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Reefs and Sedimentary Processes of Raroia

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ILLUSTRATIONS

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INTRODUCTION

Reef types of Raroia are about as diverse as those of other atolls. An outer, or sea reef (akau), is essentially continuous around the margin of the atoll, and it is somewhat different on the windward and leeward sides. Extensive slump sectors such as those of Bikini (Emery, Tracey, and Ladd, 1949) were not recognized.

There are indications that the rate of erosion of the reef front may actually exceed the accretion of organic material. The equilibrium among subsidence, reef growth, and erosion apparently has been disturbed recently by a rate change in one or more of the controlling variables. Crossland (1928, 1931, 1935) has concluded that growth of the reefs of nearby Tahiti and Moorea is not keeping pace with erosion. He tentatively suggests that the recent epoch of reef formation is drawing to a close as a result of world-wide decrease in vigor of the reef corals. The evidence as presented hardly justifies such a sweeping conclusion, and the implication of racial senescence does not have a place in modern evolutionary theory. Stearns (1945) has made the interesting suggestion that "decadency" in modern reefs is related in some way to recent negative shifts of the sea. That is, a drop in sea level would destroy the organisms of reef flats previously just awash near sea level and might thus lead to wave destruction of the exposed and shallowest parts of the reef. Such a reef might display extensive dead areas in the upper part. If, however, a reef in equilibrium to existing tide conditions were uplifted only a few centimeters, many organisms would quickly be eliminated because of exposure even though still regularly covered at high tide. Slight uplift may be responsible for observed conditions on Raroia.

Ranson (1952) makes the pertinent observation that the Marquesas Islands, which are almost lacking in reefs, and the Tuamotu atolls, although situated at low latitudes, are marginal with respect to suitable temperatures. The southern equatorial current, which bathes these islands, was quite cold as a result of up-welling at the South American continent where the Humboldt current swings westward across the eastern Pacific. The point is that these waters continually store solar energy during the westerly drift. Although the surface waters are warm at the longitude of the Marquesas and Tuamotu, the thermocline is doubtless much shallower here than at points farther west. Great storms may bring very cold waters to the surface with deleterious effects on reef corals. This promising idea requires study. It must be stressed, however, that reports of the feebleness of reef growth in the Tuamotu are exaggerated.

In the Raroia lagoon a discontinuous, generally narrow, shore reef lies along the northwest shore, where the prevailing sediment is gravel. This reef is exposed to the fetch of the prevailing winds, hence is the windward shore reef, even though it lies at the downwind shore of the lagoon. The sheltered, or lee shore, along the southeast side of the lagoon lacks a well defined reef, but small patches composed mainly of massive heads of Porites are common. The sediment here is mainly fine foraminiferal sand. An estimated 1500 to 2000 patch reefs[1] rise from all depths of the lagoon to the surface. The largest of these are termed karena in the Tuamotu language. Doubtless they are an important source of sediments in the lagoon. Coralla and rounded and irregular knolls are visible from the air over shallow bottoms, and results of dredging indicate that living corals are scattered over the deeper part of the lagoon but they generally do not rise far above the bottom.

Field identifications of the algae and mollusks cited in the following pages were made by M. S. Doty and J. P. E. Morrison, respectively. Names of corals were supplied by John W. Wells after examination of the collections obtained by the field party.

THE OUTER REEF

The sea reef (akau in Tuamotuan) is the peripheral reef zone outside the land areas and channels. It forms the outer part of the atoll rim. Since the reef is continuous around the atoll, it is hardly appropriate to refer to windward reefs and leeward reefs as though they were separate reefs. Wherever islands are lacking and the reef flat extends across the atoll rim, as at the southern end of Raroia, the inner boundary of the sea reef is not clearly delimited.

Reef front.-In some reef areas, perhaps in many, the most luxurient growth of corals is not on the reef flat or margin but lies on the reef front well below wave base of ordinary storms. This outer zone commonly is not conveniently accessible for direct observation because of the strong ocean swell. Nevertheless, as at Raroia, the bottom may be examined from a small boat by means of a water glass. This zone of maximum productivity of the corals is usually overlooked, or it is dismissed with a few words.[2]

It may be fairly argued that this rather than the algal ridge or the "spur and groove" zone is the front of the living parts of the sea reef. Almost certainly it is the chief producer of sediment at Raroia. The lower part of the reef front is an uneven, rather steeply shelving surface relatively free from loose sediment. It extends downward from approximately eight meters at the edge of the spur and groove escarpment to beyond the limit of vision at 34 meters. A terrace at approximately 20 meters (10 fathoms) comparable to

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1/ Patch reefs are flat above and reach the surface. I am reserving the term reef knoll, or knoll reef, for the rounded or irregular pinnacles that do not reach the surface. Many writers use "knoll reef" for all small, circumscribed lagoon reefs. On Raroia practically all of the visible small lagoon reefs are patch reefs.

2/ This outer zone has been recognized on the Great Barrier Reef, Andros Island, Bahamas, and elsewhere.

that at Bikini (Tracey, Ladd, and Hoffmeister, 1948) and the Bahamas (Newell, Rigby, Whiteman and Bradley, 1951) is visible on aerial photographs of Raroia. Our handline soundings in the agitated outer waters are not, however, very reliable.

The visible bottom in front of the reef spurs is blanketed by robust living corals, some of which are unlike those elsewhere on the atoll. Of the species apparently limited to this zone most conspicuous is a great flabellate _Acropora_ (_A. conigera_) which locally covers as much as 25 per cent of the bottom. This coral forms irregular horizontal plates up to two meters across and one-third of a meter thick. They are attached by a short thick trunk at the center of the lower surface or directly at one margin. The species supplies most of the coral slabs scattered over the reef flat and at least 30 per cent of the slabs of the island conglomerate. Another species, unrecognized elsewhere, is a robust staghorn, a _Pocillopora_, which rises more than one meter above the bottom as bushy clumps with stout stalks seven or eight centimeters in diameter. This form is richly represented in the island rubble, of which it comprises an estimated 10 per cent of the smaller fragments.

Great heads[1/] up to two meters in diameter of a massive _Porites_ are common as is a robust species of _Fungia_. Several of the coral species of the reef flat also occur on the outer slope, especially corymbose species of _Acropora_ and several species of _Pocillopora_ besides the staghorn referred to above. The abundance of material in the island rubble derived from the reef front indicates that an estimated one-half to three-fourths of the island debris was derived from this zone during hurricanes.

Groove and spur system.--Raroia atoll is surrounded by a conspicuous, groove and spur zone some 50 to 100 meters wide at the top of the reef front. The outer edge of this zone forms a low escarpment at a depth of about eight meters. Landward the crests of the spurs form a terrace surface which rises rapidly to about the extreme low water level at the algal ridge. The terrace is traversed by rather regularly spaced vertical walled gorges or grooves (_koehae_) which extend seaward at right angles to the margin of the atoll. Generally these grooves terminate at the algal ridge, but a few cut across the ridge and extend across the reef flat as "surge channels." The groove and spur zone is very like the "seaward slope" of Bikini, which has been interpreted as the advancing margin of the reef, composed mainly of algal deposits (Ladd, Tracey, Wells and Emery, 1950, p. 412). Many reef features of Raroia clearly combine both erosional and depositional processes, and it is probable that this is also true of reefs in general.

The outer grooves of the sea reef were investigated in several places at the surface and by means of a swimming mask and the Browne diving mask. Characteristically the deeper gorges descend precipitously from the head at the algal ridge to a depth of six or seven meters; then flattening gradually to a depth of about 10 to 15 meters they debouche on the lower slope of the reef front beyond the spurs. The grooved terrace is rather uniformly dissected, the

1/ A coral "head" as used here is a hemispherical corallum, not a knoll or patch.

deepest grooves of which terminate beyond the terrace; but many of the shallower grooves do not extend completely across the terrace but instead terminate on the terrace surface.

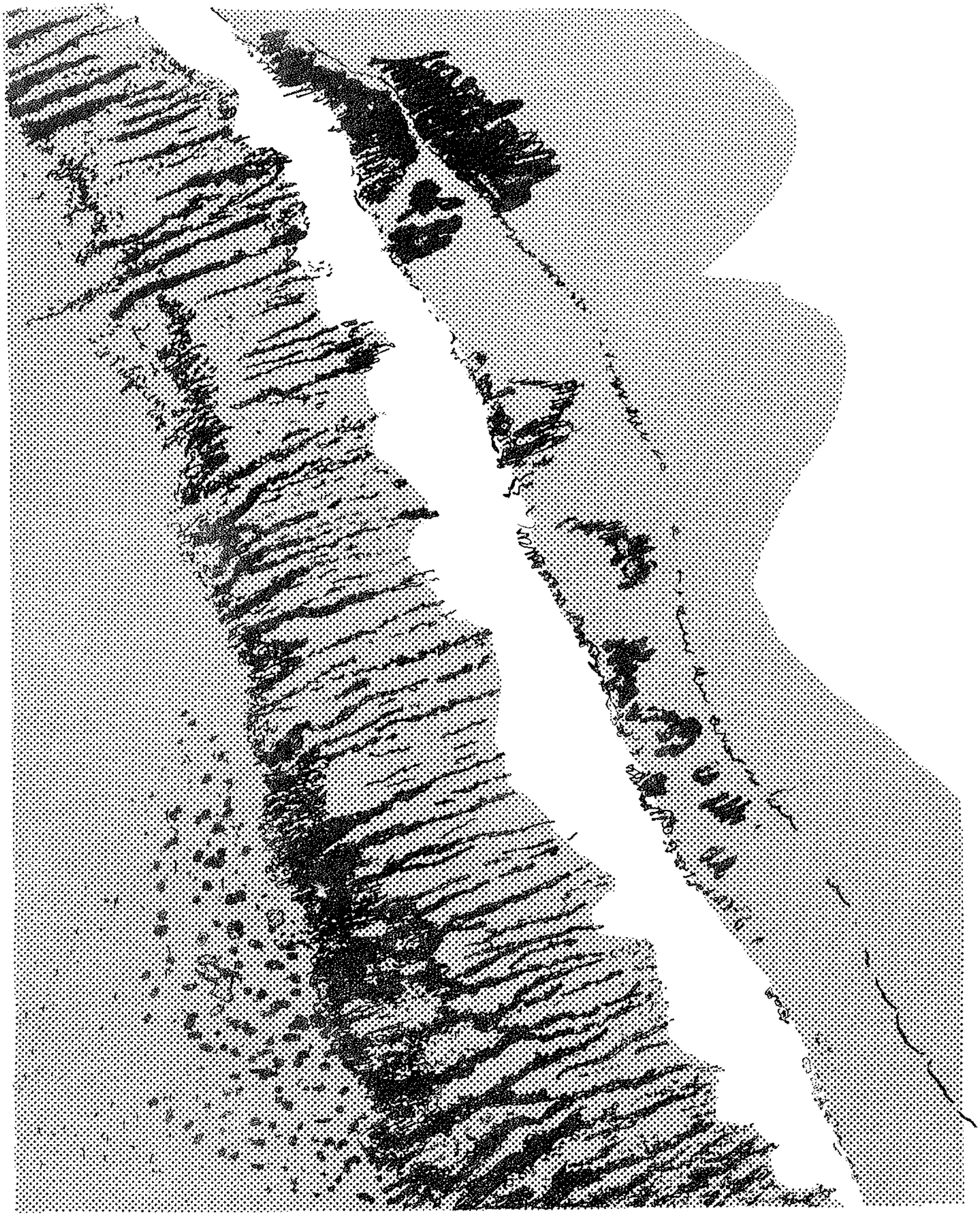
The walls and floor of the grooves generally are smooth and free from all but scattered very young colonies of corals. The rock surface is pitted, rounded, and scoured smooth, and the floor is uneven and ungraded except near the mouth where there usually is an accumulation of boulders and gravel. Here and there on the floor of the grooves are hemispherical shallow potholes of varying size more or less filled with rounded pebbles and cobbles. In some instances the potholes attain diameters up to about two meters and are occupied by boulders of worn Porites that could have been derived only from the outer slope. A few of the gorges are quite narrow, only one meter wide where they are as much as seven meters deep. For the most part they are deeper than wide at places of maximum relief but a few are as wide as they are deep near the mouth. Many of the grooves divide near the head, producing a rough dendritic pattern of tributaries. Rather capacious rooms often are formed at the confluence of these tributaries. Others show effects of a kind of "stream piracy" where they divide seaward in distributaries. Much about these grooves recalls mountain gorges of high gradient cut in massive rocks.

Pothole formation by gravel and scour by sand clearly is the chief agency of erosion along the floors of these grooves. Gravel, which is trapped temporarily in depressions, cuts pits in linear series down the slope. These eventually form more or less straight furrows. The grooves are gradually extended headward by gravel scour, in many places reaching well onto the reef flat as very shallow, more or less bare, furrows, embryonic surge channels.

Part of the gravel responsible for scour in these grooves clearly is derived from the outer slope and this is the only possible source of the largest coralla. The remainder probably originates on the reef flat.

The grooves of the windward outer reef are somewhat narrower and more closely spaced than those of the leeward side. Otherwise they are about the same.

The ridges or spurs (tauta) between grooves form the general surface of the terrace. In many places the spurs are about as wide as the grooves, and with the latter form a comb-like pattern. In other places there are sectors of the terrace as much as 50 meters long that are undissected or incompletely dissected by grooves as the reef sector on Bikini illustrated by Ladd, Tracey, Wells, and Emery (1950, Pl. 3A). In these places grooves have not been formed. Where dissection is incomplete not all the grooves extend to the outer edge of the terrace (Fig. 1). This and the fact that the terrace has a very regular outer margin suggests that the form of both spurs and grooves are effects of erosion rather than construction. There is very little roofing of the grooves by algal deposits. The spurs are quite unequal in breadth. If they were simply buttresses of algal deposits being extended seaward against the surf, they would probably advance at unequal rates and this should produce a jagged, irregular margin.



