ATOLL RESEARCH BULLETIN

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Geology of Kapingamarangi Atoll, Caroline Islands

by

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INTRODUCTION

Kapingamarangi Atoll is located at the southernmost end of the Caroline group of islands, slightly more than 1° north of the Equator. It is about 410 miles southeast of Truk and 350 miles north of Rabaul in New Britain. This isolated atoll surrounds a lagoon about 6 miles across from east to west and slightly less from north to south. It is inhabited by 426 Polynesians (1954), most of whom live on Touhou and Werua Islands on the eastern side. Details of geographic setting, climate, and general environment have been treated H. J. Wiens so will not be included here.

This report on the geology of Kapingamarangi Atoll covers preliminary results from field investigations conducted during late June, July, and August of 1954 and laboratory examination of specimens made during the winter of 1954-1955. Much attention has been devoted to studies of the islands, with special emphasis on the classification of sediments and sedimentary rocks, the occurrence and behavior of ground water, and the distribution of soils. Detailed studies also were made of the processes of sedimentation that currently are operating both on the reef and in the lagoon. These studies included the making of detailed analyses of beach and bar structures, the reconstruction of reef and offshore profiles, and the systematic sampling of the lagoon floor.

Terminology used in this report follows, in general, that recommended by Tracey and others (1955) in their recent paper titled "Conspicuous features of organic reefs." The term "atoll" is used for the peripheral reef and everything within it. The upper surface of the peripheral reef, except where covered by islands, is referred to as the reef flat. Small reefs within the lagoon, including varieties that have been called patch reefs, small table reefs, reef knolls and reef pinnacles, are discussed under the general designation of patch reef. Dense growths of staghorn or branching corals are referred to as thickets. Other terms for geomorphic and organic features are explained in the text wherever their meaning is not apparent.

ACKNOWLEDGMENTS

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My associates in the field party were Cadet Hand, Robert R. Harry, W. Jan Newhouse, William Niering, and H. J. Wiens, all of whom contributed in various ways toward the development of this report. The base maps of the islands prepared by Wiens were especially important in carrying out a geological program and the assistance of Niering in soil studies and tide recording is gratefully acknowledged. Kapingans who served faithfully as assistants throughout the summer were Taitos, interpreter, and Aisea, Exsol, and Turibureti, boatmen and test-pit diggers.

In the study of collections and samples of materials, I have been assisted by a number of specialists, and it is with pleasure that I acknowledge the following cooperation:

Coral identification -- John W. Wells, Cornell University.
Foraminifera identification -- Ruth Todd, U. S. Geological Survey.
Analyses of water from wells and lagoon -- John Hem, U. S. Geological Survey.
X-ray diffraction identification of minerals -- A. J. Gude III, U. S. Geological Survey.
Analyses of elements in soils -- P. R. Barnett, U. S. Geological Survey.

For critical reading of the manuscript and many helpful suggestions, the writer is indebted to G. D. Robinson of the U. S. Geological Survey, John Chronic of the University of Colorado, and Halka P. Chronic.

THE ATOLL FRAMEWORK

The peripheral reef of Kapingamarangi Atoll (fig. 24) encircles an oval lagoon, almost completely separating its waters, especially at times of low tide, from those of the surrounding sea. The only major breaks are relatively narrow passes on the south side where channels nearly 20 feet deep permit strong currents to flow in and out continuously. This peripheral reef includes what has aptly been termed the "frame" of the reef complex or reef mass, and is a lattice constructed through the growth of organisms, especially corals and coralline algae. As stated by Cloud (1952a, p. 2128), these organisms "serve to hold it [*the reef*] together, and the frame they build is a trap for clastic or chemically precipitated sediments."

The surface of the peripheral reef is widest -- nearly 4,000 feet across -- near the northernmost sector, although it is almost as wide in the extreme western part (fig. 24). On the southern arc, west of the main passes, the surface is no wider than 1,000 feet. The 33 islands distributed along the eastern half of the reef appear as very low mounds that rise slightly above the general flat top along its lagoonward margin. They alone stand above the level of high-tide waters. Elsewhere along the atoll, especially on the southwestern, western, and northwestern sectors, the reef surface is divided into a seaward slope and a lagoonward slope by a low but definite crest. Both slopes are extremely gentle in most places. They are referred to in this paper as the outer reef flat and the inner reef flat.

The essentially flat top of nearly all the outer part and some of the inner part of the reef forms a pitted rock pavement. Over wide areas this surface contains no organisms now contributing appreciably to growth of the reef. To the contrary, it appears to be solely the result of the wearing down, by waves and currents, of coral masses that once stood higher than the present surface. Evidence from Okinawa obtained by MacNeil (1950) indicates that similar surfaces there are the result of recent wave or solution planation. Other similar reef flats reported from many islands of the Pacific suggest, as stated by various geologists, that this widespread feature is the effect of a recent lowering of sea level with resultant death of all corals back from the reef edge, followed by a beveling of higher parts of the reef structure.

The present surface of the reef flat appears to result from an essentially static position of the sea for a time sufficient to develop a general evenness of planation and a condition of near sterility over wide areas. Today, small living algae of the genus Boodlea cover extensive areas of the rock surface; mollusks and other marine animals congregate around and under limestone boulders and coral heads that are strewn over the rock surface -- debris washed across from the seaward side. Brittle stars, eels, and marine worms inhabit cracks and cavities that extend down into the rock mass. Living corals and coralline algae, however, are largely restricted to the seaward margins of the reef and, where islands are absent, to waters of the inner reef area bordering the lagoon edge.

Clastic sediments are relatively scarce over much of the present reef-flat surface, but are progressively more abundant toward the inner margins of the reef where they form a veneer that covers a framework of coral. The small amount of fragmental material on the outer side of the reef flat consists largely of coral and coralline algal debris, up to and including boulder size, strewn over the surface, and of clastic particles from mollusk shells and echinoid spines, concentrated in pockets and cracks. Foraminifera of the genus Calcarina that are reported as common on the reef flats of many Pacific atolls are absent here; few Foraminifera of any type occur on the seaward parts of the atoll. The tests of these animals accumulate in quantities sufficient to form deposits of lime sand only on the island lagoon beaches and on the inner parts of the atoll. As pointed out by Sollas (1904, p. 6, 27), however, such lime sands ultimately fill many of the interstices in the framework limestone mass, and they develop into extensive deposits on the inner side of the "retaining wall" of coral and algal structures.

Attempts were made at Kapingamarangi to determine the lithologic character and structural features of the framework limestone through studies of material exposed in cracks below the pavement and of large boulders washed up from seaward exposures. The investigation was hampered by the extreme difficulty of digging into the reef rock and by a general lack of natural breaks exposing sections, but from a series of samples some generalizations can be made. In many specimens, the reef rock appears aphanitic, but in others the relict structures of corals are clearly preserved.

The framework limestone as a whole seems to be very cavernous, although small masses and hand specimens commonly have a relatively low apparent porosity. Cavernous structure, observed in near-surface excavations, probably extends to considerable depths. This is indicated by the behavior of the fresh-water lens on various islands, in which all parts of the lens rise simultaneously and with a similar tidal lag (described under "Ground water"). It also is suggested by evidence from the drill holes at Funafuti (Sollas, 1904, p. 6) and at Eniwetok Atoll (Ladd et al., 1953, p. 2259). On the other hand, some of what originally were cavities appear to have been filled with clastic sediment. This feature has been noted by Newell (1954, p. 18) in reference to reef blocks from the outer edge of the reef flat at Raroia.

The reef-building organisms that contribute chiefly to the framework limestone, as judged by the forms currently growing along the eastern seaward margin of the atoll, are very largely corals but include some masses of the coralline alga Porolithon onkodes. The corals are represented by many species (table 9); the most common belong to the genus Acropora, except along the inner margin, where microatolls of Porites lutea are dominant. Suggestion that much of the limestone beneath the present reef flat is composed of a comparable assemblage is found in the mineral content of selected samples examined by X-ray diffraction methods.1/ All specimens tested show

1/ Analyses by A. J. Gude III, U. S. Geological Survey.

90 percent or more aragonite, which percentage probably reflects the proportion of coral, though a small amount of aragonite may be due to interstitial deposits of clastic shells. Five to 10 percent of high-magnesium calcite2/

2/ High-magnesium calcite, as opposed to low-magnesium or normal calcite, is discussed by Chave (1954, p. 267). He points out that calcite of algal structures contains more than 10 percent magnesium carbonate, whereas that in mollusks and certain other organisms contains less than 2 percent.

in some specimens suggests the amount of algal contribution. A lack of normal calcite in all samples indicates that the common reef-dwelling Foraminifera of the genus Amphistegina were not included in the samples examined.

Unfortunately, no data are yet available on the lithology or structure of the Kapingamarangi reef at appreciable depths below the pavement of the reef flat. Judging from records of wells drilled on other atolls (Fairbridge, 1950, p. 384), however, one might expect to find zones of clastic materials representative of various depths and environments, alternating with zones of reef-forming corals and algae similar to those on the surface today. All such changes at depth appear to be related to times of advance and retreat of the actively growing framework corals and coralline algae and probably were controlled by relative changes of sea level and still-stands. Both the upward and the lateral development of the limestone framework are a record of tectonic and climatic events.

GEOLOGY OF THE ISLANDS

Character of the islands.- Thirty-three islands are distributed along the arc that forms the eastern, windward peripheral reef of Kapingamarangi Atoll. The largest is Hare Island, which is more than a mile long and 600 feet wide, and the smallest is Matukerekere Island, which is about 130 feet long and supports but a single mature tree. Some of these islands are composite, having attained their present sizes by the combining of two or more small islands through processes of sedimentation. Other islands probably represent various stages of diminution through partial destruction or dissection resulting from cyclonic storms.

The origin of islands perched on oceanic atolls is a problem about which man has speculated for a long time. Some early views on this subject are recorded in the log of Captain Cook (Lloyd, 1949, p. 266) under the date of April 17, 1777:

"There are different opinions amongst ingenious theorists, concerning the formation of such low islands as Palmerston's. Some will have it, that, in remote times, these little separate heads or islets were joined, and formed one continued and more elevated tract of land, which the sea, in the revolution of ages, has washed away, leaving only the higher grounds; which, in time, also, will, according to this theory, share the same fate. Another conjecture is, that they have been thrown up by earthquakes, and are the effect of internal convulsions of the globe. A third opinion, and which appears to me as the most probable one, maintains that they are formed from shoals, or coral banks, and of consequence increasing."

In order systematically to accumulate data relative to the islands on Kapingamarangi Atoll, geologic maps were prepared during the summer of 1954 for all of the larger and some of the smaller ones (figs. 1 to 10). Island maps on a scale of one inch equals 100 feet, compiled and surveyed by H. J. Wiens, furnished bases to work on. The distribution of materials was plotted according to the classification discussed in the section of this report on "Petrology." Dips in sedimentary strata were recorded on the maps.

Analysis of the geological maps indicates that Kapingamarangi islands are formed of three principal classes of material: (1) sedimentary rocks formed through the cementation of clastic particles and organic remains, (2) unconsolidated sediments of beaches and bars, and (3) surficial deposits forming the ramparts, rampart wash, and soils (not mapped) that partly cover and mask the other two. On the basis of the distribution and structure of these three classes of material, much of the island history may be interpreted.

Sedimentary rocks.- Beds of sedimentary rock rise above the reef flats along the seaward margins of all the large islands and many of the small ones, and they crop out locally within many islands. Because in most places the clastic particles of which they are formed are clearly discernible and because their stratification commonly is prominent after weathering these rocks, for the most part, are readily distinguishable from the reef rock on which they rest. Isolated pedestals and undercut blocks formed of similar clastic rock stand on the reef flat considerable distances seaward from some islands -- remnants of earlier island masses. Conspicuous illustrations are on the flats east of Werua Island. Likewise, relict platforms of stratified clastic rock, worn to a low level through planation but standing above the coral rock of the reef flat, extend 400 feet northeastward from Torongahai Island.

Evidence furnished by the distribution of erosional remnants of stratified rock suggests that the seaward shores of all Kapingamarangi islands have been retreating for a considerable time. Similar evidence on Raroia, indicating reef-flat extension at the expense of islands, has been noted by Newell (1954, p. 14). A second feature that tends to support this concept is the orientation of cross-stratification along shore-line exposures of island rock. On many islands, of which Werua is an excellent illustration (fig. 4), the strata in rocks that form the seaward coast dip exclusively lagoonward over long stretches in the same manner and degree as strata in the modern lagoon beaches. This fact suggests that strata in the two places were developed in a similar manner and, therefore, that the deposits forming these rocks accumulated at a time when the lagoon margin was in the present position of the seaward shore. Still further evidence of island retreat is presence of the mineral apatite in coastal stratified rock on Nunakita and Ringutoru Islands in wave-washed areas beyond the present limits of trees. This location indicates that phosphorite must have developed at some time in the past when these localities were the interiors of islands and when guano from birds was accumulating nearby.

The present distribution of stratified rock indicates not only a former, more seaward position of the islands but also a higher surface level. Stratified rocks on various islands, especially prominent on Rikumanu and Ringutoru, stand 4 to 5 feet above the present high-tide level. These rocks are formed of clastic particles and are cross-stratified; they appear to be leached and partly phosphatized. Rocks having a similar high-level position in many atolls of the Pacific have been recorded (David and Sweet, 1904, p. 67-68; Ladd et al., 1950, p. 413) and are generally considered to represent deposits residual from a time when, owing to eustatic changes, sea level was higher than at present.

Lagoon beaches and bars.- Large parts of most of the present islands, including virtually all of the lagoonward sides, are composed of unconsolidated clastic materials and foraminiferal sands. Such sediments are accumulating today on the bars or horns projecting into the lagoon from both ends of each island and along the incurving beaches between these bars (figs. 1 to 10). Test pits and wells on various islands indicate that similar unconsolidated materials extend downward in many places at least as far as low-water level, 3 or 4 feet below the surface. Sedimentary structures, especially stratification, further show that these sediments were deposited largely as beaches, dipping lagoonward, and as bars.

