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GEOLOGY OF RAROTONGA AND ATIU

BY

PATRICK MARSHALL

BERNICE P. BISHOP MUSEUM

BULLETIN 72

HONOLULU, HAWAII

PUBLISHED BY THE MUSEUM

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Geology of Rarotonga and Atiu

By

PATRICK MARSHALL

THE COOK ISLANDS

INTRODUCTION

The observations here recorded were made during a visit to Rarotonga and Atiu islands in May and June, 1926, as a Bishop Museum Fellow in Yale University. Most generous assistance was given by Sir Maui Pomare, Minister for the Cook Islands in the New Zealand Cabinet. At Rarotonga Judge F. L. Ayson, Resident Commissioner for the Cook Islands, gave every facility and help. I am particularly indebted to Mr. W. H. Scott, Resident Agent for Atiu Island, and Mrs. Scott who entertained me with the most kindly and generous hospitality, and arranged for work with the natives. Owing to Mr. Scott's influence the services of a most suitable guide, Ngapaku, a grandson of the famous Rongomatane, were enlisted.

GEOGRAPHIC SKETCH

The archipelago of Cook Islands, named for Captain James Cook, lies between 18° and 22° south latitude and 157° and 160° west longitude. It comprises six small islands—Rarotonga, Mangaia, Mauke, Mitiaro, Atiu, Takutea, Manuae, and Aitutaki. Rarotonga, the largest and by far the most lofty, is about 20 miles in circumference and its highest peak reaches 2100 feet above sea. The summit altitude of Mangaia is 550 feet; of Aitutaki, 450 feet; of Atiu, 270 feet; of Mauke, 100 feet; of Mitiaro, 90 feet. Manuae is an atoll and Takutea merely a sandbank, not more than 20 feet above high water. All of the islands are surrounded by coral reefs. Aitutaki has a barrier reef which in places is 4 miles distant from the shore, but in all of the southern islands the reefs are merely fringing. (See fig. 1.)

The vegetation of Cook Islands is most abundant and most varied on Rarotonga. (See p. 14.) On all the islands the plants of the coastal strip are the same; *Barringtonia* is dominant over *Pandanus* and *Casuarina* and the more lowly forms. In the Makatea *Aleurites* is everywhere conspicuous as well as banyan and orange trees; *Elaeocarpus* is also present. In the water-courses and on the margins of the swamps the "chestnut" (*Inocarpus*) is abundant. The volcanic ground in Mangaia and Atiu is covered with a native *Gleichenia* and a few *Casuarina* trees scattered here and there, and all the

valleys present a varied flora. The coconut is the only native palm tree of the Cook Islands except for the island of Mitiaro where Gill (15) reports a palm similar to those on Niue and Vavau. The native banana (*Musa fehi*) is not plentiful in Mangaia and is rare in Atiu but it is cultivated at Aitutaki. The guava has spread over much of the volcanic ground in both Mangaia and Atiu and grows in great luxuriance in Aitutaki.

Animal life is poorly represented in Cook Islands. The only indigenous mammal is a rat. There are a few lizards but no snakes and no native frogs.