Bikini Reef

1. Spur and groove zone of a Bikini reef. Reef front at lower left. (From a photograph published by Ladd, et al., 1950)

The tops of the spurs form a flat surface which slopes gently seaward. It is covered by a thin blanket consisting mainly of living brown Pocillopora elegans (25 per cent), and Porolithon onkodes (identified by Doty), which is most prevalent at the inner margin (50 per cent), decreasing rapidly seaward toward the outer ends of the spurs. Other abundant forms of the terrace are a green alga Microdictyon sp. and the gastropod Vermetus maximus. The boring echinoid Echinometra mathaei and a tufted coralline alga Amphiroa sp. are abundant in the shallowest water of the terrace. In addition to the ubiquitous small Pocillopora cited above, two or three species of small Acropora and small massive forms of Plesiastraea and encrusting Millepora and Montipora are visible. All of these forms are securely attached and do not project above the bottom more than 10 to 15 centimeters. This is an association of strongly turbulent shallow waters. It is evidently from this zone that most of the large reef blocks of the reef flat are derived.

The species of Porolithon and Pocillopora together form a rim which in places overhangs half a meter into the gorges and extends a few centimeters down the gravel scoured rock surface. However, under conditions now existing on Raroia these organisms are not significantly modifying the topography of the reef margin.

In summary, there is a well-defined shallow outer terrace which slopes gently seaward. This probably lies at about the wave base of heavy surf but above wave base of the greatest hurricanes. These inferences are drawn from the fact that all of the corals of the terrace are low and small, indicating that they are more or less constantly subjected to strong turbulence and are doubtless frequently decimated. On the other hand the slope in front of the escarpment formed by the spur ends carries large, in some cases, fragile corals which must be many years old. These evidently escape the violence of seasonal storms but during hurricanes they are stripped away to supply much of the island debris. The lower surfaces of the walls and the floors of the grooves generally are scoured free from algal deposits and corals. All of the corals of the rims of the grooves are small; a colony 20 centimeters across is exceptionally large. From this it must be concluded that these surfaces are rather frequently scoured clean by storm turbulence and that few planulae have an opportunity to form colonies.

The surface of the grooves, as those of the reef flat and tidal pools, is colored light pink by a film of Porolithon onkodes the "pavement Lithothamnion". This pigmentation evidently appears within a few days on fresh surfaces and does not require deposition of a heavy accumulation of calcium carbonate. Chips freshly broken from the walls and bottom of grooves and from the reef flat show that the rock is of heterogeneous origin, containing coral skeletons and foraminiferal sand. The algal deposits are quantitatively not significant although they may perform the function of cementation.

It is probable that the grooves are cut into the terrace and that both were formed more or less concurrently. However, it is clear that gravel scour so potent in the grooves does not affect the terrace, the surface of which is relatively free from loose material. As shown by recent work in the Bahamas (Newell, Rigby, Whiteman, and Bradley, 1951) grooves and spurs like those of Raroia may be formed in inorganic limestone free from the supposed influence of coralline algae, and Cloud (1952, p. 43) reports similar erosional forms in Hawaiian basalt. There is no indication that the spurs on Raroia are being extended seaward. On the contrary, abundance of reef blocks[1], fragments of s spurs thrown up by storms, clearly indicates net erosion (Fig. 2).

The algal ridge.[2] There is a well developed, narrow ridge at the outer margin of the reef flat which separates the reef flat from the grooved terrace (see Figs. 6,7).[3] The ridge commonly is from five to 15 meters wide and rises some 0.3 to 0.6 of a meter above the lowest part of the reef flat. The ridge crest rises at least one meter above the adjacent ends of spurs. In a few leeward sectors the reef flat rises gradually toward a steep seaward margin, terminating in a sort of cuesta that faces the sea. Elsewhere the ridge is more narrowly defined. At irregular intervals along the ridge a few grooves cut across the ridge at low places on the reef flat. At intermediate stages in the tidal cycle waves break over the ridge, building a head of water on the reef flat. Much of this water returns seaward in excurrent streams which issue at the gaps in the ridge. At low water stage the water of the reef flat, which in the daytime may be several degrees warmer than normal sea water and depleted of much of the dissolved oxygen, invariably drains seaward at the excurrent points. Because of less favorable living conditions in these areas the surface commonly is relatively bare of attached organisms.

In a sense the algal ridge is intertidal, but it may rise locally above mean high tide level. It is constantly bathed by breaking waves wherever exposed to the wind, but it is occasionally dry on the lee side of the atoll in quiet weather during low tides. It is difficult to determine the tidal range along a sea reef. For one thing the influence of the wind is considerably more significant in controlling the water level than are the tides. In any case the tidal fluctuation is small at Raroia, about 0.6 meter in the lagoon. The strong ocean swell, even on a windless day produces translation waves with amplitude of two meters and more along the south and southeast sides of the atoll, and perhaps half as high on the leeward or northwest side of the atoll. At low water stage with a moderately rough sea a sheet of water pours over the ridge with each breaker though the mean level of the sea has dropped well below that of the reef flat. The head produced on the reef flat in this way carries much of the water and suspended sediment to the lagoon except where blocked by islets. Opposite the latter the water returns to the sea in many well-defined excurrent streams. It is tempting to speculate on the circulation of reef flat water in the breaker zone during high water. The circulation may be somewhat like that at low tide, excurrent water passing seaward at the gaps in the algal ridge. It is probable that each groove in the terrace functions as an excurrent channel during times of great turbulence. Water laden with outgoing sediment tends to be channelled by the grooves. Circumstantial evidence that this is the case is described in subsequent pages.

1/ In spite of a natural repugnance for the inelegant term "nigger-head" or "negrohead" almost universally employed by students for these reef blocks, I would follow accustomed usage if there were justification on grounds of special aptness. There is none. Let us call a reef block a reef block.

2/ This term is preferred to "Lithothamnion ridge" because the dominant coralline is Porolithon onkodes, not Lithothamnion. The two are quite different structurally, though similar superficially.

3/ Figs. 6 and 7 appeared in Atoll Research Bulletin 31.

Mataira Islet

2. Seaward view of large reef blocks, leeward side of Raroia atoll. The block at the right is about 30 feet long, with an estimated volume of 9000 cubic feet.

Wherever the biota of the algal ridge is healthy and vigorous, the ridge is covered by pink blister-like crusts of Porolithon onkodes, with here and there small hemispheres of ramose Porolithon gardineri. The blisters of the former are often as large as a man's hand and they partially enclose open cavities, refuges of innumerable little crabs. There are many small patches of an encrusting blue-green alga colored light yellowish-green. A narrow belt of discontinuous patches of encrusting Millepora follows the outer flank of the ridge and extends around the heads of the grooves. A helmet urchin (Colobocentrotus sp.), acorn barnacles, limpets, and species of the gastropods Drupa and Turbo live here. A small brown Pocillopora elegans, one of the chief reef formers, and the green alga Microdictyon sp. extend upward over the outer flank of the ridge. Almost every fragment of rock taken from the algal ridge contains the remains of the Pocillopora, yet it is comparatively rare on the crest and landward side of the ridge. Presumably growth accretions on the algal ridge are mainly on the seaward face. Commonly the landward slope of the ridge is deeply pitted and eroded by the burrows of a large slate pencil urchin (Heterocentrotus sp.) and the boring urchin Echinometra mathaei. The latter produces a broadly U-shaped cleft several centimeters deep within which the animal moves back and forth in a plane nearly perpendicular to the surface. On the landward face of the ridge the urchin borings are but little modified by algal incrustation but on the crest and front slope the borings and barnacles are encrusted by laminae of Porolithon onkodes.

The landward face of the ridge, just below the crest, commonly is relatively free from encrustations except for a pink film of Porolithon onkodes. Here the rock, unlike the more active areas on the seaward side of the ridge, is solid. Inspection of broken fragments indicates that the spaces between algal laminae have been filled by foraminiferal sand which has since become firmly cemented by algal accretions.

In many places around the atoll the algal ridge is being reduced by erosion over most of the surface. This is especially the case around the southern end of the atoll from the elbow at Oneroa as far as the southernmost islets of the east side.

Persistent erosion of the algal ridge is in every case accompanied by sustained activity of Porolithon onkodes at a level a few centimeters to a meter lower around the heads of the grooves and over the crests of spurs. This fact might suggest a very recent drop in the relative level of the sea. If so, the drop cannot have been more than a few centimeters because the ridge is not exposed to view even on the leeward side of the atoll during times of high water. Erosion of the ridge is correlated with local depopulation of the coralline algae and corals. But the factors responsible for this are not clear.

Outer reefs of Bikini on which there is a low uninterrupted algal ridge were designated type I-A by Tracey, et al., (1948, pp. 870-871). On Raroia this is the dominant type on both leeward and windward sides of the atoll. It is noteworthy, however, that on Bikini this type of reef is poorly developed on the leeward side and is especially characteristic of reef segments between islands. On Raroia there appears to be no correlation between reef type and location of channels.

Surge channels.-In a few places around the sea reef on both windward and leeward sides of Raroia, the outer grooves extend through the algal ridge some 25 to 50 meters as narrow clefts. These are found chiefly in low areas of the reef flat. Because they are low, these places are also excurrent areas which drain seaward much of the time. In some examples the troughs are partially or completely roofed over by a thin crust of Porolithon onkodes and small corals. Spouting jets of water and hissing of air are characteristic phenomena at openings over the caverns thus formed. The channels, which form a special habitat for many reef fishes, are lined at the rim by small corals and blisters of Porolithon onkodes. The lower walls and floor, however, are scoured by sand and gravel like those of the outer grooves. Judging from the extensive deposits of coralline algae over and at the margins of the surge channels, it seems that this environment is almost as favorable for a few reef organisms as that at the front of the algal ridge. The coralline algae are not, however, very active in the gloomy recesses of the caverns where erosion clearly is dominant and accretion is at a minimum.

The surge channels are headward extensions of the outer grooves and they are now being cut and deepened by gravel scour. All of the Raroia examples contain pot holes filled with rounded cobbles and pebbles. Many extend within 15 meters of the shore.

None of the surge channels of Raroia is being filled or being displaced seaward by algal deposits. As the channels are extended headward and roofed over in the intermediate areas, they are widened toward the sea. Even where the surge channels are partly or completely roofed the cover is only a thin veneer over extensive caverns that clearly are being deepened and widened as they are extended headward. Reef sectors bearing surge channels were designated type I-B (2) on Bikini (Tracey, et al., 1948, p. 871) where they are best developed on the windward side of the atoll along convex arcs in front of islands. On Raroia surge channels are comparatively uncommon. They do occur, however, on both windward and leeward sides.

The reef flat.-This term is used in a purely descriptive sense for the flat rock pavement which extends from the algal ridge to the shore of the islands; or, where islands are lacking, as at the south end of Raroia, the reef flat extends almost to the lagoon, being practically coextensive with the atoll rim. All parts of the reef flat are not necessarily part of the reef and it may not be underlain everywhere by reef limestone. Probably the inner part of the reef flat of Raroia is an erosional surface cut in whatever rocks compose the islands. It appears to me improbable that atoll islets are always formed on a preexisting reef flat. Granted that atoll islets are ephemeral there is still little evidence that they are peculiar to the modern scene. It is more probable that island deposits (i.e., terrestrial rubble) may form an appreciable part of the interior structure of any atoll rim.

On Raroia the reef flat is a pavement which descends gently inward from the algal ridge to near low tide level opposite islands and one to three meters below low water at the lagoon margin between islands. The piling of water on the reef flat by breakers makes it very difficult to correlate water levels on the two sides of the algal ridge. The normal tidal range in the lagoon is about 0.6 meter, but the range on the reef flat of the leeward side of the atoll is about 0.35 meter as indicated by characteristic intertidal organisms and erosion forms.[1] This suggests that although the high water mark on the reef flat is probably at about the level of high tide, the low water mark may be as much as 0.25 meter above low tide. For this reason the reef flat continues to drain at low water state. As stressed elsewhere by Doty and Morrison (Atoll Research Bulletin No. 35), it is essentially a tide pool.

Characteristically, the Raroia reef flat is narrow, 30 to 150 meters, except at the south end of the atoll where there are no islands and the reef flat comprises most of the rim area. On the windward reef flat there are few attached organisms and most of these are sparsely distributed in low areas around surge channels where they are somewhat sheltered. The leeward reef flat is more populated, even though it is exposed for longer periods than the windward flat, and at many places there is an outer belt behind the algal ridge that is completely covered by a matte of small corals (especially Pocillopora elegans) and encrusting red algae. This coral-algal zone contains innumerable burrows of the echinoid Echinometra mathaei which retain water during emergence, hence provide shelter for a diverse and distinctive community of ophiuroids, crabs, gastropods and fishes. Shoreward, the corals are less crowded and the algal deposits more sparse. The coral fauna becomes specifically more diverse and extensive areas of smooth rock pavement dotted with Foraminifera appear between coral colonies.

Generally the coral colonies are small. Heads 25 centimeters across are large for most areas. From studies of growth rates in corals (Vaughan and Wells, 1943) it appears probable that the majority of the reef flat stony corals are not more than 15 or 20 years old, and probably none antedates the great hurricane of 1903. Rings of Montipora sp. one and a half meters across were observed on the leeward reef flat, but these are exceptionally large.

Wherever corals are abundant there is a rather well-defined differentiation into life zones probably determined mainly by the degree and length of exposure to the air and by the temperature conditions.

Large, brown slate pencil urchins (Heterocentrotus sp.) occur sparsely in a belt about two meters wide on the sheltered side of the algal ridge. For the most part these urchins occupy pits and depressions in the rock, similar to potholes, which they apparently have excavated. The surface in this zone is bare and smooth. There is little indication that these urchins and the much smaller Echinometra move about freely and it is presumed that food is brought to them by the circulating water.