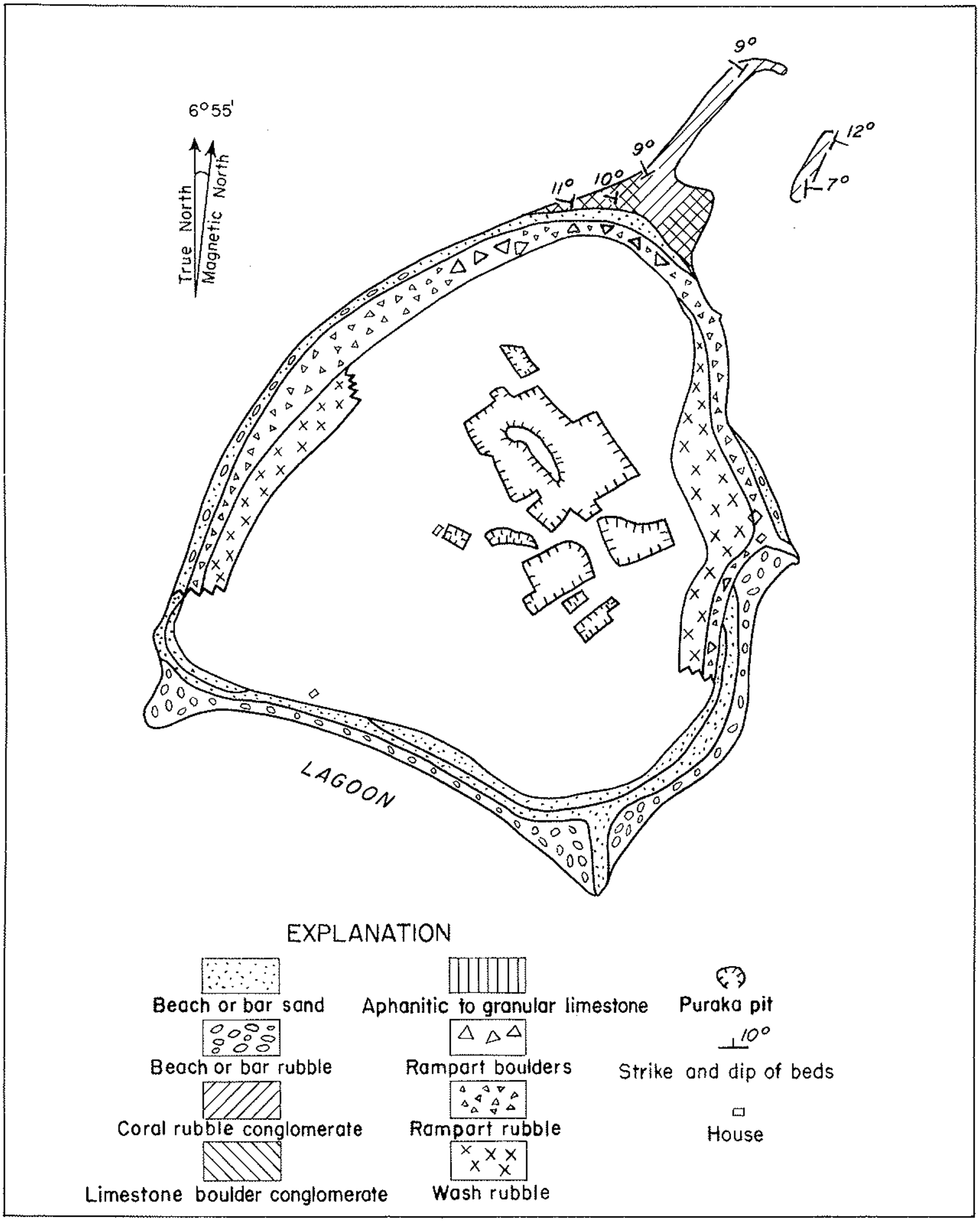


FIGURE I. – GEOLOGIC MAP OF TORONGHAI ISLAND

0 500 Feet

1954

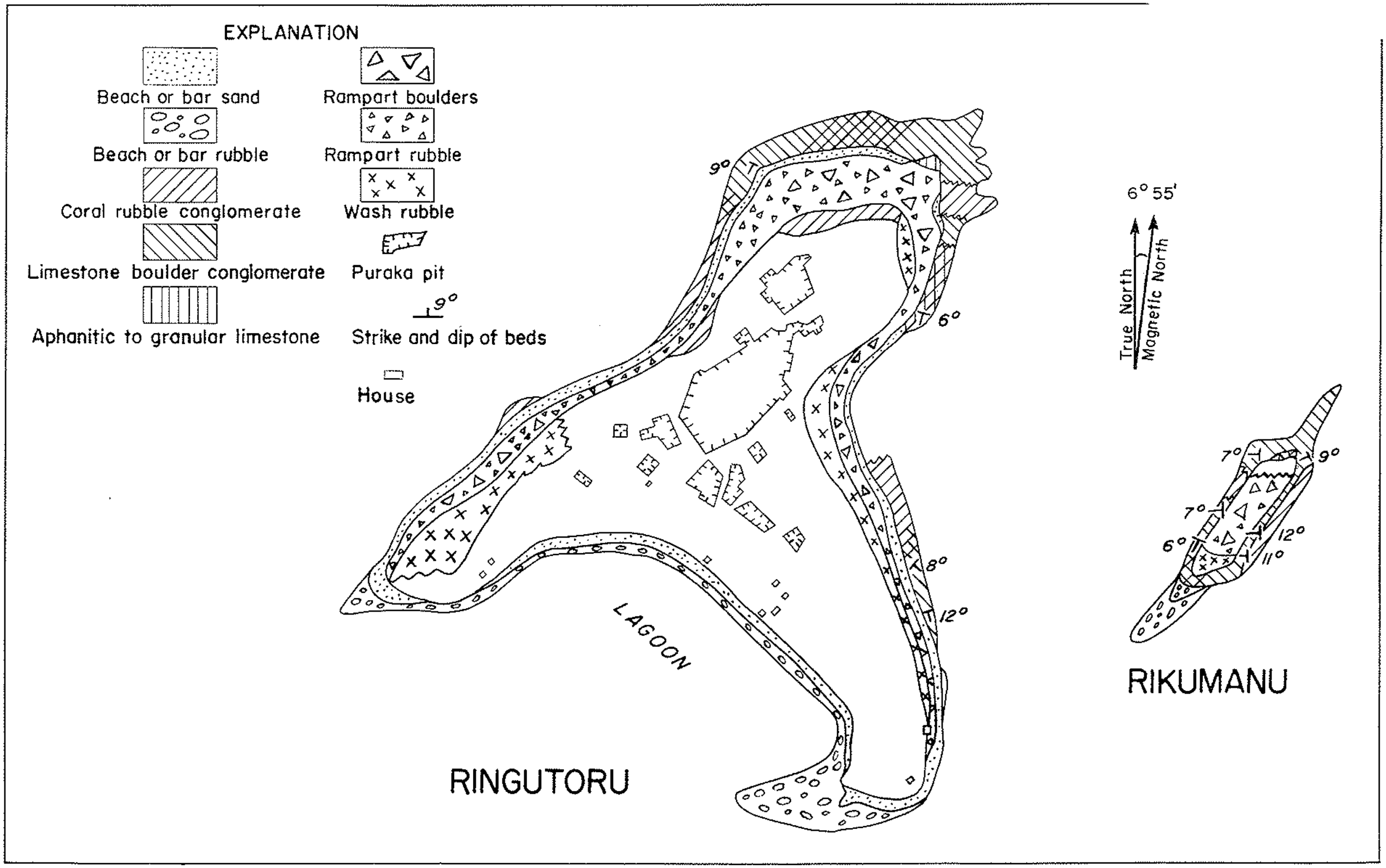


FIGURE 2.- GEOLOGIC MAP OF RINGUTORU AND RIKUMANU ISLANDS

0 500 Feet

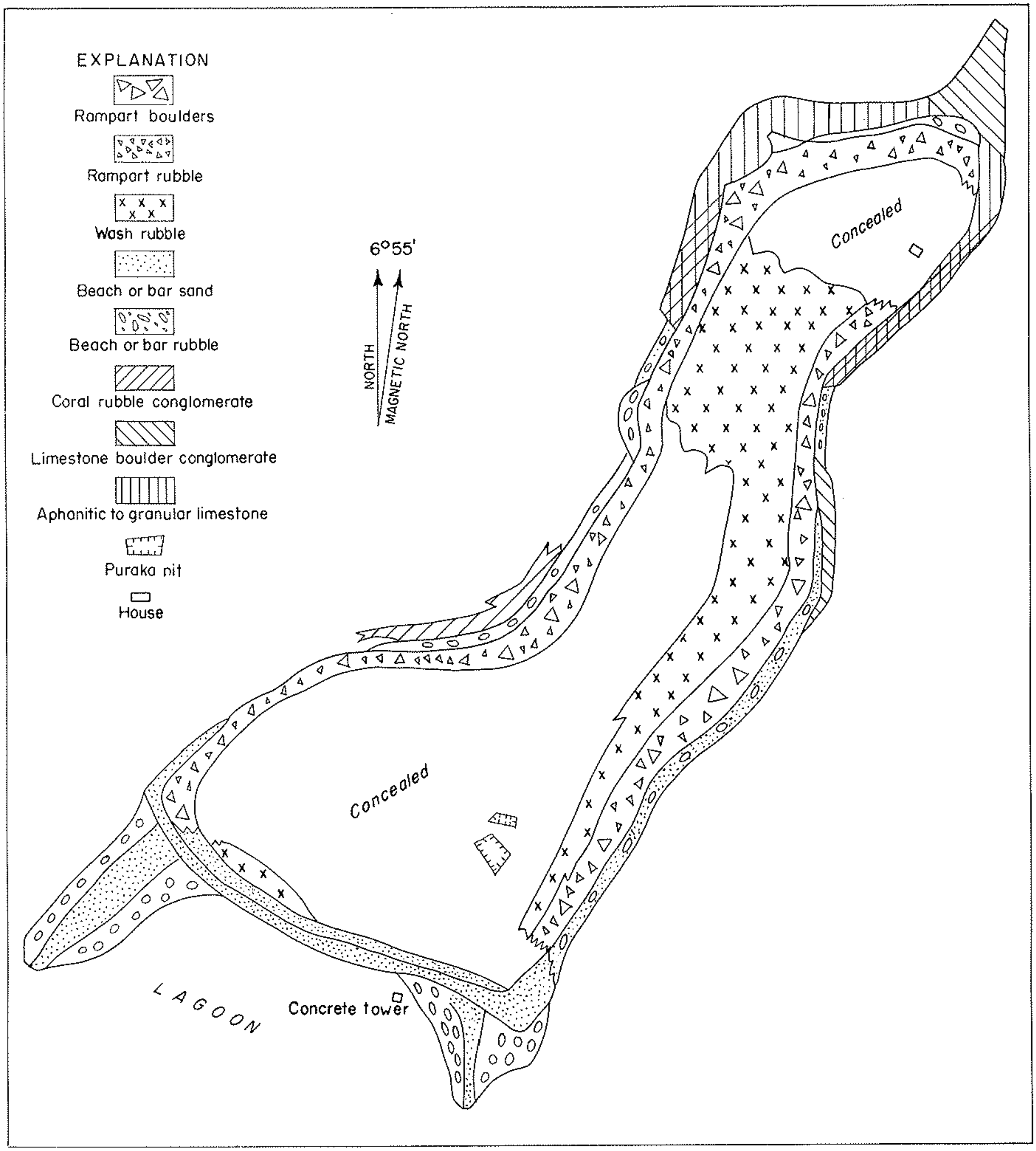


FIGURE 3—GEOLOGIC MAP OF NUNAKITA ISLAND

0 500 Feet

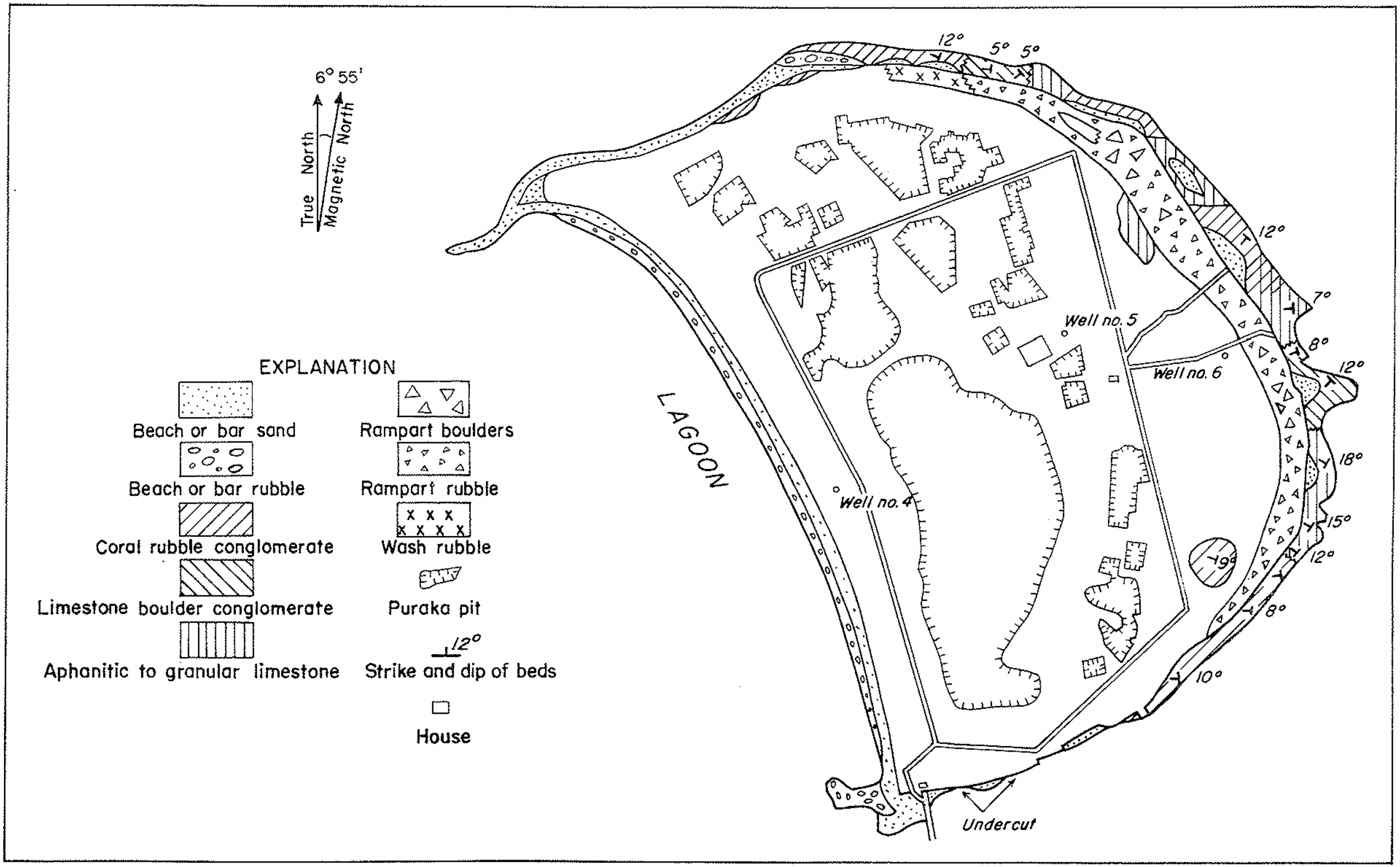


FIGURE 4.-GEOLOGIC MAP OF WERUA ISLAND

0 500 Feet

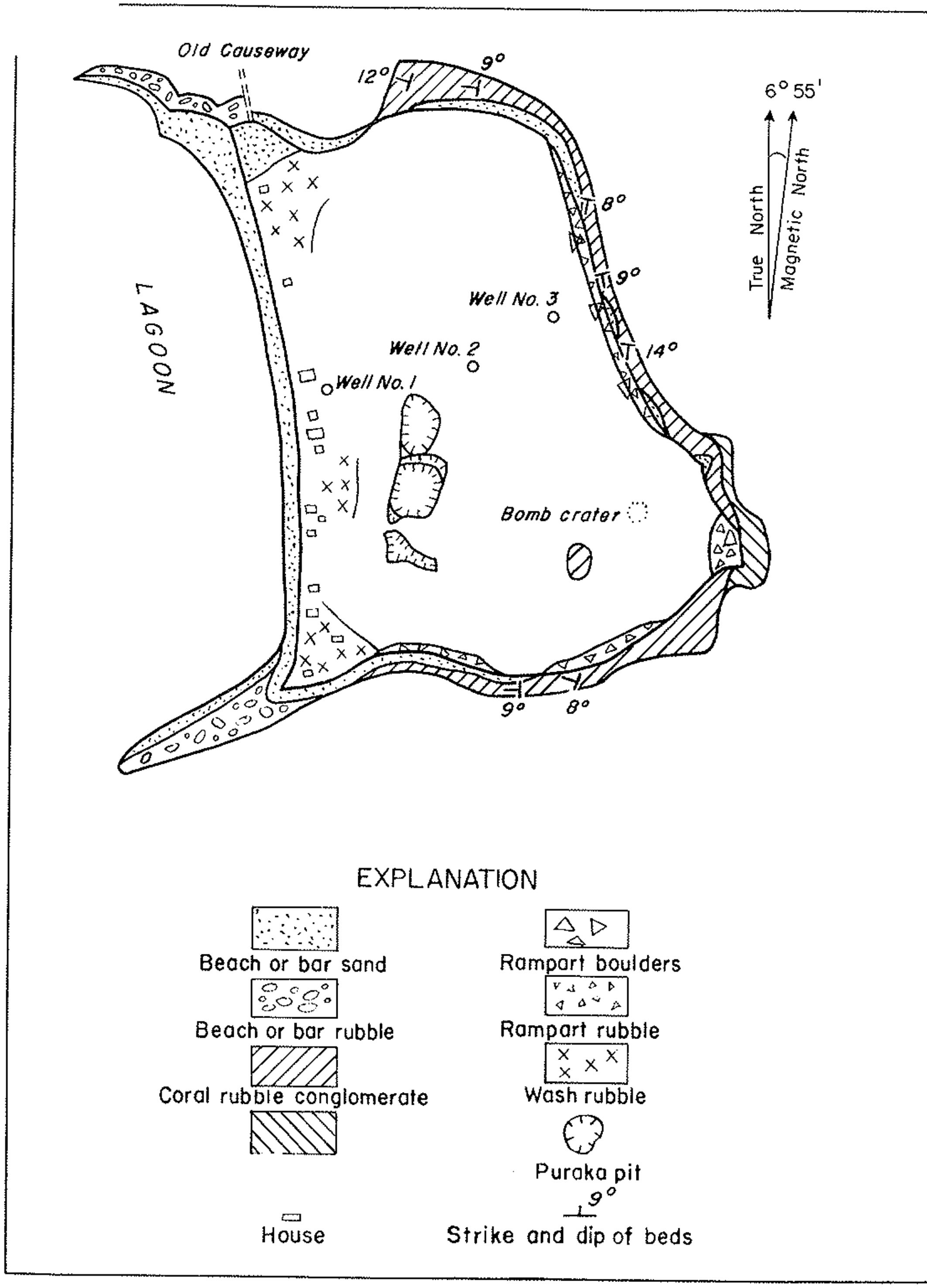


FIGURE 5.-GEOLOGIC MAP OF TARINGA ISLAND

0 500 Feet

1954

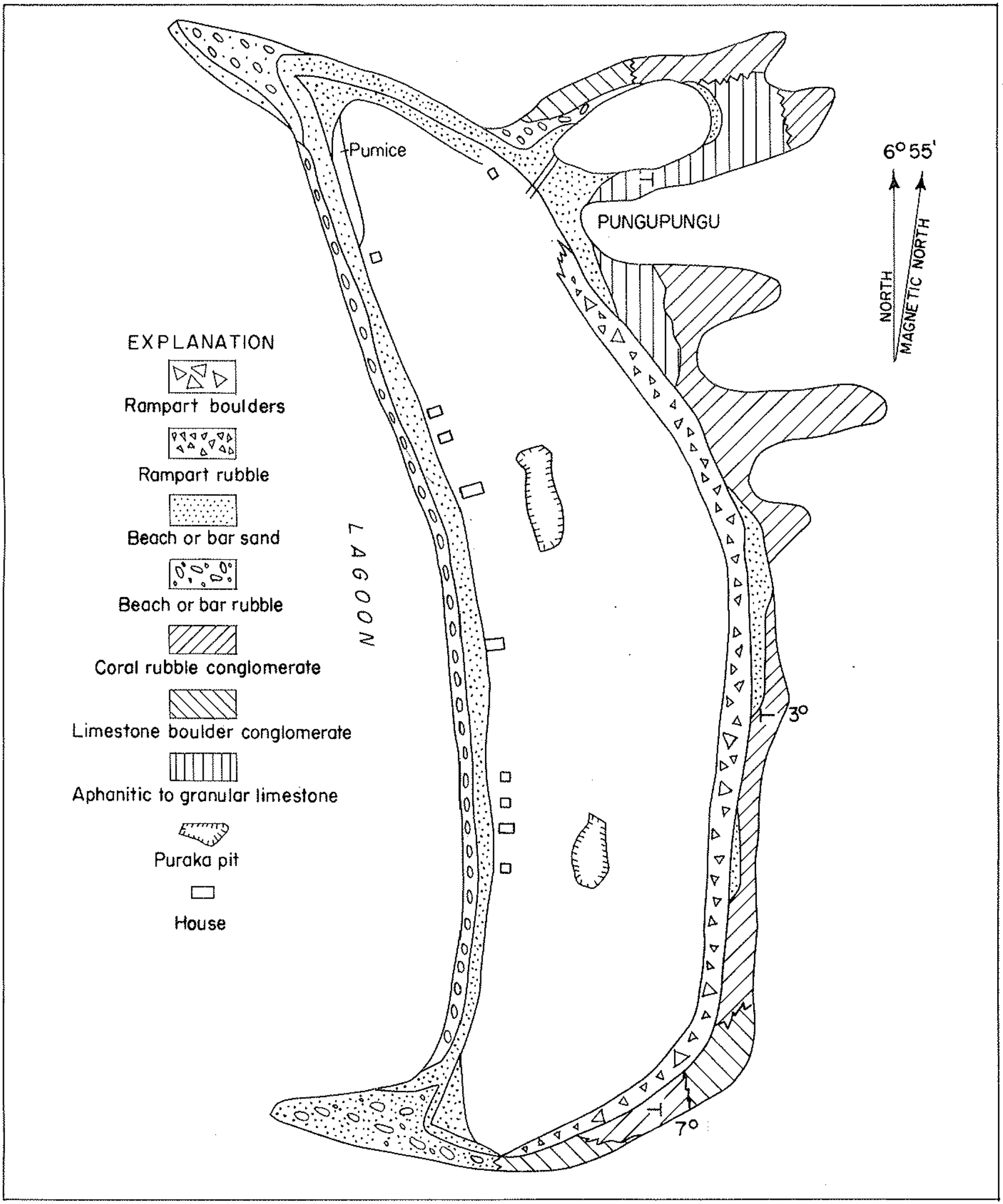
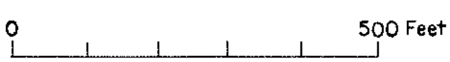


FIGURE 6—GEOLOGIC MAP OF MATIRO ISLAND



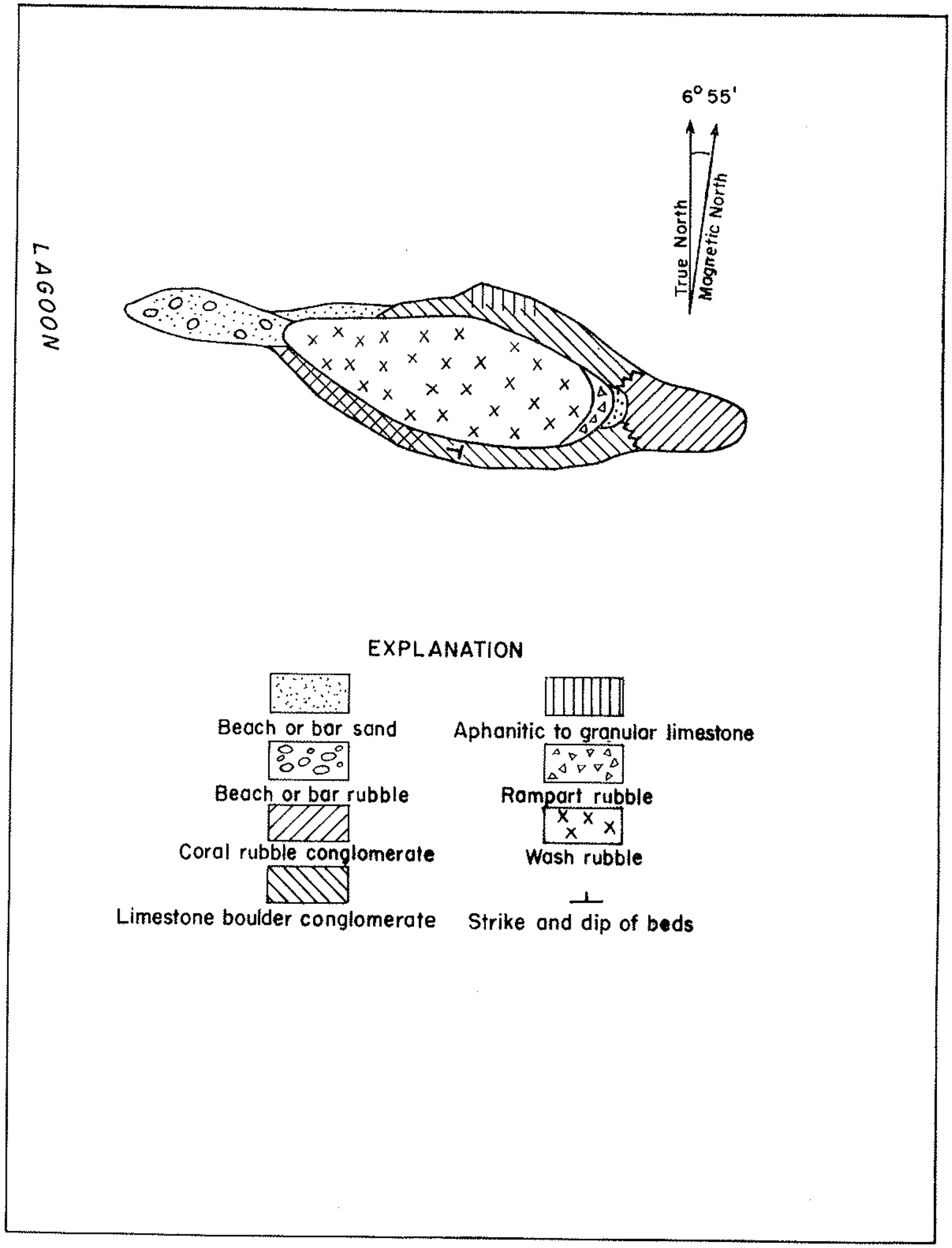


FIGURE 7.-GEOLOGIC MAP OF MATUKETUKE ISLAND

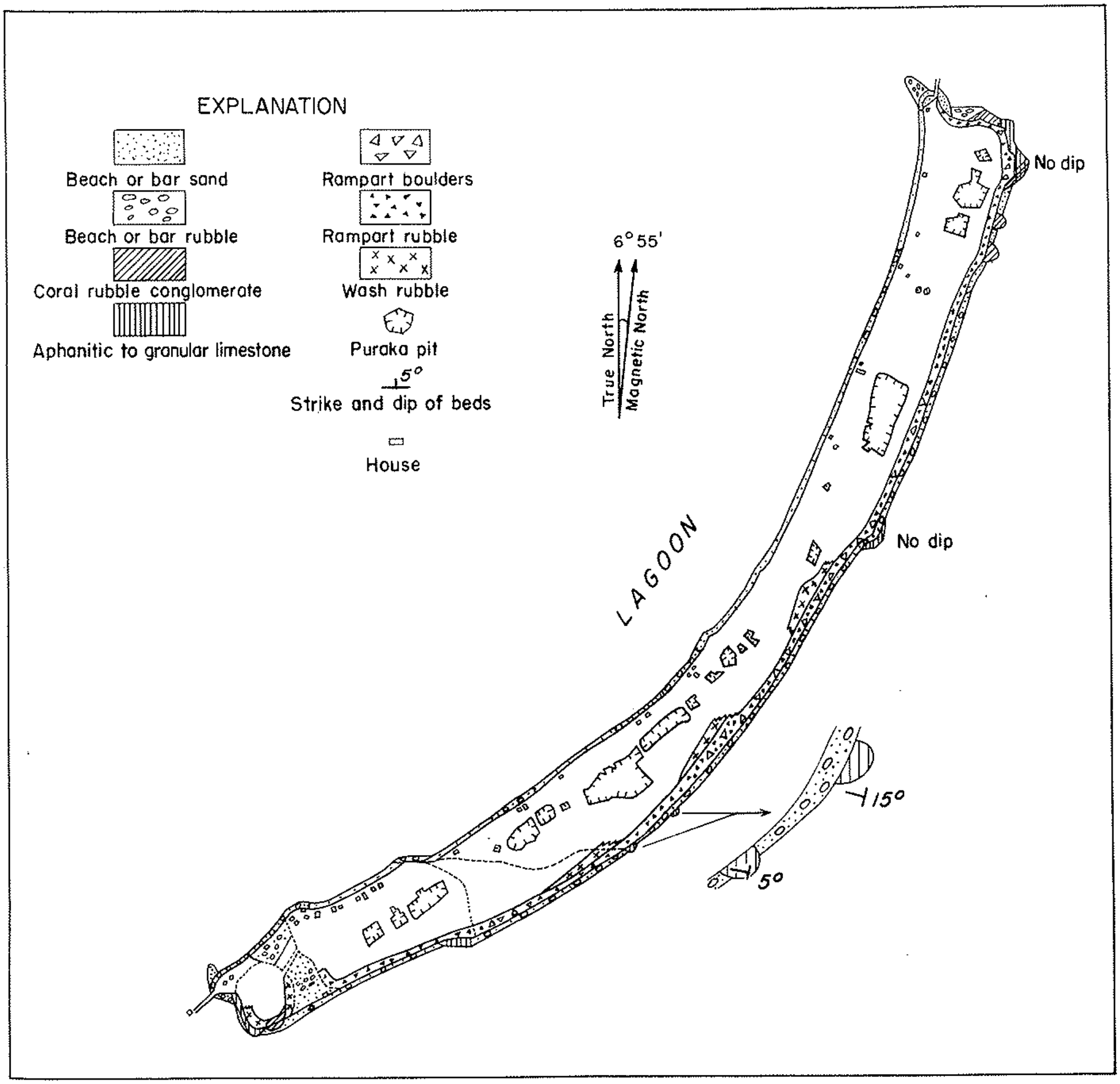


FIGURE 8.— GEOLOGIC MAP OF HARE ISLAND

0 500 Feet

1954

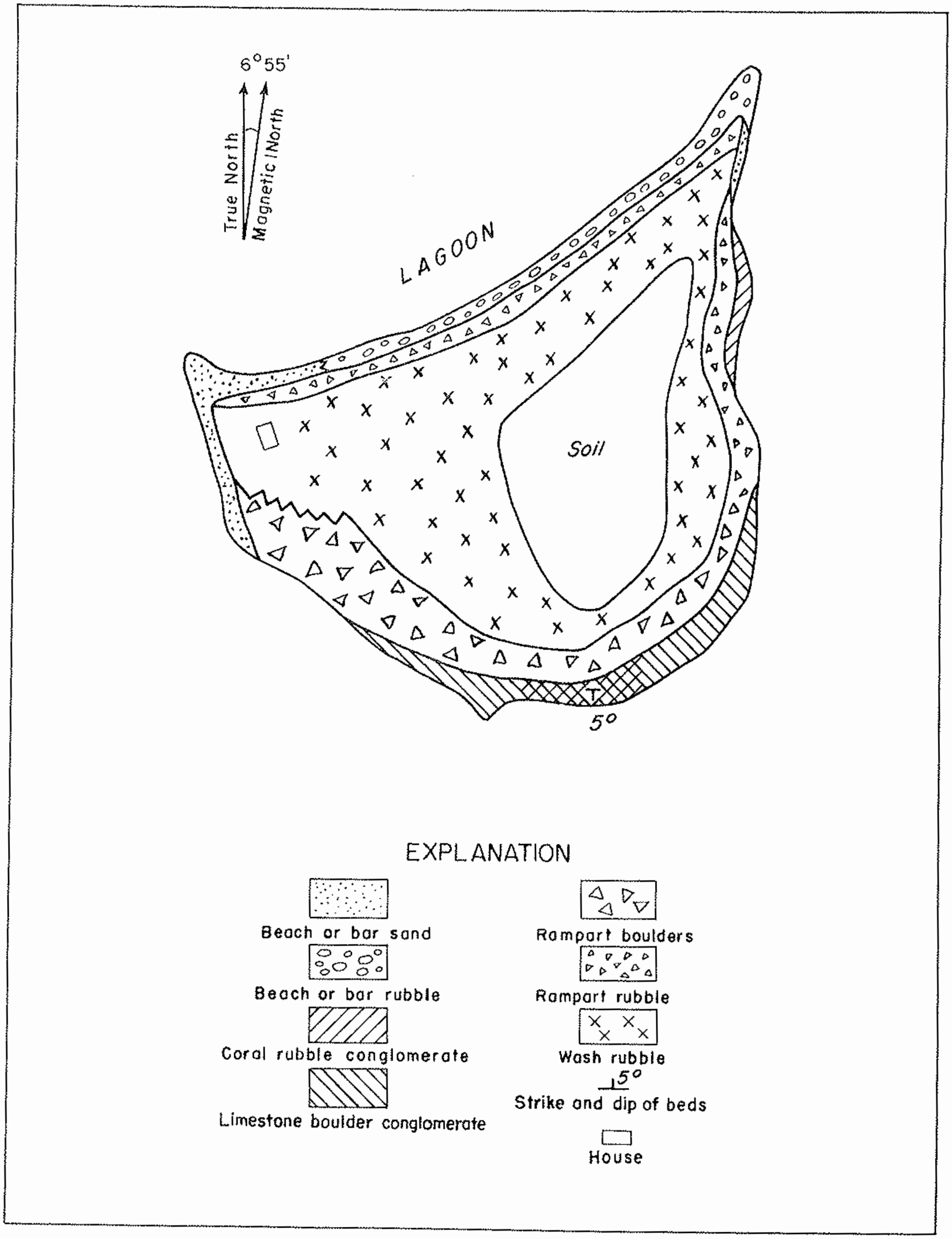


FIGURE 9.—GEOLOGIC MAP OF PUMATAHATI ISLAND

0 500 Feet

1954

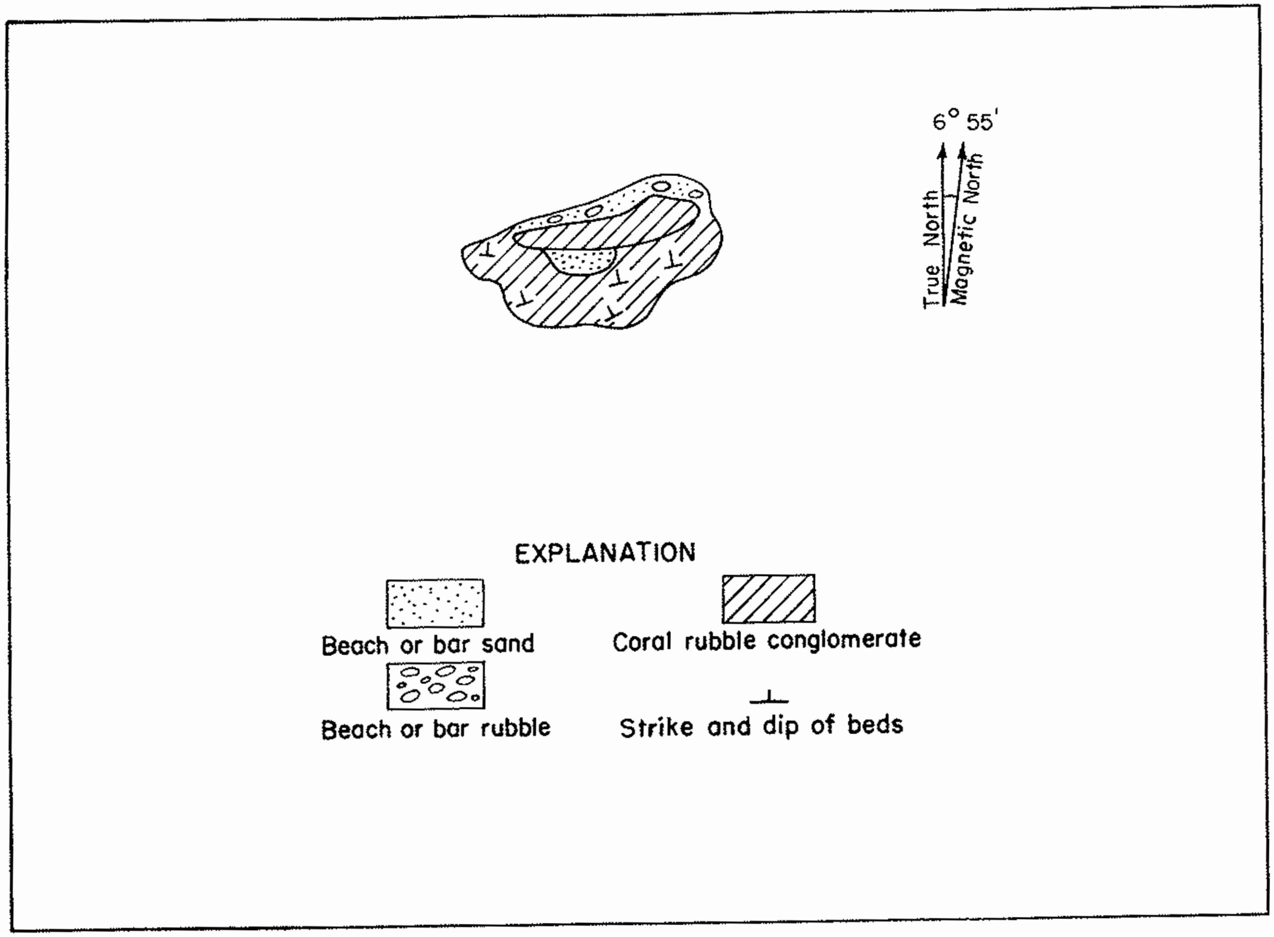


FIGURE 10.- GEOLOGIC MAP OF MATUKEREKERE ISLAND

0 50 100 Feet

Beaches and bars on all of the major islands were mapped, and details of their structure were recorded from trenches dug at right angles to the strand on Taringa, Parakahi, Matiro, Pumatahati, and Ringutoru Islands. Results of these studies must await description and analysis at a later date, but some salient features are shown on three typical beach profiles (fig. 11). The foreset beds of the beaches dip from 4° to 11° lagoonward, except for short distances immediately below beach crests, where many dip as much as 15° to 20° (table 1). Backshore beaches commonly are horizontal, but some dip inland 3° or 4°. No evidence that any of the lagoon beaches are being converted into beach rock could be found, and beach deposits encountered in test holes on the lagoon sides of many islands were unconsolidated.

