GEOLOGICAL RECONNAISSANCE OF RAROIA (KON TIKI) ATOLL, TUAMOTU ARCHIPELAGO

NORMAN D. NEWELL

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CONTENTS

Introduction 317
The Expedition to Raroia 317
Field Operations 318
The Map 318
General Results 319
Some Fundamental Problems of Atolls 320
Regional Setting of the Tuamotu Archipelago 323
Climate 327
Currents 327
Southern Swell 328
Hurricanes and Tsunamis 328
Physical Characteristics of Raroia 329
The Atoll Rim 330
Channels and Islets 330
Island Conglomerate Platform 330
Joints 332
Ramparts and Beaches 333
Island Gravel 333
Terraces 334
Erosion of the Land 335
Ground Water 335
Soils 336
Stratigraphy 337
Reefs and Sedimentary Processes of Raroia 340
The Outer Reef 340
Reef Front 341
Groove and Spur System 341
The Algal Ridge 344
Surge Channels 346
The Reef Flat 346
Erosion of the Reef Flat 351
Lagoon Reefs 351
Lagoon Shore Reefs 351
Patch Reefs 353
Reef Biota 354
Diversity 354
Reef Builders 354
Shore Processes 356
The Shore Profile 356
Solution of Limestone by Sea Water 358
Organisms as Agents of Shore Erosion 360
Exfoliation 360
Sedimentation 360
The Sediments. By John V. Byrne 361
Distribution of Foraminifera. By Joseph T. Sperrazza 363
Reef Limestones 365
Origin of Island Conglomerate and Beach Rock 368
Bibliography 370

INTRODUCTION

THE EXPEDITION TO RAROIA

AN INTENSIVE ECOLOGICAL reconnaissance of Raroia,[1] a Polynesian atoll about 450 miles northeast of Tahiti, was successfully completed during July and August, 1952, by a seven-man research team[2] representing the biological and geological sciences. This study, the third project in a program of atoll studies organized by the Pacific Science Board of the National Research Council and supported principally by contract N7-onr-291(04), NR 388-001 with the Office of Naval Research, enjoyed the active aid of the French colonial government at Tahiti, without which the study of Raroia could not have been undertaken. Funds equal to about 20 per cent of the total budget were supplied to some of the team members by the American Museum of Natural History, under a grant from the Humble Oil and Refining Company, and by the United States National Museum, the University of Hawaii, and Mr. George Vanderbilt.

Although excellent results were obtained, the team was handicapped by failure to receive approximately one-half of the expedition equipment, strike-bound on the eve of departure in a California port. Part of this highly specialized equipment, assembled at considerable cost over many months, was generally irreplaceable and the success of the expedition was therefore jeopardized. Essential items withheld from the team in this way included a boat, several rafts, outboard motors, a compound microscope, books for field determinations of corals and plants, an under-water camera, fishing gear, warfarin for studies in rat extermination, fish poison, and gasoline. Without replacement of some of the most crucial of these items a comprehensive study of Raroia could not have been undertaken.

The problem of supply was difficult for the expedition, because freight sailings from the United States to Tahiti are infrequent, and there were none from Hawaii where the team members were convening early in June. The expedition was reprieved by the circumstance that the Tahiti government had just purchased a small vessel which was being prepared in Honolulu for an early voyage to Papeete. Through the courtesy of His Excellency H. René Petitbon, Governor of French Oceania, certain replacement items were carried on this vessel to Tahiti. These included fishing gear and poison, warfarin, special fish drums, cans and canning equipment for sea weeds, and one outboard motor. The equipment and supplies were delivered to the team on Raroia in time for use of most items but too late for use of the warfarin in the projected studies on rats. The rat poison was returned to Papeete and turned over to the Institut de Recherches Médicales de l'Océanie Française for studies in Tahiti.

In the course of the trip to the South Pacific, the field team had the opportunity of observing and photographing a great variety of coral reefs from the air in the Fiji, Cook, Tonga, Society, and Tuamotu groups. Brief stops at Veti Levu, Aitutaki, Tahiti, Anaa, and Hikueru enabled the team to make closer, but cursory examinations of the reefs of these islands.

The selection of Raroia among the numerous atolls of French Oceania was most fortunate. The selection was made because the team anthropologist, Bengt Danielsson, had recently spent 18 months on the atoll studying acculturation of the people. He was thoroughly familiar with the language, the inhabitants, and working conditions. More important, he was assured of the complete support of the people. He was enthusiastically welcomed as an adopted son of a Raroia family and a member of the community. He came to the people first as a member of the intrepid "Kon Tiki" crew, later as a scholar and student of their ways, and they had acquired a respect for him that amounted almost to veneration.

Because of these special circumstances, the people made available to the expedition team their considerable resources, including boats, outboard motors, clean cistern water, several houses, a shower bath house, a toilet, refrigerators, and all-wave radio receivers. The transportation facilities were neither adequate nor reliable, but they permitted a successful comprehensive reconnaissance of the atoll.

Besides supplying transportation for part of our equipment from Honolulu to Tahiti, Governor Petitbon provided round-trip transporta-

[1] Pronounced Rah-ro-ee-a.

[2] Members of the expedition, in addition to the author, who served as leader of the field team, were John V. Byrne, Bengt Danielsson, Maxwell S. Doty, Robert R. Harry, J. P. E. Morrison, and W. Jan Newhouse.

tion from Papeete to Raroia on the government schooner "Tamara." M. Frederick Ahnne, Administrator of the Tuamotu Archipelago, accompanied the team to Raroia to explain the government's interest in the project to the people of the atoll. The Governor arranged also for the charter of the Air Tahiti Gruman-Condor seaplane for the purpose of an aerial photographic survey of Raroia by the expedition members. The Papeete government contributed a substantial part of the charter cost, so that a medical officer could visit Raroia, Hikueru, and Anaa for routine examinations of the population. He also persuaded Colonel Chavat, chief of a French mapping mission, to accompany the flight to Raroia in order to assist in obtaining suitable photographs of the atoll.

The staff of the Institut de Recherches Medicales de l'Océanie Française, Dr. John Kessel, Dr. Georges Torres, and Mr. and Mrs. Glen Parrish, were helpful and courteous to members of the expedition. Helpful aid and counsel were freely given by many of the citizens of Papeete.

Mrs. Valerie Zirkle Newell and Mr. G. Robert Adlington of the American Museum of Natural History devoted many weeks to the selection, purchase, and packaging of expedition supplies in New York, and Mrs. Newell, who preceded the research team to Tahiti, gave valuable aid there in completion of arrangements with the Government. Without Mrs. Newell's intervention it is doubtful that the difficult but urgent radio communication between Papeete and Raroia would have been finally established. Untiring efforts of the staff of the Pacific Science Board, Dr. Harold J. Coolidge, Mrs. Lenore Smith, and Miss Ernestine Akers, on behalf of the expedition were in large measure responsible for the successful conclusion of the field work.

Through the courtesy of Dr. Preston E. Cloud, Jr., a pH meter and a plane table, alidade, and surveying rod of the United States Geological Survey were made available on loan for our studies. Dr. John W. Wells identified the corals and Mr. Joseph T. Sperrazza, the Foraminifera.

Fortunately for the needs of the expedition, the people of Raroia are moderately prosperous. They live in a single village, Garumaoa[1] (Ngarumaova), situated on the lagoon near the single ship pass. The numerous facilities of the village of 127 persons were more or less continuously available to the research group. Two radio receivers monitored the Papeete programs almost continuously, so that official messages in the Tahitian language sent to us from Tahiti were promptly received and delivered. This was a valuable service during three difficult weeks before our contact with Papeete, via Hikueru, was established by means of our small hand-generated two-way radio.

The climate of Raroia is ideal, and altogether the working conditions were very comfortable.

FIELD OPERATIONS

All direct negotiations with the people were turned over to Danielsson, who was aided by Miss Aurora Natua, a Tahitian scholar. Besides his own scientific investigations of the people, Danielsson was given charge of the medical supplies, the kitchen help, and the paying of wages. General camp policies and project plans were developed by the combined team.

Scientific activities were distributed as follows: physical ecology of the atoll (geology) and coral distribution, Norman D. Newell, assisted by John V. Byrne; biological factors of ecology, and plant distribution, Maxwell S. Doty, assisted by Jan Newhouse; animal distribution, excepting corals and fishes, J. P. E. Morrison; fish distribution and ecology, Robert R. Harry; ethnology and human ecology, Bengt Danielsson.

THE MAP

The flight for aerial photographs was taken during the early morning of June 20, 1952, which luckily happened to be a clear day, the only one in a long series of overcast days. Two 35-mm. Argus C-3 cameras with K2 filter were used interchangeably for vertical views. One camera at a time was mounted in a blister replacing a side window. Bengt Danielsson and Maxwell Doty operated these two cameras,

[1] We have adopted standard Polynesian rather than French forms of the native names. The Polynesian *g* is pronounced and often spelled *ng*.

making exposures at 15-second intervals. The flight was made at an altitude of 3000 meters in order to obtain negatives of convenient scale (1:60,000), and the scale was later confirmed on the ground by plane-table traverse. Surprisingly good results were obtained in two circuits of the atoll with nearly complete coverage (95%) of the rim. In addition, oblique photographs of the lagoon show hundreds of small patch reefs. The vertical photographs were printed at 1:20,000, and this scale was employed for compilation of a base map (fig. 15). The negatives have been filed with the Colonial Government in Papeete. During this flight we visited Anaa and Hikueru atolls and examined several other atolls of the archipelago from the air.

The aerial oblique, ground, and under-water photographs included in the present paper were taken by Newell with a Contax 35-mm. camera. All the other illustrations were prepared and drawn by the author.

GENERAL RESULTS

Raroia is similar to other Tuamotuan atolls but conspicuously unlike recently studied atolls of Micronesia (Bikini, Arno, and Onotoa). Since Polynesian atolls generally have been inadequately known, Raroia may well serve as a standard of reference for Polynesia. Great quantities of field data and specimens were obtained. The collections indicate an unexpectedly rich biota comparable to those of Samoa and Bikini. Our results suggest that previous conclusions have been based on inadequate collections. For example, 286 species of fishes have been known from all of the Tuamotus, but our collections from Raroia included approximately 400 species. Fifteen species of corals have been known previously from the Tuamotus, but our collections from Raroia contain 53 species. This work shows that very many species range much farther to the east in the Pacific than had been believed, and knowledge of the biota of the central South Pacific has been expanded. Data on the people and their history are especially complete. Results on the expedition to Raroia have been issued as Atoll Research Bulletin, Numbers 18 and 31 to 36, National Research Council, Washington, D.C., 1953–1954. Danielsson (1955) has published results of his anthropological studies in book form.

SOME FUNDAMENTAL PROBLEMS OF ATOLLS

CORAL ATOLLS, justly celebrated in a voluminous scientific literature running into thousands of pages, have long attracted the fascinated attention of voyagers in tropic seas. The center of interest until recently has lain chiefly in the genesis of reef forms and the nature and origin of the central lagoon which gives atolls their most characteristic expression.

Atolls support more or less balanced marine and usually also terrestrial communities surrounded by apparently sterile waters such as characterize the plankton-poor waters of the tropics and subtropics. The origin and economy of these relatively simple communities provide many unsolved ecological problems of the greatest fundamental importance.

Consider the difficult and complex initial colonization of a newly formed shoal area or volcanic island surrounded by deep sea. In the great eruption of Krakatau in 1883 the local island life and shoal-water organisms were largely exterminated, and the area for a time was rendered uninhabitable for most species (Sluiter, 1889; Dammerman, 1948). Within a few weeks reinoculation by airborne and seaborne spores, seeds, larvae, and adults of hardy pioneers was begun. Colonization of Krakatau, carefully studied by Dutch biologists, seems to have followed predictable probabilities directly related to size, larval hardiness, length of migratory stage, and various other factors that make up the repertory of dispersal facilities in each form. Some species arrived early, others later, the relative time of introduction being directly related to the frequency with which colonizers of each species could successfully bridge the barrier of deep water. Only the barest outline in this complex series of events is really known. Much must still be inferred.

The colonization of a volcanic mountain like Krakatau on first consideration may appear much more complex than the colonization of a low, relatively sterile atoll. However, avoiding for the moment the involved question of the various origins of atolls, it is generally agreed that many atolls undoubtedly did originate through the gradual sinking of reef-encircled volcanic mountains. The biota of such atolls might be considered relicts derived from ancestral high islands, restricted and modified by relatively homogeneous and almost monotonous ecologic conditions.

The ecologic simplicity of atolls makes them especially attractive to those who would try to understand the interrelationships and processes among the organisms of a primitive sea-land community. This simplicity, however, is only apparent and misleading. Most of the ecologic problems of atolls are indeed poorly understood.

The ecologic interrelationships between coralline and other kinds of algae on the one hand and the coral animals so characteristic of tropical reefs are not understood. The intimate and almost universal association in reefs of these specialized plants and animals strongly suggests that they may be interdependent. Reef-building (hermatypic) corals invariably contain in their tissues zooxanthellae, unicellular algal symbionts, which aid the corals by utilization of animal waste and by secretion of oxygen. Many corals feed exclusively on animal plankton (Yonge, 1940), which in turn must feed on phytoplankton. Sargent and Austin (1949) have determined that the quantity of plankton swept across the reefs of the northern Marshalls by wind-driven currents is grossly inadequate to support the reef animals. They conclude, therefore, that the reefs are self-supporting, that is, the reef algae produce at least as much organic matter as consumed by the reef animals, and that the rate of production of organic matter by an atoll as a whole is several times as high as that of the surrounding ocean. Rather than filtering plankton, the marine community of the atoll, according to these investigators, absorbs inorganic nutrients from the passing equatorial current (Sargent and Austin, 1949, pp. 245–249).

Surface tropical waters in midocean are classically considered deficient in nutrient salts. The situation over deep waters near coral reefs has not been sufficiently investigated, but it is probable that the turbulent flow around coral reefs extends to considerable depth and this turbulence certainly brings nutrient-rich deeper waters to the surface. Orr (1933, p. 62) found evidence of upwelling along the Great Barrier Reef. This phenomenon probably is most pronounced during rough weather when it is difficult to make observations.

Coral animals and coralline algae generally are most productive at the outer margins of sea reefs. This growth vigor seems to be related to the relative transparency of the water which is greatest on the seaward side of the reef. Thus photosynthesis of zooxanthellae and coralline algae extends to maximum depths at the front of a reef (Yonge, 1940, p. 382). Yonge (*op. cit.*) considers this factor more important than greater supplies of oxygen and animal plankton at the outer reef edge.

It is a matter of considerable interest that a low bank of coral gravel thrown up above high-tide level by a storm very quickly supports a characteristic varied assemblage of higher plants without the development of humus. Coconuts germinate and become healthy trees in apparently sterile gravel. It has been demonstrated that several kinds of algae fix nitrogen from the air, and some of these grow better on an alkaline substratum than elsewhere. Algae aided by bacteria fix nitrogen better than do the bacteria alone (Chapman, 1941, p. 304). It may be considered as probable that the fertility of newly exposed accumulations of coral gravel and sand is to a large extent a result of the activities of nitrogen-fixing algae and bacteria having a range of osmotic tolerance such as characterizes the flora of the littoral zone. Some of these very likely are normal inhabitants of the sea.

Sea birds, which rest on rocks and gravel bars, precede the terrestrial vegetation and enrich the ground with fertilizer gathered over a wide radius of open sea. Surely investigations into the colonization and productivity of atolls should yield significant results. Hatheway (1953) has emphasized the relationship between atoll vegetation and variations in the bird populations and phosphate concentrations in the soil.

FIG. 1. Map of Pacific Ocean showing relationship of equatorial currents to the Tuamotus and other island groups.

Coral atolls are enormous accumulations of calcium carbonate held together by a comparatively thin retaining wall of reef limestone. Interest in the conditions of origin of limestones has greatly stimulated geologists to investigate calcium carbonate in modern seas. In most areas of the sea floor at the present time and during the geologic past calcareous material has been predominantly in the form of skeletal structures of animals and plants; hence the sedimentationist, the paleontologist, and the marine biologist are all directly concerned with the problem of formation of such sediments. Calcium carbonate is also precipitated directly from sea water to form inorganic muds and sands (Newell *et al.*, 1951). Although the problem has been under study for many years, final conclusions cannot be reached regarding the relative importance of inorganic precipitation because the solubility of calcium carbonate in sea water is not well understood.

Surveys by many investigators (Trask, 1938) show that the calcium carbonate content of modern marine sediments is greatest at low latitudes. This is related certainly to the higher production of calcareous skeletons of animals and plants in warm waters, and to the fact that warm marine waters often are supersaturated with calcium carbonate. It is well known that animals with calcareous skeletons, such as corals, mollusks, and Foraminifera, can extract lime from unsaturated waters, but the exact manner in which this is done is not fully understood. In any case, the secretion of lime by these organisms is enormously greater in warm, shallow seas where the waters are supersaturated with respect to calcium carbonate. In the case of lime-secreting algae, extraction of carbon dioxide during photosynthesis causes concentration of carbonate ions and precipitation of lime. Heating of the water and concentration due to evaporation will also cause precipitation of calcium carbonate from sea water, particularly when the water is agitated.

The coral reefs of the South Pacific are among the chief areas of calcium carbonate deposition. It is no doubt significant that these, like other important areas of lime accumulation in the Atlantic and Indian oceans, are bathed by warm equatorial currents (fig. 1) probably supersaturated with respect to calcium carbonate. It is highly probable that deposition of lime sediments in all these areas would be greatly diminished or even negligible without a "conveyor belt" source of supply.

REGIONAL SETTING OF THE TUAMOTU ARCHIPELAGO

LYING NEAR THE CENTER of the Pacific Ocean, the Tuamoto Archipelago is exceptionally isolated from both eastern and western continents. The atolls of this group are outposts at the southeastern fringe of the great Indo-Pacific biological realm, separated from the Americas by the most effective water barrier on earth to migrations of shallow marine and terrestrial organisms, the broad and uninterrupted deep waters of the eastern Pacific (fig. 2). The biota of the Tuamotus is an attenuated Indo-Pacific[1] assemblage having little in common with that of the Americas (Ekman, 1953, p. 72). It was derived mainly from the west, partly by innumerable island jumps and perhaps via the equatorial counter current (fig. 1) and other occasional drifts opposed to the prevalent westerly circulation at these low latitudes.

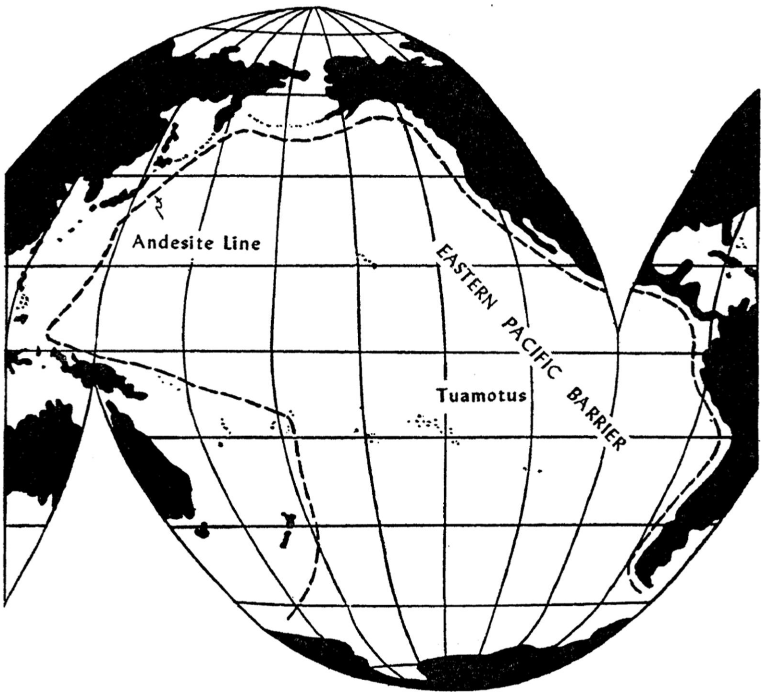


FIG. 2. Map of Pacific Ocean showing andesite line and eastern Pacific barrier to animal and plant migrations.

[1] Locally, as at Clipperton Island, less than 700 miles from Mexico, Indo-Pacific elements have successfully crossed most of the eastern Pacific without really obtaining a foothold along the Americas (Hertlein and Emerson, 1953).

Most of the Polynesian islands are oceanic in the sense that they lie well inside the andesite line (fig. 2) which is rather generally held by geologists to form the structural margin of the Pacific Ocean.

Many geologists now favor the view that the continents are gradually expanding by successive orogenies at the expense of the ocean basins. Implicit in this view is the belief that the island arcs of the western Pacific rather than representing old and collapsed areas are late increments welded to the Austral-Asiatic continent.

Next to the Maldives the Tuamotu Archipelago contains the greatest number of atolls, spread in a broad belt two hundred miles wide and more than a thousand miles long from northwest to southeast. The 78 islands of the Archipelago, of which 76 are true atolls and the remaining two elevated atolls, are arranged in several linear series reminiscent of volcanic arcs (fig. 3), but volcanic rocks are not exposed in this group. The distribution and proximity of these atolls to the volcanic Society Islands, which ideally illustrate the successive stages in Darwin's theory of subsidence, encourage the view that the Tuamotu atolls rest on chains of volcanic mountains which have sunk beneath the sea so slowly that the reef growth has been successfully maintained near the surface.

The Society group (fig. 3) provides an impressive display of all the stages in the classical theory of the evolution of coral atolls by slow subsidence of a volcanic island. Doubtless this region, more than any other, influenced both Darwin and Dana in the development of their coral atoll theory. One of the islands of this chain, Mehetia, is a recent volcano not yet encircled by a reef. It is but moderately cliffed, and, unlike the other islands, it retains part of the original crater. The volcanic islands are generally surrounded, however, by protecting reef fringes and barriers in various stages of development (pl. 22; pl. 23, fig. 2). The southeastward trend of the Society Islands includes a number of true atolls (fig. 3). It seems probable that the various islands of this chain vary considerably in age, the atolls being, in general, older than the high islands.

Stearns (1946) has suggested that the reefs of atolls were originally established in shallow water on the crests of submarine folds. However, Kuenen (1947) points out that the postulated folds would all have to rise to about the same critical level of reef growth near the surface, an extremely unlikely coincidence. Following Daly's conclusion (1910) that all pre-Pleistocene reefs were killed and destroyed during low-water levels of the Pleistocene, Kuenen argues that solution, rather than mechanical destruction, may have reduced many limestone banks and islands to the temporary low-water levels. I am inclined to believe that only the smallest limestone islands were truncated during Pleistocene lows. For example, there are innumerable small limestone cays and islands in the Bahamas, British West Indies, which were terraced during Pleistocene low levels, but the general forms of the islands were not much affected. Terraces cut at this time are rarely more than a half mile wide (e.g., Newell *et al.*, 1951). Most likely the Pleistocene low levels resulted in some deundation of exposed surfaces, but there is no compelling evidence for extensive marine planation during the short duration of the low levels. Evidently the reef organisms were not eliminated, but they were maintained near the level of the fluctuating sea. It is, of course, possible that some atolls may lie over wave-cut platforms, or guyots (see Hamilton, 1953; Dietz, 1954).

There are rather striking features that characterize most of the Tuamotu atolls, and Raroia is in most respects typical of the group. The regional trend of islands throughout the south central Pacific is from southeast to northwest, but a few of the atolls along the northeast side of the archipelago, including Raroia, are elongate towards the northeast, at right angles to the regional trend. The prevailing currents in this area are also from the northeast. However, as there is little correspondence between form and current direction in most of the atolls, it seems safe to conclude that the northeast elongation of Raroia and a few other atolls reflects structural conditions of the basement divergent from the regional trend. Doubtless the lineation of the atolls reflects ancient outpourings of lava along regional tension fractures.[1]

The configuration of the sea floor around the Tuamotu group is very poorly known. A few soundings taken by the "Albatross" suggest that the northwestern atolls of the archipelago rise from a platform or ridge about 800 fathoms beneath the surface. Soundings around the central and eastern atolls indicate smaller plateaus or spurs uniting adjoining islands and show that the eastern atolls are separated by channels of great depths (Agassiz, 1903, p. xxviii).

Subsidence is not invariably involved in the origin of atolls. Hoffmeister and Ladd (1944) have satisfactorily demonstrated that some atolls of the Fiji and Tonga Islands have been formed over platforms not subject to extensive and long-continued down-warping (pl. 23, fig. 1). The processes of deposition and accumulation by which the margins of a shallow marine platform are built up may include reef growth and the construction of various kinds of marginal ridges of detrital calcareous sediments such

[1] Ranson (1955c) suggests that details of form of the Tuamotuan atolls reflect the basement topography. According to this interpretation the atoll rim would correspond to a subcircular rim (crater?) of igneous rock, and patch reefs of the lagoons would lie over original prominences of the basement. This is an old idea that has little support today, and I am not aware of supporting evidence.

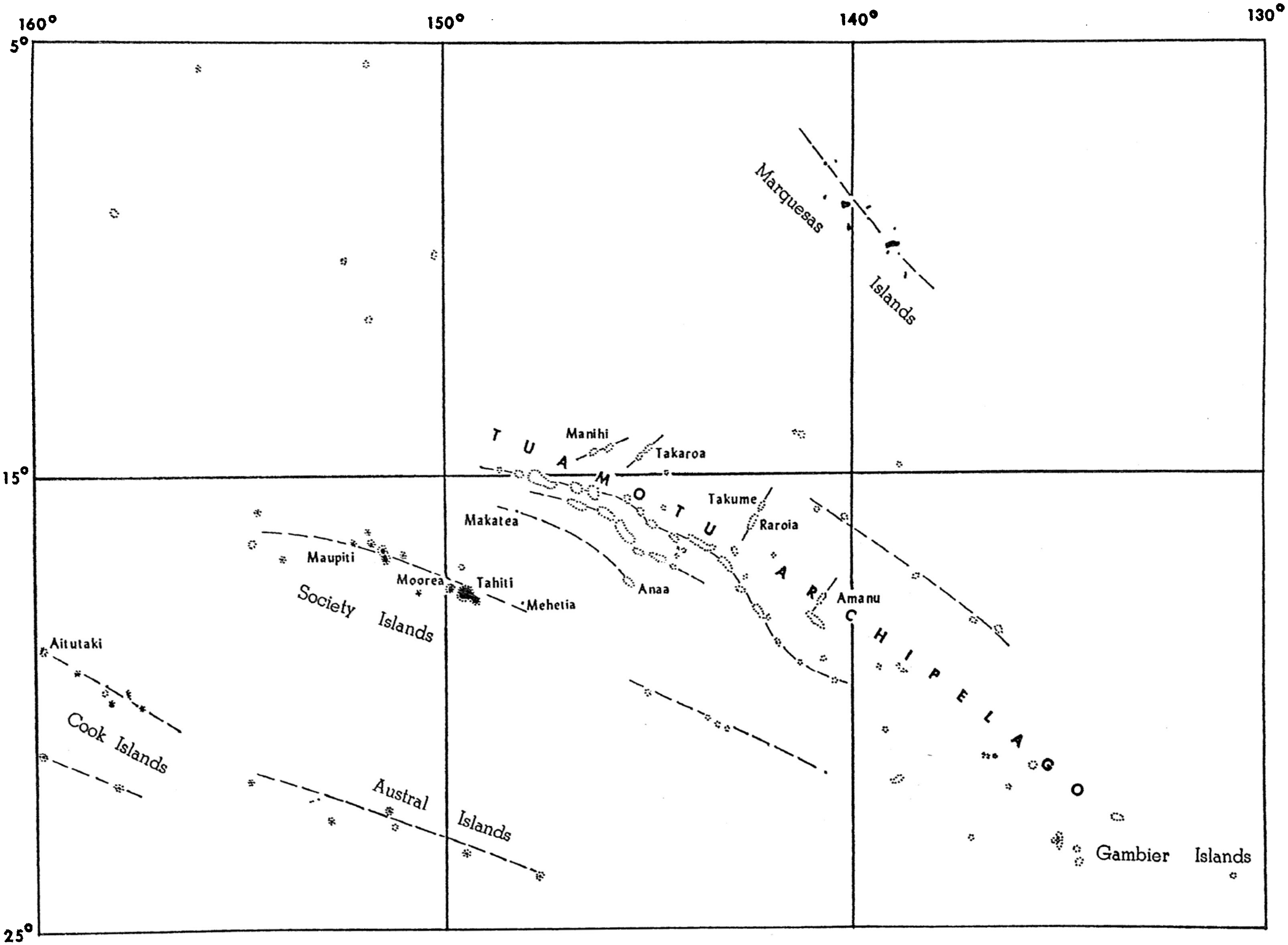


FIG. 3. Structure lines in part of the South Pacific.

as barrier bars, beach ridges, and even eolian dunes. Not only is the production of calcium carbonate sediments greatest at bank margins, but accumulation by waves and wind is also at a maximum along the margins of rapidly shelving shoals. The rim of a platform may be rapidly built up and consolidated by inorganic processes during times of lowered sea level, as occurred in the Bahama Islands during the late Pleistocene epoch (Illing, 1954; Newell, 1955b). Later submergence and reëstablishment of reef corals along the rim could completely conceal the inorganic contribution to the atoll margin.