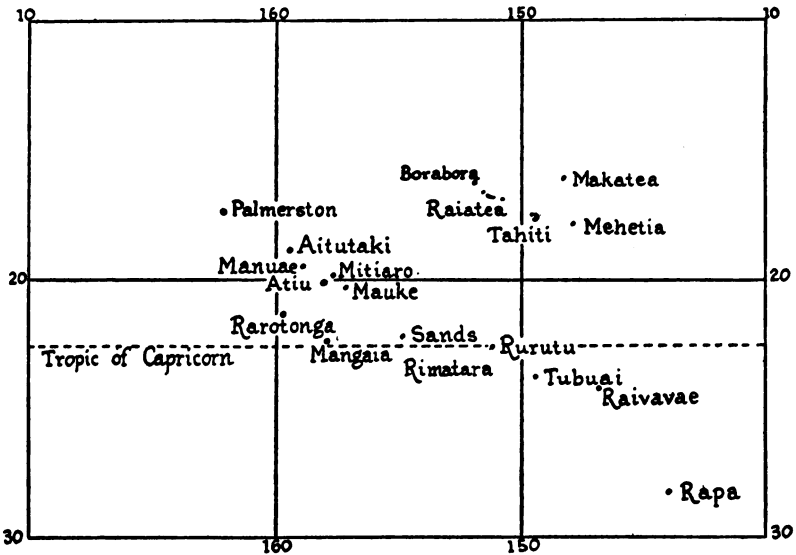


FIGURE 1.—Index map showing Cook Islands, Society Islands, Austral Islands, and Rapa Island.

Land birds are now scarce. In Rarotonga few are to be seen though the plaintive coo of one of the two native kinds of dove is often heard. Two other small birds are occasionally seen. In Mangaia a kingfisher is very common near the coast and in Atiu a small swallow is always hunting insects in the evening. The frigate bird is the largest of the sea birds but it is seldom seen in most of the islands. The "bosun bird" or tropic bird (*Phaethon*) is common in Rarotonga where it nests in some of the inaccessible cliffs. The red tailed species nests on Takutea Island. In all the islands two or three kinds of petrels are to be found and the New Zealand duck (*Anas superciliosa*) is not uncommon.

The natives of Cook Islands are typical Polynesians though of rather shorter stature and perhaps a little more darkly colored than the Maoris. Their language is nearly identical with that of the Maoris and it is noticeable

that the consonants *k* and *ng* are not dropped as in the Tahitian dialect. In manner the Cook Islanders are less noisy and truculent but in general their customs and habits are similar to those of the Maoris. They recognize the same system of deities or spirits pervading natural objects.

Rank among the natives is hereditary. The most important men are the *ariki* who can trace their lineage back to a time before their forefathers arrived in Cook Islands. Subordinate chiefs are *mataiopo* who have authority over small districts. The *rangatira* are inferior to them but still have a considerable standing. The rest of the people are referred to as *ui tangata*. At the present day respect and deference to rank and authority which were previously recognized without question have almost disappeared.

The houses of the native people were oblong with walls about 7 feet high, constructed of straight sticks of hau (*au*, *purau*, *Hibiscus*) fastened to horizontal bars at the top and bottom. Though these uprights were close together, air passed between them freely. A number of rafters extended from the top of the walls sloping to the ridgepole. Saplings were fixed across the rafters at intervals. On these the thatching of lauhala (*ara*, *Pandanus* leaves) was placed and fastened. The houses were provided with a doorway and a small window space at one end. There was neither flooring nor partitions. All the native houses were small and distributed generally through the islands. After the missionaries had instructed the people in the various arts of civilization it became the fashion to build the houses of concrete. What was gained in solidity and privacy was lost in ventilation and coolness. There is now a tendency among the natives to revert to the former type of construction.

Each native family held title to a certain portion of land originally granted by the *ariki* of his district. The land had the form of a *tapere*, an area with a base on the coast and with sides which converged to the central point of the island or district. The head of the family could divide this up among his people or dependents in any way that pleased him. In several of the islands these family estates and even individual holdings have now been accurately defined by surveyors. Land cannot now be bought by Europeans and it is difficult to lease any land.

The natives grow taro, breadfruit, kumera, yam, and coconut. Some fish are caught, shellfish are gathered on the reef, and some pigs are raised by feeding them coconuts and other vegetable products. There are also some domestic fowls. The natives have now acquired a liking for canned meats and for biscuits and other articles made of flour. The means for purchasing these are obtained by the sale of copra, oranges, bananas, and tomatoes, which are supplied to the New Zealand market. The preference for European food and the demand for European dress material, which has entirely superseded the old tapa or bark cloth, has caused the natives to become more

industrious but the area of land which has come into cultivation, though considerable, is still far less than that at the time when the islands were first visited by the missionaries. Recently picture shows and motor cars have given additional incentive to industry.