Lagoon beach deposits vary in composition from time to time and from place to place according to effective wave conditions. Four principal components are recognized, and these are normally sufficiently well sorted that they are separated into parallel bands along the beaches. The components are (1) lime sand composed largely of an orange, ovoid-shaped foraminifer (Amphistegina madagascariensis), with lesser amounts of a white, disc-shaped foraminifer (Marginopora vertebralis); (2) white coquina sand composed largely of comminuted pieces of shell; (3) gray coral rubble, worn and washed, up to 1-1/2 or 2 inches long; (4) pieces of gray or black pumice averaging from 1/4 to 1/2 inch in diameter but some as much as 5 inches, worn and rounded except where broken along fresh fractures.

The sorting of beach materials according to weight and specific gravity results in pumice being concentrated on the backshore and the other three types of sediment on foreshore beaches. The orange foraminiferal sands today dominate the foreshore surfaces of most lagoon beaches, but on Pumatahati and parts of Hare Island, coral rubble covers the surface because of special conditions responsible for strong wave action. Test trenches show that at various times the beaches of all the islands have been covered by deposits of rubble, but most of these beaches were later buried by sand as they built forward under conditions of normal wave action. Island horns or bars that are now building out into the lagoon commonly consist in part of foraminiferal sand and in part of coral rubble, the distribution of each material depending on conditions of local current and wave strength.

Table 1.-- Characteristics of lagoon beaches

Island	Width, low tide (feet)	Angle of dip toward lagoon (degrees)		
		Foreshore slope	Subcrest slope	Backshore slope
Taringa	23	5 - 11		
Parakahi	23	5 - 10	15	
Matiro	15	7	16	
Pumatahati	20	4 - 9	(Rampart 29)	
Ringutoru	26	9	15	0 - 4
Torongahai		8	20	0 - 2

Unconsolidated deposits of beach and bar that form major parts of some islands on Kapingamarangi furnish evidence that sedimentation has caused the lagoonward sides of these islands to build forward at an appreciable but undetermined rate. Beach trenches show the recent accumulation of backshore deposits over earlier foreshore sediments; test pits near the shore expose humus layers mixing with backshore deposits; wells in the interior bring to view sequences of lagoonward-dipping foraminiferal sands of former beaches. Most conspicuous of all features furnishing evidence on beach migration is the presence of relict zones of pumice, located back from the margins of some beaches and marking the backshore accumulations of earlier periods.1/

1/ Similar bands of pumice on Addu Atoll have been reported by Sewell (1936, p. 77).

Whether this aggradational process is as rapid as or more rapid than the rate of island destruction on the seaward side is not known. Presumably the rate of wearing back of land has decreased in proportion to the distance from the reef front during the current still-stand of the sea. Although the present reef flat is relatively wide in most places, there is ample evidence that erosive forces of the sea are still very effective on many of the islands. On the other hand, the rate of island building through sedimentation may be retarded as the shore moves forward into continually greater depths of the lagoon, requiring greater amounts of sediment to build up the bottom.

Seaward beaches.- Beaches are relatively scarce on the seaward sides of Kapingamarangi islands; furthermore they are small and short-lived. Most of them are perched on the bevelled surfaces of stratified island rock at various distances above low-tide level. As indicated on the geologic maps (figs. 1 to 10), few of them are continuous for long distances along the shores. It is doubtful that any of these beaches make permanent contributions to the growth of the islands.

The seaward beaches differ from the beaches on the lagoon sides of islands not only in being more patchy and far less extensive, but also in composition and color. They are formed largely from comminuted shells of mollusks and are white, in contrast to the orange lagoon beaches, which are mostly composed of Foraminifera. A small beach at the seaward end of Pungupungu Island (fig. 6) forms a coquina composed almost entirely of unbroken shells of a small pelecypod of the genus Trigonocardia.

Ramparts and rampart wash.- Accumulations of clastic debris consisting largely of coral rubble, coral heads, and limestone blocks are deposited on the borders of most islands, above wave-cut benches and beach crests, by occasional violent storms. The deposits are classified as boulder ramparts and rubble ramparts, according to their constituents, or as rampart wash where the debris has been spread out as a sheet below and beyond the inland part of the rampart ridge.

Present distribution of these surficial deposits, shown on the geologic maps of the islands (figs. 1 to 10), gives some indication of the directions

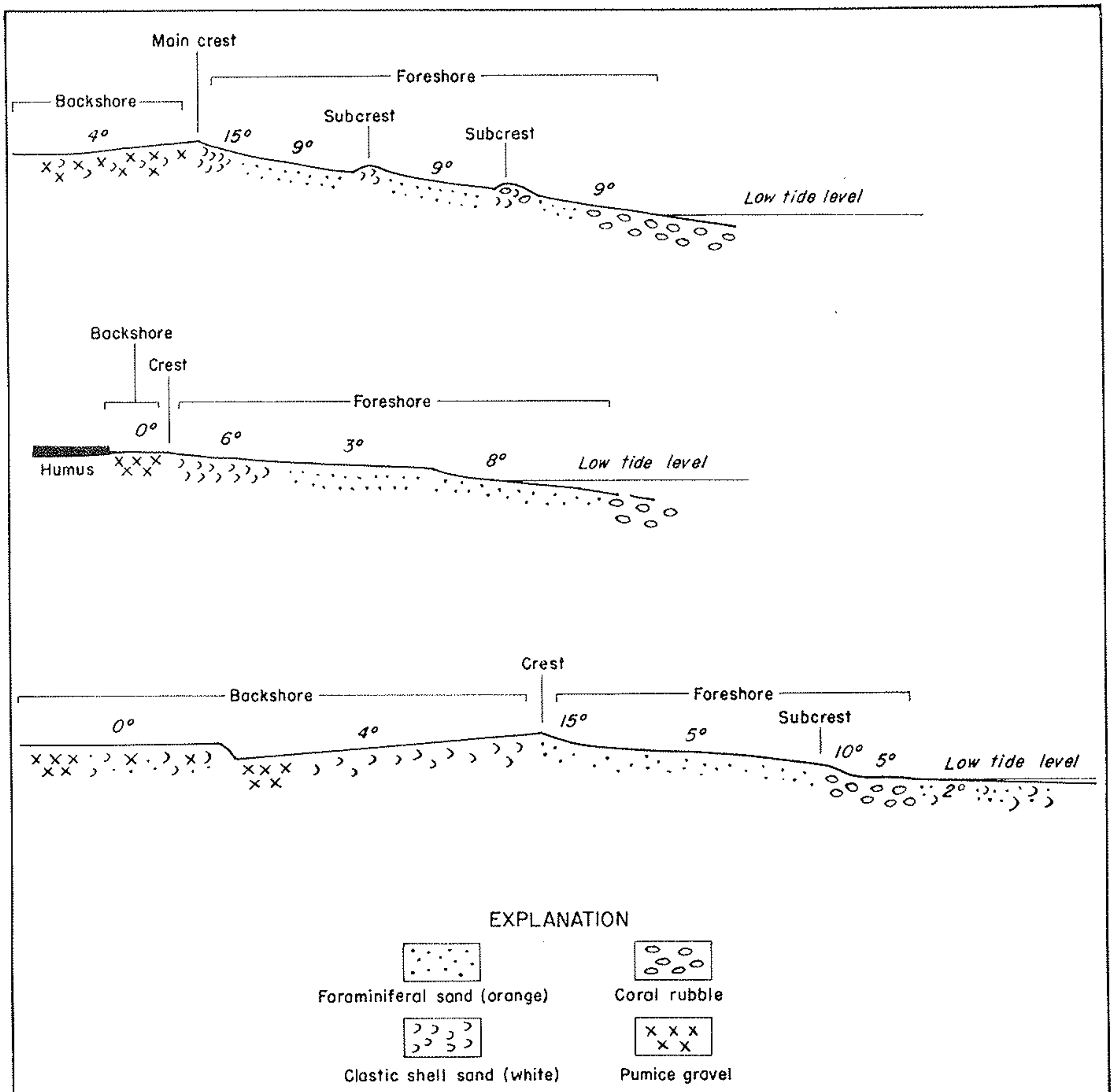


FIGURE 11.-PROFILES OF LAGOON BEACHES AND DISTRIBUTION OF BEACH SEDIMENT

0 5 ft.

of approach and the intensities of recent storms. Large islands along the northern arc of the atoll -- Torongahai, Ringutoru, and Nunakita -- all have large ramparts on both eastern and western shores. The widest are on the western sides and in these the largest blocks (36 inches in diameter on Torongahai) are concentrated near the northern ends (table 2).

Islands of the eastern arc -- Werua, Matiro, and Hare -- have ramparts on their eastern seaward sides, but these ramparts are formed mostly of fine rubble with very small areas of boulders. Individual blocks are on the average much smaller than on northern islands (table 2). On the southern arc, at Pumatahati Island, large ramparts have been formed on both seaward and lagoonward shores. The rampart to seaward consists largely of boulders; that on the lagoon side of coral rubble only. The unique development on this island of a lagoon-facing rampart must be attributed to a fetch sufficiently great to allow easterly storms in the lagoon to reach high intensity.

Rampart wash, as indicated on most of the maps (figs. 1 to 10), extends inland from the ramparts for distances as much as 250 feet, forming a surface covering of coral rubble. Because rampart wash has developed largely on the seaward sides of islands, it rests on bedrock in many places, on soil in others. Apparently it is the result of waters washing a part of the gravels and other small constituents of the rampart beyond its crest. On the northern islands especially, rampart wash covers extensive areas back from the seaward margins.

Migration of islands.- In preceding sections of this paper, geological evidence has been cited showing that the seaward sides of islands are currently being eroded back so that the outer reef flat is becoming wider at the expense of island stratified rock, and that the lagoon sides of islands are constantly growing through accumulation and deposition of beach and bar sediments. The total effect, therefore, is that of island migration across the reef, from seaward to lagoonward side. So long as sea level remains relatively stable with respect to the atoll, this process may be expected to continue, though increasing distance from the reef front causes the effective cutting power of waves to decrease, and the advance of the lagoon shore into progressively deeper waters requires more and more sedimentary material to build up a comparable amount of beach front. J. I. Tracey (written communication, July 1955) suggests that solution of rock is more effective than abrasion by waves in the retreat of islands and that wide reefs favor rapid solution. He also suggests that wide reefs may favor rapid sedimentation as they probably provide more sediment. Thus, it is not known whether or not these islands migrate at a progressively slower rate.

In addition to the evidence of island migration already given, many biological features support the thesis. One of the chief among these is the undermining of trees -- especially coconut palms -- by waves on the seaward shores. Many such trees are tilted or have fallen outward from the islands. The Kapingans are aware of the effectiveness of this process and on both Touhou and Werua Islands have constructed stone embankments along the southeast coasts to protect the land. Evidence of the recent growth of lagoon shores is found on several islands where successive lines of certain shore-fringing species of trees are now standing in the interiors, marking the sites of former shore lines. Detailed studies of the relations of island migration to plant life were made by William Niering during the summer of 1954, and results have been reported by him.

On Kapingamarangi Atoll, island migration appears to have been, in general, greatest for the northern islands and least for the southern. This is indicated not only by a greater width of outer reef flat in the north than in the south, but also by the extent to which bevelled remnants of stratified bedrock extend outward from the seaward coasts of Torongahai, Ringutoru, Nunakita, and Werua Islands (figs. 1, 2, 3, and 4). In contrast, Hare Island, on the southern part of the atoll, appears to have been relatively stable; it shows little evidence of shore recession on the seaward side and does not appear to be building out rapidly lagoonward. 1/ Its adjacent outer reef flat is comparatively narrow.

1/ Its lagoon beach probably is the type of that at Arno Atoll described by Wells (1951, p. 5) as "degrading." Much of its surface is covered by rubble concentrates, the sand having been removed, and several coconut palms growing near it are partly undermined.

Problem of Kapingamarangi beachrock.- Essentially all of the rock forming the islands of Kapingamarangi Atoll is composed of calcareous skeletal debris and rock fragments, cemented by calcium carbonate. It varies greatly in texture and in degree of cementation, some being extremely friable, some well cemented and dense. Much of it is stratified or cross-stratified, and it has all the characteristics normally attributed to beachrock. Details of its origin are not entirely clear, however, despite the numerous suggestions concerning the origin of beachrock that have been offered in the many publications on this subject.

Because modern beachrock is limited to tropical seas, its relation to warm waters appears to be beyond question. Because it develops exclusively in the intertidal zone, its relation to the rise and fall of tides seems equally definite. Other factors -- those responsible for its localization on certain beaches or parts of beaches -- are less clear. Basic requirements in the development of beachrock have recently been summarized by Ginsburg (1953, p. 88) as (1) high temperature, (2) rapid rate of beach drainage between high tides, and (3) a permanence of beach deposits sufficient to allow the cementation process to operate. The localization of beachrock is commonly explained as due to the precipitation of calcium carbonate from sea water as a result of heating and evaporation. The probable importance of blue-green algae as agents that bind sand grains together until they can be cemented has been suggested by Cloud (1952b, p. 28) and others.

As a result of observations on various Pacific atolls, a divergence of conclusions has been reached concerning the areas in which beachrock is currently developing. Ladd and others (1950, p. 416) state that on Bikini Atoll "beachrock may be formed between the reef flat and the beach." These authors refer to the fresh look of the rock and the original color of organic inclusions as evidence that lithification is going on today, but also point out that exposed parts of the beachrock are being eroded. Regarding Onotoa Atoll, Cloud (1952b, p. 28) describes "bonded limesand," which he considers to be incipient beachrock, forming on lagoon beaches, in tide pools, and in spray pools, and states that it was not found on this atoll anywhere on the seaward

Table 2.--Distribution of ramparts and rampart wash

	Island	Boulder rampart			Rubble rampart		Rampart wash	
		Location	Width (feet)	Size of boulders (inches)	Location	Width (feet)	Location	Width (feet)
Northern	Torongahai	West shore East shore	47-72 28-32	36 12	South part of east and west shores		Blanket bordering rampart	15-92
Northern	Ringutoru	North shore West shore East shore	115-164 18-77 21-54	24 6-10 6-12	Part of west shore		Southwest end borders east rampart	30-200 23-72
Northern	Rikumanu	Entire surface	100	18-24				
Northern	Nunakita	West shore East shore	22-100 31-68	12-36 6-8	South part of east and west shores		North end borders east rampart	250 32-96
Eastern	Werua	Southeast shore	57-120	24	South shore East shore	36-60 75-100	Borders east rampart	
Eastern	Matiro	Southeast shore, small area		6-24	East shore	16-40		
Eastern	Matuketuke	East end	32	6-24			Entire surface	150
Eastern	Hare	Northeast shore	42-67	6-12	East shore Southeast shore	31-100 36-45	Borders east rampart	33-85
Southern	Pumatahati	South shore	33-100	6-12	North shore	15-20	West end borders rampart	250 30-100

beach. Concerning Raroia Atoll, Newell (1954, p. 32) says that beachrock is quite rare along lagoon shores, but that it appears to be forming in "moats" in the island interiors -- behind lagoon shore ridges and, especially, back of seaward ramparts. This is probably the Cay Sandstone of British and Australian geologists.

Most of the beachrock exposed at Kapingamarangi Atoll today appears to be relatively old. This is suggested by (1) the presence of typical beds preserved as relict deposits standing above present high-tide level on several islands, (2) the bevelled remnants of typical beachrock extending seaward a few hundred feet, across the reef flat, from the present island shores, and (3) evidence of replacement of calcium carbonate by apatite in strata both in the interiors and on the shores of several islands.

Although considerable evidence indicates that active erosion dominates the seaward shores of most Kapingamarangi islands today, there is reason to believe that, locally at least, some lime precipitation is going on contemporaneously. On the reef flat near the shore of Parakahi Island a rectangle of boulders placed there by man at an unknown date has been firmly welded in place through cementation. On the east shore of Tirakaume Island, a 3-foot block of stratified limestone from an ancient outcrop of beachrock is now standing on end, incorporated in the present middle beachrock layer. How recently this development took place is not known, but it clearly shows a second stage in beachrock development. Such illustrations of recent, though local, precipitation of calcium carbonate on the seaward shores of islands are supported by records from other atolls. These include the record of a fragment of green glass from a Japanese fishnet float, embedded in beachrock deposits at Bikini (Ladd et al., 1950, p. 416) and the report of a firmly bonded gravelly sand containing brass cartridge shells on the seaward shore at Tarawa (Cloud, 1952b, p. 29).

On Kapingamarangi Atoll no development of beachrock on the lagoon shores of the islands could be detected. Although a large number of test trenches were dug across the beaches of various islands and most of the beaches were examined in connection with mapping of the islands, without exception they were found to be entirely of normal unconsolidated deposits of sand and gravel. Likewise, no clear evidence of beachrock development was found in the island interiors, for "moats" that are periodically flooded by sea water as described by Newell (1954) for Raroia do not occur at Kapingamarangi. Thus, if beachrock is forming today in appreciable amounts on the islands of Kapingamarangi, it must be on the seaward sides. Most of the rocks on these sides, however, appear to be wearing away rapidly, so it is doubtful that beachrock development is extensive there at present.

The theory that beachrock may develop by the work of ground water that dissolves calcium carbonate from lime sand and precipitates it as it seeps through the beach at low tide was proposed many years ago (Field, 1920, p. 215). Considerable evidence opposed to this idea has since been presented by Daly (1924, p. 138) and others. On the islands at Kapingamarangi, it clearly cannot apply because (1) intertidal sediments on the lagoonward margins of islands are not lithified, (2) bedrock on the seaward side rises above high-tide level and extends inland a considerable distance, and (3) no correlation between the water levels and island bedrock can be detected in the series of wells across Taringa and Werua Islands (figs. 14 and 15).

PETROLOGY

Sedimentary material that forms the atoll of Kapingamarangi is, with few exceptions, composed of calcium carbonate. Part of it is unconsolidated accumulations of clastic particles. The remainder, referred to as sedimentary rock, is lithified material developed through cementation of these clastic sediments and from the reef-building processes of corals, algae, and other organisms. For purposes of studying and mapping, principal varieties of sediment and sedimentary rock have been classified into easily recognizable types, based primarily on texture and secondarily on the major contributing organisms or rock ingredients.

Sediments.- Unconsolidated materials are separated into three groups according to particle size, following the Wentworth classification of detrital sediments. These groups are (1) lime gravel, in which particles are greater than 2 mm in diameter, (2) lime sand, in which they are between 1/16 and 2 mm, and (3) lime mud, in which they are less than 1/16 mm. Deposits of all three of these groups form significant parts of the atoll, and each accumulates in characteristic situations, as will be described later. Both lime gravel and lime sand are concentrated on the reef flats, locally forming deposits from which the islands are built. They also cover much of the lagoon floor. Lime muds, on the other hand, are confined largely to the deepest parts of the lagoon.

Two principal varieties of lime gravel are recognized. One is referred to as boulder gravel, for it contains angular blocks of reef rock, rounded coral heads, or masses of coralline algae which are of boulder (>10-inch) size. The other is formed almost exclusively of coral rubble, derived largely from broken fragments of Acropora or elk-horn coral ranging from about 1/2 to 2-1/2 inches in length. Although many mixtures or intermediate stages between these varieties of gravel exist, the importance of recognizing them as separate types is that the boulder gravel indicates the action of violent storms and accompanying large waves, whereas the much smaller coral rubble is transported also by normal waves and currents, and so is being deposited almost continuously.

Lime sands of Kapingamarangi Atoll vary according to the organisms or combinations of organisms from which they have been derived. Those of the beaches and shallow offshore waters are composed largely of the small orange foraminifer Amphistegina madagascariensis, the white wheel-shaped foraminifer Marginopora vertebralis, or both. Some beaches contain a high percentage of white fragments of mollusk shells; elsewhere beach sands locally consist of tiny, unbroken pelecypod shells forming coquinas. Some shallow-water lime sands, especially on the tops of patch reefs, include large amounts of tiny coral fragments; and in waters more than 80 feet deep, sands are formed almost exclusively of fragments of Halimeda (calcareous green algae) or of the hemispherical pale-olive foraminifer Amphistegina lessonii.

Pumice is abundant on the backshore beaches of most islands. Much of it is of granule or small-pebble size, but a few fragments are as much as 6 inches in diameter. Most of the pumice is light gray; some is black. Large specimens commonly are well rounded. This material is so concentrated on some backshores as to form essentially pure pumice layers.

Lime muds include (1) some small deposits of silt (1/16-1/256 mm) derived from shells or other organic structures and (2) extensive deposits of very fine pale-olive oozes which are sticky when wet. The silts develop largely at moderate depths in lagoon channels or other places where there are currents strong enough to gather and transport them. The calcareous oozes form only in the deepest parts of the lagoon bottom. They are composed mostly of clay-sized particles of calcium carbonate but include perhaps 10 percent of Foraminifera, largely of very small species not found in the shallower waters (discussed under "Sedimentation in the lagoon"). This calcareous ooze has high plasticity and contains a slimy residue of organic matter conspicuous for its fetid odor when wet.

The mineral composition of Kapingamarangi sediments as determined [1/]

1/ Analyses by A. J. Gude III, U. S. Geological Survey.

with X-ray diffractometer patterns shows wide variation depending upon the type of organism that dominates any particular sample (table 3). It is significant that the two common species of shallow-water Foraminifera are composed of essentially pure calcite, and the common foraminifer below depths of 100 feet, Amphistegina lessonii, is of nearly pure calcite. In contrast, corals including Acropora and other common genera are virtually pure aragonite except for a little calcite in their "dead" interior portions. Coralline algae of the genus Porolithon, which grow in abundance on the algal ridge of the outer reef, appear to be formed of calcite having a space-lattice different from that of normal calcite and interpreted by Gude as resulting from high magnesium content. Green algae of the genus Halimeda, which form important contributions to lagoon sediment below 80 feet, contain about 98 percent aragonite together with small amounts of calcite. The bottom calcareous oozes are about three-fourths aragonite and one-fourth calcite.

Sedimentary rocks.- Carbonate rocks of various types form the outer reef, parts of the islands on the outer reef, and patch reefs within the lagoon. Four mappable varieties of these rocks are recognized, based on texture and structure. These are (1) coral and coralline algal limestone, (2) aphanitic to stratified clastic limestone, (3) coral rubble limestone, and (4) boulder conglomeratic limestone. The first and second types cannot everywhere be distinguished because of recrystallization and other modifications resulting from secondary processes; the third and fourth, in many places, grade from one into the other. Nevertheless, an attempt to recognize and map these types must be made if the processes developing the atoll are to be understood.

Limestone from corals and coralline algae forms the framework of the outer reef and of the patch reefs and can be seen developing today wherever contributing organisms are growing, especially along the outer margins of the reefs. The rock developed from these organisms forms the pavement on the present bevelled reef surface. It is difficult to examine in section, however, because of its extreme resistance to breakage and because of the scarcity of exposed natural cuts into it. Samples from immediately below the pavement surface commonly show relict structures of organisms, as might be expected, but many appear aphanitic as a result of secondary processes acting on the calcium carbonate. Although hand specimens commonly appear to be low in porosity, the rock mass is cavernous and contains many cracks, some of which are filled with clastic debris.

Aphanitic to stratified clastic limestone forms an appreciable part of the bedrock on all islands and occurs in many places on the reef flats as pedestals and raised ridges considered to be relicts of former islands. Where the rock is aphanitic, little can be determined concerning its origin. Where planes of stratification remain or are etched out on weathered surfaces and characteristics of grain are preserved, however, the history of the rock can readily be determined. Dips of cross-strata and other characteristics show close similarity to features of the unconsolidated deposits of island beaches.

Boulder conglomeratic limestone and coral rubble limestone are major constituents of most islands on Kapingamarangi Atoll and form conspicuous ledges and shelves along many of the seaward shores. The limestones are easy to recognize because the gravel within the lime matrix normally weathers into prominence and, in some places, is extremely conspicuous because of color contrasts. Boulder limestone includes angular blocks of reef limestone, rounded coral heads, and masses of coralline algae of many sizes and shapes similar to those in modern boulder ramparts. The coral rubble limestone is formed entirely of small rubble in a lime matrix. These clastic limestones are distinguished in mapping, as are their nonlithified equivalents, because of the different origins that they imply.

The varied mineralogy of different limestones on the atoll doubtless is in part due to secondary processes of recrystallization and replacement. Many of the differences, however, are directly attributable to differences in the source materials. Foraminifera of which some rocks are composed are calcitic, corals in other rocks are aragonitic, and algal deposits in still others are high in magnesium (table 3). Therefore, fundamental genetic differences may account for the different compositions of many of these youthful limestones.

