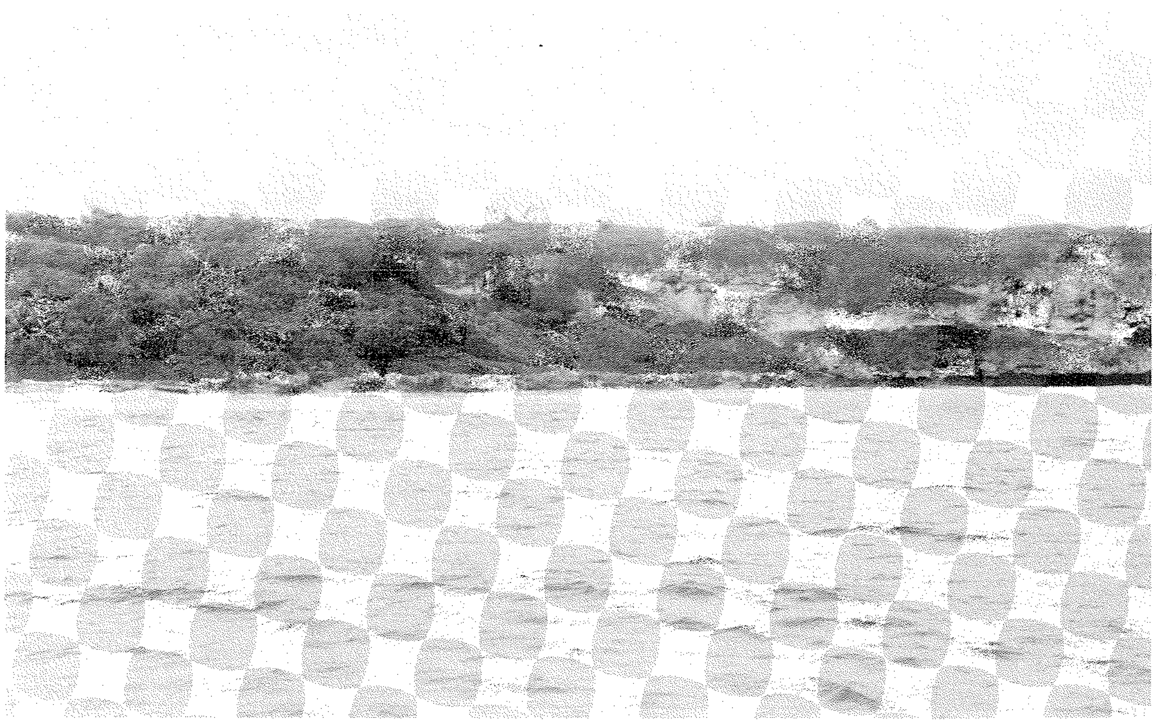

Plate 12. Southern end of North-west Beach. Note low limestone unit as terrace, with spur-and-groove margin, in bay (to left) and as cliff front veneer at bay southern margin (to right). Fossiliferous unit and notch/cave level above with high notch level (see Plate 7) near cliff top.

