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No. 31

Expedition to Raroia, Tuamotus

Part 1. Expedition to Raroia, Tuamotus

by Norman D. Newell

Part 2. Physical Characteristics of Raroia

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Part 3. General Map of Raroia Atoll

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Part 1

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Illustrations

EXPEDITION TO RAROIA, TUAMOTUS [1]

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INTRODUCTION

Preface

An intensive ecological reconnaissance of Raroia, [2] a Polynesian atoll about 450 miles northeast of Tahiti, was successfully completed during July and August, 1952, by a seven man research team 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 U. S. National Museum, The University of Hawaii, and Mr. George Vanderbilt.

Although splendid 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 underwater 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 are 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 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

1/ Pronounded Rah-ro-ee'-a

2/ Members of expedition, in addition to author, were John V. Byrne, Bengt Danielsson, Maxwell S. Doty, Robert R. Harry, J. P. E. Morrison, and W Jan Newhouse.

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.

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 Raroian family and a member of the community. Having come to them, first as a member of the intrepid Kon Tiki crew, later as scholar and student of their ways, the people had acquired respect for Danielsson 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.

Cooperation of the French Administration in Tahiti

Besides supplying transportation for part of our equipment from Honolulu to Tahiti, Governor Petitbon provided round trip transportation 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 Médicales de l'Océanie Francaise, 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.

Valerie Zirkle Newell and G. Robert Adlington of The American Museum of Natural History devoted many weeks in 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, Mr. Harold J. Coolidge, Mrs. Lenore Smith, and especially 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 U. S. Geological Survey were made available on loan for our studies. Dr. John W. Wells identified the corals and Mr. J. 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 the only clear day of 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, 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

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

the atoll with nearly complete coverage (95 per cent) of the rim. In addition, oblique photographs of the lagoon show hundreds of small patch reefs many of which eventually may be approximately plotted on the map after calculating corrections for oblique perspective. The vertical photographs were printed at 1:20,000 and this scale was employed for compilation of a base map. The negatives have been filed with the Colonial Government in Papeete. The final map is Part 3 of this Bulletin.

Collaboration in Field Work

Integration of heterogeneous field data from diverse disciplines is essential in an ecological reconnaissance such as this study of Raroia. Personal bias in the collecting and evaluation of data is not easily weighed, however, and it is usually difficult for the specialist to accommodate his attention to problems outside the fringe of his personal experience. Efforts were made at Raroia to overcome these natural difficulties. Time was taken by each participant from his special tasks to accompany the other members in the field in order to establish and maintain contacts in overlapping areas of investigation and to learn about more divergent matters. There were several round-table discussions and innumerable conversations involving various combinations of personnel. In general, the smaller groups were more satisfactory for discussions than the assembled team.

Within the framework of the project a number of special studies were undertaken involving two or more collaborating members of the team. Examples are: 1) several transect surveys, 2) land tenure and copra production, 3) classification of native names of, and utilization of plants and animals, 4) native terms for geologic features, and many others.

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. These include photogrammetric data probably superior to those available for other South Pacific atolls. 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 collecting. For example, 286 species of fishes have been known from all of the Tuamotus, but our collections from Raroia include 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 greatly expanded. Data on the people and their history are especially complete. The first results on the expedition to Raroia have been issued as Bulletin 18, Ichthyological Field Data of Raroia Atoll, Atoll Research Bulletin, 190 pp., 1953. Other reports appear in the present and subsequent numbers of the Atoll Research Bulletin.

Some Fundamental Problems of Atolls

Coral atolls, justly celebrated in a voluminous scientific literature running into tens of 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 relatively sterile waters such as characterize the plankton-poor waters of the tropics and subtropics (Sargent & Austin, 1949). 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 shaol-water organisms were largely exterminated and the area for a time was rendered uninhabitable for most species (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 chance frequence directly related to larval hardiness, length of migratory stage, and various other factors that make up the repertory of dispersal facilities. 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, in a sense, are in some quarters considered relicts derived from the 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. However, many corals may feed exclusively on animal plankton (Yonge, 1940), which in turn must feed on phytoplankton. Sargent & 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 & 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 seems probable that turbulence extends to considerable depth where coral reefs are bathed in the equatorial currents and this turbulence would certainly bring nutrient rich deeper waters to the surface. Orr (1933, p. 62) found evidence of upwelling along the Great Barrier reef. This might well be most pronounced during rough weather when adequate observations have not been made.

Coral animals, as well as coralline algae, generally are most productive at the outer margins of seaward reefs. This growth vigor on the seaward side, according to Yonge (1940, p. 382) is most probably related to the greater transparency of the water there as compared to the lagoon which allows photosynthesis of zooxanthellae and coralline algae to extend to maximum depths. He considers this factor more important than greater supplies of oxygen and animal plankton at the outer reef edge. This matter requires further study.

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 and a soil profile. Coconuts germinate and become healthy trees in apparently sterile gravel. It has been demonstrated that several kinds of algae fix nitrogen from the air. Some of these (Myxophyta) 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. Investigations into the colonization and productivity of atolls, along these and other lines, promise to yield significant results. Hatheway (Atoll Research Bulletin 16) has emphasized the relationship between atoll vegetation and variations in the bird populations and phosphate concentrations in the soil.

Coral atolls are enormous accumulations of calcium carbonate. Interest in the conditions of origin of limestones has greatly stimulated the investigation by geologists of 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, 1937), 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 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 of the world. 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 of these areas would be greatly diminished or even negligible without a "conveyor belt" source of supply.

Regional Setting of the Tuamotu Archipelago

General introduction.-Lying near the center of the Pacific Ocean the Tuamotu 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 Tuamotu 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.

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.

1/ Locally, as at Clipperton Islands, 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).

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, the island arcs of the western Pacific rather than representing old and collapsed areas are late increments welded to the Austral-Asiatic continent.