On a few islands phosphorite rather than limestone locally forms stratified rock. Phosphorite, presumably developed from the guano of sea birds through replacement of calcium carbonate, occurs on parts of Pumatahati, Nunakita, and possibly a few other islands. It is an earthy, light-colored rock resembling the local limestone in texture and structure, but commonly lighter in weight owing to high porosity. Mineral studies by Gude with X-ray diffraction patterns show that in some specimens the entire rock is composed of a variety of apatite.

Table 3.- Mineral composition of Kapingamarangi sediments as determined by X-ray diffraction patterns

Locality	Horizon (feet)	Description	Aragonite	Calcite A	Calcite B*
Lagoon, W. of Matiro	228	Calcareous ooze	80		20
Lagoon, W. of Romia	150	Calcareous ooze	60		40
Lagoon, W. of Sokoro	216	Calcareous ooze	70		30
Lagoon, W. of Tetau	224	Calcareous ooze	80		20
Lagoon, Tokahui	186	Sand (_A. lessonii_)		100	
Lagoon, Tokolala	90	Sand (_Halimeda_)	98		2
Lagoon, Matamatong	5	Coral branch	99		1
Lagoon, Matamatong	5	Core of coral	95	5	
Reef flat, Touhou		Algal crust (_Porolithon_)			100
Reef flat, Touhou		Algal crust (_Janea_)			100
Beach, Pungupungu		Sand (shell fragments)	95	5	
Beach, south reef		Sand (_A. madagascariensis_)		100	
Beach, south reef		Sand (_Marginopora_)			100
Beach, Matukerekere		Clastic coral, weathered	10		90

*Calcite A is interpreted as normal calcite; calcite B as magnesian calcite.

SOILS

General statement.- Soils of Kapingamarangi Atoll are necessarily young: the islands on which they occur are of recent origin. Most of the soil profiles are classed as A-C profiles and consist of materials little altered from the parent rock or sediment, covered by or mixed with varying amounts of dark humus. The soils show few features of well-developed horizons such as normally result from long periods of decomposition of varied source materials.

Kapingamarangi soils characteristically are well drained and alkaline. They are largely mechanical mixtures of organic material and gravel, sand, or fine calcium carbonate particles. They vary from dark brown to gray and creamy white, according to the proportions of various constituents. Soil profiles all have dark layers at the top and light-colored bedded rock or sediment below, but some layers are separated by transition zones of intermediate color and composition, whereas others are marked by abrupt change.

In order to obtain quantitative data on the soils of Kapingamarangi Atoll, soil profiles were measured and samples for analysis were collected from eight wells, dug in connection with ground-water studies, and from eight test pits. These profiles were distributed on seven islands as follows: Werua 3, Taringa 3, Parakahi 1, Pumatahati 3, Ringutoru 3, Tokongo 1, Rikumanu 1. Conclusions resulting from studies of the soil profiles and of the analyses of samples constitute the basis for most of the following discussion on soils.

Parent materials of soils.- The simplicity of soils on the islands of Kapingamarangi stems, for the most part, from the fact that they are formed almost entirely from only two basic ingredients -- (1) parent rock or sediment composed of calcium (and some magnesium) carbonate, and (2) humus from vegetable matter. The carbonate material varies considerably in physical form. Much of it is limestone which makes up all the bedrock; the rest of it occurs as unconsolidated sediment including gravel, lime sand, and lime mud. Large clastic fragments include blocks broken from the reef, coral heads, and masses of coralline algae. Small gravel is almost entirely coral rubble. Lime sand consists of shell fragments and tests of Foraminifera, with local contributions of the alga *Halimeda* and other organisms. The lime mud appears to be principally from the decomposition of stratified rock or of limestone blocks. All these clastic materials mixed with humus are relatively little decomposed even though they are in an area of prevailing warm, humid climate. This indicates that the soil is very youthful.

Variations in the soils of Kapingamarangi are in part due to differences in the amount of original contamination and in downward filtration of vegetable carbon into the calcareous host materials. High permeability of much of the sediment, allowing rain water to enter readily, the penetration of roots as found in most test pits, and the work of various animals all contribute in varying degrees to downward mixing. In some places a "transition" zone (A_3 horizon) in which small percentages of carbonaceous matter are mixed with coral rubble or lime sand has developed below the normal zone of incorporated organic matter (A_1 horizon) to a distance of 12 to 15 inches. In other places no "transition" zone is present.

Appreciable variations in the chemical character of the island soils (table 4) were not detected in the present study. In general, the youthfulness of the parent limestone virtually precludes the possibility that any appreciable concentrations of noncarbonate minerals have developed through leaching or decomposition. On the other hand, local additions to the soil may consist of pumice, bird guano, shells of crustaceans and echinoids, or skeletons of fish; the overflows of sea water possibly have affected the soil in some places. Backshore beaches composed largely or entirely of pumice (table 5) are present on the lagoon sides of several islands, and some pumice has been found in test pits, but its influence on vegetation in general is not known. Bird guano has contributed to the local development of phosphatic soil on some islands, especially Pumatahati, where according to native reports many frigate birds formerly roosted. Salts from sea water and sea spray that locally make soils highly saline have not left any conspicuous record of salt crusts, probably because evaporation is low as compared with contributions of fresh water; the salts do not seem to have affected large areas.

Alteration processes.- Factors conspicuous in bringing about the alteration both of soils and of the parent materials of soils on Kapingamarangi Atoll include those that remove substances, those that add substances, and those that mix substances. In the first category, one of the most important factors appears to be rain. Showers on the islands normally are short but violent, and permeable surfaces allow most of the water to enter readily with a flushing effect that probably accounts for the general lack of saline residues. Also significant is the abundant evidence of solution work in limestone beds, probably largely the result of carbonic acid from plants, which enables the migrating waters to dissolve carbonates.

At the low levels in the centers of some islands, especially where pits for growing puraka 1/ have been excavated by the natives, ground water reaches the soil level and, locally, appears at the surface of the ground. Where this occurs, normal oxidation of organic matter is retarded or stopped by the water and black mucks develop. The fresh-water lens, moving up and down in response to tidal fluctuations, apparently has a considerable solvent effect on calcium carbonate in the soil wherever it comes within range, as shown by the calcium bicarbonate content of water samples from the wells.

Extraneous but significant elements in the soil include nitrogen, added by legumes and some types of algae. Calcium carbonate introduced through evaporation does not seem to be important, for no caliches such as occur in arid or semiarid regions were observed, and fresh water above the water table appears to be removing rather than contributing calcium carbonate.

A process that is especially important in the forming of soils through the mixing of materials is the burrowing of certain animals. Especially

1/ A plant with a tuberous, starchy root, related to the taro.

conspicuous are holes resulting from the activities of land crabs. Systematic studies of the distribution and effects of these animals on several islands were made by William Niering of the 1954 Pacific Science Board party. Probably also important though less apparent are the borings of earth worms; observations on the distribution of these were also made by Niering. The effects of roots in penetrating and breaking up soil materials were seen in the sides of all wells and test pits. Roots are effective only in the upper 1 or 2 feet of soil and sand, however, for their abundance and size diminish rapidly with depth. Only a few were observed as deep as 4 feet.

Relation of soil to position on island.- Because seaward and lagoonward parts of most islands on Kapingamarangi Atoll differ considerably in age, the stage of soil development on each side likewise is varied. On large and medium-sized islands the seaward sides are composed largely of limestone bedrock, believed to be relict from deposits of a former and higher stage of sea level, overlain in most places by rubble. In contrast, the lagoon sides of these islands are formed of relatively recent beach and bar deposits such as are developing today along the lagoon shores.

Excavations representative of the seaward and lagoonward sides and the centers of islands demonstrate the differences in their soil profiles. Wells and pits located approximately 100 feet from the lagoon beaches of Ringutoru, Taringa and Werua Islands show soil layers of $2\frac{1}{2}$-, 2- and 5-inch thickness, respectively (figs. 12, 14 and 15). Soil layers measured near the centers of the same islands are 8, 11 and 15 inches thick, and on the seaward sides 8, 14 and 32 inches. Small islands like Rikumanu and Tokongo, composed largely of bedrock from an earlier stage of sea level, probably correspond in age to the seaward portions of the larger islands. Commensurate with this age, soil layers of 29 inches on Rikumanu, and 18 and 7 inches on Tokongo were noted in test pits (fig. 13).

Buried profiles occur on the seaward sides of at least three islands and may be expected on others in corresponding positions. On Ringutoru, Taringa, and Werua (Figs. 12, 14 and 15) the soil profiles include a relatively thin upper layer of dark-brown soil, separated from a lower, much thicker soil by 9 to 24 inches of light-gray sediment, including sand, coral rubble, and small amounts of humus. This light-colored layer is interpreted as representing an interruption in the soil development process, during which time waters deposited clastic sediments. It is postulated that this deposition was a result of sheet wash at a time of storm activity. Much sand and some rubble, but no very coarse materials, are included. Judging from the appreciable thickness of the overlying layer of soil (4-9 inches), which is comparable to that of the entire soil layer on the other side of the island, and from the fact that buried profiles have not been found on the lagoon sides of any islands, a period longer than that required for development of the present lagoon side is considered probable for this interruption in soil formation. Thus, although the buried profile may be the result of some recent storm, more likely it dates back to the time of an earlier sea-stand.

Extremely youthful soil occurs locally where two islands have, within historic times, become joined through sedimentation resulting from causeway

Table 4.- Elements in Kapingamarangi soils determined by semiquantitative spectrographic method. Analyses by Paul Barnett, U. S. Geological Survey. Elements reported by percent ranges.

Well	Depth (inches)	Si	Al	Fe	Ti	Mn	P	Ca	Mg	Na	B	Ba	Cr	Cu	Pb	Sr
Werua #5	4	.01 .02	.02 .05	.1 .2	Not found	.002 .005	2 5	>10	.1 .2	.2 .5	.001 .002	.01 .02	.0005 .001	.001 .002	.0002 .0005	.5 1.0
Werua #5	20	.002 .005	.002 .005	.005 .010	Not found	.0002 .0005	.5 1.0	>10	.5 1.0	.2 .5	.001 .002	.0005 .001	.0002 .0005	.0001 .0002	Not found	.5 1.0
Werua #5	31	.01 .02	.01 .02	.02 .05	Not found	.0002 .0005	Not found	>10	.5 1.0	.2 .5	.001 .002	.002 .005	.0002 .0005	.0002 .0005	.0002 .0005	.5 1.0
Taringa #2	5	<.01	.02 .05	.05	<.005	.002 .005	5 10	>10	.1 .2	.2 .5	.001 .002	.002 .005	.0002 .0005	.0005 .0010	0	.2 .5
Taringa #2	20	<.01	.002 .005	.002 .005	<.005	0	0	>10	.2 .5	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0005 .0010	0	.5 1.0
Taringa #2	39	<.01	.002 .005	.001 .002	<.005	0	0	>10	.2 .5	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0002 .0005	0	.5 1.0
Taringa #2	55	<.01	.002 .005	.005 .010	<.005	.0002 .0005	0	>10	.5 1.0	.2 .5	.001 .002	.0005 .0010	.0005 .0010	.0002 .0005	0	.5 1.0
Taringa #3	2	<.01	.002 .005	.002 .005	<.005	.0005 .0010	0	>10	.2 .5	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0005 .0010	0	.5 1.0
Taringa #3	8	<.01	.002 .005	.001 .002	<.005	0	0	>10	.5 1.0	.2 .5	.002 .005	.0005 .0010	0	.0002 .0005	0	.5 1.0
Taringa #3	18	<.01	.01 .02	.01 .02	<.005	.0005 .0010	2 5	>10	.2	.2 .5	.001 .002	.002 .005	.0005 .0010	.0005 .0010	0	.5 1.0
Taringa #3	34	<.01	.002 .005	.002 .005	<.005	0	0	>10	.5 1.0	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0005 .0010	0	.5 1.0

The following elements were also looked for but not found:

Sensitivity limit	Elements
.00005	Ag
.0001	Be, Yb
.0005	Co, Ge, Ni, Pd
.001	Bi, Ga, In, Mo, Nb, Sn, V, Y, Zr
.003	Au, Pt
.005	Cd, Er, Gd, Ir, La, Os, Re, Rh, Ru
.01	Li, Nd, Sb, Sm, Tl, W
.03	Te, Zn
.05	As, Ce, Dy, Hf, Ta, Th, U
.5	K
1.0	Hg

Table 5.- Pumice analyses; elements determined by semiquantitative spectrographic method. Analyses by Paul Barnett, U. S. Geological Survey. Elements reported by percent ranges.

Element*	Gray pumice Matukerekere	Black pumice Hare Island	Element*	Gray pumice Matukerekere	Black pumice Hare Island
Si	> 10	> 10	Cr	.0001-.0002	.0001-.0002
Al	> 10	> 10	Cu	.0005-.0010	.001-.002
Fe	2.2-4.6	1-2	Ga	.0005-.0010	.0005-.0010
Ti	.2-.5	.2-.5	La	.005-.010	.005-.010
Mn	.05-.10	.05-.10	Mo	.001-.002	.001-.002
Ca	1-2	1-2	Nb	.005-.010	.005-.010
Mg	.5-1.0	.2-.5	Nd	.005-.010	.005-.010
Na	1-2	1-2	Pb	.0002-.0005	.0002-.0005
K	1-2	1-2	Sc	.0005-.0010	.0005-.0010
B	.001-.002	.001-.002	Sr	.05-.10	.02-.05
Ba	.05-.10	.05-.10	V	.001-.002	.001-.002
Be	.0002-.0005	.0001-.0002	Y	.005-.010	.005-.010
Ce	.01-.02	.01-.02	Yb	.0005-.0010	.0005-.0010
Co	.0002-.0005	.0002-.0005	Zr	.02-.05	.02-.05

*The following elements were looked for but not found: Ag, As, Au, Bi, Cd, Dy, Er, Gd, Ge, Hf, Hg, In, Ir, Li, Ni, Os, P, Pd, Pt, Re, Rh, Ru, Sb, Sm, Sn, Ta, Te, Th, Tl, U, W, Zn.

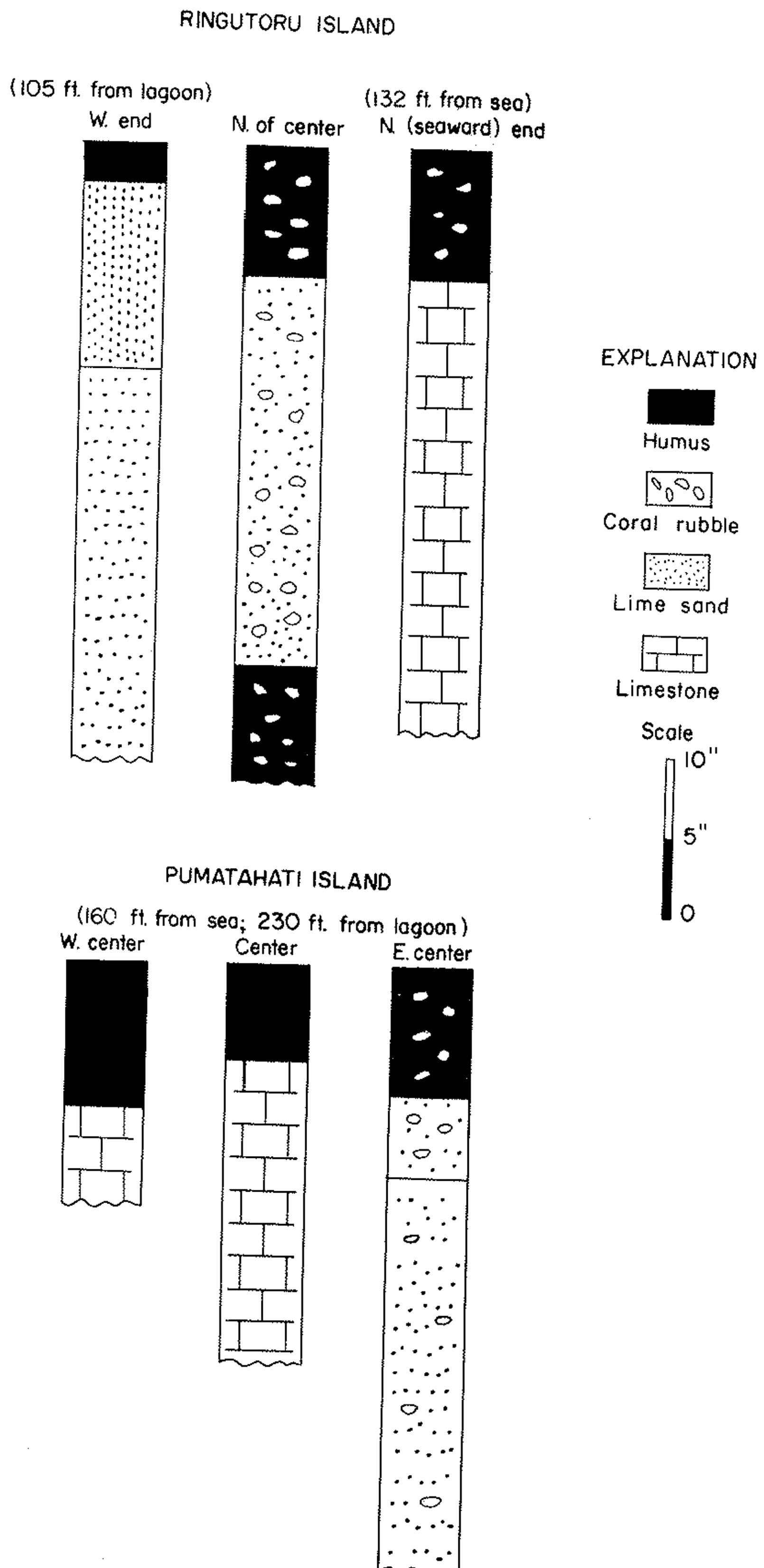


FIGURE 12 – TYPICAL SOIL PROFILES IN TEST PITS ON RINGUTORU AND PUMATAHATI ISLANDS

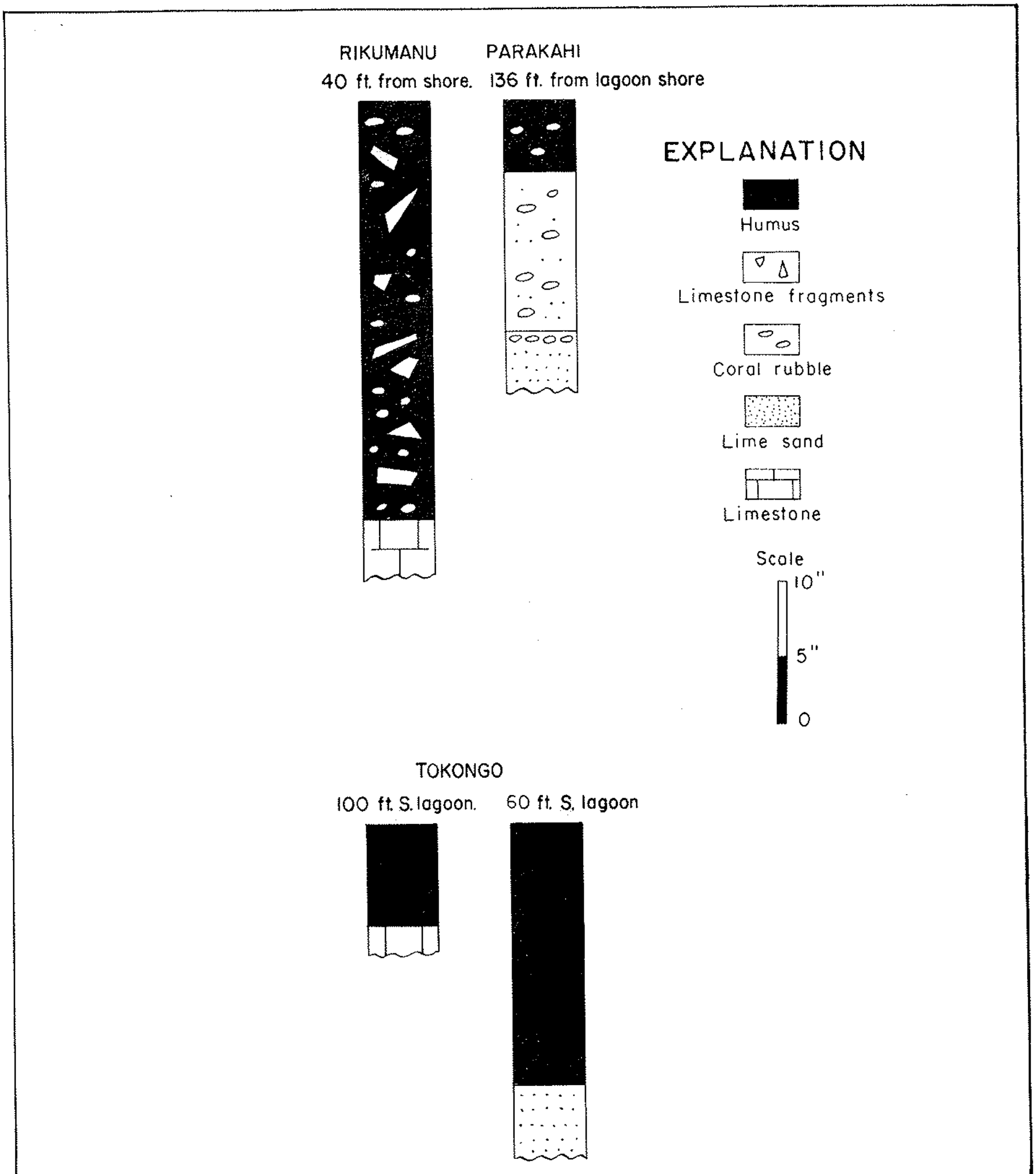


FIGURE 13.— TYPICAL SOIL PROFILES IN TEST PITS ON RIKUMANU, PARAKAHI AND TOKONGO ISLANDS

construction. Several illustrations of this process, in various stages of development, are known; and the natives are fully aware of the possibilities of increasing the size of their islands by this method. One of the best examples of sedimentation resulting from the process is near the south end of Hare Island, where a small islet has been attached and completely incorporated into the main island (fig. 8). Remnants of a stone causeway about 150 feet long are still visible in the middle of the area though sediments have accumulated to a considerable height on both sides of it. Seaward from the causeway an area about 300 feet long has been entirely filled in by natural processes, locally with sand and elsewhere with mixed sand and rubble. Soil has not yet developed. On the lagoon side sand and rubble have been piled up on the shoreward part, leaving a depressed area inland toward the causeway; this low area is swampy and already has accumulated some black sticky mud.

According to soil nomenclature used on other atolls of the Pacific (Stone 1951, p. 19-37), most of the soil at Kapingamarangi probably should be classed as belonging to the "Shioya soil series." This is especially true where the soil has developed in the very young sediments on the lagoon sides of islands. In some places on the older, seaward parts of islands, development has gone beyond the Shioya stage and greater, more concentrated accumulations of organic material have resulted in a darker soil which perhaps should be assigned to the "Arno soil series." In these two soil types there is great textural variation both vertically and laterally. Such variations, as shown in test pits (figs. 12 to 15), include organic materials that are relatively pure and others that are mixed with lime sand, coral rubble, or limestone blocks. Because nearly all the soils are developed on surfaces above the water table that allow rain water to pass through rapidly and that are conducive to relative dryness, mangrove swamps do not exist and muck or peat is scarce. Only puraka pits and a few bomb craters where water accumulates permanently have an environment favorable to these soils.

Many illustrations of correlations between plant indicators and types of soil and sediment are apparent on Kapingamarangi. The constant association of Scaevola with sandy beaches and of Guettarda with coarse rubble ramparts or with small islets covered by rubble are examples. This subject has been studied in detail by William Niering and will be described by him.

DEVELOPMENT OF PHOSPHORITE

Phosphatic soils and rock phosphate or phosphorite occur at numerous places on various islands of Kapingamarangi Atoll. The soils appear to be very similar to other soils that are composed of lime sand and humus, but X-ray diffraction tests show that mineralogically they contain apatite in addition to calcite and aragonite and that a few samples consist of apatite only. The phosphorite or rock phosphate resembles in texture and structure the limestone from which it developed, but commonly it is very light in weight owing to high porosity. In many places it is various shades of brown, and in general has a powdery, earthy appearance.

The origin of the phosphorite from the guano of birds is attributed to phosphorization of salts in the guano, involving reactions with foraminiferal or coral limestone. According to Aso (1953, p. 19) the principal components of this type of phosphate normally are secondary calcium phosphate, $CaHPO_4$; tertiary calcium phosphate, $Ca_3P_2O_8$; and calcium carbonate, present in varying ratios. Thus, the phosphate probably represents a stage intermediate between fresh guano and tertiary calcium phosphate, the conversion taking place under the influence of organic acid and carbonic acid gas. The ease with which calcium carbonate is dissolved by phosphatic solutions is a significant factor in this process (Aso, 1953, p. 17).

The distribution of phosphatic soils and phosphorite at Kapingamarangi and the concentration of these products (table 6) appear to have a significant relationship to the history of island development. At Pumatahati Island, test pit 1 near the island center shows complete phosphorization of limestone in both soil and stratified rock to a depth of 2 feet or more (table 6). Test pit 2, farther east on the same island, shows only a little apatite present, and that is near the surface. Nevertheless, the fact that surface soil is affected in both places suggests recent development. High concentration in the central area is expectable, for this island is reported by the natives to have been the roosting place of large numbers of frigate birds for many years.

Varying concentrations of phosphatic soil are recognized on several islands other than Pumatahati. These include Taringa (table 6) and Werua (table 4) and probably others for which analyses have not been made. The localization of apatite near the soil surfaces on these islands suggests that its development may be relatively recent. Phosphorite comprising the stratified rock on several other islands, however, clearly is of considerable age, i.e., formed before the islands had migrated to their present positions. On Ringutoru and Rikumanu, for instance, high-level remnants of stratified rock considered to antedate the latest fall in sea level, and standing above areas of soil on the island margins, are highly phosphorized. On Hare, Nunakita, and Rikumanu, stratified rock that today is on the seaward shores, beyond the outer fringe of vegetation, and is periodically covered by high-tide waters, likewise is high in apatite (table 6). These deposits are interpreted as relicts from a time when they were in island interiors, such as the frigate birds inhabit today, and when birds in numbers frequented the areas.