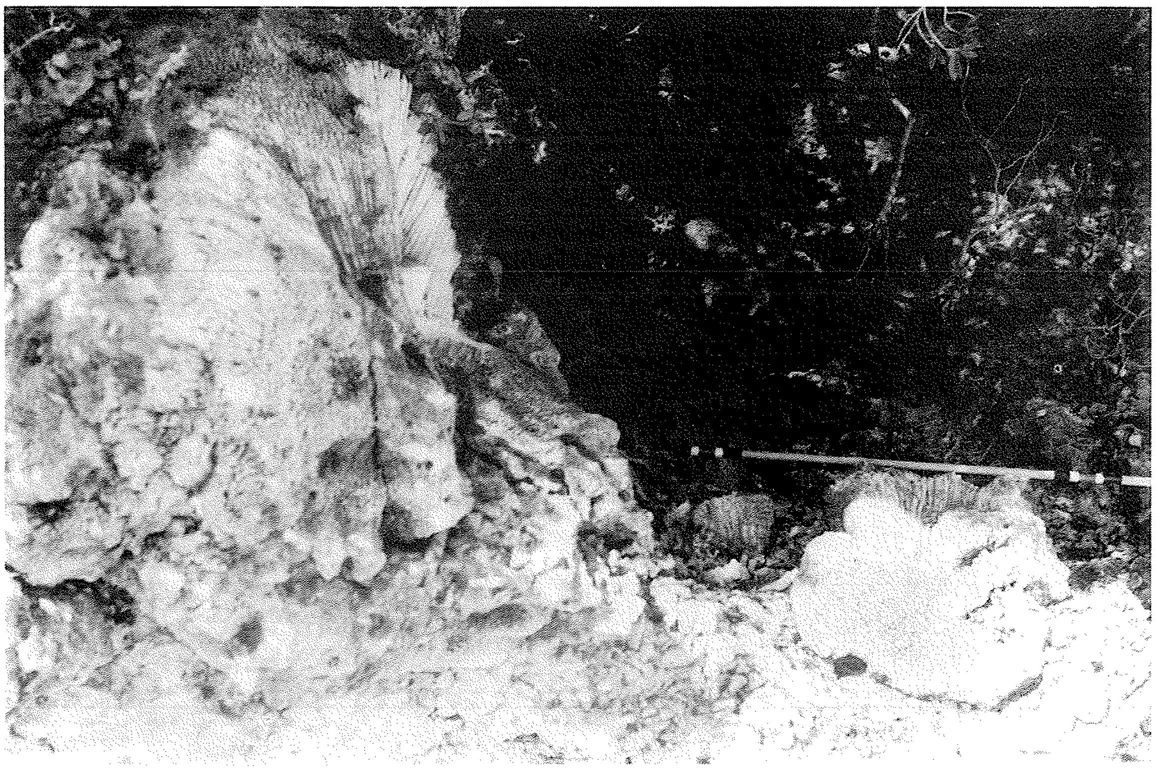

Plate 13. Groove exit in low limestone unit, eastern end of central section, North Beach. Note massive *Montastrea* sp.1 colony to left and similar colonies on groove floor.