A large part of the islands of atolls is composed of unconsolidated coral rubble ("shingle"). If this material were cemented and protected by an encrusting reef during subsidence, it would contribute significantly to the internal structure of atoll rims and would accentuate the relief between rim and lagoon floor.

MacNeil (1954b) has made the interesting suggestion that the lagoon basins of uplifted atolls may have been excavated or at least deepened by subaerial agencies during emergent episodes. The rim is explained as an erosional remnant of "case-hardened" rock etched into relief by subaerial leaching. This may, indeed, be a factor in the formation of atoll lagoons, but constructional agencies seemingly are entirely adequate to account for the observed bottom topography, and unequivocal evidence of an erosional origin of the lagoon basin has not yet been cited with respect to any typical atoll.

Thus, in summary, it is clear that coral atolls may be formed over either subsiding or emergent foundations. However, so far as known, the latter variety is never found within the true ocean basins. It seems most probable that the atolls inside the andesite line have generally developed over a subsiding sea floor.

The bottom deposits in the deep parts of the ocean (1700 to 2500 fathoms) separating the groups of Tuamotu atolls are predominantly red clay. In shallower waters petropod and coral sandy ooze are the principal sediments (Agassiz, 1903, p. xvii). Soundings near the atolls show steep slopes characteristic of atolls (*ibid.*, p. xxix).

Several observers have recognized elevated reef limestone in some of the atolls at the northwest end of the archipelago. From this evidence Agassiz has concluded that Makatea, which is somewhat dissected, was uplifted almost 230 feet (Agassiz, *ibid.*, p. 20), Matahiva, 10 to 12 feet (*ibid.*, p. 55), Tikahau, several feet (*ibid.*, p. 52), Hangiroa, 15 to 16 feet (*ibid.*, p. 20), Kaukura, 17 feet (*ibid.*, p. 17), and Niau, 20 feet (*ibid.*, p. 20). In addition might be cited elevated coral-reef limestone examined by us on Anaa, which rises at least 18 feet above low water near the village, along the northern shore of the atoll.

Evidence of appreciable and uneven recent uplift throughout the northwestern part of the Tuamotus seems to be well established. Agassiz' observations bearing on uplift farther to the southeast, however, must be taken with reservation, because he frequently mistook large reef blocks thrown up by storms and welded to the reef flat as erosion remnants of once higher platforms.[1] Dana had earlier correctly interpreted these as erratic reef blocks (Dana, 1890, pp. 179-180).

As pointed out long ago by both Dana (1890) and Agassiz (1903), the Tuamotu atolls are characterized by a narrow rim (probably indicative of centripetal growth) and by relatively few and narrow ship passes (pls. 24-26). Of the 76 typical atolls of the group 47 are without a ship pass, 21 have a single pass, and 10 are each provided with two ship passes (Anonymous, 1952). The passes mark old gaps in the atoll rim where organic accretions evidently have not kept pace with the general upward growth during subsidence. The majority of the

[1] In general, Agassiz' work on coral reefs is poorly documented and strongly colored by his crusade for the view expresed by Semper (1863) that subsidence is not involved in the origin of atolls. Many of Agassiz' assertions, such as the prevalence of outcrops of basaltic rocks on barrier reefs in the Society Islands, lack documentation and subsequent confirmation. His general explanation of the origin of the Tuamotus seems fantastic: "In the Tuamotus there is a great development of Tertiary coralliferous limestone, the last remnants of the former elevated land once covering a large area of the atolls as found also in the Gilberts" (Agassiz, 1903, p. xvii). "It is to the cutting down of the elevations of the old ledge to the general level, and the subsequent building up of the atolls by the material supplied from the reef flats and from the coral slopes that is due the great uniformity of all these atolls" (*ibid.*, p. 13). This casual dating of elevated limestones of Tuamotu atolls was based entirely on supposed lithologic resemblances to certain Tertiary limestones of Fiji (Agassiz, *ibid.*, p. 18).

passes occur approximately on the leeward side (fig. 4). This suggests that the distribution of passes may in some way be controlled by the prevailing winds. Production and deposition of calcium carbonate sediments apparently are greatest on the windward side of Raroia atoll, as the deepest part of the lagoon is downwind from the center (fig. 5). Early gaps such as stream channels that may have occurred along the windward rim (pl. 22, fig. 2) doubtless were filled before those of the leeward rim. Possibly the flow of waters through the leeward passes, especially concentrated at ebb tide, inhibits growth of corals and coralline algae, but the particular factors involved are not clearly understood.

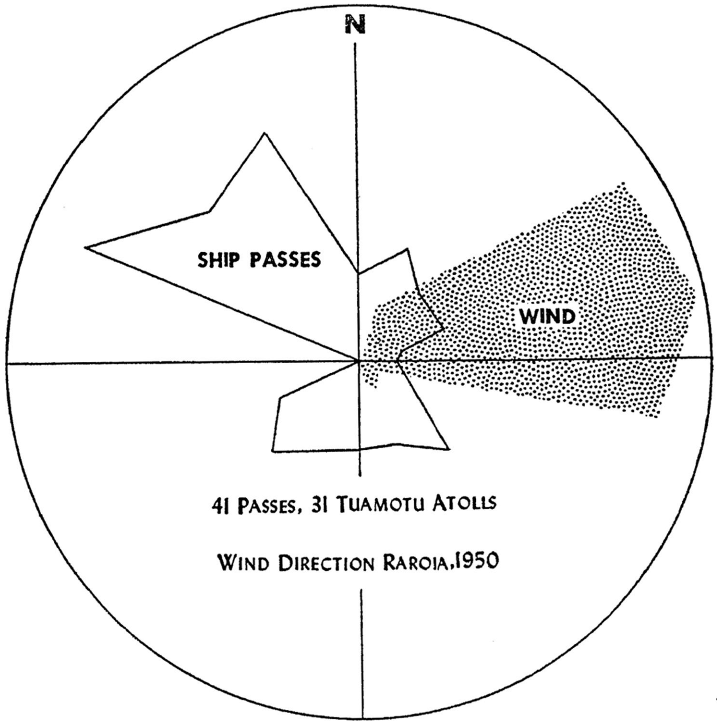


FIG. 4. Relationship between ship passes and prevailing winds in the Tuamotus.

CLIMATE

The Tuamotu Archipelago lies within the belt of southeast trade winds and enjoys a mild and equable climate. Danielsson reports dominantly easterly winds[1] at Raroia with a maximum velocity in 1950 of 7 (Beaufort). There were 37 calm days in 1950. The mean diurnal high temperature was 30.4° C. and the mean low 23.3° C., giving an average of 26.8° C. The rainfall for that year was 1181 mm. Out of the entire year 215 days were clear (Danielsson, 1951). According to the inhabitants of Raroia, 1950 was not an exceptional year. However, Danielsson does not record westerly winds such as are supposed to occur during the rainy season United States Hydrographic Office, 1940).[2]

CURRENTS

In accordance with the Coriolis effect, the circulation of surface waters in the Tuamotus moved along by the southeast trades is usually towards the southwest at rates ranging from 5 to 25 miles a day. "In the rainy season, from October to March, when westerly winds, squalls, and rains are frequent, the currents vary most

[1] Wind directions given by Danielsson (personal communication) were uncorrected for magnetic declination. The declination at Raroia for 1950, when his observations were made, was approximately 12° 02′ east.

[2] Ranson (1953) reports that the wind is sometimes from the northwest during the period from November to April.

and occasionally set to the eastward at rates from one-half to two knots" (United States Hydrographic Office, 1940).

Dispersal of larvae of shallow-water animals towards the east may be largely accomplished at these times.

SOUTHERN SWELL

Atolls of the Tuamotus are pounded on the south and southwest by a strong swell which produces continuous surf, usually heavier than that of the windward side. The south and southwest margin of the rim in many of the atolls is relatively broad, low, and free from islets, characteristics that result apparently from the exceptionally vigorous and continuous sheet flow of water across this sector (pl. 24, figs. 2, 3; pl. 27, fig. 2).

"The effect of the prevalent southwesterly gales in high southern latitudes in transmitting the heavy sea, which is felt many hundreds of miles from the latitudes of its origin, occasions a serious obstacle to landing on these low islands by rolling in on the shore in an opposite direction to the trade wind, making it often more dangerous to land on the lee than on the weather side of the islands" (United States Hydrographic Office, 1940).

HURRICANES AND TSUNAMIS

According to native tradition, violent storms have played an important part in modification of Tuamotu atolls, and this is abundantly confirmed by the physical characteristics of the islands. According to the Raroians, winds of hurricane velocities that occasionally strike Raroia and neighboring Takume generally blow from the northwest, ordinarily the lee side of the atolls. This fact suggests that the tracks of the hurricanes are mainly to the south of Raroia, probably extending from the northwest towards the southeast (Tannehill, 1942, fig. 2). Raroia, Takume, and many of the Tuamotu atolls have the highest and most extensive land and the largest displaced reef blocks on the lee side.

The actual frequency and tracks of tropical cyclones in these waters are unknown, but there are published records of seven severe hurricanes in the Tuamotus between 1878 and 1906. There are also less well substantiated accounts of a hurricane in 1823 and another in the 1850's. The latest hurricane, of minor consequence, touched Raroia in 1926. The wind of this storm is said to have blown from the southeast quarter.

During the storm of January 13, 1903, still clearly recalled by many inhabitants at Raroia, sea waves were 40 feet high at the outer reef, and water was higher than the house tops at the village. Opposing waves are said to have swept over the highest land from both sea and lagoon, meeting within the islands. Topographic forms of the islands, including conspicuous flow-lines in the coarse coral rubble, generally at right angles to the atoll rim, strongly suggest that the land has been inundated many times, indeed built up in places, by translation waves that sweep across the atoll rim to the lagoon.

Native traditions refer to rises in sea level doubtless resulting from tsunamis, but apparently these have had but little geological significance in the Tuamotus. The latest occurrence was on April 1, 1946, when the water of the lagoon at Raroia rose some 2 feet above the level of spring highs, flooding the village, Garumaoa, to a depth of about 1 foot.

PHYSICAL CHARACTERISTICS OF RAROIA

ACCORDING TO A SURVEY of Raroia and Takume, made in 1920 by the Service Hydrographique (L. V. Nay), Raroia lies between latitude 15° 55′ S. and latitude 16° 14′ S. and longitude 142° 18′ W. and longitude 142° 32′ W. It is elliptical, with the long dimension towards the northeast. In size it is intermediate among the atolls of the Tuamotus, with dimensions of 14.4 kilometers by 44 kilometers. The most obvious features of Raroia are a relatively large proportion of land surface to water along the rim and a large number of shallow, narrow channels, many of which are storm spillways, incomplete at the seaward end. The land surface is low, rarely exceeding 4 meters above normal high water,[1] and for the most part the surface is less than 1 meter high. The average tidal fluctuation in the Tuamotus is small, about 0.6 meter, according to the United States Hydrographic Office (1940), attaining somewhat more than 1 meter at spring tides; wind direction and velocity influence the water level far more than do the tidal fluctuations. Tidal range in the lagoons, of course, is much less.

Raroia, as have many other Tuamotuan atolls (fig. 5), has a single ship pass on the leeward side of the atoll. The lagoon waters are clear, and relatively deep (55 meters) in the center.[2] On the other hand, neighboring Takume, Anaa (pl. 25), Hikueru, and several other atolls of the Tuamotus lack passes. Lagoons of these atolls are shallow, being largely filled with muddy sediments.[3] Evidently sediments ac-

TABLE 1

CHARACTERISTICS OF RAROIA

Location	Latitudes 15° 55′–16° 14′ S., longitudes 142° 18′–142 32′ W.
Winter temperature of surface sea water	26° C.
Prevailing winds	Easterly
Cyclones (hurricanes)	Dominantly westerly
Rainfall (1950)	110 cm.
Tides	*Ca.* 0.6 m.
Area of atoll, including lagoon	400 km.^{2}
Area of lagoon	340 km.^{2}
Area of atoll rim	60 km.^{2}
Length of atoll	44 km.
Breadth of atoll	14 km.
Maximum depth of lagoon	55 m.
Maximum height of land	6 m.
Circumference at outer reef edge	90 km.
Average breadth of atoll rim	0.6 km.
Land area (35% of rim)	21 km.^{2}
Vegetated area	6 km.^{2}
Number of lagoon patch reefs	*Ca.* 2000
Number of ship passes	1
Visibility of 8-inch Secchi disk	
Ocean	34 m.
Lagoon	28 m.

[1] The outer gravel rampart at the elbow of Oneroa, the westernmost point of Raroia and therefore most exposed to hurricanes, reaches the extreme elevation of 19 to 20 feet above normal high water. A few other points on the atoll are 12 to 15 feet above average high water.

[2] A fathometer profile along the deep axis of the lagoon was made by a ship of the United States Fish and Wildlife Service shortly after completion of our field work. This supports our conclusion about the maximum depth of the Raroia lagoon. I wish to acknowledge the cooperation of Dr. William F. Royce, who made this fathometer profile available to me.

[3] Ranson (1954) makes the interesting suggestion that the characteristically milky waters of shallow lagoons (25 meters or less) in the Tuamotus contain

cumulate relatively slowly in the open lagoons, which are underlain by sand and gravel, and finer sediments are swept out to sea.

Distribution of under-water terraces, reef, and land forms recognizable on the photographs were studied, and salient geologic features were recorded by means of aerial and ground photographs and by maps and cross sections. A number of topographic profiles were constructed across the atoll rim, and in certain critical places levels and horizontal distances were surveyed by means of alidade and plane table. Underwater observations and photographs were made with the aid of two Browne masks and a motor-compressor built by G. Robert Adlington at the American Museum of Natural History. A bathymetric map of the lagoon was prepared by Byrne from hand-line soundings. All these observations reveal a number of facts of interest.

THE ATOLL RIM

The rim of Raroia atoll (fig. 5) is narrowest, averaging 500 to 700 meters wide, along the northwest side where there are relatively few channels and the greatest extent of vegetated island "upland." Much of the surface here rises from 1.5 meters to 3 meters above normal high-water level. On the other hand, the broadest sector of the rim, 800 to 1250 meters wide, is at the south end of the atoll (pl. 27, fig. 2) where the surface is more or less continuously awash. This is the lowest part of the rim. In other sectors intermediate conditions between these extremes are found (pl. 26).

Although it cannot, of course, be supposed that the rates of reef growth are uniform around the atoll, it is probable that wave truncation of the existing land areas and lagoonward extension of the rim by deposition of the resulting debris would result in a more nearly uniform rim width than is actually the case. It appears that the relative narrowness and height of the northwestern rim are a result of full exposure to the most violent storms.

a fine suspension of calcium carbonate secreted by pelecypods, mainly *Cardium fragum*. The fine sediments are characteristic of closed lagoons. May they not be formed of both shell detritus and chemical precipitates?

Undoubtedly the very shallow, enclosed lagoons become much warmer than the deeper "open" lagoons of atolls like Raroia. Conditions for inorganic precipitation of aragonite mud would seem to be especially favorable in the shallowest lagoons.

Channels and Islets

There is only one ship pass, through the leeward rim (pl. 26, fig. 2; pl. 30, fig. 1), and on the neighboring twin atoll, Takume, there is none. The Raroia pass is narrow (700 meters) and shallow (5.5 to 8 meters) and choked by vigorous coral growth which may eventually block the pass. At the south end of the atoll, facing the strong southern swell characteristic of the region, there is a broad inundated sector of the rim approximately 5 kilometers long and 1.5 kilometers wide which is barely awash at low tide (pl. 27, fig. 2; pl. 32, fig. 2). Elsewhere, there are approximately 260 shallow channels across the rim which are drained or are awash during low water at the seaward ends and filled by 2 to 2.5 meters of water near the lagoon ends. There are roughly 280 islets around the atoll, of which only 60, including most of the larger and higher land areas, are on the leeward (northwest) side of the atoll (pl. 26). Although the larger islets also lie on the leeward side of the neighboring Takume, this is unusual among atolls, even in the Tuamotus, because most frequently the land areas are concentrated to the windward where gravel and sand are most vigorously heaped by waves. The storms of greatest violence, however, regularly strike the west (lee) side of Raroia and Takume, and there is much evidence of island building there by hurricanes.

In addition to the shallow channels or spillways between islets, there are some 160 deep, angular clefts or notches (incomplete channels) in the lagoon shore similar to the channels except that they do not extend across the island to the seaward side (pl. 32, fig. 1; pl. 34, fig. 1; pl. 35, fig. 1). These clearly are being lengthened headward as storm waters cross the islets towards the lagoon, and they represent various steps in the formation of shallow channels. It is concluded that the shallow channels are all of very recent origin and were formed chiefly by mechanical (hydraulic) erosion of the uplifted rim, but the ship pass probably has been inherited from an earlier gap in the rim.

Island Conglomerate Platform

The islets are formed of a groin or platform of coarse limestone conglomerate (*pakokota* in Tuamotuan) from about 0.5 to a little less than 1 meter above average high water on which,

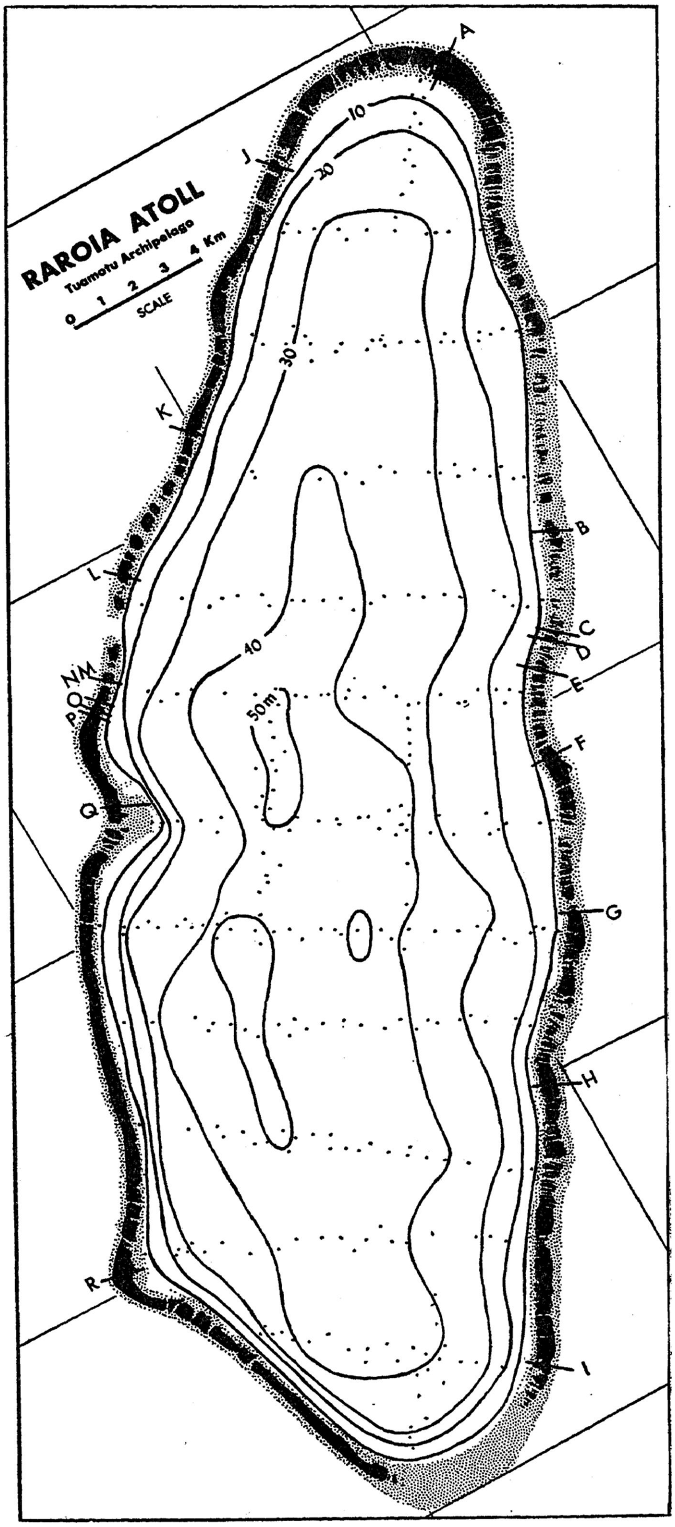


Fig. 5. Hydrographic map of Raroia atoll and location of profiles.

here and there, are ramparts and patches of sand and coral debris lying sometimes lagoonward of the islet center (figs. 6, 7; pl. 28; pl. 46, 47). Many of these patches of rubble are vegetated; the rock platform is bare. The larger islands are bordered by the rock platform, but wells dug in the interior (Garumaoa, Oneroa, Tetou) reveal that the central areas are underlain by uncemented sand and gravel to the water table, becoming loosely cemented below the water table. The platform slopes gently towards the lagoon, and the coarse coral fragments characteristic of the conglomerate at the outer margin of the platform rapidly are replaced lagoonward by fine calcareous sand. The rock is clearly bioclastic throughout and does not contain *in situ* reef material. It is not an elevated platform of planation, a reef flat, but it is a depositional surface formed mainly of cemented coral rubble. It could have been formed at or near the existing sea level. Indeed, new contributions to this platform are spread over the low areas after each storm and subsequently become welded to the pre-existing rock surface.

Joints

Irregular joints are visible here and there on the rock pavement, but they do not show lineation. Joints somewhat opened by erosion are occasionally visible on bare areas of the outer reef flat near the shore (pl. 40, fig. 1). These are slightly sinuous and generally are approxi-

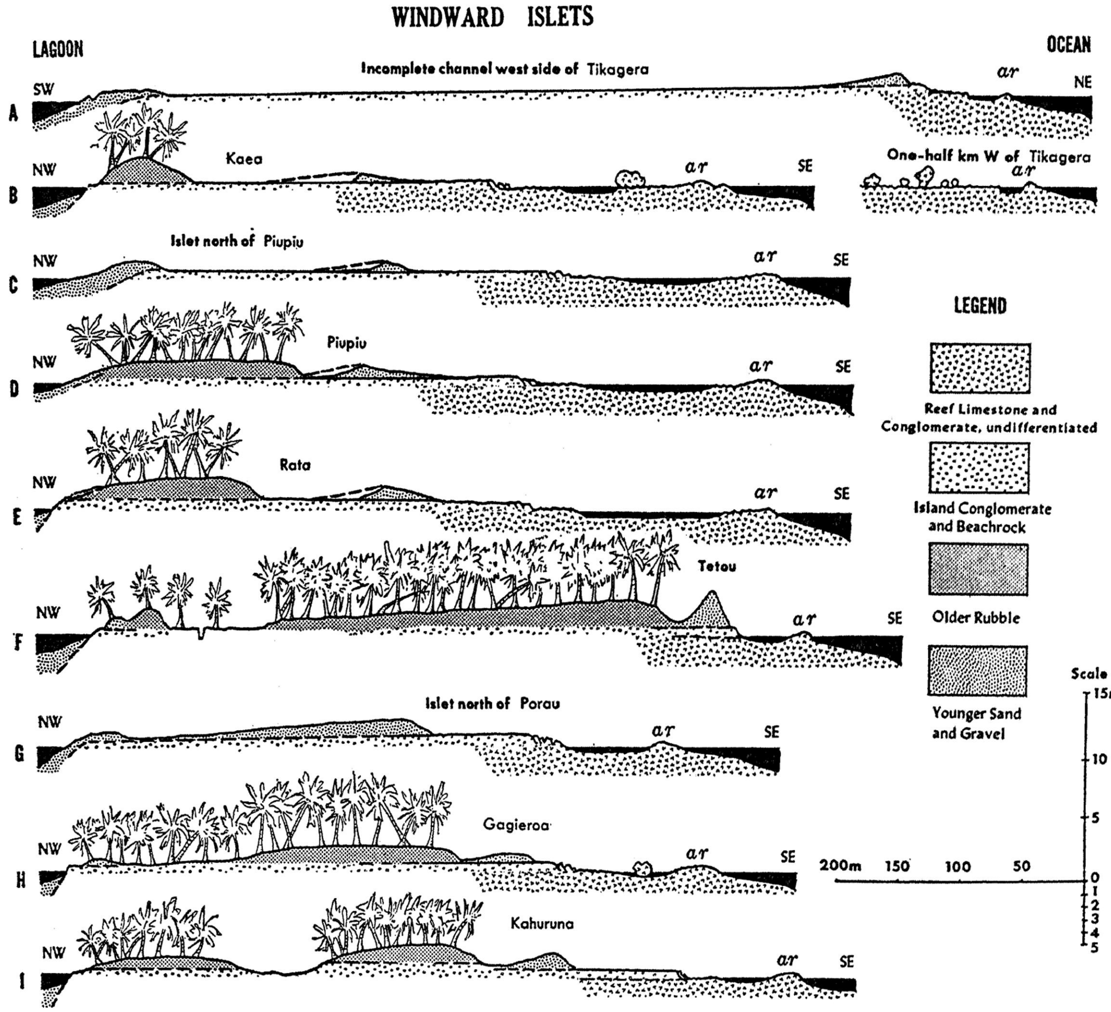


FIG. 6. Windward islets, profiles; location shown on figure 5.

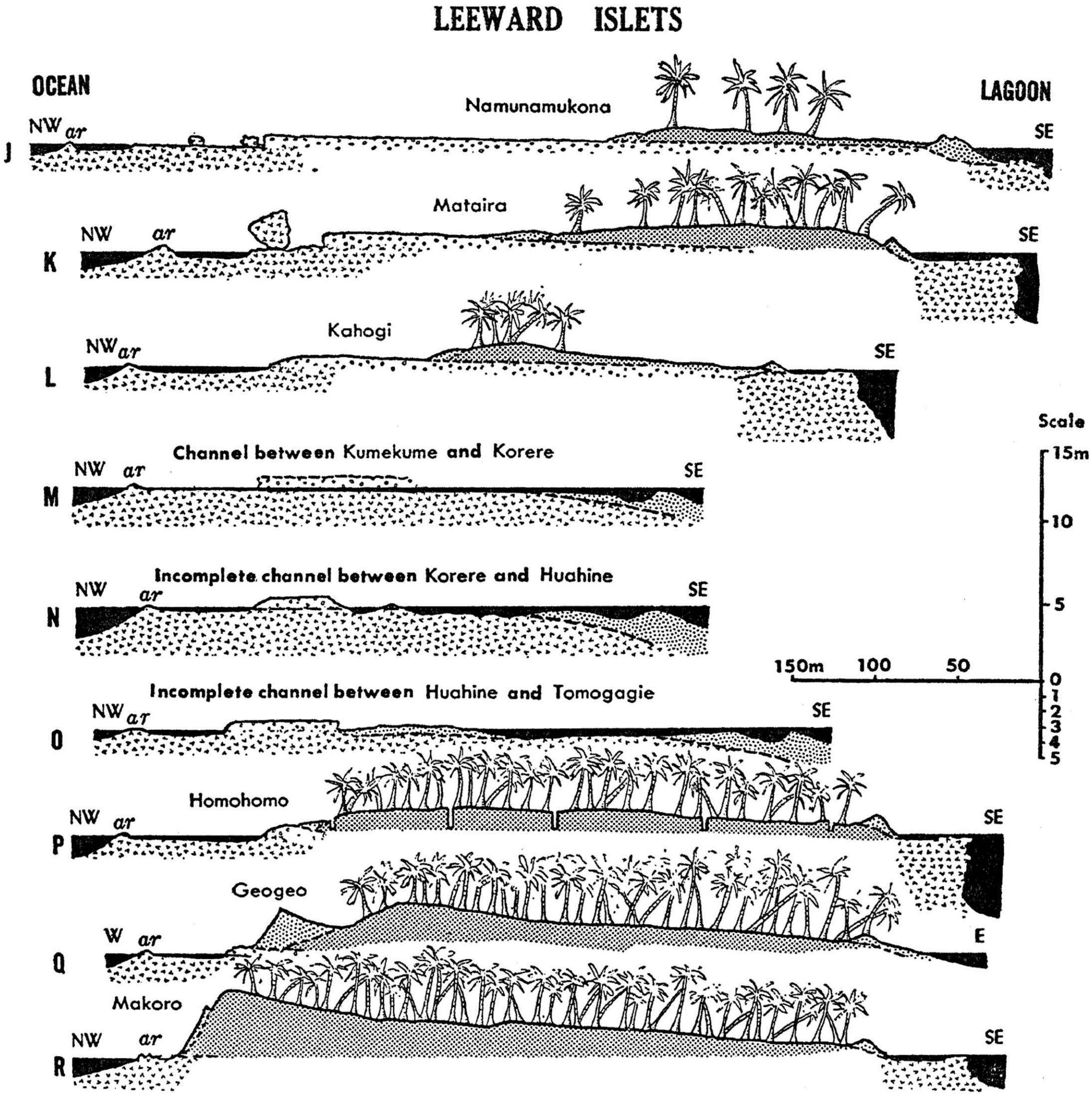


FIG. 7. Leeward islets, profiles; location shown on figure 5.

mately parallel with the reef front. None can be followed more than about 100 meters. Presumably they have been produced by adjustments or slump in the marginal talus of the atoll. There is no visible displacement along these joints, but the effects of differential movement would probably be quickly effaced by erosion.