GROUND WATER

General features.- The presence on most small islands of fresh or brackish ground water floating on the relatively heavy salt water within island rocks and the lens shape normally assumed by such bodies of fresh water have long been recognized by hydrologists. The name "Ghyben-Herzberg lens" commonly is used in referring to these lenses of fresh water (Stearns and Vaksvik, 1935, p. 237-239).

Most of the islands on Kapingamarangi Atoll contain ground water of varying degrees of freshness. On the larger islands this water is potable

Table 6.- Percentages of apatite as determined by X-ray diffraction analyses. Data from James Gude, U. S. Geological Survey.

Island	Stratigraphic Position	Depth (inches)	Apatite (percent)	Comments
Ringutoru	High-level remnant	0	50	Relict bedrock.
Rikumanu	High-level remnant	0	75	Relict bedrock.
Rikumanu	Stratified shore deposits	0	20	Relict bedrock.
Rikumanu	Stratified shore deposits	0	40	Relict bedrock.
Nunakita	Stratified shore deposits	0	30	Relict bedrock.
Hare	Stratified shore deposits	0	20	Relict bedrock.
Pumatahati	Soil, top	3	100	Pit 1, near island center.
Pumatahati	Upper bedrock	8	100	Pit 1, near island center.
Pumatahati	Lower bedrock	20	100	Pit 1, near island center.
Pumatahati	Top soil	4	2	Pit 2, eastern interior.
Pumatahati	Transition soil	11	2	Pit 2, eastern interior.
Pumatahati	Unconsolidated	22	0	Pit 2, eastern interior.
Taringa	Top soil	5	50	Well 2, near island center.
Taringa	Transition soil	25	0	Well 2, near island center.
Taringa	Coral rubble	40	0	Well 2, near island center.

and of sufficient quantity for domestic use. The natives have dug wells penetrating it in a number of places, but in general they prefer cistern water for drinking. This is fortunate, for the wells near the places of habitation are apt to be polluted. In the village on Touhou, water from the community well is used largely for washing purposes; much of it is carried in buckets to bath houses but some is used in the immediate vicinity.

Because of drouths the supply of cistern water becomes low from time to time and locally is exhausted. At such times the ground water of the islands constitutes an important supplementary supply of potable water. Factors that control the location, quality, and amount of this water are similar to those that have been described in connection with the ground water of other atolls (Cox, 1951; Arnow, 1954), but distinctive features of climate, lithology, and terrain are responsible for local variations and make desirable an analysis of the local water problems.

Objectives of investigation.- Ground-water studies on Kapingamarangi Atoll, made periodically during June, July and August of 1954, were conducted on four islands -- Taringa, Werua, Parakahi, and Hukuniu. These islands were selected partly because of accessibility but largely because they were considered representative of the principal island types. Taringa is an example of a moderately long but narrow (600 ft.) island with stratified rock forming the seaward shore and sand beaches the lagoon shore. Werua is similar but considerably wider (1000 ft) and with more variation in topographic character resulting from larger size. Parakahi is a small island (400 ft x 300 ft) the surface of which is formed entirely of unconsolidated sediments. Hukuniu is a very small island (250 ft x 150 ft) in which stratified rock forms all of the shores and also the surface, except for a thin mantle of humus in the interior.

The principal objectives of the ground-water investigation were to obtain data on (1) the depth to water in various parts of the islands, (2) the amount of change in water level as compared with tidal changes in adjoining sea and lagoon, (3) the amount of lag between the extremes of tide and the corresponding changes represented in well levels, (4) the effects of permeability in different types of rock and in unconsolidated sediment, (5) the variations in ground-water lenses resulting from differences in size of islands, and (6) the quality of the water resulting from various situations. All these features have a close relationship to the availability and usefulness of ground-water on Kapingamarangi.

Methods of study.- A series of eight wells -- three on each of the large islands and one on each of the small islands -- were dug by native labor to a depth below the lowest level of the water table for each area involved. Records were made of the types of sediment penetrated (figs. 14 and 15) and a staff gage was installed in each well for measuring water fluctuations. Three times during the summer hourly readings were made for 24-hour periods to obtain from this series of wells relative measurements of the times and extent of water fluctuations. Some water samples were analyzed in the field for salinity and pH. Others, representative of all the wells, were brought back to the U. S. Geological Survey in Denver, where analyses were made by John D. Hem.

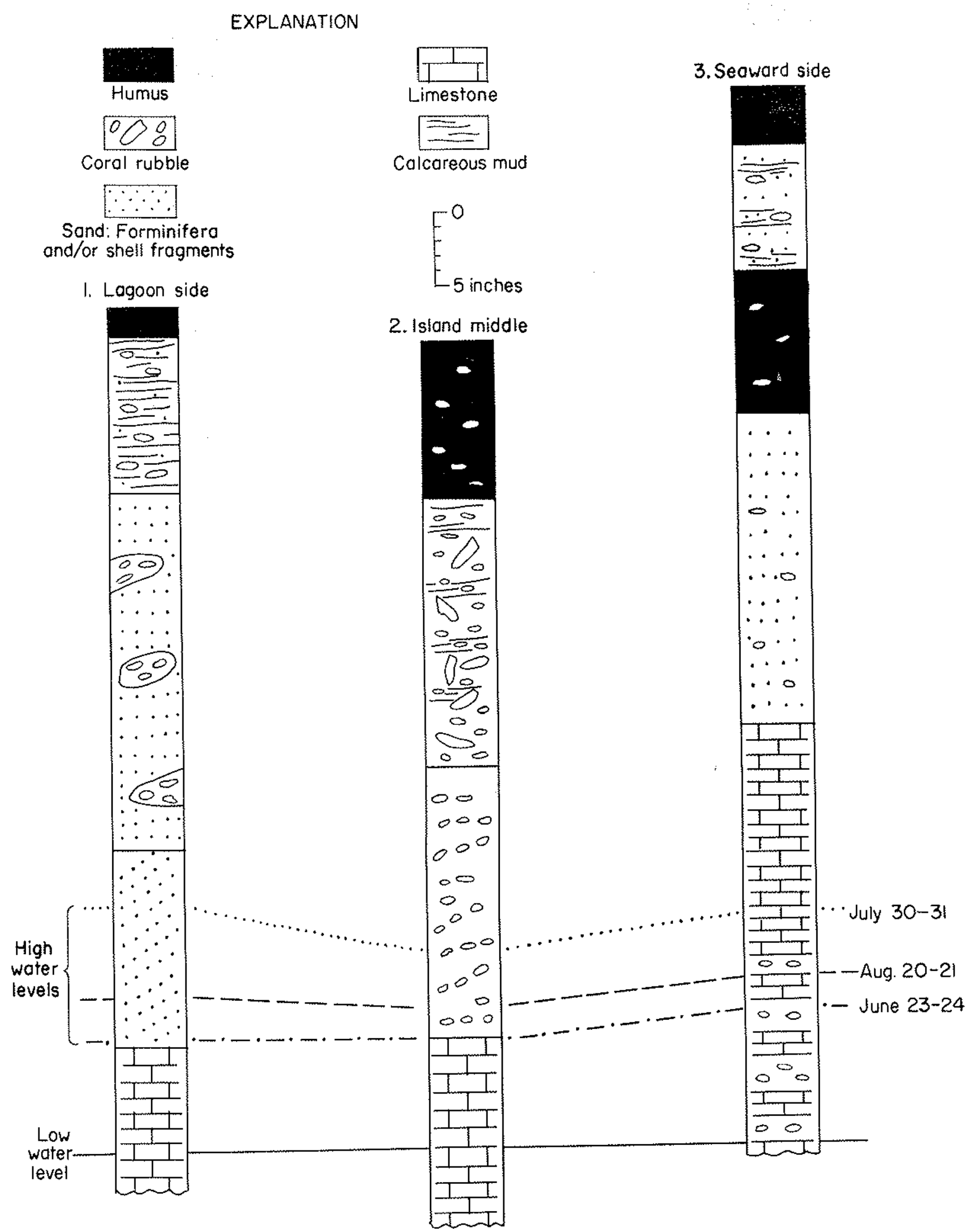


FIGURE 14– LITHOLOGY AND WATER LEVELS IN WELLS ON TARINGA ISLAND

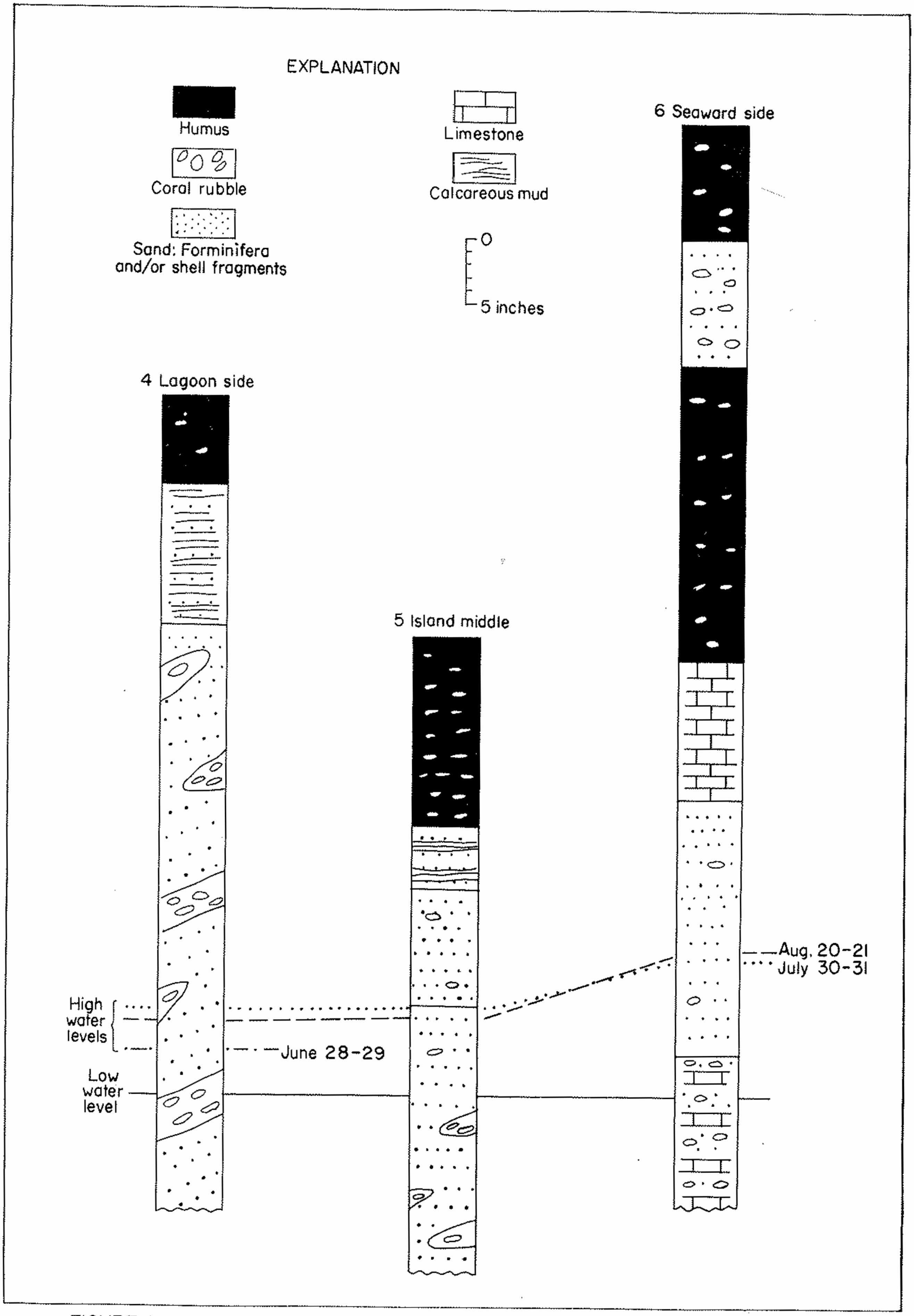


FIGURE 15 – LITHOLOGY AND WATER LEVELS IN WELLS ON WERUA ISLAND

The wells on both Taringa and Werua Islands were dug in a row across the islands from west (lagoon shore) to east (seaward shore) and about midway along the length (north-south dimension) of each island. Locations of wells are shown on maps (figs. 4 and 5). The spacing of the three wells relative to the coasts on these islands was as follows:

	Lagoon to well 1	Well 1 to well 2	Well 2 to well 3	Well 3 to sea
Taringa	68 ft	250 ft	160 ft	125 ft
Werua	65 ft	500 ft	300 ft	125 ft

The single wells on the two small islands were dug near the centers. Locations were as follows:

	From lagoon (W) side	From sea (E) side	From north side	From south side
Parakahi	136 ft	288 ft	145 ft	156 ft
Hukuniu	100 ft	164 ft	91 ft	54 ft

The wells on Taringa and Werua Islands ranged in depth from 4 feet 2 inches to 7 feet 1 inch, depending on the depth to ground-water at its lowest stage. The two deepest wells were those adjacent to the seaward coast. They were not located on boulder ramparts but on lower ground inland from the ramparts. These wells were the most difficult to dig, for stratified rock was encountered in each a little more than halfway down.

Depth to ground water.- As stated in the Ghyben-Herzberg principle, the highest part of the fresh-water lens within the rocks of most small islands is somewhat higher than sea level adjacent to the island. Because the ratio of fresh- to salt-water density that controls this lens is approximately 40/41, it follows that the elevation of fresh water above sea level is slight on islands the size of those on Kapingamarangi. Cox (1951, p. 22) and Arnow (1954, p. 3) show that an average height of about a foot is to be expected on the islands that they examined in different parts of the Marshall group.

Equipment was not adequate to measure the elevation of ground-water lenses with respect to sea level at Kapingamarangi. It seems safe to assume, however, that the elevation on any of those islands does not exceed 10 to 12 inches and in most places is far less. Thus, the water level on those islands may be regarded as roughly equal to sea level, and the depth to water in any well is approximately equal to the elevation above sea level of the surface at the well site. Because the lagoon margins of islands commonly are slightly higher than the island centers and because the seaward margins are considerably higher than the lagoon margins, the depth to ground water normally is greatest near the seaward margins of the islands and least near the centers. Figures 14 and 15, using low-water level as a datum plane (not allowing for the increase in elevation in the island center that results from the lens effect of the fresh water body), show the following depths to the highest recorded water level:

	Lagoon side	Middle island	Seaward side
Taringa	43 inches	43 inches	58 inches
Werua	48 inches	29 inches	66 inches

The figures in the preceding table probably are representative of depths required to reach the upper limits of water on all the larger islands at Kapingamarangi, but to reach the level of permanent water (low-water level) an additional 8 to 12 inches is required. Further, if wells are to be used for domestic purposes, allowances must be made for normal drawdown, for lowering due to periods of little recharge and for adequate storage, so additional depth is necessary. The depth should not be greater than necessary to achieve the above objectives, however, or salt-water contamination of the wells may occur.

On the very small islands at Kapingamarangi, the water table commonly is closer to the surface than on Taringa and Werua. This is due to lower topography. However, the amount of fresh water (if present at all on these small islands) normally is much less and the degree of salinity higher than on islands with large recharge surfaces, as shown by the wells on Parakahi and Hukuniu Islands.

Variations in water level.- Fluctuations in water level in islands like those of Kapingamarangi Atoll are principally of two types. In one the changes are gradual and are the result of increases or decreases in the amount of recharge; in the other the movement is observable from hour to hour and results from rising and falling tides that cause the salt water under the fresh water lens to go up or down. Fluctuations due to gain or loss in recharge were not detected during the period spent on Kapingamarangi Atoll, though doubtless such changes were continuously affecting the water levels of all islands, especially the very small ones. On the other hand, significant data were obtained on the effects of tide on ground-water levels.

Figures 14 and 15 show the total rise and fall of water levels in the wells on Taringa and Werua Islands, respectively, as shown by readings taken on June 28, July 30, and August 20. The low-water level for each well, as measured with respect to the well bottom, was essentially the same for the three dates. The high-water levels, however, show marked differences, especially on Taringa, and these differences are directly related to tidal fluctuations as indicated by tide records. The amount of rise in the two wells located in island centers is slightly to moderately less than that of the wells on the corresponding island margins. This difference undoubtedly results from incomplete readjustment of the fresh-water lens, due to increased friction from distance of travel, during the short intervals between tidal changes. It supports the principle, pointed out, for example, by Cox (1951, p. 14), that fluctuations in the water table of small islands are inversely proportional to distance from the coast.

Lag in rise and fall of ground water.- The elapsed time between attainment of high or low stage by the tide in waters adjacent to an island and the attainment of a corresponding high or low level by the ground waters in the island is variable according to the size of the island, the permeability of rock or sediment involved, and other lesser factors. In any event, this elapsed time is represented by a definite lag, which on Taringa Island was 3 to 4 hours and on Werua 4 to 5 hours (figs. 16a, 16b, 16c, 17a, 17b, 17c). On the small island of Hukuniu, however, there was virtually no lag between the time of high tide and high-water level (fig. 18a and 18b). This is interpreted as primarily the result of high permeability, as will be discussed later, rather than merely the small size of the island.

Analysis of the charts showing tide and well fluctuations (figs. 16, 17, 18) shows that the lagoon tidal variation is consistently greater than the variation on the seaward side of the islands, but that in the areas studied, the high and low tides arrive in both places at about the same time. Water levels in the wells on each island likewise show differences in amount of fluctuation, but on each island they reach their peaks at approximately the same time. These data suggest that differences in permeability as well as in distances from the shore and in tidal fluctuation at the shore are responsible for differences in the amount of rise and fall of the water table in any particular part of an island. Thus, in these small islands the fresh-water lens acts as a unit insofar as the time of rise and fall is concerned.

Relative permeability of sedimentary materials.- An asymmetry in the permeability of atoll islands has been indicated in the work of numerous geologists (Cox, 1951, p. 19). In most islands the lagoon shores are composed of beach sands, whereas the seaward shores are composed of stratified rocks, boulder ramparts, or both. The fine-grained sediment of the lagoon side is far less permeable than the coarse detrital fragments of the rampart or the cavernous limestone that constitutes much of the stratified rock. Fluctuations in water table on atoll islands appear to be proportional to the permeability of the sediment or rock through which the water moves.

On the islands of Taringa and Werua the seaward coasts are formed of stratified rock up to and above high-tide level and of narrow boulder ramparts above the rock. The ramparts are not significant insofar as the movements of the fresh water lenses are concerned, for, as illustrated in well profiles, all of the ground-water movement on this side of the islands is within the stratified rocks. Furthermore, water from wells on the seaward side is definitely brackish, mostly not potable, which suggests that it enters through open cavities or cracks with free circulation rather than by the slow percolation that constitutes intergranular movement in the sands. In contrast, ground water on the lagoon sides of these islands is fresh and drinkable almost to the beaches.

Parakahi and Hukuniu illustrate the effects of permeability on the ground water of very small islands. Well levels on Parakahi show approximately the same lag behind tide fluctuations as represented in wells of the larger islands. The water, which is potable, must enter through sand deposits from any direction. In contrast, water level in the well on Hukuniu

Island, which is formed almost entirely of stratified rock, reaches its high and low points essentially at the same times that high and low tides arrive. Furthermore, the salinity of the water in this well is close to that of sea water -- again suggesting easy access through large channels.

Effects of island size on lens.- Observation wells in the centers of the two very small islands -- Parakahi (400 ft x 300 ft) and Hukuniu (250 ft x 150 ft) -- suggest that, on these islands at least, permeability of the rock or sediment, rather than size of the island, controls the amount of water-level rise and fall. Figure 18 shows that on Parakahi the rise is comparable to that of wells dug in similar sediments on the larger islands, whereas on Hukuniu, where cavernous stratified rock is involved, the rise is considerably greater, even approaching in amount the corresponding total rise of the tide.

The real significance of island size in regard to the fresh-water problem is whether or not a lens can develop and, if developed, can be maintained in a particular area. Because continued operation of a lens depends in large measure on the amount of recharge, a sizable surface area for catching precipitation and a sufficient amount of precipitation are basic. In considering how small an island may maintain a fresh-water lens, Parakahi Island, in a region of only moderate rainfall, is noteworthy for having a lens of fresh, potable water. Hukuniu, which is still smaller, has highly saline water but this may be due as much to contamination from free circulation through open channels in limestone as to small size of the island. Thus, only a rough qualitative measure of the minimum size requirement, furnished by the example of Parakahi, is available for Kapingamarangi Atoll.

Quality of the ground water.- Water samples collected on August 20, 1954, from each of the eight test wells and analyzed by the U. S. Geological Survey are summarized in table 7.

Data presented in table 7 illustrate that well waters from Taringa and Werua Islands are progressively higher in chemical components, total hardness, and percent sodium from the lagoonward to the seaward side of each island. This trend almost certainly is related to the amount of mixing with sea water in each place and probably results from differences in permeability of island sediments and rocks. The cavernous nature of rock beds on the seaward sides apparently allows relatively greater mixing than is possible in the intergranular spaces of sands on the lagoonward sides.

Comparison of water from the two small islands -- Parakahi and Hukuniu -- shows differences similar to those noted from one side to the other of the large islands, but contrasts are greater. These contrasts apparently also result from variations in permeability and in degree of mingling with sea water. Water from the Parakahi well illustrates relatively poor mixing; that in the Hukuniu well has nearly the composition of sea water.

The hardness of the well waters of Kapingamarangi Atoll undoubtedly reflects contributions of calcium and magnesium from limestone and lime sand. The hardness increases across Taringa and Werua from lagoon to sea, reflecting an increase in the degree of mixing of ground water with sea water.

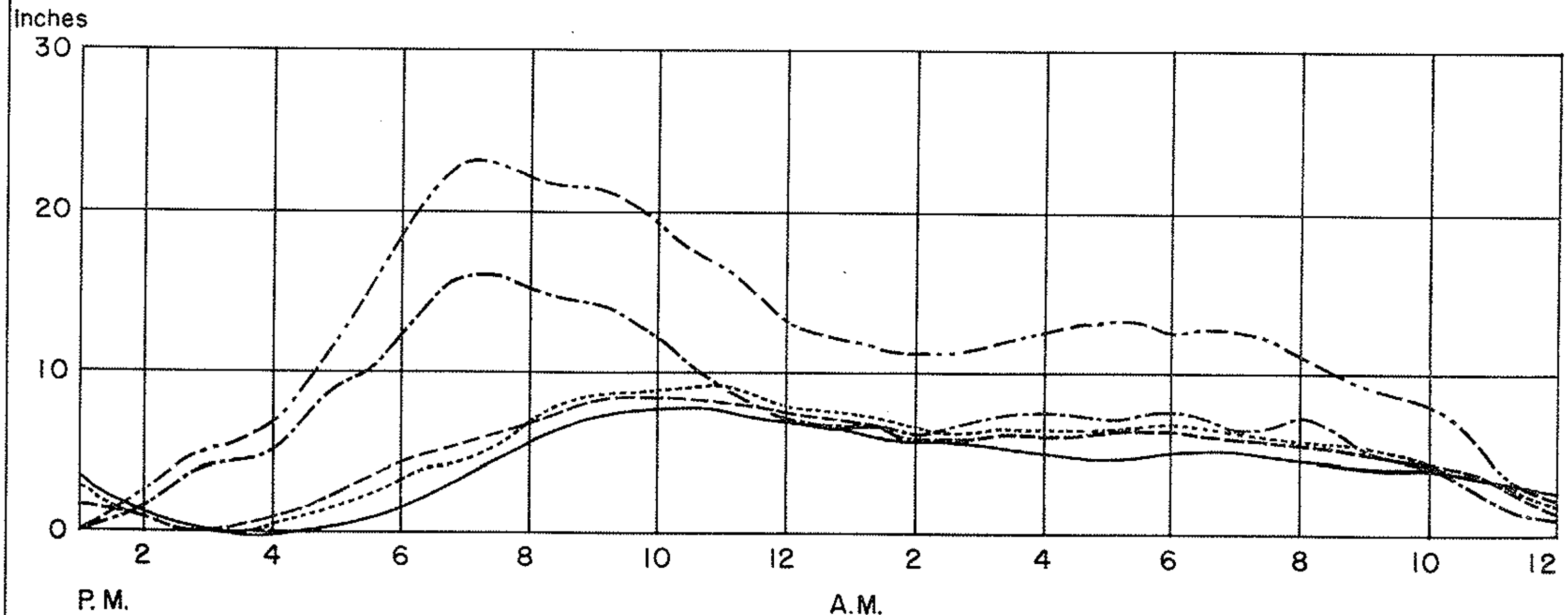


FIGURE 16a TIDE AND WELL FLUCTUATIONS, TARINGA ISLAND
JUNE 23–24, 1954

—·—·— Tide on seaward shore
——·· Tide on lagoon shore

——— Well #1, Lagoon side
– – – – Well #2, Center of island
········· Well #3; Seaward side

