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THE ORIGIN OF CHANNEL-FILL SANDS AND GRAVELS ON AN ALGAL-DOMINATED REEF TERRACE, RAROTONGA, COOK ISLANDS

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ABSTRACT

A reconnaissance sounding and side-scan sonar survey of the nearshore area round the reef-fringed, volcanic island of Rarotonga was carried out in May 1978 to assess the potential for offshore sand and gravel aggregate and to explore for habitats where precious coral might occur.

It was shown that beyond the fringing reef there is a 200-600m wide reef-front terrace extending out to a depth of 26-31m. Beyond that the seafloor falls away steeply (> 30°) to a depth of 350-500m when the slope begins to gradually flatten out to merge with the 4000m deep floor of the Southwest Pacific Basin. The reef appears to have built up about 400m on a subsiding basement since late Pliocene times.

Coral and algal debris, derived from the inner part of the reef-front terrace, washes over the reef and onto the reef flat at most stages of the tide and particularly during storms and hurricanes. On the reef flat and on the beaches it is mixed with minor amounts of volcanic pebbles derived from streams. Ultimately the sediment follows the hydraulic flow out through one of the deep channels that extend from near the mouths of major streams, through one of the reef passages and across the reef-front terrace. There the sediment is lost to the system down the steep slope to the deep sea.

Sediment in the channels along the south coast is predominantly, highly porous Halimeda-rich sand with coral pebbles. It is considered unsuitable for most constructional purposes. However off Avarua and Avatiu there are wide, relatively shallow (5-15m deep) channels filled with a less porous sand, rich in rounded coral fragments and with a gravel of basalt pebbles. This deposit could be suitable for constructional purposes and its removal would have no serious environmental implications.

Deep, debris-free channels and rises suitable for the growth of precious (pink and white) coral do not appear to occur around Rarotonga. Scuba dives to steep slopes beyond the reef-front terrace revealed no black coral. It was noticed on dives at many places around the island that living coral was rare both on the reef flat and on the terrace outside. The dearth of living coral may possibly be attributed to a plague of Crown-of-Thorns Starfish (Acanthaster planci) reported around several intensively cultivated Pacific Islands in the late 1960's and early 1970's. The drab blanket of algae that has replaced coral may have increased the contributory of friable sand to the reef flat and ultimately the channels.

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INTRODUCTION

Rarotonga

Rarotonga is the social, economic, administrative and tourist centre of the Cook Islands. It is a high, rugged, kidney-shaped island some 11km across at its widest point. The interior of the island is a densely forested, highly dissected, Late Pliocene (2-3 million year old), basaltic-lava cone rising to a jumble of craggy peaks having a maximum altitude of 640m (Wood 1967; Tarling 1967; Wood and Hay 1970). Surrounding this is a fertile and intensively cultivated, coastal fringe which is generally 0.5 to 1.0km wide. The fringe consists of gently sloping fans and fertile terraces of strongly weathered volcanic alluvium (Nikao Gravels), separated by a taro-growing swamp from a back-beach ridge of broken coral debris (Aroa Sand). The main road and most of the villages and hotels are built on this dry ridge.

To seaward there is a fringing reef that is narrower on the northern and eastern sides of the island than on the southern and western sides. The reef is continuous except for six narrow boat passages. There are several reef islets, notably off the southeast corner of the island.

Beyond the reef, published information has been based mainly on hydrographic soundings by H.M.S. VERONICA in 1922 of the approaches to Avarua and Avatiu Harbours and on an echo-sounding circum-navigation of the island, some 2km from shore, by HMNZS ENDEAVOUR in 1963 (British Admiralty 1976). The Rarotongan volcanic cone merges with the 4km deep floor of the Pacific Ocean some 20km from shore. (Summerhayes and Kibblewhite 1967; Summerhayes 1967).

Rarotonga is buffeted by predominantly easterly to northeasterly trade winds, by winter storm swells from the southern ocean, and by hurricane intensity cyclonic storms that come mainly from the north and northwest (N.Z. Met. Off. 1943; N.Z. Met. Serv. 1955; Wiens 1962). Although the eastern side is the most wind and wave swept, nowhere is particularly well sheltered.

The island is bathed by southwestward flowing water from the South Equatorial Current. It has a tidal range of 0.85m at spring tides and 0.33m at neap tides (Stoddart 1972). The mean sea-surface temperature in the vicinity of southern Cook Islands is 26°C (Stoddart 1975a).

Present Supplies of Constructional Material and Precious Coral

At present, supplies of building and constructional materials are derived from a variety of small, local sites. Sand comes from borrow pits and beaches; aggregate comes from stream beds, Avatiu Harbour bed; and, as crushed rock, from Black Rock, Nikao. Many of these stocks are local and limited or, in some cases, environmentally worthy of preservation.

Precious coral is imported from Hawaii and is manufactured into simple jewellery for sale to tourists.

THE SURVEY

Arrangements for Survey

At the Fifth and Sixth Sessions of CCOP/SOPAC, reports were presented on the likely occurrence of precious coral in the South Pacific and on the possibilities for mining submarine sands for constructional purposes (CCOP/SOPAC 1977; 1978). Since both precious coral and constructional sand-aggregate could be of value for an expanding tourist trade, it was decided to survey the nearshore area around Rarotonga with a view, firstly to defining sediment sources, migration patterns and sinks and secondly to defining areas suitable for the occurrence of precious (including black) coral.

Workable deposits of constructional materials might reasonably be expected on flat terraces and in channels at less than a few tens of metres deep and jewellery grade coral might be expected on steep slopes and banks between 25m and 500m deep (Grigg 1976). Thus the first stage of the survey was necessarily a bathymetric reconnaissance around the island between the reef and 750m deep. The second stage was to investigate suitable terraces and channels in more detail using side-scan sonar and dredges. The third stage was to investigate suitable steep slopes and knolls with divers and tangle nets.

The survey was arranged by the CCOP/SOPAC Technical Secretariat, Suva for May 1978 using a combined team from the Cook Islands Dept. of Survey and Physical Planning, who provided the expertise and equipment necessary for accurate theodolite fixes, the Cook Islands Scientific Research Office, who provided a suitably equipped vessel, the ALBACORE, by arrangement with the Cook Islands Fisheries Research Department, and the New Zealand Oceanographic Institute, who provided side-scan sonar equipment, a marine geologist, and an electronics technician/diver under its annual commitment to CCOP/SOPAC.

The CCOP/SOPAC Technical Secretariat in Suva arranged the despatch of sounding equipment together with funds for travel and accommodation.

Mr. and Mrs. D. Dorrell of Rarotonga generously provided, free of charge, a high speed launch, scuba tanks, diving companions and local knowledge of conditions for several dives along the south coast.

Survey Procedures

Using a Raytheon PTR-106C-1 7kHz sounder linked to an EPC 4100 recorder, some 55 sounding lines were made radiating out from the island to a point where the seafloor was at least 750m deep (Fig. 1). Lines were generally 400-800m apart at their inner end. They began 100-300m outside the reef and continued offshore for 1.5-2.0km.

Positions were fixed by shore-based theodolite parties at the start and at the end of each line.