Ramparts and Beaches

One or more rampart ridges of loose gravel on the rock platform defend the seaward sides of nearly all the islands. These are coarsest and highest along exposed promontories (pls. 47, 48). The highest surface on the atoll (approximately 6 meters) is the crest of a rampart on the leeward side of the atoll (at Oneroa, fig. 7R). In more sheltered places the ramparts change to sandy beaches (pl. 47, fig. 1). These are all storm features which lie inland upon the rock platform at some distance from the normal high-water line. Eolian sediments are completely lacking on Raroia.

Island Gravel

A striking feature of the surface of the islets is a veneer of coarse, algal-blackened coral rubble with very little sand. Reef blocks up to a meter or so in diameter, including corals which live only in fairly deep water outside the atoll (*Acropora conigera*), are scattered over the land on the leeward side of the atoll as far as the lagoon shore. These are storm gravels deposited by sheet flood during hurricanes. The gravel is coarsest on the northwest rim of the atoll, appreciably finer on the southeast side, which generally is the sheltered side during hurricanes. This surface gravel does not contain fine sediment, but the interstices are sand filled a few centimeters below the surface. Presumably the water that passes over the islands during storms has capacity to carry sand and humus lagoonward, leaving well-washed coarser rubble on the higher ground near the outer shore and somewhat finer sediments near the lagoon. Some sand is trapped between pebbles, however, and doubtless it is washed downward by the rain. Pits dug on the larger islands show that the upper 1 to 2 meters of earth is composed of coarse rubble and entrapped sand which could have been deposited only by violent storms.

Terraces

There is evidence of an outer terrace believed to lie at a depth of approximately 20 meters (fig. 9; pl. 34, fig. 1; pl. 35, fig. 2) similar to those described in the Marshall Islands (Tracey, Ladd, and Hoffmeister, 1948) and along Andros Island (Newell *et al.*, 1951), and there is a shallower terrace which slopes outward at the reef front from about low-water level to 8 meters. Both terraces are grooved and otherwise similar in general appearance. Probably the rim of the deeper terrace was the reef front during a Pleistocene low level of the sea. A submerged rock terrace, possibly also at about 8 meters, lies along the lagoon shore. This is largely covered, however, by sediments and fringing reefs, so that the depth to the terrace rim cannot be determined accurately. Usually there is a pronounced break in slope at about 5 meters or so.

Geologists have repeatedly described elevated erosional terraces a few feet above sea level along many coasts throughout the world, and these were attributed by Daly (1910) to a high eustatic level of the oceans some 3000 years ago during an epoch of generally mild climate. Correlation of these low terraces from place to place is highly uncertain, but it seems that there is a terrace a few meters above "sea level" in widely scattered places throughout the Pacific and elsewhere. This is commonly referred to as the 5-foot or 6-foot terrace, but there is surprisingly little documentation with respect to the particular level of the sea taken as the datum for local measurement. As marine terraces presumably are formed at or below the lower limit of tidal fluctuations, low rather than mean sea level should be taken as a datum from which to measure the heights of elevated terraces. This has not always been the practice.

Cloud (1954) has reviewed the evidence for a recent eustatic drop of about 6 feet and concluded that many of the characteristic superficial features of modern reefs, spur and groove zone, reef flat, and reef flat islands, are related to a recent drop in sea level.

At least several of the islands of the Society group are girdled by a low terrace within the "6-foot" range (pl. 22, fig. 1), but a terrace at this height has not been recognized in the Tuamotus. In fact, the southeastward tilting evident among these atolls tends to disqualify this area from consideration in any compilation of evidence bearing on recent eustatic changes in sea level. On Raroia, dissection of the reef flat, as described on a subsequent page, suggests relative uplift of 15 or 20 cm.

Radio-carbon analysis of limestone of one of the great reef blocks at Garumaoa (pl. 41) at Lamont Geological Observatory indicates an age of about 2500 years for the composing limestone. Of course the limestone is somewhat older than the block itself, but probably it is not much older, because these blocks are invariably torn from the reef spurs at the living margin of the reef. It is probable that the block was torn from the reef margin more than 2000 years ago and deposited upon a reef flat which was forming in the intertidal zone. Subsequent uplift of Raroia by not more than 15 to 20 cm. has brought about dissection of the old level, but extensive remnants are still preserved here and there at this level above the new reef flat.

Raroia atoll evidently had attained approximately its present size at the time of formation of the great blocks. These were torn from notches along the reef front still clearly visible.

The humus of the deepest fossil soil zone under Garumaoa islet (fig. 8, section C, bed 7) gives a radiocarbon date of 800 years. This may represent the first heavy cover of vegetation of this part of the atoll.

This date may be too young, however, because of possible contamination by organic matter from above through the large spaces between pebbles. Coral fragments within this old soil furnish an age of 1350 to 1730 years. Presumably the fragments were deposited by a storm shortly after they were being secreted by living corals. As the soil horizon is underlain by more than a foot of gravel (20 inches), it seems probable that the abrupt change from deposition of dominantly fine to coarse sediments took place approximately 2000 years ago, and this probably coincided with the production of the unusually large reef blocks along the outer lee reef of Raroia.

Fisk (1944) and LeBlanc and Bernard (1954) doubt that sea level has been appreciably higher than the present level since the close of the Pleistocene. They marshal an impressive body of evidence from the Gulf Coast region of North America that the sea has not extended across the continent beyond the present shore line after the present level was reached at the close of the post-Wisconsin recession.

By the nature of the problem, it is difficult to evaluate the significance of the many low terraces in the Pacific. Is it possible that each of these elevated terraces is a result of local diastrophic causes? What was the effect on isostatic balance beneath oceanic islands of removal of water during the Pleistocene low levels? As the islands became emergent, standing 400 or 500 feet above sea level, the isostatic balance must have been locally disturbed, with a consequent acceleration in the rate of local crustal subsidence. Rise of the sea to the "normal" level might result in small negative anomalies and delayed slight uplight. May this have been the origin of the "6-foot" terrace? Or is it more likely that the "6-foot" terrace dates from an interglacial high level of the sea? The problem has not yet been resolved.

Erosion of the Land

The rocky outer shore all around the atoll is being cut away, and the land area is decreasing. Outlying erosion remnants on the reef flat show clearly that the shore has retreated along a broadly curved front as much as 20 or 30 meters since the conglomerate platform was formed and elevated (pl. 27, fig. 1; pl. 32, fig. 1; pl. 35, fig. 1). Most of the products of this erosion together with the coral gravel and foraminiferal sand swept through the channels during storms accumulates in the lagoon, which in spite of heavy sedimentation is moderately deep (55 meters) and is floored by fine sand and gravel rather than mud.

The water of the channels on the windward side and at the broad reef flat at the south end of the atoll generally flows lagoonward, even during low water, because of the strong swell. There is reversal of flow in the larger channels on the leeward side of the atoll, where the wind generates a feeble seaward current during high water, but this current carries hardly any sediment.

Lagoon shore currents receive and rework the debris from the seaward reef which, together with lagoonal sediments, forms a nearly continuous band of beaches, beach ridges, spits, and bars; these are mainly sand along the leeward (southeastern) shore and sand (pl. 31) and gravel on the windward (northwestern) shore of the lagoon (pl. 35; pl. 47, fig. 2). Each channel is marked at the lagoon by a small crescentic delta of more or less loose sediments, and there is little or no reef growth at these places.

Deltaic accretions of sediments along the lagoon margin (pl. 27) tend to mask signs of erosion and retreat of the shore, but almost all the islands have low headlands and outliers of beach rock rising a few centimeters above high water. The edge of the beach rock has been cut back at many places some 15 or 20 meters since it was formed.

Ground Water

Analyses of nine well waters were made at Garumaoa village near the close of a dry period (June 29) when the wells were being used to capacity. Therefore the salinity was probably higher than the average for a year. Salinity was determined by hydrometer measurement. Values for pH were obtained with a Gamma electric meter lent by the United States Geological Survey for the purpose. Total hardness was determined by titration. Because of inadvertent omission of an essential reagent, chlorinity of the water could not be determined. The wells

TABLE 2

ANALYSIS OF GARUMAOA AND OTHER WELL WATERS

Well No.	Temperature in Degrees Centigrade	Salinity in Parts per Thousand	Hardness in Parts per Million	pH
1	26.5	14.4	320±13	7.8
2	25.0	14.6	360±13	7.6
3	25.0	13.9	280±13	7.7
4	26.0	14.2	240±13	7.7
5	26.0	14.2	300±13	7.6
6	25.0	14.1	340±13	7.8
7	27.0	14.2	360±13	7.7
8	15.0	15.4	360±13	7.7
9	26.0	16.6	360±13	7.6
10[a]	—	4.1	—	—

[a] Well at Tetou, little used, August 23. The others are at Garumaoa, June 29.

ranged from about 14 to 17 parts per thousand salinity, with pH of 7.6 to 7.8. Total hardness ranged between 240 ± 13 to 360 ± 13 parts per million.

Five test pits were dug to the water table in a series across the north end of Garumaoa Islet (fig. 8). The pits at each end of the series were within 75 meters of the sea. Analyses of water samples from these pits are shown in table 3. Pits 4 and 5 were not dug until after the onset of showers which came shortly after the middle of July, breaking a drought of many weeks.

All the wells and moat ponds rise and fall with the tides, but the details of effects of tides on the lens of ground water were not studied. In general it appears that the fresh-water lens is adequate for plants and animals on the larger islands even during periods of drought. Rain-water cisterns supply nearly all the drinking water, however, at the village. In all the wells and pits the sand and gravel were unconsolidated down to the highest level of the fluctuating water table. Below this level the sediments are loosely cemented to form friable calcarenite.

SOILS

The land areas of Raroia are almost destitute of soil over all but the lowest surfaces. Probably leaf mold and humus are periodically stripped away or buried by sheet flood during hurricanes. Sulphurous muck is found in a few swampy areas just inside the lagoon beach ridges. These are natural moats, and the waters are quite saline (see table 3, pond 1). Farther inland are small taro pits, all dug before the present

TABLE 3

WATER ANALYSES FROM TEST PITS ON GARUMAOA

Number	Temperature in Degrees Centigrade	Salinity in Parts per Thousand	Hardness in Parts per Million	pH
Pit A (5)	26.0	4.1	380±13	7.5
Pit B (2)	26.0	9.0	420±13	7.9
Pit C (4)	25.0	3.5	420±13	8.0
Pit D (3)	27.5	7.6	420±13	8.1
Pit E (1)	24.2	3.7	420±13	7.9
Pond 1	24.7	35.5	4000±13	7.9
Pond 2	23.5	5.6	400±13	8.3

century. The muck of these pits is acid. As might be expected, the surface rubble of the islands generally is alkaline. The conglomerate, coral gravel, and foraminiferal sand that compose the islands are nearly pure calcium carbonate. Clay minerals and silica occur only as traces and do not form significant accumulations. High alkalinity is assured by the local custom of periodically burning over underbrush and coconut husks, which results in the disintegration and calcining of the surface gravel.

Stratigraphy

Five test pits 2 to 3 meters deep were dug across Homohomo (north end of Garumaoa Islet) so that the succession of deposits could be studied and samples of ground water (fig. 8) could be obtained. The outer pits were near the two shores, and the oceanward hole was dug within 20 meters of the conglomerate platform. Contrary to expectation, the conglomerate, composed of firmly cemented coarse debris of corals, was not encountered in any of the pits, although all were deep enough. Thus apparently it does not form the foundation of this large island as it does the small islands. The succession of strata penetrated in these pits is remarkably uniform across the island. There is a lower unit of well-sorted medium limesand which extends upward from the high-water level some 50 to 240 cm. This is overlain by coarse, sandy gravel 150 to 350 cm. thick containing one or two buried soil zones and a poorly developed humus zone at the top. Wells at Garumaoa, at Oneroa, and at Tetou also show that the sediments are generally finer below and coarser above. Samples of the sediments exposed in the five test pits were collected for soil analysis and carbon-14 determination. It seems probable that the onset of deposition of the coarse materials may have originated in the slight uplift of the atoll discussed below. This probably resulted in effective island building during storms and in increased rates of erosion of reef and island conglomerate. This depositional change certainly marks an important event in the history of the atoll.

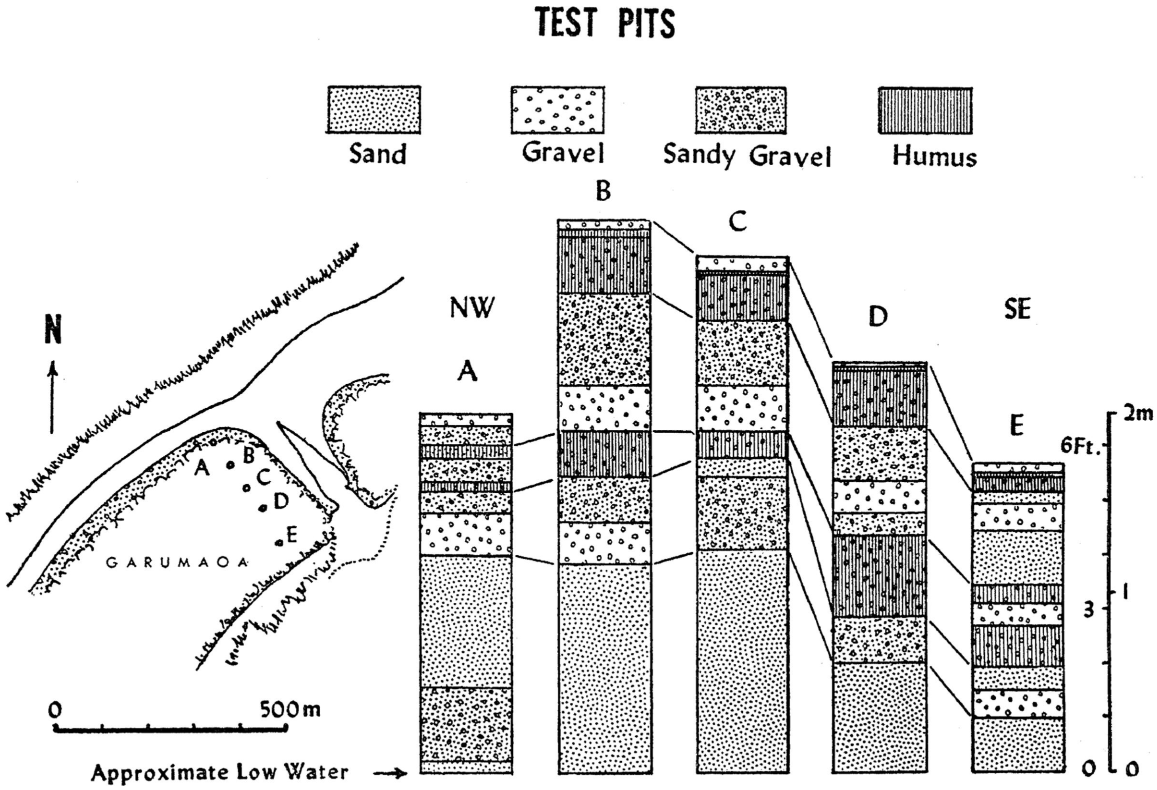


FIG. 8. Correlation of strata in test pits, Garumaoa islet

TABLE 4

LOGS OF FIVE TEST PITS AT THE NORTH END OF GARUMAOA ISLET
(See figure 8.)

Pit No.	Inches
Pit A (5),[a] northeast corner of Garumaoa Islet; depth of hole: 79 inches	
Top	
Bed 1. Loose gravel	2
Bed 2. Algal crust on pebbles	½
Bed 3. Gray-buff sand and gravel	4
Bed 4. Gray sand with some humus	3
Bed 5. Gravel, subangular pebbles up to 4 inches	5
Bed 6. Sandy gravel with roots	2
Bed 7. Sand, light buff with scattered pebbles	5
Bed 8. Coarse gravel, washed, angular, a few boulders	9
Bed 9. Sand, medium, well sorted, light buff	29
Bed 10. Sand, gravelly, grayish	16
Bed 11. Sandstone, like above	3+
Salinity: 4.1; original temperature: 27° C.	
Pit B (2), north end of Garumaoa Islet; depth of hole: 121 inches	
Top	
Bed 1. Mantle of coarse angular coral fragments, the whole coated black at surface by blue-green algae	2
Bed 2. Dark gray sandy gravel with organic material	2
Bed 3. Gray sandy gravel with many roots	12
Bed 4. Gray sandy gravel	20
Bed 5. Open coarse gravel	10
Bed 6. Small cobbles with open interstices several inches across; lowest root zone	10
Bed 7. Poorly sorted sand and gravel	10
Bed 8. Poorly sorted subangular gravel, no sand, unconsolidated	9
Bed 9. Semi-consolidated, coarse sand, light buff, rather well sorted (beach sand)	46
Water table	
Salinity: 9.0; original temperature: 27.5° C.; pH: 7.92; hardness: 420±13 ‰o	
Pit C (4), north end of Garumaoa Islet; depth of hole: 113 inches	
Top	
Bed 1. Unsorted coral gravel, washed	3½
Bed 2. Algal film on pebbles, black	½
Bed 3. Gravelly sand, dark gray, with small roots	6
Bed 4. Sand and gravel, darker, major root zone	4
Bed 5. Sand and gravel, light gray, buff, some cobbles	14
Bed 6 Angular small cobbles and gravel, grading down into sand, light gray	10
Bed 7. Brownish dark gray, sandy, with a few roots, humic soil with a few pebbles	6
Bed 8. Brown, well-sorted medium to fine sand	4
Bed 9. Brown gravel, sandy, fragments up to 8 inches	16
Bed 10. Sand, coarse, light tan, well sorted, with a few small pebbles; lightly cemented	49
Water table	
Salinity: 3.5 (diluted by recent rain); original temperature: 28° C.; pH: 8.0	

[a] Roots occur scattered throughout, but predominate at the levels indicated. The section appears as though beds above bed 6 are the result of burial of older profile, perhaps by the 1903 hurricane.

TABLE 4—(*continued*)

Pit No.	Inches
Pit D (3),[a] north end of Garumaoa Islet; depth of hole: 90 inches	
Top	
Bed 1. Surface veneer gravel	1
Bed 2. Black humus and leaf mold	1
Bed 3. Gravel, gray, sandy, with roots	12
Bed 4. Gravel and cobbles, sandy, light gray, with a few small roots	12
Bed 5. Gravel, washed, subangular, up to 3 inches with open interstices, fine roots	7
Bed 6. Sand and coarse gravel, light buff, fine roots	5
Bed 7. Brown sandy humic soil, gravelly, darker at top	18
Bed 8. Gravelly sand, yellowish tan	10
Bed 9. Sand, coarse, light buff, well sorted, with a few small pebbles	24
Water table	
Fluctuation of water level: at least 10 inches	
Pit E (1), northeast corner of Garumaoa Islet (see fig. 8); depth of hole: 68 inches	
Profile	
Top	
Bed 1. Surface coral rubble, partly calcined by burning; no sand visible; fragments small pebbles to boulders	2
Bed 2. Upper half-inch black, humic, lower part dark brownish gray sandy gravel full of small roots, mainly horizontal (2 samples)	4½
Bed 3. Sand with pebbles, light gray (sample taken)	2½
Bed 4. Pebbles and cobbles, subangular, light gray, no sand	6
Bed 5. Sandy gravel, light gray	12
Bed 6. Humic soil, dark gray, sandy gravel, full of living roots, both horizontal and vertical (sample)	4
Bed 7. Gravel, hardly any sand (sample)	5
Bed 8. Sand, brown, pebbly (sample)	9
Bed 9. Buff sand and pebbles (sample)	5
Bed 10. Gravel, washed, no sand	6
Bed 11. Sand, buff, with a few pebbles (sample)	12
Water table	
Original temperature: 27.5° C.	

[a] The sediments below bed 7 are tan; those above it are light buff to bone colored.

REEFS AND SEDIMENTARY PROCESSES OF RAROIA

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 atolls in the Marshall group (Emery, Tracey, and Ladd, 1949, 1954) were not recognized.

There are many indications that the rate of erosion of the reef front may actually exceed the accretion of organic material; hence, the atoll rim probably is shrinking. 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 (1928a, 1931, 1935) has concluded that reef growth on near-by Tahiti and Moorea is not keeping pace with reef erosion (pl. 22). 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 justified 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 (or uplift of a reef) would destroy the organisms of reef flats previously just awash 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 probably was responsible for some of the 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. Although these waters store solar energy during the westerly drift and the surface waters are warm at the longitude of the Marquesas and Tuamotus, the thermocline doubtless is still shallow. In this region it may be so shallow that great storms bring 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 Tuamotus are exaggerated.

In the Raroia lagoon a discontinuous, generally narrow, shore reef lies along the northwest shore where the prevailing sediment is gravel (pls. 33–35). This reef is exposed to the fetch of the prevailing winds; hence it is the windward shore reef, even though it lies at the downwind side of the lagoon. The sheltered, or lee, shore along the southeast side of the lagoon lacks a well-defined reef because of heavy sedimentation, but small patches composed mainly of massive heads of *Porites* are common (pl. 31). 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 (pl. 26). 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 (pl. 34, fig. 1), 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 zone of non-clastic organic accretions outside the land areas and channels. It forms the outer retaining wall of the atoll rim. Be-

[1] Patch reefs reach the surface, therefore are flat above. 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 virtually all of the visible small lagoon reefs reach the surface.

cause the reef is continuous around the atoll, it is hardly appropriate to refer to windward reefs and leeward reefs as though they were separate. Wherever islands are lacking and the reef flat extends across the atoll rim inside the reef, as at the southern end of Raroia (pl. 32, fig. 2), the inner limit of the reef flat is poorly defined.

Reef Front

In some reef areas, perhaps in many, the most luxuriant growth of corals is not on the reef flat or edge but lies on the reef front well below wave base of ordinary storms (fig. 9). This outer zone commonly is not conveniently accessible for direct observation because of the strong ocean swell. Nevertheless, as at Raroia, the reef front on the lee side of the atoll 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.[1]

It may be fairly argued that this rather than the algal ridge of the "spur and groove" zone is the front of the sea reef. Almost certainly it is the chief producer of coarse sediment at Raroia. The reef front is an uneven, rather steeply shelving surface relatively free from loose sediment. It extends downward from approximately 8 meters at the edge of the spur and groove escarpment to beyond the limit of visibility at 34 meters. A terrace at approximately 20 meters (10 fathoms) comparable to one at Bikini (Tracey, Ladd, and Hoffmeister, 1948) and the Bahamas (Newell *et al.*, 1951) is visible on aerial photographs of Raroia (pl. 35, fig. 2). Our hand-line soundings in the agitated outer waters were not, however, very accurate.

[1] This outer zone of rich coral growth has been recognized on the Great Barrier Reef, Andros Island, the Bahamas, and elsewhere.

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 2 meters across and about 0.3 meter thick. They are attached by a short thick trunk at the base or margin. This 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* (*P. verrucosa*), which rises more than 1 meter above the bottom as bushy clumps with stout stalks 7 or 8 cm. 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[2] up to 2 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 at least 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 margin of the reef (pls. 31, 33, 35). The outer edge of this zone forms a low escarpment at a depth of about 8 meters (fig. 9). Landward the crests of the spurs form a ter-

[2] A coral "head" as used here is a corallum, not a knoll or patch reef.

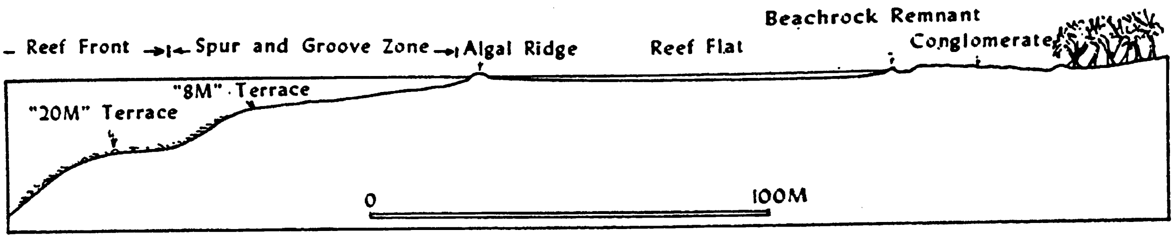


Fig. 9. Outer reef profile, Korere, just south of Garue pass, Raroia.

race 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 originate at the algal ridge, but a few cut across the ridge and extend across the reef flat as "surge channels" (pl. 36, fig. 2). 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; Emery, Tracey, and Ladd, 1954, p. 145). 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. Emery, Tracey, and Ladd (1954) regard the spurs as constructional forms, but it is not at all clear just how processes of organic accretion could produce the serrate reef front. In any case, erosion is clearly dominant at Raroia.

The outer grooves of the leeward sea reef were investigated in several places at the surface and under water 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 6 or 7 meters; then, flattening gradually to a depth of about 10 to 15 meters, they debouch on the lower slope of the reef front beyond the spurs. The grooved upper terrace is rather uniformly dissected, the 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.

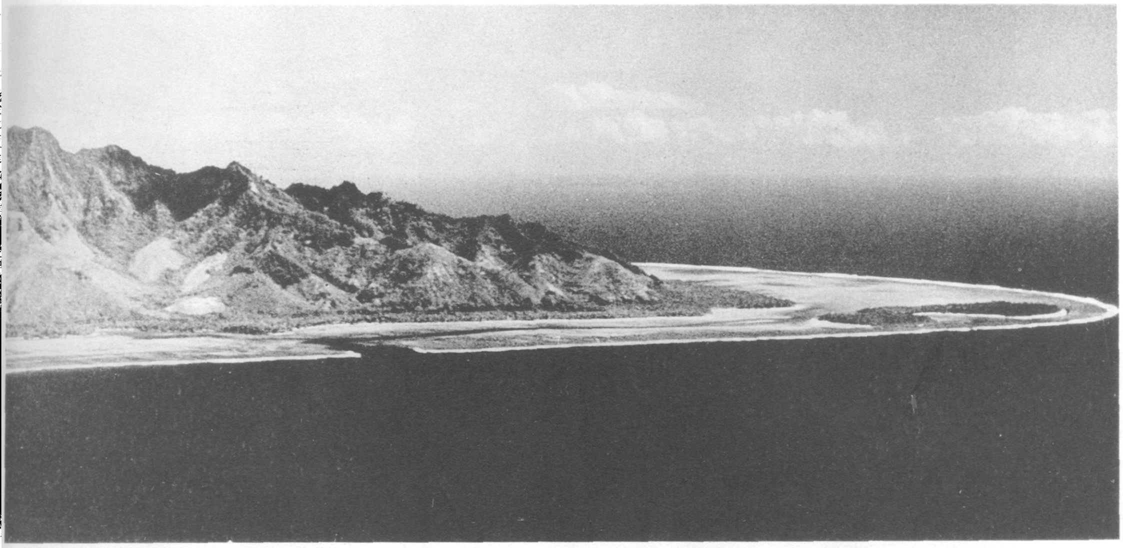
The walls and floor of the grooves generally are smooth and free from all but scattered, very young colonies of corals. The rock surface is pitted, rounded, and scoured smooth, and the floor is uneven and ungraded except near the mouth where there usually is an accumulation of boulders and gravel (pl. 38). 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 of up to about 2 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 1 meter wide where they are as much as 7 meters deep. For the most part the depth is greater than the width 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. 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 scour of gravel and sand clearly is the chief agency of erosion along the floors of these grooves. Coarse detritus, which is trapped temporarily in depressions, cuts linear series of pits down the slope, and these eventually coalesce to 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, or embryonic surge channels (pl. 39, fig. 1).

