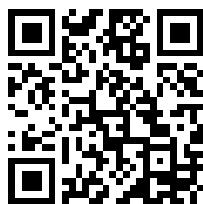

This is a reproduction of a library book that was digitized by Google as part of an ongoing effort to preserve the information in books and make it universally accessible.

Google™ books

<https://books.google.com>



AM

101

.B54

no. 36

B

1,430,820

Gen. Lib.

GEOLOGY OF MANGAIA

BY

P. MARSHALL

BERNICE P. BISHOP MUSEUM

BULLETIN 36

HONOLULU, HAWAII
PUBLISHED BY THE MUSEUM
1927

Dup. U. of W.
Oh.



AM
101
.254
75.36

-38

AM
101
B57
no.36

GEOLOGY OF MANGAIA

BY

P. MARSHALL

BERNICE P. BISHOP MUSEUM *of Polynesian*

BULLETIN 36

*ethnology and natural
history, Honolulu.*

Smithsonian Institution

HONOLULU, HAWAII
PUBLISHED BY THE MUSEUM
1927

PATRICK MARSHALL, M. A., D. SC., ex-PRESIDENT OF THE NEW ZEALAND INSTITUTE IS THE AUTHOR OF MANY PAPERS ON THE GEOLOGY AND PALEONTOLOGY OF NEW ZEALAND, COOK ISLANDS, AND SOCIETY ISLANDS. IN CONSEQUENCE OF THE AWARD OF A BISHOP MUSEUM FELLOWSHIP BY YALE UNIVERSITY, DR. MARSHALL HAS UNDERTAKEN THE STUDY OF A SERIES OF LITTLE-KNOWN RAISED CORAL ISLANDS, BEGINNING WITH MANGAIA, AITU, AND AITUTAKI.

Am
101
B54
no. 36

CONTENTS

	PAGE
Introduction	3
Location and extent	3
Acknowledgments	3
Discovery and settlement	4
Inhabitants	4
Physiographic outline	7
The fringing reef	10
Microscopic structure	14
The terrace slope	17
Microscopic structure	19
The Makatea	20
General features	20
Makatea soil	23
Composition	25
Microscopic structure	28
Chemical composition	29
Age	31
Raised limestones of other islands	34
Taro flats	35
Volcanic slopes	36
Petrographic descriptions	37
Geologic history	39
Sequence of events	39
Conclusions based on study of limestones	43
Conclusions based on physiographic and paleontologic evidence	43
Comparison with Christmas Island	45
Coral reef construction	46
Bibliography	47

ILLUSTRATIONS

Plate I	Topographic sketch map of Mangaia Island.....(In pocket)	
II	Topographic features of Mangaia Island	Following page 48
III	Microphotographs of reef structures	" " "
Figure 1	Bird's eye sketch of Mangaia Island	PAGE
2	Sketches showing topographic features	7
3	Sketch showing stages in the geologic development.....	15
		40

Geology of Mangaia

By

P. MARSHALL

INTRODUCTION

LOCATION AND EXTENT

Mangaia, the southeastern unit of Cook Islands, lies in latitude $21^{\circ} 54' 30''$ S., longitude $157^{\circ} 58'$ W. Its circumference as determined in 1924 is 17.62 miles. These figures differ from those previously published. Captain Cook (9)¹ gives the position of Mangaia as latitude $21^{\circ} 57'$ S., longitude $158^{\circ} 7'$ W.; the British Admiralty (6) as latitude $21^{\circ} 55'$ S., longitude $157^{\circ} 56'$ W.; both the British Admiralty and the New Zealand Year Book (25), state that the circumference of the island is 30 miles.

There is no official map of Mangaia and no Admiralty chart. The only published map is a sketch of the southwest coast made by Captain Cook. Through the courtesy of Mr. A. McGruther, schoolmaster of Mangaia, I was permitted to make a tracing of a map made by E. C. Hall, master of the *John Williams*, from running surveys in 1894-96. Additions to this map were made by Lieutenant Tizard-Ellis, R. N., on the basis of a plan loaned by J. M. Cullen, missionary. Rev. Bond James of Rarotonga sent me the traced outline of a map made during missionary voyages—a map on which the shore features are clearly shown. For my investigations, carried out during July and August, 1923, the existing fragmentary sketch maps were inadequate and unsuitable. It was therefore necessary to make a rough survey of the whole island—a task difficult to accomplish, because of the deep seated belief of the natives that their lands, if actually measured, would be lost to them. The distances had therefore to be estimated by pacing. Accuracy has in consequence suffered considerably. (See Pl. I.)

ACKNOWLEDGMENTS

I wish to record my thanks to Sir Maui Pomare, Minister for the Cook Islands, and to Mr. F. L. Ayson, Resident Commissioner, and the other Government officials at Rarotonga for kindly help and advice. At Mangaia, Mr. A. McGruther, who is in charge of the schools of the island, gave me great assistance, and Mrs. McGruther extended the most generous hospitality during my stay on the island. Mr. Prenderville of Ivirua also helped me greatly and my native guide, Mama Akau, went to

¹ The numbers in parentheses refer to Bibliography (p. 47).

much trouble in pointing out localities of special interest and in obtaining correct native names. From all, Europeans and natives alike, I received helpful courtesy.

DISCOVERY AND SETTLEMENT

The date of the discovery of the islands by the Polynesians is not known. The lists of priests and kings recorded by Gill (14, pp. 314-317) account for 14 generations, and a genealogy recited to me by Daniela Tangi Tarie gives 29 generations. Daniela said that after the migrants who peopled Mangaia had left "Hawaiki" they stayed for two years at Manumanu, which he thought was in Papua, and that from Manumanu they came direct to Mangaia. According to this account the immigrants brought with them taro, banana, coconut, and utu (*Barringtonia*); they found no people on the island and little food; they landed at Avarua—hence the sacredness of that locality and the reason for the erection of the great and most sacred morai there. Daniela added: "The original settlers were peaceful people, but soon after the arrival of a canoe from Tonga fighting began" [about eight generations ago]. Accounts of other traditional migrations to Mangaia are given by Gill.

It is said that the original name of the island was Auau and that the present name was given by a party of Aitutaki natives who had drifted to it when trying to return to Aitutaki after a visit to the island of Manuae, fifty miles distant. Driven about the ocean by perverse winds, these waifs sighted Mangaia, and their leader, Tamaeu, cried out, "Wake up, friends; we have reached Mangaia nui neneva." The meaning of this phrase is apparently "Mangaia absurdly large"—presumably in comparison with Aitutaki, their home. The name Mangaia, which perhaps means "peace," was adopted by the inhabitants in place of the name Auau (Terraced), a term not particularly appropriate to the island. Captain Cook states that the natives sometimes added to the name Mangaia the words "Mooi Nai Naiwa."

Captain Cook (9, vol. 2, pp. 170-179) visited Mangaia in March, 1777, but found it impracticable to effect a landing. He describes the geographic features of the island as follows:

Thus were we obliged to leave, unvisited, this fine island, which seemed capable of supplying all our wants. It lies in the latitude of $21^{\circ} 57'$ South; and in the longitude $201^{\circ} 53'$ East. Such parts of the coast, as fell under our observation, are guarded by a reef of coral rock, on the outside of which the sea is of an unfathomable depth. It is full five leagues in circuit, and of a moderate and pretty equal height; though, in clear weather, it may be certainly seen at the distance of ten leagues; for we had not lost sight of it at night, when we had run above seven leagues, and the weather was cloudy. In the middle, it rises into little hills, from whence there is a gentle descent to the shore, which, at the South West part, is steep, though not above ten or twelve feet high; and has several excavations made by the beating of the waves

against a brownish sand-stone of which it is composed. The descent here is covered with trees of a deep green colour, very thick, but not high, which seem all of one sort, unless nearest the shore, where there are great numbers of that species of *dracaena* found in the woods of New Zealand, which are also scattered in some other places. On the North West part, the shore, as we mentioned above, ends in a sandy beach; beyond which the land is broken down into small chasms or gullies, and has a broad border of trees resembling tall willows; which, from its regularity, might be supposed a work of art, did not its extent forbid us to think so. Farther up on the ascent, the trees were of the deep green mentioned before. Some of us supposed these to be the *rima*, intermixed with low cocoa palms; and a few of some other sorts. They seemed not so thick as on the South West part, and higher; which appearance might be owing to our nearer approach to the shore. On the little hills, were some trees of a taller sort, thinly scattered; but the other parts of them were either bare, and of a reddish colour, or covered with something like fern. Upon the whole, the island has a pretty aspect, and might be made a beautiful spot by cultivation.

In its main features this description by Captain Cook is quite applicable at the present day, though of course the vegetation is in reality varied and generally similar to that of the other islands of volcanic origin in the tropical Pacific. The "trees resembling tall willows" are almost certainly *Casuarina*.

Subsequent to Captain Cook's visit two whaling ships called at Mangaia, from one of which people were landed. In 1823 the Rev. Williams attempted to establish a mission by bringing some Christianized natives from Tahiti. The converts were landed but were forced to leave on the following day. In 1824 other Tahitian converts were more favorably received. In 1825 Rev. Bourne arrived, and a mission firmly established under the leadership of Rev. W. Wyatt Gill (1841) soon became noted for its energy and enterprise in supplying converts to undertake pioneering work in other Pacific islands.

INHABITANTS

The natives of Mangaia are true Polynesians, though perhaps a little darker skinned than some other members of their race, darker, for instance than the Samoans. The average height of the men seems to be about 5 feet, 10 inches. From accounts given by Gill it appears that the population includes people from several islands. The group that inhabits the Keia district is said to have its origin in immigrants from Rarotonga. The ancestors of the Ivirua people are said to have come from some part of Tahiti, those of the Koranga people from Taiarapu Peninsula, Tahiti, and those of the Tamarua people from Tonga. Some Aitutaki natives who were stranded on Mangaia afterwards returned to their own island.

Hereditary dignity and rank were as important in Mangaia as elsewhere in Polynesia. The *ariki* were the overlords and the *rangitira* the landed gentry of high rank. Apart from these people of hereditary rank there were *toa* who attained a high reputation because of their prowess in war. There

was a recognized king or overlord of the inland portions of the island and a ruler almost independent of him who controlled the coastal districts. There is now and apparently was in the past a lord of feasts and ceremonies. It seems, too, that one man controls the activities of those who fish and that another is responsible for the canoes. There were also hereditary priests for the more important deities.

The native houses, enclosed structures resembling those of the New Zealand Maori, are grouped in villages situated on the narrow terraces along the ocean shore or on the top of the Makatea. In former days, however, the people lived on the lower portions of slopes or in the valleys which radiate out from Rangimotia. The Makatea was practically deserted and was crossed by comparatively few paths, from which the natives seem to have strayed but seldom. There were no permanent settlements on the shore terraces, though there were huts which were used by fishing parties. When traveling from one village to another, the general practice was to follow up one of the volcanic spurs to Rangimotia and then descend another spur—the most practicable route when the villages were far apart as it did not involve passage through settlements which might be hostile.

The lord of Mangaia for the time being established his position on the battle field, but mere military success or prominence did not affect the hereditary influence or position of the *ariki*. However, it appears that the lord of Mangaia could deprive an opponent of his estates or reward an adherent by giving him land which had been taken from an opponent. The land was laid out in districts known as *tapere*, that is, sectors which included an arc of the coast and separated from adjoining sectors by straight radial lines converging at the summit of the island. (See Pl. I.) This was considered the most equitable manner of land division, as each family thus obtained as its estate a portion of each kind of land: sea coast, Makatea, taro flats, and high-level slope.

For many years the Cook Islands were recognized as within the British sphere of influence, and in 1901 they were formally annexed to the Dominion of New Zealand. The Government of New Zealand is represented by a Resident Agent, and the laws of New Zealand are applied with special modifications. Land questions and matters of local administration are decided by the island council, which consists of the Resident Agent and representative chiefs. No foreigner can purchase land. All land transfers must be approved by the Government of the Cook Islands, represented by the Resident Commissioner at Rarotonga. At the present time the Government maintains a schoolmaster and a nurse in Mangaia. There are also three European traders and a planter who is married to a native woman.