From the pencil urchin belt landward for some 5 to 25 meters the reef flat is here and there completely overgrown by the small brown Pocillopora of the algal ridge and small colonies of Acropora spp. Many of these are heavily encrusted by Porolithon onkodes which generally is brownish, apparently moribund, and abundantly perforated by the boring urchin Echinometra mathaei. Some of the openings, however, are partly closed by algal deposits. In some areas there are as many as 50 to 100 of these urchins to a square meter. Most individuals are black but a few are brown. The superficial deposits over the reef

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1/ According to Doty, the interval is less than this.

flat form a superstructure of coarsely cellular material 10 to 20 centimeters thick over a basement of solid rock in which pores have been filled by cemented foraminiferal sand. The open burrows and entrapped water provide shelter for a variety of ophiuroids, crabs, snails, fishes and octupi at low tides when much of the surface is out of water.

In a few places the surface adjacent to the algal ridge is overgrown by meadows of a purplish-red jointed coralline Amphiroa sp. The black, long spined urchins (Diadema) range from the edge of the algal ridge (at high water) to the shore, migrating back and forth as necessary to remain covered by water.

Census of a square meter in Amphiroa belt

	Per cent of total area (estimated)
Porolithon onkodes, covered by Amphiroa sp.	40
Pocillopora elegans (27 small colonies less than 12 cm across)	25
Echinometra (chiefly of black form)	20
Porites sp. (pavement type with Vermetus sp.)	10
Alga, blue-green	5
	100

Census of another square meter in Amphiroa belt

	Per cent of total area (estimated)
Porolithon onkodes and Amphiroa overgrowing dead corals	60
Pocillopora elegans (21 heads less than 12 cm across)	15
Echinometra (burrows of black form)	20
Acropora conferta (purple corymbose form) five colonies less than 12 cm across	2
Plesiastrea spp.? (five small colonies)	2
Porites sp. (two colonies)	1
	100

Corals become more varied as Porolithon decreases in importance toward the inner margin of the coral-algal zone where the water is a few centimeters deeper and the surface is more continuously covered than the slightly higher surface near the algal ridge. A square meter in this part of the coral-algal area provided the following estimates.

Census of a square meter near inner margin of coral-algal area

	Per cent of total area (estimated)
Porolithon onkodes encrusting dead corals (mainly Pocillopora elegans)	58
Pocillopora (17 live colonies less than 20 cm across)	3
Echinometra burrows (black variety)	30
Porites (encrusting)	5
Acropora spp. (three colonies) less than	1
Montipora sp.	1
Massive coral (Plesiastraea sp.?) less than	1
Diadema setosa (six individuals) more than	1
	100

Shoreward from the coral-algal area the supersturcture of small ramose corals and Porolithon onkodes breaks up into scattered, more or less isolated coral colonies, separated by flat low areas of solid pavement. Porolithon onkodes is relatively unimportant here and forms only a thin pink film on dead corals and the pavement. Discoid Foraminifera (Peneroplidae) are abundantly scattered over the surface loosely adherent by their pseudopods. Dead tests may become permanently anchored by the algal film eventually to be incorporated in the rock of the reef flat. Serpulid tube worms are scattered over the rock pavement.

There are perhaps a number of environmental factors which prevent the extension of the coral-algal cover to the shore. Porolithon onkodes finds optimum growth conditions near the algal ridge. Reproductive activity of this alga apparently decreases rapidly away from the ridge, both seaward and landward. On the reef flat wherever conditions greatly reduce the number of coral colonies that can become established and wherever the coralline alga is unable to encrust dead corals and roof over the intervening space the superstructure does not develop. There are several factors near the shore that inhibit coral growth and limit the number of larvae that can successfully establish themselves. In the first place, there is a tendency for ephemeral deposits of sand and gravel to be accumulated temporarily near the shore, so that undoubtedly the effects of cover and scour are much more important here. Effects of scour, of course, are much more deleterious to larvae and very young colonies and the corals do rise well above the bottom where scour is most pronounced. A second unfavorable factor is the great temperature fluctuations found in the shore waters. Water draining from shore rocks and tide pools at night and early in the morning is cooled by evaporation to a degree or so below the general temperature of the reef flat waters. In the daytime, especially when low tides coincide with high air temperatures, excurrent water draining from the exposed areas of reef flat is heated to 32°C and more as compared to the (winter) temperature of 26° C of the incoming water which splashes over the ridge and flows shoreward over the flat.

Zonation, more or less parallel to the reef margin, is largely a consequence of the fact that the reef flat slopes shoreward from the crest of the algal ridge to a trough or pool some two-thirds to three-fourths of the distance from the reef edge (Figs. 6 and 7, Atoll Research Bulletin No. 31). The trough may be as much as 20 or 30 centimeters lower than the outer part of the reef flat. Because of this the outer part of the reef flat generally is drained before the slightly lower inner part; hence, during very quiet weather the latter is less exposed to the air. On the other hand, the outer part, corresponding to the coral-algal belt, is nearer to the source of normal sea water with its more abundant supplies of food and oxygen.

The most conspicuous feature of the middle area of the reef flat is low, irregular colonies of the coral Montipora spp., usually alive only around the periphery. These usually accommodate several individuals of the gastropod Vermetus maximus in the dead central area.[1/] Several massive corals and one or two "brain" corals are better developed here than elsewhere. Individuals of Diadema setosa are common to abundant in this zone, but Echinometra is represented by relatively few individuals, and these are the reddish-brown phase rather than black. Tufts of the arborescent coralline alga, Goniolithon sp. are common here on dead corals. The Montipora zone /This is the "Heliopora zone" of Doty and of Doty and Morrison, Atoll Research Bull. 33 and 35. Ed./ ranges in breadth from about 5 to 30 meters, and it is limited to the leeward side of the atoll.

Census of a square meter in the Montipora belt

	Per cent of total area (estimated)
Rock pavement, covered with discoid Foraminifera, blue-green algae, and film of Porolithon onkodes	70
Montipora (a single colony)	5
Acropora digitifera (three colonies)	5
Acropora conferta (purple, two colonies)	1
Massive coral (Plesiastrea sp.?, nine colonies)	8
Porites sp., encrusting (four colonies)	5
Echinometra (burrows of brown form)	5
Diadema setosa	1
	100

1/ The term "microatoll" for these and other single colonies of corals is not very appropriate. Why not reserve the term for ringed patch reefs enclosing more or less dead central areas such as are so abundant in the Bahamas (Newell, et al., 1951)?

Census of another square meter in Montipora belt closer to shore

	Per cent of total area (estimated)
Rock pavement, with surface film of discoid Foraminifera, blue-green algae, and *Porolithon onkodes*	76
Montipora (two colonies)	10
Acropora digitifera (three colonies)	2
Acropora (purple, two colonies)	1
Pocillipora elegans (five colonies)	2
Massive coral (spiny, *Favites*?)	1
Massive coral (*Plesiastrea* sp.?)	3
Echinometra (burrows of brown form)	5
	100

A shore strip of the reef flat some 15 to 30 meters wide, as well as the floor of many rock pools behind outlying masses of beachrock, consists predominantly of smooth pavement almost continuously inundated even at low spring tides. Most of the loose rubble of the reef flat and blocks broken from the shore passes over this zone and serves as tools for the excavation of numerous shallow potholes below the general surface of the reef flat. The entrances to small landlocked rock basins within the area of beachrock commonly lie 20 centimeters or so below the general level of the bottom.

The reef flat descends gently from the algal ridge to a low trough some 5 to 10 meters from the shore. The slope is the result both of upbuilding along the reef margin and erosion near the shore. The surface even near the shore is covered by a thin film of pink coralline algae, presumably *Porolithon onkodes*[1] and adherent discoid Foraminifera. As will be shown below, much of the inner part, at least, of the reef flat is an erosional platform cut in old island conglomerate.

Two species of large black holothurians are abundant in this area. One is sausage shaped and ordinarily is coated by adhering grains of sand. The other is extensible, living mainly under rock slabs and thrusting its oral crown out many centimeters in search of food. A large rock "oyster," *Chama pacifica*, occurs in some abundance here with several gastropods, *Morula* sp., *Conus sponsalis*, *Vasum* spp., and others. Flat, knobby encrusting plates of *Porites* spp. occupy as much as 30 per cent, locally, of the bottom.

1/ Maxwell S. Doty has made the suggestion to me that the algal film of the shore zone and the deeper parts of the outer grooves may be non-reproductive colonies of *Porolithon onkodes* incapable of secreting massive deposits of calcium carbonate.

The excurrent areas of the reef vary considerably around the atoll. They are alike in being appreciably lower than adjoining reef sectors. Some of these, as at the Garumaoa transect (Homohomo), may be nearly devoid of bottom organisms, although adjoining reef sectors are well populated. These areas commonly are furrowed by potholes and irregular shallow grooves converging, fan-like, toward the gaps in the algal ridge. The grooves are discontinuous and erratic. For example, a groove five meters long and a quarter-meter wide abruptly shallows from a maximum depth of 20 or 25 centimeters toward both ends and disappears, being continued a few meters farther on by another more or less aligned groove. The floors of the grooves are scoured clean by gravel and sand but are very uneven and interrupted here and there by gravel-filled potholes. These grooves are incipient surge channels, and like the latter they lead to outer grooves.

Some excurrent areas are populated by scattered corals; and perhaps because of the greater depth of water in these places, the corals attain relatively large dimensions as compared with other reef flat corals. They attain very frequently a lateral diameter of one-half meter and a height of 20 or 30 centimeters. In these areas more than two-thirds of the bottom is devoid of corals, and hardly any of the colonies are very small. Hence, an inference may be drawn that the area is most commonly unfavorable for planulae, perhaps because of sediment scour, perhaps because of unfavorable temperature conditions. On the other hand these areas are not too unfavorable for the continuance of colonies established under temporarily more favorable conditions.

On the windward reef flat the excurrent points are at rather shallow basins on the reef flat around surge channels. These basins contain a few small corals but the general surface of the flat is completely devoid of corals. The general barrenness of the windward reef flat is difficult to understand. This area is not subjected to protracted exposure to the air, in fact it is almost always inundated by piling up of adjacent waters. It may be that sediment scour is responsible for these special conditions.

<u>Erosion of the reef flat</u>.-Both the outer and inner parts of the reef flat are being conspicuously eroded over large sections of the sea reef. It is perhaps more accurate to say that the reef flat is being extended landward by planation of the shore to a level approximating the deepest parts of the reef flat. Aligned outlying erosion remnants of beachrock, elevated reef pedestals beneath reef blocks, and distinctive pitted areas all clearly indicate that the beachrock was formerly considerably more extensive seaward than at present and that the inner reef flat is being lowered by erosion. On the windward side of the atoll the shore has retreated at least 50 meters for long distances and on the leeward side at least 15 or 20 meters. Thus the reef flat has been extended by this amount at the expense of the land. Lacking facilities to excavate the reef flat in these places we were unable to ascertain whether the rock is composed of conglomerate or organic accretions. There is no indication that the beachrock and island conglomerate were welded to a preexisting reef flat.

In many places around the atoll the landward flank of the algal ridge shows generally a moribund condition of the reef builders and consequent erosion. Along the windward side and the southern end of the atoll the outer part of the reef flat, some 10 to 30 meters wide, is deeply pitted by potholes. Joints in the reef flat are clearly etched in relief. All evidence points to net erosion.

The same deep pitting occurs at the outer margin of the reef flat at many places along the leeward side of the atoll. Usually this zone is narrow, one or two meters wide, and it is not recognizable at all in a few areas of exceptional growth activity.

This evidence of erosion of the reef flat, taken in conjunction with the generally sterile appearance over great areas, suggests an appreciable very recent relative drop in sea level of perhaps 20 or 30 centimeters (the local relief of erosion remnants between excurrent channels) with attendant far-reaching effects on the life zones and acceleration of clastic sedimentation.

LAGOON REEFS

Lagoon shore reefs.-A discontinuous reef lies along the windward (northwest) shore of the lagoon (in Tuamotuan, tahora). Reef growth is inhibited or prevented at the mouths of channels and along the edge of the lagoon at the southern end of the atoll where there is active deposition of fine sediments. The leeward (southeast) shore lacks well-developed shore reefs but instead has innumerable coral heads (mainly massive Porites) and small patch reefs. The differences in lagoon reefs on the two sides of the atoll probably are attributable to 1) more effective delivery of oxygen and food to the windward shore, and 2) more favorable conditions there of sedimentation. The shore reefs rest on a shallow terrace which may correspond to the eight-meter terrace of the sea reef. Few of the shore reefs rise more than about six or seven meters above the bottom, and in most places the relief at the reef front, well inside the terrace rim is only three or four meters. An exception to this is found at Oneroa, where a small barrier reef extends across a broad bay in about 20 meters of water. Presumably this reef originated as a fringing shore reef and maintained upward growth during subsidence of the bottom.

Well-defined habitat zones are shown by the windward shore reefs. Commonly, the beach is formed of fine gravel which forms the border of a narrow reef flat. A black, sausage-shaped holothurian, presumably the same as one of those of the outer reef flat, ranges from the low water line at the shore outward to the outer limit of the reef flat pavement. The holothurians ingest Foraminifera and other particles not firmly attached to the pavement. Loose pebbles in the holothurian belt are commonly heavily encrusted by a knobby pink coralline alga, possibly Porolithon onkodes with a small commensal Vermetus sp., and an Isognomon.

A small club-shaped Acropora digitifera, a finger-like ramose Porites mordax, and Chama pacifica locally are numerous among the holothurians.

Two to 10 meters or so from the shore flattened hemispherical "millstones" of knobby Porites make their appearance. The largest of these heads is about one-half meter high and one meter across the disk, but the majority are less than a quarter this size. The massive Porites forms a favored habitat for a species of small Chama, a Vermetus of intermediate size, Isognomon sp., and burrowing pelecypods of several species (Tridacna maxima, Lithophaga sp., Pedum sp., Barbatia sp.).