Part of the gravel responsible for scour in these grooves clearly is derived from the outer slope, as 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 regularly 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 "8-meter" terrace. In many places the spurs are about as wide as the grooves and with the latter form a comblike pattern. In other places there are sectors of the terrace as much as 50 meters long that are undissected or incompletely dissected by grooves (pl. 33, fig. 2), as the reef sector on Bikini (fig. 10) 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. This and the fact that the terrace has a very regular outer margin suggest that the form of both spurs and grooves is the effect of erosion rather than construction. There is very little roofing of the grooves by algal deposits on Raroia. On the other hand, the spurs are quite unequal in breadth. If they were simply buttresses of algal deposits being extended seaward against the



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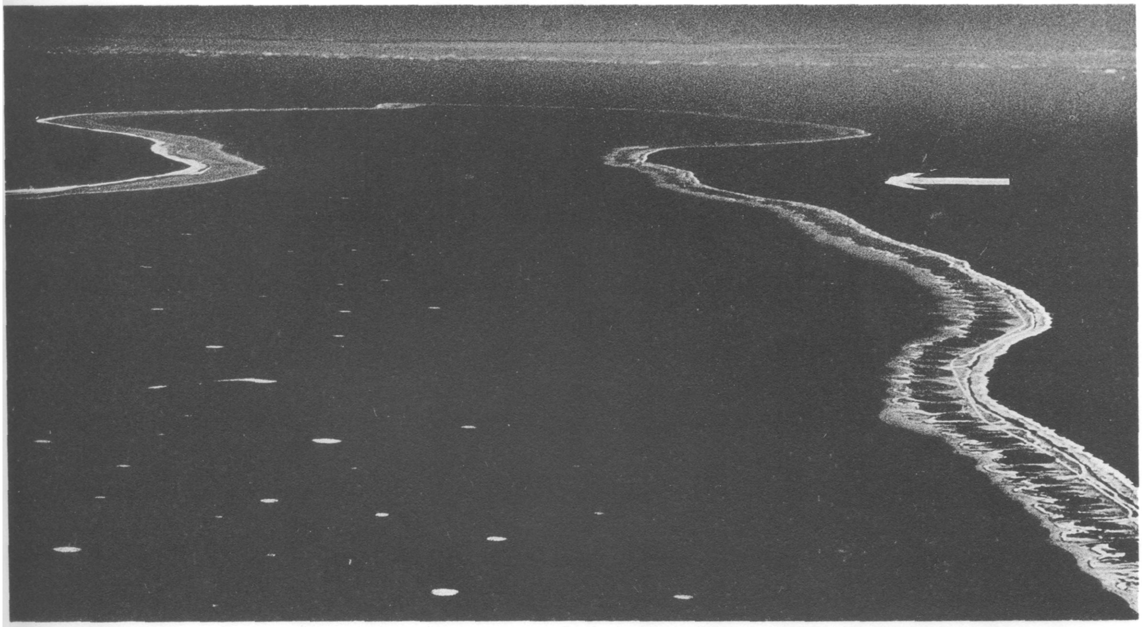
Fringing reef, Moorea, Society Islands
1. Aerial view south-southeast, west end of Moorea
2. Aerial view southwest across Faatoai Bay. Fresh-water streams from the island inhibit reef growth, forming channels through the reef and an incipient lagoon near shore. Drowned valleys and truncated spurs indicate subsidence; elevated low terrace suggests relative drop in sea level

1

2

1. Coral atoll in area of uplift; aerial view southeast from point over Eua Iki Island near Tongatab
Eua Iki is an elevated reef over an igneous rock core. Circular reef is about one-half mile in diameter

2. Aerial view of Maupiti, an "almost atoll," high island of the Society group. Configuration of centr
island of igneous rock suggests subsidence. Diameter of outer reef is about 3 miles



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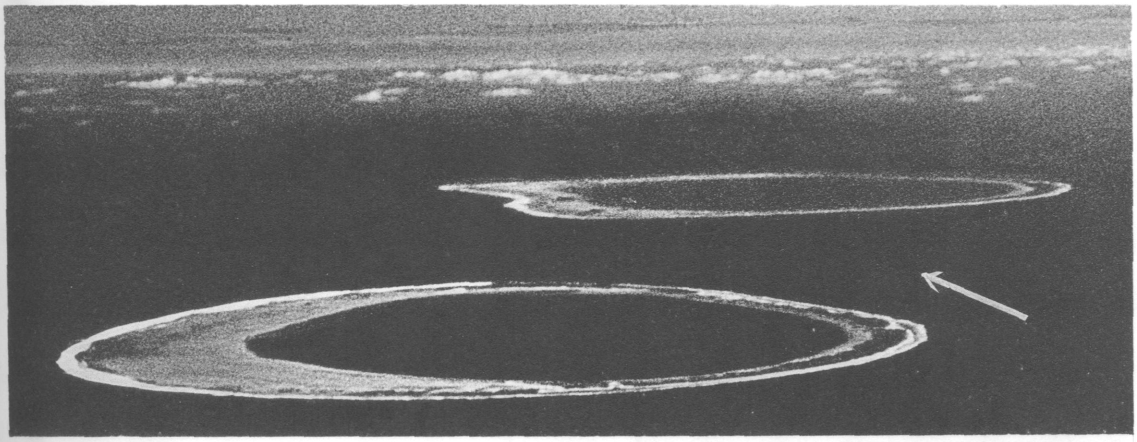

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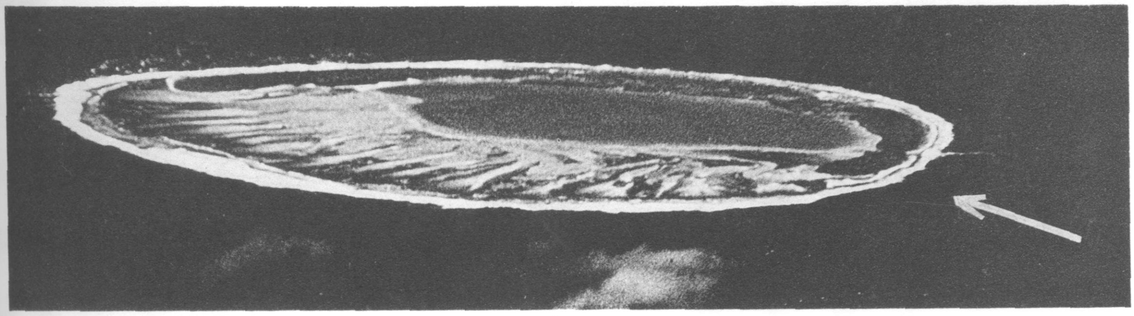


3

Tuamotuan atolls. Prevailing winds blow west-southwest (shown by arrow). Southwestern rim, exposed to a persistent swell, is broad and free from islets

1. Makemo, 45 by 12 miles in diameter, has a single gap in the rim, and a moderately deep lagoon which contains numerous patch reefs, except where reef growth is inhibited near windward rim by heavy sedimentation. View towards northwest

2. Tuanake and Hiti (foreground), circular atolls with unbroken rims. Diameter about 3 miles. View towards west

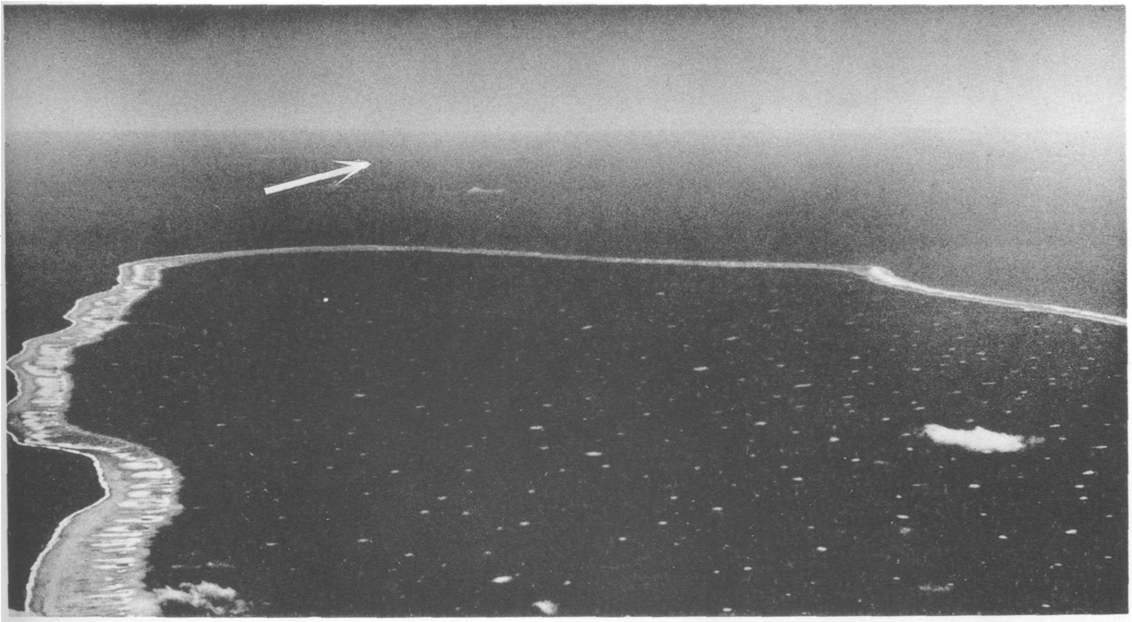
3. Tepoto, a small, closed atoll with infilled lagoon. Diameter estimated at 2 miles. View towards north-northwest

1

2

Anaa Atoll, Tuamotus, example of slightly uplifted, medium-sized atoll with unbreached rim and nea filled lagoon. Diameter about 9 by 20 miles

1. General view of lagoon
2. View seaward. Sheet flood over atoll rim into lagoon forms radial islets of limestone and gravel a deltas of sand



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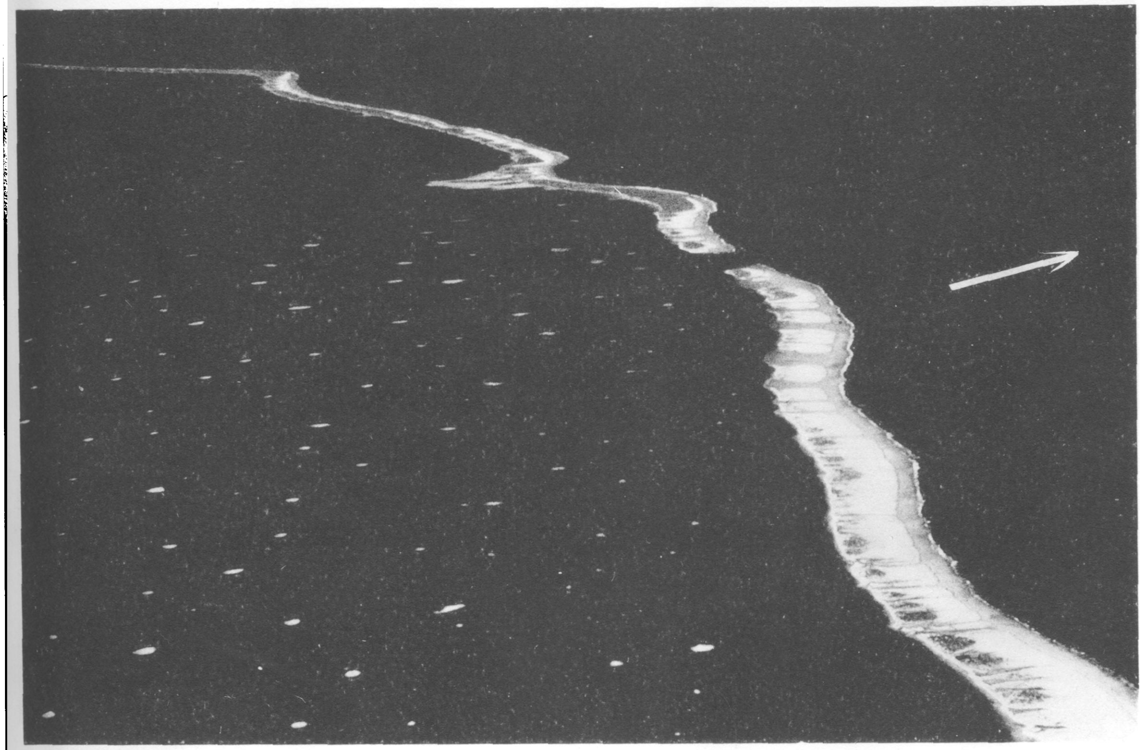

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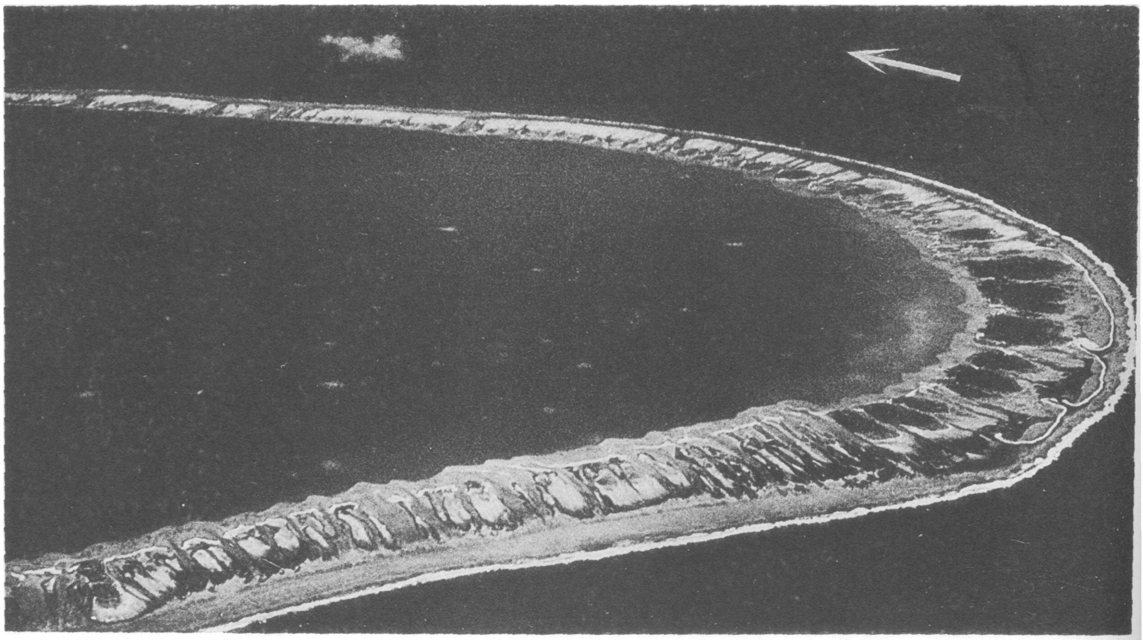
Aerial views of Raroia Atoll, showing deep-water lagoon, a single gap, or pass, and many oriented patch reefs. Wind direction (towards west-southwest) shown by arrows. Views towards southwest



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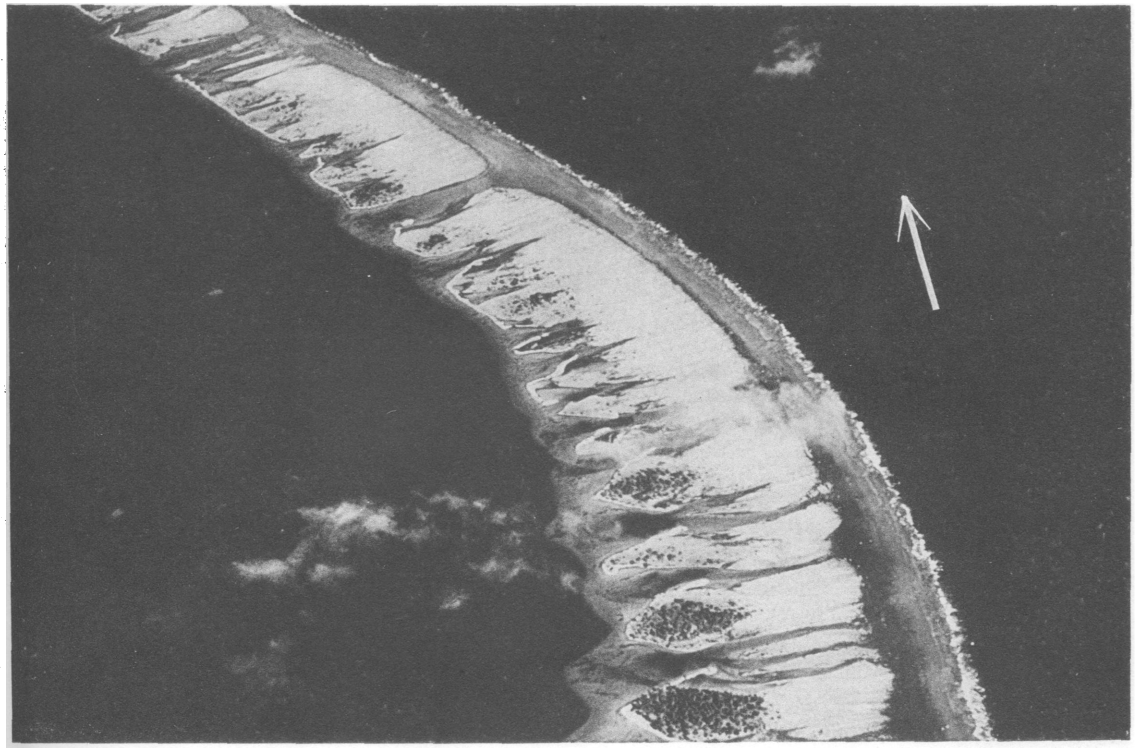
Oblique aerial views of Raroia Atoll. Prevailing wind direction (towards west-southwest) indicated by arrow

1. Northeast end of atoll
2. Southeast end of atoll



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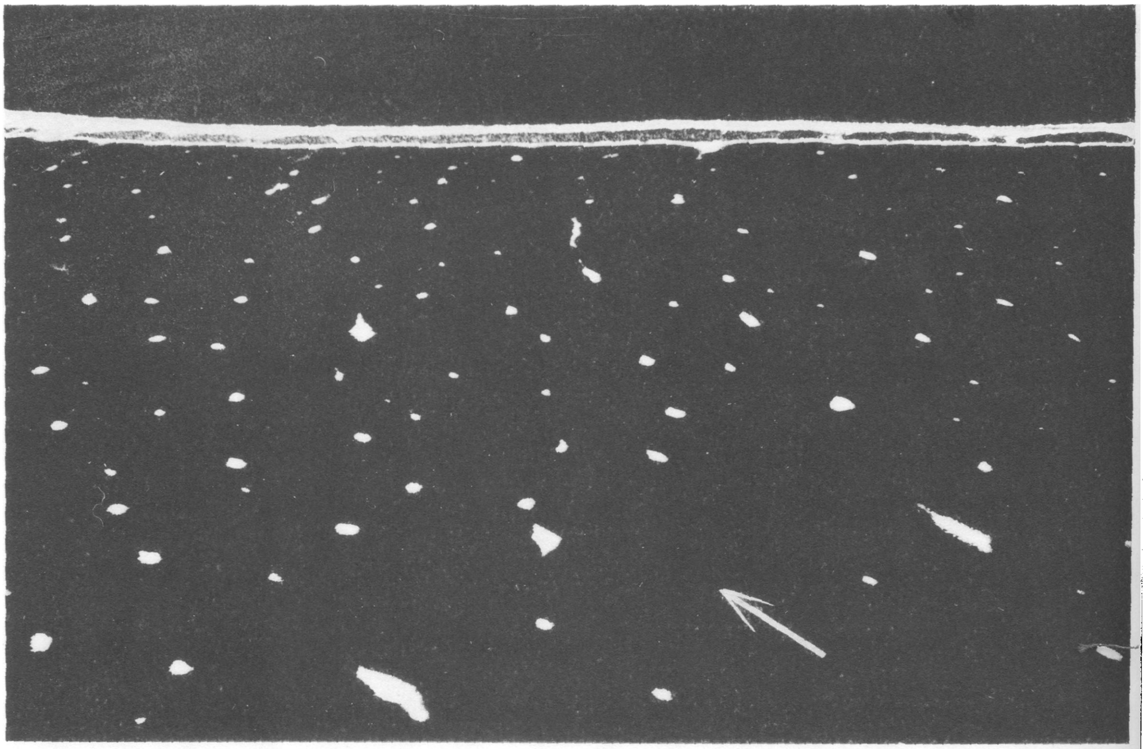
Oblique aerial views of Raroia Atoll. Prevailing wind direction (towards west-southwest) indicated by arrows
1. Northern part of atoll rim
2. Southern part of atoll rim



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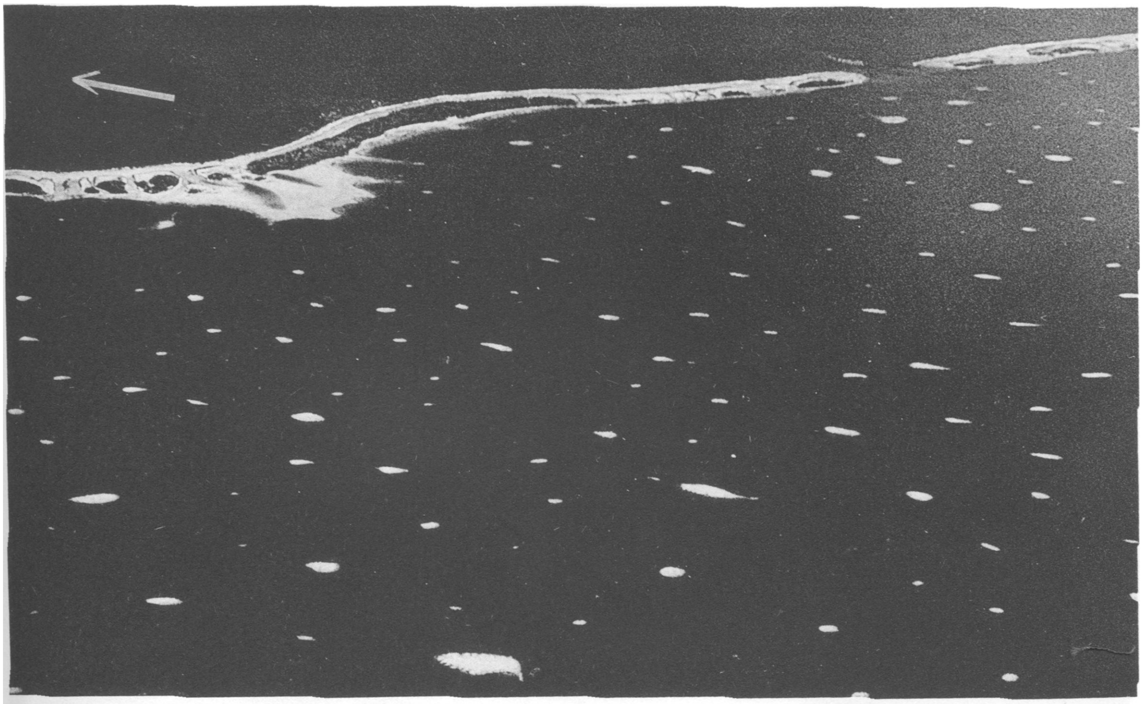
Oblique aerial views of patch reefs, Raroia Atoll. Prevailing wind direction (towards west-southwest) indicated by arrows

1. View northwest towards Teputaiti. Linear series of reefs follow wind direction in central part of lagoon but are deflected towards the right in shallower waters and intersect the shore at right angles
2. Stream-lined patch reefs. The largest shown are about 100 meters long at the surface



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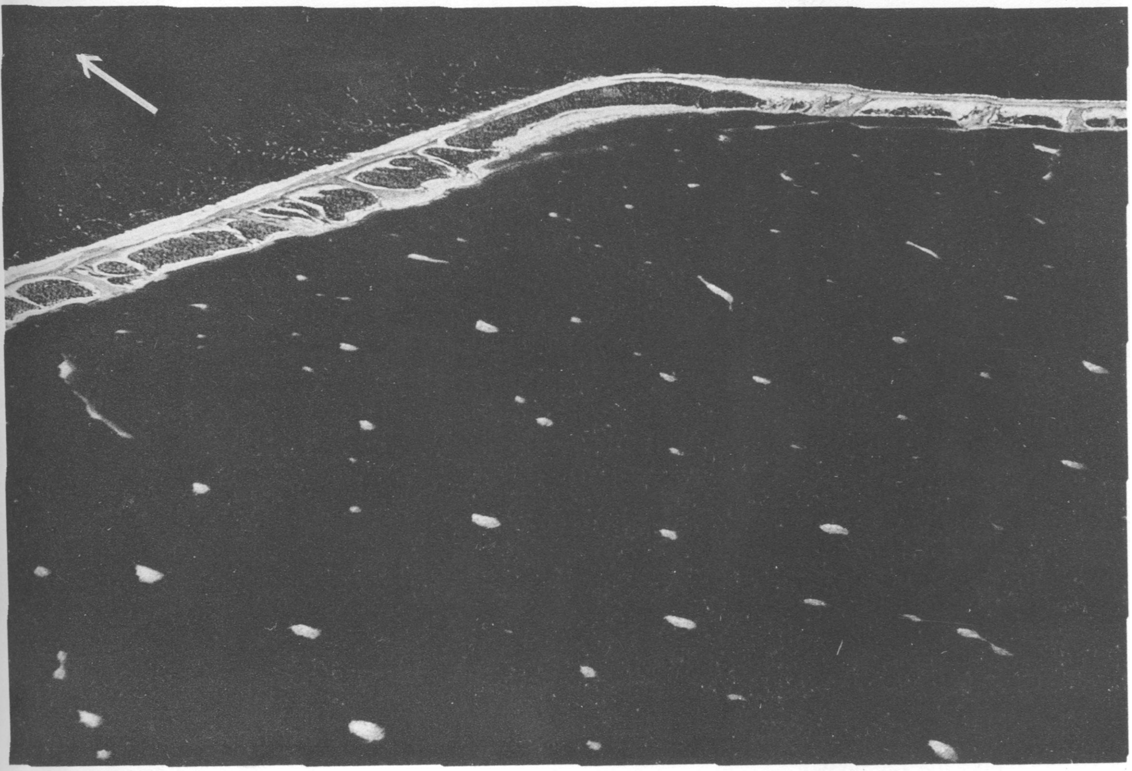

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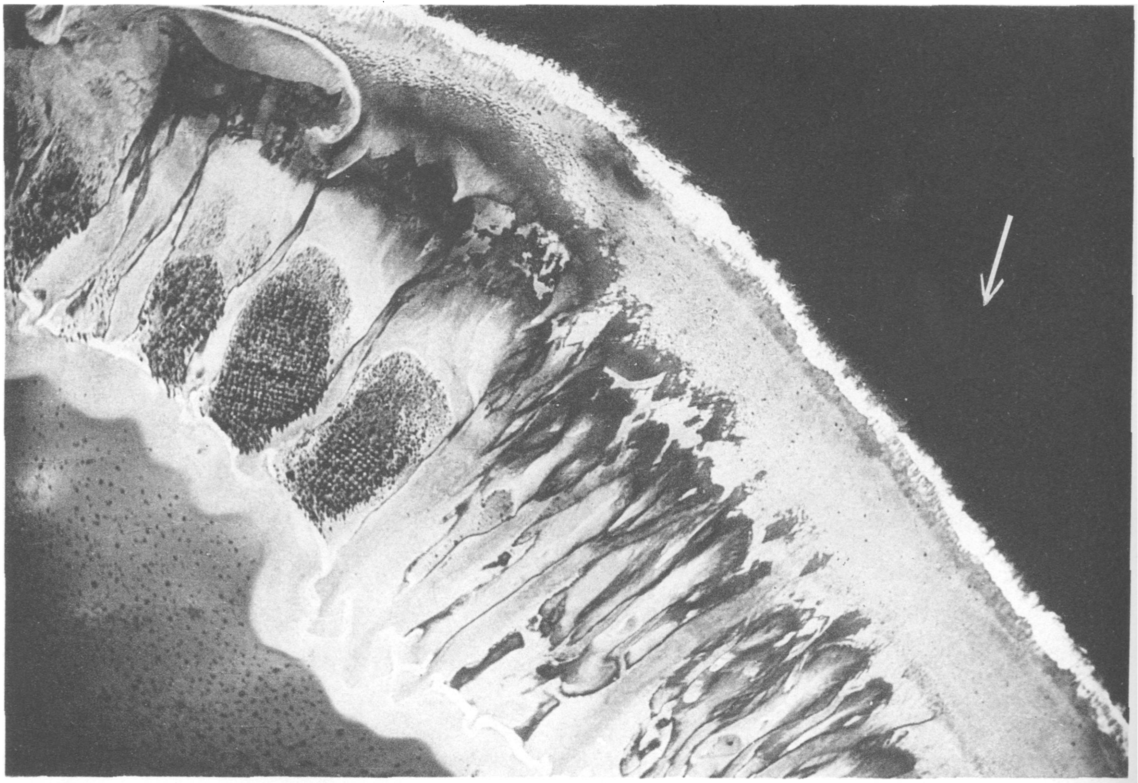
Oblique aerial views of patch reefs, Raroia Atoll. Wind direction shown by arrows
1. North view towards Garumaoa and Garue Pass
2. West view towards Oneroa