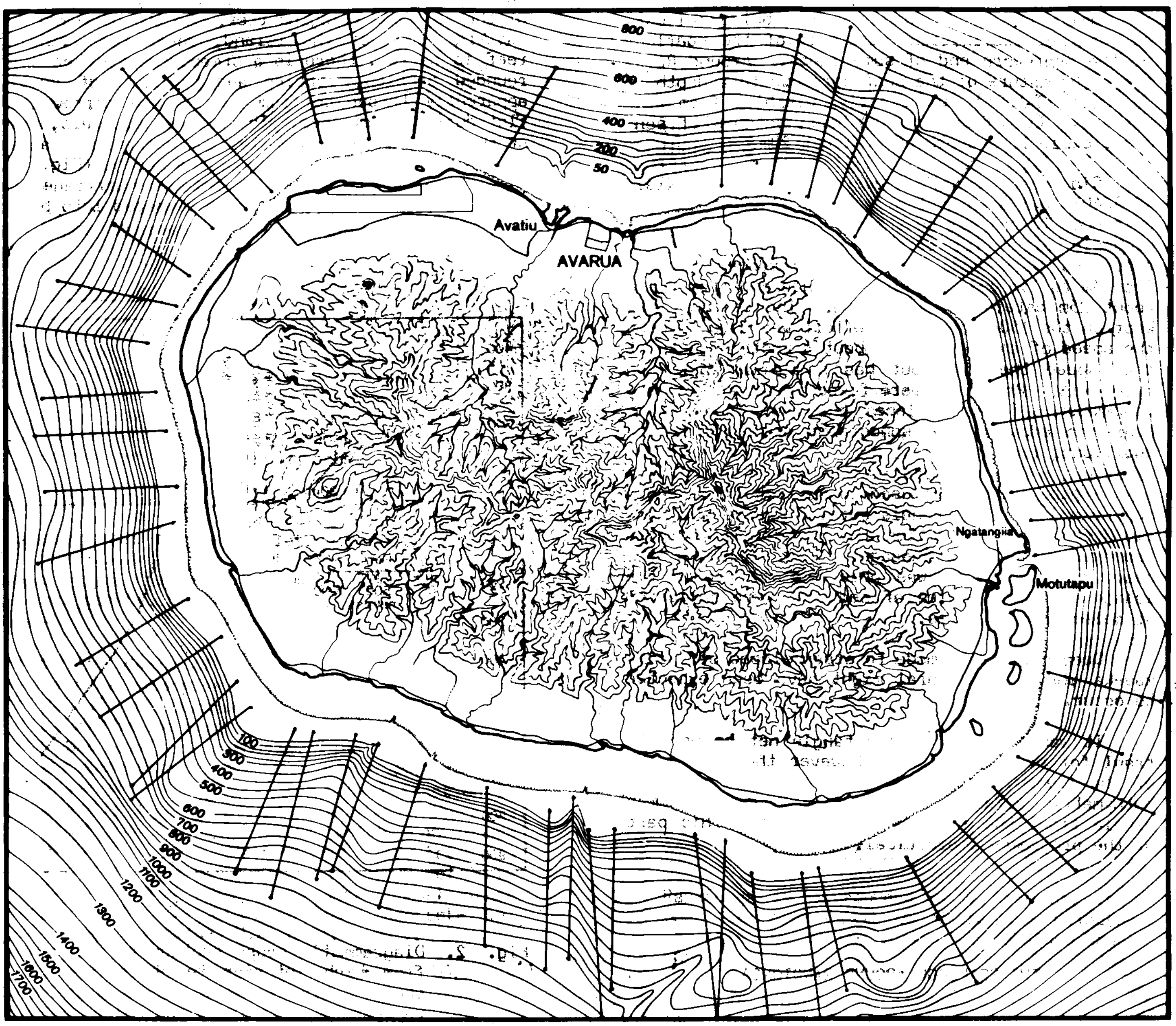

Fig. 1. Map of Rarotonga showing survey lines and bathymetric results of survey. Contour interval 50m.

Fixes were announced from the launch by both radio and by flag fall. Arrangements were made to fix at intermediate positions as necessary. The launch was maintained at a constant engine speed along each line. It was kept on a constant course with the aid of a 'flag' party who raised a large white diamond on a pole at predetermined points along the beach. The helmsman maintained the diamond in a constant relationship with known landmarks behind it.

While theodolite stations were being relocated, snorkel examinations were made of the seafloor at the nearshore end of some lines. Around Rarotonga the nature of the seafloor down to a depth of 25-30m (80-100') is clearly visible from the surface. Even from a moving boat, patches of sand are visible to a depth of at least 20m.

Side-scan sonar traverses using a Klein 402A/401 dual scan system, were made seaward of the entrances to all six passages, these being the only probable sites for offshore sand migration. The traverses were made with the transducer ranging from 3m to 15m below the sea surface and from 2m to about 25m astern of the launch. The recorder was kept on the 150m range. An effort was made to keep the speed of the launch at about 4 knots because at that speed the print-out has a similar scale on each axis. Positions were fixed by aligning known landmarks. In many places the reef is recorded near the edge of the sonographs and provides an additional fix.

A pipe dredge was used to collect three sediment samples from channels outside Avarua and Avatiu Harbours. In addition divers collected samples from outside Rutaki Passage. The nature of the beach and reef flat was observed all around the island and ten samples of sediment were collected at selected localities.

Deep dives were made to steep slopes off Titikaveka where black coral might have been expected to occur.

It was intended that a tangle net be used to trawl for precious coral. However the small size of the launch, deteriorating weather, unfavourable bathymetric evidence and negative evidence from a single trawl the previous year, all made this part of the programme impractical.

THE SEAFLOOR AROUND RAROTONGA

The Beach

The present shoreline is somewhere near the middle of a 1.0-1.8km wide, gently sloping platform that extends from about 30m above sea level to about 30m below sea level (Fig. 2). This platform has probably been formed mainly by peripheral coral growth and backfilling on a subsiding basement. Upward growth will have occurred mainly during interglacial phases, when the sea was within a few metres of its present level (Stoddart 1975). The present beach is a more or less transitory feature representing a complex balance between reef growth and sediment build-up, both before and since the last glacial low sea level.

Around the island, the slope and grain size of the beach bear an inverse relationship to the width of the adjacent fringing reef. On the northern and eastern sides of the island, where the fringing reef is narrow, there is a steep, cuspate beach of rounded pebbles, cobbles and boulders of coral, apparently thrown up from outside the narrow reef flat during hurricanes. The largest boulders, some of them nearly 1m in diameter and darkened by algae are concentrated at the toe of the beach. (Fig. 3). Coral/algal sand accumulates between hurricanes at mid-tide levels. It is locally cemented into beach

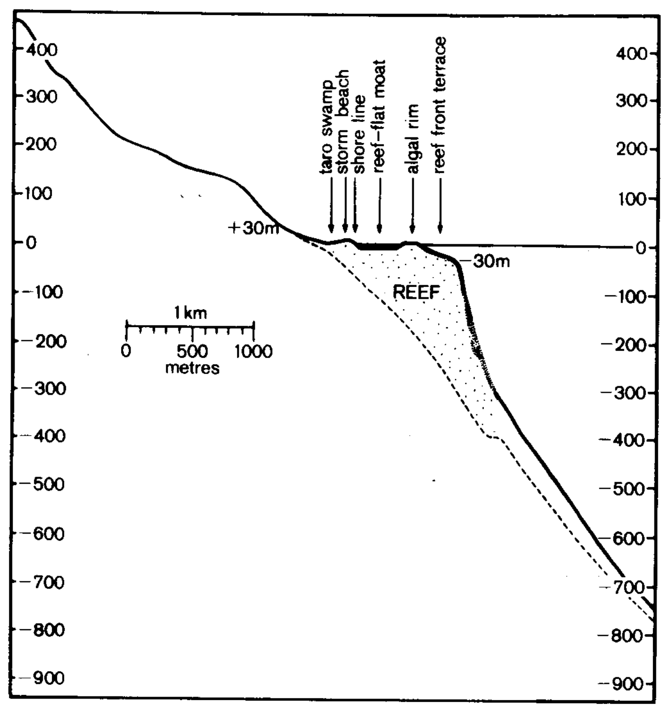

Fig. 2. Diagrammatic cross section of Rarotonga from high interior to about 3km offshore. Line seaward of the algal rim represents sounding line with defuse reflector between about 30m and about 400m deep. Dotted line indicates probable position of boundary between volcanic basement and reef growth plus backfill.

rock, sometimes incorporating the boulders at the toe of the slope. However, unless this sand is cemented, or filters down between boulders or is blown inland, it is removed at the next hurricane. Bleached coral gravel occurs above high tide.

On the less exposed southern and western sides of the island, where the fringing reef is wider, the beach is a gentler slope of white algal, coral, mollusc and foraminiferal sand derived from the adjacent reef, mixed with black volcanic grains

Fig. 3. The beach at Matavera on the exposed northeastern side of the island. Reef flat is narrow and moat shallow. Beach is narrow, steep and coarse with beach rock and algae covered coral boulders at toe.

derived from the streams (Fig. 4). At many places the large friable, sometimes recrystallised, plates of calcareous algae are the most conspicuous constituent.

Around Ngatangiia Harbour, in the southeast corner of the island, there are some more unusual types of shoreline. On either side of the harbour entrance the sea laps against 3m high, undercut cliffs of well-cemented, reef limestone of probable Last Interglacial Age (Stoddart 1972; 1975). Reef limestones at similar heights on Mangaia and in French Polynesia have been dated by Uranium series methods at around 100,000 years old (Veeh 1966). Schofield (1970) obtained a radiocarbon age of 28,000 years for the Ngatangiia outcrop but Thom (1973) has discussed the difficulties of accepting radiocarbon dates in this age range. Inside the harbour, which is sheltered by reef islets, there is a muddy delta at the mouth of the Avana Stream, Rarotonga's largest stream, and there are beaches of relatively well-sorted fine sand at Muri.

Fig. 4. The beach at Arorangi on sheltered western side of island. Reef flat is wide and up to 1.5m deep at low tide. Beach is wide, gentle and fine with scattered coral pebbles.

The Reef Flat

The reef at Rarotonga is a text-book example of a fringing reef (Wiens 1962; Ladd 1977): it hugs the island without a true, navigable lagoon between it and the shore. Its outer edge, is 50-100m from shore on the northern and eastern sides of the island, 200-400m from shore on the western side of the island and 400-600m away from shore along the southern coast.

The most conspicuous part of the reef (Fig. 2) is the 20-50m wide causeway referred to in reef geomorphology texts as "the algal rim" or "algal ridge" (Wiens 1962). It is usually just drying or just awash at low tide. It is a fairly smooth, hard surface of mainly encrusting algae, with pools, grooves and surge channels containing a more diverse fauna of calcareous algae and small encrusting corals.

The algal rim is separated from the beach by a reef flat moat that ranges from a few centimetres to about 1.5m deep at low water. This is not a deep-water, navigable "lagoon" in the geomorphological sense (if it were, the fringing reef would be a barrier reef) but in the south and west it is sufficiently wide and deep to be popularly referred to as such.

In the northern and eastern sides of the island the whole reef flat is typically a smooth hard pavement with a line of shallow pools forming the only evidence of a moat at low tide (Fig. 3). There is commonly a dusting of algal sand in these pools and scattered boulders or blocks of coral. Locally near Avatiu, where a stream has been diverted onto the reef flat behind a mole, the reef flat is being blanketed by mud.