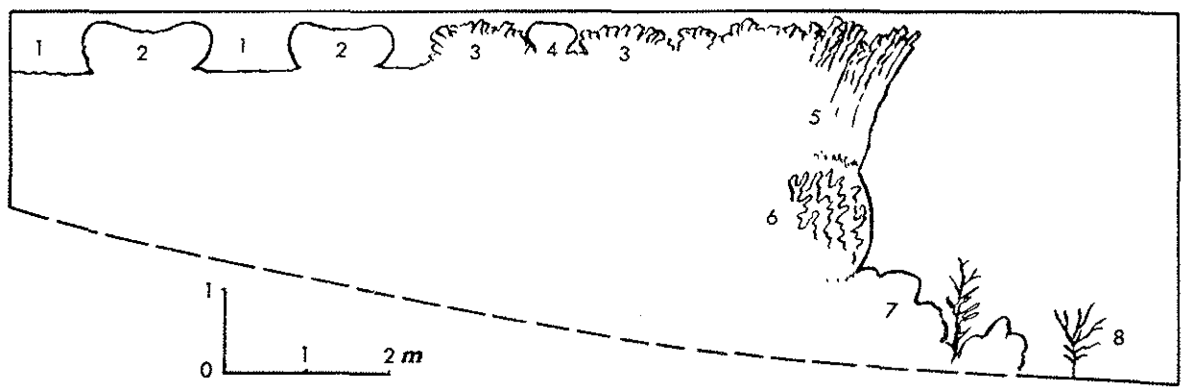
Rather abruptly, within two to 20 meters of the reef rim a small brown Pocillopora elegans?, interspersed with a few small Acropora and massive corals of several kinds become abundant. Dead corals are in places overgrown by Porolithon onkodes and Zonaria sp., a brown alga which forms a superstructure 15 to 20 centimeters thick on the reef pavement, like that of the coral-algal surface of the outer reef flat. Here, conditions are favorable for the brown phase of the boring urchin (Echinometra mathaei). The black phase was not encountered in the lagoon.

The Pocillopora belt varies in breadth. It is replaced a meter or so from the reef rim by a more robust species of staghorn Pocillopora sp. and knobby massive coral (Plesiastrea sp.?) which extends down the reef front, forming heads a half meter in diameter. The front of the reef drops nearly vertically or with slight overhang a few meters to the sediment-covered terrace below (Fig. 3). Somewhat shaded from the sun beneath the rim is a coarse "brain" coral (Lobophyllia costata?) which forms massive surfaces. The most conspicuous of the reef-front corals, however, is a massive Montipora sp., most prevalent in the lower part of the reef face, composing a large part of the living surface. Small and fragile Acropora spp. are scattered over the front of the reef, extending over the bottom beyond the reef edge.

Opposite the south end of Garumaoa Islet the shore reef spreads far into the lagoon, forming the most conspicuous feature of the windward shore of the lagoon. The reef flat here is about 700 meters wide, occupied mainly by the holothurian association. There is circulation across the atoll rim through several shallow channels at this place, but these do not offer a clue to the exceptional development of the shore reef. The atoll rim swings inward here in an embayment, so directed as to form a sort of funnel to ocean swell from the northwest, the direction from which the strongest winds blow. It is probable that the expanded shore reef is built on a gravel fan or delta. The form of the reef suggests that this is the case.

At irregular intervals around the lagoon shore, especially on the northwest, there are slender tongues of the shore reef which extend into deeper water as spurs at right angles to the shore. These are termed kaoa in Tuamotuan and many are given distinctive names. Exceptionally the kaoa extend a half kilometer into the lagoon (e.g. Miramirau). Apparently they represent fusion of patch reefs with the shore reef by growth across the intervening gap. The consistent orientation of the reef tongues at right angles to the shore must be related in some way to the prevailing circulation of the lagoon waters. This problem will be again considered in the discussion of patch reefs.

The leeward (southeast) shore of the lagoon has very few shore reefs, those being quite small patches, and there is only one kaoa reef. The black holothurian which characterizes the near-shore belt elsewhere is abundant here below low water level. Pebbles are coated with deposits of Porolithon onkodes. Massive disks of Porites with all of their commensals are scattered abundantly over the sand. They are not attached to the substratum and can easily be turned over. A finger-shaped Porites mordax and a fragile Acropora implicata are occupants of the sand bottom.



3. Profile of lagoon shore reef at north end of Garumaoa Islet. 1, Reef flat pavement; 2, large disks of Porites; 3, Pocillopora sp. 1; 4, Favia; 5, Pocillopora sp. 2; 6, Lobophyllia; 7, Montipora; 8, Acropora prolixa

Patch reefs.-Viewed from an airplane the Raroia lagoon is impressive for the large number of patch reefs scattered over the entire lagoon, but somewhat less numerous toward the leeward (southeast) shore than elsewhere. Practically all of these are near the surface, just awash at low spring tides, and there are few coral knolls visible at intermediate depths although the water is sufficiently clear[1] for them to be visible from the air at 10 or 20 meters. Dredging shows that most of the bottom between patch reefs is covered by sand, gravel and corals rather than by fine sediments. Evidently the finest sediments do not accumulate in the lagoon. It seems justifiable to conclude from these observations that there are many low coral knolls on the bottom and many patch reefs, and that there are relatively few intermediate knoll reefs.

There are an estimated 1500 to 2000 patch reefs outside the shore zone in the Raroia lagoon. They range from circular patches three or four meters across to great streamlined reefs a half kilometer long and 200 meters across. Hand-line soundings indicate that they are characteristically steeper on the windward than leeward end and they have slopes of intermediate steepness on the sides. The margins down to about 10 or 15 meters are very steep with a few overhanging ledges. Most of the living corals are within this depth range. At greater depths the slopes flatten to angles less than 45 degrees.

Viewed from a boat, or better from the air, the windward margin of the patch reefs is invariably colored olive-brown by the living corals. The leeward margin is marked by turquoise-colored streaks of shallow water over gravel and sand. The loose sediments are shed mainly to the leeward through shallow channels or gaps between living corals, and in the larger patch reefs much of the leeward surface is occupied by gravel and sand heaped up by the waves.

The marginal and surface corals of the patch reefs form the same associations as those of the windward shore reef. Black holothurians live in the sand areas to the leeward of the summits of the patch reefs, and the associated corals are dominated by species of Porites and Acropora. Small Pocillopora elegans? become crowded together forming a marginal zone at the rim on the windward and intermediate sides. Coralline algae and the boring Echinometra occur with Pocillopora near the rim in some patch reefs, but for the most part the soft green algae Zonaria and Caulerpa are more conspicuous here.

In plan, some of the patch reefs are roughly equidimensional but many are four or five times as long as wide, elongate roughly in the direction of the prevailing wind. The majority of these show a tendency for the leeward end of the reef to taper more gradually than the windward end, streamlined in teardrop form.

In air views it can readily be seen that the patch reefs are not entirely distributed at random. Many are arranged in rows generally oriented downwind, but there is some deviation near the windward shore where the linear series of patch reefs gradually assume an orientation normal to the shore. The majority of reef tongues (kaoa) of the shore reef are aligned with and apparently are the terminal members of individual series. Probably the distribution of these reefs is controlled by wind induced currents, perhaps broken into many jets at the windward channels.

1/ An eight-inch Secchi disk was visible from a small boat down to 28 meters.

Unfortunately it was impossible to survey the lagoon by vertical photographs and a map of the lagoon from aerial oblique photographs has not yet been completed. It is expected that a map of the coral patches would lead to satisfactory inferences regarding their distribution and possible relationship of the patch reefs to channels.

The tendency for the reefs to lie in parallel rows suggests linear cells of turnover presumably with a counter-clockwise motion in accordance with the Coriolis principle. Plans to test this theory by means of fluoricine dye were frustrated by unavailability of transportation during suitable weather.

REEF BIOTA

Diversity.-Outer and lagoon reefs of various types are well developed and contain a flourishing biota probably more diverse than that of Tahiti and comparable to that of Samoa. The often cited attenuation of reef organisms eastward across the Pacific is much more marked between Hawaii and the Tuamotu group than between the latter and Samoa.

Reef builders.-The only quantitatively important reef-forming coralline alga on Raroia, according to Doty, appears to be Porolithon onkodes which has the unique ability to deposit extensive encrustations in the surf zone, especially at intertidal levels. This alga is most conspicuous on the algal ridge and around the heads of grooves and around surge channels where it truly is a rock-former, composing perhaps as much as 25 per cent or more of a very cellular rock. Pocillopora elegans perhaps makes up as much as 25 per cent here and the rest is represented by voids on a fresh example, or by foraminiferal sand in an old example. The alga effectively binds corals together in a rigid framework in the algal-coral belt of the reef flat, and on the unshaded crests and edges of the spurs to a depth probably not much greater than six or eight meters below low water level.

The innumerable reef blocks cast up on the reef flat by storm waves permit direct examination of reef limestone from the groove and spur zone of the reef. In most of the blocks examined the cellular rock consists mainly of tier above tier of small Pocillopora elegans with an occasional massive coral and a staghorn Pocillopora. On the surface, interstices between corals are unfilled. An occasional fresh fracture across a reef block reveals that the unweathered interior is compact and the space between corals is filled with lithified sand composed largely of Foraminifera. This sand "matrix" weathers away readily on exposure, leaving corals, almost unaffected, standing in relief. Besides interstitial material and voids the substance of the blocks generally is 50 to 95 per cent Pocillopora elegans. Porolithon onkodes rarely occupies as much as 15 per cent of the volume, and in many blocks we were unable to recognize algal deposits without microscopic examination.

Certainly Porolithon onkodes plays an important role as a building agent and its importance should not be underrated, but quantitatively it is a great rock builder only along the algal ridge. Algal deposits are rarely recognized in the island rubble.

About 600 pounds of corals representing the common shallow-water species at Raroia were transmitted for identification to John W. Wells who reports 53 species in the collections, of which only eight had previously been reported from the Tuamotus. Six species reported from the Archipelago are not represented in our collections.

PRELIMINARY LIST OF REEF CORALS COLLECTED AT RAROIA (identified by John W. Wells)

Pocillipora danae Verrill
- P. elegans Dana
- P. ligulata Dana
- P. verrucosa (E. and S.)

Acropora conferta (Quelch)
- A. conigera (Dana)
- *A. corymbosa (Lam.)
- A. danai (M. E. and H.)
- A. digitifera (Dana)
- A. exilis (Brook)
- A. formosa (Dana)
- *A. humilis (Dana)
- A. implicata (Dana)
- A. cf. nobilis (Dana)
- A. procumbens (Brook)
- A. prolixa Verrill
- A. quelchi (Brook)
- A. rayneri (Brook)
- A. rotumana (Gardiner)
- A. sp.
- A. syringodes (Brook)
- A. tubicinaria
- A. variabilis (Klunzinger)

Montipora australiensis Bernard
- M. venosa (Ehrenb.)
- M. caliculata (Dana)
- M. verrilli Vaughan
- M. verrucosa
- M. n. sp.

Astreopora myriophthalma (Lam.)

Pavona clavus Dana

Leptoseris hawaiiensis Vaughan

*Fungia scutaria Lam.

Fungia concinna Verrill

Herpolitha limax (Esper)

Porites australiensis Vaughan
- P. lobata Dana
- P. mordax Dana
- P. n. sp.
- P. superfusa Gardiner

*Favia stelligera (Dana)
- *F. rotumana (Gardiner)
- F. pallida (Dana)

Favites hemprichii (Ehrenb.)

*Plesiastrea versipora (Lam.)

*Platygyra rustica (Dana)

Cyphastrea serailia (Forskaal)

Leptastrea purpurea (Dana)

*Acanthastrea echinata (Dana)

Lobophyllia corymbosa (Forskaal)
- L. costata (Dana)

Culicia rubeola (Q. and G.)

Millepora platyphylla Ehrenb.

*Previously reported from the Tuamotu group.

Other species reported from the Tuamotus but not found in the Raroia collections:

Acropora hyacinthus (Dana)

Favia favus (Forsk.)

Fungia cooperi Gardiner
- F. paumotuensis Stutchbury

Pocillopora meandrina Dana

Pavona (Pseudocolumnastraea) sp.

SHORE PROCESSES

The shore profile.-A vertical succession of well-defined, narrow biozones occurs on the shore and outlying reef blocks around the atoll but these are best developed on the leeward side of the atoll. These zones are readily distinguished by the character of the surface and the color of the encrusting blue-green algae. Each zone is occupied by gastropods which feed on the algae or on the herbivores. In addition tube gastropods (Vermetus) and boring goose-neck barnacles are conspicuous on the reef blocks between high and low water marks. All of the animals are truly marine forms in that they pass at least the larval stage in the sea and their shore distribution depends on the varying degrees of their tolerance to exposure to sun, air and rain, and to competition and predator pressure. Probably to a lesser degree they show preference for various kinds of algal pastures.

At the bottom, always covered by sea water, is the scoured pavement covered by adherent Foraminifera and a film of pink coralline algae. The surface is smooth, undulating, or pitted by potholes.[1/] Foraminifera can be scraped from the surface where they cling to the bottom by means of their pseudopods. This is the holothurian belt of the reef flat. In some places it is bordered by a vertical rise of smooth, pinkish rock surface some 20 centimeters high to the clearly defined low water mark.

Above the low water mark the rock surface is yellowish-brown and scoriaceous through a vertical interval of 40 to 45 centimeters (a little less on the windward outer shore). Although this is considerably less than the normal tide range of 0.6 of a meter, it represents approximately the usual range between low and high water at the outer shore. A species of Turbo, a medium-sized Vermetus, a Drupa and a boring gooseneck barnacle dwell here.