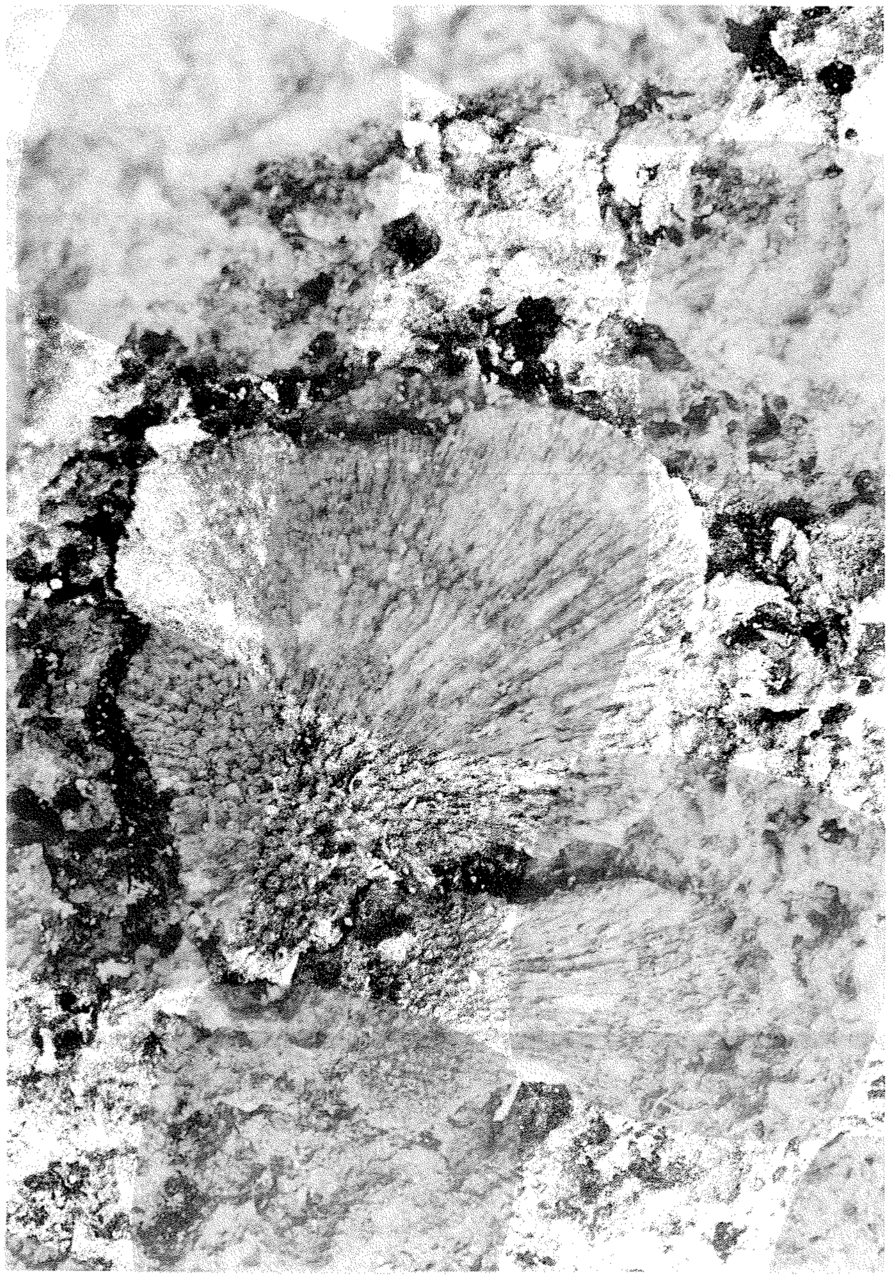

Plate 14. *Montastrea* sp. 1 in bevelled ramp, North-west Beach.

Plate15. Pinnacle-pitted limestone on transect to island interior from the North-west Beach.

Plate 16. Massively branching *Acropora* (group 2) colony, near interior lagoon margin, North-west Beach. (Scale bar: 50 cm.)