On the southern and western sides, there is a step down from the coral-fringed algal rim to a sand-floored reef flat moat that is typically 0.5 to 1.5m deep at low tide (Figs 4 and 5). There is commonly a sharp change in slope and sediment type between beach and reef flat. The thickness of sand on the wider reef flats is unknown but it is probably not more than a few metres.

The algal rim is broken by some half a dozen named passages, the breaks continuing across the reef flat as deep channels. These channels range from 10-20m deep at the passages to only a few metres deep near the shore. Most are steep-sided with nearly flat sediment covered floors. Each of the channels is directly off the mouth of a large stream and presumably represents an "antecedent" drainage system inherited from glacially lowered sea level, coral having grown up on either side. The passages and reef flat channels off the main, north coast settlements of Avarua and Avatiu have been extensively modified for port facilities.

Aerial photo mosaics (Survey Dept. Rarotonga 1966), oblique colour photographs taken by Mr. D. Dorrell of Rarotonga (Fig. 5) and vertical photos taken by the R.N.Z.A.F. (Fig. 6) show conspicuous lineations on the southern and western reef flats. These lineations, which appear to represent lines of coarser debris and/or growing organisms, are at right angles to the rim across most of the reef flat but tend to curve round to run parallel with it as they approach the shore or where they are adjacent to one of the reef flat channels.

The lineations appear to record the movement of water and sediment in the fringing-reef environment. Water crashes over the algal rim at most stages of the tide. Particularly during storms it carries with it algal and coral debris torn from the zone immediately outside the algal rim. In most conditions this debris will only be sand-sized grains but in hurricane conditions it can be massive boulders. The water and sediment continue towards shore until they reach the inner reef flat and then turn to run along the toe of the beach until they either reach one of the deep reef flat channels or one of the slight "canoe pass" depressions in the rim. There the water (and sediment) flows off the reef flat. At all times, except just after low tide in calm weather, water flows out through the channels and passages.

At many places < shaped walls have been built across the main flow as fish traps, fish being swept into the angle of the < (Fig. 5). In general, the height of sediment is the same on either side of the traps and they do not appear to have played a major roll in damming sediment movement.

It seems probable that sandy sediments build up slowly over decades and are scoured during hurricanes, when coral boulders are thrown up onto the reef flat.

Again, Ngatangiia is a somewhat special case (Fig. 6). A line of reef islets appears to continue the line of, what elsewhere is, the coastal "hurricane" ridge. The sheltered and picturesque Ngatangiia Harbour occupies the depression that is elsewhere the taro swamp. This depression may be a moat inherited from the Last Interglacial Age, it may be a result of solution during the Last Glacial Age (Wood and Hay 1970) or it may be a Holocene feature. Perhaps more likely, it is a complex combination of all three. The islets at Ngatangiia appear to be anchored to a Last Interglacial reef limestone, the harbour behind them was partly eroded by the Avana Stream, and the islets themselves are predominantly Holocene rubble and sand accumulations (except for Taakoka which is volcanic). Stoddart (1972) describes the islands as "sand cays" although in 1978 they appeared to

Fig. 5. Aerial photo of Avaavaroa Passage. Coast is at the top and algal rim, marked by breakers, is about two-thirds of the way down. Sediment transport is from reef-front terrace, over algal rim, and across reef flat to inner reef flat or beach. Lineations at right angles to algal rim mark route. Sand trapped at head of channel on inner reef flat, moves down deep channel, which bifurcates just outside algal rim, to deposit in channels on reef-front terrace. Y shaped objects on inner flat are fish traps. (Photo D. Dorrell, Rarotonga).

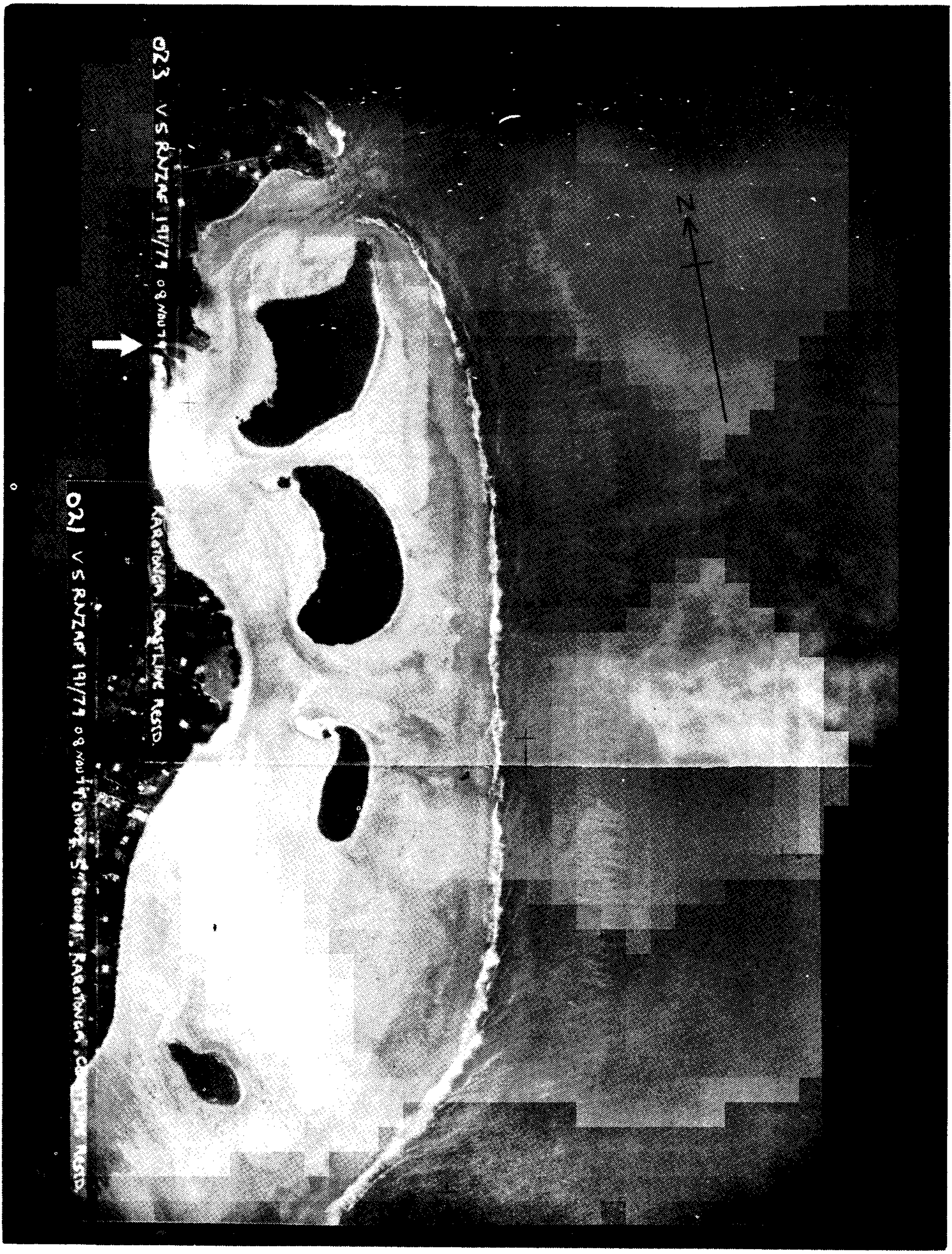

Fig. 6. Vertical aerial photos of Ngatangiia Harbour in the south-eastern corner of the island showing reef islets on reef flat, and reef-front terrace outside the surf-covered, algal rim. Note lineation of coarse debris parallel with water flow out through reef-passage in the north. Note also increasing width of reef flat in front of islets towards the south. Sandy reef flat between islets and coast occupies some geomorphic position as taro swamp elsewhere. (Courtesy of RNZAF).

have a seaward armour of coarse coral gravel similar to the "motus" of the Taumoto Group (Chevalier 1973).

The Reef-Front Terrace

One of the major results of the bathymetric survey was the definition of a 200-600m wide, reef-front terrace right around the island.

Although the inner part of the terrace is often difficult to observe because of heavy surf, aerial photographs and side-scan sonographs suggest that at most places there is a steep, groove and spurred, face to the algal rim (Figs 7A and 7B). The face appears to range from about 2m to about 8m high, and from about 5m to about 40m wide and it is generally steepest near its base. At the toe of the algal ridge there is commonly a flat area of seafloor up to 30m wide.