This yellowish-brown surface grades into the lower part of a grayish surface above which is wet less frequently. This higher belt may be termed the Nerita zone from the dominant gastropod, Nerita plicata (Fig. 4). This form feeds mainly at night and ranges into the intertidal zone as the tide recedes. However, the species is most characteristic of the surface immediately above the high water level. The numerous pits of the Nerita zone are rounded and smooth and colored bluish-gray. The projecting coral fragments between pits are etched in relief by removal of intervening matrix. The projections are tan in the lower part of the zone, becoming brown in the upper part. The interior of the rock a millimeter or so beneath the surface is white, and the bluish-gray color of the pits, as observed in fresh fracture, is a stain which penetrates the rock below the algal film. Immediately outside the bluish-gray

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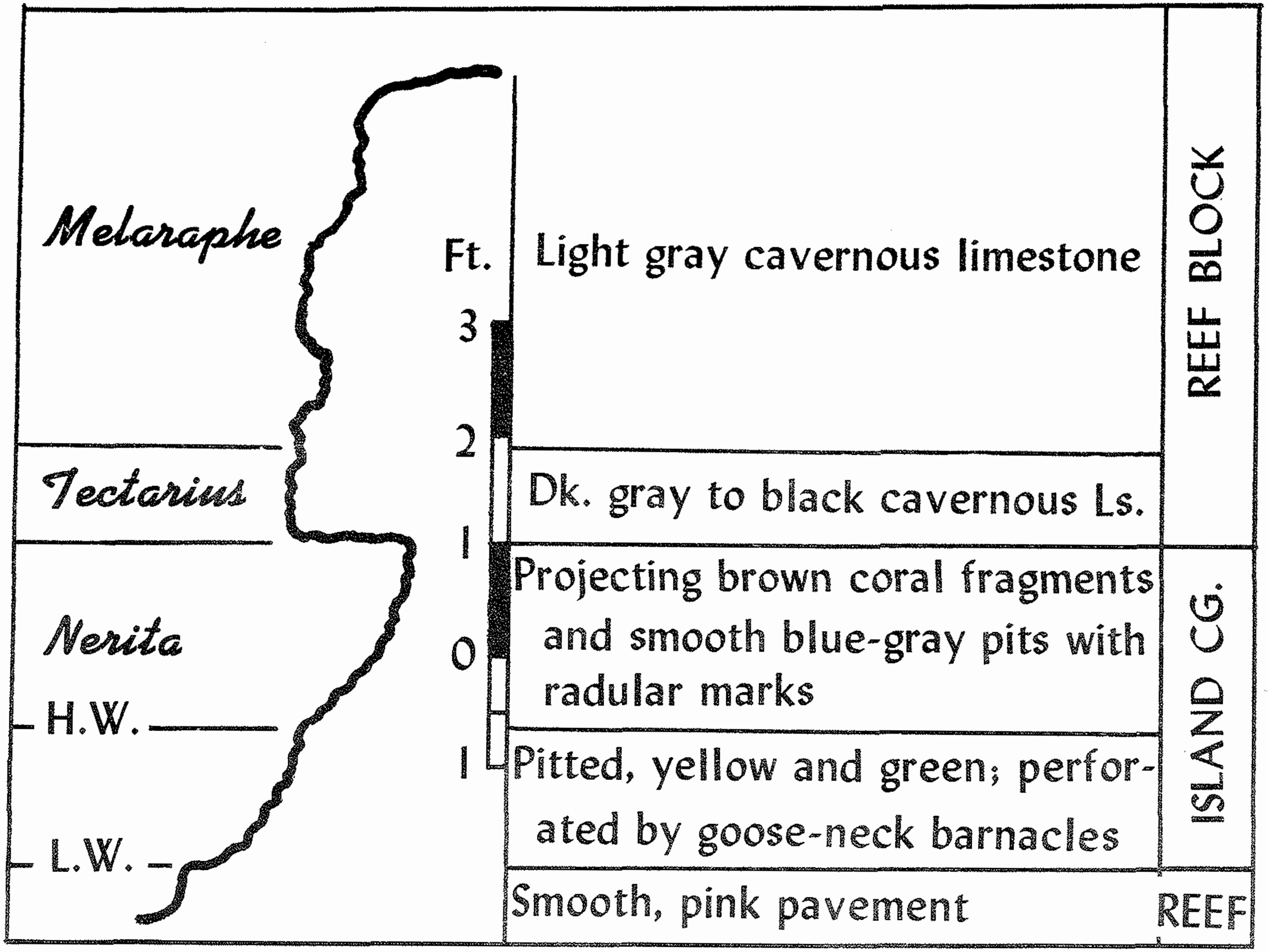
1/ Emery (1946, p. 225) implies that potholes are more frequently deep and narrow than shallow and broad. At the beginning of excavation a pothole can be shallow as are many of the examples alluded to here.



4. Shore profile, reef block, leeward side of Garumaoa Islet.

layer, but covered by the superficial gray film, there often occurs a thin pink layer. Presumably these are pigments derived from the algae.[1/] The bluish-gray pits are striated by radular marks of a gastropod, presumably Nerita plicata, the only abundant form in this zone. These gastropods feed on the surface algae and possibly also the algal filaments below the rock surface. The grooved surfaces over which the gastropods have browsed clearly have been modified by radular rasping. It is interesting that the projections between pits correspond to coral fragments and the pits to matrix of foraminiferal sand. The latter is relatively non-resident to the prevailing processes of erosion. As tested by scraping the surface with a knife blade, the pits are underlain by much softer material than the coral fragments, and it may reasonably be supposed that the pits have been excavated largely by the feeding activities of the Nerita plicata. Above the zone of Nerita plicata, moistened chiefly by spray, the rock is uniformly blackened by a film of blue-green algae.[2/] This blackened area, reaching above high water some 20 to 60 centimeters or more is the feeding ground of a robust turbinate snail (Tectarius grandinatus). This gastropod does not scrape the surface deeply, although radular marks are plentiful, and there is little indication that it significantly modifies the rock surface. The Tectarius is rarely seen on the windward shore except on reef blocks. The blackened algal stain of this belt shows distinctly on aerial photographs as a narrow band at the shore on the leeward shore and a broader band on the windward shore. Apparently enough moisture as salt water spray reaches the surface to maintain an algal cover sufficient to color the rock and to supply pastures for the Tectarius. Immediately above the normal reach of spray the rock surface changes from black to gray, the color, as shown elsewhere by Newhouse, being derived from dessicated blue-green algae. On reef blocks this grayish surface is occupied by a small bluish gastropod, Melaraphe coccinea, which is most active at night and following rains when foraging is best. This species does not produce conspicuous effects on the rocks. Melaraphe coccinea ranges over the surface of the conglomerate platform to the edge of beaches or ramparts. Doty and Morrison have described the shore profile more fully on an earlier page in connection with ecological zonation.

Solution of limestone by sea water.-In spite of the well-known fact that tropical sea water normally is saturated or supersaturated with calcium carbonate a number of investigators have suggested that aerated sea spray and the sea water of rock pools may become sufficiently acid from CO_2 liberated by organisms to dissolve limestone (Emery, 1946). Kuenen (1950) has recently summarized these various views and cites quite a lot of evidence in support of the theory that sea water does dissolve limestone, particularly in the intertidal zone, even though attempts generally have failed to satisfactorily demonstrate that the water, excepting in small enclosed pools, is sufficiently acid to dissolve limestone. The topographic forms produced by rainwater above the reach

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1/ Bergman expresses the following opinion about these color zones: "I believe that your original suspicion was right that the pigment is indeed of the porphyrin type, or the closely related bile-pigment group. It is probable that it is derived from the algal pigments, that it is acidic in nature, that it has penetrated into the lower layers where they form calcium salts (Werner Bergmann, personal communication 3/18/53). Newhouse has gone into this matter more fully in a preceding report (Atoll Research Bulletin No. 33).

2/ This film of blue-green algae was mainly Entophysalis crustacea.

of the sea are strikingly unlike those of the intertidal and spray zones and the bottom topography beneath low water is also different. Emery has shown that intertidal gastropods play an important, if unevaluated, role in erosion. Newell, Rigby, Whiteman and Bradley (1951) and Ginsburg (1953) have concluded that mechanical as well as biochemical activities of organisms are adequate to produce the distinctive erosion forms of the intertidal zone on limestone coasts.

On Raroia many of the reef blocks of the reef flat rest on deeply undercut pedestals. The pedestals in some cases consist of beachrock which is reduced by erosion more rapidly than the overlying reef rock and this tends to accentuate the distinction between overhanging cap rock and pedestal below. As pointed out by Kuenen (1933) these pedestal rocks are notched uniformly on all sides; therefore, it is unlikely that action of waves is particularly involved. If solution by sea water is the dominant process, then it follows that at times the waters of the entire reef flat must become sufficiently acid to dissolve the limestone, since undercutting is as pronounced on the reef flat as at the shore and the process is not peculiar to small enclosed basins.

Cloud (1952, p. 40) has found that at Onotoa the pH often rises toward a maximum of 8.6 in open shoal water and 9.1 in tide pools during the day when CO_2 is being diminished by photosynthesis. At night when the CO_2 content of these waters is increasing, pH falls to 7.3 or 8.0. He believes that it is probably at times of lowering of pH below about 7.8 to 8.0 that solution occurs (Op. cit., p. 40).

The solubility of calcium carbonate in sea water under natural conditions is rendered particularly complex by buffering effects and by great variations in CO_2 concentration. Unfortunately, pH determinations alone are not very helpful in determining whether or not calcium carbonate is being dissolved or precipitated, but these must be considered in conjunction with analyses for titration alkalinity (Smith, 1940; Emery, 1946). While precipitation is taking place, the pH will fall because of release of carbon dioxide from the bicarbonate, and vice versa. My plans to make alkalinity determinations at Raroia were frustrated by failure to receive essential reagents included in our strike-bound Los Angeles shipment.

A number of pH measurements were made with a Gamma electric pH meter in an enclosed high rock pool and on the outer leeward reef flat at Garumaoa with the following results:

Time	Large Rock Pool		Reef Flat	
	Temp.	pH	Temp.	pH
9:00 pm	22.0° C	8.09	23.0° C	8.01
10:00 pm	21.7°	8.02	23.3°	8.10
12:00 mn	21.5°	8.06	23.0°	8.06
2:00 am	22.5°	8.11	24.5°	8.20
5:00 am	25.0°	8.20	25.0°	8.20
7:00 am	23.5°	8.11	25.0°	8.10
9:00 am	26.5°	8.15	27.5°	8.20

At 5:00 am the rock pool was receiving fresh sea water. At other times it was isolated. Additional isolated measurements were made several times with the result that pH values were invariably above 8.00, too high for solution of calcium carbonate.

Rock surfaces of the reef flat and the land are generally covered by a thin film of algal vegetation (See Atoll Res. Bull. No. 33 on algae). Outlying blocks and shore rocks between low and high water levels are conspicuously colored tan to brown and are particularly roughened by erosion. A fresh fracture of this rock reveals that the filaments of blue-green algae penetrate the capillary fringe of the rock and the entire surface in places is blanketed by the algae. It seems likely that the carbon dioxide and possibly other acids liberated by plant metabolism and decay are brought into intimate contact with the substratum, providing an acid environment in which the rock is rather rapidly leached, much as a limestone surface is leached by a blanket of lichen, or a calcareous soil by plant roots. This would explain the marked solution effects in precisely the zone where blue-green algae are most active on limestone shores in the intertidal and splash zones. It also explains why solution effects are about the same on outlying reef blocks and in rock pools where pH conditions are generally different.

Organisms as agents of shore erosion.-We have inferred that the life processes of blue-green filamentous algae, which are especially active between low water level and the top of the splash zone, are responsible for the characteristic pitted surface of the rocks at this level. But it is noteworthy that the deepest part of the shore notch of the pedestal rocks of the reef flat on Raroia is not below or within the intertidal zone as might be expected if erosion were accomplished mainly by inorganic solution by sea water or solely by algal leaching. Instead it is at the high water level. Undoubtedly direct solution by sea water and algal penetration of the rock are both significant but not dominant factors. The zone of *Nerita plicata* occupies the deepest part of the furrow around the pedestal rocks (Fig. 4). Assuming that the growth of blue-green algae on and below the surface initiates erosion by penetration of algal filaments into the rock, it may safely be concluded that the rasping of the softened surface film by gastropod radulae accelerates the process of limestone removal. Newhouse, Doty and Morrison arrive at this same conclusion in earlier reports.1/ Erosion in the underlying intertidal zone is only a little less pronounced. The surface of the reef blocks, more rarely the shore rocks, is perforated deeply at this level by a boring gooseneck barnacle which, in extreme cases, removes as much as 20 per cent of the rock to a depth of two or three inches.

Exfoliation.-Erosion by organic agencies and by wave action have resulted in many places in a low escarpment one-half to one meter high at the edge of the island conglomerate. This is highest on the leeward side of the atoll. This bench breaks down by exfoliation along fracture planes which dip seaward at low angles ranging from nearly horizontal to about 35 degrees. The fracture planes cut smoothly through coral blocks and cobbles. Freshly broken tabular masses are shifted by the waves exposing fresh surfaces. These displaced slabs remain near the place of origin until a storm carries them onto the conglomerate platform.

1/ Atoll Res. Bulls. 33 and 35.

The exfoliation planes generally intersect the front of the conglomerate bench at the undercut notch near the high water line. It seems probable that the hydraulic pressure of storm waves concentrated below the overhanging rim of conglomerate is responsible for the fractures.

SEDIMENTATION

Introduction.-Presumably the outer slopes of Raroia at depths of several hundred meters are talus slopes inclined at the repose angle. Down to the limit of direct observation at 34 meters on the outer slope the bottom is covered by living corals and is kept relatively free of loose sediment. Gravel and large worn boulders of *Porites* more than a meter across are strewn over the floors of the grooves where they reach the outer slope. The size and constitution of the boulders indicate clearly that they are derived from the outer slope and are swept into the grooves by storm waves.

Sand and gravel of the outer beaches and ramparts accumulate well inland from the rock shore where they are deposited by storm waves of intermediate amplitude. This debris is composed partly of corals and Foraminifera that live on the reef flat. There is a direct interrelationship among degree of exposure to ocean swell, texture, and height of the ridges. The ramparts progressively become higher and coarser where the coastline forms a high angle or an embayment directed toward the prevailing storm directions. The sediment includes fine sand, composed mainly of brown Foraminifera (*Amphistegina lessoni*) and discoid Peneroplidae, the largest of which are about five or six millimeters across.

The prevalence of the brown Foraminifera gives the sand decidedly a reddish-brown color. The more conspicuous Foraminifera of the beach sand were all observed on the reef flat, where they cling to the pavement, to algae and dead corals. Detrital material is inconspicuous and subordinate to the Foraminifera among particles of sand size.