PHYSIOGRAPHIC OUTLINE

The outstanding physical features of Mangaia are shown in figure 1. The island is surrounded by a coral reef, which in most places has a width of not more than 300 feet; at one place its width is nearly 1,000 feet. From the inner side of the reef platform the coast rises abruptly to a height of 10 to 30 feet and continues as a gentle and more or less uniform slope, which rises 20 feet in a distance of about 600 feet. From the inner edge of this slope a cliff 65 feet high rises abruptly, forming a wall which may be climbed at very few places. Extending inward from the top of the cliff is a broad surface, from which project innumerable sharp limestone pinnacles, when travel is impracticable except where paths have been made. This raised platform of eroded coral rock is called the Makatea; a little more than a half mile from the coast its surface stands about 200 feet above

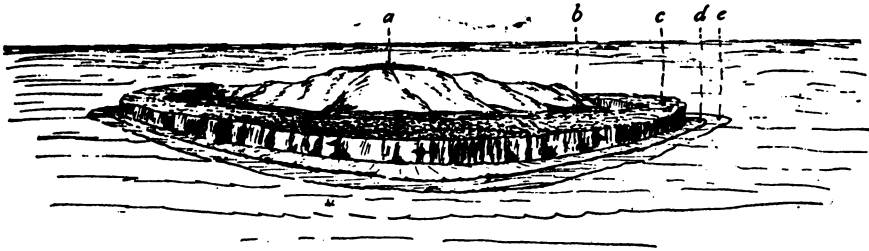


FIGURE 1.—Bird's eye sketch of Mangaia Island: (a) Rangimotia, flat summit 554 feet above sea level; (b) Taro flats 0-500 yards wide, 20-40 feet above sea level; (c) Makatea, raised barrier reef $1/2$ to $1-1/2$ miles wide, 110-210 feet above sea level; (d) Terrace Slope about 100 yards wide, 45 feet high at inner margin; (e) present coral reef 300 yards wide; the boundary between d and e is a cliff 15 to 35 feet high. (Reproduced from B. P. Bishop Mus. Bull. 21, 1925.)

sea level. At its inner edge, the Makatea is terminated by a steep cliff which descends 150 feet or more—in places almost to sea level—and which is unscalable for the greater part of the circumference of the island. At the foot of this inward-facing escarpment lie extensive swamps, which receive all the run-off from the central part of the island. The swamps are drained by subterranean channels passing to the sea through the Makatea at depths of more than 150 feet. The central part of the island is a dissected mass of volcanic rock, which rises gradually to a height of 554 feet above sea level. Generally this igneous core is separated from the Makatea by the moat which contains the swamps; but in a few places projecting spurs extend downward to the Makatea platform. The summit of the island is a flat surface three-quarters of a mile long and less than a quarter of a mile wide. The central point of this flat is called Rangimotia, the "Crown of Mangaia."

Traced from deep water inland the outstanding topographic features of Mangaia are as follows:

1. Steep submarine slope.
2. Lithothamnion ridge, 20 to 30 yards wide.
3. Reef flat, 80 to 300 yards wide.
4. Low cliff, 4 to 20 feet high.
5. Terrace Slope, sloping ground 200 yards wide with two ill-defined terraces rising to 45 feet.
6. Outer cliff of the Makatea, 65 feet high.
7. Surface of the Makatea rising inland 100 feet in 300 to 2500 yards.
8. Inner cliff of the Makatea 200 feet high (except where higher ground abuts against it).
9. Taro Flats, 0 to 400 yards wide.
10. Volcanic Slopes rising to center of the island.
11. Central Plateau 1200 yards long, 20 to 200 yards wide, standing 554 feet above sea level.

John Williams (31, p. 39) speaks of Mangaia as "about 20 to 25 miles in circumference and moderately high. The island is rather singular in its form and appearance, a broad ridge girding the hills at about 100 feet from their base." On the basis of descriptions by Williams, Darwin (11, pp. 132, 139) comments as follows:

Mangaia is nearly 300 feet high with a level summit, and according to Mr. S. Wilson it is an upraised reef and there are in the central hollow, formerly the bed of the lagoon, many scattered patches of coral rock, some of them raised to the height of 40 feet. These knolls of coral rock were evidently once separate reefs in the lagoon of an atoll. Mr. Martens of Sydney informed me that this island is surrounded by a terrace-like plain at about the height of 100 feet, which probably marks a pause in its elevation.

The improbability of Mangaia, a fringed island of the same group [Cook Islands], having retained its nearly perfect atoll-like structure during any lapse of time after its upheaval There can be scarcely any doubt that Savage [Niue], Aurora [Makatea Island], and Mangaia Islands and several of the islands in the Friendly Group existed originally as atolls, and these have undoubtedly since been raised to some height above the level of the sea; so that by our theory there has here also been an oscillation of level, elevation having succeeded subsidence instead of, as in the Red Sea and at the Hervey Islands, subsidence having probably followed recent elevation.

The British Admiralty (6, p. 38) states:

Mangaia is about thirty miles in circumference and otherwise differs from most of the Pacific islands. It is 656 feet high and at a distance appears almost flat; there is a fringing reef all round, extending from 50 yards to two cable lengths from the shore and about two feet above highwater mark; but there is no passage through it. Ships can approach the edge of the reef to within one cable, as there are no outlying dangers; but there is no anchorage, the reef being steep to everywhere.

The following particulars have been obtained from Berghaus Physical Atlas: Rise and fall of tide, one meter; the island is on the margin of a slow warm current from the north, though in February there is a cool current from the southwest; temperature of the water is 24° C. in January and 21° C. in July, the annual average being 22.5° C. The island lies on the barometric isobar of 760 mm.; in January it lies on the southern boundary of the Trade Winds with an average barometric reading of 758 mm.; in July it lies to the south of the Trade Winds with a barometric reading of 761. The winds, however, are variable, and the island is rarely visited by hurricanes.

THE FRINGING REEF

Mangaia is surrounded by a fringing reef, the raised rim of which is 60 to 90 feet wide. The seaward edge, exposed to a maximum height of two feet at low water, is very irregular; deep chasms, varying in width and in depth but not exceeding 30 feet in width, penetrate far into the rim and in places cross it. The chasms are bounded on both sides by large masses of limestone formed in situ by organic growth, and large masses project seaward beyond the average front of the reef. Rounded and extending outward beyond their support they form overhanging bosses of the reef precipice. The fringing reef is always kept awash by surf.

Everywhere the outer margin of the reef descends abruptly, but in the absence of soundings the nature of the slope is not known. It can only be said that no spot has been found where anchorage is practicable and that there are no off-shore shallows. The native fishermen say that everywhere at a distance of about 1000 feet a depth of 100 fathoms is found and that no depth less than 30 fathoms is to be found anywhere round the island. Inside the slightly raised outer border of the reef there is a sudden downward step of two or three feet. Here the true reef flat begins and extends to the island shore. The outer ridge present on all exposed Pacific reefs is the well-known "Lithothamnion ridge," so named from the calcareous seaweed of which it is almost entirely formed. The surface of the outer ridge of the reef, which appears to be generally smooth, is quite rough in detail. The roughness is partly due to the irregular growth of this seaweed and partly to the destructive effect of various boring animals. These agencies produce a knobby surface with narrow but rounded projections two to six inches high. Darwin, who first called attention to the outer ridge of a coral reef, described it as due to the growth of nullipores, now more accurately described as calcareous seaweeds. Many succeeding authors have noticed this feature, and the Lithothamnion ridge has now a recognized place in the description of coral reefs. Many of the irregular perforations of the surface connect with branching narrow passages throughout the ridge, which is in effect a huge rigid spongy structure on which the heavy surges of the Pacific break and spend their force. In stopping waves this irregular knobby growth seems far more effective than more solid structures, as the force of the wave is widely dispersed and the risk of damage is naturally far less. The Lithothamnion of which this portion of the reef is formed must be kept constantly wet or it dies. Hence the ridge extends only as far as the limit of the tongue of the breaking wave at low tide in calm weather. Hence also, the rougher and the more constant the swell the higher this protecting Lithothamnion ridge of the reef will grow.

The small pockets between the projections of the Lithothamnion are much favored as cosy corners by echinoids. On the southern side of Mangaia, in particular, where the surf is almost always fierce and the reef is seldom visited by the natives, echinoderms can be seen in thousands and cannot be extracted from their guarded chambers unless the rock around them is broken with a hammer. Numerous shell fish also live in the crevices, and in the larger ones corals may be seen, though these are not abundant except in the more sheltered corners and on the outer slope of the reef below the level of violent surf action.

As soon as the outward growth of the reef prevents the surf from reaching the inner edge of the Lithothamnion ridge, the seaweed there dies. Deprived of its vital strength the material soon breaks up and is washed away to the inner side of the reef flat and onto the beach in the form of sand. The surface of the reef flat is always below low-water level. Where the rise and fall of the tide is considerable or where the surf is high, the water on the reef platform is deeper than elsewhere. On the south side of Mangaia it is in many places as much as three feet deep, but on the western and northern side it is far shallower. The actual depth, as Mayor (23, p. 35) points out, is really a measure of the erosive power of the waves which sweep over the top of the Lithothamnion ridge. Heads of coral grow sporadically on this flat, and examination of fragments of the rock obtained at distances of fifty and a hundred yards from the outer edge of the reef at Oneroa showed that the surface of this flat consists of rock formed by true corals. How much of the Mangaia reef flat has been formed by the outward growth of the reef at the present sea level and how much by the marine erosion of the Terrace Slope (p. 17) could not be determined. The proportions, in all probability, differ in accordance with the aspect of the reef. On the southeast, where erosion is most rapid and the cliff that bounds the reef flat is highest, it is probable that as much as 30 yards of the Terrace Slope has been removed, but on the west, where the erosive action is far less intense, the width of reef flat formed in this way is much less.

Microscopic preparations of specimens obtained from the top of the Lithothamnion ridge at Oneroa and at Ivirua showed that the ridge was almost entirely composed of encrusting organisms. It would require an expert biologist to identify all the organisms that combine in the construction of the Lithothamnion ridge of such a coral reef as that of Mangaia. The actual projecting knobs are hard limestone, which has a fracture that is almost splintery. Examined with a lens it is impossible to discern any structure in it except here and there a fragment of coral, which may have been jammed into a crevice and rapidly encrusted by some of the vigor-

ous vegetable growth. A few Foraminifera may be seen; they were forced into some cranny and again covered with some protecting encrusting growth. But the general mass of this Lithothamnion ridge is dense and hard. Under the microscope, Lithothamnion and Lithophyllum are seen to be the prevalent forms, but Polytrema is common, also an organism that is perhaps Carpenteria.

The surface of the knobs on the ridge is almost covered with the encrusting lichenous form of Lithothamnion, which in the hand specimens can with difficulty be distinguished from Lithophyllum. In all specimens, Polytrema can be seen as bright red discs and also as the branched form with curious siliceous rods projecting from the orifices. But everywhere the surface supports a thick growth of Corallina in slender filaments, which soon become calcareous. It is curious that Mayor, who gives such excellent descriptions of the Lithothamnion ridge, failed to record the presence of the Polytrema, which is so important as an incrusting organism and as a reef builder, and of Corallina, which covers so much of the reef with its fine mossy growth. David (12, p. 156) ascribes to Polytrema its important part round the edges of the blow holes and channels but scarcely mentions the general occurrence of this organism over the surface of the knob processes and hollows of the whole ridge. Even this report, however, passes in silence over the profusion of growth of Corallina, which, in Mangaia at least, is perhaps the most abundant of all the organisms of the Lithothamnion ridge. At Mangaia this ridge is different in structure from that described by Mayor (22) as typical of the Samoan reefs.

The Lithothamnion itself grows so slowly at tide level that it alone would not form a ridge were it not for the fact that it quickly covers, smooths over, and cements upon the reef flat all corals that have died, thus securing the retention of any accession of limestone which the seaward edge of the reef may have once attained. The Lithothamnion itself is merely a cementing, binding, veneering, smoothing, and wave-breaking sheet which covers and preserves to the reef the limestone formed of the dead coral which once grew upon it.

On this reef the violence of the surf prevents the accession of any coral fragments except the most occasional ones that happen to become rigidly wedged in the irregularities of the reef, a conclusion based on observation of the surface of the ridge, consideration of the conditions to which it is subject, and microscopic examination of rock slices. As is to be expected, the whole fabric of this ridge is almost everywhere perforated by the borings of worms and other animals. However, much fine sand is entangled among the algae and microscopic preparations show it to be an important constituent of parts of the reef.

In no place is the fringing reef penetrated by a channel from its outer margin to the strand, all the crevices which extend far into it being narrow,

although at Oneroa one of the crevices though shallow has been artificially enlarged. The cause for the absence of animal and vegetable growth in these crevices is hard to discover. It is not to be found in the violence or erosive power of the waves nor in a lack of growing organisms, though it is possible that the activity of these is less than normal. It is possibly a matter of temperature. During falling tides, water from the reef platform, which has lain for hours in shallow pools under the torrid rays of the sun, flows outward, and in calm weather the temperature of this outflowing water must be some degrees higher than the ocean water. Soon after the change of tide more and more ocean water forces its way into the channel at a temperature which must be distinctly lower than that of the water which has been lying on the flats of the reef platform. I know of no records that give a measure of the change in temperature and can only suggest that this frequent and considerable variation in temperature may cause less active growth on the part of the organisms that have established themselves on the sides of these crevices.

The fresh water supplied by the inland streams flows along underground channels beneath the Makatea and issues as springs near the inner edge of the reef flat. (See p. 35.) One spring is near Avarua where the water of the Tareao and other streams wells up. Another is at Wainato on the south side of the island where the water of the Taurangakakaia issues after passing through Lake Tiriara. It is very noticeable that at both of these places there is no channel over the reef flat or through the Lithothamnion ridge. This fact shows clearly that the mere presence of fresh water cannot be the cause of the existence of channels through the reef.

Mayor (20, pp. 31, 32) records the temperature of the ocean water and of the water on the reef flat of Murray Island (Torres Strait) taken from September 30 to October 23, 1913. On the reef flat, 200 feet from the shore, the highest temperature was 34.5° C. and the lowest 22° C., while in the breakers at the outer edge of the reef the corresponding records were 28.4° C. and 24.9° C. There must then be rapid changes of temperature where the reef flat water flows outward to the ocean when the tide falls. The temperature variation on the reef flat near the beach is 9° C. greater than in the ocean water.

The present living reef of Mangaia has, of course, been formed during a period of stillstand of unknown duration. The period has been long enough to allow of the formation of a reef flat which attains at Atukora a maximum width of 636 feet. The steep slope outside the reef indicates that the outward growth of the reef is slow, but in the absence of exact soundings no quantitative measures of growth are possible. The variation in the width of the reef flat probably is related to the form of the submarine slope of

the island rather than to the action of ocean currents or of prevailing winds. The ocean currents are supposed to fluctuate considerably during the year, and in this island where the reef has its greatest extent it is most sheltered from the Trade Winds and from the ocean swell.