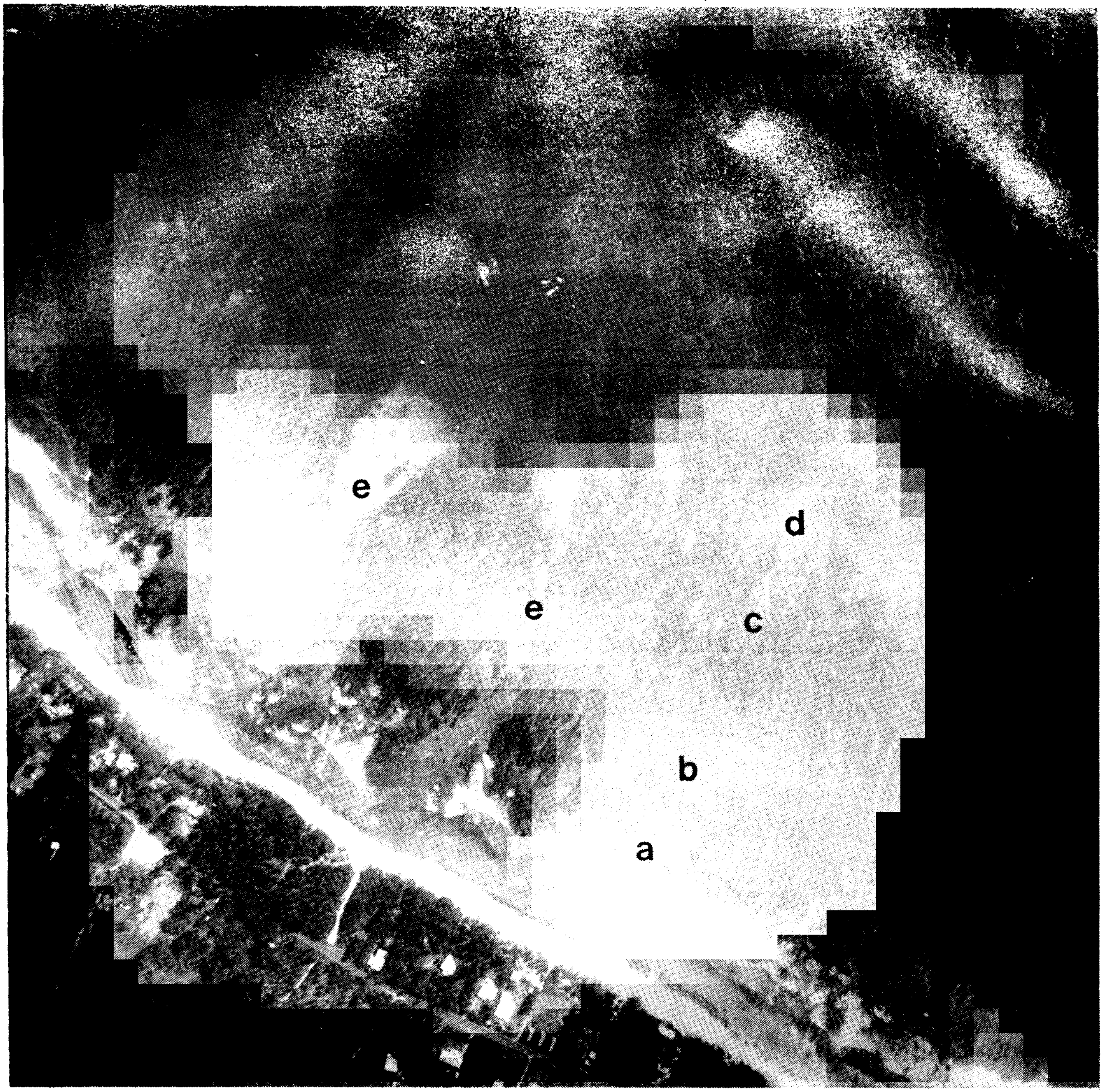

Fig. 7A. Aerial photo of reef-front terrace on northeastern side of island, off Tupapa Stream. Area approx. 500m x 500m.

a. grooves and surge channels in seaward face of algal rim
b. flat area at toe of algal rim
c. coral heads on inner reef-front terrace
d. sandy outer reef-front terrace
e. small sand-filled channels

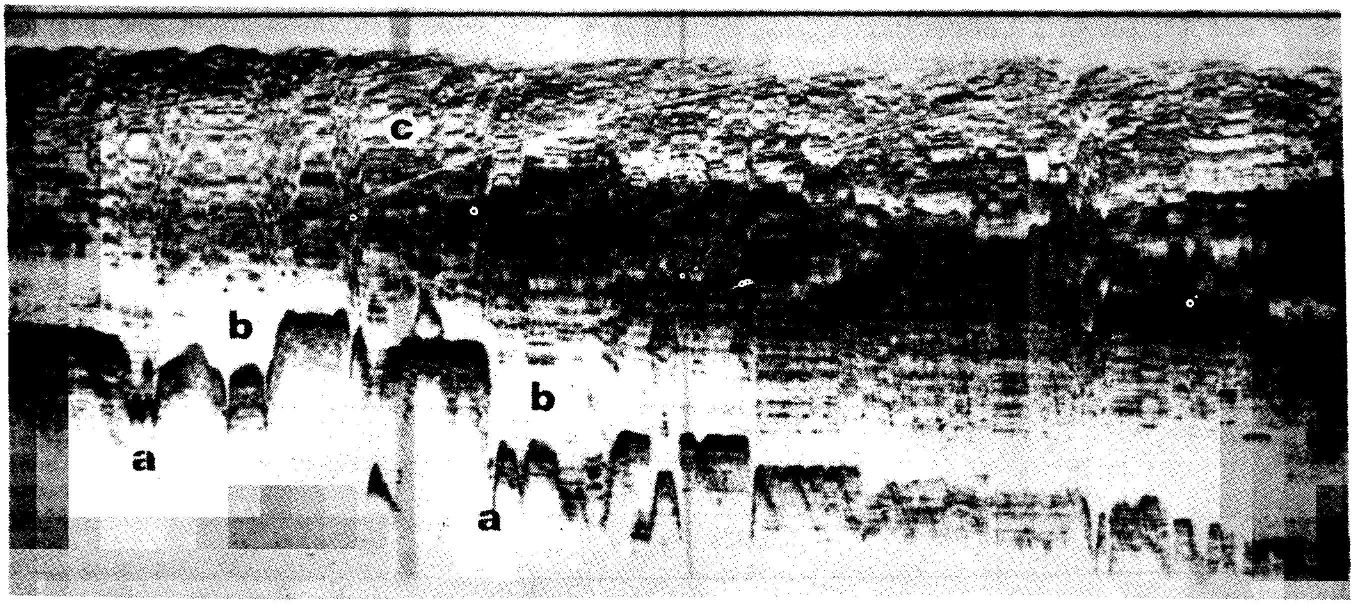

Fig. 7B. Side-scan sonograph of inner-reef-front terrace on northeastern side of island off Met. Office. Area approx. 150m x 350m.
a. grooves and surge channels on seaward face of algal rim
b. flat area at toe of algal rim
c. coral heads on inner reef-front terrace

Beyond this notch, the reef-front terrace slopes seaward at angles ranging from 2° to 7° out to a depth ranging from 17m to 20m. This is the "10 fathom terrace" observed around a number of Pacific Islands (Emery et al 1954; Newell 1956; Wiens 1962; Chevalier 1973; Stoddart 1975a). The terrace has a botryoidal appearance on sonographs indicating a closely spaced profusion of coral heads several metres high (Wong et al 1970). There also appears to be some general onshore-offshore lineation (as on the reef flat) which is immediately noticeable at alterations of course (Fig. 8). The higher coral heads appear to be aligned in some response to the approaching wave fronts: this alignment may help to dissipate energy gradually.

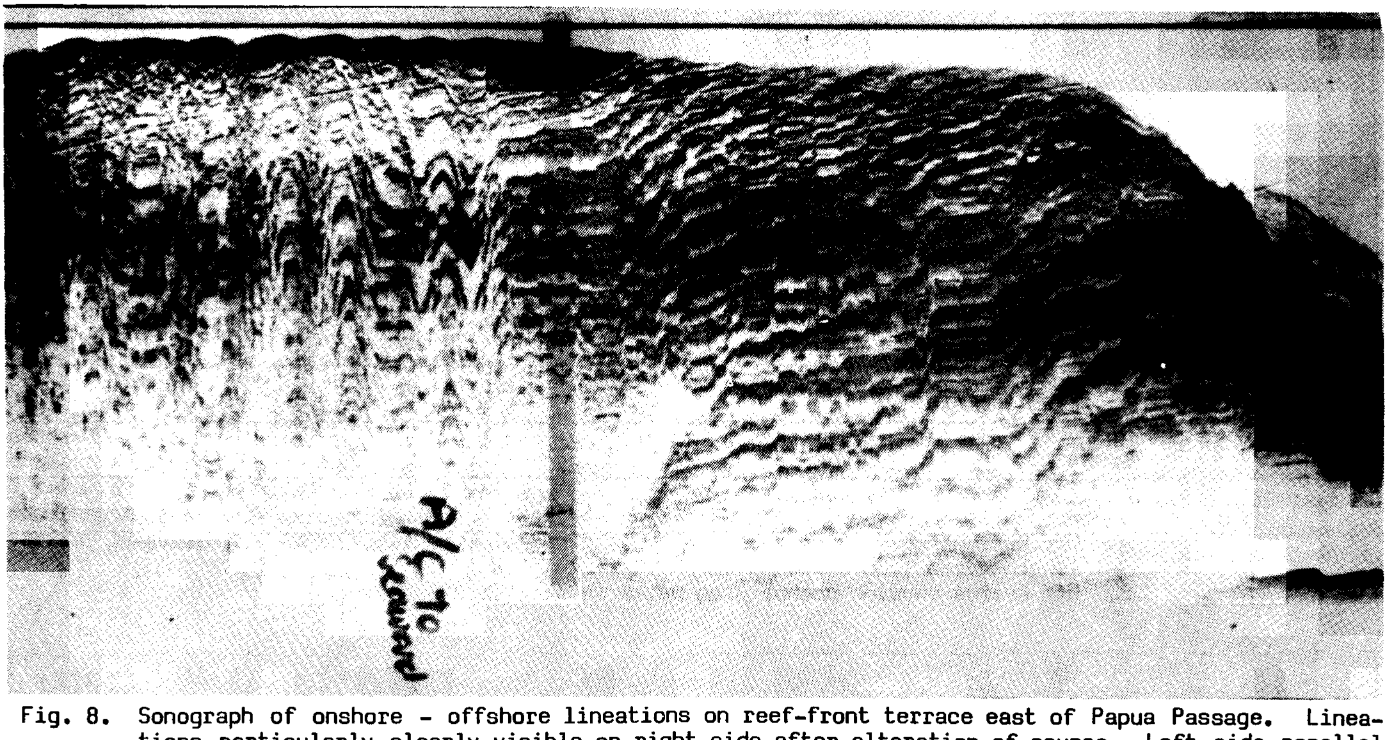

Fig. 8. Sonograph of onshore - offshore lineations on reef-front terrace east of Papua Passage. Lineations particularly clearly visible on right side after alteration of course. Left side parallel with reef, right side moving offshore. Range 150m.