As discussed elsewhere, the land surfaces behind the outer rampart are covered by coarse gravel and boulders of coral, much of which clearly must have been derived from the outer slope at depths of more than eight meters. Much of this material is coarser than that of the rampart, hence it is judged to represent deposits left by hurricances. The outer slopes of the gravel ramparts are white in color, the normal color of bleached coral debris, but the surface of the moat and higher ground beyond the moat is stained dark gray by a film of blue-green algae, and this supports the view that these surfaces are disturbed only infrequently and by the greatest storm waves. The surface gravel becomes progressively finer toward the lagoon.

All evidence, including testimony of the inhabitants, shows that the sediments of the outer reef are driven overland across the islets or toward the lagoon through the channels by storms. Apparently there is relatively little migration of sediments seaward.

According to eyewitnesses the land is swept during hurricanes by great waves from both the sea and lagoon, but the sea waves generally are by far the greater, even on the leeward side of the atoll. Most of the hurricane winds, judging from inadequate records, strike Raroia from the westerly quadrants, normally the lee side of the atoll. These reports are borne out by the fact that the highest ramparts and the coarsest storm debris are found on the leeward side. However, it is clear that the southeast, or upwind, side of the lagoon receives more sediment than does the northwest side. The deepest part of the lagoon lies well to the northwest of the midline of the lagoon (see Atoll Res. Bull. No. 31, Fig. 5). This observation harmonizes well with the fact that most of the channels occur on the windward side of the atoll, and these flow lagoonward practically continuously.

The lagoon beaches are composed of sand to fine gravel and much of the finer sediment is idential with that of the outer beaches and ramparts from which it evidently was derived.

Dredging by hand for sediments in the lagoon turned out to be discouraging. Only five samples were obtained after 40 unsuccessful hauls, each involving laborious recovery of the dredge. In several attempts branches of the sand-tolerant Acropora prolixa were brought up from various depths in separate localities, leading to the inference that this coral is abundant on the lagoon floor. The sediment samples recovered consisted mainly of silt and sand-sized particles of calcium carbonate. Very few segments of Halimeda were observed. It is supposed that most of this sediment is the fine fraction winnowed from the lagoon shore sands.

General lack of mud-bottom areas in the lagoon suggests that the finest detrital fractions do not accumulate but are carried out the pass in suspension. The adjoining atoll, Takume, which lacks a ship pass, has extensive areas of mud bottom, as also is the case with Hikueru, Anaa, and probably other enclosed Tuamotu atolls. In general, those atolls of the Tuamotu group with lagoons more than 40 meters deep have one or two passes and the waters are clear.

Preliminary report on the sediments (by John V. Byrne).-Lack of proper dredging equipment and boats made the collection of lagoon sediments at Raroia extremely difficult. Nevertheless, more than a dozen lagoon samples were collected from depths greater than 10 feet by the use of a biological dredge, hauled by hand from an outrigger canoe equipped with outboard motor. Samples were collected at points evenly spaced along traverses between known locations on opposite sides of the atoll. Most of the dredge samples consisted solely of biological material, but several hauls containing sediments were made. The abundance of bottom coral was evidenced by the number of times the dredge caught on the bottom or returned with only fragments of coral. The dredge caught on bottom coral on approximately 90 per cent of the hauls.

The lagoon sediments consist of recognizable coral and shell fragments, Foraminifera, fine sand and silt, probably derived from the comminution of shells and coral fragments, echinoid spines and other organic skeletons. Halimeda is represented in the samples. However, unlike Bikini and other atolls of the northern Marshalls remains of this alga comprise a very small percentage of the total sediment.

Particles composing the bottom sediments range from fine silt to cobbles, but fragments of cobble size were infrequently recovered. Median diameters in the samples range between 0.08 mm and 0.74 mm. The average, based on 15 samples, is in the medium sand class, 0.36 mm. The sorting of most of the samples is good but a few of the exhibit medium to poor sorting.

Composition analyses were made in order to determine percentages of the major constituents of the sediment. The samples were divided under the microscope into shell, coral, Foraminifera, fine sand and silt, and miscellaneous. All material finer than 0.25 mm in diameter was classified as fine sand and silt. The miscellaneous classification includes echinoid spines, algae and other material not classifiable in the other groups.

Generally, fine sand and silt make up the largest percentage of each sample; in one case 79 per cent. The average percentage, based on 15 samples, however, is 42 per cent. Coral fragments are consistent in making up fair-sized portions of each sample, averaging 25 per cent, but comprising up to 60 per cent of some of the samples. Foraminifera, averaging 16 per cent, make up no more than 25 per cent of any single bottom sample. "Miscellaneous" material, including unrecognizable material, comprises not more than 10 per cent of any sample and averages 3 per cent for the 15 samples.

The beach samples have not been completely analyzed, but preliminary study indicates that sand is more than 75 per cent of the material. Sampling errors may be responsible for this high value, for field observations seem to indicate that material coarser than sand is more abundant than preliminary studies showed. It may be pointed out that Foraminifera make up more than 85 per cent of some of the beach samples collected.

The lagoon bottom samples obtained at Raroia are not adequate for the determination of distribution patterns; however, there are points of resemblance with the distribution of sediments obtained from previously studied atolls.

A traverse across Raroia lagoon opposite Garumaoa village shows that the percentage of Foraminifera is greatest close to shore on both sides of the atoll. Likewise, shell fragments make up a larger percentage of sediment near the islets than in the center of the lagoon. Deposits in the deeper parts of the lagoon are dominated by fine sand and silt which decreases toward the rim of the atoll. The relative abundance of miscellaneous material is fairly uniform throughout. The coral constituents, however, are irregularly distributed. The abundance of patch reefs throughout the lagoon may account for this lack of trend. The distribution of sediments, as suggested by the few available samples, resembles those observed by K. O. Emery for atolls of the northern Marshalls (personal communication). In fact, the only conspicuous difference between the two areas seems to be in the role played by Halimeda. In atolls of the northern Marshall Islands, Halimeda makes up a major portion of the sediment, particularly in deeper parts of the lagoons. At Raroia it is insignificant as a sediment producer.

The patch reefs supply much coarse sediment which tends to complicate the over-all pattern of deposition in the lagoon. In general it may be said that Foraminifera and shell fragments make up a larger per cent of the sediment in a zone around the outer edge of the lagoon than elsewhere. These constituents are probably equally abundant in the central, deeper areas of the lagoon where they are masked by fine sand and silt which accumulates there.

Lagoon-beach sediments on the windward side of the atoll consist primarily of fine material, mainly Foraminifera. Lagoon beaches on the opposite side of the atoll are more exposed. They are composed essentially of coarse shell and coral fragments. Where these fragments are abundant, they are usually deposited in small beach ridges. There are, however, areas on both sides of the atoll in which the above generalization is reversed. The seaward sides of the islands are characterized by coarse cobble and boulder ramparts and ridges, storm beaches behind beachrock areas, and well sorted accumulations of sand in depressions; both along the landward margin of the reef flat and on the island conglomerate behind the reef flat. In general, the more exposed shores are characterized by coarse material, whereas protected areas have accumulations of finer material.

<u>Distribution of Foraminifera</u> (by J. Sperrazza).-A preliminary survey of sediment samples from Raroia atoll reveals the usual tropical shallow water species of Foraminifera of the Indo-Pacific fauna. Many of these range from southeastern Africa to the Polynesian Islands. The Foraminifera are closely related to those of Samoa described by Cushman (1924) and those of the Kerimba Archipelago of southeast Africa covered in studies by Heron-Allen and Earland (1914). Several of the Raroia species are known from Hawaii, the Philippine region, the Malay region and Funafuti.

A check list and a table showing the percentage of foraminiferal content per sediment sample are presented in this preliminary survey. Volumetric measures were used in estimation of percentages. The Foraminifera were separated from a representative sample from each station and volumetrically compared with the total representative sample. The determinations are believed to be accurate within an error of plus or minus three per cent of the recognizable foraminiferal fraction.

The beach sands show varying percentages ranging from 0.1 per cent to 72 per cent in Foraminifera content, depending, probably, on the degree sorting by waves. Shoal reef benthonic forms of larger Foraminifera are abundant and generically represented by <u>Marginopora</u>, <u>Sorites</u>, <u>Amphisorus</u> and <u>Amphistegina</u>. <u>Amphistegina</u> is by far the most abundant form and appears in all samples. Small and large forms of Miliolidae are also common in the beach sands.

The dredge samples show a richly diversified fauna with depth. Families commonly represented are the Miliolidae, Amphisteginidae, Peneroplidae, Valvulinidae, Textularidae, Cymbalopoidae and Anomilinidae, with the greatest diversity of genera occurring in the family Miliolidae. Less abundantly represented are the Alveolinidae, Camerinidae, Heterosteginidae, Nonionidae, Lagenidae, Fischerinidae, Buliminidae and Rotaliidae.

Pelagic forms are present but of rare occurence. They are represented by <u>Globigerina</u> and the adult floating stage of <u>Tretomphalus</u>.

The tests of Foraminifera in lagoon sediments may be classed in depth zones as follows:

Zone 1. Depth range 0 – 6 meters

Abundant: Amphistegina lessoni
Amphistegina madagascarensis
Marginopora vertebralis
Quinqueloculina sulcata

Common: Acervulina inhaerans
Amphisorus hemprichi

Zone 2. Depth range 6 – 30 meters

Abundant: Amphistegina madagascarensis
Sorites marginalis
Archaias adunca
Clavulina pacifica
Clavulina difformis
Textularia candeiana
Anomalinella rostrata

Common: Acervulina inhaerans
Amphisorus hemprichi
Articulina sulcata
Gypsina globulus
Heterostegina depressa
Nubeculina divaricata var. advena
Quinqueloculina parkeri
Quinqueloculina tropicalis
Schlumbergerina alveoliniformis
Quinqueloculina samoaensis

Zone 3. Depth range 30 meters and over

Abundant: Textularia candeiana
Quinqueloculina samoaensis

Common: Bolivina tortuosa
Anomalinella

Percentage by volume of Foraminifera per smaple

Sample	Per cent of total	Location
7-9-1	22.0	Sand from small beach between seaward reef flat and beach rock at traverse north of Garumaoa village.
7-9-4	25.0	Outer beach sand just inside conglomerate platform at Garumaoa traverse.

7-9-5	13.0	Sand and gravel 10 meters inland from outer platform of beach rock; first zone of coarse material at Garumaoa traverse.
7-9-6	11.0	Sand and gravel 20 meters inland from outer platform of beach rock at Garumaoa traverse.
7-9-7	7.0	Sand and gravel inland from preceding station, Scaevola zone at Garumaoa traverse.
7-13-1		Gravel, lagoon beach, Garumaoa transect.
7-13-2	20.0	Beach sand from beneath large cobbles just below small ridges of gravel of sample 7-13-1.
7-13-3	24.0	Coarse sand from lagoon beach just north of Garumaoa village.
7-13-4	2.0	Fine sand taken near Garumaoa village on lagoon beach.
7-21-1		Pink forams on piece of drift (lagoon shore).
7-22-1	38.0	Sand from depth of 6 inches in test pit C(4).
7-23-1	7.0	Sand from test pit A(5) bottom 3 feet.
7-26-x		Lagoon beach samples collected south of Garumaoa village.
7-26-2	14.0	Lagoon beach south end of Garumaoa Islet.
7-26-3	16.0	From rocky point near sample 7-26-2.
7-26-4	4.0	Lagoon beach at embayment behind spur to south of Garumaoa village.
7-26-5	3.0	Lagoon beach south of Garumaoa village.
7-26-6	10.0	Lagoon beach south of Garumaoa village.
7-26-7	14.0	300 meters south of old pier, Garumaoa village.
7-27-1	7.0	At Garue pass, lagoon beach between gravel ridges.
7-27-2	20.0	Lagoon beach, north side of channel mouth south of Takeke Islet, south of Garue pass.
7-27-3	25.0	Lagoon beach, north side of channel south of Temari Islet, south of Garue pass.
7-27-4	10.0	Lagoon beach, north end Korere Islet, south of pass.

7-27-5	9.0	Lagoon beach, south side of incomplete channel, Korere Islet, south of pass.
7-27-6	12.0	Lagoon beach, 20 meters north of incomplete channel. Between Tomogagie and Garumaoa Islet.
8-5-1	0.1	Patch reef top near south end of lagoon.
8-5-2	14.0	Patch reef top near south end of lagoon.
8-5-3	20.0	Lagoon beach, Kakipuku.
8-5-4	55.0	Lagoon beach, Kakipuku.
8-5-5	72.0	Lagoon beach, Kahuruna.
8-7-1	8.0	Outer beach, Oneroa.
8-9-1	8.0	Sand patches between corals, lagoon pavement bottom, 10 feet of water, off second channel mouth north of Oneroa (Marie).
8-11-1	9.0	Dredge sample, lagoon half way between Oneroa and Garumaoa village.
8-11-2	10.0	Dredge sample, lagoon 300 meters east of Ohava patch reef, near Garumaoa village.
8-12-1	15.0	Dredge sample, lagoon 200 meters east of Ovete patch reef near Garumaoa village, depth 90 feet.
8-13-1	20.0	Dredge sample, lagoon, half way between Ohava reef and old wharf, near Garumaoa village, depth 65 feet.
8-13-2	5.0	Dredge sample, lagoon, 200 meters southwest of Kumekume Islet, depth 45 feet.
8-13-3	9.0	Dredge sample, lagoon, 400 meters southwest of Tomogagie Islet, depth 70 feet.
8-13-4	12.0	Dredge sample, lagoon, 100 meters east of end of Miramirau reef spur, south of Garumaoa village, depth 40 feet.
8-13-5	16.0	Dredge sample, lagoon, 400 meters southwest of Ovete patch reef, near Garumaoa village, depth 60 feet.
8-13-6	14.0	Same location as 8-13-4.
8-13-10	11.0	Beach sample, ocean side at extreme northern tip of Raroia atoll.