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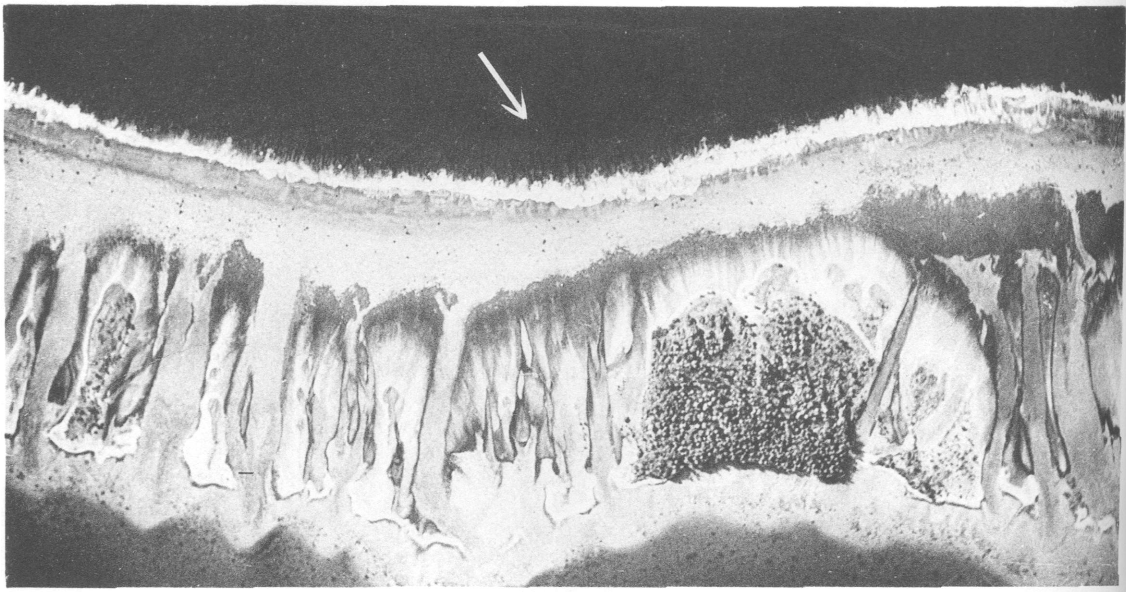

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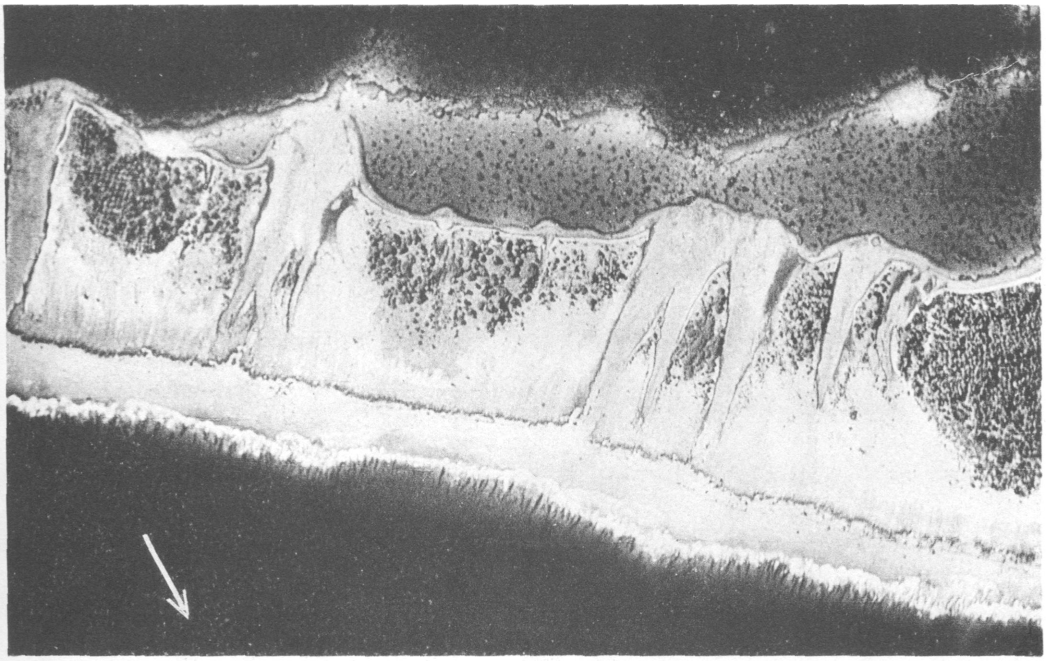
Vertical views of eastern rim of Raroia. Arrows show prevailing wind direction (west-southwest); length of arrows represents 150 meters

1. Northeast end of atoll, Marokohua and Mararo cocoanut groves left of center. Note crescentric gravel rampart at upper left

2. Southeastern area, Gagieroa at right of center



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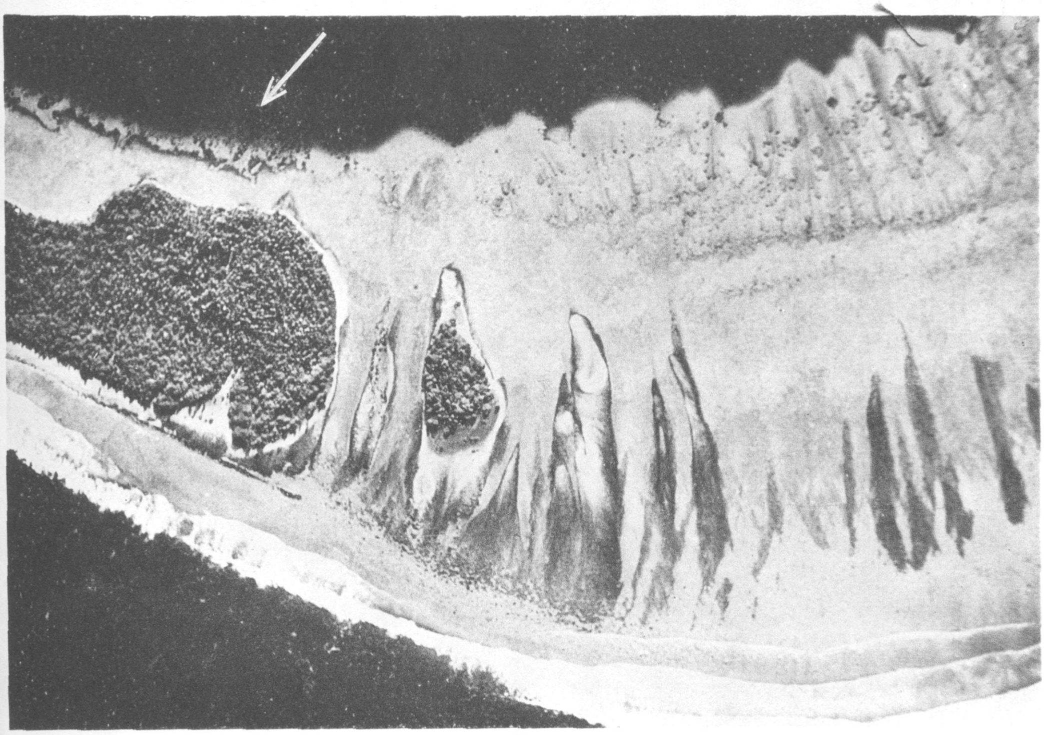

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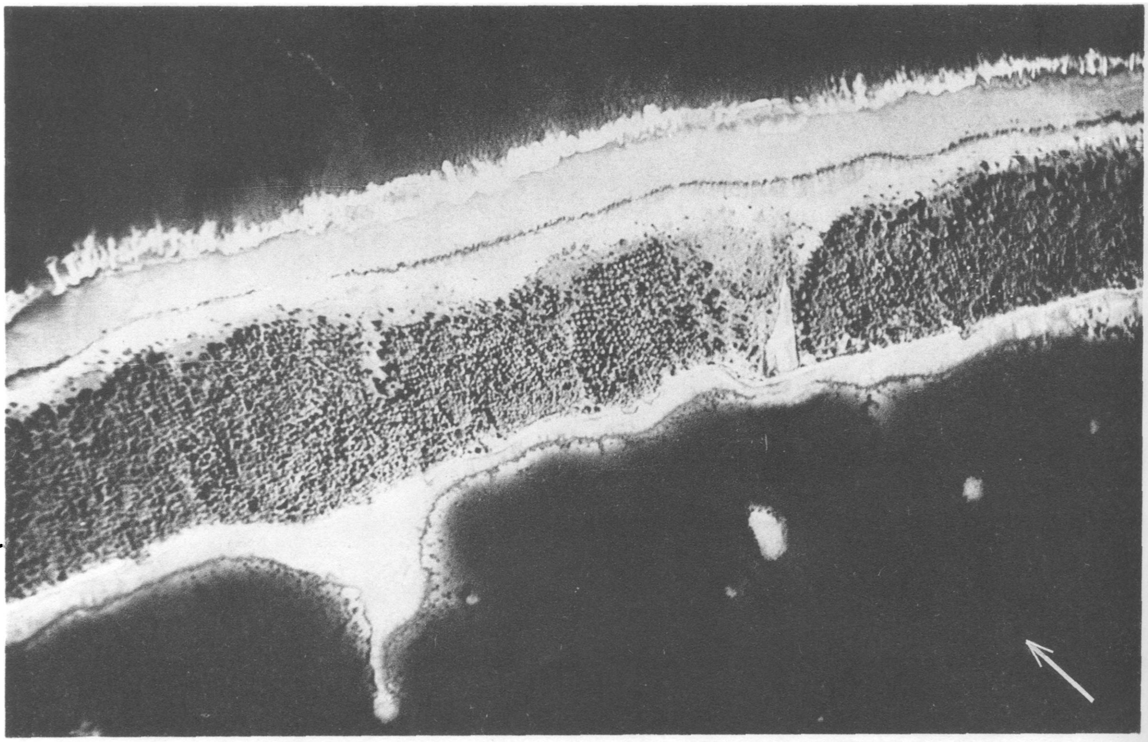
Vertical views of southern area of Raroia Atoll. Arrows indicate prevailing winds (west-southwest); their length represents 150 meters

1. Small reef barrier in lagoon (upper part of photograph), Makoro islet on right, Turei islet on left
2. Southern end of Opakea islet and adjacent submerged rim of atoll which is being extended lagoonward by deposition of deltaic fans of gravel and sand



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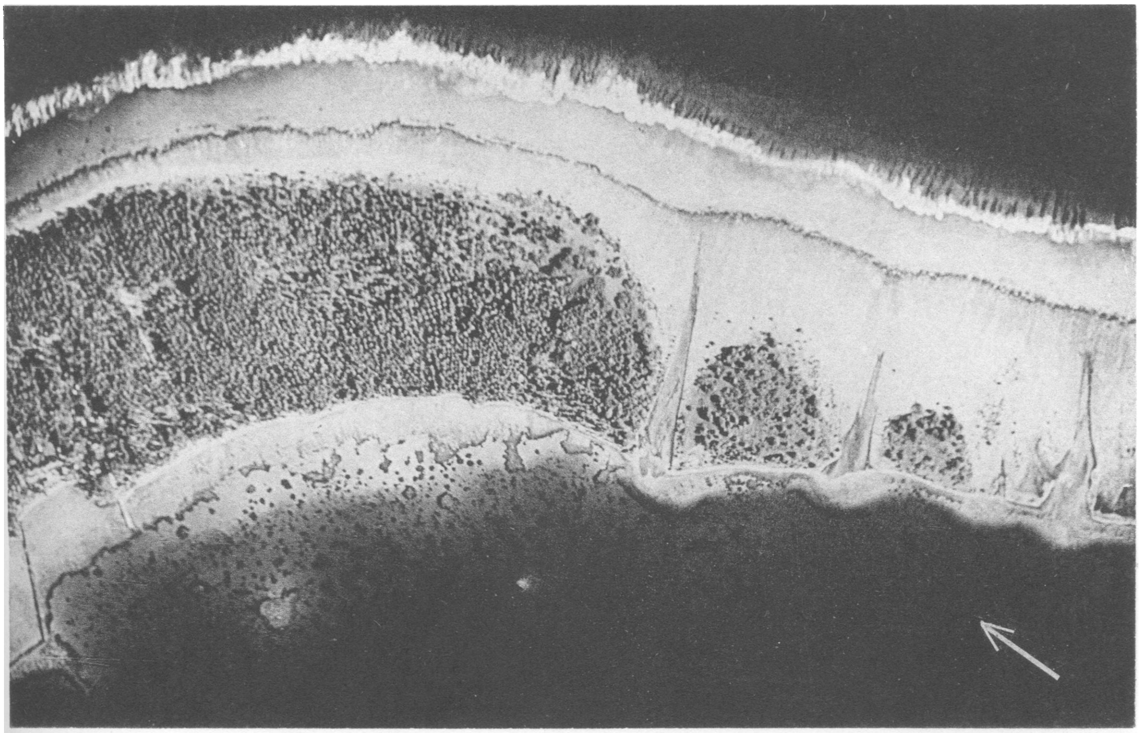
Vertical views of western rim of Raroia Atoll. Arrows indicate prevailing winds (towards west-southwest); their length represents 150 meters

1. Peninsular extension of shore reef (*kaoa*) of Teputaiti islet
2. Atoll rim just south of Garumaoa islet, Kukina islet at center



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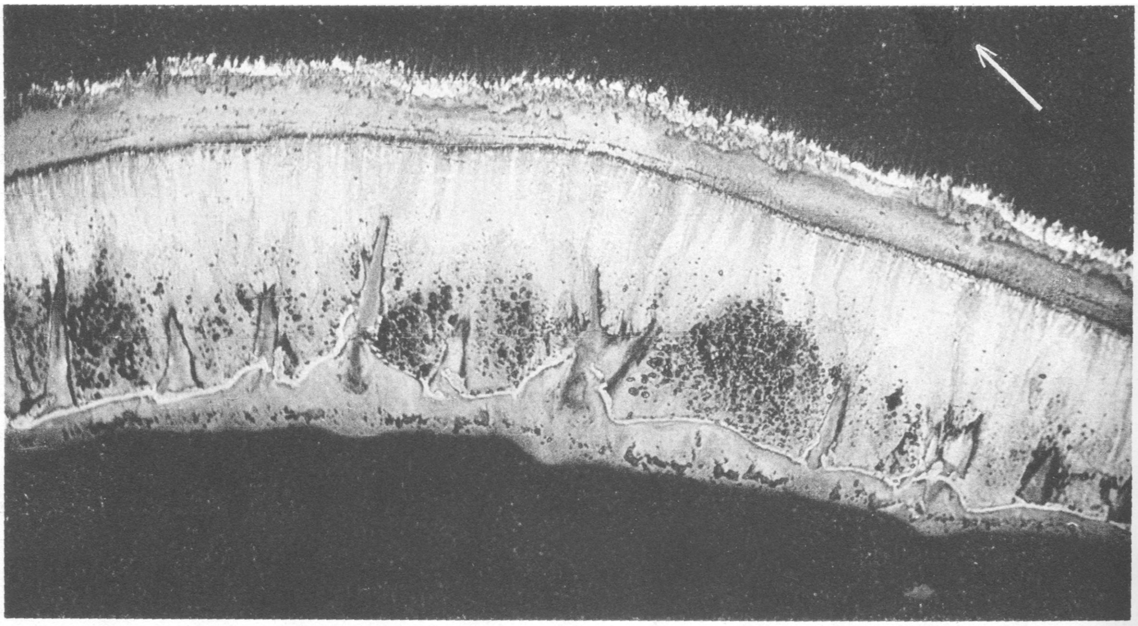
Western rim of Raroia Atoll. Arrows indicate prevailing winds (towards west-southwest)

1. Vertical view showing incomplete channels at right, Garumaoa jetty and wharf at left. Length of arrow represents 150 meters

2. Oblique aerial view of great lagoon reef, probably built on gravel fan, at south end of Garumaoa; Miramirau, tongue reef, or *kaoa*, in background



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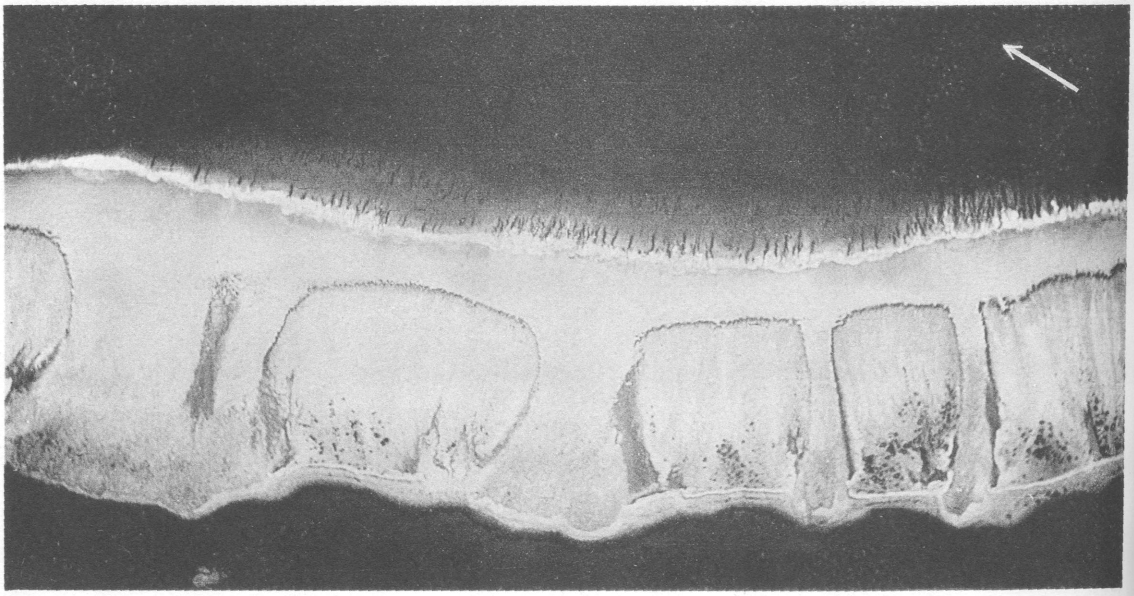


2

Vertical views of northwest rim of Raroia Atoll. Arrows indicate prevailing winds (towards west-southwest); length of arrows represents 150 meters

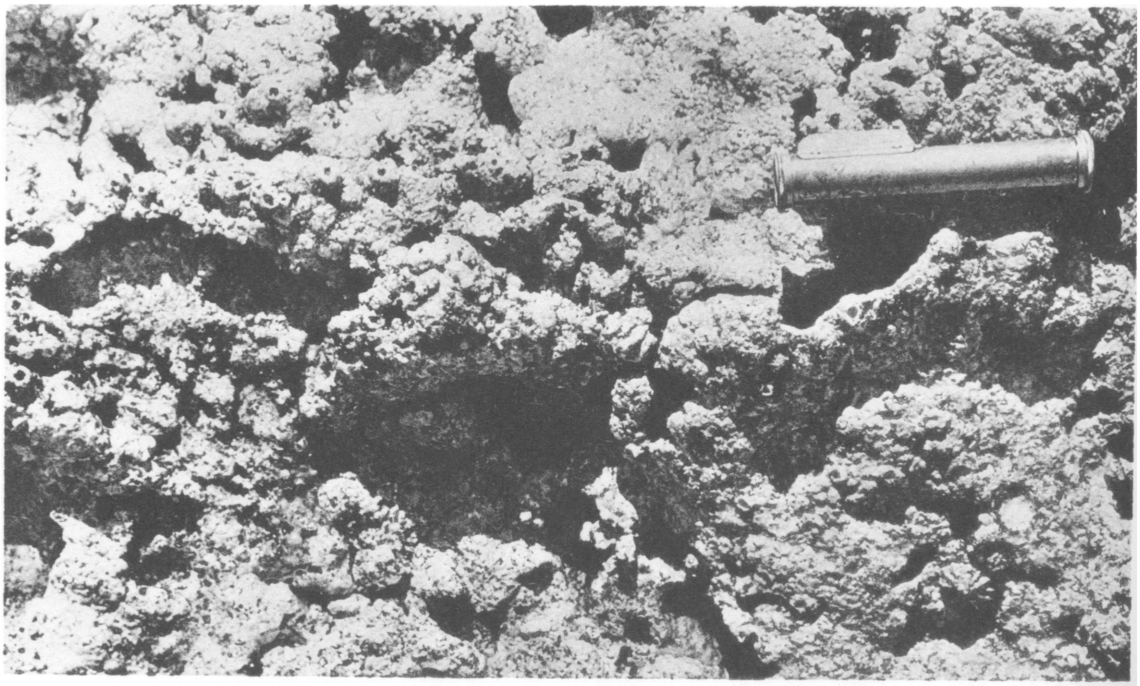
1. Dendritic pattern of incomplete channels in conglomerate platforms between gravel heaps; Kanakana cocoanut grove just right of center. Light line along lagoon shore is storm ridge of gravel

2. Area north of Garue Pass, south end of Farakao islet at left. Submerged, grooved terraces at "20 meters" and "8 meters" are shown above middle of photograph

1

2

Outer lee reef, Garumaoa, Raroia Atoll
1. Algal ridge at rim of reef flat. The latter is an inter-tidal platform probably mainly erosional in origin
2. Surge channel rimmed and locally bridged by accretions of coralline algae. Prominence at right is being
...vely eroded



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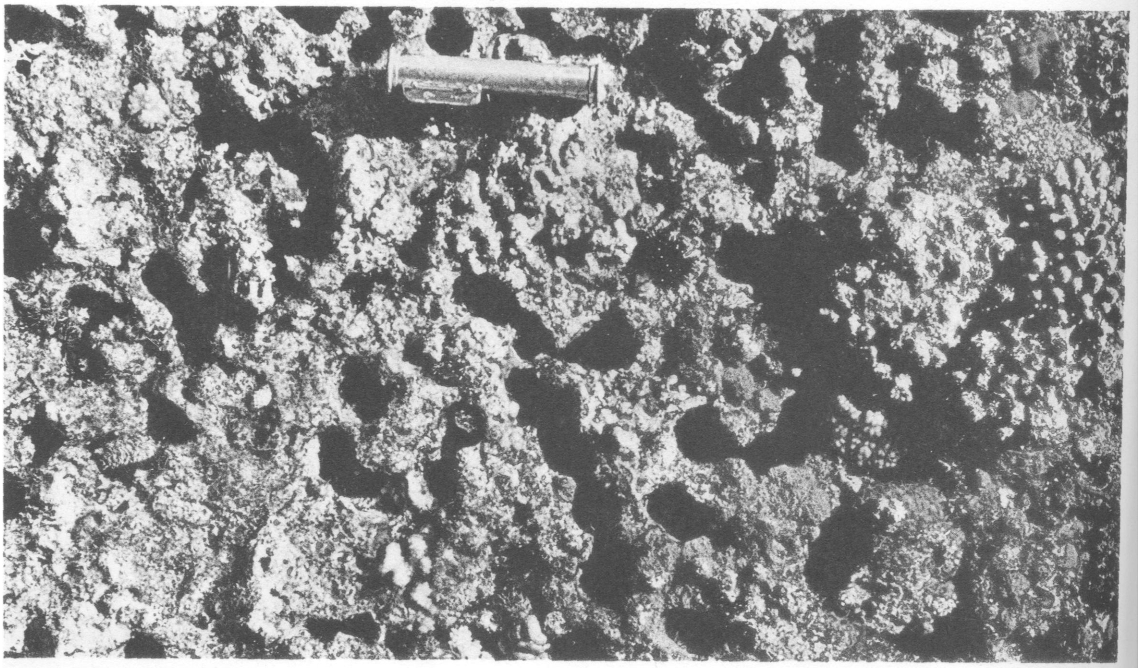

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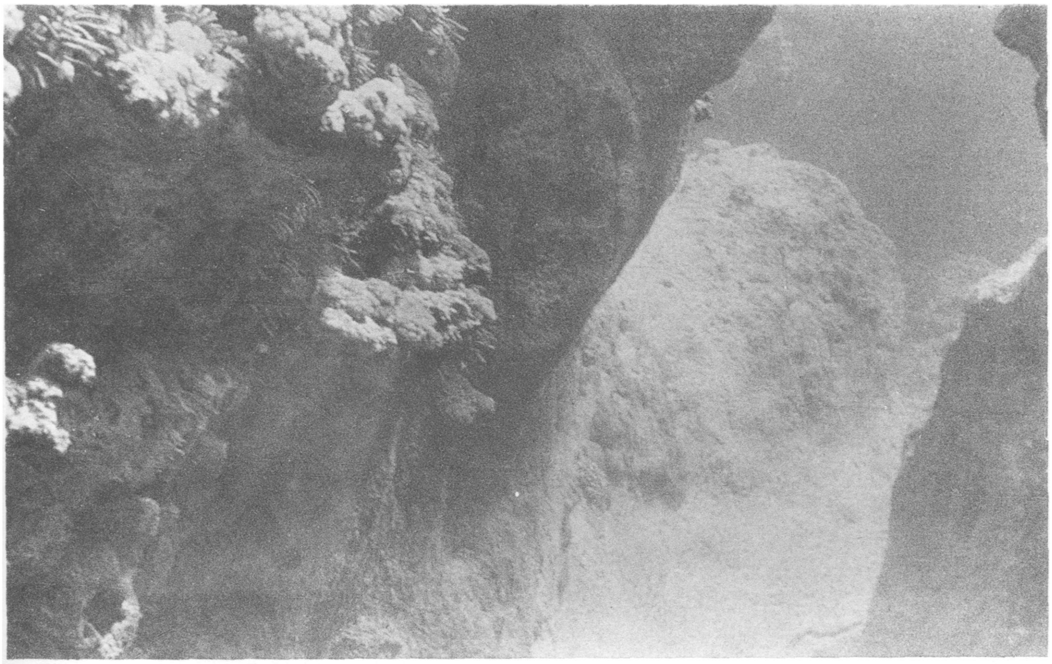
Outer lee reef, Garumaoa, Raroia Atoll

1. Seaward face of algal ridge, showing characteristic crustose and cellular structure. Surface animals shown here are limpets and barnacles, partly overgrown by coralline algae

2. Reef flat just inside algal ridge. Coarse burrows are formed by the echinoid *Echinometra mathaei*. Hand level is about 5 inches long



1

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Under-water photographs of reef grooves at Makoro, just north of Oneroa, southwestern rim of Raroia Atoll

1. A bare, gravel-scoured gorge about 7 feet wide and 25 feet deep
2. Gravel-filled depression in floor of a groove, viewed from above. The largest boulder is about 2 feet across

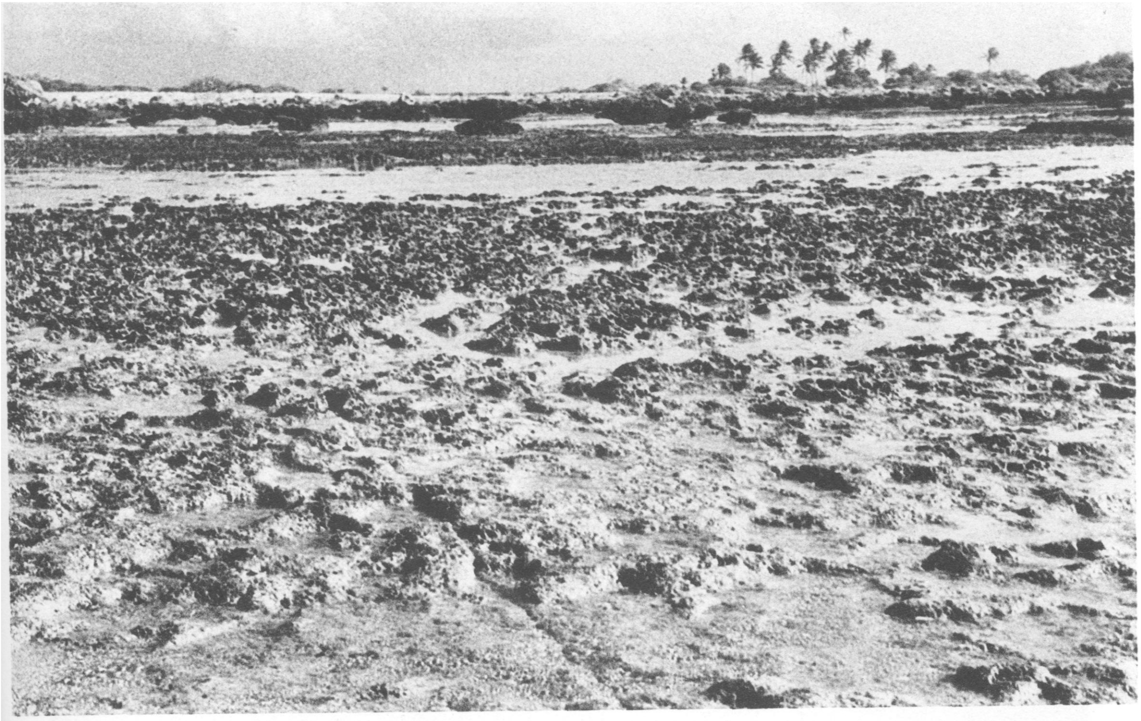
1

2

Erosion of the reef flat, Raroia Atoll

1. Anastomosing furrows, at a gap in algal ridge, formed, probably, by mechanical scour. Seen at low spring tide

2. Dissected reef flat at Oneroa. There is no algal ridge here to protect the reef flat. Reef growth is active a few feet below low-tide level