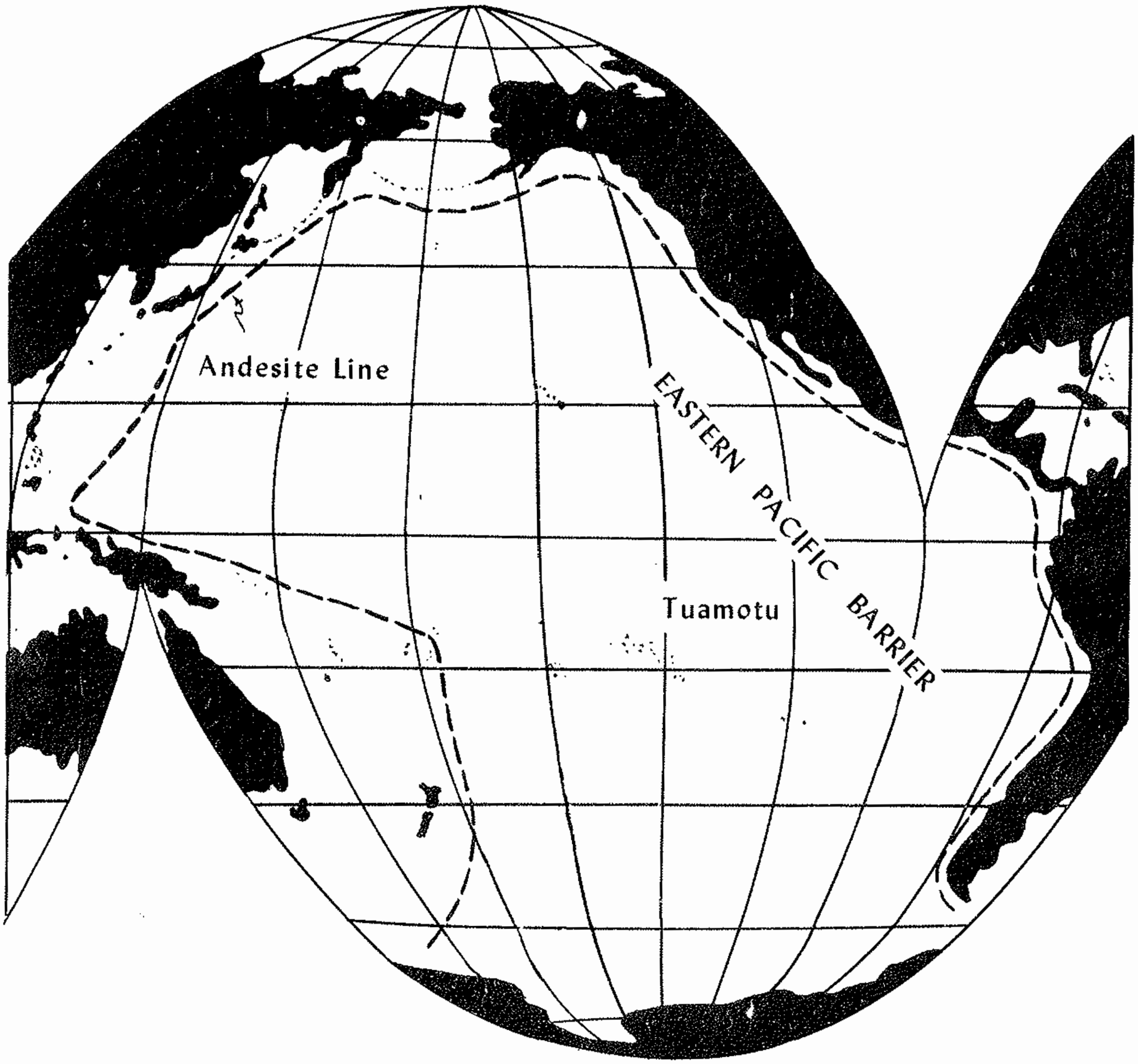
Next to the Maldives the Tuamotu Archipelago contains the greatest number of atolls, spread in a broad belt two hundred miles wide and more than a thousand miles long from northwest to southeast. The 78 islands of the Archipelago of which 76 are atolls are arranged in several linear series reminiscent of island arcs (Fig. 3). 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. This is not the same as Stearns (1946) suggestion that the reefs of low islands were formed in shallow water on the crests of submarine folds.1/

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 in 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 toward the northeast, at right angles to the regional trend. The prevailing currents in this area are also from the northeast. However, since there is no correspondence of form with current directions in most of the atolls, it seems safe to conclude that the northeast trend of Raroia and a few other atolls reflects structural conditions of the basement divergent from the regional trend.

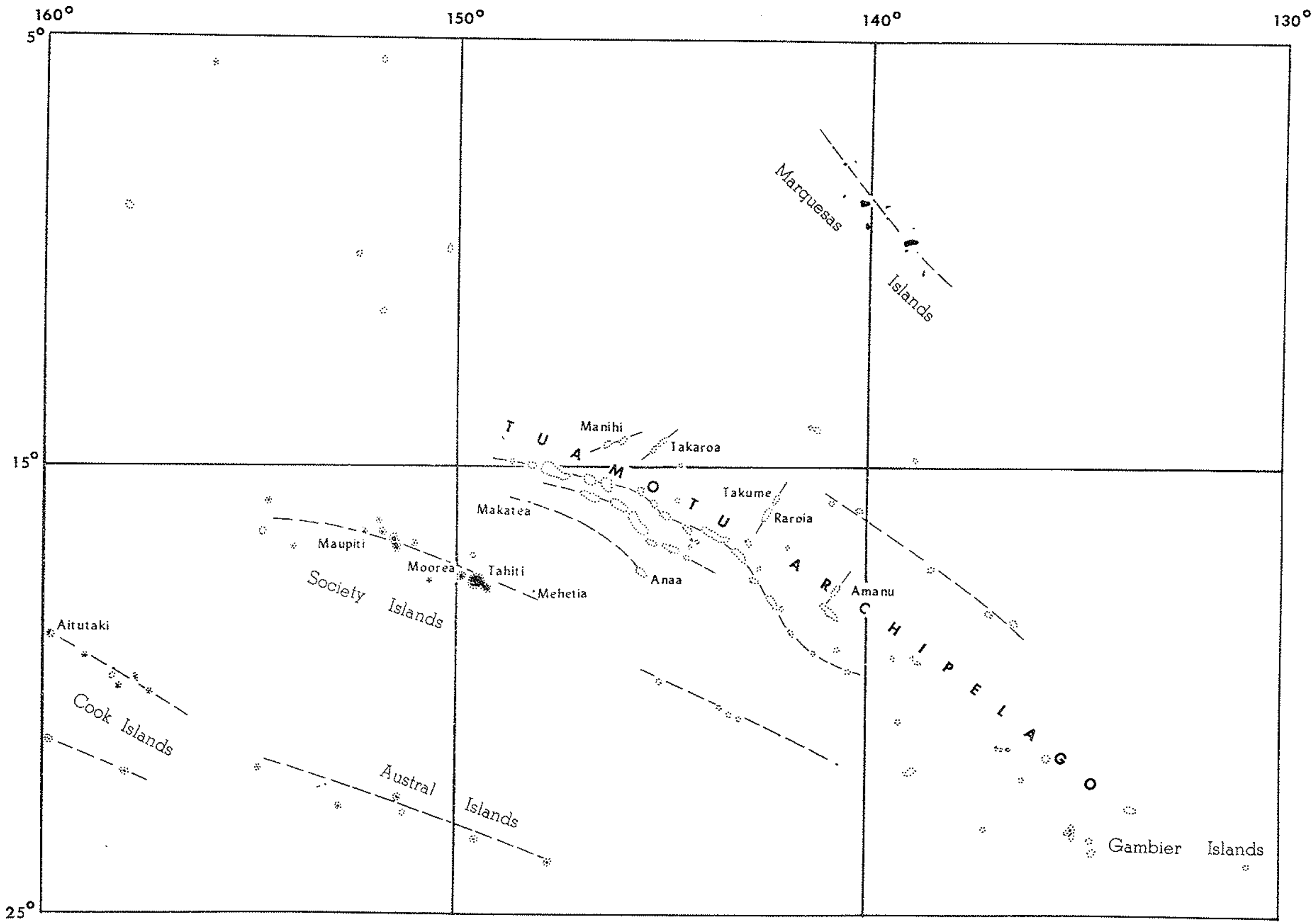
The configuration of the sea floor around the Tuamotu group is very poorly known. A few soundings taken by the Albatross suggest that the northwestern atolls of the archipelago rise from a platform about 800 fathoms beneath the surface. Soundings around the central and eastern atolls indicate smaller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

1/ 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, B.W.I., 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 denudation 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. Of course, this argument does not affect the possibility that some atolls may lie over submerged guyots (see Hamilton, 1953).