At 17-22m there is an increase in slope to between 6° and 30°, out to a depth of 26-31m, where at some places there is a slightly flatter zone. Below about 30m the seafloor slopes at more (locally appreciably more) than 30° and there may be a further increase in slope recognizable at 45m.

This outer part of the reef-front terrace is distinguished on the sonographs by a gradually increasing proportion of sediment between coral heads (Fig. 9A). This sediment is locally formed into sand waves, 3m in wave length, parallel to the regional contours and at right-angles to the lineation of coral heads. Off Avarua, anchor drag marks are evident in the sediment and scattered coral (Fig. 9B).

Limited snorkel and diving observations suggest that the reef-front terrace is generally floored by dead, algae-covered coral with small patches of coral/algal sand between the dead coral heads. Only a few massive <u>Porites</u> heads were seen to be alive. The drab terrace and reef flat at Rarotonga is in marked contrast to the multicoloured living reefs of some other Pacific Islands where the reef-front terrace is the most prolific part of the system (Harry 1953).

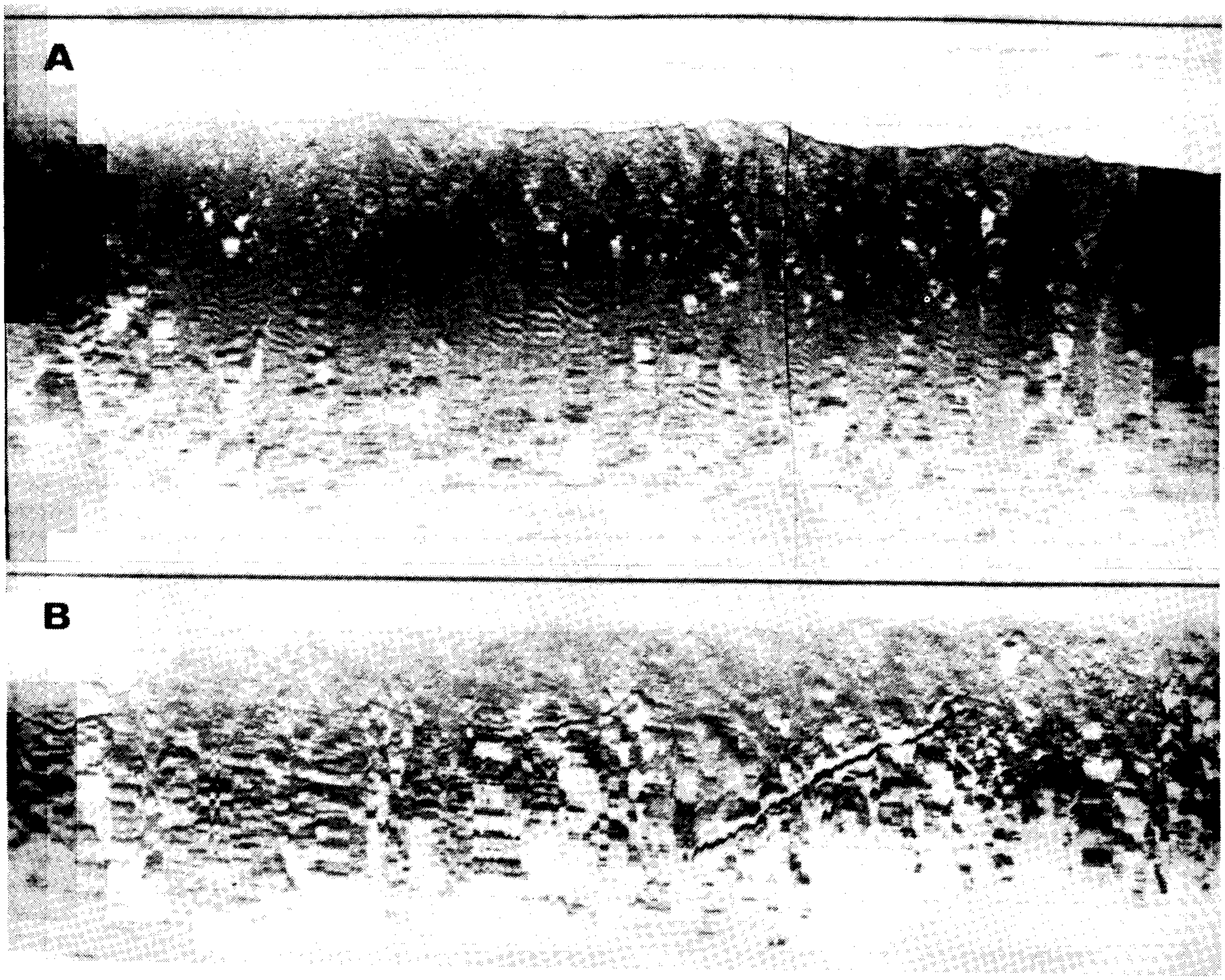

Fig. 9. Sonographs of outer reef terrace showing sediment between large coral masses.
A. Off Met. Office (Airport) showing sediment formed into waves 3m in wave length (area 150m x 300m).
B. Off Avarua showing anchor drag marks (area 150m x 300m).

The dearth of live coral occurs right around the island and is not, therefore, likely to be hurricane damage or local pollution. It may be due, in part at least, to a heavy infestation of the Crown-of-Thorns Starfish, Acanthaster planci that occurred in the late 1960's and early 1970's (Devaney and Randall 1973; Endean and Chesher 1973). None were noticed in 1978. Devaney and Randall (1973) reported that in 1971 there were patches of live coral at depths of about 12m on the southern terrace but elsewhere 50-90% of the coral was dead. They found 23, 26, 38 and 57 adult Acanthaster browsing on the, even then, sparce live coral on four of their 30 minute dives. These were the highest numbers found anywhere in their survey of the Southeastern Pacific Islands. The only other areas where they reported Acanthaster in "plague" proportions were Tahiti and near the main island of Aitutaki. In each case they considered there to be a positive correlation between dense Acanthaster populations and dense human habitation, or more specifically, with the extensive use of highly toxic, agricultural pesticides: in addition to their legitimate use, pesticides were reportedly used around Rarotonga to poison fish on the reef flat (Randall 1972). At Tahiti the plague was controlled by the painstaking collection and destruction of more than 10,000 individual starfish (Devaney and Randall 1973). In Micronesia, divers killed about 280,000 starfish by injecting them with formalin (Marsh and Tsuda 1973).

Some observers consider devastation by Acanthaster plagues are a natural part of reef building processes resulting in compaction of what would otherwise be a too open reef lattice (Vine 1970; 1973). The starfish feed only on the surface skin of live polyps, leaving the calcareous skeletons. Their predation would have no serious, long term effects on the structure of the reef, even dead reefs being generally resistant to erosion for many thousands of years.

However, there are cogent reasons for believing that Acanthaster population explosions are the result of unusual interference, generally human interference, with the delicate coral ecosystem (Endean 1976; 1978). At many, but not all, places, heavy infestations can be correlated with the destruction of the large fish and large molluscs that prey on young Acanthaster. These large species have either been collected for food and ornaments or, they have been selectively poisoned by concentration of toxic wastes at the end of the food chain. Zooplankton that feed on larval starfish may have been similarly poisoned (Randall 1972). The coral itself is surprisingly resistar to these wastes but succumbs indirectly.

A "herd" of Acanthaster migrating uncheck over a reef can destroy it in only a few years Then there is a switch from the spectacular coral dominated community to a drab algal-dominated com munity with, generally, a reduction in fish numbe and diversity and possibly, a reduction in touris potential. The regeneration of a living reef in evitably takes many decades even in the absence o further Acanthaster plagues (Endean 1976; 1978). I the meantime, the abundant growth of corallin algae that covers the dead coral may contribute more rapid supply of algal sand to the reef flat.

The Channels

Incised into the reef-front terrace are th same channels that begin off-stream mouths, cros the reef flats, and breach the algal rim at th recognised boat passages. They appear to be "ante cedent" remnants of low sea level stream valley and they now form ebb channels for the water an calcareous debris that pours over the reef.

Except at Avarua and Avatiu where they hav been extensively modified by harbour works, the have a somewhat similar pattern (D. Dorrell, pers comm.). At their head is a tongue of beach o nearshore sand that cascades as a tip face into th 30-60m wide, steep-sided channels (Fig. 5). At th toe of this face the channels are 4-10m deep an they deepen gradually until, just inside or level with the algal rim, they are 10-20m deep. There is commonly some shoaling just outside the algal rim and sand coming down the channel cascades into the segment of the channel that crosses the reef-front terraces.