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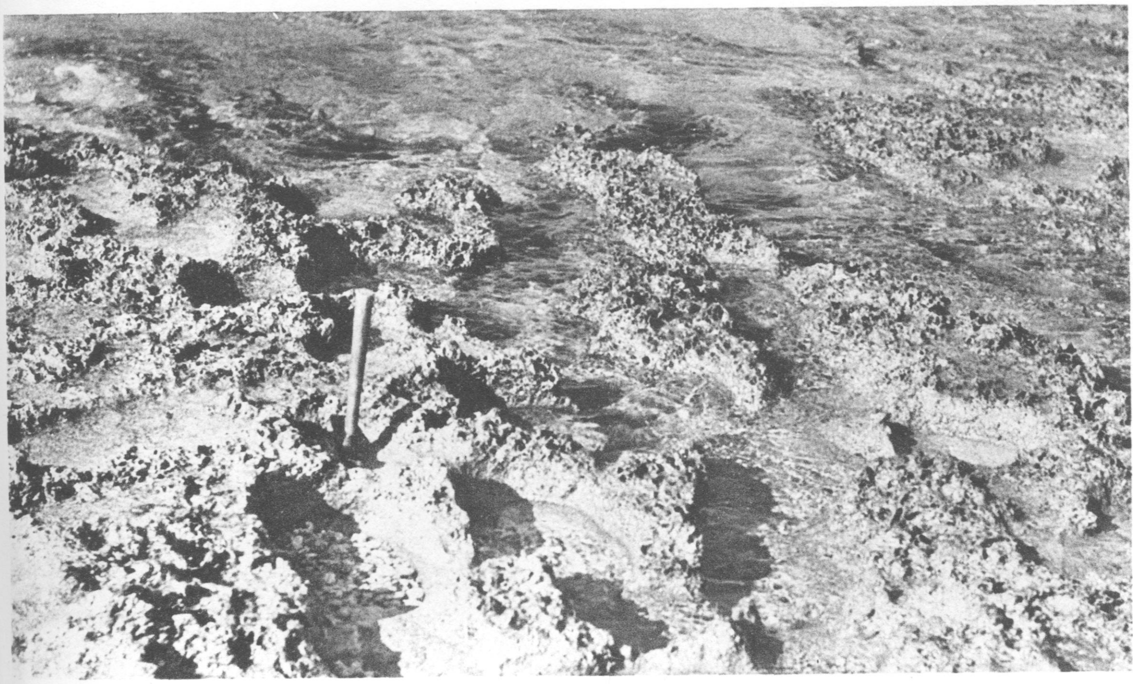
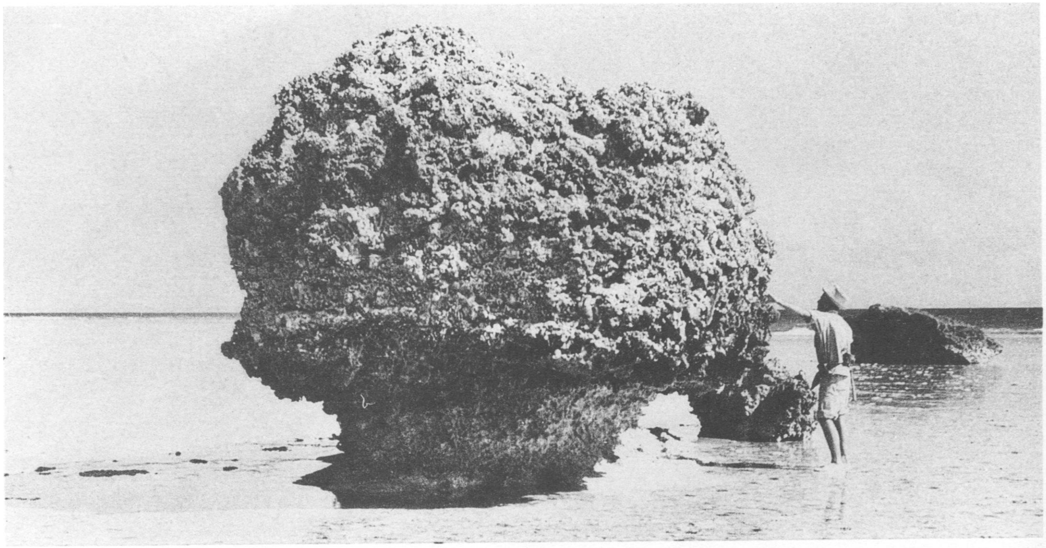


2

Erosion of the reef flat, Raroia

1. Roughened surface of reef flat and etched joint line near Hoa Tahuna Havana, northwestern Raroia. Reef flat is being extended landward mainly by organic erosion and gravel scour of the island conglomerate

2. Potholes on reef flat excavated by gravel scour; same locality as above



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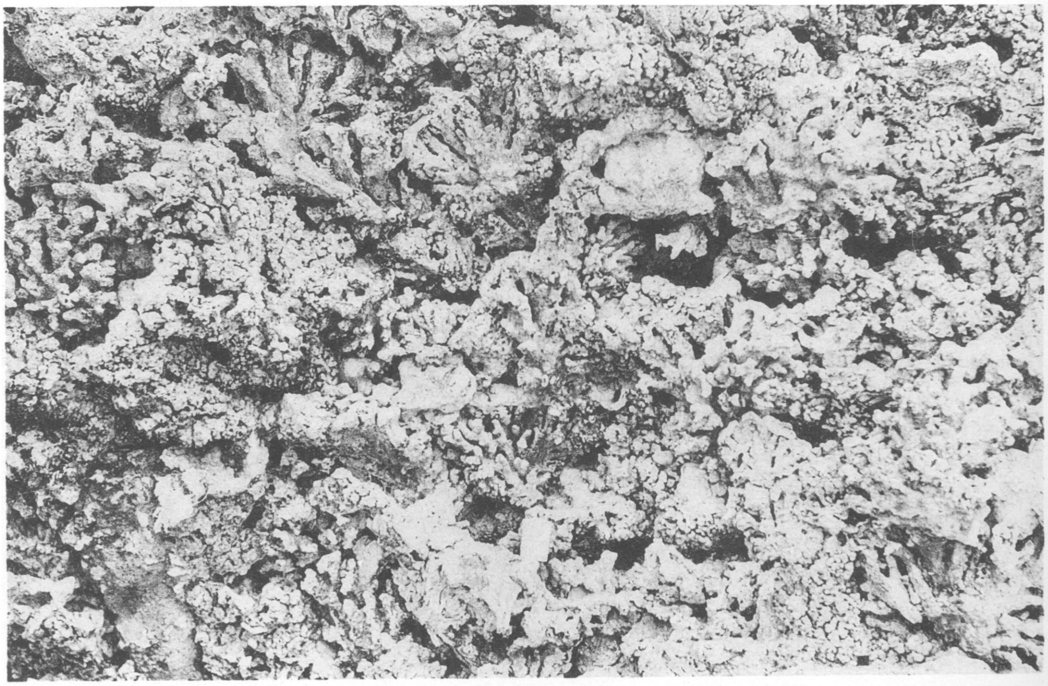
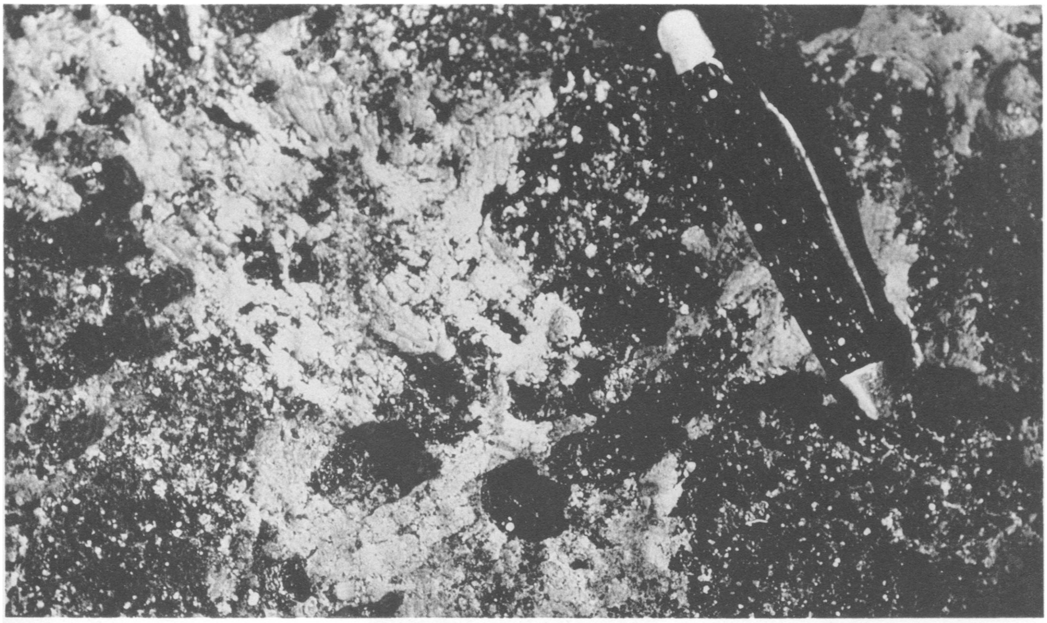


2

Erratic reef block on reef flat; Oneroa, Raroia Atoll

1. The block represents fragment of reef spur transported and deposited on the erosional platform by storm waves. The nip is a characteristic intertidal feature of limestone coasts. It is thought to be mainly a result of the activities of organisms: leaching, below a film of blue-green algae, and mechanical rasping and boring by animals. There is no compelling evidence that it is a result of solution of the rock by sea water. "Black zone" lies at waist level

2. Detail of figure 1, showing reef frame of corals and algae characteristic of coral reefs



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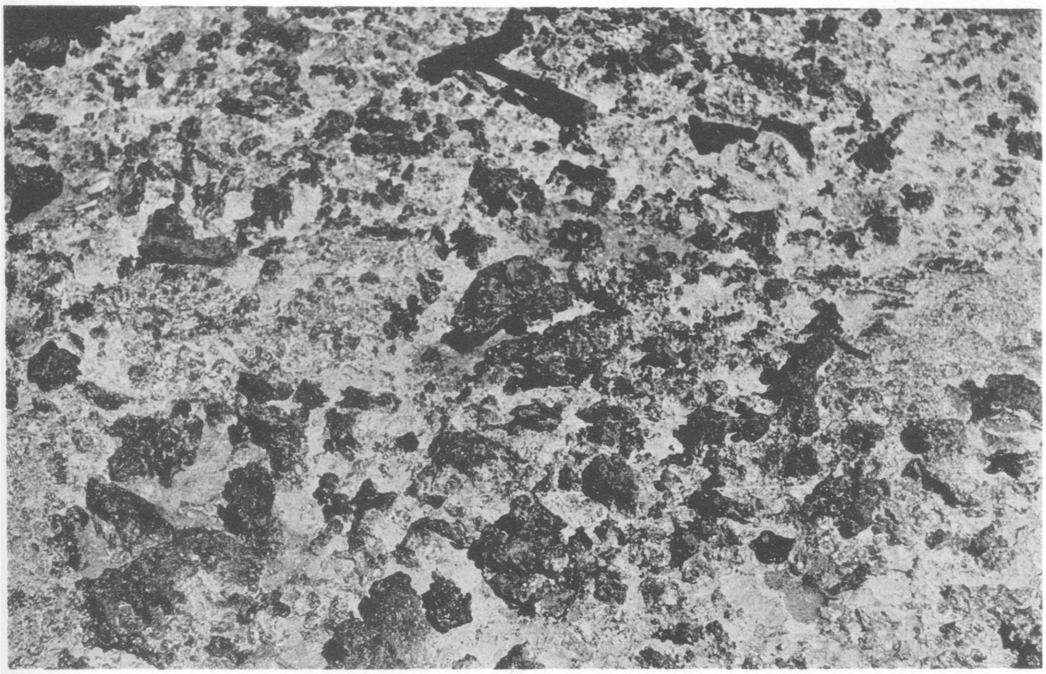
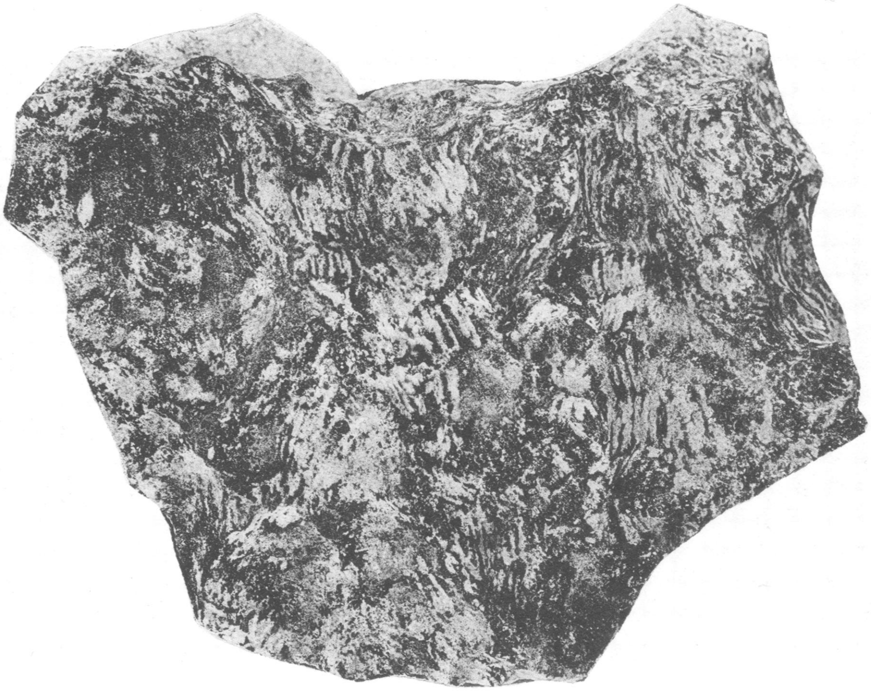


2

Gastropods as agents of erosion in intertidal zone, Raroia

1. Radular furrows in limestone produced by *Turbo argyrostomus.* This gastropod systematically grazes on blue-green algae and removes much limestone in the process

2. Light-colored depressions between erosional pinnacles of coral fragments are covered by radular furrows of *Nerita plicata.* Pinnacles are not striated; they are stained black by an algal film



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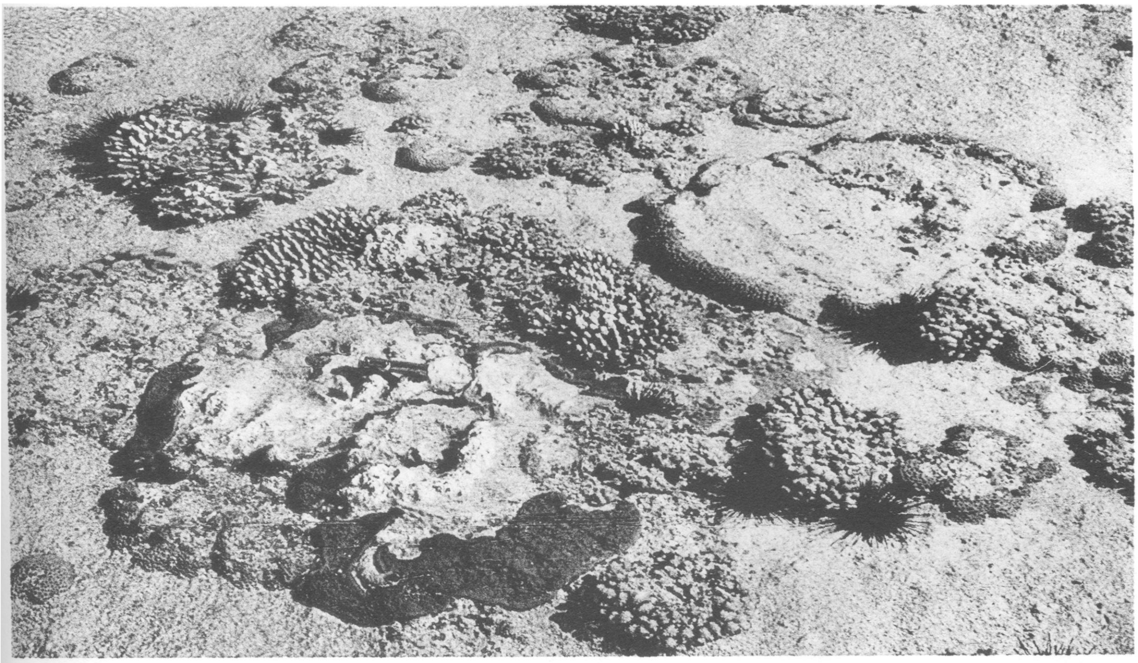
2

Parrot fish as agents of erosion of reef flat, Raroia

1. Dry fragment of limestone from reef flat, approximately natural size. Paired furrows are produced by parrot fish as they scrape the rock for algae

2. Striated reef flat limestone beneath a few inches of water. Paired grooves are in some cases 0.5 mm. or more deep. Tool is 6 inches long



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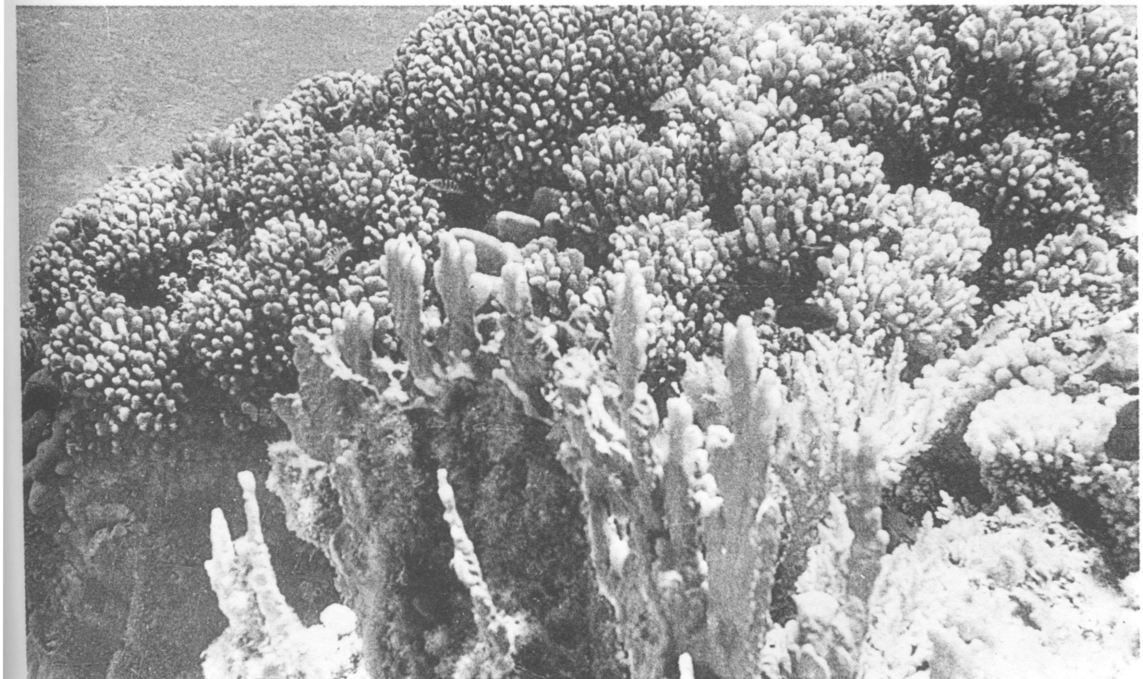
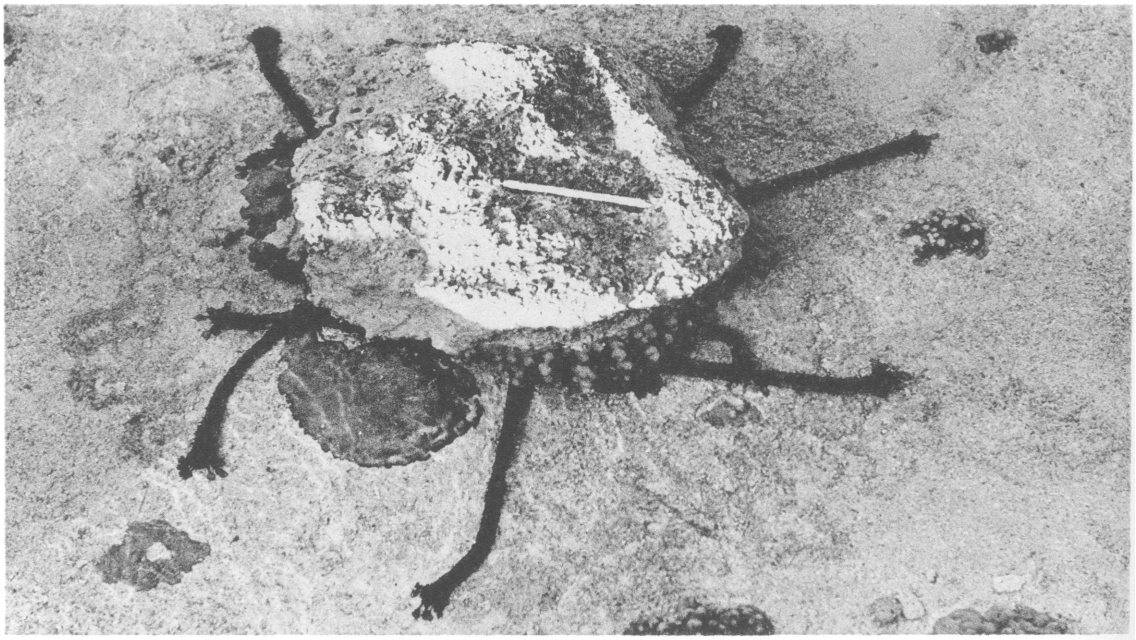


2

Reef corals, Raroia Atoll
1. Outer reef flat organisms beneath a few inches of water, Homohomo, Garumaoa islet
2. Lagoon shore reef windward, Homohomo, Garumaoa islet



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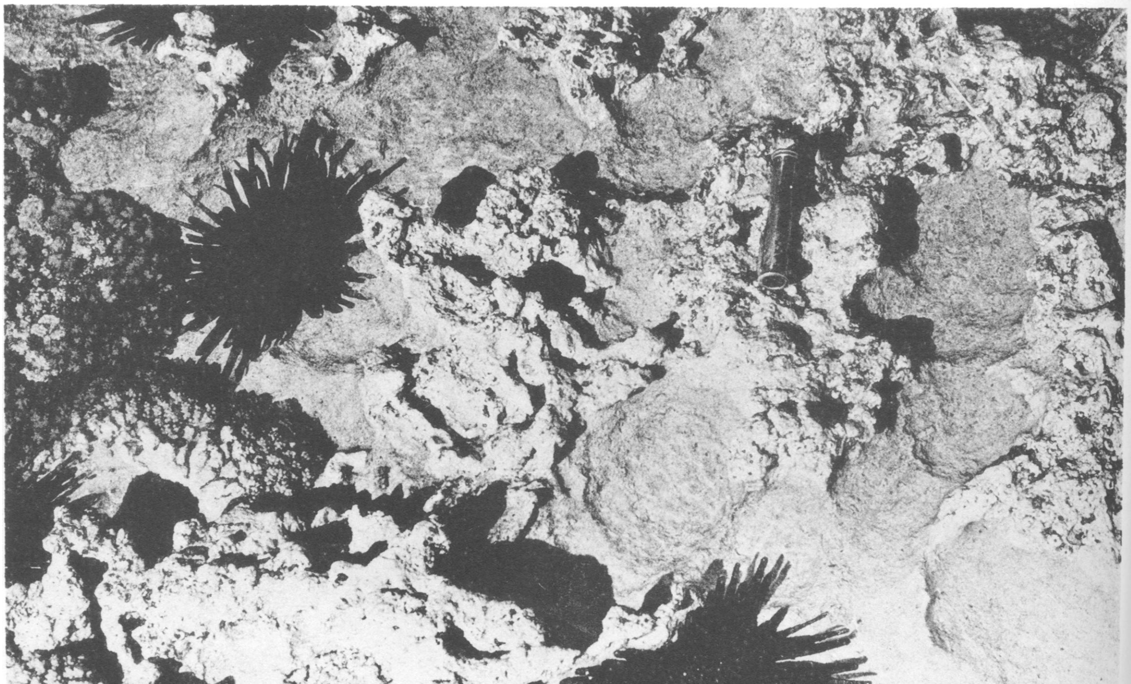

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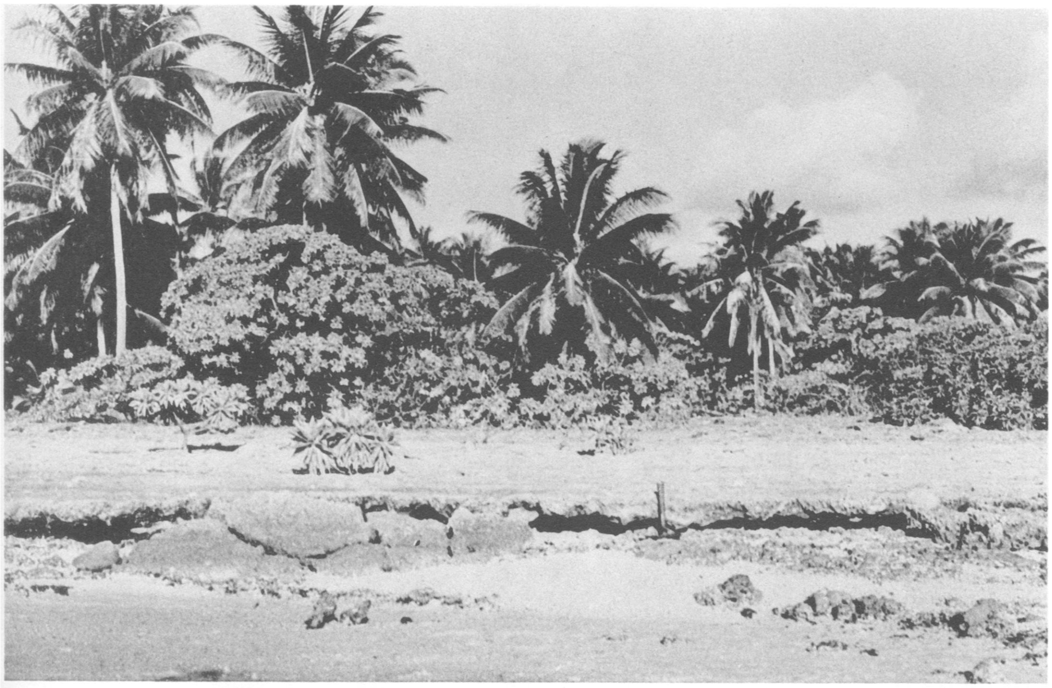
Reef flat animals, Raroia Atoll
1. Holothurians in shallow water near shore
2. Pencil urchins and their shallow excavations behind algal ridge, Garumaoa islet