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



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



3. Structure lines in part of the South Pacific.

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 pteropod and coral sandy ooze is the principal sediment (Op. cit., p. xvii). Soundings near the atolls show steep slopes characteristic of atolls (Op. cit., 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, op. cit., p. 20), Matahiva, 10 to 12 feet (Op. cit., p. 55), Tikahau, several feet (Op. cit., p. 52), Rangiroa, 15 to 16 feet (Op. cit., p. 20), Kaukura, 17 feet (Op. cit., p. 17), and Niau, 20 feet (Op. cit., 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 is well established. Agassiz's observations bearing on uplift farther to the southeast must be taken with reservations 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 and by relatively few and narrow ship passes. Of the 76 atolls of the group 47 are without a ship pass, 21 have a single pass, and 10 are each provided with two ship passes (Carte de la Marine, No. 1716). The passes mark gaps in the atoll rim where organic accretions evidently have not kept pace with the general upward growth during subsidence. The majority of the 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 is greatest on the windward side of Raroia atoll since the deepest part of the lagoon is downwind from the center. Early gaps along the windward rim doubtless were filled before those of the leeward rim. Possibly the flow of waters through the leeward passes, especially concentrated at ebb tide,

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1/ In general, Agassiz's work on coral reefs is poorly documented and strongly colored by his crusade for the view expressed by Semper (1863) that subsidence is not involved in the origin of atolls. Many of Agassiz's 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" (Op. cit., 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" (Op. cit., 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, op. cit., p. 18).

inhibits growth of corals and coralline algae, but the particular factors involved are not clearly understood.

Climate.-The Tuamotu Archipelago lies within the belt of southeast trade winds and enjoys a mild and equable climate. Danielsson (1951) 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 in 1950 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 millimeters. 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 (Sailing directions, Pacific Islands, vol. 2, Eastern groups, 1940, Publ. 166, U. S. Hydrographic Office).

Currents.-In accordance with the Coriolis effect the circulation of surface waters in the Tuamotus moved along by the southeast trades is usually toward the southwest at rates ranging from five 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 and occasionally set to the eastward at rates from one-half to two knots." (Saling directions, Pacific Islands, vol. 2, Eastern groups, 1940, Publ. 166, U. S. Hydrographic Office).

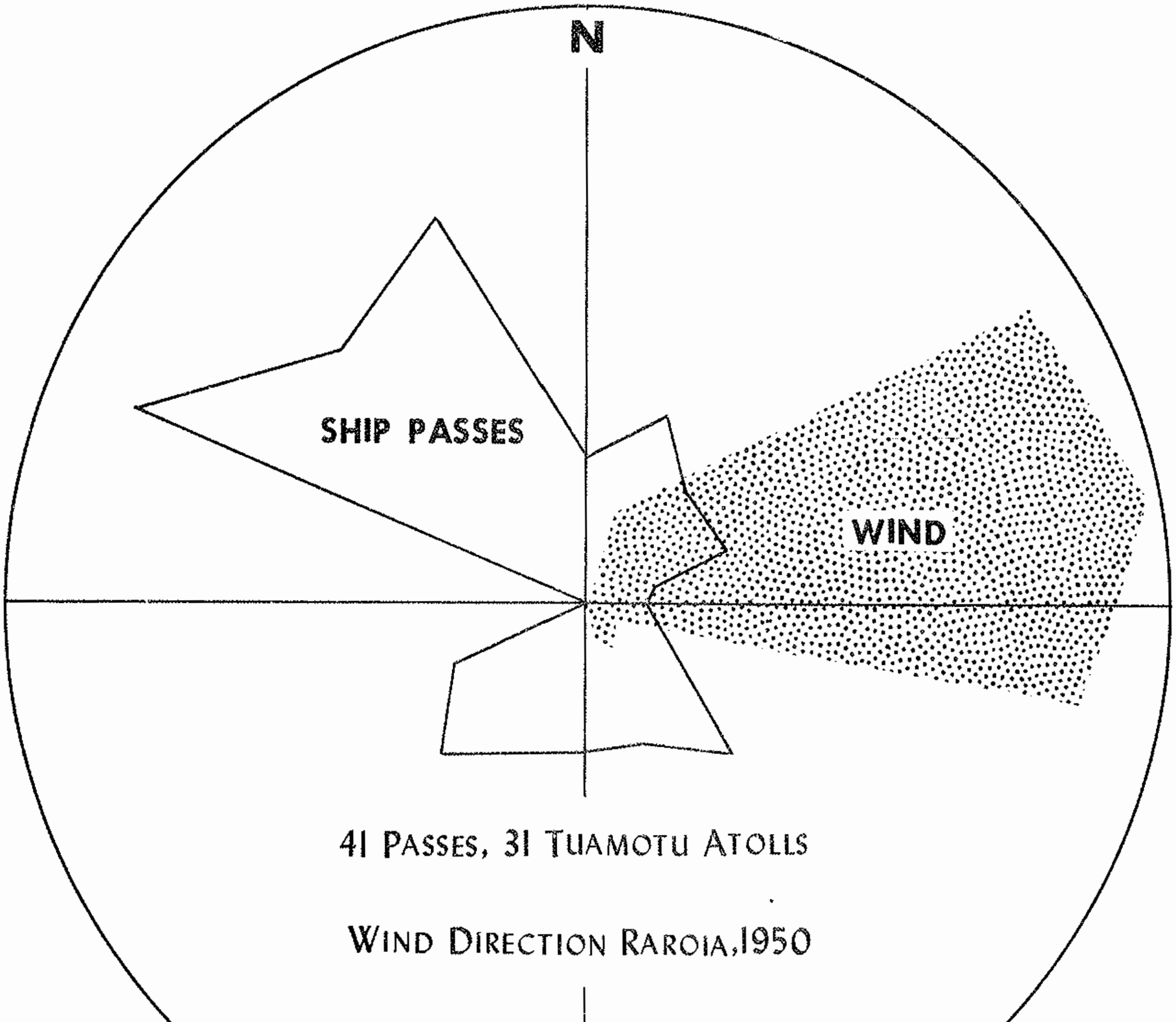
Dispersal of larvae of shallow-water animals toward the east may be largely accomplished at these times.

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 margin of the rim in many of the atolls is relatively broad, low, and free from islets, characteristics which result apparently from the exceptionally vigorous and continuous sheet flow of water across this sector.

"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." (Sailing directions, Pacific Islands, vol. 2, Eastern groups, 1940, Publ. 166, U. S. Hydrographic Office).

Hurricanes and tsunami.-According to native tradition violent storms have played an important part in modification of Tuamotuan 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. These and many of the Tuamotu atolls have the highest and most extensive land, the coarsest coral rubble, and the largest displaced reef blocks on the lee side.

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.



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

The actual frequency of tropical cyclones in these waters is 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 at Raroia.