It is evident from aerial photographs (Figs 5 and 6) and from sonographs collected on the survey that each of the channels bifurcate immediately outside the algal rim and then anastomose in a broad trough that continues right across the reef-front terrace and down the slope. It was noteworthy that heavy coral buttresses with deep grooves commonly grow either side of the passages (Figs 10 and 11).

The channel 100-130m outside Rutaki Passage was observed by diving. It was flat floored with near vertical side walls 10m high. The sediment on the floor was mainly rippled algal/coral sand similar to that on the beach and reef flat from which it was derived. Lines of rounded coral pebbles and boulders were aligned up and down the

Fig. 10. Oblique aerial photograph of Rutaki Passage showing similar features to Fig. 5 but also clear bifurcation of channel and heavy coral buttresses just outside algal rim. (Photo D. Dorrell).

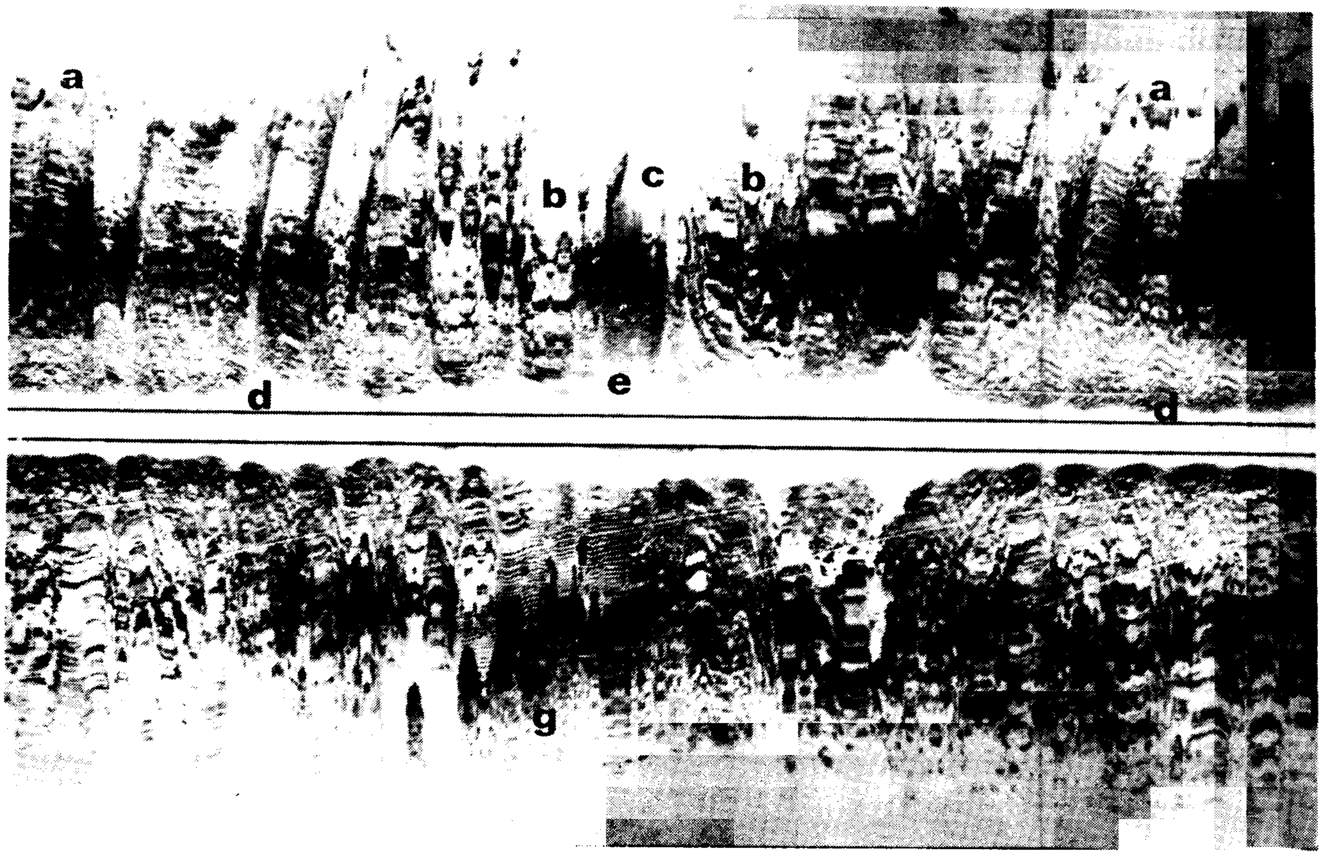

Fig. 11. Dual-scan sonograph of inner reef-front terrace outside Rutaki Passage showing -
(a) normal face of algal rim; (b) heavy buttresses on either side of passage;
(c) main channel; (d) reef-front terrace;
(e) flat sand floor of channel; (f) sand-waved floor of channel;
(g) coral-gravel covered floor of outer part of channel.
(Area 300m x 450m).

channel. It is evident from the sonographs (Fig. 11) that at mid-terrace depths about 150m outside the passage the channel becomes broader with sand formed into sand waves, 2.5m in wave length paralleling the coast. At outer terrace depths the channel is floored by coral gravel.

Avaavaroa Channel is apparently very similar to Rutaki Channel (Fig. 5).

Papua Channel is much smaller: it starts in the middle of the reef flat and ends on the middle of the reef-front terrace.

Ngatangiia Channel traps sediment moving in the harbour behind the 'motus'. The channel head 'tip' of sediment (presumably awaiting flushing during a storm) is evident on aerial photographs northeast of the mouth of the Avana Stream (Fig. 12). Outside the harbour, the gently troughed channel is strewn with coral heads for 150m offshore but beyond this a double, 20m deep channel system is floored with sand to the edge of the reef-front terrace (Fig. 13).

Outside the northern harbours, the Avarua and Avatiu Channels are much broader and shallower than

Fig. 12. Oblique aerial photo of Ngatangiia Harbour showing "tip" (light tone) of algal and coral sand into channel that begins near the mouth of the Avana Stream (top left) and descends towards harbour entrance, (bottom right).

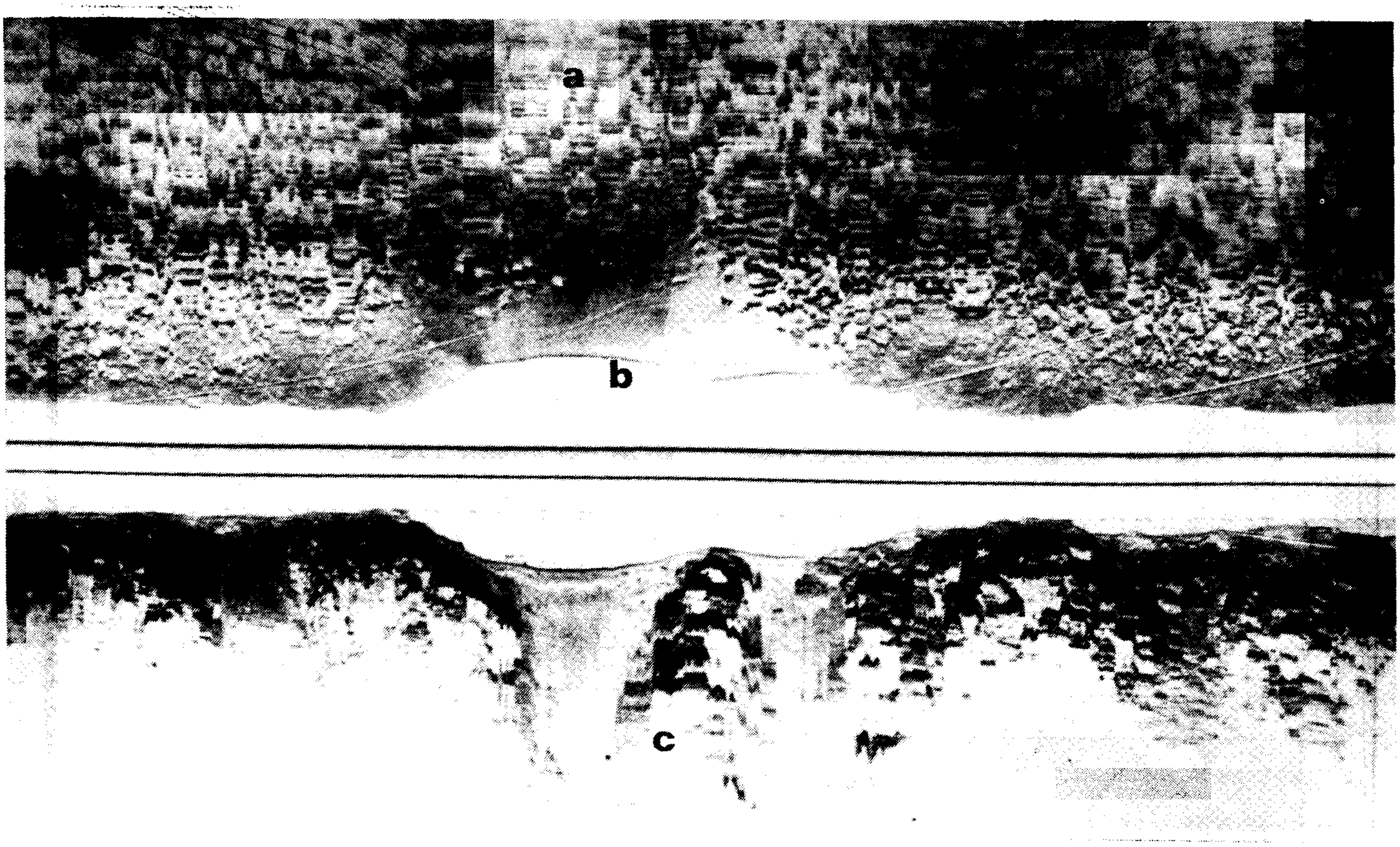

Fig. 13. Dual-scan sonograph of mid reef-front terrace off Ngatangiia Harbour showing -
(a) boulder floored inner channel;
(b) sand floored mid channel and
(c) bifurcated outer channel (area approx. 300m x 450m).

the channels along the south coast (Fig. 14). The Avarua Channel, in particular, broadens to a 50-200m wide, 5-15m deep sand and gravel-floored expanse that is barely deeper than the adjacent terrace (Figs 15 and 16). The more sandy sediment seems to bifurcate around a central gravelly area (Fig. 15). The sediment is formed into sand and gravel waves, 3m in wave lengths, and parallel to the coast (Fig. 16). Samples are limited but the sand fraction appears to contain more worn coral fragments and less friable algal plates than the sand from the south coast. The gravel also is different being composed predominantly of river worn volcanic pebbles rather than rounded coral.