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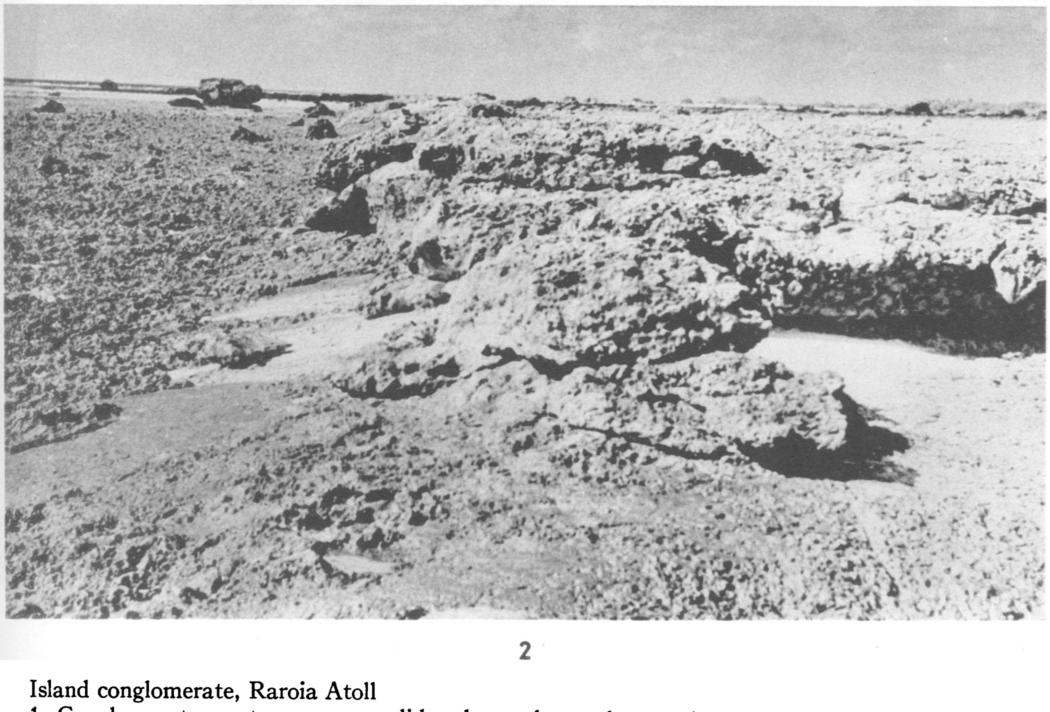

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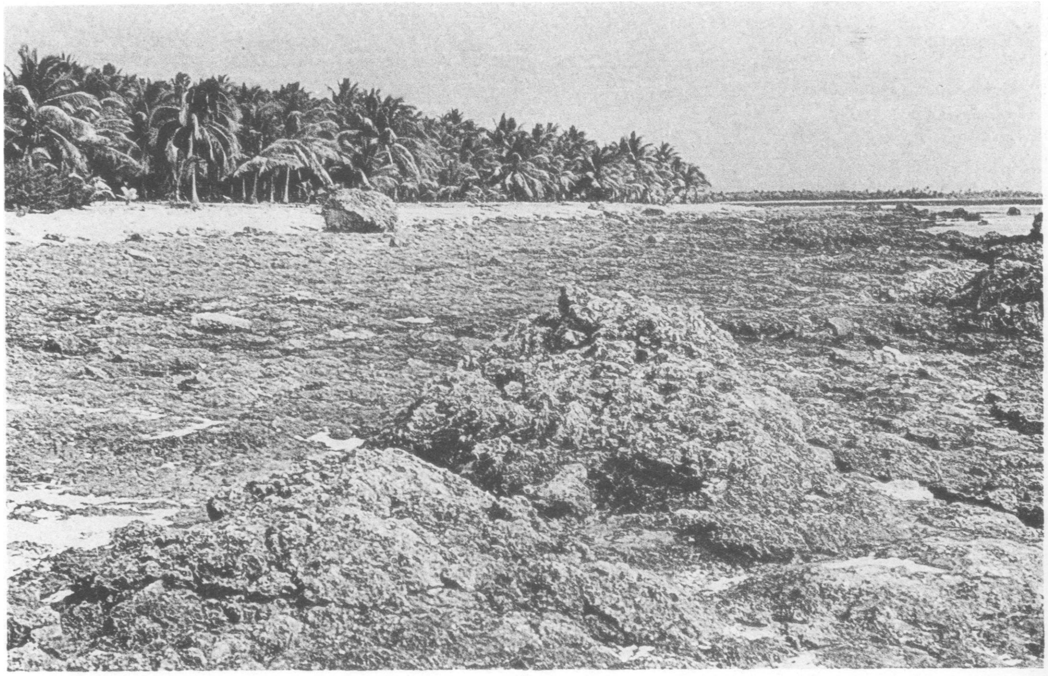
Island conglomerate, Raroia Atoll

1. Conglomerate crust over unconsolidated gravel, near lagoon shore, Teuriamote, northern Raroia
2. Retreating edge of conglomerate platform, Garumaoa islet, western Raroia. Storm waves break off blocks of the rock along low curved fracture planes



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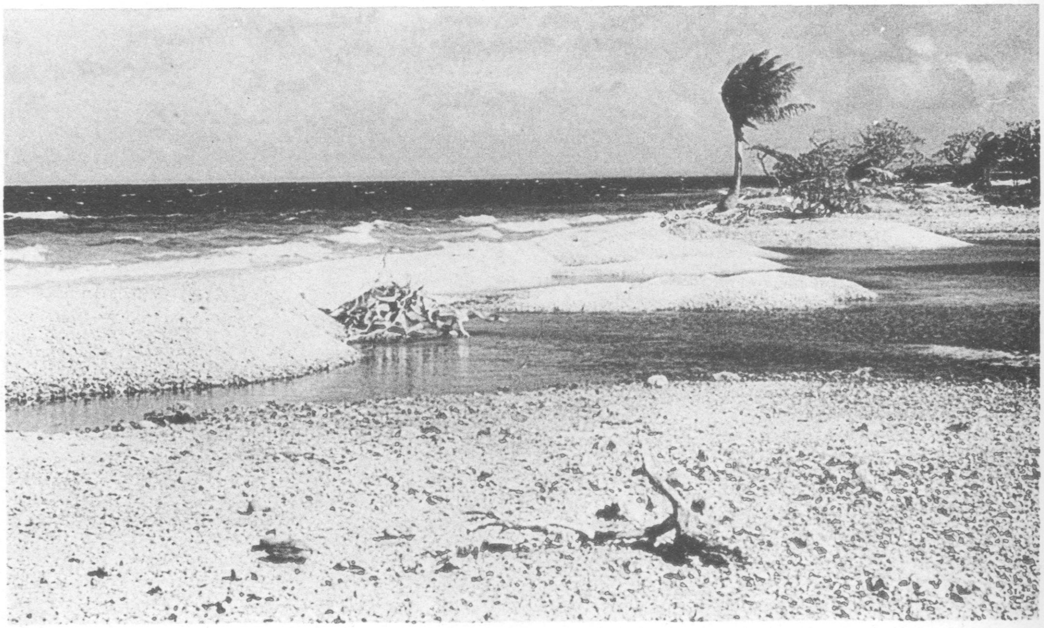


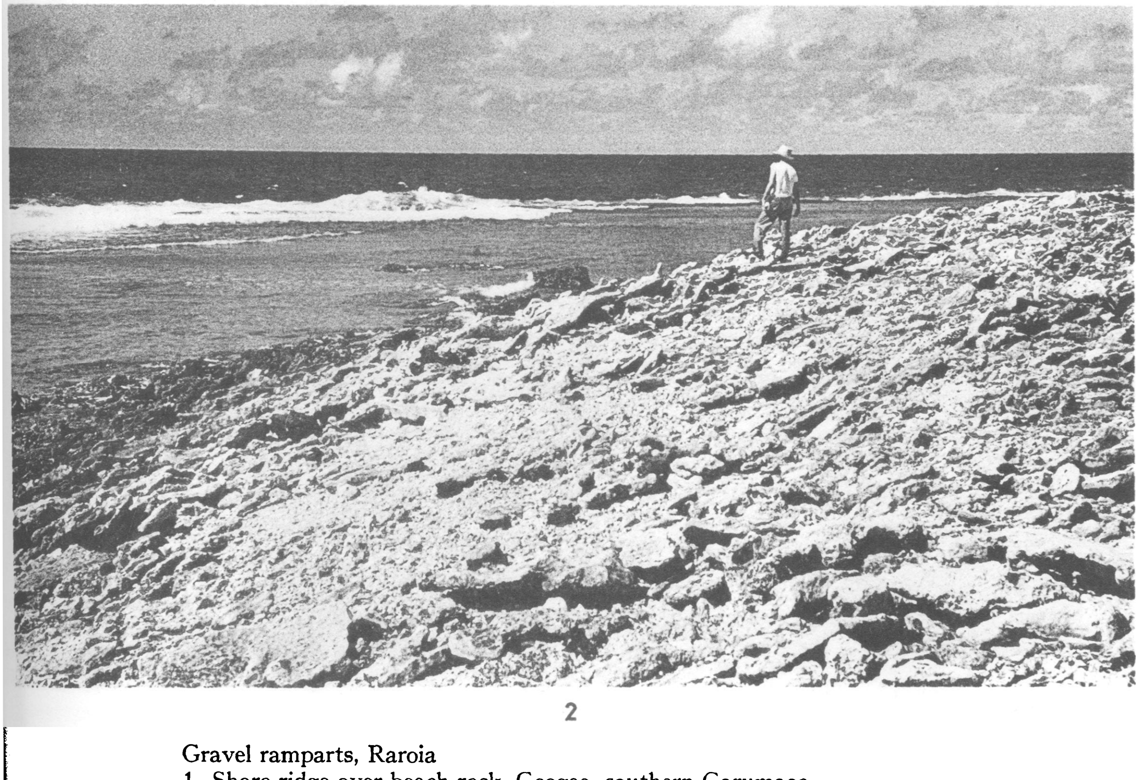
2

Beach ridges, Raroia

1. Outer sand ridge, northern end of Garumaoa islet. In background is an erratic block of reef limestone. Prominences in foreground are ancient blocks that have been incorporated in conglomerate platform

2. Gravel ridge across incomplete channel, lagoon, windward shore between Tomagagie and Huahine, north of Garumaoa islet

1



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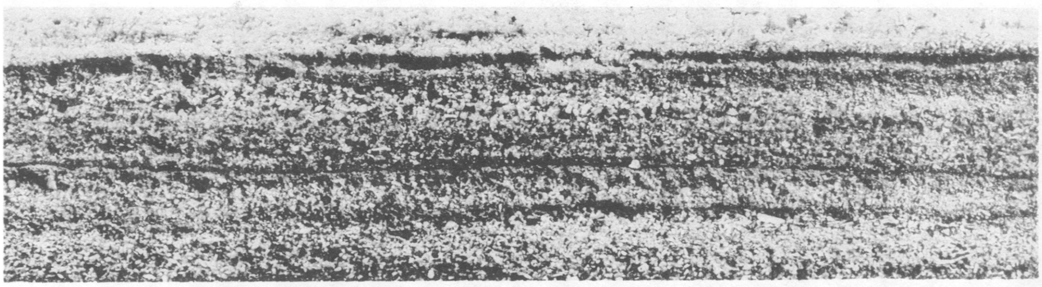
Gravel ramparts, Raroia

1. Shore ridge over beach rock, Geogeo, southern Garumaoa
2. Imbricate slabs of *Acropora conigera*, windward side of atoll; Tetou islet



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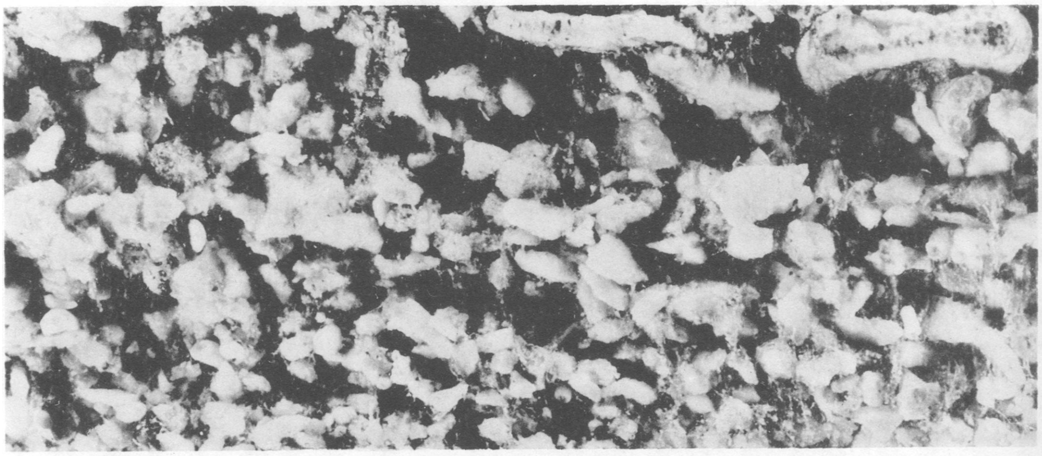

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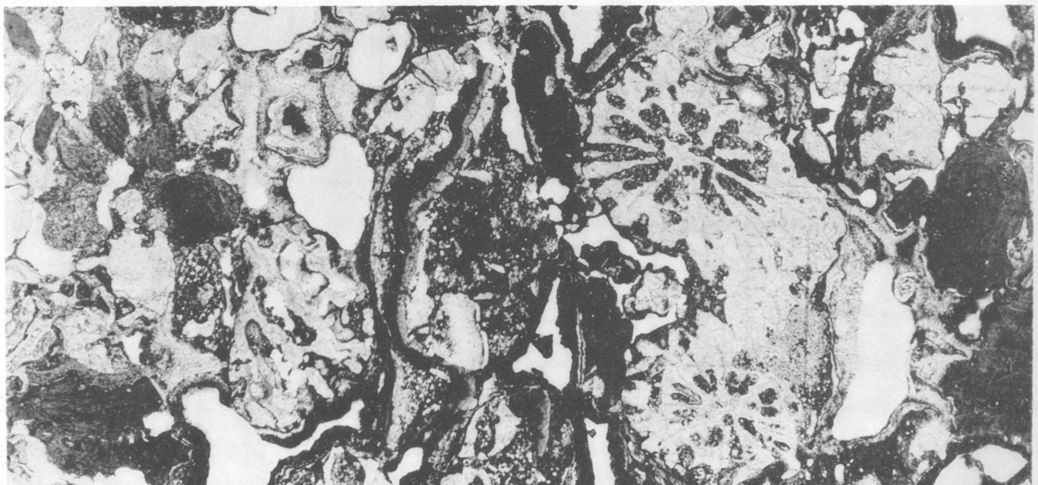

3

Cementation of limesand, Raroia

1. Partly indurated sand interlaminated with algal films, ×2; from a moat marsh, northern Garumaoa islet

2. Same, ×20, showing algal fibers which give considerable cohesion to the sediment

3. Thin section, ×10; limestone from outer shore zone, Garumaoa islet, showing voids and encrusting laminae of prismatic aragonite which cements the detrital grains. There is no evidence here of leaching

surf, they would probably advance at unequal rates, and this should produce a lobate or irregular margin.

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%), and *Porolithon onkodes* which is most prevalent at the inner margin (50%), decreasing rapidly seaward towards the outer ends of the spurs. Other abundant plant and animal 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 these forms are securely attached and do not project above the bottom more than 10 to 15 cm. This is an association of strongly turbulent shallow waters. It is evidently from this zone that most of the large erratic blocks of the reef flat are derived (pl. 41; text fig. 11).

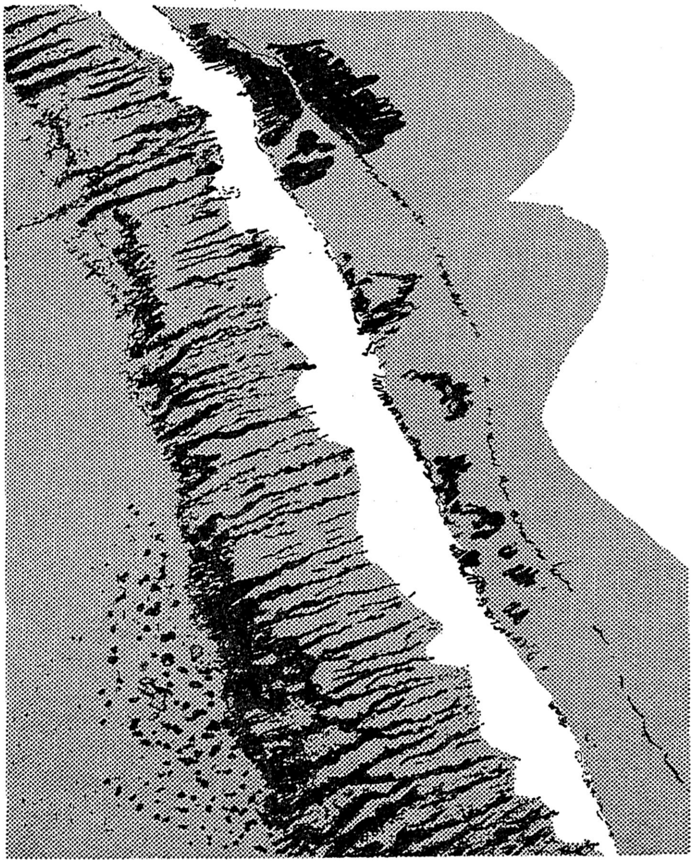

FIG. 10. Spur and groove zone of a Bikini reef. Reef front and deep water at lower left. (From a photograph published by Ladd *et al.*, 1950.)

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 grooved terrace which slopes gently seaward to a rim at approximately 8 meters. This probably lies at about the wave base of usual storms. This inference is drawn from the fact that all 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 and outer (20-meter) terrace in front of the escarpment carries large, in some cases fragile, corals which must be several years old. These evidently escape the violence of seasonal storms, but during hurricanes they probably are stripped away to supply much of the island debris. These observations tend to support a general conclusion that the destructive action of shore waves of hurricanes is restricted to shallow waters (Cline, 1926, p. 242). The lower surfaces of the walls and the floors of the grooves generally are scoured free of algal deposits and corals. All the corals of the rims of the grooves are small; a colony 20 cm. 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 deeper surfaces 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 necessarily involve deposition of a thick lamina 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 very significant, although they may perform the important function of cementation.

It is probable that the grooves are cut into the terrace, but both may be formed more or less concurrently. However, it is clear that gravel scour, which is so potent in the grooves, is not so effective at the top of the terrace, the surface of which is relatively free from loose material. As shown by recent work in the Bahamas (Newell *et al.*, 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; 1954, p. 200) reports similar erosional forms in volcanic rocks. There is no indication that the spurs on Raroia are being extended seaward. On the contrary, abundance of reef blocks, fragments of spurs thrown up by storms, clearly indicates net erosion (fig. 11).

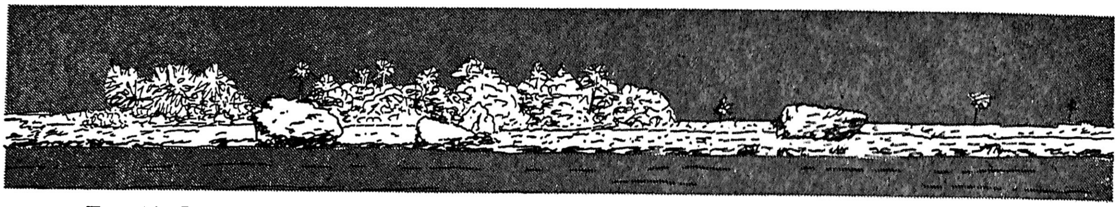

FIG. 11. Seaward view of large reef blocks, Mataira islet, leeward side of Raroia atoll.

THE ALGAL RIDGE[1]

There is a well-developed, narrow ridge at the outer margin of the reef flat which separates the reef flat from the grooved 8-meter terrace (pl. 36, fig. 1). The ridge commonly is from 2 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 1 meter above the adjacent spurs. In a few leeward sectors the reef flat rises gradually towards a steep seaward margin, terminating in a sort of cuesta that faces the sea. Elsewhere the ridge is more narrowly defined. At irregular intervals 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 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 (pl. 39, fig. 1). Because of gravel scour and other unfavorable living

[1] 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.

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 in exposed places, 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, and mean sea level probably is lower on the leeward than on the windward side. In any case the tidal fluctuation is small at Raroia, probably not more than 0.6 meter. The strong ocean swell, even on a windless day, produces translation waves with amplitude of 2 meters and more along the south and southeast sides of the atoll, and perhaps half as high on the leeward or northwest side. 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 leeward sea may have dropped 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 these the waters return 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 on both leeward and windward sides at gaps in the algal ridge. It is probable that each groove at the reef front functions as an excurrent channel during times of great turbulence. Water laden with outgoing sediment tends to be channeled by the grooves.

Wherever the biota of the algal ridge is healthy and vigorous, the ridge is covered by pink, blister-like crusts (pl. 37, fig. 1) 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 (pl. 45, fig. 2) 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* (pl. 37).

The landward face of the ridge, just below the crest, commonly is relatively free from encrustations except for a film of pink *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 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 matched 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 suggests a recent drop in the relative level of the sea. If so, however, 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 entirely clear.

Outer reefs of Bikini on which there is a low uninterrupted algal ridge were designated type I-A by Tracey *et alii* (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 clear 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 (pl. 36, fig. 2). 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 a few 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 as are 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 being cut and deepened by gravel scour. All the Raroia examples contain potholes 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 towards the sea. Even where they 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. The inner part at least of the reef flat of Raroia is an erosional surface cut in whatever rocks compose the islands, and it is probable that the entire reef flat, excepting the algal ridge, is a product of marine planation. It appears to me improbable that atoll islets invariably rest on a preëxisting reef flat. Granted that the 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. Islets may be formed on reefs by hurricanes without the necessity of negative movements of sea level.

On Raroia the reef flat is a pavement which descends gently inward from the algal ridge to near low-tide level opposite islands and 1 to 3 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 mean tidal range in the Tuamotus is said to be about 0.6 meter, but the extreme range on the reef flat of the leeward side of Raroia atoll is at least 0.9 meter, as indicated by characteristic intertidal organisms and erosion forms (fig. 14). Although the high-water mark along the shores may be at about the level of the highest tides, the low-water mark lies above low-water levels of the surrounding ocean depressed by the prevailing winds. Because of this the water of the reef flat continues to drain at low-water stage; the reef flat is essentially a tide pool behind the algal ridge. The reef flat of the windward side of the atoll is rarely emergent at low tide, being piled upon the platform by the wind.

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 much of the rim area (pl. 28, fig. 2). On the windward side of the atoll there are few attached organisms on the reef flat, and most of these are sparsely distributed in low areas around surge channels where they are somewhat sheltered and are bathed in normal sea water most of the time. The leeward reef flat is more populated, even though it is exposed to the air for longer periods than the windward flat, and at many places there is a marginal 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* (pl. 37, fig. 2) 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. Midway between the algal ridge and the shore the coral fauna becomes diversified, and there are extensive areas of smooth rock pavement dotted with Foraminifera.

Generally the coral colonies are small (pl. 44, fig. 1). Heads 25 cm. wide 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. 1.5 meters wide 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 2 meters wide on the sheltered side of the algal ridge (pl. 45, fig. 2). 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* sp. 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 flat form a superstructure of coarsely cellular material 10 to 20 cm. 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 octopuses 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 (pl. 44, fig. 1).

Corals become more varied as *Porolithon* decreases in importance towards 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 estimates shown in table 7.

Shoreward from the coral-algal area the superstructure of small ramose corals and *Porolithon onkodes* breaks up into scattered, more or less isolated coral colonies, separated

TABLE 5

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. wide)	25
Echinometra (chiefly of black form)	20
Porites sp. (pavement type with *Vermetus* sp.)	10
Alga, blue-green	5
	100

by flat low areas of solid pavement (pl. 44, fig. 1). *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 deleterious to larvae and very young colonies. Wherever gravel scour is most pronounced the few living corals rise well above the bottom. 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

TABLE 6

CENSUS OF A SECOND 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. wide)	15
Echinometra (burrows of black form)	20
Acropora conferta (purple corymbose form), 5 colonies less than 12 cm. wide	2
Plesiastrea? spp. (5 small colonies)	2
Porites sp. (2 colonies)	1
	100

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). The trough may be as much as 40 or 50 cm. lower than the outer part of the reef flat. Because of this the outer part of the platform generally is drained before the 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 is low, irregular colonies of the coral *Montipora* spp., usually alive only around the periphery (pl. 44, fig. 1). 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 (the "*Heliopora* zone" of Doty, *in* Doty *et al.*, 1954, and of Doty and Morrison, 1954) ranges in breadth from about 5 to 30 meters, and it is limited to the leeward side of the atoll.

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 mean low spring tides. Most of the loose rubble of the reef flat and the blocks broken from the shore pass over this zone and serve as tools for the excavation of numerous shallow potholes below the general surface of the reef flat (pl. 40, fig. 2). The entrances to small, landlocked rock basins within the area of beach rock commonly lie 20 cm. 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*,[2] and adherent discoid Foraminifera. As is shown below, much of the inner part, at least, of the reef flat is an

TABLE 7

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. wide)	3
Echinometra burrows (black variety)	30
Porites (encrusting)	5
Acropora spp. (3 colonies)	Less than 1
Montipora sp.	1
Massive coral (*Plesiastraea?* sp.)	Less than 1
Diadema setosa (6 individuals)	More than 1
	100

[1] The term "microatoll" for these and other single colonies of corals is not very appropriate, as they are not comparable to atolls.

[2] Maxwell S. Doty suggests 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.

TABLE 8

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 (3 colonies)	5
Acropora conferta (purple, 2 colonies)	1
Massive coral (*Plesiastrea?* sp., 9 colonies)	8
Porites sp., encrusting (4 colonies)	5
Echinometra (burrows of brown form)	5
Diadema setosa	1
	100

erosional platform probably 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 (pl. 45, fig. 1). 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. locally occupy as much as 30 per cent of the bottom.

The excurrent areas of the reef flat 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 irregular shallow grooves converging, fan-like, towards the gaps in the algal ridge (pl. 39, fig. 1). The grooves are discontinuous and erratic. For example, a groove 5 meters long and 0.25 meter wide abruptly shallows from a maximum depth of 20 or 25 cm. towards both ends and disappears, being continued a few meters farther on by another more or less aligned groove. The floors of the

TABLE 9

CENSUS OF A SECOND 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 (2 colonies)	10
Acropora digitifera (3 colonies)	2
Acropora (purple, 2 colonies)	1
Pocillipora elegans (5 colonies)	2
Massive coral (spiny, *Favites?*)	1
Massive coral (*Plesiastrea?* sp.)	3
Echinometra (burrows of brown form)	5
	100

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 0.5 meter and a height of 20 or 30 cm. In these areas more than two-thirds of the bottom is devoid of corals. Hardly any of the existing colonies are new. 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.

Erosion of the Reef Flat

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 islets and it is being reduced to a level approximating the deepest pools of the reef flat. Aligned outlying erosion remnants of beach rock, elevated pedestals beneath reef blocks, and distinctive pitted areas (pl. 40) all clearly indicate that the beach rock and island conglomerate were formerly considerably more extensive seaward than at present and that the reef flat is being extended and 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 (pl. 35, fig. 1). 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 beach rock and island conglomerate were welded to a preexisting reef flat.

At 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 (pl. 40, fig. 1). 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, 1 or 2 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 uplift or drop in sea level of perhaps 15 or 20 cm. (the local relief of erosion remnants around reef blocks and between excurrent channels) with attendant far-reaching effects on the life zones and acceleration of clastic sedimentation (see fig. 14).[1]

LAGOON REEFS

Lagoon Shore Reefs

A discontinuous reef (pl. 32, fig. 1; pl. 34; pl. 35, fig. 1) 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

[1] I have been unable to find evidence on the atolls visited by me of a terrace 5 or 6 feet above the present level said to characterize Pacific islands (Cloud, 1954). The platform of island conglomerate is a depositional feature not to be confused with erosional terraces. There is, however, a well-defined low terrace around at least some of the high islands of the Society group (pl. 22, fig. 1). It is theoretically possible that the atolls were completely truncated by wave erosion near the present level after production of this terrace, but there is no evidence for this.

there is active deposition of fine sediments (pl. 32, fig. 2). The leeward (southeast) shore lacks well-developed shore reefs but instead has innumerable coral heads (mainly massive *Porites*) and small patch reefs (pl. 28, fig. 2; pl. 31). 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 8-meter terrace of the sea reef (fig. 9). Few of the shore reefs descend more than about 6 or 7 meters below the top, at sea level, and in most places the relief at the reef front is only 3 or 4 meters. An exception to this is found at Oneroa, where a small barrier reef extends across a broad bay rising to the surface in about 20 meters of water (pl. 32, fig. 1). Presumably this reef originated as a fringing shore reef protected by an islet from sediments and maintained upward growth during subsidence of the bottom.

Well-defined habitat zones are shown by the windward shore reefs of the lagoon. 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 *Isognomon perna*.

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 0.5 meter high and 1 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 perna*, and burrowing pelecypods of several species (*Tridacna maxima, Lithophagus teres, Pedum spondyloideum,* and *Barbatia parva*).

Rather abruptly, within 2 to 20 meters of the reef rim, a small brown *Pocillopora elegans?*, interspersed with a few small *Acropora* and massive corals of several kinds, becomes abundant. Dead corals are in places overgrown by *Porolithon onkodes* and *Zonaria* sp., a brown alga, which together form a superstructure 15 to 20 cm. 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 *Pocillopora, P. ligulata* (pl. 44, fig. 2), 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. 12). 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 prolixa* 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 (pl. 34, fig. 2). 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; pl. 34, fig. 2; pl. 33, fig. 1). 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 wave impact and circulation of the lagoon waters. This problem is considered below in the discussion of patch reefs.

face, 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 depths of 20 meters or more. 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 at the surface, but there are relatively few intermediate knoll reefs.