During the storm of 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 tsunami, but apparently these 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 two feet above the level of spring highs flooding the village, Garumaoa, to a depth of about one foot.

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Part 2

PHYSICAL CHARACTERISTICS OF RAROIA

by Norman D. Newell

Illustrations

PHYSICAL CHARACTERISTICS OF RAROIA

by Norman D. Newell

General Introduction

According to a survey of Raroia and Takume, made in 1950 by the Service Hydrographique (L. V. Nay), Raroia lies between 15° 55' and 16° 14' south latitude and 142° 18' and 142° 32' west longitude. It is elliptical with the long dimension toward the northeast. In size it is intermediate among the atolls of the Tuamotus with dimensions of 14.4 km by 44 km. 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 four meters above normal high water[1/], and for the most part the surface is less than one meter high. The normal tidal fluctuation is small, about one-half meter, attaining perhaps one meter at spring tides; hence wind direction and velocity influence the water level far more than do the tidal fluctuations.

Raroia, like 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 m) in the center. Neighboring Takume on the other hand, and several other atolls of the Tuamotus lack passes. In every case, these lagoons are shallow, being largely filled with muddy sediments. Evidently sediments accumulate slowly in open lagoons.

Characteristics of Raroia

Location 15° 55' S to 16° 14' S Lat., and 142° 18' W to 142° 32' W Long.	
Winter temperature of surface sea water	26° C
Prevailing winds	Easterly
Cyclones (hurricanes)	Westerly
Rainfall (1950)	110 cm
Tides	0.6 m
Area of atoll (including lagoon)	400 km²
Area of lagoon	340 km²
Area of atoll rim	60 km²
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

1/ The outer gravel rampart at the elbow of Oneroa, the westernmost point of Raroia, 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 normal high water.

Land area (35% of rim)	21 km^2
Vegetated area	6 km^2
Lagoon patch reefs (number)	ca 2000
Ship passes (number)	1
Visibility of 8" secchi disk	
Ocean	34 m
Lagoon	28 m

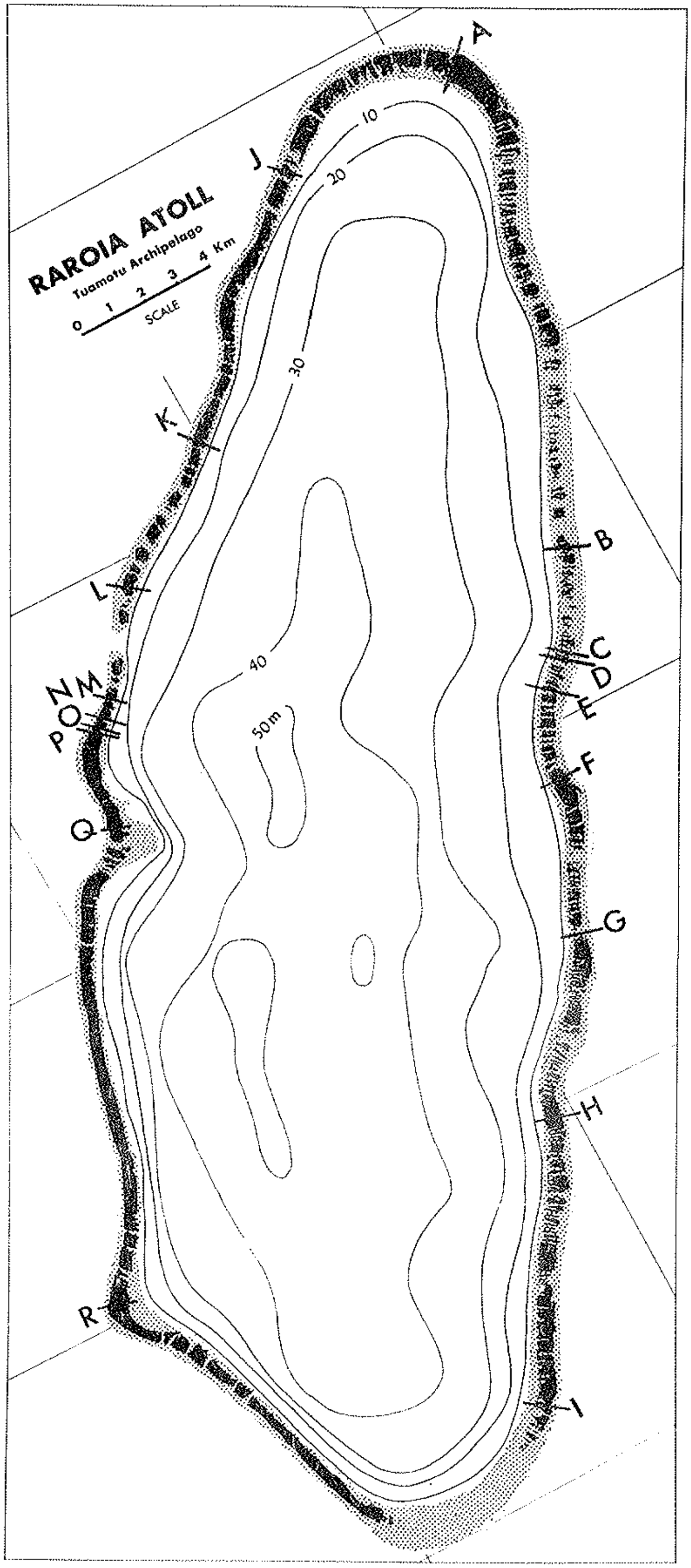
Distribution of underwater terraces, reef, and land forms recognizable on the photographs were mapped for the entire atoll and salient geologic features were recorded by means of aerial and ground photographs and by maps and cross-sections. A number of topographic profiles were constructed across the atoll rim, and in certain critical places levels 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 at The American Museum of Natural History. A bathymetric map of the lagoon was prepared by Byrne from handline soundings. All of these observations reveal a number of facts of interest.

The Atoll Rim

Introduction.-The rim of Raroia atoll 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 one and a half meters to three 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 (see general map, Section 3 of this Bulletin), 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.

Although it cannot, of course, be supposed that the rates of reef growth are uniform all around the atoll, it is probable that wave truncation of the existing land areas and deposition of the resulting debris in the lagoon would result in a more nearly uniform rim width than is now the case. We may surmise with confidence that the relative narrowness and height of the northwestern rim are a result of full exposure to the most violent storms.

Channels and islets.-There is only one ship pass through the leeward rim and on the neighboring twin atoll, Takume, there is none. The Raroia pass is narrow (700 m) and shallow (five and one-half to eight 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 five kilometers long and one and a half kilometers wide which is barely awash at low tide. Elsewhere, there are approximately 260 shallow channels across the rim which are drained or are awash during low water at the seaward ends and covered by two to two and a half 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. Although the larger islets also lie on the leeward side of neighboring Takume, this is



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

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 up by waves. The storms of greatest violence regularly strike the west (lee) side of Raroia and Takume and there is much evidence of island building by hurricanes there.

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. These clearly are being lengthened headward as storm waters cross the islets toward the lagoon, and they represent various steps in formation of shallow channels. The method of formation of the channels is itself an interesting problem considered more fully on subsequent pages. 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 a Pleistocene low water level.