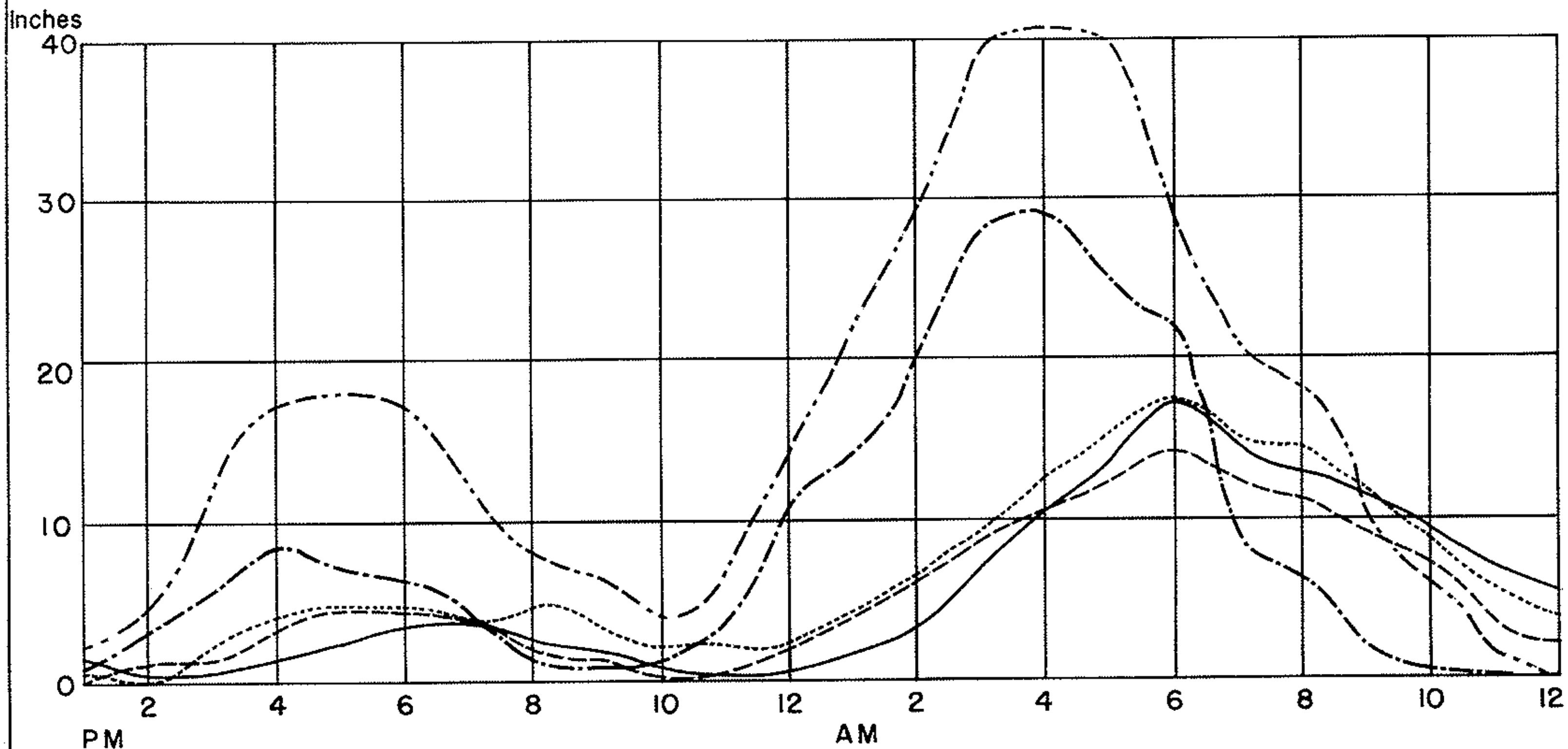


FIGURE 16b TIDE AND WELL FLUCTUATIONS, TARINGA ISLAND
JULY 30-31, 1954

Tide on seaward shore
Tide on lagoon shore
Well #1, Lagoon side
Well #2, Center of island
Well #3, Seaward side

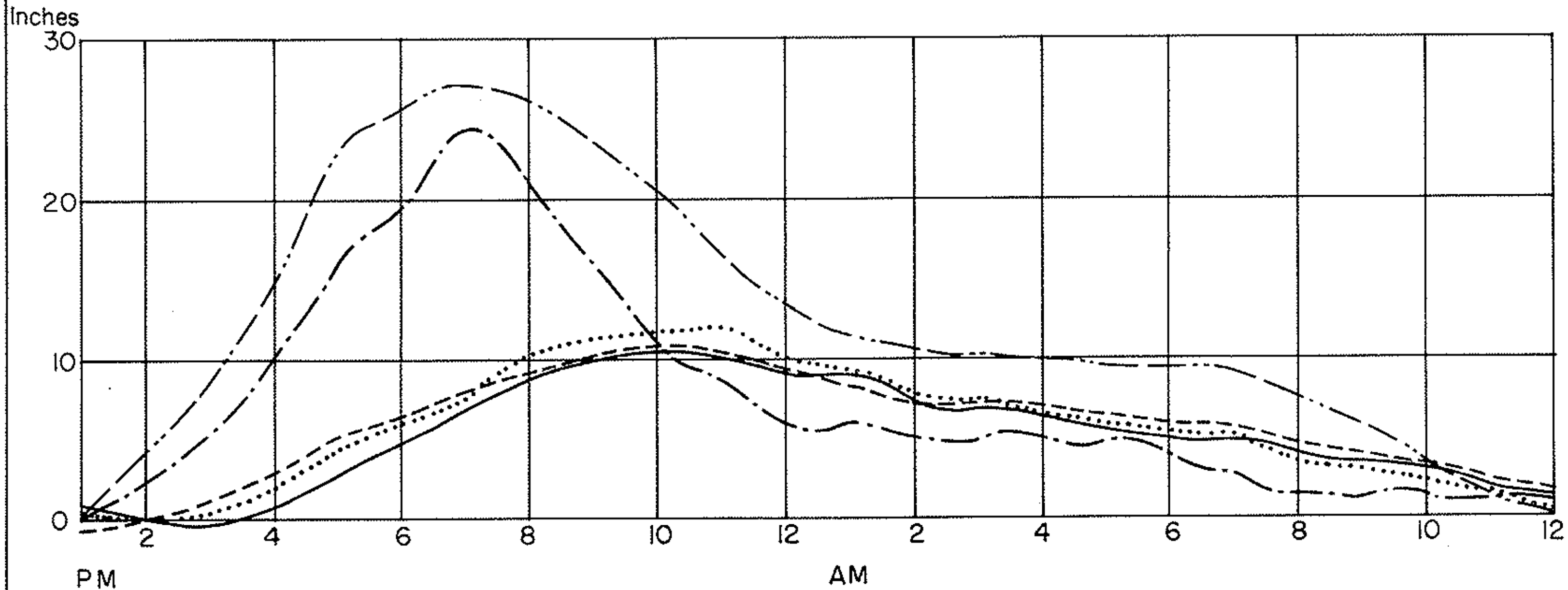


FIGURE 16c TIDE AND WELL FLUCTUATIONS, TARINGA ISLAND
AUG. 20-21, 1954

—·—Tide on seaward shore
——·· Tide on lagoon shore

——Well # 1, Lagoon side
----Well # 2, Center of island
·······Well # 3, Seaward side

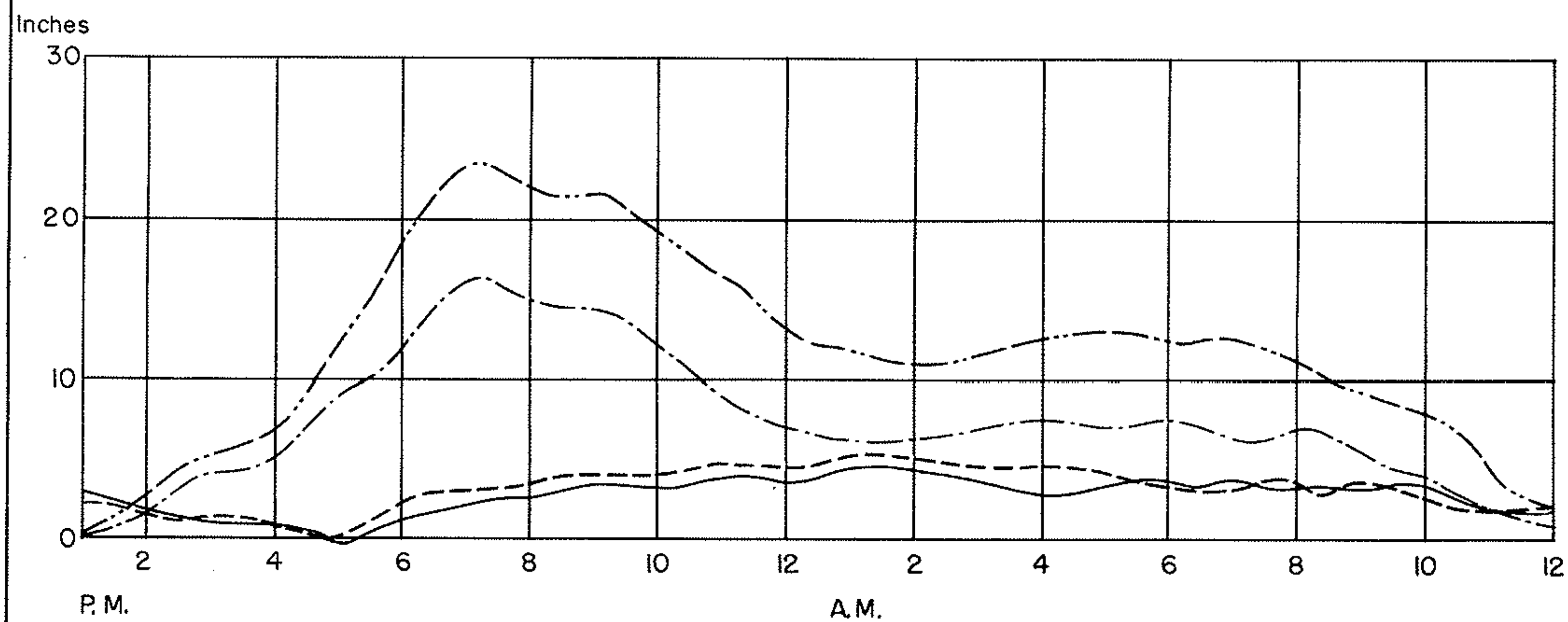


FIGURE 17a—. TIDE AND WELL FLUCTUATIONS, WERUA ISLAND
JUNE 23–24, 1954

—·—Tide on seaward shore
——--Tide on lagoon shore
——Well #4, Lagoon side
----Well #5, Center of island

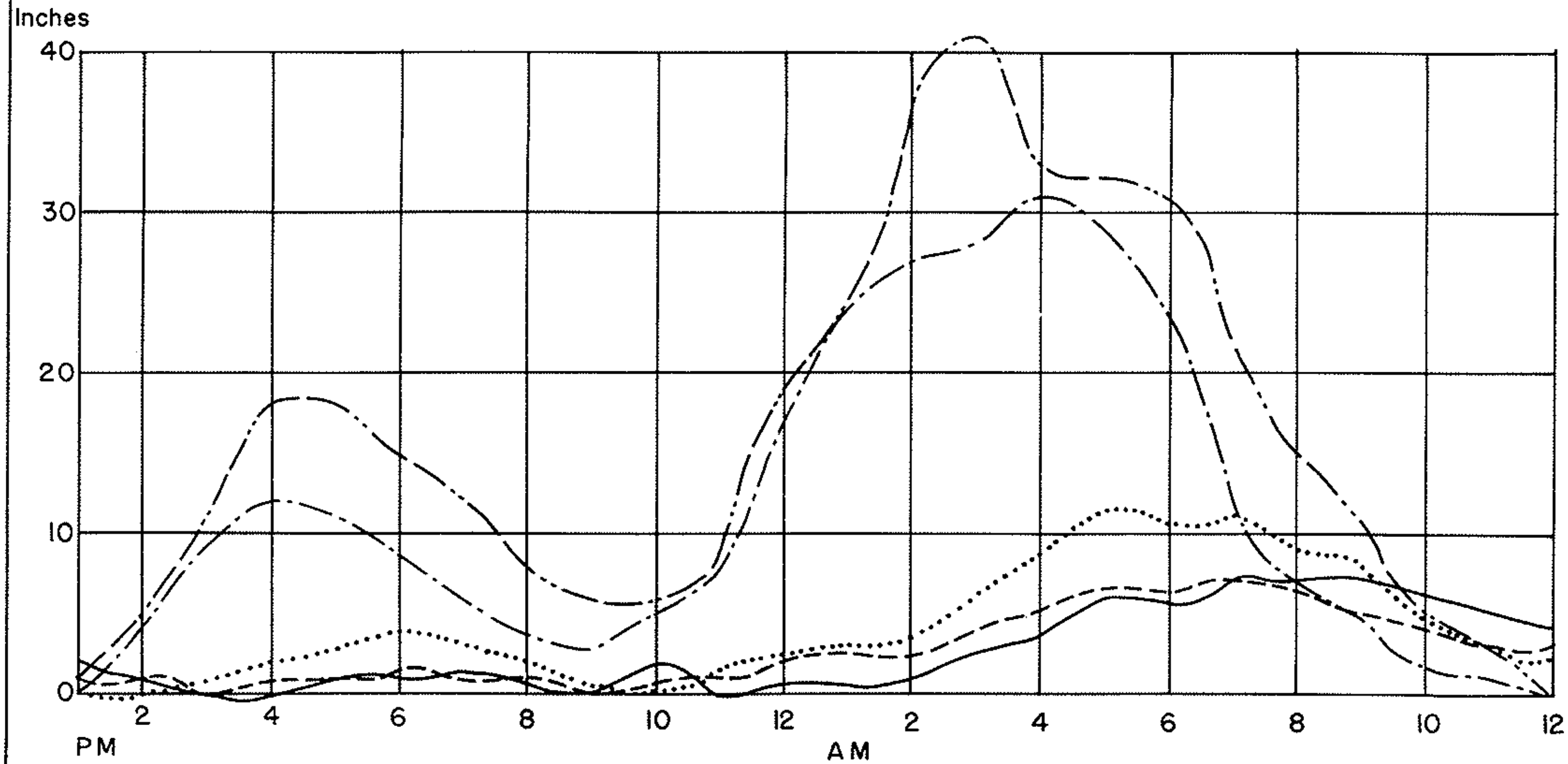


FIGURE 17b TIDE AND WELL FLUCTUATIONS, WERUA ISLAND
JULY 30-31, 1954

—·—Tide on seaward shore
——··Tide on lagoon shore
———Well #4, Lagoon side
-----Well #5, Center of island
······Well #6, Seaward side

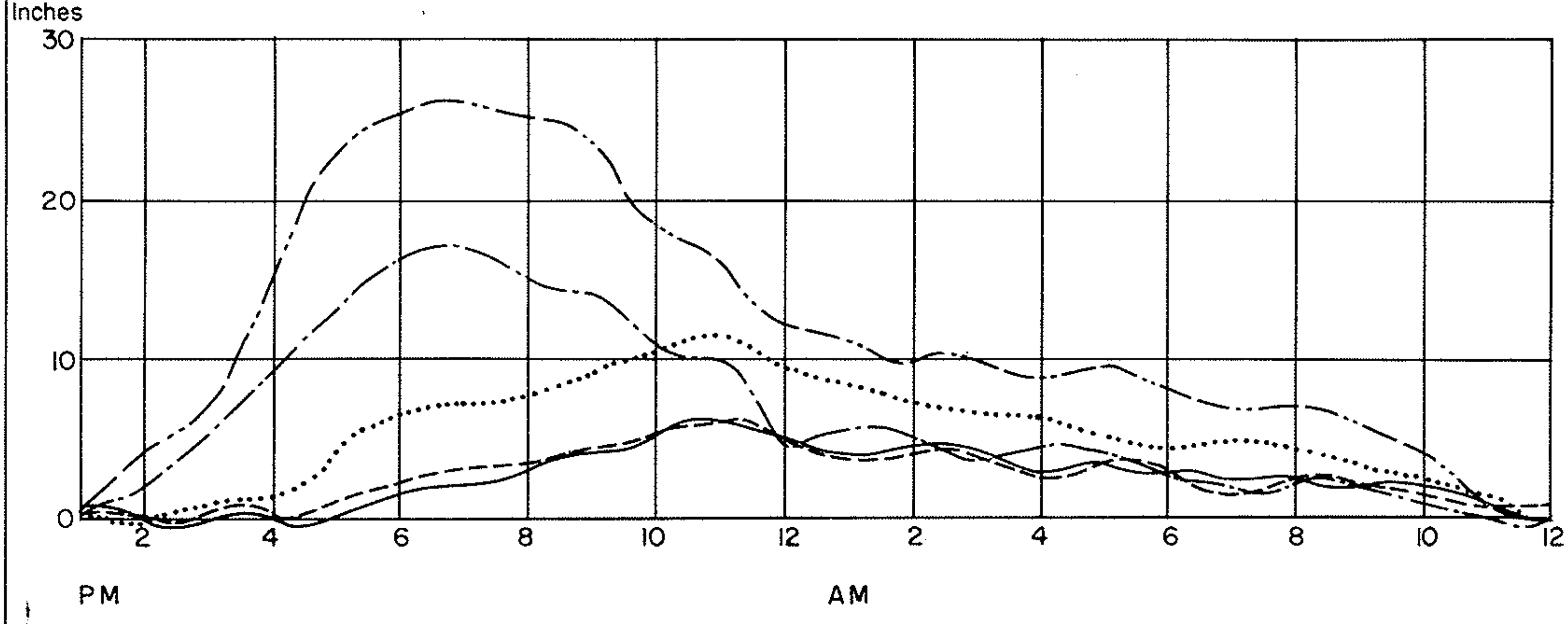


FIGURE 17c TIDE AND WELL FLUCTUATIONS, WERUA ISLAND
AUG. 20-21, 1954

—·— Tide on seaward shore
——·· Tide on lagoon shore
——— Well #4, Lagoon side
– – – – Well #5, Center of island
······ Well #6, Seaward side

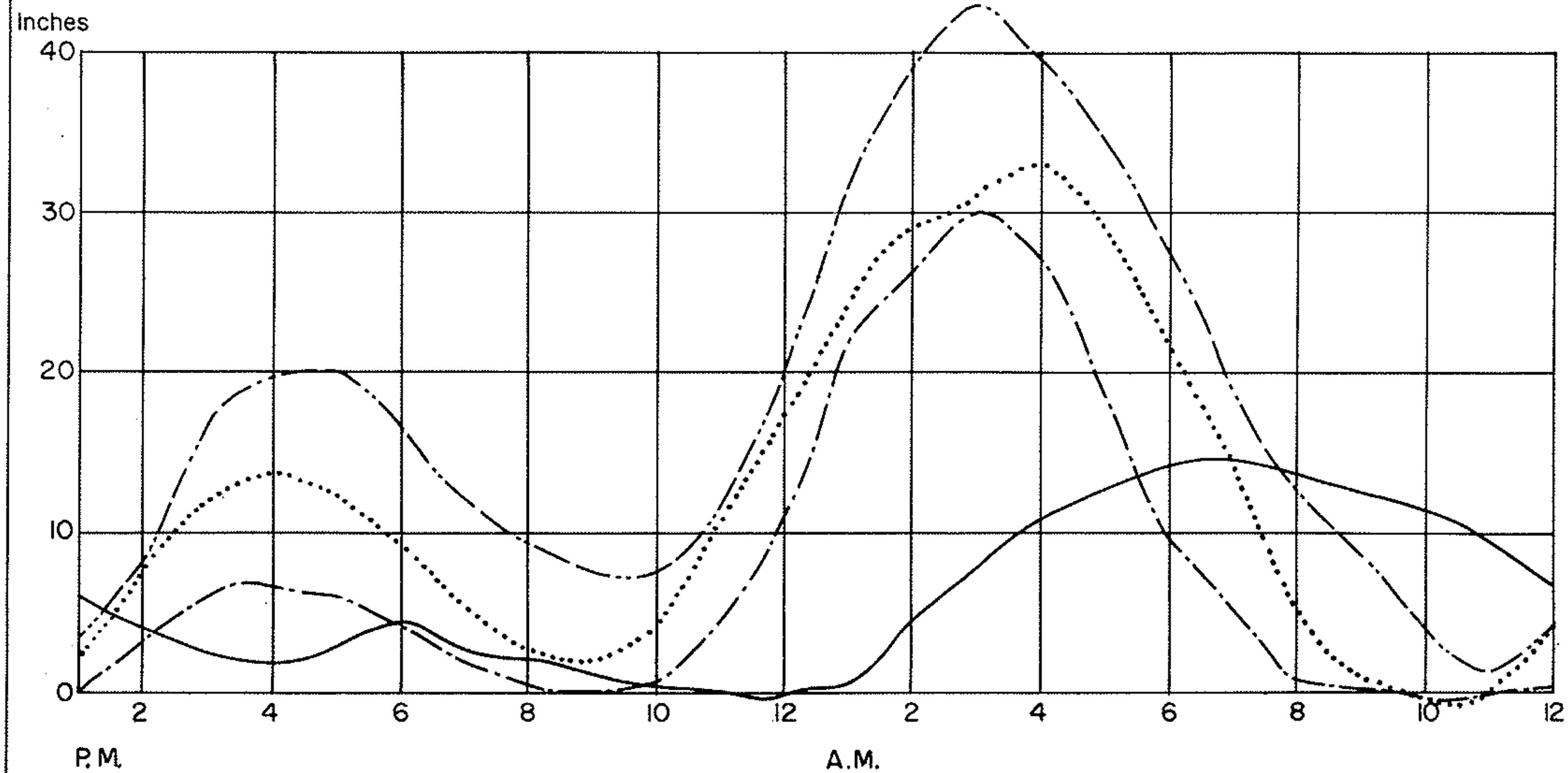


FIGURE 18a—. TIDE AND WELL FLUCTUATIONS, HUKUNIU AND PARAKAHI ISLETS
JULY 30-31, 1954

—·—Tide on seaward shore
——··Tide on lagoon shore
——Well #7, Parakahi
······Well #8, Hukuniu

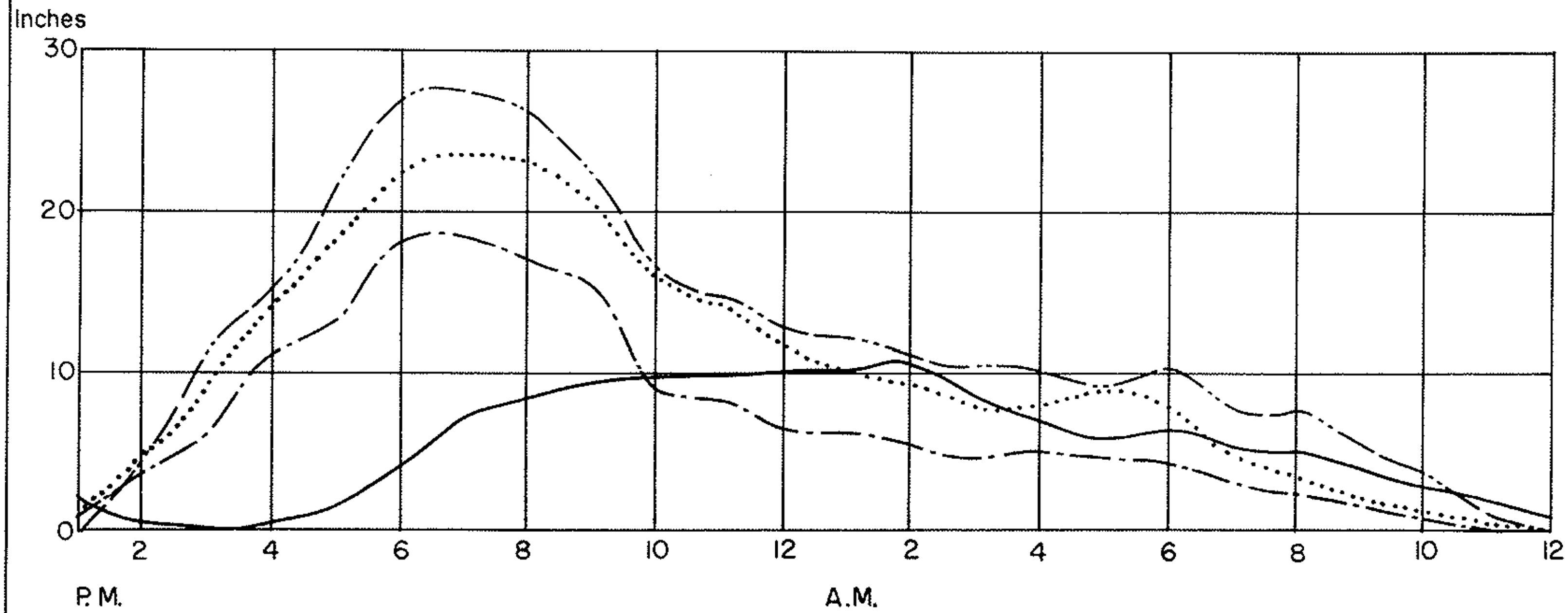


FIGURE 18b TIDE AND WELL FLUCTUATIONS, HUKUNIU AND PARAKAHI ISLETS
AUG. 20-21, 1954

— · — Tide on seaward shore
— — · Tide on lagoon shore
——— Well #7, Parakahi
· · · · · · Well #8, Hukuniu

Table 7.- Analyses of water samples from test wells and comparative data for normal sea water. (Analyses by U. S. Geological Survey)

	Taringa			Werua			Parakahi	Hukuniu	Normal sea water
	1	2	3	4	5	6	7	8	
Chemical components (ppm)									
Calcium (ca)	89	174	255	132	194	368	258	517	400
Magnesium (mg)	24	63	249	12	13	204	54	1,160	1,270
Sodium (Na)	38	560	2,010	22	23	1,580	400	9,390	10,560
Potassium (K)	2.4	18	75	3	2.4	55	12	359	380
Sulfate (SO_4)	16	4.1	459	1.2	4.1	288	30	2,290	2,650
Chloride (Cl)	55	1,100	3,810	20	18	2,980	875	17,500	18,980
Physical characteristics									
Hardness (ppm)	320	693	1,660	379	538	1,760	866	6,060	6,215
Percent sodium*	20	63	71	11	8	65	50	76	79

*Percentage of sodium among the principal cations (sodium, potassium, calcium, and magnesium), all expressed as chemical equivalents.

These relationships are illustrated by the fact that calcium is much higher than magnesium in the near-lagoon samples, reflecting solution of calcium carbonate and relatively little mixing with sea water, whereas calcium exceeds magnesium only moderately in the near-sea samples, reflecting mixing with sea water, which has a proportionately higher magnesium content.