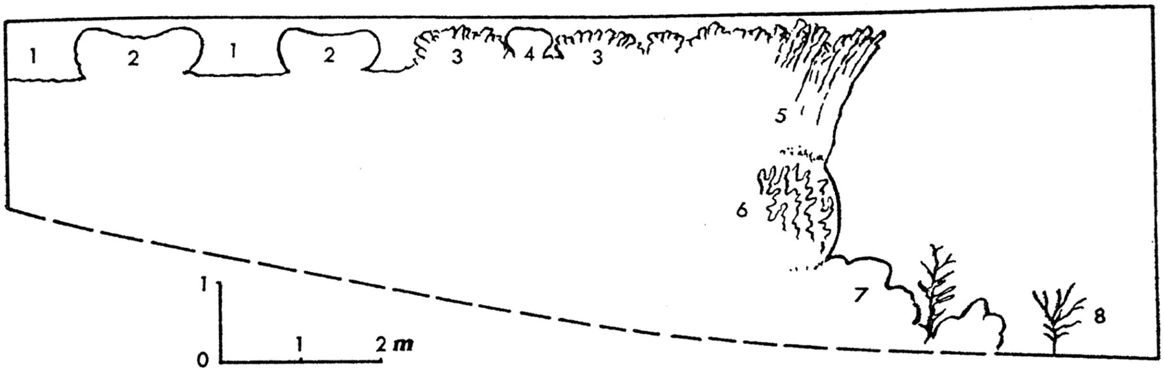

FIG. 12. Profile of lagoon shore reef at north end of Garumaoa islet. 1, Reef flat pavement; 2, large disks of *Porites;* 3, *Pocillopora elegans?;* 4, *Favia* sp.; 5, *Pocillopora ligulata;* 6, *Lobophyllia* sp.; 7, *Montipora* sp.; 8, *Acropora prolixa.*

The leeward (southeast) shore of the lagoon is very sandy, therefore it has very few reefs, those being quite small patches, and there is only one *kaoa* reef. The black holothurian that 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 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.

Patch Reefs

Viewed from an airplane, the Raroia lagoon is impressive for the large number of patch reefs that are scattered over the entire lagoon, but are somewhat less numerous towards the leeward (southeast) shore than elsewhere (pls. 26, 27, 29, 30). Virtually all are near the surface.

There are an estimated 1500 to 2000 patch reefs in the Raroia lagoon. They range from circular patches 3 or 4 meters wide to great streamlined reefs a half kilometer long and 200 meters wide. 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

[1] An 8-inch Secchi disk was visible down to 28 meters from a small boat.

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 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. Many of these show a tendency for the leeward end of the reef to taper more gradually than the windward end, streamlined in teardrop form (pl. 29, fig. 2).

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 (fig. 13; pls. 29, 30) or more rarely transverse to the wind direction, but there is some deviation near the windward shore where the linear series of patch reefs gradually assume an orientation normal to the shore (pl. 29, fig. 1). 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 was originally controlled by wind-induced currents or surface jets of sea water which entered at the windward channels. There is little or no relationship, however, between the present channels and the rows of patch reefs.

Unfortunately it was impossible to map the lagoon systematically by vertical photographs, and construction of a map of the lagoon from the few aerial oblique photographs is not possible.

The tendency for some of the reefs to lie in rows suggests that they may lie along horizontal convection cells of turnover aligned generally downwind. Linear water slicks, occasionally observed between the rows of patch reefs, suggest that these are areas of convergence. The reefs then apparently lie in zones of upwelling water. Because the rows of reefs are spaced from a quarter to one-half of a kilometer apart, the convection cells must extend to the lagoon floor, effectively mixing the entire body of water and preventing accumulation of the finest sediment.

REEF BIOTA

Diversity

Outer and lagoon reefs of various types are well developed and contain a fluorishing fauna much more diverse than the known fauna 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, 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* makes up an additional 25 per cent, 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 6 or 8 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 on tier of small *Pocillopora elegans* with an occasional massive coral and a staghorn *Pocillopora* (pl. 41). On the surface, interstices between corals are unfilled. An occasional fresh fracture across a reef block reveals that the

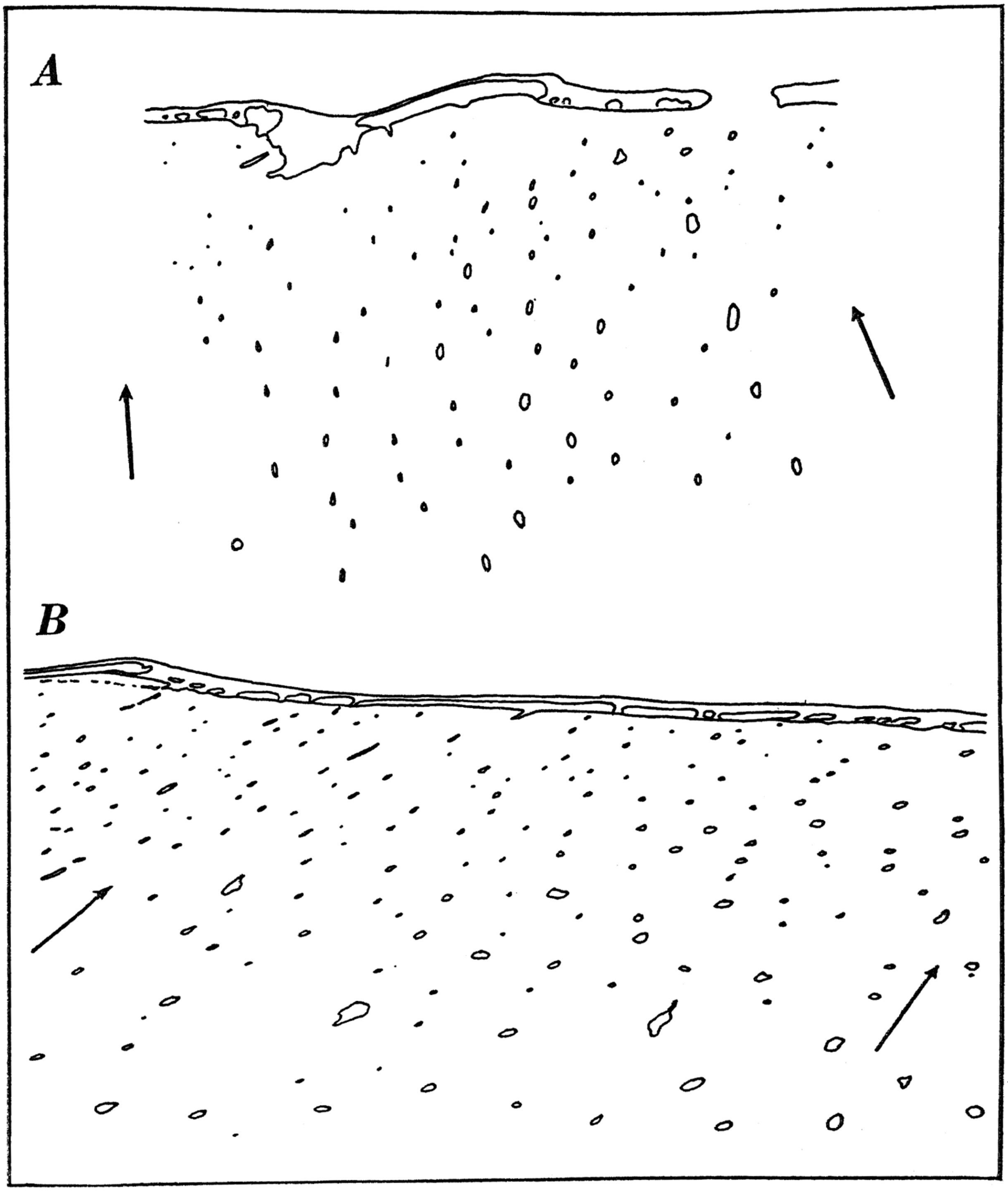

FIG. 13. Patch reefs, Raroia lagoon. The arrows indicate the prevailing wind direction, towards the west southwest. A. Garumaoa islet in background. B. Teputaiti islet in background. Oblique aerial views.

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 per cent 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 prominent 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 previously reported from the Archipelago are not represented in our collections.

Preliminary List of Reef Corals Collected at Raroia

Identified by John W. Wells

Pocillopora danae Verrill
Pocillopora elegans Dana
Pocillopora ligulata Dana
Pocillopora verrucosa (Edwards and Haime)
Acropora conferta (Quelch)
Acropora conigera (Dana)
Acropora corymbosa (Lamarck)[1]
Acropora danai (Milne-Edwards and Haime)
Acropora digitifera (Dana)
Acropora exilis (Brook)
Acropora formosa (Dana)
Acropora humilis (Dana)[1]
Acropora implicata (Dana)
Acropora cf. *nobilis* (Dana)
Acropora procumbens (Brook)
Acropora prolixa Verrill
Acropora quelchi (Brook)
Acropora rayneri (Brook)
Acropora rotumana (Gardiner)
Acropora species
Acropora syringodes (Brook)
Acropora tubicinaria (Brook)
Acropora variabilis (Klunzinger)
Montipora australiensis Bernard
Montipora venosa (Ehrenburg)
Montipora caliculata (Dana)
Montipora verrilli Vaughan
Montipora verrucosa (Dana)
Montipora, new species
Astreopora myriophthalma (Lamarck)
Pavona clavus Dana
Leptoseris hawaiiensis Vaughan
Fungia scutaria Lamarck[1]
Fugia concinna Verrill
Herpolitha limax (Esper)
Porites australiensis Vaughan
Porites lobata Dana
Porites mordax Dana
Porites, new species
Porites superfusa Gardiner
Favia stelligera (Dana)[1]
Favia rotumana (Gardiner)[1]
Favia pallida (Dana)
Favites hemprichii (Ehrenburg)
Plesiastrea vesipora (Lamarck)[1]
Platygyra rustica (Dana)[1]
Cyphastrea serailia (Forskaal)
Leptastrea purpurea (Dana)
Acanthastrea echinata (Dana)[1]
Lobophyllia corymbosa (Forskaal)
Lobophyllia costata (Dana)
Culicia rubeola (Quoy and Gaimard)
Millepora platyphylla Ehrenburg

[1] Previously reported from the Tuamotu group.

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

Acropora hyacinthus (Dana)
Favia favus (Forskaal)
Fugis cooperi Gardiner
Fugis 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 coralline and blue-green algae (fig. 14). Each zone is occupied by gastropods which feed on the algae or on the herbivores. In addition tube gastropods (*Vermetus*) and boring barnacles are conspicuous on the reef blocks between high- and low-water marks. All 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.

less than the extreme range between low and high water; it may represent the range between the fixed level of the tide-pool and high-water neaps. Species of *Vermetus, Drupa, Morula,* and a boring barnacle, *Lithotrya,* dwell here.

This yellowish brown surface grades upward into a grayish zone which is frequently exposed to the air (upper part of yellow zone of Doty and Morrison, 1954, p. 33). This higher belt may be termed the *Nerita* zone from the

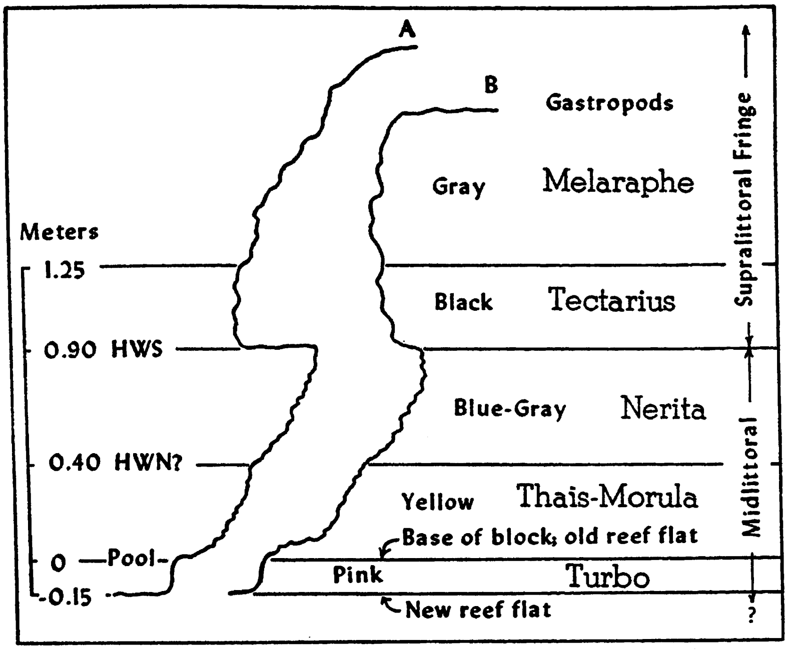

FIG. 14. Outer lee shore profile, reef blocks. A. Garumaoa. B. Onotoa.

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 (pl. 40, fig. 2). Foraminifera can be scraped from the surface when they cling to the bottom by means of their pseudopods. This is the holothurian, or pool, belt of the reef flat. In most places it is bordered by a vertical rise of smooth, coralline coated, pinkish rock surface some 15 or 20 cm. high to the clearly defined low-water mark or pool level.

Above the low-water mark the rock surface is yellowish brown and scoriaceous through a vertical interval of 40 cm. (a little less on the windward outer shore). This is considerably dominant gastropod, *Nerita plicata* (fig. 14). This form feeds mainly at night and ranges downward into the yellow zone as the tide recedes. Howevere, the species is most characteristic of the surface immediately above the yellow zone. 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 the intervening matrix (pl. 42). The projections are tan in the lower part of the zone, becoming brown above. 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 layer, but covered by the superficial gray film, there often occurs a thin pink layer. Presumably the colors of these layers are pigments derived from the algae.[1] The bluish gray pits are striated by radular marks of *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 correspond to coral fragments and the pits to matrix of foraminiferal sand. The latter is relatively yielding 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 *Nerita plicata*. Above the zone of *Nerida plicata*, moistened chiefly by spray, the rock is uniformly blackened by a film of blue-green algae.[2] This "black zone," reaching above high water some 20 to 60 cm. or more (pl. 41, fig. 1), 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 (pls. 31, 33). 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 (*in* Doty, Newhouse, Miller, and Wilson, 1954), being derived from dessicated blue-green algae. On reef blocks this grayish surface is occupied by a littorine, 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 erosional effects on the rocks. *Melaraphe coccinea* ranges over the surface of the conglomerate platform to the edge of beaches or ramparts.

[1] Dr. Werner Bergman expresses the following opinion about these color zones: "I believe that your original suspicion was right that the pigment is indeed of the prophyrin 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 Bergman, personal communication, March 18, 1953). See also Newhouse (*in* Doty, Newhouse, Miller, and Wilson, 1954).

[2] This film of blue-green algae was mainly *Entophysalis crustacea.*

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 demonstrate satisfactorily that the water, except in small enclosed pools, is sufficiently acid to dissolve the rock. The topographic forms produced by the rain water above the reach of the sea are strikingly unlike those of the intertidal and spray zones and the bottom topography beneath the low-water level. Emery has shown that intertidal gastropods probably play an important, if unevaluated, role in erosion. Newell *et alii* (1951), Ginsburg (1953), and Ranson (1955b) have concluded that biomechanical and biochemical activities are adequate to produce most of the distinctive erosion forms of the intertidal zone on certain limestone coasts.

On Raroia many of the reef blocks of the reef flat rest on deeply undercut pedestals (pl. 41, fig. 1). The pedestals in some cases consist of beach rock 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, as 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 to 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 (*ibid.*, 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 conclusive in whether or not calcium carbonate is being dissolved or precipitated, but they must be considered in conjunction with analyses for titration alkalinity (Smith, 1940; Emery, 1946). While precipitation is taking place, the pH falls 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 inconclusive results shown in table 10.

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

Rock surfaces of the reef flat and the islets are generally covered by a thin film of algal vegetation (see Doty, Newhouse, Miller, and Wilson, 1954). Outlying blocks and shore rocks between low- and high-water levels are conspicuously colored tan to brown, and they 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 would explain why erosion effects are about the same on

TABLE 10

pH VARIATIONS IN A TIDE POOL

Time	Large Rock Pool		Reef Flat	
	Temperature in Degrees Centigrade	pH	Temperature in Degrees Centigrade	pH
9:00 P.M.	22.0	8.09	23.0	8.01
10:00 P.M.	21.7	8.02	23.3	8.10
12:00 P.M.	21.5	8.06	23.0	8.06
2:00 A.M.	22.5	8.11	24.5	8.20
5:00 A.M.	25.0	8.20	25.0	8.20
7:00 A.M.	23.5	8.11	25.0	8.10
9:00 A.M.	26.5	8.15	27.5	8.20

outlying reef blocks and in rock pools where pH conditions are generally different. This is not, however, solution by "sea water."

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.[1] But it is noteworthy that the deepest part of the shore notch of the pedestal rocks of the reef flat on Raroia is not at an intermediate level 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 lies at the high-water level (see also Kuenen, 1950, p. 435). Direct solution by sea water may be a factor, and algal penetration of the rock doubtless is significant, but these are not dominant factors. The zone of *Nerita plicata* occupies the deepest part of the furrow around the pedestal rocks (fig. 14). If it be assumed that the growth of blue-green algae on and below the surface initiates erosion by biochemical action and penetration of algal filaments into the rock, it may safely be concluded that the rasping of the softened surface rock by gastropod radulae accelerates the process of limestone removal. Newhouse, Doty, and Morrison also arrive at this conclusion (see Doty, Newhouse, Miller, and Wilson, 1954; Doty and Morrison, 1954). Erosion in the underlying yellow 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 barnacle (*Lithotrya* sp.) and a sipunculid which in extreme cases remove as much as 20 per cent of the rock to a depth of 2 or 3 inches (see also Ranson, 1955b).

The characteristic paired furrows in the rock produced by algal-feeding parrot fish are abundant over the reef flat pavement and the lower shore rocks (pl. 43). These grooves commonly are as much as 0.5 mm. deep. I have often observed these fish gnawing the horizontal reef flat, with their heads down and tails well out of the water. Without doubt they are effective agents of erosion and planation of the flat.

[1] Ranson (1955d) has also been impressed by the corrosive action of the blue-green algae. He attributes a similar function to *Porolithon onkodes*, but I find no evidence that the latter corrodes the surface over which it grows.

Exfoliation

Erosion by organic agencies and by wave action in many places has resulted in a low escarpment 0.5 to 1 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 (pl. 46, fig. 2). 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 then onto the conglomerate platform.

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 these fractures.

SEDIMENTATION

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 wide 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 (pl. 28, fig. 2; pl. 47, fig. 1; pl. 48). This debris is composed mainly of corals and Foraminifera that live on the reef flat and on the outer slope of the reef front. 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 coast line forms a high angle or an embayment directed towards 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 5 or 6 mm. in diameter.

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 and 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 8 meters. Much of this material is coarser than that of the rampart, hence it is judged to represent deposits left by hurricanes. 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 are 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 towards the lagoon.

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

According to eyewitnesses the land is swept during hurricanes by great waves from both the sea and the 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 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 virtually continuously.

The lagoon beaches are composed of sand to fine gravel, and much of the finer sediment is identical 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 (pl. 25), 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. There is no apparent relationship between atoll diameter and lagoon depth, as in many atolls (Emery, Tracey, and Ladd, 1954, p. 150).

The Sediments

By John V. Byrne

Lack of proper dredging equipment and boats made the collecting 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. At Bikini and other atolls of the northern Marshalls, remains of this alga comprise a large percentage of the total sediment. This is not true, however, at Raroia.

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 them 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 included 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 decrease towards 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 that 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 accumulate there.

Lagoon-beach sediments on the southeast 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. There are areas on both sides of the atoll in which the above generalization is reversed. The seaward sides of the islands are characterized by coarse rampart ridges and storm beaches behind a protecting groin of conglomerate. Accumulations of well-sorted sand occupy depressions 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.

Distribution of Foraminifera

By Joseph T. 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 a total representative sample. The determinations are believed to be accurate within an error of plus or minus 3 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 *Marginopora, Sorites, Amphisorus,* and *Amphistegina. Amphistegina* 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, Textulariidae, Cymbaloporidae, 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 occurrence. They are represented by Globigerina and the adult floating stage of *Tretomphalus.*

The generally reworked tests of Foraminifera in the 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*

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 limesands, 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 0.1 per cent to 72 per cent. The greater percentages of Foraminifera to other constituents occur along the shallow, southeastern 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 beach sands and patch reef sands contain six predominant species. They differ chiefly in relative abundance of individuals. 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 the most abundant in outer and inner beach sands and on shallow lagoon bottom less than 6 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

TABLE 11

PERCENTAGE BY VOLUME OF FORAMINIFERA PER SAMPLE

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 Foraminifera 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 of 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

TABLE 11—(*continued*)

Sample	Per Cent of Total	Location
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 halfway between Oneroa and Garumaoa village
8-11-2	10.0	Dredge sample, lagoon 300 meters east of Ohave 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, halfway between Ohave 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 Pirikautaringa 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 and 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 Foraminifera collected on seaward reef, Garumaoa islet, at first transec

attains maximum dimensions on the seaward reef.

7. Of the total of 126 species, approximately 22 per cent were found only in the sand of the lagoon and sea beaches. These are indicated in table 12. All the species found in the outer beaches are also represented in the lagoon samples, which is to be expected, as sediments are continually being swept lagoonward by storm waves.

Reef Limestones

The calcareous deposits of coral reefs are diverse in type and origin. Besides reef limestones, *sensu stricto,* the detrital debris of a coral reef produces marginal sediments that extend far seaward and lagoonward as bedded deposits. The latter interfingers marginally with other kinds of sediments containing fossils of other facies (Newell *et al.,* 1953). It is impracticable to designate all the calcium carbonate sediment produced by the reef community as reef deposits or to term the lithified equivalents reef limestone (Newell, 1955a). The sedimentary complex of reef-derived materials has been termed the reef complex, but this term, while very useful for describing stratigraphic facies, is of little value as a lithologic term, because reef-derived clastic materials usually are indistinguishable from bedded shelf limestones. Geologists must deal with lithologic and structural characteristics of rocks. Consequently, I prefer to limit the term "reef limestone" to the lithologically distinctive reef-frame of

TABLE 12

FORAMINIFERA FROM RAROIA ATOLL

Distribution and Occurrence of Dead Lagoon Foraminifera in Dredge Samples

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 d'Orbigny										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
Cymbaloporella squamosa (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 fragillissima (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

Occurrence of Foraminifera from the Shore Sands in Beach Samples (+ indicates Seaward Reef)

Beach Samples

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	r	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 d'Orbigny																																
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												
Cornuspira involvens Reuss																																
Cymbalopora bradyi Cushman																																
Cymbaloporella squamosa (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 fragillissima (H. B. Brady)																																
Hauerina ornatissima (Karrer)																																

Symbols: a, abundant; c, common; r, rare; f, fragments.

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	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													r																																		
Massilina crenata (Karrer)	r									r				r																																		
Massilina inequalis Cushman									r																																						
Massilina planata Cushman												r		r																																		
Miniacina miniacea (Pallas)			f	f			f		f									f	f	f			f		f		f			f		f	f	f		f	f	f			f	f	f	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 anguina 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															r																	
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 (Linné)	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						r			c									r			r											
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																											r					
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																				r												
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	c	c	c	c	c	c	r	c	c	c	c	c	r	c	c	c		c		c	c		c	r	c	a			c	r	c	c
Spirillina inequalis H. B. Brady				r																																												
Spirillina limbata H. B. Brady			r						r					r																																		
Spirillina spingera Chapman				r																	r																									
Spirillina subbertheloti Cushman									r																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							r					r	r						r														
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										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						c														r											
Tretomphalus milletti Heron-Allen and Earland											r	r	r																																				
Triloculina austriacea d'Orbigny			r	c	r		c		c							c												r		r																	
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																																
Tubinella funalis (H. B. Brady)	c	c						c	c					r		r												r																				
Virgulina pauciloculata (H. B. Brady)													r	r		r																																

hermatypic organisms (pl. 44). The detrital waste from reefs, which may make up 90 per cent or more of the mass of an atoll, is not reef limestone according to this definition but is reef-derived sediment. My conclusion is at variance with that of MacNeil (1954a) and Emery, Tracey, and Ladd (1954) who would use "reef complex limestone," or "reef limestone," as a genetic rather than a lithologic term.

Most of the calcium carbonate of the reef complex is in the form of bedded and intertonguing lagoonal and talus deposits that become indistinguishable from other sorts of carbonate deposits. Therefore, this classification as "reef deposits" would depend not on their physical characters but on the regional relationships and inferred origin.

Dissatisfaction with the diverse and inexact meanings of the term "reef" in the popular mind has led some geologists to favor the word "bioherm" in place of "reef" or "organic reef." It is not possible to demonstrate, however, that any significant confusion has ever originated over the use of "reef" with the restricted and consistent meaning of Darwin, Dana, Semple, Gardiner, Agassiz, Yonge, and others. None of these students considered the deep-sea deposits surrounding atolls, or the shallow deposits of lagoons, as reef deposits. The idea that atolls *are* reefs is a new and unfamiliar concept. It is no more logical to class reef-derived clastic sediments as reef deposits than it is to consider the talus fans around an eroded batholith as part of the batholith. In both cases the parent rock and derived sediments are lithologically, structurally, and even genetically unlike. MacNeil argues that "in the present geologic phase, which is believed to have followed closely a drop of sea level and resulted in the planation of a surface across structures of organic growth and detrital sediments alike, we have a feature that has never been called anything but a reef. To restrict the term reef to the growing portion would be to call the seaward margin a reef whereas the reef flat is not a reef" (MacNeil, 1954a, p. 387).

Although a reef flat has always been recognized as a highly characteristic feature of many reefs, the idea that it is mainly an erosional feature, although not new, is only now gaining wide acceptance. The common assumption that reef flats are everywhere underlain by organic accretions of frame-building organisms can now be readily discredited, but this misconception about the origin of the reef flat should not figure importantly in our present understanding of the fundamental nature of reefs. Except in the nautical and topographic sense, the reef flat has never been synonymous with the reef.

Origin of Island Conglomerate and Beach Rock

The solid rock of the islands of Raroia consists mainly of tightly cemented gravel of low porosity. The coarsest texture, in which the coarsest fraction consists 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 beach rock 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 beach-rock ridges composed of strata of fine-grained conglomerate dipping seaward at 15 degrees to 20 degrees (pl. 48, fig. 1). These ridges form low cuestas a few centimeters to about 1 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 now clearly obliterated by erosion (pl. 35, fig. 1). These generally have been completely removed by the waves on the windward shore.

Inclined beds of beach rock 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. Most 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 (pl. 47, fig. 2). In many places these areas 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 (pl. 49). Beneath the gray stain of the surface is a thin green layer, colored, probably, by chlorophyll. The pebbles and sand are there bound together in laminae by algal filaments into a friable fabric several centimeters thick. The sediments immediately below the surface 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.[1]

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 the enclosed basins behind ramparts 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 probable that lime is precipitated under these conditions and that part of it is incorporated as cement in the sediments.

There are other situations in which lithification of sediments apparently is taking place. The test pits and water wells on Garumaoa Islet contain friable sandstone below 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 *Acropora conigera*, imbricating towards 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 (pl. 27, fig. 1; pl. 35, fig. 1). Apparently reef blocks are temporarily and loosely attached at the shore to be later stripped away during storms. Under more stable conditions preceding the present epoch, reef blocks were rigidly cemented to the reef flat (pl. 41, fig. 1; pl. 47, fig. 1), but erosion processes are now so effective that erratic blocks are moved or destroyed before they can become welded to the reef flat.

[1] Ranson (1955a) doubts that blue-green algae could bring about the cementation of calcareous sediments because they have a corrosive effect on calcium carbonate. It seems, however, that solution of the carbonate at contact with the algal fibers might well be accompanied by redeposition in near-by areas.

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RAROIA ATOLL
Tuamotu Archipelago
SCALE
Kilometers
0 1 2 3 4
16° 00′ S. LAT.
16° 05′ S.
16° 10′ S.
16° 15′ S. LAT.
15° 55′ S.
142° 20′ W. LONG.
142° 25′ W.
142° 30′ W.
N
GARUE PASS
Hundreds of lagoon patch reefs not mapped
Hundreds of lagoon patch reefs not mapped
Fathometer Profile, U. S. Fish and Wildlife Service
Feet
0
100
200
EXPLANATION
Reef edge
Island conglomerate and beachrock
Island gravel and sand
Island vegetation
Delta top, gravel and sand