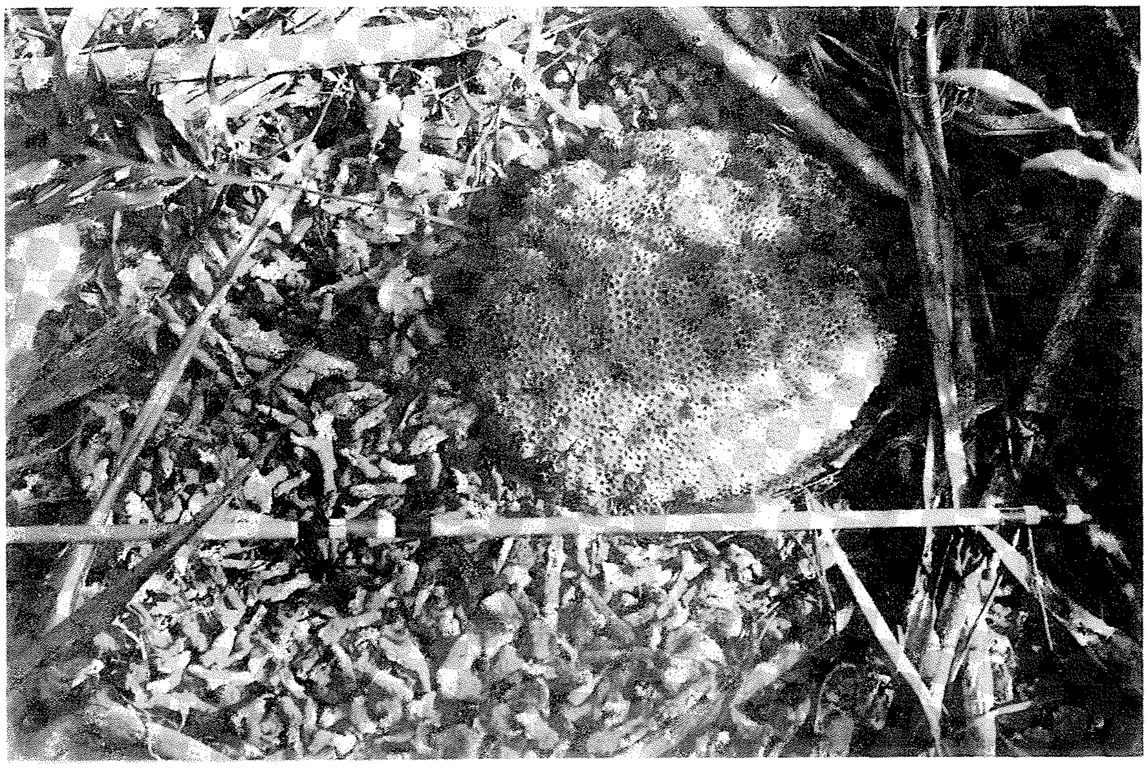

Plate 17. *Montastrea* sp.1 with *Acropora* sticks, interior lagoon deposits, North-west Beach. (Scale bar: 50 cm).

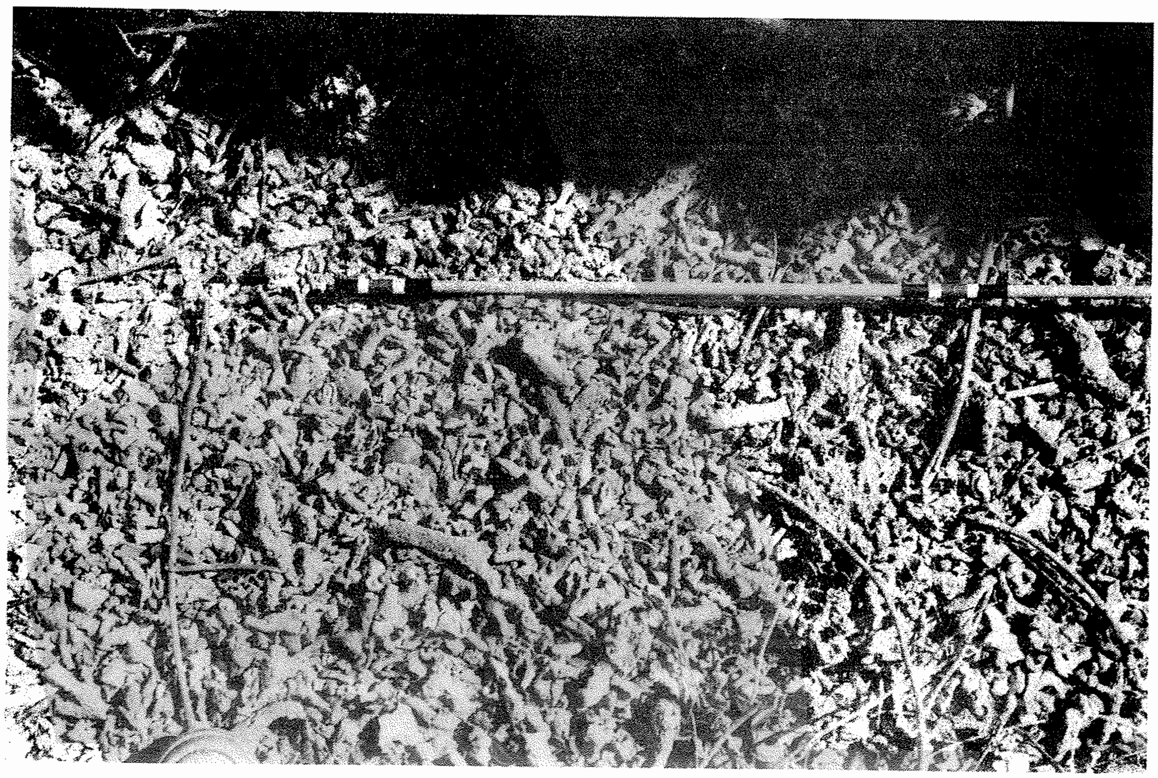

Plate 18. *Acropora* rubble of lagoonal patch reef, North Beach. (Scale bar: 50cm).