8-13-11	32.0	Beach sample, lagoon side at extreme northern tip of Raroia atoll.
8-19-1	6.0	Dredge sample, lagoon, taken off Nengonengo Islet; depth 150 feet.
8-20-1	40.0	Beach sample, lagoon side at Tetou.
8-20-2	10.0	Dredge sample, lagoon, 500 meters west of Pirikau-taringa Islet, depth 80 feet.
8-20-3	12.0	Dredge sample, lagoon, 1000 meters west of Rata, depth 70 feet.
8-21-1	10.0	Dredge sample, center of lagoon between Fakatomo Tahuna Maro, depth 110 feet.
8-21-2	4.0	Dredge sample, lagoon, 500 meters east of Tetou, depth 90 feet.
8-21-3	7.0	Dredge sample, lagoon, 1000 meters east of Tetou, depth 85 feet.
8-21-4	3.0	Beach sample, seaward side at Tetou Islet.
Bottle		Contains forams collected on seaward reef, Garumaoa Islet, at first transect.

In summary, the following conclusions may be drawn with respect to the Foraminifera of Raroia:

1. The lagoon and outer reef of Raroia Atoll support a prolific foraminiferal fauna.

2. Foraminiferal lime sands, silts and mixtures of these were found to be the predominant types of sediments in the lagoon.

3. All samples collected in and around the lagoon contained Foraminifera, ranging from .1% - 72%. The greater percentages of Foraminifera to other constituents occur along the shallow, southeastern or windward side of the lagoon and in general, the smaller percentages appear to occur at the greater depths of the lagoon and along the outer seaward reef.

4. The outer and inner block sands and patch reef sands contain six predominant species. They differ chiefly in relative abundance of individuals of those species. The tests may be largely derived from the reef flats.

5. In general, there is a decrease in relative abundance of Foraminifera with depth.

6. The sediments of Raroia lagoon contain a rich foraminiferal fauna consisting of 56 genera and 126 species. Amphistegina lessoni, was found to

be most abundant in outer and inner beach sands and on shallow lagoon bottom less than six meters deep. Amphistegina madagascarensis, which is common in the beach sands, is the most abundant form in the lagoon becoming rare only at the greatest depths. Marginopora vertebralis is a common associate of Amphistegina lessoni in the beach sands, and has a similar bathymetric distribution. It attains maximum dimensions on the seaward reef.

7. Of the total of 126 species, approximately 22% were found only in the beach sands of the inner and outer reef. These are indicated in the distribution chart. All of the species found in the outer beaches are also represented in the lagoon samples. This is to be expected since sediments are continually being swept lagoonward by storm waves.

Origin of Island Conglomerate and Beachrock.-
The solid rock of the islands of Raroia consists mainly of tightly cemented gravel of low porosity. The coarsest texture, dominantly of cobbles and boulders, is found along the seaward coast, particularly on the lee side of the atoll and along the windward shore of the lagoon. Some of the shore outcrops on the upwind side of the lagoon consist of fine-grained calcarenite, but even along this sheltered shore much of the beachrock consists of pebbled sandstone with fragments an inch or so in diameter.

The fragmental constituents of the rock are mainly broken and worn colonies of corals. An occasional disoriented reef block, however, is incorporated in or welded to the conglomerate. These blocks are composed of entire colonies of Pocillopora elegans in parallel arrangement bound together by Porolithon onkodes.

On the leeward outer shore there are erosional remnants of one or more low, parallel ridges, old beachrock ridges along the seaward lee shore, composed of strata of fine-grained conglomerate dipping seaward at 15 degrees to 20 degrees. These ridges form low cuestas a few centimeters to about one meter high between shallow tide pools. The ridges originally extended seaward as much as 20 to 30 meters as shown by detached low ridges on the reef flat parallel to the shore, and nearly obliterated by erosion. These generally have been completely cut away by the waves on the windward shore.

Inclined beds of beachrock are quite rare along the lagoon shore. At most of the outcrops the rock is essentially unstratified and it is exposed in a low ledge with a vertical face which rises from low water level, or a few centimeters below, to as much as 25 centimeters above normal high water. Clearly the rock has been eroded to some extent and the normal lagoonward inclination of the strata of the original beach has been cut away by erosion.

The modern beaches and ramparts show no tendency for cementation, perhaps because they are frequently disturbed by storms. Small patches of blue-green algae on the sand beaches lightly bind together thin crusts of the sand, but these are not cemented by calcium carbonate. Moat areas behind the lagoon shore ridges and behind the seaward ramparts, particularly those of the windward side of the atoll, frequently are inundated by the sea. In many places these areas

Table 1. Foraminifera from Raroia Atoll, Tuamotu Archipelago, French Oceania

Legend

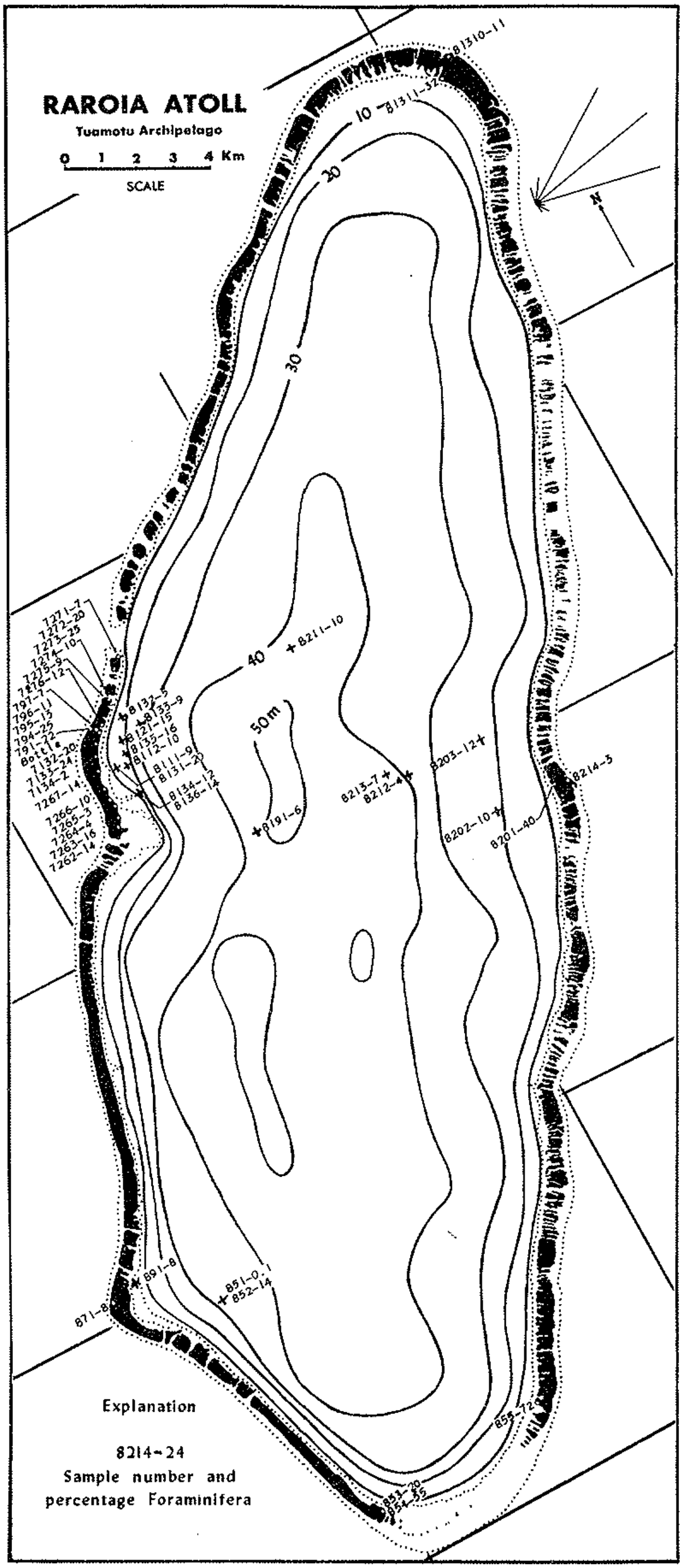
Abundant a
Common c
Rare r
Fragments f

Bathyal distribution and occurrence of lagoon Foraminifera — Dredge Samples (Ft.)

Recent Species	8-9-1 (10')	8-13-4 (40')	8-13-6 (40')	8-13-2 (45')	8-13-5 (60')	8-13-1 (65')	8-13-3 (70')	8-20-3 (70')	8-20-2 (80')	8-21-3 (85')	8-12-1 (90')	8-21-2 (90')	8-21-1 (110')	8-19-1 (150')	8-11-1 (?)	8-11-2 (?)
Acervulina inhaerens Schultze		c	c	c	c	c	c	c	c	c		c	a			c
Amphisorus hemprichi Ehrenberg	c	c				c	c		c						c	
Amphistegina lessoni d'Orbigny	a	r	r	r		r	r	r	r	r		r	r	r	a	
Amphistegina madagascarensis d'Orbigny	a	a	a	a	a	a	a	a	a	a	a			r	a	a
Anomalina globorata Cushman			r						c							
Anomalina grosserugosa Gumbel (?)							r		c							
Anomalinella rostrata (H. B. Brady)			c	c	a	r	c	c	c	c	c	c	a	c	r	a
Archaias aduncus (Fichtel and Moll)	c	a	c	a	c	c	c	c			c	c	c	c	c	
Articulina antillarum Cushman													r	r		
Articulina sagra d'Orbigny			r		c	c	c			c				r		c
Articulina sulcata Reuss					c				c	c	r		r	r		c
Bolivina capitata Cushman		r					c						c	c		c
Bolivina compacta Sidebottom	r										c				r	c
Bolivina ligularia Schwager						c										
Bolivina punctata										c						
Bolivina rhomboidalis (Millet)	r				c	c		c			c	c		r		c
Bolivina striatula Cushman						r				r						
Bolivina subertheloti Cushman											r					
Bolivina tortuosa H. B. Brady	r	r			c					c	c			c	r	r
Bolivina vadescans Cushman											c			c		
Bolivina variabilis (Williamson)		r	c													c
Bolivina vilardeboana d'Orbigny	c		c											c	c	c
Bolivinella folia (Parker and Jones)	c		c		c	c	c		c	c	c	c		c		c
Bolivinella folia (Parker and Jones) var. ornata Cushman											r			r		r
Borelis melo (Fichtel and Moll)	r	r							r							
Buliminella milletti Cushman										r						
Cancris peroblongus (Cushman)										c	c		r	r		
Cassidulina laevigata d'Orbigny														r		
Cibicides lobatulus (Walker and Jacob)							c					c		c	a	
Cibicides refulgens Montfort					c				c	c	c		c	c	r	c
Clavulina communis d'Orbigny						r									r	
Clavulina difformis H. B. Brady	r	r	r	c	c	c	c	a		c	c	c	c	r		a
Clavulina pacifica Cushman			r	c	c	c	c	a		a	c	c	c		a	a
Cornuspira involvens Reuss				r						r						
Cymbalopora bradyi Cushman	c	r		c			r	c	c			c	r	c		c
Cymbaloporetta squammosa (d'Orbigny)					r	c	c		c	c						
Cymbaloporella tabellaeformis (H. B. Brady)						c							c	r		
Discorbis globularis d'Orbigny				c	r	c		c	c	c	c	c		c		c
Discorbis subertheloti Cushman	c		c					r	r			r		c	c	
Discorbis vilardeboana (d'Orbigny)								r								
Eponides punctulatus (d'Orbigny)									c				r	r		
Eponides repandus (Fichtel and Moll)	r				r				r	r	r	r	r	r		
Elphidium jenseni Cushman				c	c	c	c	c	c		c	c		c		
Elphidium macellum (Fichtel and Moll)	c	c		a	a	a	c	c	a	c	c	c	c	a		c
Elphidium macellum (Fichtel and Moll) var. limbatum (Chapman)										c				r		
Fisherina pellucida Millet	r	r		c	c	c	r						r		r	
Globigerina bulloides d'Orbigny	r	r		r			r	r			r		r	r		
Globorotalia canariensis (d'Orbigny)				r	r		r	r	r		r	r	r	r		r
Gypsina globulus (Reuss)		r				c		c	c					r		c
Gypsina vesicularis (Parker and Jones)			r						c	c		r			c	
Heterostegina curva Moebius	c		r		c		r		c		c		c			c
Heterostegina depressa d'Orbigny			c	c	c	c	r	c	c	c	c	r	r		r	c
Heterostegina suborbicularis d'Orbigny			r				r	r	c	r						c
Hauerina bradyi Cushman	c				c			c			c		r	c		c
Hauerina fragilissima (H. B. Brady)	c				c	c	r			r	r			c	c	c
Hauerina ornatissima (Karrer)		c	c	c		c	c	c		c	c	c		c	c	c
Lagena spiralis H. B. Brady														r		
~~Loxostomum limbatum (H. B. Brady)~~		~~c~~			~~c~~						~~c~~		~~c~~	~~c~~		
Loxostomum limbatum (H. B. Brady) var. costulatum (Cushman)		r					c			c						c
Loxostomum mayori Cushman				r												c
Marginopora vertebralis Blainville	c	r	r			r		f	f	f					c	r
Massilina sp.																
Massilina alveoliniformis Millet														r		
Massilina crenata (Karrer)	r									r				r		
Massilina inequalis Cushman									r							
Massilina planata Cushman												r		r		
Miniacina miniacea (Fallas)			f	f			f		f							
Monalysidium sollasi Chapman										r						
Monalysidium politum Chapman	c	c			c		c		c		c	c	c	r		
Nubeculina divaricata (H. B. Brady) var. advena Cushman					r		c	r	c	c	c					
Nonion grateloupi (d'Orbigny)		r	r			c		r				r		r	r	r
Parrina bradyi (Millet)																r
Peneroplis pertusus (Forskal)	c	c					c				c					
Planorbulina larvata (Parker and Jones)	c	c	c	c	c	c	c		c	c		c	c	c		
Pyrgo denticulata (H. B. Brady)		c		c		r		c		c	c		c	c	r	c
Quinqueloculina anquina Terquem	c				c	r	r	c		c			r	r	c	
Quinqueloculina bidentata d'Orbigny		c	c			a	c			a	c				c	c
Quinqueloculina berthelotina d'Orbigny					c									r		c
Quinqueloculina costata d'Orbigny	c	c	c	c		c	c		c	c	c	c		c	c	
Quinqueloculina crassa d'Orbigny															r	
Quinqueloculina linnaena (d'Orbigny)		c	c												r	
Quinqueloculina parkeri (H. B. Brady)				r	c	c	c	c	c	c	c	c	c	c		c
Quinqueloculina polygona d'Orbigny		r	r							c	c			r		
Quinqueloculina samoaensis Cushman	c	c	c			c	c		a	c	c	a	a	a		
Quinqueloculina seminulum (Linne)	c				c	c	c	c	c	c	c	c		c	c	c
Quinqueloculina sulcata d'Orbigny	a	c	c	a	a	a	c	c		c	c	c	c	c	c	c
Quinqueloculina striata d'Orbigny	r															
Quinqueloculina tropicalis Cushman			c	c	c	c	c			c	c			r		c
Quinqueloculina transversicata H. B. Brady														r	r	
Quinqueloculina undosa Kerrer						r										
Quinqueloculina sp.	c	c				c	r				c			c		c
Rotalia sp.										r						
Reussella spinulosa (Reuss)	c	c	c		c	c	c	c	c	c		c	c	c	c	c
Schlumbergerlina alveoliniformis (H. B. Brady)			c	c	c	r	r		r		c	r	r	c	c	c
Siphogenerina raphana (Parker and Jones)		r	r	c	c	c	c		c	c	c	c		c	c	c
Siphonina tubulosa Cushman						r	r		r	r	r	r				
Sorites marginalis (Lamarck)	c	c	c	a	c	a	a	c	c	c	c	c	c		c	c
Spirillina inequalis H. B. Brady				r												
Spirillina limbata H. B. Brady			r						r					r		
Spirillina spingera Chapman				r												
Spirillina subbertheloti Cushman									r							
Spirillina vivipara Ehrenberg							r									
Spirolina arietinus (Batsch)	c	c	c	c	c	c	c	c	c	c	c	c			c	c
Spirolina acicularis (Batsch)	c	r		c	c	c	c		c		c	c	r	c	r	c
Spiroloculina antillarum d'Orbigny	a	c	c		c	c	c	c	c	c	c	a			a	
Spiroloculina antillarum d'Orbigny var. angulata Cushman		c						c	c			c				c
Spiroloculina grataloupi d'Orbigny										r			r			
Spiroloculina mayori Cushman				r		c	c	r	r	c	c	c	r	r		r
Spiroloculina planissima (Lamarck)				r	r				r			r				
Spiroloculina sp.								r		r						
Textularia agglutinans d'Orbigny		r		c	c	c	c	c	c	c	c	c		c	r	c
Textularia candeiana d'Orbigny		r	r	c	c	a	a	a	a	a	a	a	a	a	r	c
Textularia conica d'Orbigny		r		r			r		c	r	r	c		r	r	c
Textularia corrugata Heron - Allen and Earland				r		r										
Textularia sp.										r		r				
Tretomphalus bulloides (d'Orbigny)	c	c	r	r		r		r		c			a	c	c	r
Tretomphalus milletti Heron - Allen and Earland											r	r	r			
Triloculina austriacea d'Orbigny			r	c	r		c		c							c
Triloculina circularis Borneman									r				r	r		
Triloculina irregularis (d'Orbigny)			c	c		c	c	c		r			c	a	c	
Triloculina labiosa d'Orbigny								c		c		r				
Triloculina oblonga (Montagu)										r				r		
Triloculina oceanica Cushman					r											
Triloculina tricarinata d'Orbigny	c	c	c		c		c			c		c	c	c	c	
Triloculina trigonula (Lamarck)						c		c					c			c