Isolated fragments of limestone, "nigger heads," are uncommon on the reef at Mangaia. On the south and east coasts, where they are very rare, they are found close to the cliffs, from which they evidently are derived. On the north and west coasts a few were seen. There is a conspicuous one near Atuakora which Numangatini, the king of Mangaia, says that within his memory was washed ashore by a hurricane. This distribution of "nigger heads" may be explained in part by the fact that the most violent hurricanes come from the northwest toward a shore which generally is calm and in part by the fact that the swell from the prevalent trade wind on the south and east coast sweeps boulders inward before they became cemented to the reef by organic growth. My field observations show that this explanation of the distribution of "nigger heads" applies also to the islands of Rarotonga and Aitutaki. The living reef at Mangaia presents no features which indicate a recent rise of land or fall of sea level.

MICROSCOPIC STRUCTURE

Microscopic preparations of the material of the Lithothamnion ridge at Ivirua and at Oneroa show a preponderance of Lithothamnion. (See Plate III, *A, B, C.*) The edges of the thallus are brown with organic matter, but the interior is nearly colorless. Some thin sections show an abundance of encrusting *Carpenteria*; others show none. All specimens include a small amount of *Polytrema* which even in thin sections shows something of its pink color. This color remains even when the organism has become completely surrounded by a continuous growth of Lithothamnion. A slender branched coralline having round transverse section, is everywhere. No success was achieved toward distinguishing between *Lithophyllum* and *Lithothamnion*, but both are probably represented in all of the preparations. Occasional spines of echinoids occur. Sand, mainly fragments of joints of *Halimeda*, constitutes about one-third of some slices of the rock. Grains of *Carpenteria*, *Polytrema*, *Corallina*, rare grains of *Lithothamnion*, and small fragments of coral, echinoderms, or molluscan shells are also present. In seven preparations only one test of a free foraminifer was seen. In sections made from the ridge at Oneroa there are many round sections .03 mm. in diameter with radiate crystalline structure of aragonite. These objects seem to be similar to the aragonite crystallized round the tubes formed by boring algae in limestone described by Skeats from Niue Island (28, p. 107, fig. 2). The sand grains are

cemented together by secondary calcite in the form of slender prisms with their long axes at right angles to the surface on which they grow. This is clearly the fibrous calcite found by David (12, p. 396; 28, p. 67) at

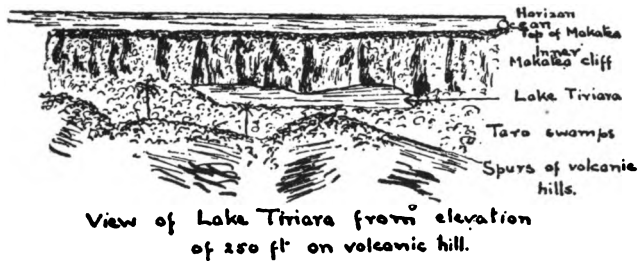
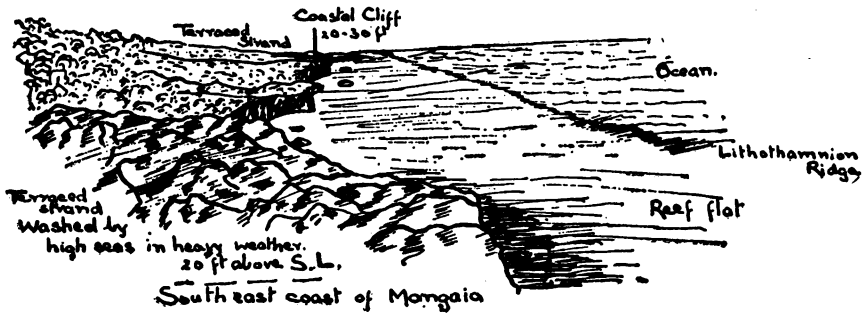


FIGURE 2.—Sketches showing topographic features of Mangaia Island.

Funafuti in borings at 30-80 ft., 20-72 ft., 20-30 ft., and 800-1100 ft. None of the prisms appearing in the preparations made from specimens taken from the superficial part of the reef exceeds 0.012 mm. in length. This

important fibrous substance appears at first sight to be aragonite, but tests by the staining methods described by Skeats and David show definitely that the substance is calcite. On the other hand, the prisms developed in continuity with coral fibers at Funafuti were proved to be aragonite. In the preparations of Mangaian rocks, the fibrous deposit has precisely the same appearance whether developed on corals, Lithothamnion, Halimeda, or echinoids.

The material of the Lithothamnion reef is very tough. It is more difficult to break with a hammer than are most igneous rocks. It is thought that the presence of secondary calcite deposited almost at the actual surface of the Lithothamnion ridge in large part accounts for the resistance of the portion of the reef on which the surf breaks. The very existence of many Pacific islands depends on the efficiency of the Lithothamnion ridge in breaking the force of the huge ocean waves. Even after a severe hurricane like that of March 25, 1926, at Rarotonga, the surface of the Lithothamnion ridge appeared unbroken and no boulders derived from it were found on the Fringing Reef. Many new boulders were seen, but like the older ones, they consist of coral, evidently torn from the outer edge of the reef below the Lithothamnion protection.

This record appears to establish the probability that the protection of the oceanic islands in the coral seas is due to the rapid deposition of secondary calcite within the material of the Lithothamnion ridge in all the interstices between the sand grains and the organisms of which it is mainly formed. The skeletons of the coral polyps by themselves seem unable to withstand the violence of the boiling surf which is flung against the reef.

THE TERRACE SLOPE

A narrow beach fringes the reef flat at Mangaia. It is continuous at Oneroa, where it extends for about two miles. Even at places along this coast, cliffs of hard limestone 8 to 20 feet high rise direct from the reef flat and elsewhere they are almost continuous. These cliffs are irregular in outline, in most places are undercut and penetrated by chasms. As the floor of these chasms rises gradually to the level of the Terrace Slope, the reef flat may be easily reached. At high tide the sea washes to the base of the cliff, and in rough weather a moderate sea dashes against it.

From the top of the cliff, the ground slopes gently upward to an elevation of 20 or 25 feet, where there is an ill-defined terrace, not more than 20 yards wide, from which the ground again slopes upward but forms a second and rather more distinct terrace 90 to 120 feet wide at an elevation of 40 feet. These terraces are not well defined but are merely observable steps in gradual upward slope from the top of the low sea cliff. In places the sloping ground and the terraces together have a total width of 450 to 600 feet, though rarely more than 300 feet. The actual distance was measured in a few places only, as the ground was difficult to traverse because of the highly irregular nature of the limestone surface of the Terrace Slope and the denseness of the vegetation with which it is covered. The terraced ground with its main features is, however, continuous all round the island. The upper terrace is used for a road which passes from Tamarua through Oneroa and extends almost as far as Ivirua, but it is not used on the exposed southeast portion of the coast line, which is practically uninhabited. It is said that during the hurricanes which visit the island about once in twenty years the sea rises as high as the upper terrace.

The rock of which the Terrace Slope is formed is coral limestone, in which the structure of the corals may be clearly seen on weathered surfaces. On the southeast coast, one mile south of Ivirua, the rock is entirely composed of joints of *Halimeda*. Very little *Lithothamnion* is to be seen in this limestone.

The surface of the limestone, though highly irregular, supports a vigorous vegetation, and over a considerable area coconuts have been planted. On the most exposed portion of the coast there is little vegetable growth; though *Pandanus* trees flourish there. The terraced ground is without running water, and the inhabitants of the coastal villages rely upon rain water caught in concrete tanks. There is but little soil on this rough limestone ground, but at Oneroa, where the limestone blocks have been re-

moved and the ground has been leveled, the surface is covered with an attractive sward of grass.

The upper of these two terraces is perhaps the coral growth at the foot of the steep slope at the outer edge of the old reef, which is now the Makatea. It is, however, clear that both of these ill-defined terraces were formed at periods of relative stillstand during the elevation of the island. Their small size, however, indicates that these intervals of rest were brief and were perhaps merely periods of less rapid movement during a prolonged uprise. The receding water, however, removed the veneer of *Lithothamnion*, which grows so freely on the water-washed surface of a reef but which dies when raised beyond the reach of the low-tide waves.

Little or no sand or other fragmentary matter has accumulated directly at the foot of the Makatea cliff, though the surface of the terraces and the sloping ground between is covered with boulders and large irregular masses of coral rock.

The low irregular cliff at the seaward edge of the Terrace Slope varies greatly in height. It attains a maximum elevation of 30 feet on the south-east coast and gradually decreases in height both north and west. At Kumu Kumu and at Wainato its height is not more than 20 feet, and at Atuakora it is 3 to 4 feet high. These facts suggest that the differences in height are due to erosion resulting from the action of waves which at high water rush over the reef and fling themselves with some violence against the cliffs. The heaviest ocean swell comes from the south-southeast, and it is in this quarter of the island that the cliffs are highest. At Atuakora, where the shelter is most complete, the cliffs are inconspicuous and the accumulation of sand on the sea coast is great. It is evident that marine erosion at the present level has been in operation for a long period. If the seaward slope of the present shelving Terrace Slope extended outward with its present inclination it would have reached almost half way across the reef at Maniania but a very little distance at Atuakora. At Maniania, during the same period of time, the reef has grown outward 75 yards, and marine erosion has worn the limestone back for 50 yards. Unfortunately the data are so uncertain that no conclusion of importance can be based on this statement.

Except along the southeast shore there are little beaches of coral sand and shells between and beneath the projecting rocks of the Terrace Slope. On the west coast, sandy beaches are continuous from Oneroa to Autakora, but at no place is the coast line growing outward.

Hard cemented beach rock appears at many places, especially north of Oneroa. It includes many large shells and large fragments of coral, thus

giving the rock an appearance quite different from the beach sands. This hard beach rock is a feature of coral beaches. It is extremely well developed at Palm Island inside the Great Barrier Reef of Australia. The suggestion of Daly (10, p. 135) that this material results from the detritus thrown on the beach during hurricanes and rapidly cemented by the deposition of calcium carbonate is supported by observations at Mangaia.

MICROSCOPIC STRUCTURE

Specimens of limestone were collected only on the outer side of the Terrace Slope. It could be seen in the field that the rock is mainly composed of corals growing in situ and that sand is present in relatively small amount.

Microscopic preparations show that among the grains of sand are many fragmentary joints of *Halimeda* which have retained their organic matter. There is some *Amphistegina*, but otherwise the materials of this sand call for no particular notice. The sand grains are cemented together by fibrous prismatic crystals of calcite, which towards the center of the large cavities are crowned by rhombohedral crystals not found in the superficial material of the *Lithothamnion* ridge. There are also prismatic crystals of aragonite. As shown by David (12, pl. F, fig. 1, p. 399, fig. 32) the association of fibrous and rhombohedral calcite at Funafuti is far less marked.

Specimens from the bottom of the Makatea cliff contain *Halimeda* also, but here it is without organic matter. Unfortunately, no specimen was obtained from the surface of the limestone exposed over the area between the outer foot of the Makatea and the outer edge of the Terrace Slope. It is not known whether the change in field occurrence of *Halimeda* in the limestone rock is sudden or gradual.

THE MAKATEA

GENERAL FEATURES

The Makatea on Mangaia is a circular platform of limestone bounded on the inner and outer sides by cliffs (figs. 1 and 2). The outer cliff at the landward edge of the Terrace Slope is nearly 70 feet high, and for the greater part of the circuit of the island it is practically perpendicular. In a few places, for example, one mile west of Tamarua and at the extreme northern point of the island the cliff rises in two terraces continuous for only short distances. In its original condition the cliff is extremely difficult to climb. Steps have been formed artificially up the face of the cliffs in twelve places known to me, and a steep roadway has been formed by blasting the rock and by excavating at two places—the western side of Tamarua and the northern side of Ivirua. In these two places minor local terraces of the edge of the Makatea have made road building possible. Viewed from the top of the cliff the general surface of the Makatea appears from a distance to be almost level, but an attempt to cross it reveals its extraordinary roughness. It is an exaggerated *karrenfeld* of the Karst region, on a small but more intricate scale. The surface is formed entirely of hard, splintery limestone projecting everywhere in sharp serrated pinnacles ten to fifteen feet in height and is trenched by numerous crevices with vertical or even overhanging sides, many of them expanding into caves of irregular form and extent. The whole Makatea structure is riddled with chasms, while vertical pinnacles and palisades with needle-like projections and razor edges are found everywhere in extravagant profusion. And this intricate rocky maze is covered with a tangle of interlacing vegetation, making a surface almost impossible to traverse.

Barometric observations taken at Oneroa show that the seaward edge of the Makatea stands 114 feet above high-tide mark. The altitude rises inland, and, at the inner edge a maximum altitude of 232 feet was recorded. The slope of the surface inland is not regular; in places there are more or less defined steps, but the covering of vegetation and the irregularities of the surface make it difficult to determine whether or not the height of the surface increases by well-defined and more or less continuous terraces. When a comprehensive view was taken of the surface of the Makatea from an equivalent level of the central volcanic hill, its surface was found to be generally coincident with the line of the horizon. Near Tamarua, however, the level is 40 to 50 feet lower than elsewhere. Exact leveling is required to determine the form of the surface. It was likewise found difficult to measure the width of the Makatea. The roughness of the surface and the

objection of the natives to actual measurements made it necessary to depend upon pacing, and even this was impossible except along the winding native paths. It is estimated that the Makatea is 2,850 feet wide opposite Oneroa, about 2,100 feet wide at Iriuvua, and only 900 feet wide at Tamarua. At the southeast end of the island it is about two miles wide.