The Avatiu Channel (Fig. 14) is somewhat narrower and deeper than the Avarua Channel but otherwise it contains most of the same features. Both channels continue as 60m deep troughs across the outer reef-front terrace although the sediment fill in these troughs becomes spasmodic.

The Coral Wall

From a depth ranging from 30m to 100m, down to a depth ranging from 350m to 500m, the signal recorded on the echo soundings is "fuzzy" and appears to represent a slope of 40° or more (Fig. 2). This slope of 40° is recorded on a bathymetric chart (Utanga and Lewis, in press) although it is realised that upper parts of the slope may be much steeper, sound being reflected from the top edge of a precipitous drop as the launch moved away from it.

Off Titikaveka, on the south coast, the steep slope appeared to begin at a depth of about 30m and it was explored by diving. The apparent slope of 40-45° did, in fact, slope at 75-80°. It was a precipitous coral wall down which sand and gravel appeared to be cascading in narrow "waterfalls", becoming lodged temporarily on ledges. Some larger fragments appeared to have knocked lumps off the "honey-combed" walls as they bounced down the cliff.

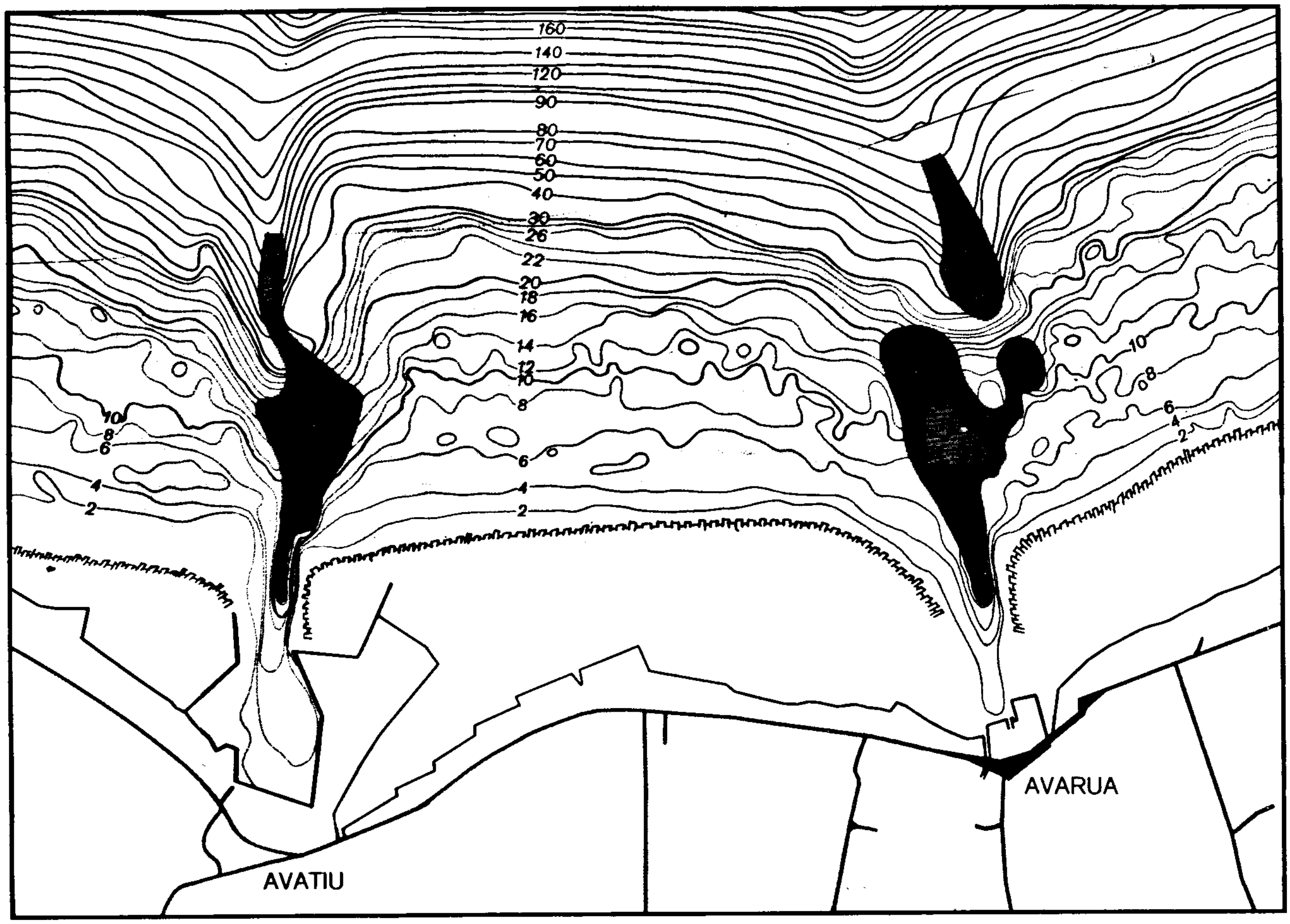

Fig. 14. Bathymetric chart of Avarua - Avatiu showing area of sand and gravel deposits (stippled). Data from N.Z. Hydrographic Office, sonographs and sediment samples.

This slope is far too steep to be an original volcanic feature and it clearly represents the classical Darwinian upbuilding of a coral reef associated with subsidence of the volcanic cone. At Rarotonga, the cone appears to have subsided about 400m since the reef first began to grow. As it grew, a progressively wider coastal platform of reef and coastal flat has formed.

The Talus Slope

Below about 400m the record is again a smooth firm line, and the seafloor slopes fairly consistently at 20-22° decreasing gradually to 16-18° between 600m and 800m deep (Fig. 2).

At many places around the island there are irregular traces, obviously from rocky outcrops, at depths below 500m. The most conspicuous jagged topography is off Titikaveka where there is a series of pinnacles at depths of around 600m (Utanga and Lewis, in press).

Tangle nets trawled across this slope in 1977 (J.V. Eade, pers. comm.) collected boulders of reef coral.

Below 400m the seafloor is generally a talus or apron of reef debris covering the lower slopes of the volcano. Thus the ultimate fate of all Rarotonga's sediment is to smooth the volcanic topography of the lower slope.

SAND AND GRAVEL FOR CONSTRUCTIONAL PURPOSES

Beaches

Coral sand and gravel was originally burned and slaked for construction purposes but since World War II it has been successfully used as a mix or aggregate for concrete (Howdyshell 1974).

The most readily accessible sediment for constructional purposes is that on and immediately behind the beach. Minor amounts may continue to be taken for concrete aggregate but at many places beach sediments are not particularly suitable because of the high proportion of highly porous algal debris. At Muri the beach sand is finer, better sorted and less porous than elsewhere, but unless

Fig. 15. Oblique aerial photograph of Avarua Harbour showing tongue of sand with central gravelly area in channel on reef-front terrace. Note also heavy buttressing around passage.

Fig. 16. Sonograph Mosaic of Avarua Channel showing -
(a) normal face of algal rim
(b) buttressing around passage
(c) entrance to Avarua Harbour
(d) sand and gravel filled channel with sand-waves of 3-4m wavelength
(e) sediment filled channel on outer reef-front terrace (area approx. 450m x 600m).

it can be shown that the replenishment rate is particularly rapid, then the sand there is likely to be of more value as a recreational and tourist attraction than as concrete. At all places, removal of beach sediment for large scale construction or landfill is likely to remain environmentally unacceptable unless it can be shown that mining will not cause danger during hurricanes and will not affect any of Rarotonga's recreational beaches.

Reef Flat

In general sediment on the reef flat is fresher, less recrystallised and more porous than sediment on and behind the beaches. It is thus of a lesser value as a constructional material. It may also be the source for, and in equilibrium with, the sediment on the beaches.

At some places tongues of beach and reef flat sediment near the heads of some channels e.g. Rutaki, Avaavaroa and Ngatangiia (Figs. 5, 10 and 12) might be removed without serious ecological damage.

Channel-fill Sediments

Channel-fill sediments have already been lost to the environmentally sensitive beach/reef flat system. They have generally been longer in the system and are less porous than most reef flat sediments. Given the demand and the technology (CCOP/SOPAC 1978) they could probably be considered further for constructional purposes.