The hardness of water from wells on the lagoon sides and in the island centers ranges between 300 and 700 ppm, so they are much higher than for soft waters ($<$ 50-60 ppm) as recognized in the United States. These waters would require "water softeners" for domestic use in America. They are similar in quality to waters from the northern Marshall Islands recorded by Arnow (1954, p. 7).

Water samples from test wells on Taringa and Werua Islands were checked at various times during the summer for PH and temperature. The PH readings ranged from about 7.0 to 7.5, and those from the relatively brackish waters of wells on the seaward side were consistently high, apparently reflecting a slight alkaline increase from sea water mixing. Temperature readings for all well waters were 27.5° to 28° C (81.5°-83° F) in the early morning, but they commonly rose 1° or 2° C during the warmer part of the day.

Water from wells on the lagoon margins of islands is generally more potable than that from other parts and is easier to reach by digging. Probably all wells thus situated will furnish water of good quality which, if protected from pollution, can be used to advantage by the Kapingans. The U. S. Public Health Service recommends 250 ppm of sulfate (SO_4) and the same amount of chloride (Cl) as upper limits for water used in normal domestic consumption, although water considerably higher in these components may be used without apparent harm by people who have become adjusted to it. Water from the island centers is moderately good, but that on the seaward sides is too brackish to be acceptable.

NEAR-SHORE CURRENTS

Currents moving along the shores of the Kapingamarangi islands are, in part, normal longshore currents generated by waves and, in part, the results of tides. They contribute to the work of erosion and deposition; also they are significant in maintaining ventilation within the lagoon, introducing and circulating new sea water with each rise in tide. The tide rises 6 to 13 inches higher within the lagoon than it does on the seaward sides of the islands (figs. 16, 17, and 18), probably because the passes between islands form constrictions that limit the movements of water entering and leaving the lagoon.

In order to obtain specific data on the movements of near-shore currents, records were tabulated on the direction and relative rates of movement with respect to nine islands (figs. 19 and 20). Three of these islands -- Nunakita, Torongahai and Ringutoru -- are in the northern section of the atoll, four -- Werua, Matiro, Hare, and Taringa -- on the eastern side, facing the dominant wind direction, and two -- Pumatahati and Matukerekere -- on the southern arc. To observe currents, fluorescein dye, which produces an orange color readily observable even at a distance, was poured in the water. Movements recorded at times of both rising and falling tides were plotted for contrast.

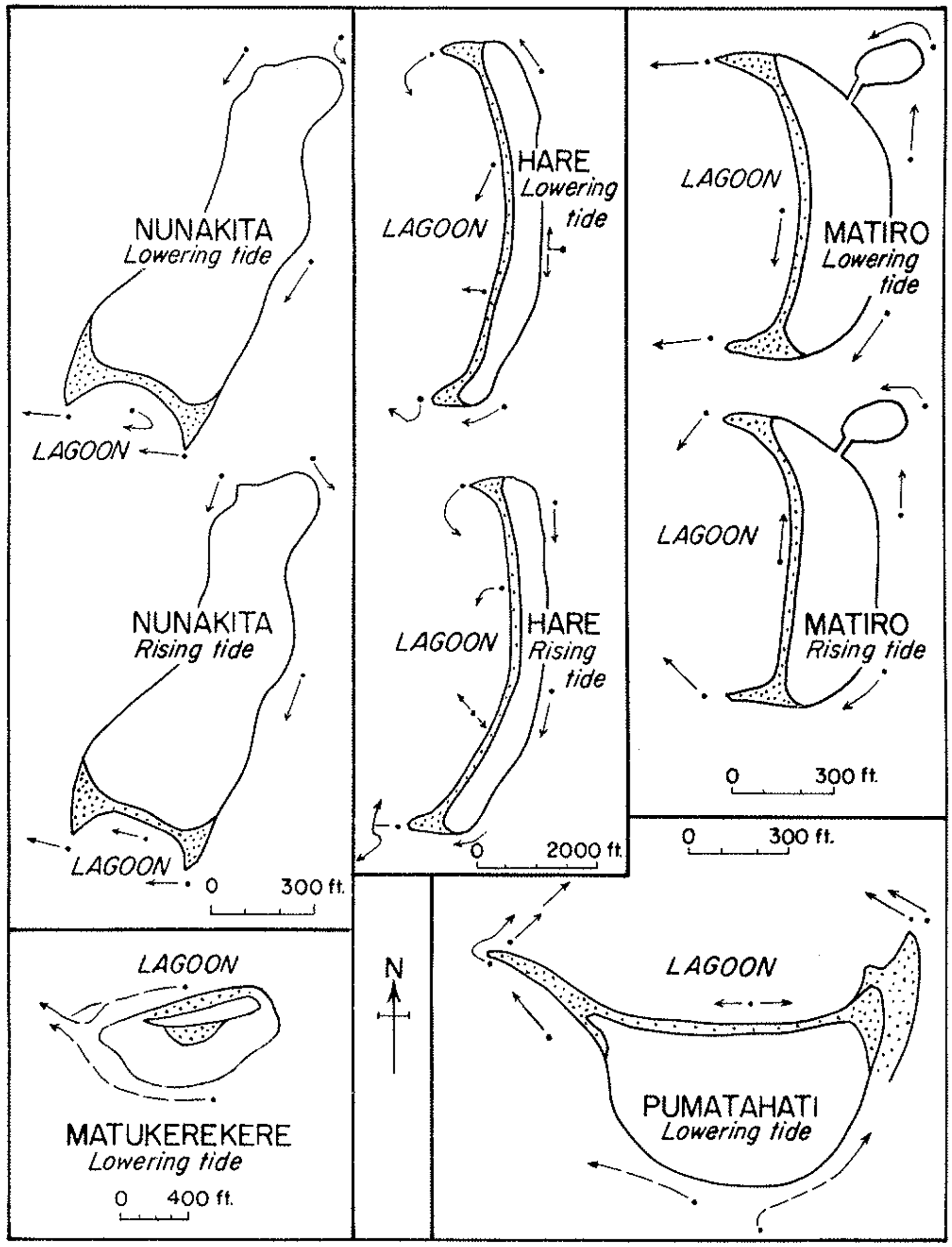


FIGURE 19.-NEAR-SHORE CURRENTS OF 2 SOUTHERN, 2 EASTERN AND 1 NORTHERN ISLANDS OF KAPINGAMARANGI

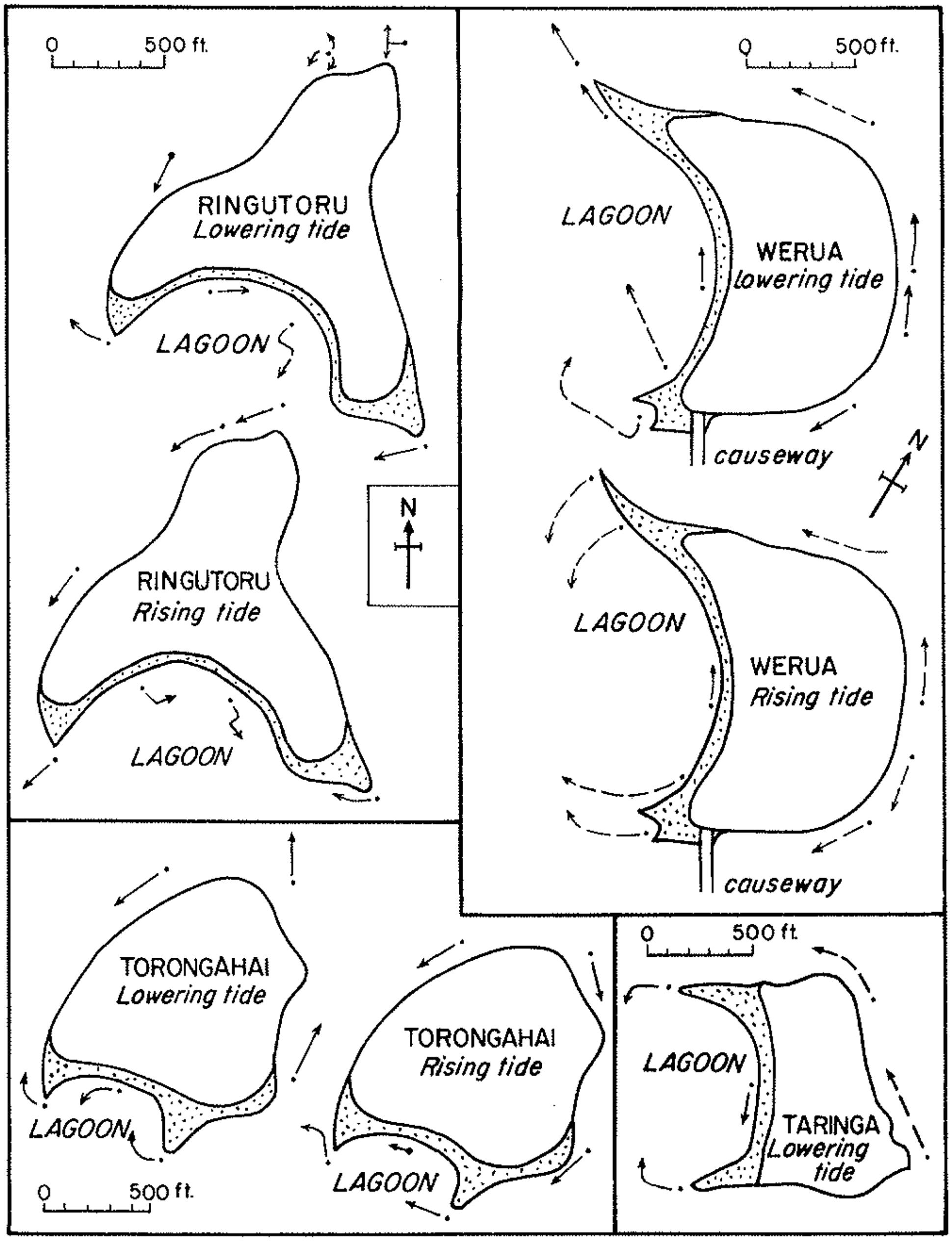


FIGURE 20.- NEAR-SHORE CURRENTS OF 2 EASTERN AND 2 NORTHERN ISLANDS OF KAPINGAMARANGI

The results of observations on near-shore currents as summarized in figures 19 and 20 show that on the seaward sides of most islands tidal currents normally move in opposite directions from a central point. During rising tides, however, longshore currents may develop with sufficient strength to direct all movement in one direction. The maps also show that on the concave lagoon sides, near the sand beaches, which are protected by horns or bars at the island extremities, movement of currents is extremely small at most times and has no dominant direction.

The most significant current movements adjacent to islands are those passing along the sides between islands. These are especially effective during rising tides. Such currents consistently travel toward the lagoon, moving clastic sediments and building rubble and sand bars out into the lagoon from the ends of each island. Furthermore, between the bars of adjacent islands these currents produce submerged deltas that protrude well out into the lagoon. The deltas are prominent in airplane photographs and are conspicuous even from a boat; normally they are composed dominantly of coral rubble in their headward parts and of foraminiferal sand in deeper waters beyond.

Because bare reef flats and little sand occur seaward of the Kapingamarangi islands, 1/ relatively little sediment has accumulated on this side.

1/ This is in contrast to the conditions on Nukuoro and certain other atolls where Foraminifera (Calcarina) live in abundance on the reef flat outside the islands and form extensive sand deposits.

Shores at and below sea level are largely of stratified rock, which shows the effects of planation as should be expected from known current trends. The few lime sands that wash into this area normally do not remain but are moved along by currents and waves through the gaps between islands and thence into the lagoon. Even coral rubble from the reef edge, which is introduced in considerable amounts, appears to be transitory with respect to most seaward shores. Only the ramparts of boulders or rubble that stand above high-tide level and are formed by the waves of occasional large storms form significant deposits on seaward parts of the islands.

In the near-shore waters on the lagoon sides of islands, protected from the prevalent easterly winds by the islands themselves and from tidal currents by the horns or bars at island extremities, the normal, extremely weak and variable currents seem incapable either of depositing or of removing sediments of the beach. Most of these beaches are of foraminiferal sand and the species represented appear to live in the shallow waters nearby, but their accumulation and that of coral rubble as found at Hare and some other islands probably result from the occasional reversals in wind direction, which bring waves from west to east across the lagoon. These wind reversals result in a considerable piling up of water and sediment against lagoon shores of the islands.

The island of Pumatahati, on the southern rim of the atoll and near the western end of its islands, is unique in that its lagoon beach is formed almost entirely of coral rubble rather than sand and in that it has a well-developed rubble rampart on the lagoon side (fig. 9). Both of these features can be explained only as the results of the action of large waves caused by strong winds. Furthermore, the winds must have come from east to west across the lagoon, for the source of rubble on the rampart and the greatest concentration of rubble on the beach are at the eastern end. Such features developed on this island and not on others probably because of its far westerly position on the southern reef.

SEDIMENTATION IN THE LAGOON

The lagoon at Kapingamarangi covers an area of about 15.5 square miles and has maximum dimensions of 5 by 6 nautical miles (Nugent, 1946, p. 755). Although it is roughly circular in plan, its symmetry is far from perfect because of an almost straight southwestern side. Profiles of the lagoon bottom, disregarding the many irregularities caused by patch reefs that rise from it, are those of a shallow basin (fig. 21). Even with the greatly exaggerated vertical scale used in the sections, the slope appears gentle, and sections of near-shore areas (fig. 22) and of Manin knoll (fig. 23), made with the same vertical and horizontal scales, demonstrate the low-angled slopes on which sediments are accumulating.

The deepest parts of the lagoon, in the north-central and east-central areas (fig. 24), are recorded as 43 fathoms on U. S. Navy Hydrographic Office Chart 6042. The greatest depth measured by the writer in more than 200 soundings was 40 fathoms (240 feet); however, this depth was reached in at least five places, suggesting a relatively flat bottom. Because of the slightly asymmetrical distribution of the deepest areas, resulting in gentle slopes on the south and west sides of the lagoon, Nugent (1946, p. 756) postulated that Kapingamarangi "is apparently tilted to the northeast." This feature of distribution can be equally well explained in other ways, however, and the relative narrowness of the southwest arc of the atoll as compared to the northeastern arc argues against the postulate.

In order to obtain a detailed record of bottom sediments in the lagoon, samples were collected systematically along many lines forming a modified grid pattern. Both grab samplers and bottom drags were employed during the work, and in relatively shallow waters samples were obtained by diving. Approximately 250 samples, representative of essentially all parts of the lagoon, were collected. Time has not yet permitted study of these samples except in a general way, so details regarding their characteristics, distribution, and significance must await publication at a later date. Only a generalized statement can be made at this time.

A relationship between type of sediment and depth of water (fig. 25) is apparent in the lagoon at Kapingamarangi. Of seven principal types of sediment that are recognized, six are restricted to relatively narrow limits in depth, forming a series of bands encircling the deepest parts of the lagoon. The seventh type of sediment is a white silt, apparently formed of comminuted shells, corals, and other debris; it is distributed along the paths of strong bottom currents at depths ranging from a few feet down to at least 200 feet. The other sediments and their general ranges are as follows:

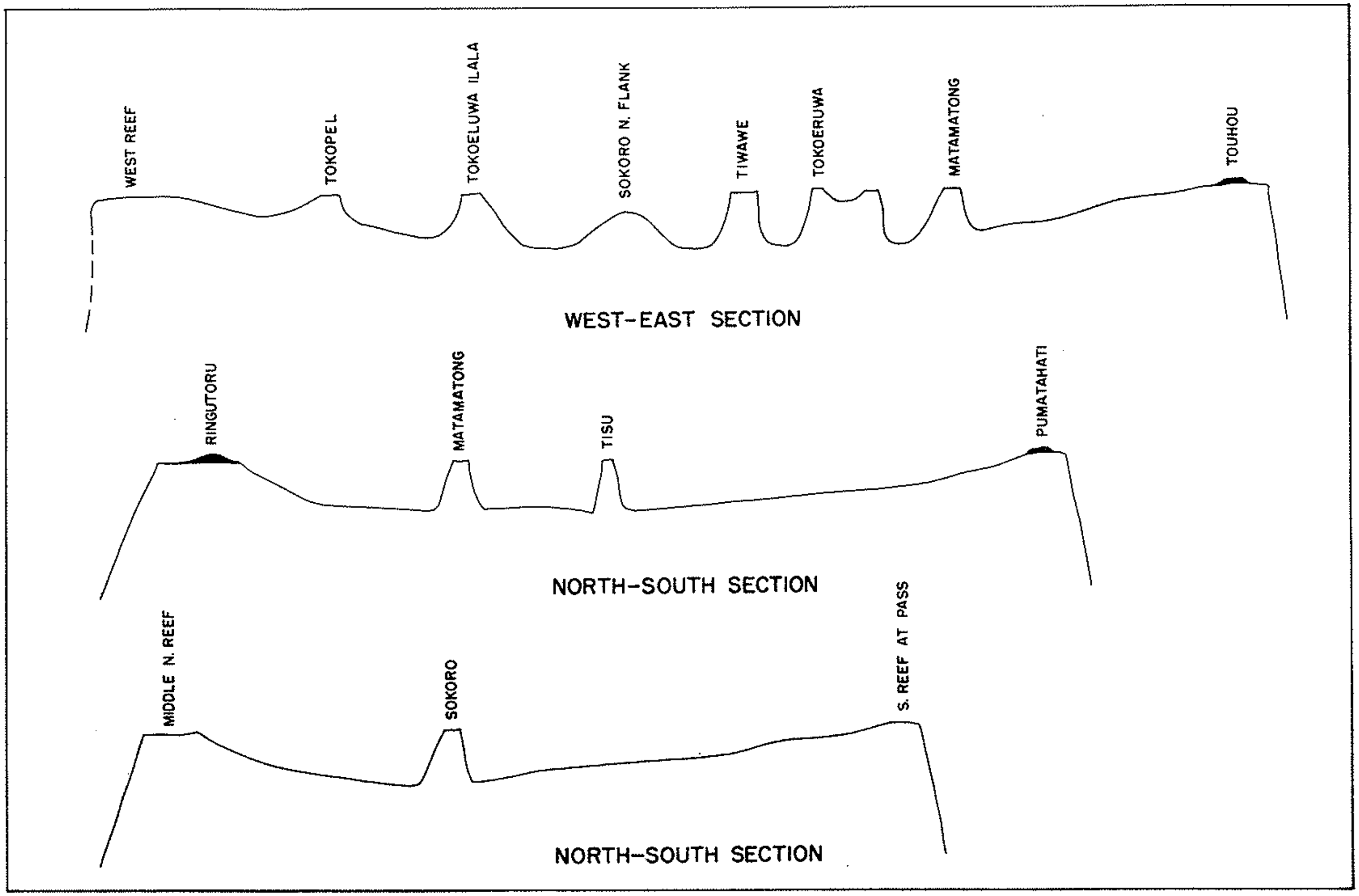
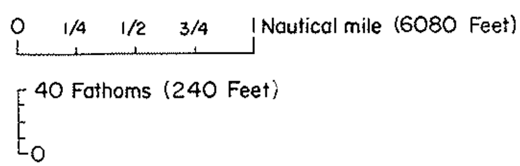


FIGURE 21.- SECTION ACROSS KAPINGAMARANGI LAGOON
(VERTICAL EXAGGERATION APPROXIMATELY X30)