Everywhere between the pinnacles there is a red friable soil in which thrive coconuts, oranges, limes, coffee, kumara, and yams.

Here and there native paths cross the Makatea. Most of them are narrow, uneven trails winding between the pinnacles, ridges, crevasses, and caverns which abound everywhere. The roadway leading from the landing at Oneroa is forty-five feet wide. From Lake Tiriara a path extends westward for a distance of two miles. My native guide greatly disliked to cross the Makatea anywhere except along the well-known paths. I persuaded him to leave the trail at Kumu Kumu and again at Tamarua; but he soon became lost in the intricate ravines and ridges.

Coconut palms flourish in the soil between the jagged rocks of the Makatea, although there are large areas in which no palms appear. It is interesting to note that in these areas there are no native paths. This peculiarity of distribution appears to justify two conclusions: (1) that the coconut has been brought to the island by human agency; (2) that it was brought at such a recent date that it has not yet been able to distribute itself over all the ground that is suitable for its growth.

Originally the natives had no habitations on the Makatea. The want of water and the absence of ground suitable for taro growth made it unattractive. In general they lived in the interior where taro could be grown and water was plentiful, and they visited the seashore only for fishing. The present villages of Tamarua, Ivirua, and a large part of the village of Oneroa are on the Makatea. However, the men of these villages often fish outside the reef or attend the coconut plantations within the Makatea, and the women plant or weed taro in the swampy flats at the inner base of the Makatea, and do the family washing in the streams which issue from the volcanic country.

The limestone cliff which forms the inner border of the Makatea and faces the volcanic nucleus of the island is a most conspicuous feature. Opposite the mouth of the Taurangakakavaihi, near Oneroa and on the northwest side of Lake Tiriara, it stands as a vertical wall, and nearly everywhere else it is vertical for the greater part of its height. In places the cliff is bare; elsewhere much of its surface is obscured by trailing fig roots or by lofty palms growing on the ground at the base of the cliff. (See Pl. II, B.)

The inner edge of the Makatea stands at about 200 feet above sea level. Measurements with an aneroid and an Abney level showed that in Tamarua where Makatea is narrowest, its height is at least fifty feet less than elsewhere. At the north end of Ivirua also the height is somewhat less. The fact that the inner edge of the Makatea is lower on this southeast side of the island prompted the idea that it might be higher on the northwest side. But measurements at Atuakora show no departure from the normal level. Consequently there appears no definite indication that tilting has taken place since the formation of the reef that now constitutes the Makatea. Accurate leveling, however, may show slight tilting.

A series of rock specimens was obtained at two localities on the face of the inner cliff of the Makatea and two other series from the outer cliff. These have been submitted to chemical and microscopic examination.

At the very base of the inner cliff at the bottom of the sink hole where the water of the Tareao and of other streams from the high land passes under the Makatea, two corals were found in the partially weathered rock. Regarding these, Dr. T. Wayland Vaughan wrote to me as follows: "One of your specimens is a species of *Pocillopora* and the other seems to be *Orbicella* sp. near *O. curta* Dana. As you know, the specimens are not very good, but I think I have given you the correct generic names. Both specimens are of corals of reef facies."

These genera demand a depth of water less than the 209 feet implied by the thickness of the limestone rock. The actual base of the old reef at its junction with the igneous rock unfortunately is not exposed; though the bottom of the sink from which the corals were obtained is not more than ten feet above present sea level.

The vertical inner wall of the Makatea is an important feature; for it appears that during the period of its upward growth the reef which formed the Makatea was sufficiently wide to prevent the transport of much material over its surface. There appears also to have been little or no growth over the wall itself. This suggests that the reef encircled the island completely and that water within it was to a great extent cut off from the ocean thereby lacking some of the freshness and agitation that seems to be necessary for the growth of corals and to a less extent of various other reef-building organisms.

Except at Lake Tiriara, no facts were discovered which indicate whether or not the limestone wall of the Makatea descends to or below the present sea level. The base of the wall is concealed and its relation to sea level and to the adjoining volcanic core of the island can be determined only by physiographic evidence. By extending in imagination the slopes of volcanic rock to the point where they intersect the Makatea, it appears that the base

of the inner wall is 20 to 30 feet below the present sea level. At Lake Tiriara, the wall of the Makatea descends below the lake level which is no more than 15 feet above sea level. It may seem curious that the Makatea includes no fragments of volcanic rock, even at those places where it abuts directly against the volcanic spurs. To discover if this relation is characteristic of reefs, a careful examination was made of Black Point, Rarotonga Island, where a bluff of leucitophyre 30 feet high projects onto a fringing reef 600 feet wide. Although the rock is washed by the waves at high tide, it was found that no fragments of it are swept onto the reef. They all seem to be thrown directly onto the beach.

Though the inner wall of the Makatea is mostly straight and uninterrupted, there are some minor spurs and islands inside the general line. These, however, are so few and exceptional that they do little more than emphasize the surprising regularity of the wall.

MAKATEA SOIL

The following analysis by Mr. B. C. Aston of the Department of Agriculture, New Zealand, shows the composition of the red soil which occurs generally over the surface of the Makatea at Mangaia:

SiO ₂	8.84
TiO ₂	5.10
Al ₂ O ₃	19.70
Fe ₂ O ₃	31.74
P ₂ O ₅	2.48
CaO	1.60
Loss on ignition.....	30.80
Total	100.26

This unusual composition suggests that the soil is in origin a completely lateritized remnant of basaltic material mixed with some phosphoric acid derived from bird excrement.

The question at once arises as to how this material was brought to the Makatea, in view of the fact that the physiography of the island shows no volcanic action subsequent to the beginning of the formation of the reef. It might be suggested that this material was carried by winds, but its uniform distribution as well as the present complete cover of vegetation discounts this. One theory that I have to offer at the present time is that the red soil was carried from the central volcanic hill to the Makatea by birds for the construction of their nests. Several of the larger sea birds, such as the albatross and petrels, build mud nests. When first the Makatea emerged above the sea it would be destitute of vegetation and would afford a secure nesting ground, while the thick covering of vegetation on the volcanic land

might discourage nest building there. It is noticeable that a somewhat similar surface soil covers much of the limestone at Christmas Island, where its occurrence is ascribed by Andrews to supposed preexisting volcanic rock completely decomposed (4, pp. 50, 191). It has the composition SiO_2 5.0, $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ 32.5, CaO 2.5, P_2O_5 39.0. However, Andrews specially mentions that the nest of the thrush (*Merula erythropleura*) is not mud lined. Another suggestion is based on the distribution of wild duck (*Anas superciliosa*). This bird is now fairly numerous on Mangaia Island and at earlier stages when the old lagoon was a fresh water lake surrounding the volcanic land and before the arrival of the Polynesian migrants the duck may well have been abundant. The Makatea would have provided a most suitable surface on which the birds could alight and sun themselves. Duck feed in shallow water and swallow with their food a quantity of the inorganic matter forming the floor of the sheet of water. Their excrement, therefore, contains a considerable proportion of inorganic matter.

Mr. B. C. Aston of the Department of Agriculture, New Zealand, has called my attention to the following analyses:

	1a	2b
Water	56.60	46.65
Organic matter	26.60	35.12
Nitrogen	1.00	
Phosphoric acid	1.40	3.15
Potash	0.62	0.32
Lime	1.70	3.01
Magnesia	0.35	
Sand		10.75
	88.27	100.00

a As compiled by Storer (30, p. 616).

b As compiled by Johnstone (16, p. 297).

In analysis No. 1 it appears that no estimate was made of the inorganic matter present and it is noticeable that the substances that were isolated fell short of 100 by 12.13 per cent. In analysis No. 2, the sand probably represents the inorganic matter. The quantity of this would amount to approximately 85 per cent of the residue after prolonged atmospheric action.

It may seem that the amount of earth on the Makatea is so great that the explanation offered is insufficient. However, the quantity of material at Mangaia Island is less difficult to explain than at Nauru and Makatea islands, where the phosphate rock is ascribed to the action of the phosphatic constituent of the dung of sea birds on the coral limestone. No more than 8 per cent of the excrement is available, to form the large amount of phos-

phate rock. In the Makatea soil of Mangaia, as much as 14 per cent of the excrement would escape destruction by atmospheric action. As the Makatea has been above sea level continuously since the Miocene, sufficient time has elapsed for great accumulations.

COMPOSITION

In general, the limestone forming the Makatea has a dense, compact appearance, in which no structure is discernible in hand specimens. Even corals cannot be distinguished, and some of the limestone appears like consolidated sand. At the time my collections were made it was thought that this limestone was all of recent age, like the limestones collected by Lister at Eua and by David and his colleagues at Funafuti Island.

The only free specimens of coral found in any part of the Makatea were *Pocillopora* and *Orbicella*, described by Vaughan as certainly belonging to the reef facies. They were undoubtedly in the position of growth (p. 43). Microscopic examination of the rock (S1) at the Tareao Sink in which the corals were embedded reveals various species of calcareous algae, especially *Lithothamnion*, *Lithophyllum*, and *Halimeda*, and a small foraminiferous shell thought to represent a species of *Amphistegina*. There are also specimens of encrusting species of *Foraminifera*, which have large numbers of small irregular chamberlets and represent forms like *Polytrema*. Thus this lowest part of the Makatea formation presents clear evidence of the presence on the Mangaian shores of that remarkable association of corals, calcareous algae, and *Foraminifera* which is still the active brotherhood in forming coral reefs on exposed coasts wherever they are found.

A stratum in the Makatea, S2, about 15 feet above the horizon represented by S1, contains calcareous algae, a few *Amphistegina* and a species of *Cycloclypeus*, but the most common organism is a species of *Operculina*. The *Operculina* is of comparatively small size and does not show the wide flange which in many specimens is such a conspicuous feature of the genus. The encrusting species with its irregular chamberlets is common, and there is also a large conical shaped foraminifer which has not yet been specifically identified. The steepness of the cliff made it impossible to obtain specimens along the upper part of the Makatea face at this point.

A series of seven specimens was collected from the inner cliff of the Makatea at a point where steps ascend the face of the Makatea, about one mile southeast of Tareao Sink. These specimens were taken at nearly equal intervals from the bottom to the top of the cliff. The specimen from the lowest of these levels (Ib1) is consolidated sand with inconspicuous *Foraminifera*. The second specimen (Ib2), which comes from a horizon approximately 60 feet above sea level, is of great interest. It is a hard, com-

compact limestone with an even fracture and in hand specimens apparently homogeneous. However, the microscope reveals in abundance a species of *Lepidocyclina*, in addition to the ordinary reef-forming organisms. There are also encrusting Foraminifera and some sections of *Cyclocypeus*. Fragments of echinoids are found in all the specimens obtained from the limestones of the island; but they are not an important constituent of the rock.

The third specimen (Ib3) of this series, collected 80 feet above sea level, is a sandy limestone which contains a *Lepidocyclina* of thin, discoid form, somewhat resembling *Lepidocyclina proteiformis* Vaughan.

Specimen No. 4 (Ib4) comes from a horizon about 110 feet above sea level. It contains a small, globose, well-pillared form of *Lepidocyclina*, which suggest *L. insulae natalis*.

Specimen No. 5 (Ib5), collected on the cliff face 145 feet above sea level, is a very dense rock, which contains the thin discoid *Lepidocyclina* seen in Specimen No. 3, the form seen in Specimen No. 4, and another *Lepidocyclina* with probably a stellate form. There is also a thick-walled *Operculina*.

Specimen No. 6 (Ib6) contains the stellate form of *Lepidocyclina* and some *Cyclocypeus*.

Specimen No. 7 (Ib7) comes from the top of a pinnacle on the surface of the Makatea. Prominently in it is a species of *Lepidocyclina* without well-defined pillars, and most of the specimens in section show by their irregular thickening that they are probably stellate in form or that they have an irregularity in outline similar to that of *L. murrayana*, Jones and Chapman (*Eulepidina formosa* Nuttall Schlumberger), from Christmas Island. Wide-flanged *Cyclocypeus* are common.

A series of specimens obtained from the inner cliff of the Makatea nearly opposite Niiniimoko, about half a mile north of Tareao Sink, show a much smaller development of *Lepidocyclina*; in fact only two preparations showed any. One of these (I 4) contains thick-walled *Operculina* and a small *Lepidocyclina* similar to that in Specimen Ib5, which was collected at the same horizon—140 feet above sea level. A specimen taken from the top of the limestone (I 6) contains one small *Lepidocyclina* and a great number of wide-flanged *Cyclocypeus*.

At Waimotu and at Waitotara specimens were obtained from the top of the Makatea within 30 feet of the end of the volcanic spurs. The limestone at both of those places contains no fragments of volcanic rock and no *Lepidocyclines*, though wide-flanged *Cyclocypeus* is abundant.