Island conglomerate platform.-The smaller islets are formed of a flat platform of coarse limestone conglomerate (pakokota in Tuamotuan) from about one-half to a little less than one meter above normal high water on which, here and there, are small patches of sand and coral debris generally lagoonward of the islet center (Figs. 6, 7). A few 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.

Joints.-Irregular joints are visible here and there on the conglomerate pavement but they do not show lineation. Joints somewhat opened by solution are occasionally visible on bare areas of the outer reef flat near the shore. These are slightly sinuous and generally are approximately 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 not any 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 gravel on the rock platform defend the seaward sides of nearly all the islands. These are coarsest and highest along exposed promontories. The highest surface on the atoll (approximately six meters) is the crest of a rampart on the leeward side of the atoll (at Oneroa, Fig. 7,R). In more sheltered places the ramparts tend to flatten, becoming sandy beaches. 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 away from the lagoon shore on the lee side of the atoll 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 sandfilled a few centimeters below the surface. Presumably, the water which 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 one to two meters of earth is composed of coarse rubble and entrapped sand which could have been deposited only by violent storms.

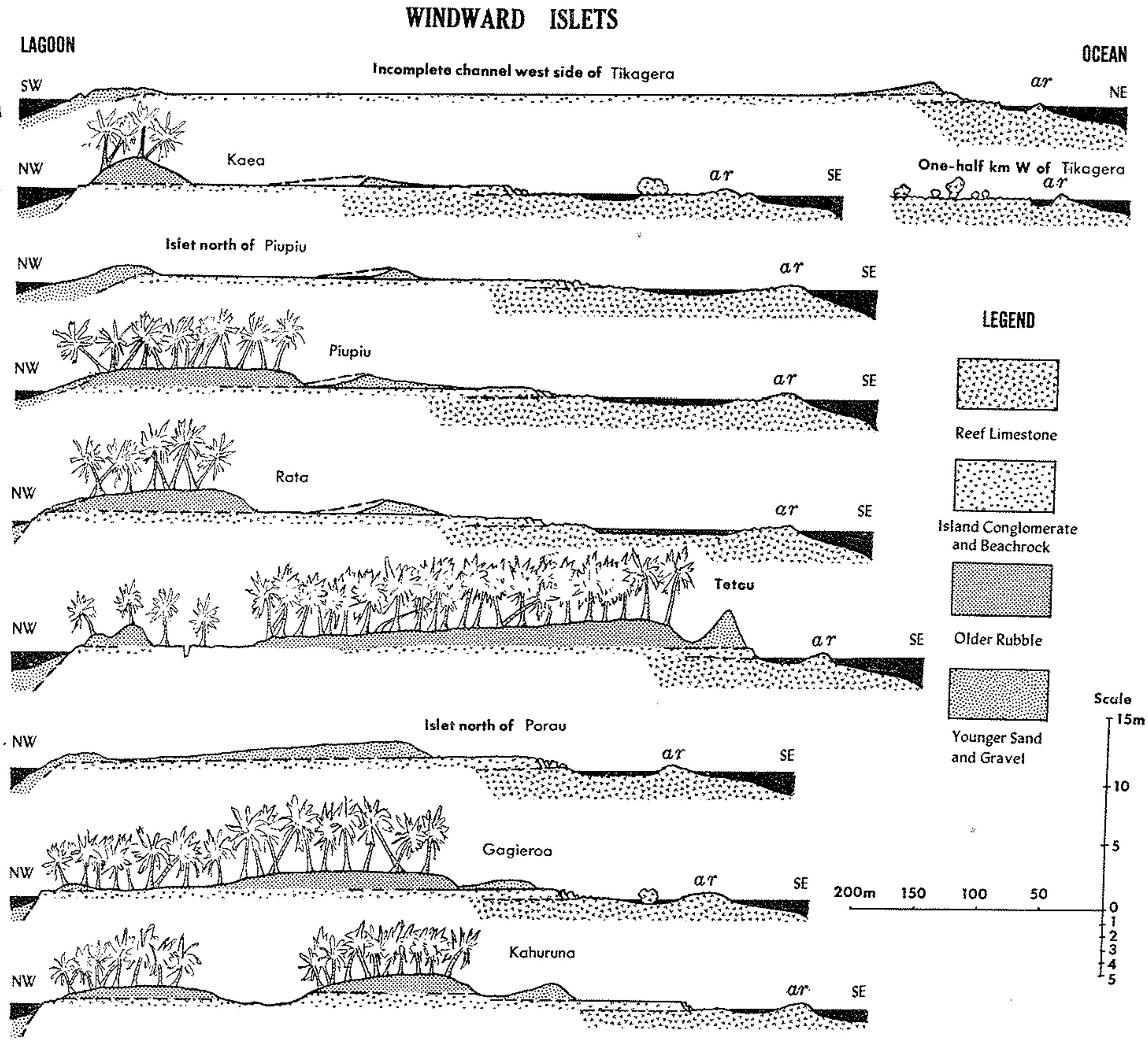
Submerged terraces.-There is evidence of an outer terrace believed to lie at approximately 20 meters similar to those described for Bikini (Tracey, Ladd, and Hoffmeister, 1948) and Andros Island (Newell, Rigby, Whiteman and Bradley, 1951) and there is a shallower terrace which slopes outward at the reef front from about low water level to eight meters. A submerged rock terrace, probably also at about eight 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 five meters or so.

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. 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 m) and is floored by fine sand and gravel rather than mud.