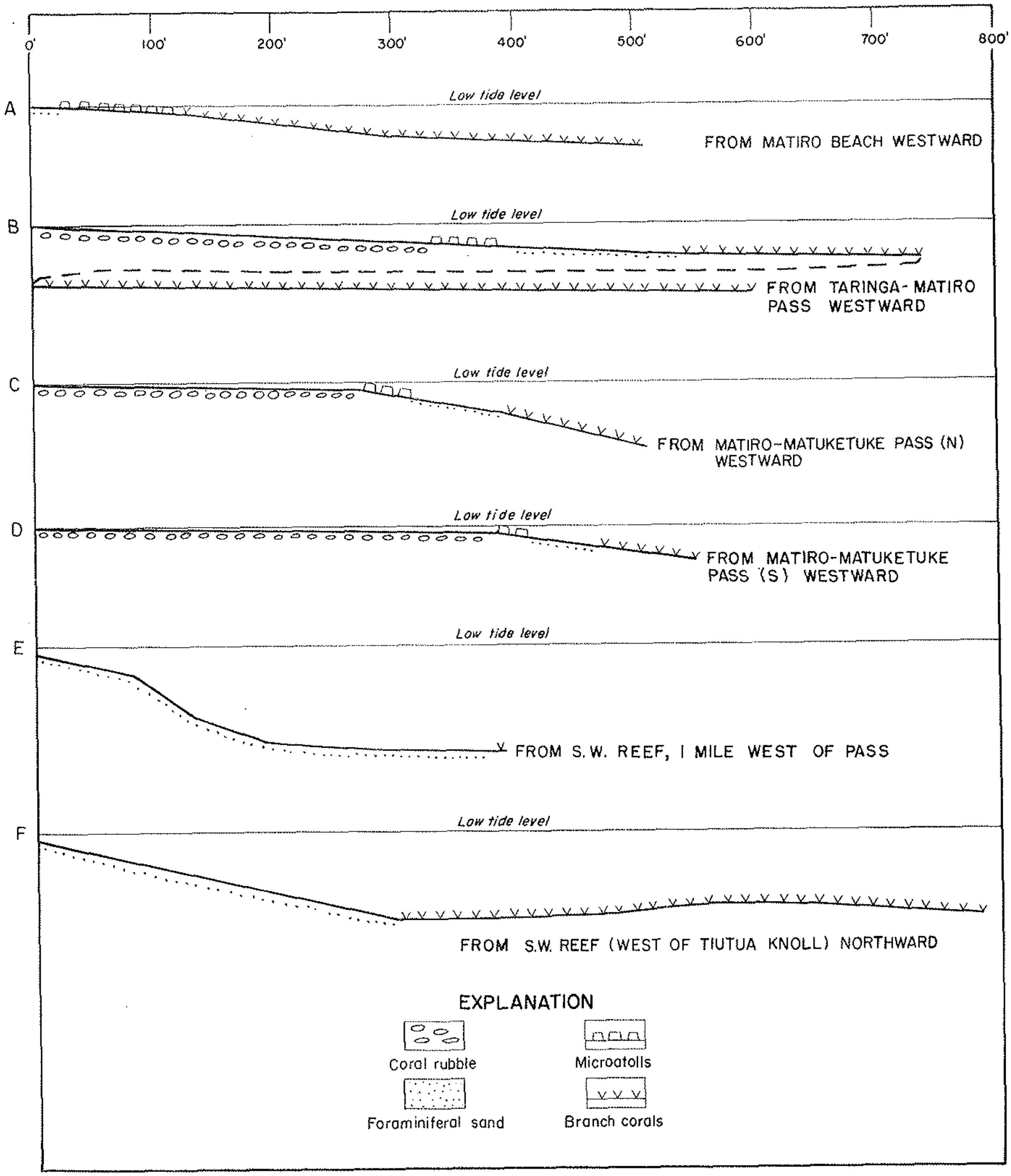


FIGURE 22.- OFF-SHORE PROFILES IN EAST AND SOUTH SECTIONS OF ATOLL AND DISTRIBUTION OF BOTTOM SEDIMENTS

0 50 Feet

Vertical and horizontal scale

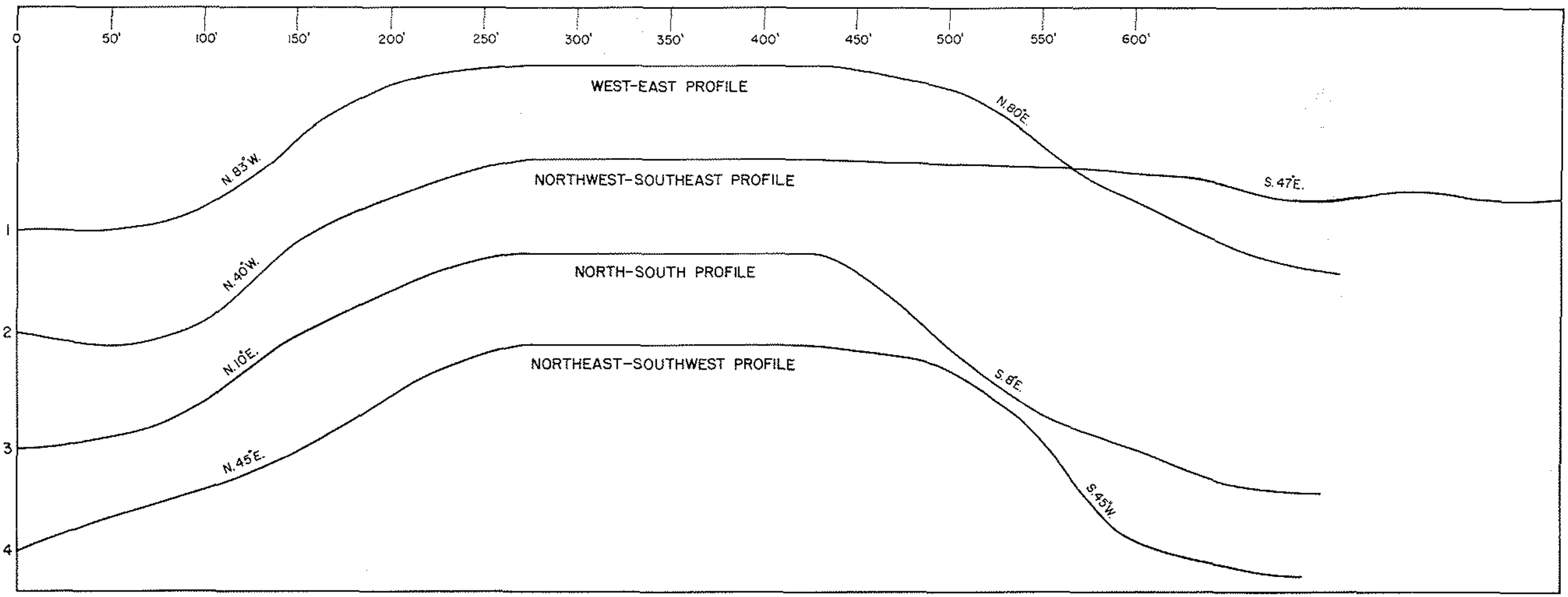


FIGURE 23.-PROFILES OF MANIN PATCH REEF

0 50 100 Feet

Vertical and horizontal scale

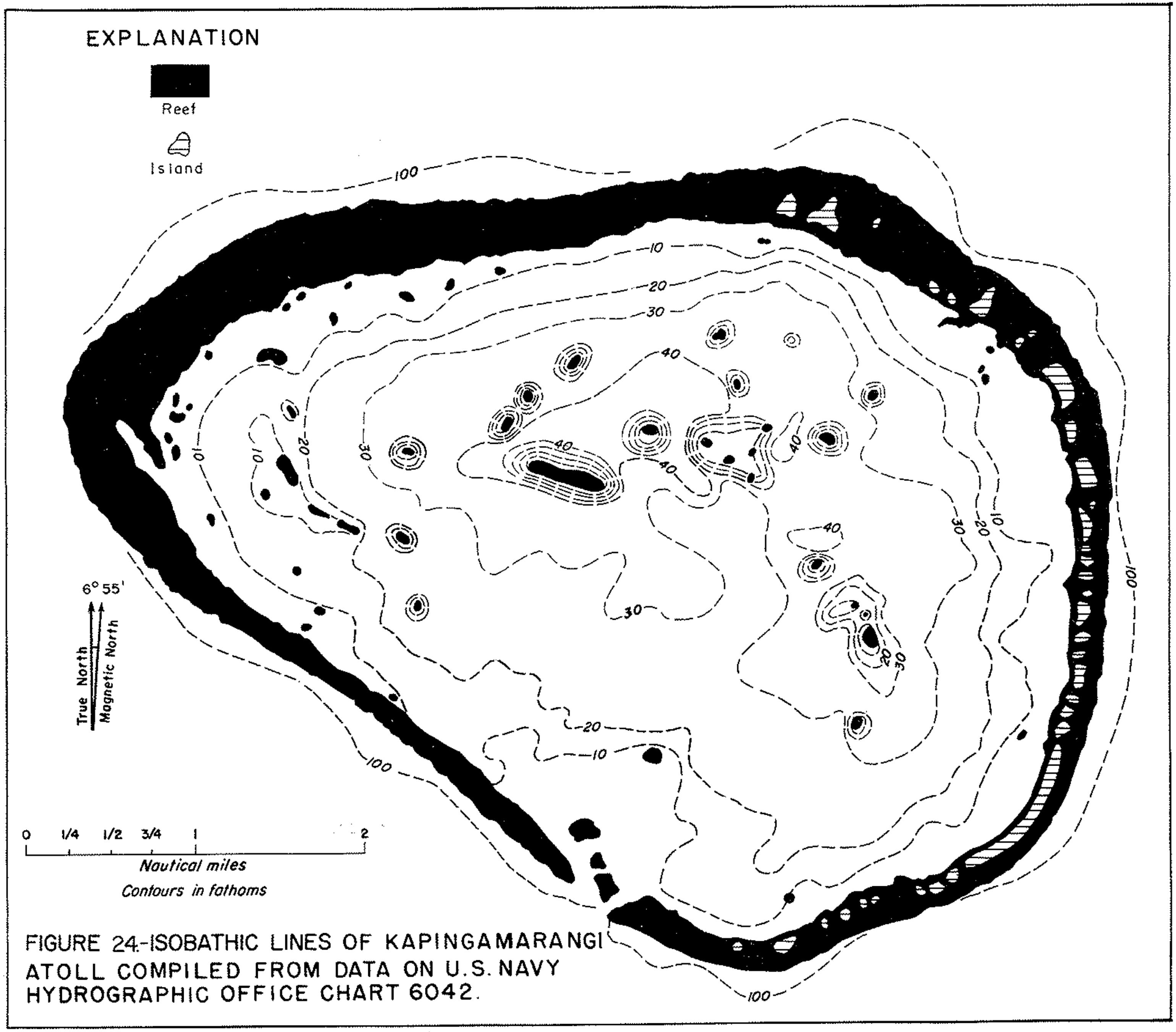


FIGURE 24.-ISOBATHIC LINES OF KAPINGAMARANGI ATOLL COMPILED FROM DATA ON U.S. NAVY HYDROGRAPHIC OFFICE CHART 6042.

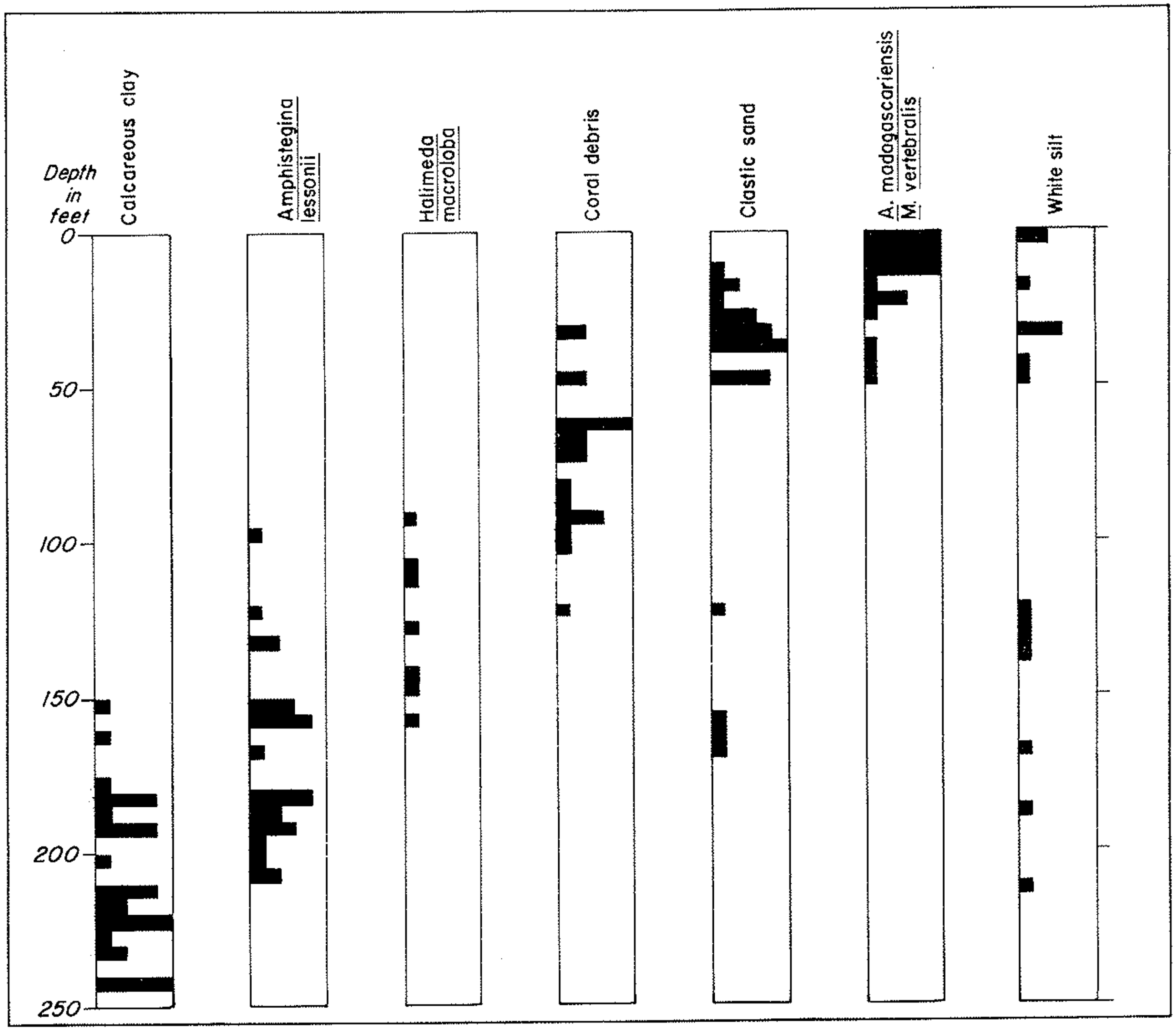


FIGURE 25.-RELATIVE PROPORTIONS OF PRINCIPAL TYPES OF SEDIMENT AT 5-FOOT DEPTH INTERVALS AS DETERMINED BY SAMPLING

1. Sand dominantly of Foraminifera /Amphistegina madagascariensis d'Orbigny, Marginopora vertebralis Blainville, and Elphidium craticulatum (Fichtel and Moll)/ -- <50 feet; mostly 0-25 feet.

2. Sand dominantly of clastic shell fragments -- 10-50 feet; mostly 25-50 feet.

3. Coarse debris, largely of dead branch corals, accumulated between and below thickets of living corals -- 30-105 feet.

4. Accumulations of Halimeda macroloba fragments -- 90-160 feet (patchy).

5. Foraminiferal sand (Amphistegina lessonii d'Orbigny) 1/-- 120-210 feet.

1/ Chief minor faunal elements are Heterostegina suborbicularis d'Orbigny and Operculina ammonoides (Gronovius); others associated are Spiroloculina communis Cushman and Todd, Cibicides lobatulus (Walker and Jacob), and Planorbulinella larvata (Parker and Jones). Identified by M. Ruth Todd.

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6. Calcareous mud (contains aragonite needles and about 10 percent of small Foraminifera) -- 150-240 feet.

Sedimentary belts within the lagoon appear to represent, for the most part, the normal habitats of the various organisms involved, for a large proportion of samples show little of the mixing that would be expected if organisms had been transported by currents into pockets of accumulation. Orange foraminiferal sand of near-shore areas (belt 1) grades outward and downward into white clastic sand of belt 2. Likewise, there is gradation between the Halimeda macroloba sand of belt 4 and the Amphistegina lessonii sand of belt 5. Corals, especially branching types that cover the bottom surface mainly between depths of 30 and 90 feet, form an effective barrier in most parts of the lagoon between the sediments above and below these depths. Fragments of broken coral, many of them large, cover most of the lagoon floor between the living corals.

The calcareous mud which covers most of the lagoon bottom at depths below 34 fathoms (204 feet), but which has been obtained from stations as shallow as 25 fathoms (150 feet), is pale olive green and very plastic and sticky when wet. Mineral analyses made with X-ray diffraction patterns 2/ show that much of this mud is aragonite, but it contains a small proportion

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2/ Analyses by A. J. Gude III, U. S. Geological Survey.

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of calcite. The calcite probably is attributable to the Foraminifera included. These form only a small percentage of the mud but are represented by a rich fauna including many genera and species. In a single sample from a depth of 36 fathoms, Ruth Todd of the U. S. Geological Survey noted 39 species. She reports the following as crude estimates of the percentage of the total foraminiferal fauna:

	Percent
Cibicides lobatulus (Walker and Jacob)	20
Spiroloculina communis Cushman and Todd................	20
Virgulina complanata Egger	10
Textularia agglutinans d'Orbigny)................ ...	12
T. foliacea Heron-Allen and Earland)	
Amphistegina madagascariensis d'Orbigny)...............	10
A. sp. (small, flat worm))	

"The remaining 28% is composed of about 32 additional species among which one species each of *Tretomphalus*, *Globigerina*, *Cymbaloporetta*, *Loxostomum*, and *Operculina* make up the bulk (perhaps as much as 15 or 20% of the whole fauna). The *Globigerina* is a planktonic form and the *Tretomphalus* is an attached form with a planktonic stage. *Cymbaloporetta* and *Cibecides* may be attached, but are not necessarily always attached. All the others are benthonic forms, so far as known."

The origin of the calcareous mud is not known, and detailed studies of it have not yet been made. Evidence at hand, however, suggests that the mud is not derived primarily from the residue of sediments occurring at higher levels. Although its composition is principally aragonite, it is largely surrounded by a belt of *Amphistegina lessonii* with a composition of normal calcite. If the aragonite were derived from either coral or shell debris of shallower depths, the difficulty of explaining how it bypassed the surrounding calcite belt is encountered. On the other hand, the presence of some aragonite needles suggests the possibility that it formed as a chemical precipitate.

The overall pattern formed by belts of sedimentation in the lagoon at Kapingamarangi is, of course, much complicated by the many patch reefs that rise above the floor. Each of these has sediments on its top and sides of varieties in keeping with the general depth ranges, except that where slopes are especially steep the lower limits of various sedimentary types extend deeper than otherwise. Further complications in the pattern of sedimentary belts are caused by bottom currents in certain areas. The white silts characteristic of these current zones are especially well developed in and near the main pass on the south, in a broad area bordering the south side of the atoll and within a mile of it, and in narrow zones bordering the western and northern arcs. The east-trending deposits of current-transported silts are prominent in airplane photographs of the southern part of the lagoon.

The problem of why belts of sediment comparable to those in Kapingamarangi lagoon are not recognized in other atolls merits consideration. A likely answer is found in comparative depths: most other lagoons that have been sampled are shallower than the one at Kapingamarangi. Available descriptions indicate that belts corresponding to those of the relatively shallow waters do occur, i.e., the belts of near-shore foraminiferal sand, of clastic sand, and of coral debris. At Raroia, in the deeper parts (20-25 fathoms), Newell (1954, p. 25) reports a lack of bottom mud but records some accumulations of Halimeda. This distribution parallels closely that for corresponding depths at Kapingamarangi.

GEOLOGY OF THE PATCH REEFS

The evenness of the bowl-shaped basin that contains the lagoon at Kapingamarangi is disrupted in many places by patch reefs that rise as mounds from its sides and floor. Many of these reefs are subcircular in plan, but others are linear, and still others very irregular. They range in size from low knolls or pinnacles a few dozen feet across and 10 or 20 feet high to wide platforms that are 100 feet high or more. Among the largest is Sokoro, whose top is 2,900 feet long and 700 feet wide, and Tokopel, which has an upper surface approximately 1,400 feet by 900 feet (fig. 26).

The total number of patch reefs is not known, but 20 of those listed are more than 500 feet long. Available maps show approximately 75 of all sizes, yet even this number probably is far from the total, for many very small ones and others that do not reach the surface are not included. Counting of patch reefs is further confused because some reefs that appear separate at the surface are connected at shallow depths. Of the approximately 75 indicated on maps, 35 are in waters deeper than 60 feet, including some of the very large ones that rise from the deepest parts of the lagoon. The other 40 patch reefs shown on the maps are mostly small and occur in shoal waters bordering the inner margin of the atoll, especially along its northern and western sides.

Nearly all the patch reefs at Kapingamarangi have flat tops at or slightly above low-tide level, giving to each mound the appearance of a mesa rising up through the lagoon. Only on a few of the submerged reefs do top surfaces appear to be somewhat rounded and irregular. Flat tops are characteristically developed and maintained in most patch reefs because the upward growth of organisms is controlled by tide levels and the surface is continually being bevelled by wave action. The sides are steep, in general, and commonly slope off at angles of 30° to 40°. They have the appearance of being far steeper than this and locally seem to be nearly vertical, but measurements show that most visual estimates are high.

The general shape of Manin knoll in the northeastern part of the lagoon was determined from soundings (table 8). This patch reef probably is typical of most at Kapingamarangi. Profiles (fig. 23) show that its southwest side, in its steepest part, slopes down at about 50° within a vertical distance of 40 to 50 feet, and that the northwest side has a slope of about 40°. These are extremes, and other sides of the reef have more gentle slopes, including the southeastern sector, which extends as a slightly submerged promontory or ridge far out into the lagoon.

Table 8.- Depth (in feet) of lagoon floor surrounding Manin patch reef

Distance (in ft) outward from reef margin	Direction from reference point								
	N40°W	N10°E	N45°E	N80°E	S59°E	S 47°E	S8°E	S 45°W	N83°W
0	2	2	2	2	2	6*	2	2	2
75	24	24	30	18	18	12	54	12	12
125	48	48	60	54	24	24	90	42	42
175	90	84	--	80	30	20	108	102	78
225	102	102	96	102	30	24	126	120	90
275	96	108	114	114	30	24	132	126	90

*Along submarine ridge, 128 feet outward from 2-foot margin.

The distribution and orientation of patch reefs in the lagoon seem to reflect in large measure the trends of currents and waves. A cluster of patch reefs, some of them large, near the ship's pass on the south side of the atoll probably is directly related to the strong currents that maintain good circulation in that area. The many small patch reefs immediately inside the northwestern and western arcs of the atoll apparently developed in response to waves of maximum fetch before the dominant winds. Likewise a general northwestward lineation of many reefs in the lagoon center probably reflects this dominant wave direction. The fact that many of the patch reefs are subcircular rather than elongate is believed to be due to the relative quietness of lagoon waters, allowing nearly equal growth in all directions, as suggested by Cloud (1952a, p. 2140).

All of the patch reefs in deep water, and many of those in shallow, rise from parts of the lagoon bottom that are covered with extensive deposits of foraminiferal sand and calcareous mud. The patch reefs themselves, however, are largely mantled with growing corals. Dense thickets or forests of the yellow, branching Porites andrewsi cover most of the sides, and both micro-atolls and smaller coral heads, representing numerous species, cover extensive areas on the flat tops, especially along the margins. Typical coral assemblages from three Kapingamarangi patch reefs, identified by J. W. Wells, are listed in table 9. The list served to indicate the principal forms, though others contribute to the reefs also. A comparison of these lists with those of Wells (1954, p. 390-393) for the Marshall Islands shows that all of the genera and all but two of the species of Kapingamarangi occur also in the Marshall Islands.

Table 9.- Some characteristic coral assemblages on Kapingamarangi Atoll, determined by J. W. Wells

	Seaward margin outer reef at Touhou	Lagoon at Matiro Island 50'-1000' out	Patch reef Tokohui	Patch reef Matamatong	Patch reef Thokotaman
Psammocora nierstraszi v.d. Horst			x		
Seriatopora hystrix Dana		x			x
Pocillopora damicornis (Linnaeus)	x	x		x	
danae Verrill				x	x
eydouxi M.E. & H.	x				
Acropora corymbosa (Lamarck)	x				
digitifera (Dana)	x				
formosa (Dana)		x			x
striata Verrill					x
variabilis (Klunzinger)	x				
Astreopora myriophthalma (Lamarck)					x
Montipora composita Crossland				x	
sp. cf. M. marshallensis Wells					x
prolifera Brueggemann		x	x		
verrilli Vaughan	x				
verrucosa (Lamarck)			x		x
Pavona clavus (Dana)	x				
Herpolitha limax (Esper)					x
Goniopora sp. cf. G. traceyi Wells			x		
Porites andrewsi Vaughan		x	x	x	
fragosa Dana		x	x	x	x
lutea M. E. & H.	x			x	
Favia pallida (Dana)			x		x
stelligera (Dana)			x	x	
Favites abdita (E. & S.)		x		x	
Plesiastrea versipora (Lamarck)	x				
Platygyra rustica (Dana)				x	x
sinensis (M. E. & H.)		x			
Merulina ampliata (E. & S.)			x	x	
Cyphastrea microphthalma (Lamarck)		x	x	x	x
Heliopora coerulea (Pallas)			x	x	x
Millepora platyphylla H. & E.			x	x	x
tenera Boschma		x			x

The surfaces of patch reefs, where not covered with living corals, are either occupied by accumulations of clastic and foraminiferal sands or are barren areas of dead coral. The proportion of each is extremely variable from reef to reef. The amount of dead coral area seems to depend, in large measure, on the elevation of the reef top with respect to low-tide level. Tokohui and Timan, for example, are knolls with top surfaces 2 to 3 feet lower than those of most associated patch reefs (fig. 26) and as a result have no extensive areas of barren, dead coral. Their surfaces are largely covered with well-formed corals. Few of the massive types of coral have dead centers or form microatolls, and many of the yellow, branching Porites, which on other knolls grow only on the margins and sides, are well developed even near the centers of these reefs. In contrast, on Sokoro and Tiwawe knolls, both of which stand well above low-tide level, extensive areas of dead, bevelled coral occur in the centers, and microatolls are common along the tops (fig. 26).

Lime sand that accumulates on the upper sides and tops of most patch reefs is similar to that accumulating at corresponding depths off the lagoon beaches and lagoon reef margins of the atoll. This sand consists largely of orange tests of the foraminifer Amphistegina madagascariensis but contains varying amounts of small clastic particles derived chiefly from mollusk shells and corals. Some sand contains moderate amounts of locally derived Halimeda opuntia fragments. From field sketches of 10 representative patch reefs (fig. 26), the characteristic distribution of sand is apparent. In general, sand is concentrated in the centers and on the northeastern margins, below which it commonly covers slopes down to depths of 20 feet or more. The thickness of sand accumulations on most patch reefs does not appear to be great (table 10), and on some, where coral growth is especially luxuriant, sand is confined to small pockets. In contrast, Sokoro, Tokopel, and a few other knolls contain sufficient sand to form bars of appreciable size that rise well above low-tide level.

Table 10.- Thickness (in inches) of sand accumulations on patch reefs

Patch Reef	NE Margin	Center	SW Area
Tisu	6	5	5
Matamatong	11	7	-
Sokoro	-	18	16

Why sand that extends over the rims of the knolls is confined almost entirely to the northeastern slopes is not known. On other sides, where thickets of branching corals are absent, the slopes normally are covered with the debris of dead coral branches instead of sand.

As stated by Ladd and others (1950, p. 421), "the age, origin and internal constitution of the knolls is not known, as no structure of this

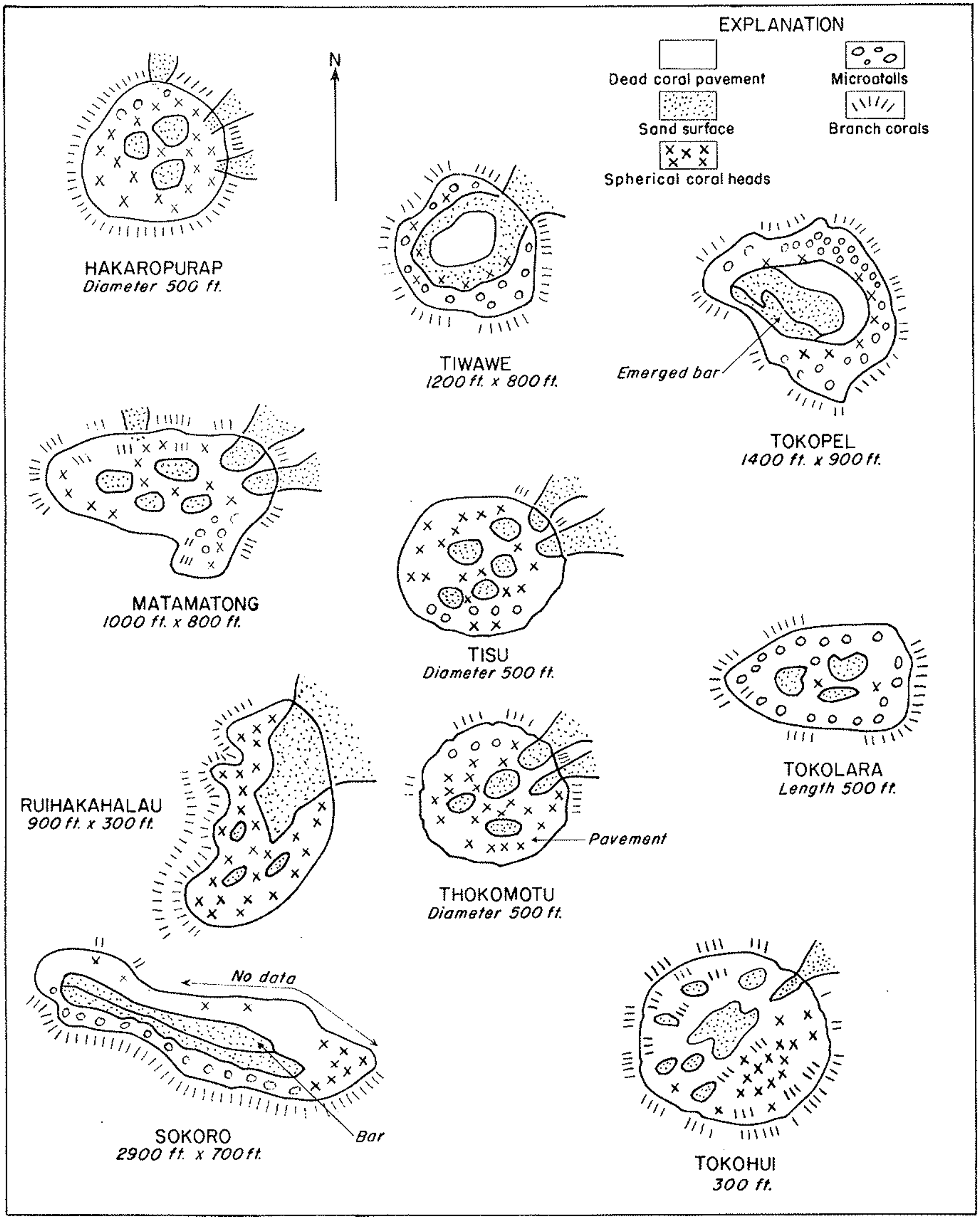

FIGURE 26.-FIELD SKETCHES OF PATCH REEFS SHOWING DISTRIBUTION OF SEDIMENTS AND CORALS

type has ever been drilled." Those writers suggest that the patch reefs may have developed through sporadic coral growth that was initiated during a part of the Pleistocene epoch, when sea level was much lower than now. Such an hypothesis would fit very well the meager knowledge available concerning the shape of the lagoon basin, the extensive bottom sands and muds that are helping to fill it, and the patch reefs that rise to low-tide level within the lagoon. Furthermore, the bevelled surfaces of dead coral, back from the actively growing rims on most of the high knolls, strongly suggest that like the outer reef of the atoll they were higher than at present not far back in history and have been truncated because of a recent drop in sea level. From what may be observed of their simple shape and structure, it seems probable that these patch reefs are similar in all essential respects to the bioherms that have been described from many ancient deposits, especially those of Silurian and Devonian age (Shrock, 1939).

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