Occurrence of Foraminifera from the shore-sands — Beach Samples
+ indicates seaward reef

Recent Species	+7-9-1	+7-9-4	+7-9-5	+7-9-6	+7-9-7	7-13-2	7-13-3	7-13-4	+7-22-1	+7-23-1	7-26-2	7-26-3	7-26-4	7-26-5	7-26-6	7-26-7	7-27-1	7-27-2	7-27-3	7-27-4	7-27-5	7-27-6	8-5-1	8-5-2	8-5-3	8-5-4	8-5-5	+8-7-1	+8-13-10	8-13-11	8-20-1	+8-21-4
Acervulina inhaerens Schultze																																
Amphisorus hemprichi Ehrenberg		r	r	r		r			c		r												c	c						r		
Amphistegina lessoni d'Orbigny	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Amphistegina madagascarensis d'Orbigny	c	c	c	c	r	r	r	c	c	c	r	c	c	c	c	c		c		c	a	[illegible]	c	c	c	r	c	r	c	c	c	c
Anomalina globorata Cushman																																
Anomalina grosserugosa Gumbel (?)																																
Anomalinella rostrata (H. B. Brady)							r	r																					r			
Archaias aduncus (Fichtel and Moll)																																
Articulina antillarum Cushman																																
Articulina sagra d'Orbigny																																
Articulina sulcata Reuss																																
Bolivina capitata Cushman																																
Bolivina compacta Sidebottom																																
Bolivina ligularia Schwager																																
Bolivina punctata																																
Bolivina rhomboidalis (Millet)																																
Bolivina striatula Cushman																																
Bolivina subertheloti Cushman																																
Bolivina tortuosa H. B. Brady																																
Bolivina vadescans Cushman																																
Bolivina variabilis (Williamson)																																
Bolivina vilardeboana d'Orbigny																																
Bolivinella folia (Parker and Jones)																																
Bolivinella folia (Parker and Jones) var. ornata Cushman																																
Borelis melo (Fichtel and Moll)																										r						
Buliminella milletti Cushman																																
Cancris peroblongus (Cushman)																																
Cassidulina laevigata d'Orbigny																																
Cibicides lobatulus (Walker and Jacob)																																
Cibicides refulgens Montfort																																
Clavulina communis d'Orbigny																																
Clavulina difformis H. B. Brady																																
Clavulina pacifica Cushman																		r		r												
Cornuspira involvens Reuss																																
Cymbalopora bradyi Cushman																																
Cymbaloporetta squammosa (d'Orbigny)						c			c												r											
Cymbaloporella tabellaeformis (H. B. Brady)	r								c																							
Discorbis globularis d'Orbigny																																
Discorbis subertheloti Cushman						r										r																
Discorbis vilardeboana (d'Orbigny)																																
Eponides punctulatus (d'Orbigny)																																
Eponides repandus (Fichtel and Moll)																																r
Elphidium jenseni Cushman						r																										
Elphidium macellum (Fichtel and Moll)																																
Elphidium macellum (Fichtel and Moll) var. limbatum (Chapman)																r								r								
Fisherina pellucida Millet																																
Globigerina bulloides d'Orbigny																																
Globorotalia canariensis (d'Orbigny)																																
Gypsina globulus (Reuss)				r																								c	c			
Gypsina vesicularis (Parker and Jones)																																
Heterostegina curva Moebius																																
Heterostegina depressa d'Orbigny	r					r	r													r								r				
Heterostegina suborbicularis d'Orbigny																				r												
Hauerina bradyi Cushman																																
Hauerina fragilissima (H. B. Brady)																																
Hauerina ornatissima (Karrer)																																
Lagena spiralis H. B. Brady																																
~~Loxostomum limbatum (H. B. Brady)~~																																
Loxostomum limbatum (H. B. Brady) var. costulatum (Cushman)																																
Loxostomum mayori Cushman																																
Marginopora vertebralis Blainville	a	a	a	a	c	c	a	c	c	a	a	c	r	r	c	a	r	r		c	c	r	a	c	a	a		c	c	a	c	c
Massilina sp.																																
Massilina alveoliniformis Millet																																
Massilina crenata (Karrer)																																
Massilina inequalis Cushman																																
Massilina planata Cushman																																
Miniacina miniacea (Fallas)		f	f	f			f		f		f			f		f	f	f		f	f	f			f	f	f	f	f	f	f	
Monalysidium sollasi Chapman																																
Monalysidium politum Chapman																																
Nubeculina divaricata (H. B. Brady) var. advena Cushman																																
Nonion grateloupi (d'Orbigny)																																
Parrina bradyi (Millet)																																
Peneroplis pertusus (Forskal)																																
Planorbulina larvata (Parker and Jones)																																
Pyrgo denticulata (H. B. Brady)																																
Quinqueloculina anquina Terquem																																
Quinqueloculina bidentata d'Orbigny																																
Quinqueloculina berthelotina d'Orbigny																																
Quinqueloculina costata d'Orbigny																																
Quinqueloculina crassa d'Orbigny																																
Quinqueloculina linnaena (d'Orbigny)																																
Quinqueloculina parkeri (H. B. Brady)															r																	
Quinqueloculina polygona d'Orbigny																																
Quinqueloculina samoaensis Cushman																																
Quinqueloculina seminulum (Linne)																																
Quinqueloculina sulcata d'Orbigny						r			c									r			r											
Quinqueloculina striata d'Orbigny																																
Quinqueloculina tropicalis Cushman																																
Quinqueloculina transversicata H. B. Brady																																
Quinqueloculina undosa Kerrer																																
Quinqueloculina sp.																											r					
Rotalia sp.																																
Reussella spinulosa (Reuss)																																
Schlumbergerlina alveoliniformis (H. B. Brady)																				r												
Siphogenerina raphana (Parker and Jones)																																
Siphonina tubulosa Cushman																																
Sorites marginalis (Lamarck)	c	c	c	c	c	c	r	c	c	c	c	c	r	c	c	c		c		c	c		c	r	c	a			c		c	c
Spirillina inequalis H. B. Brady																														r		
Spirillina limbata H. B. Brady																																
Spirillina spingera Chapman						r									r																	
Spirillina subbertheloti Cushman									r																							
Spirillina vivipara Ehrenberg																																
Spirolina arietinus (Batsch)																																
Spirolina acicularis (Batsch)																																
Spiroloculina antillarum d'Orbigny						r					r	r						r														
Spiroloculina antillarum d'Orbigny var. angulata Cushman																																
Spiroloculina grataloupi d'Orbigny																																
Spiroloculina mayori Cushman																																
Spiroloculina planissima (Lamarck)						r																										
Spiroloculina sp.																																
Textularia agglutinans d'Orbigny																																
Textularia candeiana d'Orbigny																																
Textularia conica d'Orbigny																																
Textularia corrugata Heron - Allen and Earland																																
Textularia sp.																																
Tretomphalus bulloides (d'Orbigny)						c															r											
Tretomphalus milletti Heron - Allen and Earland																																
Triloculina austriacea d'Orbigny												r		r																		
Triloculina circularis Borneman																																
Triloculina irregularis (d'Orbigny)																																
Triloculina labiosa d'Orbigny																																
Triloculina oblonga (Montagu)																																
Triloculina oceanica Cushman																																
Triloculina tricarinata d'Orbigny																																
Triloculina trigonula (Lamarck)																																



5. Map of Raroia showing location of samples of foraminiferal sand

are actually below the level of high water. Wherever a surface inlet is lacking, sea water seeps through and beneath the gravel rampart at high water stage. These places are swampy and are underlain by organic muck and sand. Moats with surface access to the sea at high water levels commonly are free of muck and have a firm floor of gravel and sand. It is particularly in these areas that cementation of the sediments by calcium carbonate is taking place. Here blue-green algae extend several millimeters into the sediments and into the coral fragments. Beneath the gray stain of the surface is a thin green layer colored, probably, by chlorophyll. The pebbles and sand are here and there bound together by filaments into a firm friable fabric several centimeters thick. The sediments immediately below the algal crust are lightly cemented for a few millimeters, below which the rock is firmly cemented.

Without experimental data it is difficult to judge the function, if any, of the blue-green algae in cementation of the sediments. Certainly the binding action of the algae is of significance in anchoring the sediments until they can become cemented, a process which on Raroia evidently requires much more time than elapses between storms (Cloud, 1952, p. 29). It is also possible that the algae dissolve calcium carbonate at surfaces of contact. If so, this dissolved calcium carbonate might be available for cementation immediately below the surface.

I agree with K. O. Emery (personal communication) that sea water, which is saturated with calcium carbonate, is probably the most important source of the cementing agent. There is little evidence that meteoric water plays a significant role here. Normal sea water floods these moats twice daily, and for hours at a time the areas are exposed to the air with consequent concentration of salts held in the sediments. It is highly probable that lime is precipitated under these conditions and that part of it is incorporated as cement in the sediments.

There are two other situations in which lithification of sediments apparently is taking place. The test pits and water wells on Garumaoa Islet contain friable sandstone below about the highest level of the fluctuating water table. The water ranges from brackish to fresh and presumably is saturated with calcium carbonate most of the time. Rain water, percolating down through the loose sediments carries dissolved lime to the water table where it is concentrated. There is no indication of large scale upward migration of calcium carbonate by capillarity to form caliche. Evaporation rates probably are not high under existing mild climatic conditions.

The third condition is encountered on the seaward reef flat, particularly on the windward side of the atoll at the edge of the conglomerate platform, where coral blocks and reef blocks are occasionally welded loosely to the reef flat by means of blue-green algae. Algal blackened coral slabs, mainly <u>Acropora conigera</u>, imbricating toward the sea, form continuous patches of rubble in the intertidal zone. Fresh fractures reveal a green layer of living algae beneath the blackened surface film. At first examination it seems that the conglomerate platform of the windward shore is being extended by deposition at the shore of coral rubble. However, closer examination indicates that the rock platform is generally retreating. The algal cementation is not permanent under existing conditions. An earlier margin of the platform is identifiable by the erosion remnants and can be mapped well out on the reef flat. Apparently reef blocks are temporarily and loosely attached at the shore to be later stripped away during storms.

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