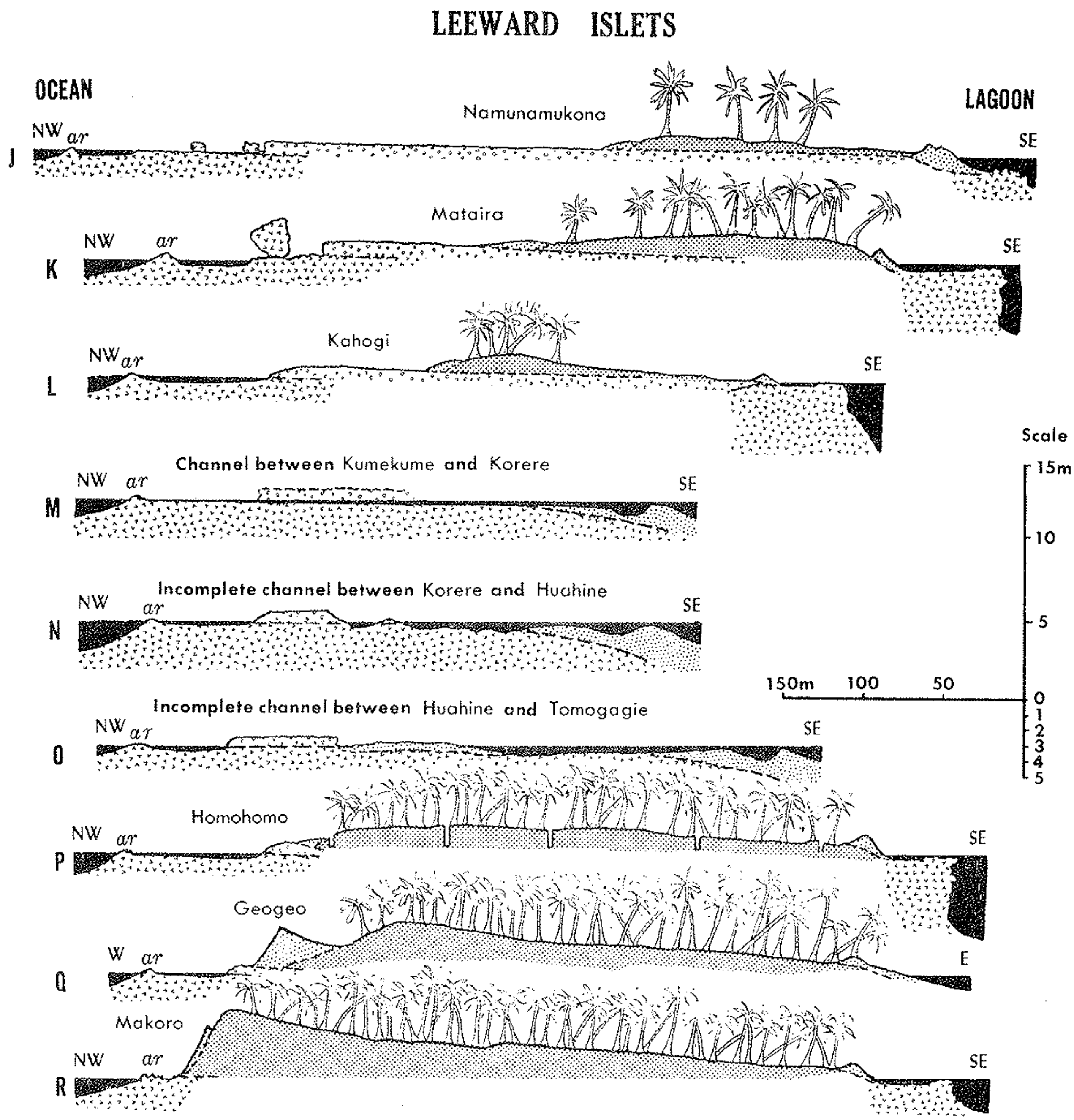
The water of the channels on the windward side and at the broad reef flat at the south end of the atoll generally flows lagoonward, even during low water, because of the strong swell. There is reversal of flow in the larger channels on the leeward side of the atoll where the wind generates a feeble seaward 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 and gravel on the windward (northwestern) shore of the lagoon. 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.

Accretion of sediments along the lagoon shore tends 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 beachrock has been cut back at many places some 15 or 20 meters since it was formed. However, it appears that the lagoon shore may be advancing lagoonward at the northeast and southwest ends of the atoll.



6. Windward islets, profiles.



7. Leeward islets, profiles.

Ground water.-Analyses of nine well waters were made at the 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 loaned by the U. S. 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 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.

Garumaoa and other well waters

Well #	Temperature C°	Salinity o/oo	Hardness o/ooo	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	25.0	15.4	360 ± 13	7.7
9	26.0	16.6	360 ± 13	7.6
10*	--	4.1	-- -	-

*Well at Tetou, little used, August 23; the others are at Garumaoa, June 29.

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 below. Pits four and five were not dug until after the onset of showers which came shortly after the middle of July, breaking a drought of many weeks.

Water analyses from test pits on Garumaoa

Pit #	Temperature C°	Salinity o/oo	Hardness o/ooo	pH
A (5)	26.0	4.1	380 ± 13	7.5
B (2)	26.0	9.0	420 ± 13	7.9
C (4)	25.0	3.5	420 ± 13	8.0
D (3)	27.5	7.6	420 ± 13	8.1
E (1)	24.2	3.7	420 ± 13	7.9
Pond #				
1	24.7	35.5	4000 ± 130	7.9
2	23.5	5.6	400 ± 13	8.3

All of 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 of the drinking water, however, at the village. In all of 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.

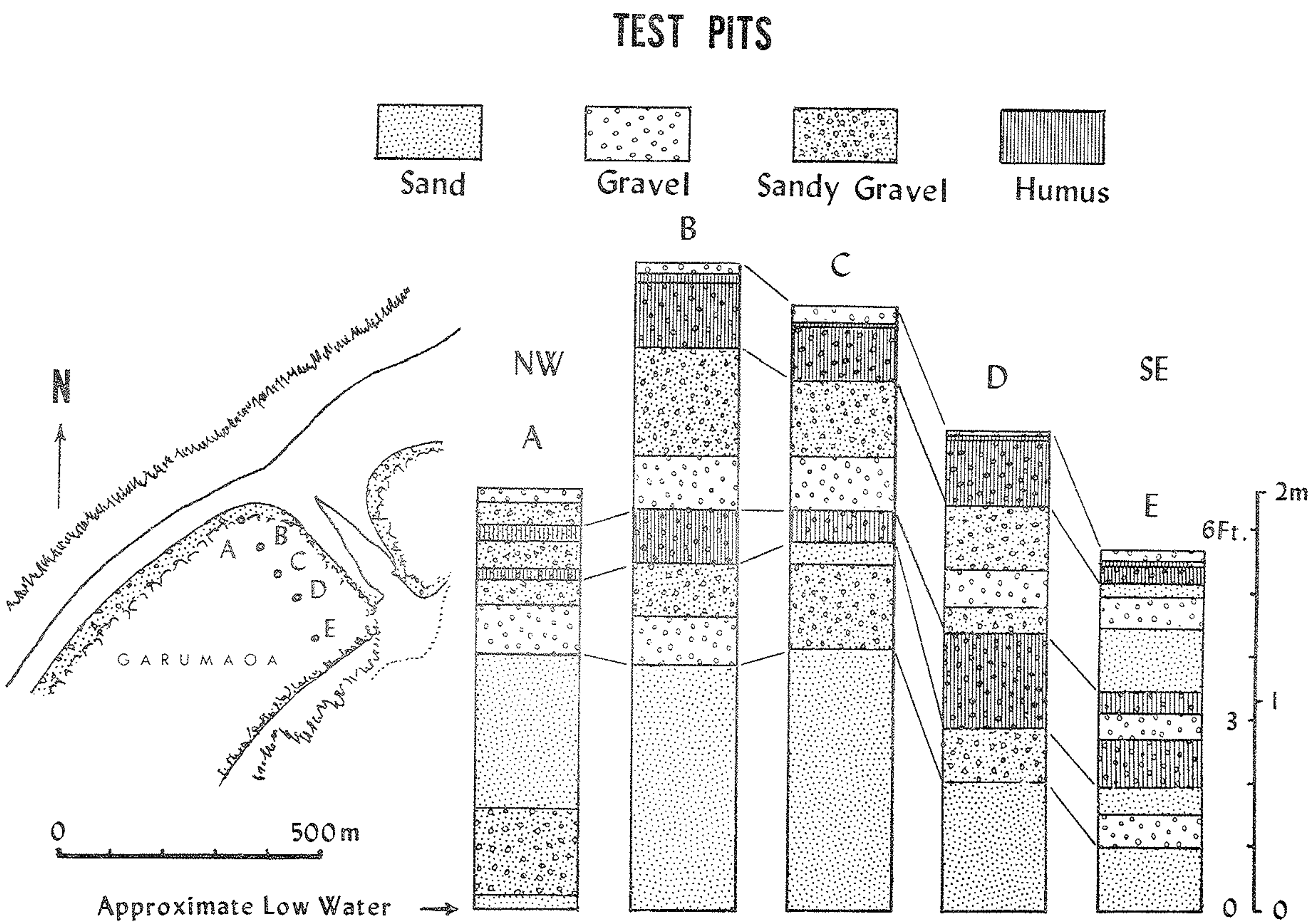
Soils.-The land areas of Raroia are almost destitute of soil over all but the lowest surfaces. Probably leaf mold and humus are periodically stripped away or buried by sheet flood during hurricanes. Sulphurous muck is found in a few swampy areas just inside the lagoon beach ridges. These are natural moats and the waters are quite saline (see preceding table, pond 1). Farther inland are small taro pits all dug before the present 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 which 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 two to three meters deep were dug across Homohomo (north end of Garumaoa Islet) in order to study the succession of deposits and to secure samples of ground water (Fig. 8). 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 with 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 centimeters. This is overlain by coarse, sandy gravel 150 to 350 centimeters thick containing one or two buried soil zones and a poorly developed humus zone at the top. Wells at Garumaoa, at Oneroa and Tetou also show that the sediments are generally finer below and coarser above. Samples of the sediments exposed on 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 a marked climatic change, such as development of, or shift in, a hurricane track. The slight drop in sea level discussed earlier probably resulted in increased rates of erosion of reef and island conglomerate.