Near the outer (seaward) cliff of the Makatea, two series of specimens were collected: one at the steps three-quarters of a mile north of Oneroa; the other, at Tearatoiro. *Lepidocyclina* was found in only one specimen (Oa4) of these two series. It was collected on the surface of the Makatea at Tearatoiro about 100 yards back from the edge of the irregular, low cliff, 110 feet above sea level. The species attains a diameter of 15 mm.—much larger than those obtained elsewhere. It has no definite pillars, but the walls between adjacent chamberlets are thick, and the embryonal chambers have the form of *Nephrolepidina*.

The discovery of *Lepidocyclines* in the Makatea of Mangaia Island is of special interest, and as none of the specimens at first collected came from the lowest available horizon, the services of Mr. A. McGruther, the school-master on the island, were enlisted. He kindly obtained for me specimens of rock from the water level of the subterranean outlet of Lake Tiriara within the Makatea, 30 yards back from the inner wall. This locality must be close to sea level for at times in heavy weather salt water is driven through this channel from the reef which is nearly half a mile distant.

The rock is extremely compact. One specimen is pink, owing to the infiltration of iron oxide. Most of the material is recrystallized into rhombohedra of calcite, but the organisms generally remain distinct. Much *Lithothamnion* and *Lithophyllum* and some *Halimeda* are present, also encrusting Foraminifera. The collection includes a small free form like *Rotalia* and a small species of *Lepidocyclina* is common. Corals, echinoid fragments, and shell fragments are also present. Thus from the lowest available horizon of the Makatea, the structure of the rock is that of a typical coral reef.

Four specimens of limestone were collected from the surface of the Makatea at distances of 200, 400, 600, and 800 yards respectively from its outer edge. No examples of *Lepidocyclina* were found in any of these.

At 800 yards, few *Operculina* and an organism that may be *Miogypsina*; rock rather more sandy than is usual in the Makatea.

At 600 yards, some large *Operculinas* 2.6 mm. in diameter; an abundance of *Amphistegina* and an organism doubtfully referred to *Miogypsina*; a sandy type with little *Lithothamnion* but much encrusting Foraminifera.

At 400 yards, a sandy type with *Operculina*; much *Amphistegina*; and some *Miogypsina* (?).

At 200 yards, sandy type with *Amphistegina*; *Cycloclypeus*; and perhaps *Miogypsina*.

MICROSCOPIC STRUCTURE

Apart from the organisms contained in the Makatea limestone, the cementing matter that unites them into a solid rock is of interest. In the Lithothamnion ridge this material consists of finely fibrous calcite. In the reef flat the specimens collected include no cementing matter, consisting of coral only. In the Terrace Slope, fibrous calcite lines the cavities, but the central part of the larger cavities is filled with clear rhombohedral calcite in relatively large crystals. In the Makatea, this fibrous layer can still be recognized but it is almost entirely changed to rhombohedral calcite, though it is no thicker than in the living reef. The limits of the original fibrous layer are to be seen as a distinct, dusty line. Some dusty material is distributed over the portion that was originally fibrous, but the central portion of the original cavity is filled with clear rhombohedral crystals.

A series of specimens taken from the bottom to the top of the outer cliff then across the Makatea and down its inner side show a regular development of the cementing matter. The edge of the deposit that was originally fibrous becomes less and less distinct and the rhombohedral form of the crystals becomes gradually more uniform until at the base of the inner wall, no distinction can be seen between the material that fills the marginal portion and the central part of the original cavity. The conversion of the aragonite into calcite in such organisms as *Halimeda* and corals also has become complete and the whole rock has become in structure a fine grained uniformly crystalline limestone. Though this change may be quite complete, the original structure of the various organisms can be distinctly seen.

In *Lithothamnion* and *Foraminifera*, the structural lines are apparently unchanged; in *Halimeda* and in the corals, darker dusty lines border all the margins of original structures.

From these observations it appears that the fibrous calcite is very generally distributed and perhaps was deposited at the time that the limestone formed the edge of the reef. There seems to be no subsequent growth of this substance; in the rocks of the Terrace Slope and originally, too, in the Makatea, the layer is no thicker than in the living reef.

The change into rhombohedral calcite and its subsequent complete merging with the calcite at first deposited is clearly a slow process, but pressure is not required to complete it. The chemical composition of the Makatea shows that the formation of the fibrous deposit is not necessarily associated with the replacement of calcium by the magnesium of sea water, as is suggested to explain its appearance in the structure of the

Lithothamnion ridge. None of the specimens of Makatea limestone that were analyzed contained any important amount of magnesium carbonate.

It cannot be said that the examination of these limestones has thrown light upon the origin of dolomite, except to the extent that in the Mangaian reef the outer ridge alone contains a notable amount of magnesium carbonate.

CHEMICAL COMPOSITION

A number of the specimens of limestone from Mangaia were analyzed in order to discover whether any of them had a dolomitic character. The results show that these limestones contain a surprisingly high percentage of calcium carbonate; in other words, they are remarkably pure limestones. The following table gives the percentage of calcium carbonate, as estimated by volumetric analysis.

TABLE I. CHEMICAL COMPARISON OF LIMESTONE

Symbol	Locality	CaCO ₃ percent	Altitude
X	Te Ananui, Lake Tiriara.....	97.20	10 feet
S1	Tareao Sink, opp. Oneroa.....	97.84	20 "
Ib1	Inner cliff of Makatea	96.72	30 "
Ib2	" " " "	98.76	50 "
Ib3	" " " "	95.03	70 "
Ib4	" " " "	96.42	100 "
Ib5	" " " "	96.42	130 "
Ib6	" " " "	94.76	170 "
Ib7	" " " "	94.52	200 "
	Upper surface of Makatea, opposite Aritoa.....	95.03	200 "
01	Outer cliff of Makatea	94.13	45 "
02	" " " "	94.67	60 "
03	" " " "	94.26	75 "
04	" " " "	93.52	85 "
05	" " " "	93.20	95 "
06	" " " "	94.56	115 "
	Surface of Makatea, 400 yards from outer edge	93.52	
	Surface of Makatea, 600 yards from outer edge	96.82	
	Outer edge of Terrace Slope.....	96.05	
	Raised Halimeda limestone.....	93.80	
	Reef flat 50 yards from beach	94.13	
	Reef flat 100 yards from beach	93.45	
	Lithothamnium ridge at Oneroa	83.89, 82.48, 82.01	
	" " " Ivirua	83.93, 83.89, 83.87	
	Dead knobby Lithothamnion	74.97	

The amount of magnesium carbonate in the three samples from Ivirua and in the sample of dead knobby Lithothamnion was estimated

as: 12.41 per cent, 12.71 per cent, 12.75 per cent, and 12.71 per cent respectively.

These analyses show clearly that the Makatea of Manguaia Island consists of nearly pure calcite, though of course there may be large patches of magnesian limestone. In so large an area complete sampling was not possible. It is also clear that, as far at least as the analyzed specimens are concerned, magnesium carbonate can have replaced calcium carbonate to a very slight extent. It is noteworthy that the only specimens that contain less than 93 per cent of calcium carbonate were those obtained from the recent Lithothamnion ridge now forming where the surf breaks and a specimen of dead knobby Lithothamnion. In these specimens magnesium carbonate amounted to more than 12 per cent. If the stony matter of these specimens alone is considered, the amount of magnesium carbonate becomes 12.86 per cent, 13.15 per cent, and 13.10 per cent respectively. In the Lithothamnion itself, the amount is 14.49 per cent—a figure comparable to those obtained by Hogbom (12, p. 377) in the analysis of museum specimens.

It is, however, surprising that the mixed material of the ridge, one-third to one-half of which on the average consists of Lithothamnion, should contain such a high percentage of magnesium carbonate. The specimens were obtained from the upper surface of the ridge. In view of these results it would be interesting to examine samples obtained from some feet within the rocky material of the ridge. Arrangements are now being made to obtain such samples from the Cook Islands.

It is noticeable that the two samples from the reef flat at a distance of 50 to 100 yards from the beach contain 94.13 per cent and 93.46 per cent respectively of calcium carbonate. There can be little magnesium carbonate here. The rock consists of dead coral and there has been no deposition of secondary carbonate in the cavities of the organic remains. No previous analyses of specimens from a Lithothamnion ridge have been found in the literature. This is surprising in view of the high importance of this structure in stopping the fury of the waves.

From a study of the composition of the Manganian limestone, it appears that the only material in which magnesium carbonate is present in important amounts is that of the Lithothamnion ridge. A large quantity of secondary calcite has been deposited even in this superficial material. As there is no sign of decay or solution of any of the organisms of which the rock is composed, it would seem that the only source from which this calcite could have been derived is the action of the magnesium salts of sea water which has resulted in the replacement of calcium by magnesium. The combination of the liberated lime with additional carbonic acid might

result in the deposition of calcite in all the empty spaces. If this be admitted, the question at once arises as to how far the process can go. It is possible that further inquiry into the composition of the deeper parts of the Lithothamnion ridge may provide an explanation of the origin of magnesium limestones (27, p. 194).

Although not defined as such, the rocks from Rose Atoll may possibly represent material of a Lithothamnion ridge. Mayor (24, p. 76) describes one specimen as "Rock from the solid floor of the atoll rim west of the main entrance to the lagoon," and gives its composition as CaCO_3 , 83.86 per cent; MgCO_3 , 14.36 per cent. The composition of a "loose boulder" is given as CaCO_3 , 77.28 per cent; MgCO_3 , 18.30 per cent; and of the "largest boulder on reef" as CaCO_3 , 79.50 per cent; MgCO_3 , 14.54 per cent.

A large number of analyses of calcareous structures of organisms made by Clarke and Wheeler (8) show that tests of many organisms contains notable amounts of magnesium carbonate: in *Polytrema*, 11.22 per cent; in echinoderms, 6-12 per cent; in calcareous algae, 11-25 per cent.

These authors suggest that the magnesian content of calcareous seaweeds is related to the temperature of the water in which they grow. On the other hand, they show that aragonite organisms such as *Halimeda* and corals contain almost no magnesium. In the light of these results, the purity of the limestones at Mangaia and many other islands is remarkable.

It cannot be supposed that the maximum amount of magnesium carbonate has been found by the comparatively few analyses yet made of calcareous algae. It is also possible that since the percentage of this substance is apparently so variable, different conditions in previous geological times may well have been associated with larger amounts of absorption and deposition of magnesium carbonate.

It is at least suggestive that the conditions of the Lithothamnion ridge in coral reefs of the present day appear to approximate more closely those under which dolomitic limestones have been formed, than does any other set of conditions at present known.

AGE

The variation in the type of *Lepidocyclus* as found in different parts of the Makatea strongly suggests that the coral limestone of which it is formed grew with extreme slowness. It is of course unwise to assume that when *Lepidocyclus* or other genera are absent from the microscopic preparations of any horizon that the organism was not living in the Mangaia area at that time. In the limestones of Christmas Island *Lepidocyclus* is extremely abundant, yet many hand specimens contain none. Close inspection shows

that these tests of *Lepidocyclina* usually appear close to vacuoles in a coral rock, and it seems that they have fallen into the spaces between the coral branches. Tests of species of this genus are almost entirely absent from all those specimens that have a sandy structure.

The exact identification of the *Lepidocyclina* in chance sections is hazardous, and can be done with certainty only by those who have had wide experience with these fossils. For this reason, preparations and specimens of the limestones have been sent to Mr. W. L. F. Nuttall of the Sedgwick Museum, Cambridge, who writes that the beds are certainly of Miocene age. Mr. Nuttall has undertaken to identify and describe the species. As he has recently made a revision of the species of *Orbitoides* found in the limestones of Christmas Island (26, p. 23), he is in position to make accurate comparisons. In the meantime, the suggestions in this paper must be regarded as tentative. This is particularly necessary because Douvillé (13, p. 91) has recently stated that the specimens referred by Chapman and Jones to their species *Lepidocyclina insulac-natalis* really should be distributed among three previously known species: *Eulepidina dilatata*, *E. formosa*, and *E. inermis*. Nuttall's work also shows that the original classification of these island forms made at a time when the study of the genus had just begun was somewhat inexact. For some of the forms he retains the classification of Chapman and Jones (7). Other specimens placed by Chapman and Jones in *Lepidocyclina* are classed by Nuttall in the genera *Miogyopsina* and *Spiroclypeus*.

At an elevation 35 to 40 feet above sea level at Tareao Sink, opposite Oneroa, the rock (S2) is arenaceous and contains many specimens of *Operculina*, rare *Amphistegina*, and a few *Spiroclypeus*. It is curious that *Operculina* appears to be absent from the lower rock (S1), of which nine microscopic preparations were made. Vaughan (30, p. 806) states that the genus *Operculina* ranges in America from middle Oligocene to Miocene. In New Zealand the genus is abundant in the rock resting on the coal at Kawakawa, probably of Eocene age. It is also found in the Mokau limestone of middle Miocene age and at Pongaroa in a pebbly limestone probably of older Pliocene age. It is common in limestones as far south as Castle Point. These occurrences show that the genus gives no exact stratigraphic information in New Zealand and that the identification and description of species from chance sections is of doubtful value in defining any horizon. The genus *Heterostegina* also is of little value for defining the exact horizon. It is, however, probable that the great abundance of these large forms indicates a horizon of middle Tertiary age. As this abundance is not noticeable except in those specimens that were obtained from near the top of the

Makatea it seems that the lowest accessible part of the Makatea should be placed in the lower Miocene or the Oligocene period.