Accumulation in the reef flat sections of some of the southern passages are probably the most accessible but they are relatively small deposits and tend to include a high proportion of highly porous algal fragments that makes them unsuitable for most constructional purposes.

On the basis of only a very few samples it appears that extensive sand and gravel deposits in the channel off Avarua (and to a lesser extent Avatiu) may be the most suitable for many constructional and landfill purposes. The sand fraction contains more smashed and worn coral and less porous algae than elsewhere. The gravel fraction is predominantly rounded basaltic pebbles. There is little or no volcanic glass which can cause problems in concrete. The sediment's low friability and porosity suggest that it may be of more value in concrete manufacture than most other available materials (J.D. de Boch, Concrete Research Assoc., Porirua, N.Z. pers. comm.).

Although outside the algal rim the northern channel deposits are relatively shallow (5-15m), relatively wide (50-200m), close to the main settlements, and environmentally safe. Dredging here may also aid access to the harbours. However, it must be stressed that more extensive sampling is required to prove the overall composition of these deposits and their suitability for concrete manufacture.

PRECIOUS CORAL

Imported black and precious coral are used for the manufacture of jewellery in Rarotonga.

The bathymetric survey indicated several suitable habitats for black coral - i.e. 'steep drop-offs at depths between 40 and 70m'. What appeared to be the best of these, off Titikaveka, was investigated by diving. Below the 'shelf edge' at 30m there was a precipitous wall sloping at 75-80°. Visibility was good. At a depth of 45m the launch was clearly visible on the surface and visability was estimated to be 70m along the walls in each direction and a further 35m downwards. There was no sign of black coral. D. Dorrell (pers. comm.) reported that despite having dived on several occasions to appropriate depths he had never seen black coral around Rarotonga.

The bathymetric survey did not highlight any particularly suitable environments for precious pink coral, which prefers rocky outcrops and strong currents at depths of 350 to 574m (Grigg 1976). At most places at the appropriate depth, the seafloor appeared to be a smooth debris slope with no channels, saddles or rocky seamounts which might exaggerate deep currents. A year earlier, tangle nets used for snagging precious coral were tested off the southeast corner of the island. They produced only rounded boulders of coral reef limestone similar to those on the beaches. This suggests a scree slope of coral debris unsuitable for the growth of precious coral.

CONCLUSIONS

1. Rarotonga is surrounded by a fringing reef that has been built up while the Pliocene volcanic cone of the island has subsided about 400m.

2. There is a narrow "10 fathom" reef-front terrace right around the island; the terrace and reef flat are intersected by channels off six of the largest streams.

3. Both terrace and reef flat have a drab, algae-dominated ecosystem, which may be partly the result of a "plague" of crown-of-thorns star-fish having destroyed coral in the late 1960's and early 1970's. The change may result in a greater supply of friable algal sediment to the reef flat.

4. No black coral was found on dives to suitable habitats. No suitable habitats for deep water, precious (pink) coral are present around Rarotonga.

5. Sand and gravel suitable for constructional purposes may occur in the reef-front channel off Avarua but further sampling to discover the variability and construction properties of the deposit are required. Other reef-front deposits are more friable and much deeper. Being outside the reef, channel deposits are not environmentally sensitive.

REFERENCES

BRITISH ADMIRALTY, 1976: Islands and Anchorages in the Cook Islands (3rd Edition): B.A. 1264.

CCOP/SOPAC 1977: "Proceedings of the Fifth Session, Rarotonga, Cook Islands, 2-8 November 1976 including Report of the Fifth Session of its Technical Advisory Group", Tech. Sec., CCOP/SOPAC, MRD., Suva: 31 pp.

CCOP/SOPAC 1978: "Proceedings of the Sixth Session, Port Moresby, Papua New Guinea, 11-17 October 1977 including Report of the Sixth Session of its Technical Advisory Group and Technical Documentation", Tech. Sec., CCOP/SOPAC, MRD., Suva: 64 pp.

CHEVALIER, J.P. 1973: Geomorphology and geology of coral reefs in French Polynesia. In Jones, O.A. & Endean, R. (eds): "Biology and Geology of Coral Reefs Vol. 1 Geology 1": 113-141.

DEVANEY, D.M.; RANDALL, J.E. 1973: Investigations of Acanthaster planci in southeastern Polynesia during 1970-1971. Atoll Res. Bull. 169: 1-23.

EMERY, K.O.; TRACEY, J.I.; Jr.; LADD, H.S. 1954: Geology of Bikini and nearby atolls. U.S. geol. Surv. Prof. Pap. 260-A: 1-265.

ENDEAN, R. 1976: Destruction and Recovery of coral reef communities. In Jones, O.A. & Endean, R. (eds): "Biology and Geology of Coral Reefs Vol. 3 Biology 2": 215-254.

ENDEAN, R. 1978: Pollution of Coral Reefs. In FAO. "Lectures presented at the Fifth FAO/SIDA Workshop on aquatic pollution in relation to protection of living resources, Manila 1977", FAO, Rome.

ENDEAN, R.; CHESHER, R.H. 1973: Temporal and spatial distribution of Acanthaster planci population explosions in the Indo-West Pacific Region. Biol. Conserv. Vol. 5: 87-95.

GRIGG, R.W. 1976: Fishery Management of Precious and Stony Corals in Hawaii. Hawaii Inst. Mar. Biol. Seagrant-Tech. Rep., 77-03: 48 pp.

HARRY, R.R. 1953: Ichthyological field data of Raroia Atoll, Taumoto Archipelago. Atoll Res. Bull. 18: 1-190.

HOWDYSHELL, P.A. 1974: The use of coral as an aggregate for Portland Cement Concrete structures Construct. Eng. Res. Lab. Tech. Rep. M-88: 43 pp.

LADD, H.A. 1977: Types of coral reef and their distribution. In Jones, O.A. & Endean, R. (eds): "Biology and Geology of Coral Reefs Vol. 4 Geology 2": 1-19.

MARSH, J.A.; TSUDA, R.T. 1973: Population levels of Acanthaster planci in the Mariana and Caroline Islands 1969-1972. Atoll Res. Bull. 170: 1-16.

NEWELL, N.D. 1956: Geological reconnaissance of Raroia (Kon Tiki) Atoll, Taumoto Archipelago. Bull. Am. Mus. nat. Hist. 109: 311-372.

NEW ZEALAND METEOROLOGICAL OFFICE 1943: "The Climate of Rarotonga". NZMO Serv. C No. 5: 8 pp.

NEW ZEALAND METEOROLOGICAL SERVICE 1955: "Cook Islands and Niue". Meteorol Notes 3-B (Wellington).

RANDALL 1972: Chemical pollution in the sea and the Crown-of-Thorns Starfish. Biotropica 4: 132-144.

SCHOFIELD, J.C. 1970: Notes on Late Quaternary sea levels, Fiji and Rarotonga. N.Z. Jl Geol. Geophys. 14: 240-241.

STODDART, D.R. 1972: Reef Islands of Rarotonga (with list of vascular flora by F.R. Fosberg). Atoll Res. Bull. 160: 1-7.

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

STODDART, D.R. 1975b: Reef Islands of Aitutaki. Atoll Res. Bull. 190: 59-72.

SUMMERHAYES, C.P. 1967: Bathymetry and topographic lineation in the Cook Islands. N.Z. Jl Geol. Geophys. 10: 1382-1399.

SUMMERHAYES, C.P.; KIBBLEWHITE, A.C. 1967: Rarotonga provisional bathymetry N.Z. Oceanogr. Inst. Chart, Island Series 1 : 200,000.

SURVEY DEPT. RAROTONGA 1966: Rarotonga Mosaic Map 1 : 15,840 Surv. Dept., Rarotonga, Cook Is.

TARLING, D.G. 1967: Some paleomagnetic results from Rarotonga, Cook Islands. N.Z. Jl Geol. Geophys. 10: 1400-1406.

THOM, B. 1973: The dilemma of high interstadial sea levels during the last glaciation. Progr. Geog 5: 167-231.

UTANGA, A.T.; LEWIS, K.B.: In press. Rarotonga Nearshore Bathymetry: 1 : 20,000 CCOP/SOPAC Chart/ N.Z. Oceanogr. Inst., Misc. Series Chart.

VEEH, H.H. 1966: Th 230/ U 238 and U 234/ U 238 ages of Pleistocene high sea level stands. J. geophys. Res. 71: 3379-3386.

VINE, P.J. 1970: Field and Laboratory Observations of the Crown-of-Thorns Starfish, Acanthaster planci. Nature 228: 341-342.

VINE, P.J. 1973: Crown-of-Thorns (Acanthaster planci) plagues: The natural causes theory. Atoll Res. Bull. 166: 1-10.

WIENS, H.J. 1962: Atoll environment and ecology, Yale Univ. Press, New Haven & Lond.: 532 pp.

WONG, H.K.; CHESTERMAN, W.D.; BROMHALL, J.D. 1970: Comparative side-scan sonar and photographic survey of a coral bank. Int. hydrogr. Rev. 47: 11-23.

WOOD, B.L. 1967: Geology of the Cook Islands. N.Z. Jl Geol. Geophys. 10: 1429-1445.

WOOD, B.L.; HAY, R.F. 1970: Geology of the Cook Islands. Bull. N.Z. geol. Surv., n.s. 82: 103 pp.

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