Logs of five test pits at the north end of Garumaoa Islet (Fig. 8)

Test pit A (5). Northeast corner of Garumaoa Islet, Depth of hole, 79 inches.

Top		Inches
Bed 1.	Loose gravel	2
2.	Algal crust on pebbles	$\frac{1}{2}$
3.	Gray-buff sand and gravel	4
4.	Gray sand with some humus	3
5.	Gravel, subangular pebbles up to 4"	5



8. Correlation of strata in test pits, Garumaoa Islet.

Bed 6.	Sandy gravel with roots	2
7.	Sand, light-buff with scattered pebbles	5
8.	Coarse gravel, washed, angular, a few boulders	9
9.	Sand, medium, well sorted, light-buff	29
10.	Sand, gravelly, grayish	16
11.	Sandstone, like above	3+

Salinity 4.1; original temperature 27°C.

N.B. Roots occur scattered throughout, but predominate at levels indicated above. The section looks as though beds above #6 are result of burial of older profile, perhaps by 1903 hurricane.

Test pit B (2). North end Garumaoa Islet. Depth of hole, 121 inches.

Top		Inches
Bed 1.	Mantle of coarse angular coral fragments, the whole being coated black at surface by blue-green algae	2
2.	Dark-gray sandy gravel with organic material	2
3.	Gray sandy gravel with many roots	12
4.	Gray sandy gravel	20
5.	Open coarse gravel	10
6.	Small cobbles with open interstices several inches across; lowest root zone	10
7.	Poorly sorted sand and gravel	10
8.	Poorly sorted subangular gravel, no sand, unconsolidated	9
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 parts per million.

Test pit C (4). North end of Garumaoa Islet. Depth of hole, 113 inches

Top		Inches
Bed 1.	Unsorted coral gravel, washed	$3\frac{1}{2}$
2.	Algal film on pebbles, black	$\frac{1}{2}$
3.	Gravelly sand, dark-gray, with small roots	6
4.	Sand and gravel, darker, major root zone	4
5.	Sand and gravel, light-gray, buff, some cobbles	14
6.	Angular small cobbles and gravel, grading down into sand, light-gray	10
7.	Brownish dark-gray, sandy, with a few roots, humic soil with a few pebbles	6
8.	Brown, well sorted medium to fine sand	4
9.	Brown gravel, sandy, fragments up to 8 inches	16
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.

Test pit D (3). North end of Garumaoa Islet. Depth of hole, 90 inches.

Top		Inches
Bed 1.	Surface veneer gravel	1
2.	Black humus and leaf mold	1
3.	Gravel, gray, sandy, with roots	12
4.	Gravel and cobbles, sandy, light-gray, with a few small roots	12
5.	Gravel, washed, subangular, up to 3 inches with open interstices, fine roots	7
6.	Sand and coarse gravel, light-buff, fine roots	5
7.	Brown sandy humic soil, gravelly, darker at top	18
8.	Gravelly sand, yellowish tan	10
9.	Sand, coarse, light-buff, well sorted with a few small pebbles	24
	Water table	

Fluctuation of water level at least 10 inches.

N.B. The sediments below #7 are tan, those above are light-buff to bone colored.

Test pit E (1). Northeast corner of Garumaoa Islet (see Figure for location). Depth of hole, 68 inches.

Profile

Top		Inches
Bed 1.	Surface coral rubble, partly calcined by burning; no sand visible; fragments small pebbles to boulders.	2
2.	Upper half inch black, humic, lower part dark brownish-gray sandy gravel full of small roots, mainly horizontal (2 samples)	$4\frac{1}{2}$
3.	Sand with pebbles, light-gray (sample taken)	$2\frac{1}{2}$
4.	Pebbles and cobbles, subangular, light-gray, no sand	6
5.	Sandy gravel, light-gray	12
6.	Humic soil, dark-gray, sandy gravel, full of living roots, both horizontal or vertical (sample)	4
7.	Gravel, hardly any sand (sample)	5
8.	Sand, brown, pebbly (sample)	9
9.	Buff sand and pebbles (sample)	5
10.	Gravel, washed, no sand	6
11.	Sand, buff, with a few pebbles (sample)	12
	Water table	

Original temperature 27.5°C.