The studies so far made seem to indicate a very definite succession of the larger Foraminifera. It is particularly noticeable that there is no repetition of any species in successive horizons. Unfortunately the occurrence of such highly important fossil species was wholly unexpected at the time that the collection was made, and the specimens obtained are hardly numerous enough to establish definite horizons. When collecting the specimens it was thought that all the raised limestones at Mangaia were of recent age, and material was taken for examination on the chance that features of importance might be discovered in it. It is quite possible that further collecting will bring to light more fossils of diagnostic value. But the task is difficult, for only after much handling and inspection of hand specimens in which fossils are known to occur is it possible to discern the presence of even the larger *Lepidocyclines*. The series of six and seven specimens, respectively, from the inner Makatea cliff cannot be expected to give complete information. But they definitely show that the inner cliff of the Makatea at Mangaia is of Tertiary age and indicate that the lower part of the cliff is surprisingly older than the upper part. If this is subsequently confirmed, the formation of a coral reef is a far slower process than has been imagined. The comparative rarity and the form of the only larger type that has been found 100 yards back from the top of the outer cliff is taken to mean that this part of the Makatea is much younger than the part near the inner edge. The two specimens of limestone from the terraced strand contain none of the larger forms of Foraminifera, though *Amphistegina* is abundant in them.

No *Lepidocyclina* has yet been recorded from New Zealand. I have, however, a preparation of the Mokau limestone, from a point forty miles east of New Plymouth, and of the Whangara limestone, fifteen miles north of Gisborne, in which specimens of it occur. They are unpillared and show indication of having a sellate form. They appear to be more closely related to those from Oa4 than to any others at Mangaia. The formation in which these limestones occur in New Zealand is of upper Miocene age. It is stated also that a species occurs in similar rocks at Hokianga Heads and at Titirangi Point, ten miles from Auckland. Though there is a large number of Tertiary limestones of greater age than this in New Zealand and nearly all have been examined microscopically, none of the older forms of Orbitoids have yet been found. It is possible that climatic conditions account for this. Chapman (7a) has recently recorded two species of *Cycloclypeus*, one of *Lepidocyclina*, and one of *Miogypsina* from the Lower Miocene and Miocene of New Zealand.

RAISED LIMESTONES OF OTHER ISLANDS

Many islands in the western Pacific Ocean are wholly or partly constructed of limestone rock, which in many places occurs at an elevation of several hundreds of feet. Guppy (15, p. 63) has described such limestones in the Solomon Islands. He apparently concludes that they are all of recent age, though formed under widely varying conditions, some of them representing coral reefs and others abyssal deposits. In the New Hebrides, particularly in Malekula and Southwest Santo islands, Mawson and Chapman (19, pp. 261, 418) found limestones that contain *Lepidocyclina* and *Lithothamnion*, which they consider to be of Miocene age. In Fiji, Agassiz (3, p. 81) collected fossils of marine molluscs from raised limestones. These fossils were said by Dall to be of Tertiary age—not older than the Miocene. E. C. Andrews (5) collected many specimens of limestones at the Lau Islands and other localities in Fiji and forwarded them to Agassiz. These were examined by Skeats (28), who records *Orbitoides sumatrensis* in one specimen from Mango and in one from Namuka.

Fossil molluscs were collected by Agassiz (3, no. 4, p. 59; 1, pp. 34-43) on a terrace of Makatea Island, at the extreme west of the Tuamotu Islands. It is stated that these were identical in all respects with the specimens that had been found in Fiji. Skeats made a microscopical examination of these limestones, but found no *Lepidocyclina*.

Lister (17, p. 602) reports that preparations of the limestones of Eua, the eastern island of Tonga, were submitted to Murray, who found it impossible to assign the organic deposits of the island to a definite geological epoch, though he was of the opinion that no satisfactory reason exists for referring them to the Tertiary Period. Skeats reports that specimens from Tonga and from Niue Island collected by Agassiz give no evidence of Tertiary age.

I am unable to find any detailed account of the raised limestones in the Cook Islands, the Austral Islands, Henderson Island, or of any other Pacific oceanic island composed of raised limestone, though the examination of rock from many islands shows that some of the limestone has been changed to dolomite.

The "bedded" limestones of Christmas Island (Indian Ocean) extend in age from the Eocene to the Miocene, and the youngest "bedded" rock is capped with "reef" limestones at the height of 1100 feet. Much of the coast of Christmas Island is at the present day surrounded by a coral reef.

TARO FLATS

Beneath the towering inner wall of the Makatea, over the greater part of its circuit, there are low-lying swamps in which taro is cultivated. This region—the Taro Flats, extends about half a mile up the valleys of the larger streams, but small patches may be found two miles from the Makatea. (See figs. 1 and 3.) Where the supply of water that comes down the volcanic slopes is not sufficiently constant to allow of the cultivation of taro, the flat ground is covered with forest and other growth.

The taro ground is but a narrow strip, in few places more than a quarter of a mile wide. At four places in the whole circuit of the island the spurs of the Volcanic Slopes extend to the Makatea, and it is possible at these spots to walk along narrow causeways from the Makatea onto the Volcanic Slopes without descending to the low-lying taro fields. In the Te Vaenga District, gently undulating ground occupies the usual position of the Taro Flats, but even here the slopes descend almost to sea level at the base of the Makatea wall.

The Taro Flats are about 40 feet above sea level, where the streams that supply the water to them issue from the valleys. They descend in a series of artificial terraces and end about twenty feet above sea level at the foot of the Makatea cliff. Here the water enters a sink, which may be as much as ten feet below the general surface, and passes in channels through the Makatea, finally issuing on the inner edge of the reef flat in the form of springs. The whole drainage of the interior of the island (about 27 square miles) is disposed of in this manner. At Lake Tiriara the level of the flat approaches so closely to that of the sea that the water never drains away and a permanent lake remains, 400 yards long and 150 yards wide. It is said that in heavy weather some sea water is driven into the lake through the outlet channel, the water becomes brackish, and marine fish, such as the mullet, come in from the reef.

At Ivirua and probably at many other places there are long subterranean passages extending far into the Makatea. The smooth walls and nearly constant diameter of the one that was seen (which is said to pass entirely through to the reef) point to the possibility that when the island was less deeply submerged this tunnel was a channel along which drainage water from the hills passed through the Makatea. It is now twenty feet above the water level in the Taro Flats. The material of the Taro Flats consists of the detritus derived from the volcanic hills, together with a great deal of organic matter.

VOLCANIC SLOPES

The central part of Mangaia is a mass of basalt. Behind the taro ground the Volcanic Slopes rise rather steeply but not precipitously. This volcanic core is deeply dissected, but no rock outcrops are to be found on the spurs, and with few exceptions the valley floors slope evenly throughout. The spurs however, are seldom reduced to that razor-back form that is so striking a feature of Tahiti, Rarotonga, and many other high islands of volcanic origin. This may in part be due to the comparatively low elevation of the island. From all parts of the periphery of this volcanic core spurs converge to the center of the island, where at an elevation of 554 feet is the Central Plateau which measures three-quarters of a mile in an east-to-west direction; but over the greater part of this distance it is very narrow from north to south. (See Pl. II, *A*.)

The tops of several spurs are either flat surfaces or wide gentle slopes. The highest spur flats are at a slightly lower level than the plateau summit, but those nearer to the peripheral portion of the volcanic land are distinctly lower. All the larger streams of the island take their rise from the edge of the Central Plateau, the middle of which is called Rangimotia. The valley slope at the headwaters is steep, in places as much as 35 degrees for the first 50 or 100 feet. From the bottom of this steep slope the streams flow outward along an even grade except where small terraces have been built to intercept the flow of the water to form wet land for taro growing. The alluvial matter on the stream floor increases as the Taro Flats is approached, which most streams enter at grade. Very little bed rock is exposed on the valley floor except at the entrance to the Vao Roa and the Vaiaua. It may be that before the growth of the coral reefs afforded protection, the land on the southeast side of the island was cut back into higher cliffs than elsewhere. The volcanic rock everywhere is greatly weathered, and it is hard to find unaltered fragments. Pieces of a dense fine-grained basalt are to be found near the western and southern slopes of the Central Plateau. On the south side of the Vao Roa valley, near its head, are many specimens of a coarse basaltic rock with large crystals of augite and olivine. The Vao Roa and the Vaiaua rivers pass over a dyke of basalt just before they enter the Taro Flats. Basalt was the only volcanic rock that was found in any part of the island.

The hillsides of Mangaia are so thickly covered with vegetation, that the structure of the volcanic core could not be determined. However, the surface of some spurs is bare along the paths used by the natives. I

have gained the general impression that the island is mainly composed of scoria and volcanic ejectamenta arranged in beds that generally dip outwards and that numerous dykes more or less radial in their arrangement traverse these scoria beds irregularly.

The weathering of the rock has been of a lateritic nature, though, as the analyses show (p. 38), the alteration has not been complete. On the surface of Rangimotia and on the flat spurs, little spheres of limonite cover the ground, and beneath a thin layer of them there is a dark red unctuous clay which extends to a considerable depth—certainly as much as 30 feet in some places. During the weathering process a great deal of silica has been removed in solution, but much of it has been redeposited close at hand. On the slopes of Niiniimoko silica appears in the form of chert which has replaced and petrified the creeping rhizomes of a fern, *Gleichenia*, with which most of the hilly volcanic ground is covered. On the slopes above Ivirua huge boulders of chert strew the hillsides. The more solid boulders yield chips with the typical sharp edges, and it is remarkable that the natives did not use these chips for cutting purposes, though my guide, Mama Akaui, and other natives told me that chips with jagged edges were used as saws. The New Zealand natives used flint and obsidian chips for cutting, but the Mangaiaans seem to have preferred shells. The most even and gradual slopes from the summit to the Taro Flats face the northwest; the steepest hills face south and south-east. This suggests that the present winds and ocean swells are similar to those existing before the island was protected by a reef.

Besides the fern with which the hills are covered there are many toa trees (*Casuarina*), and the stream valleys have dense thickets of small trees and shrubs. As soon as the supply of water in the stream becomes sufficient and permanent, patches of taro are planted.

No coral rock was found in situ on any portion of the Volcanic Slopes. If any fringing reef was formed at any time on or about the level of the top of the Makatea it has now entirely disappeared. Marshall has shown (18, pp. 140-5) that such fringing reefs now occur in the Society Islands.

PETROGRAPHIC DESCRIPTIONS

1. Basalt: a dense, fine, and even-grained rock occurring on the south and western slopes of the Central Plateau.

Feldspar in narrow long laths with high extinction angle, a basic labradorite, also in small irregular plates that occur interstitially. Augite very abundant in small crystals, the microlites are gray in color but the small crystals are pink and pleochroic. Olivine in small swallow-tailed crystals 0.3 mm. in length, in many cross sections hollow squares. Iron ore common in short angular forms, apparently octahedrons.

2. Basalt: a coarsely porphyritic rock occurring on the western side of the upper part of Vao Roa Valley.

Large idiomorphic crystals of augite 9 mm. by 6 mm. All the interior part of each crystal is pale-green in color and is diopside except a narrow border which is pale-pink. The crystals show the characteristic steel-blue interference color where cut at right angles to an optic axis. Olivine crystals large and many idiomorphic; some slightly serpentinized. Ground mass: feldspar laths with the extinction angle of basic labradorite not common. Augite very abundant, a few in short idiomorphic prisms but also many granular, always pink and pleochroic. Small grains of serpentine represent olivine. A specimen obtained from Rangimotia in 1909 contains large feldspar crystals and aggregates with extinction angle of 45 degrees. No unweathered material could be found in the decomposed clay of this locality in 1924.

The following analyses show the chemical composition of the two basalts and the clay that is derived from their decomposition:

ANALYSES OF BASALT

	A	B	C	D
Si O ₂	42.31	44.12	30.30	11.50
Ti O ₂	2.15	3.20	4.14	2.35
Al ₂ O ₃	17.21	13.58	22.73	15.15
Fe ₂ O ₃	2.14	1.95	22.17	53.68
Fe O	19.56	10.20		
Ca O	9.32	10.87		
Mg O	8.74	9.92		
Na ₂ O	3.42	2.12		
K ₂ O	1.76	1.20		
P ₂ O ₅	.32	.31		
H ₂ O	2.42	2.32	19.34	16.77
	99.35	99.79	98.88	99.45

(A) Fine-grained basalt, south slope Rangimotia, Mangaia Island; (B) Coarse-grained basalt, head of Vauroa Valley, Mangaia Island; (C) Clay from foot of spur near Ivirua, four feet from the surface; (D) Clay from low spur of Niimoko, six feet from the surface.

Analyses A and B show that the basalts are similar to those from Tahiti and Samoa and call for no special remark. Analyses C and D show that lateritization has acted to a considerable extent with some concentration of oxides of alumina and iron.

GEOLOGIC HISTORY

SEQUENCE OF EVENTS

There can be no doubt that a volcanic eruption was the prelude to the first appearance of the island of Mangaia. Whether the volcanic activity was continuous or interrupted and spasmodic is not known. After the cessation of activity, marine erosion reduced the island to an extensive shoal, the remnant of which is now to be seen in the Central Plateau—the Rangimotia or “Crown of Mangaia” (p. 7).

After the formation of this plane of marine erosion a slow and continuous negative movement took place and the island gradually emerged as a low dome with a gently sloping surface, fragments of which are still preserved in the flat tops of the spurs in various parts of the island. (See Pl. I.)