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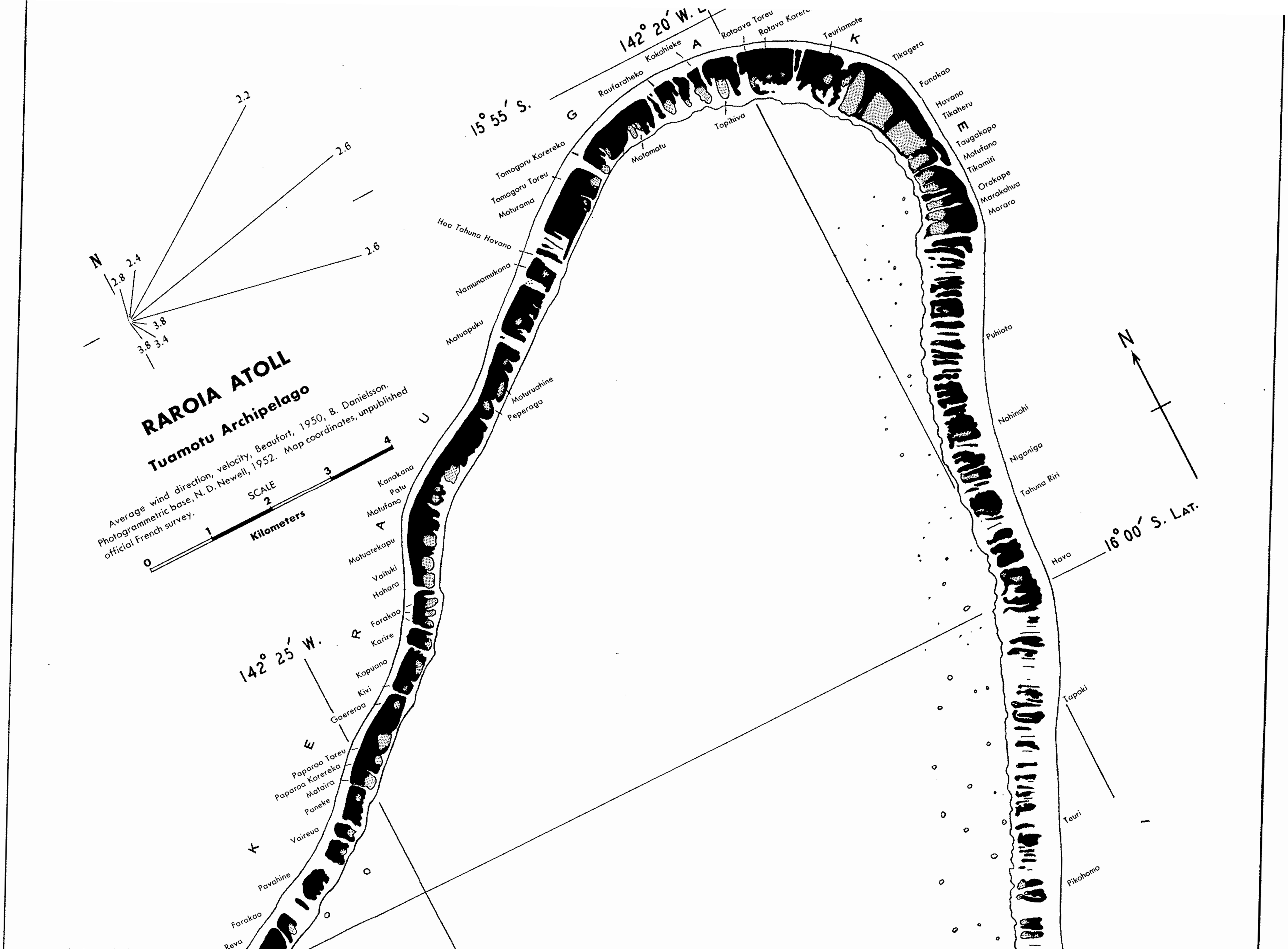
Part 3

GENERAL MAP OF RAROIA

by Norman D. Newell

Abundant patch reefs across the central part of the lagoon have not been mapped. Stippled areas, vegetation cover; black areas, bare land surface (limestone, gravel and sand). Original wind data corrected for magnetic declination.


RAROIA ATOLL
Tuamotu Archipelago
Average wind direction, velocity, Beaufort, 1950, B. Danielsson.
Photogrammetric base, N. D. Newell, 1952. Map coordinates, unpublished
official French survey.
SCALE
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Hava
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Motufano
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Karire
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Kivi
Gaereroa
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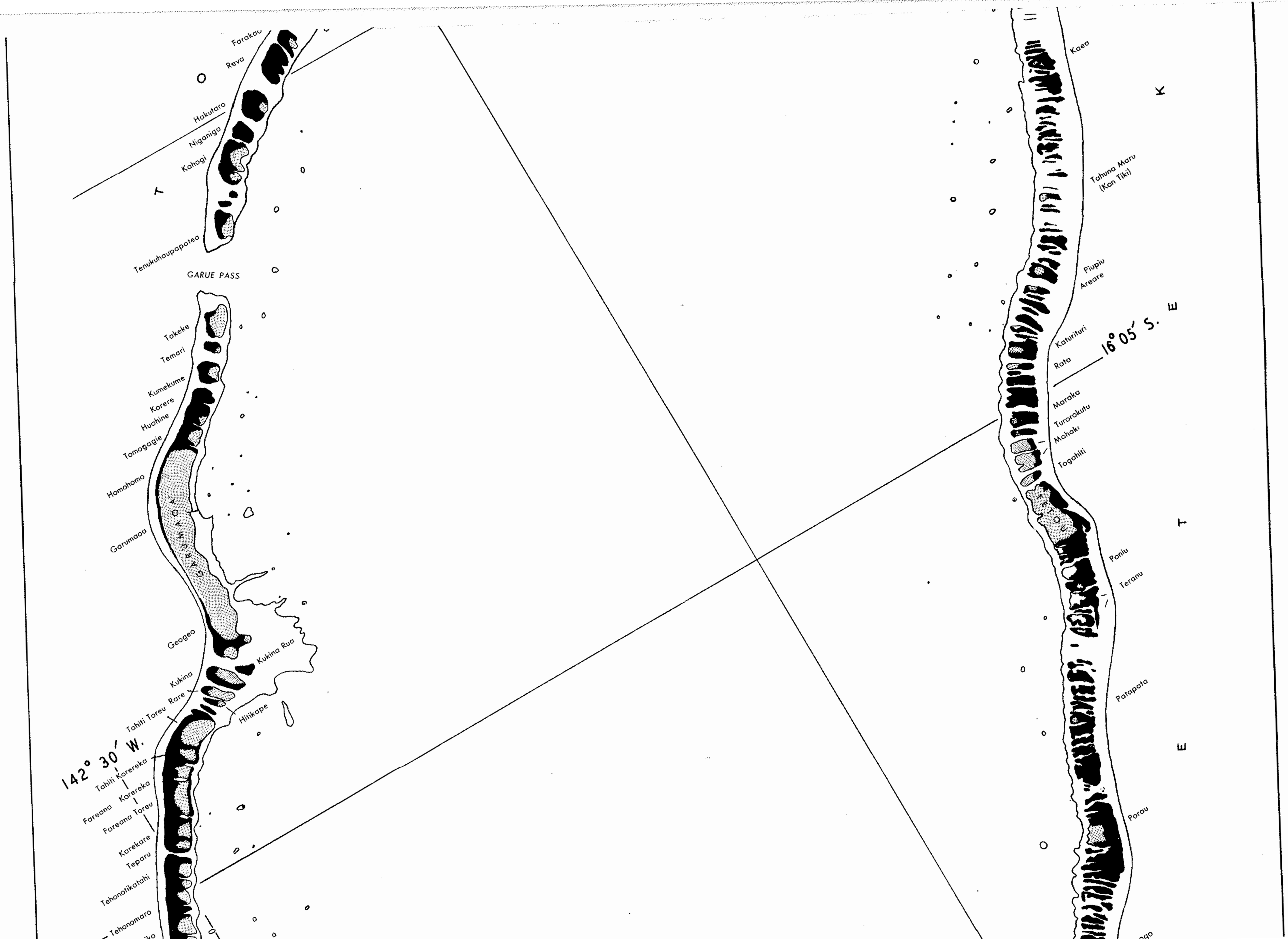
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Tetakaga
Marie
Makoro
ONEROA
Hopekore
Koutuvarokia
Kupakupa
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