This upward movement continued until the elevation of the island was rather greater than at the present day. Stationary conditions followed and continued for a long period; and during this time subaerial and marine erosion developed their characteristic effects. Radiating stream valleys rather deeper than the present ones—perhaps 40 feet deeper in the peripheral portions—and marine cliffs some 250 feet high were formed at the ends of the projecting spurs. It is hard to decide what the actual sea level was at this time, but it is believed that the land extended at least as far as the foot of the Makatea, which means that sea level was 40 feet lower than at present.

After the stream valleys and cliffs had been formed, a coral reef commenced to grow round the shore. A slow positive movement took place, and the upward growth of the coral reef just kept pace with it. The vertical form of the inner cliff of the Makatea makes it seem probable that no important pauses occurred during the progress of this movement. If any pauses had taken place the coral reef would have extended outwards; and when the rise of the sea level relative to the island recommenced, the line of most active growth of the reef would have migrated outwards and a small terrace would have been developed on the inner wall of the Makatea.

The large amount of *Lithothamnion* and of sand contained in all of the specimens of limestone rocks taken from the inner wall of the Makatea leads to the opinion that during its upward growth the reef was subject to surface marine conditions all the time. This, of course, is uncertain as no study has been made of the organisms that live on the inner wall of a barrier reef like that of the Society Islands, where the conditions appear to be similar to those that existed at Mangaia during the gradual rise of the sea level.



FIGURE 3.—Sketch showing stages in the geologic development of Mangaia Island.

After this slow positive movement had amounted to about 250 feet it ceased, and during a period of stillstand the reef slowly extended outwards. An extremely slow negative movement now commenced, and the widened reef gradually rose above the sea level. This movement was so slow that while it was in progress the reef was still able to grow outwards to an important extent. During the lapse of time that the reef was able to extend outward to the average extent of 3000 feet, the fall in sea level amounted to about 100 feet only. During the gradual recession of the water the higher portions of the reef would be subject to wave action, and this in part may be the cause of the roughness of the surface of the Makatea. A similar surface is found on the east shore of Nauru Island.

The data at hand are unfortunately quite insufficient at the present time to allow of a satisfactory explanation of the variation in width of the Makatea (p. 20). The great width at the southeast point of the island could easily be due to a more gentle slope of the volcanic rock on which the reef has been built up. In the region where the Makatea has its maximum width, the present ocean swell that rolls up from the South is most heavy and fierce. Even if it is assumed that the same conditions prevailed when the Makatea was formed, it seems that such conditions would not satisfactorily explain its great breadth, as the present living reef is narrower in this part of the island than elsewhere. So little is known about the direction and strength of ocean currents in this part of the Pacific that it is useless to speculate about the effect that they may have had upon the growth of the old reef.

The composition of the Makatea was gauged from examination of four series of microscopic preparations made from specimens collected on the cliffs, two of them from the inner cliff and two from the outer cliff. Of all the organisms that are represented in these specimens, *Lithothamnion* is by far the most common. This appears to imply that throughout the growth of the reef its surface was washed by the waves, for on the present living reef it is only in that situation that *Lithothamnion* has such a preeminence. The general occurrence of *Lithothamnion* on the inner wall of the Makatea suggests that it grew as a narrow reef; the *Lithothamnion* ridge on the present living reef is nowhere more than 30 yards wide. At Tamarua there may have been a passage over the reef about fifteen fathoms in depth at the time of maximum depression.

Below the level at which the waves break, coral heads are far more abundant, if those fleeting glances that alone were possible over the edge of the ocean face of the reef at Mangaia can be trusted. Such observations, however, are quite in accord with the brilliant work of Mayor (21), who, using a diving hood, actually walked over the submarine slope outside the

reef at Aua, Samoa. The coral there has its maximum growth in 6 to 10 fathoms of water. Below that depth the heads are smaller and more widely spaced. The work of David (12, p. 155) at Funafuti makes it clear that at 20 fathoms Halimeda becomes the dominant organism and remains so to a depth of perhaps 45 fathoms. It is interesting to note that the Makatea at Mangaia consists almost entirely of Halimeda joints over a large area about a mile to the south of the village of Ivirua.

As soon as the sea rose as high as the top of the Makatea, that is, 230 feet above its present level, slow elevation once more began. Whether this elevation was continuous or was interrupted by periods of stillstand was not determined. If terraces exist on the surface of the Makatea they are obscured by the vegetation and must be relatively unimportant. During this period of elevation the island had a peculiar appearance. The Makatea formed a continuous ring with an average height of about 100 feet. Except in a few places this ring of limestone was separated from the central volcanic mass by a lagoon or moat more than 100 feet deep and in places half a mile wide. The water in this lagoon must have been fresh or at least brackish as soon as the elevation had made the ring complete.

The outer cliff of the Makatea is only 50 to 75 feet high. In places, especially near Ivirua and Tamarua, it rises in two distinct stages with an intervening platform five to twenty feet in width. Generally, however, the slope is very abrupt, in many places vertical, and for the greater part of its length cannot be climbed. It is, of course, free from the projecting volcanic spurs which interfere with the complete continuity of the inner cliff. The steep outer cliff of the Makatea implies rapid elevation, too rapid to permit the formation of terraces or of a slope. But it is not necessary to assume one spasmodic elevation. It seems possible that the outer wall of the Makatea corresponds with the precipice that crowns the submarine slope outside the coral reef at Funafuti and Tutuila. Certainly the cliff has not been subjected to an important amount of marine erosion. The absence of beach sand and of the irregularities and caves marks a distinct difference between this precipice and the smaller one which now rises on the landward side of the living fringing reef. At Funafuti, however, the submarine precipice is 620 feet high.

In summary the significant events in the geologic history of Mangaia may be listed as follows:

1. Volcanic activity.
2. Marine erosion of the volcano and the formation of a shoal.
3. Elevation of island to 100 feet above present sea level.
4. Prolonged subaerial erosion.

5. Commencement of growth of fringing reef (Oligocene or Lower Miocene).
6. Slow depression to 220 feet below present sea level, accompanied by upgrowth of coral reef forming a barrier.
7. Slow depression of 100 feet with outgrowth of barrier reef.
8. Further elevation of 100 feet to present level, but movement interrupted by slight pauses.
9. Period of stillstand with formation of fringing reef.

CONCLUSIONS BASED ON STUDY OF LIMESTONE

The study of the raised coral reef at Mangaia gives rise to the following conclusions:

1. The formation of coral reefs is extremely slow. The limestone of the Makatea, though bedded in appearance and similar in this respect to the sediments of Christmas Island, as recorded by Andrews (4, p. 271), is essentially of reef origin. Pocillopora and Orbicella occur at its base, and Lithothamnion, Halimeda, and other calcareous algae, encrusting Foraminifera, corals, alcyonarians, and echinoids occur throughout its mass in association characteristic of coral reefs. Sandy patches are found at all levels, as in modern reefs.

2. The curious association of corals, free and encrusting Foraminifera, encrusting algae, echinoids, and mollusks had developed in the Southern Pacific round an oceanic island in middle Tertiary time.

3. The inner part of the Makatea shows that a barrier reef had developed round Mangaia in the middle Tertiary.

4. The barrier reef extended outward so slowly that when its average width was 3,000 feet all Tertiary organisms, as illustrated by the Foraminifera, at least, had become extinct.

CONCLUSIONS BASED ON PHYSIOGRAPHIC AND PALEONTOLOGIC EVIDENCE

1. The original volcanic action which probably produced Mangaia took place perhaps before the end of the Cretaceous period, but certainly not later than the early Tertiary. This opinion is based upon the evidence that the volcanic island had been reduced first to an extensive shoal, then raised some 600 feet and dissected by streams before middle Tertiary time. The remnants of the old low dome formed as the island gradually rose, now found on the spurs, shows that the elevation movement was a slow one. The amount of dissection that took place before the formation of a reef commenced, compared with the small amount that seems to have taken place since that time, shows that a great deal of time elapsed before the beginning of reef formation.

2. The growth of coral reef at Mangaia has been continuous from middle Tertiary time to the present day. The vertical and untterraced inner cliff of the Makatea is believed to prove continuous growth from middle Tertiary times to the Upper Miocene. The gradual and nearly even outward slope of the Makatea indicates that there was no break in the continuity of its formation until it was complete, near the end of the Tertiary. The absence of beach sand and of features of marine erosion at the foot of the outer cliff of the Makatea shows that no important marine erosion followed the elevation of the Makatea; such as would have taken place if there were no protecting coral reef. The relatively small cliff at the foot of the Terrace Slope shows that it, too, was always protected by some amount of reef structure.

3. The ordinary action of rain and of small streams can have but little effect on raised coral rock. The Makatea emerged above sea level towards the end of the middle Tertiary (upper Miocene?), and the unfilled moat and the absence of any cliff or beach deposit on the Volcanic Slope show that it has not been submerged since that time. The surface of the Makatea, however, remains at the same general level throughout; no channels have been cut through it; almost everywhere its inner cliff remains sharp and clean cut, usually without any talus slope at the base though fully exposed to the climatic conditions of the Tropics.

4. Owing to the constant presence of a living reef, marine erosion throughout all the time that has elapsed since the formation of the first reef in early Tertiary times has produced no important result other than the cutting of a small cliff at the shore line.

5. There is no evidence of a greater height above the sea level during Pleistocene times, for native fishermen maintain that there is no submarine shelf above 100 fathoms, beyond which depth there is practically no knowledge of the form of the sea floor. It is probable that if the height above sea had been greater at any time, the subterranean streams would have enlarged their channels to such an extent that overlying masses of limestone would have fallen into them, forming deep gorges across the Makatea.

6. That denudation of the volcanic land must have proceeded with extreme slowness throughout Tertiary times is shown by the following observations: (a) The early Tertiary plateau has not been wholly destroyed; flat tops are still found on several of the radiating spurs. (b) The slope of the valley floors is considerable and no alluvial flats of any size have been formed in them. (c) The thickness of alluvial deposits on the Taro Flats above the level at which water enters the channels beneath the Makatea is only 15 feet, and the entrance of the underground channels is no more

than 15 feet above sea level. The amount of suspended matter carried through these channels is insufficient to form a deposit on the beach. In heavy rain the channels are too small for the outflow of water, and the Taro Flats are then covered deep with water, and the greater part of the suspended matter is deposited on them. (d) The volcanic rock is decomposed to a depth of 50 feet, and unweathered rock is rare, even on the valley floors. The thick growth of *Gleichenia dichotoma* on the volcanic hills, with their dense mat of underground rhizomes, may partly account for this exceedingly slow rate of denudation. In their original state the hills probably were thickly covered with this fern. Even now after repeated burning the growth is extremely thick on the sides of valleys remote from settlements. On the valley floors within the flow of water, the *mape* (the so-called chest-nut of Polynesia) grows as large trees. Its thickly interwoven roots much reduce the erosive effect of the stream.

7. The stability of the floor of the Pacific Ocean must be great in the neighborhood of Mangaia. The earth movements during and since the Tertiary have been relatively small and have taken place without any noticeable tilt.

8. It appears certain that Mangaia has never formed a portion of a larger land mass but that the island has been continually above the sea level since the close of the Eocene. These conditions, which may reasonably be expected to apply to other isolated islands and groups of islands, give an immense period of time for the gradual collection and distribution of the Pacific fauna and flora.

COMPARISON WITH CHRISTMAS ISLAND

As compared with Christmas Island the geologic history of Mangaia has been far more uniform and free from vicissitudes. The elevation of the limestone rock is much less—230 feet, compared with 1170 feet; the outward sloping surface is far less interrupted by cliffs. On Christmas Island, strata of volcanic matter are interstratified with the bedded limestone. On Mangaia there was no volcanic action after the beginning of limestone deposition. Evidently at Christmas Island there were periods of rapid upward movement separated by periods of stillstand, and at times parts of its coast were not protected by coral reefs—a condition which exists at the present time. In Mangaia the reef is now continuous and appears to have been so throughout Tertiary times. It is somewhat surprising that there is no gap through the Makatea—the old barrier reef of Mangaia. There are only occasional tortuous channels which penetrate for a short distance. The complete continuity of the present reef is also somewhat unusual though essentially like that of many other Pacific islands.

CORAL REEF CONSTRUCTION

The light that is shed by the structure of Mangaia on the general problem of coral reefs is worthy of consideration.

If my interpretation of the geologic history of Mangaia is correct, it is obvious that there has been some rise and fall of the ocean floor on which the island is based. If the steepness of the spurs near the Makatea and the relatively small height of the cliffs can be taken as criteria, the erosion platform on which the coral first began to develop was narrow. The growth of the coral reef began on the inner portion of this erosion shelf, for it is in contact with the ends of some of the spurs which can reasonably be supposed to have ended in cliffs. The steep or precipitous form of the inner side of the Makatea indicates that it does not represent an inward extension of a reef that commenced its growth further away from the shore.

It is probable that the submarine slope of the volcanic material is steeper than the emerged portion, which has been flattened down by marine erosion. If this assumption is well-founded, the limestone rock at the outer edge of the Makatea must be approximately 1,000 feet thick. Thus the Makatea represents a small but typical raised barrier reef. A further depression of 360 feet, added to the 300 which actually took place, would have converted this barrier reef into an atoll about 6 miles in diameter, or 17 miles in circumference.

There is no indication of a postglacial rise of the sea level after prolonged erosion and formation of an extensive shelf; for there is no known anchorage outside the reef. There is no indication of a recent fall of the sea level of the order of 10 feet. Since the inner and highest portion of the Makatea was formed, there has been constant though not a uniform fall in the sea level relative to the land.

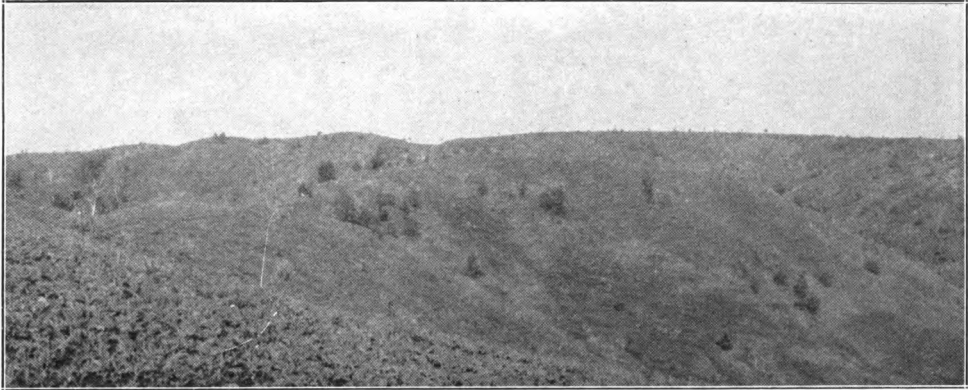
The coast line of the island has been protected by a reef of coral for the whole time that has elapsed since first the formation of the base of the Makatea commenced. The stillstand condition has lasted long enough to allow of the outward growth of a coral reef for 300 yards in deep water.

If the postglacial period of erosion was of sufficient length to permit the cutting down to sea level of such a large island as is supposed to have extended over the area of the Rangiroa (2, p. 49) lagoon, all the emergent part of such a small island as Mangaia should have been eliminated.

BIBLIOGRAPHY

1. AGASSIZ, A., Exploration of the "Albatross" in the Pacific Ocean: *Am. Journ. Sci.* 4th ser., vol. 10, 1900.
2. AGASSIZ, A., The coral reefs of the tropical Pacific: *Mus. Comp. Zool. Mem.*, vol. 28, 1903.
3. AGASSIZ A., The islands and coral reefs of Fiji: *Mus. Comp. Zool., Bull.*, vol. 33, 1899.
4. ANDREWS, C. W., A monograph of Christmas Island: *British Mus. Trustees*, London, 1900.
5. ANDREWS, E. C., Notes on the limestone and general geology of the Fiji Islands: *Mus. Comp. Zool., Bull.*, vol. 38, 1900.
6. BRITISH ADMIRALTY, Sailing directions, eastern groups, Pacific islands, vol. 3, London, 1900.
7. CHAPMAN, F., and JONES, RUPERT, Monograph of Christmas Island: *British Mus. Trustees*, London, 1900.
- 7a. CHAPMAN, F.: *N. Z. Geol. Survey, Bull.* 11, 1926 (in press).
8. CLARKE, F. W., and WHEELER, W. C., The inorganic constituents of marine invertebrates: *U. S. Geol. Survey, Prof. Paper* 102, 1917.
9. COOK, JAMES, A voyage to the Pacific Ocean, vol. 2, London, 1784.
10. DALY, R. A., The geology of American Samoa: *Carnegie Inst.*, pub. no. 340, pp. 95-142, 1924.
11. DARWIN, CHARLES, Geological observations on coral reefs, volcanic islands and on South America, London, 1851.
12. DAVID, T. W. E., The atoll of Funafuti: *Roy. Soc. London*, 1904.
13. DOUVILLÉ, HENRI, Revision des Lepidocyclines: *Soc. Geol. de France, Memoirs*, Nov. ser. no. 2, 1925.
14. GILL, W. W., From darkness to light in Polynesia, London, 1894.
15. GUPPY, H. B., The Solomon Islands: *Swan Sonnenschein*, London, 1887.
16. JOHNSTONE, W., Elements of agricultural chemistry, Edinburgh, 1894.
17. LISTER, J. J., *Geol. Soc. London, Quart. Journ.* 1891.
18. MARSHALL, P., Coral reefs of the Cook and Society islands: *Australian Assn. Adv. of Sci.*, vol. 13, 1912.
19. MAWSON, D., and CHAPMAN, F., The geology of the New Hebrides: *Linnean Soc., New South Wales, Proc.*, 1905.
20. MAYOR, A. G., Ecology of the Murray Island coral reef: *Carnegie Inst. of Washington, Dept. Marine Biology*, vol. 9, 1918.
21. MAYOR, A. G., Growth rate of Samoan corals: *Carnegie Inst. of Washington*, pub. no. 340, pp. 51-79, 1924.
22. MAYOR, A. G., Structure and ecology of Samoan reefs: *Carnegie Inst. of Washington*, pub. no. 340, pp. 1-25, 1924.
23. MAYOR, A. G., Causes which produce stable conditions in depth of the floors of Pacific fringing reef flats: *Carnegie Inst., of Washington*, pub. no. 340, pp. 27-36, 1924.
24. MAYOR, A. G., Rose Atoll of American Samoa: *Carnegie Inst. of Washington*, pub. no. 340, pp. 73-78, 1924.
25. NEW ZEALAND GOVERNMENT, New Zealand official year book, Wellington, 1925.

26. NUTTALL, W. L. F., A revision of the Orbitoides of Christmas Island: Geol. Soc. London, Quart. Journ., vol. 82, pt. 1, 1926.
27. SKEATS, E. W., The formation of dolomite and its bearing on the coral reef problem: Am. Journ. Sci., vol. 45, 1918.
28. SKEATS, E. W., The chemical composition of limestone from upraised coral islands . . . : Mus. Comp. Zool., Bull., vol. 42, pp. 53-126, 1903.
29. STORER, F. H., Agriculture in some of its relations to chemistry, London, 1897.
30. VAUGHAN, T. Wayland, American and European Tertiary larger Foraminifera: Geol. Soc. Am. Bull., vol. 35, 1924.
31. WILLIAMS, JOHN, A narrative of missionary enterprises in the South Sea Islands, London, 1838.

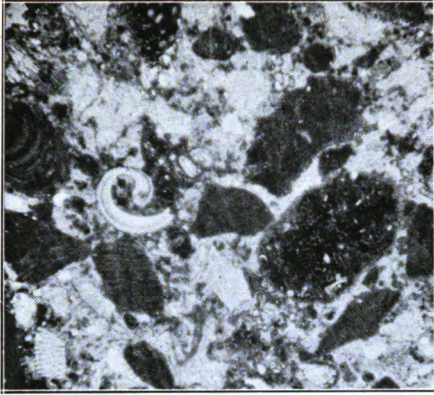
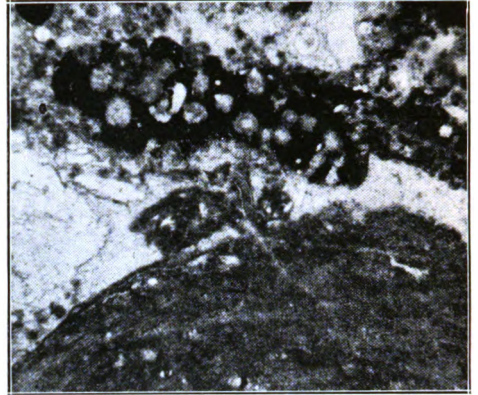
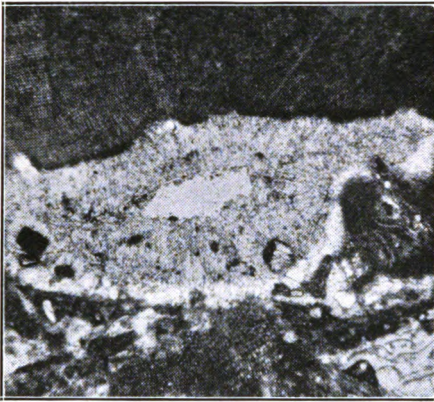
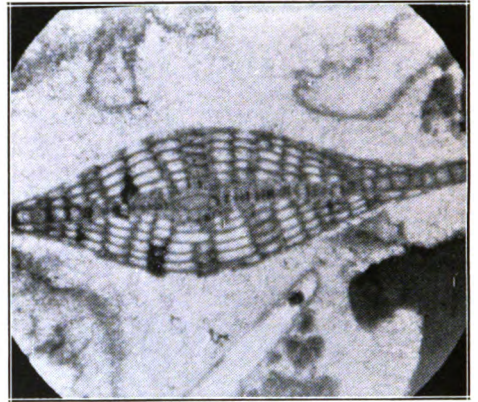


A



B

TOPOGRAPHIC FEATURES OF MANGAIA ISLAND: *A*, UPPER SLOPES AND FLAT CREST OF CENTRAL PLATEAU; *B*, INNER CLIFF OF THE MAKATEA VIEWED FROM THE SLOPES OF UKE.

*A**B**C**D*

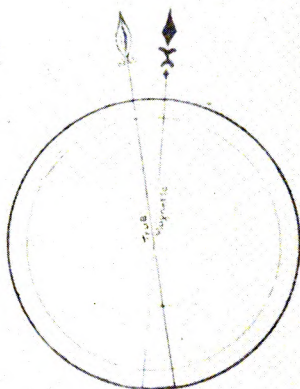
MICROPHOTOGRAPHS OF REEF STRUCTURES: *A*, TYPICAL PORTION OF SAND OF LITHOTHAMNION RIDGE, ONEROA (x 27), SHOWING GRAINS OF VARIOUS REEF ORGANISMS CEMENTED BY CALCITE; *B*, SECTION OF LITHOTHAMNION RIDGE, ONEROA (x 50), SHOWING LITHOTHAMNION AND A GRAIN OF HALIMEDA IN CEMENTING CALCITE; *C*, SECTION OF LITHOTHAMNION RIDGE, ONEROA (x 80), SHOWING FIBROUS GROWTH OF SECONDARY CALCITE NEARLY FILLING A LARGE CAVITY, LITHOTHAMNION SHOWN ABOVE AND BELOW, POLYTREMA AT RIGHT HAND LOWER CORNER; *D*, LEPIDOCYCLINA SP. FROM THE LOWEST HORIZON OF THE MAKATEA AT TE ANANUI (x 35), DUST LINES AROUND THE REMAINS OF OTHER ORGANISMS CAN BE SEEN AS WELL AS FAINT OUTLINES OF INTERLOCKING CRYSTALS OF CALCITE. ALL PHOTOGRAPHS HAVE BEEN REDUCED ONE-FIFTH IN THE PROCESS OF REPRODUCTION.

(PHOTOGRAPHS BY DR. W. P. EVANS)

BE

n true scale

B



One Mile

Matie Kura



4/11/11

P 24

20035



BOUND

MAY 22 1945

**UNIV. OF MI
LIBRARY**

Filmed by Preservation

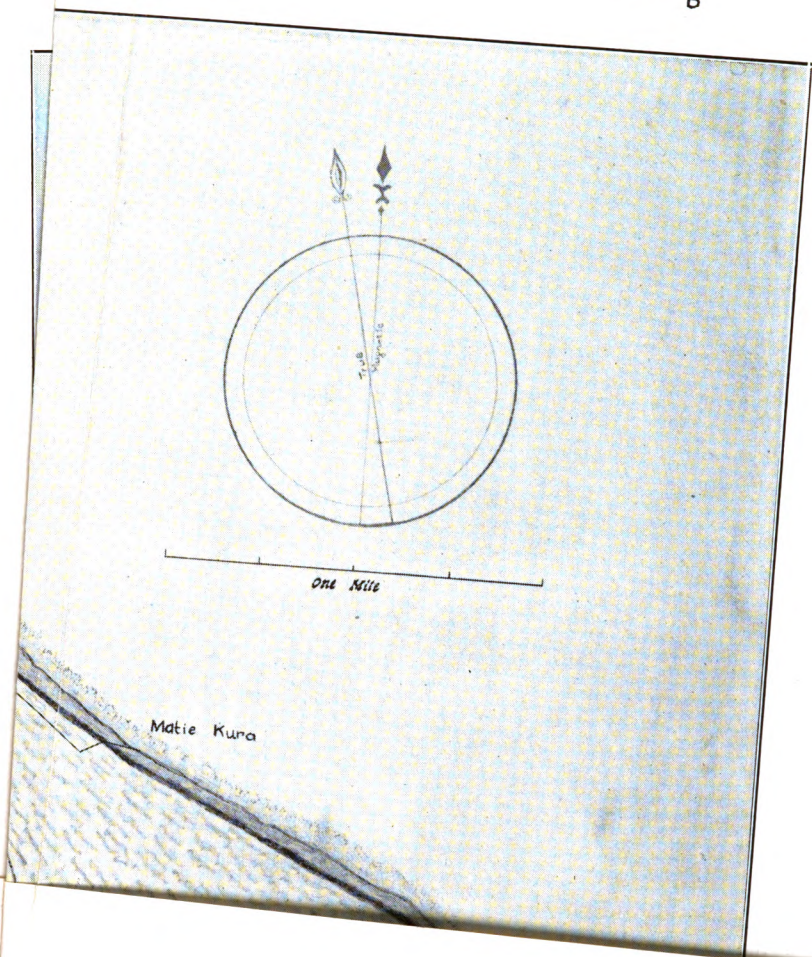
1997

N

BE

n true scale

B



969 NOV 26
DEC 10 1957
DEC 26 1957
JAN 9 1958

**DO NOT REMOVE
OR
MUTILATE CARD**



PRINTED IN U.S.A.

Cat. No. 23 520

BOUND
MAY 22 1945
UNIV. OF MI
LIBRARY



Filmed by Preservation

1997

IV