The ordinary trade of the Cook Islands is based entirely on vegetable products. Copra, which ranks first in value is exported mostly to Europe. Oranges and tomatoes are sent in considerable quantity from Rarotonga to New Zealand and from the other islands oranges are occasionally shipped. The money that is obtained from this trade is spent in buying dress goods, tinned beef, tools, and vehicles. The picture theatre in Rarotonga calls for considerable expenditure.

A considerable number of natives of Mangaia and Atiu live in Rarotonga where it is easier to obtain paid work and where the mail steamers which anchor off the island every four weeks bring customers for the island products. There are also settlements of Cook Islanders in Tahiti.

The discouragement that is given to alien ownership of land in Cook Islands has naturally prevented Europeans from settling in large numbers. The native population seems to be much smaller than at the time when the islands were discovered by the early voyagers and missionaries. Of late years, however, there has been a slight increase. The census of 1925 gave the following figures:

	RAROTONGA	AITUTAKI	MANGAIA	ATIU	MAUKE	MITIARO	TOTAL
Polynesians	3,713	1,418	1,233	923	506	236	8,029
Europeans	192	15	16	10	5	2	240
Total	3,905	1,433	1,249	933	511	238	8,269

When discovered by Europeans, each of the Cook Islands was governed by a chief, always a man of ancient lineage, who exercised despotic power over life and land. Afterwards missionaries working in conjunction with the chiefs caused the enactment of a code of laws which in some of its details now seems laughable. At a later time Ariki's courts and a federal parliament were established. For many years Cook Islands was a protectorate of Great Britain but in 1900 the group was annexed by New Zealand. A Resident Commissioner living in Rarotonga is responsible for the administration of all the islands and is President of the high court. (See New Zealand Year Book for 1907.) In each of the other islands the Government is represented by a resident agent. There is a hospital in Rarotonga and nurses in charge of dispensaries in the other islands. Education is compulsory and all instruction is in English.

GEOLOGIC FEATURES

The general geology of Cook Islands is simple. Rarotonga is formed of volcanic rock with a fringe of raised coral only 15 to 20 feet above high water.

On Atiu the raised coral rock stands 70 feet above sea and the volcanic material is relatively small in amount. On Mangaia the raised coral rock—Miocene in age—attains a height of 200 feet but the volcanic material is much less extensive than in Rarotonga. Mauke has very little volcanic rock and the height of the raised coral is perhaps 100 feet, though accurate measurements are lacking. Mitiaro has no volcanic ground but the center of the island, where from analogy with Mangaia and Atiu, volcanic rock would be expected, is occupied by a lake. Manuae is an atoll and Takutea merely marks the site of a coral reef. Aitutaki has a small island of volcanic rock in the corner of a barrier reef some eight miles in diameter.

REGIONAL GEOLOGIC RELATIONS

The altitude of the coral rock on the different islands suggests that so far as the latest movements are concerned a neutral line of movement extends from a point close to the northern shore of Rarotonga in a northeast direction and passes between Atiu and Manuae islands. Whether the effect of such a movement extended beyond the limits of the Cook Islands cannot be stated. For the islands lying southeast of Mangaia information is available only for Rurutu and Rapa. It is, however, noticeable that Palmerston Island, 200 miles west-northwest of Aitutaki, is an atoll. On the northern side of this neutral line there has been a depression and on the southern side an elevation. The upward movement seems to have increased with the distance from the neutral line but the amount of depression is unknown—downward movements in oceanic islands are registered less clearly than upward ones. There is no indication that this movement was associated with rock folding.

The relation between the Cook Islands and other island groups in the South Pacific is not clear. It is not certainly known whether the different islands arise from one plateau or whether they are the emergent peaks of a submarine ridge, as their somewhat linear arrangement suggests. The only soundings given in the British Admiralty chart are one of 2,498 fathoms 120 miles west of Aitutaki, one of 2,632 a hundred miles still further west, and one of 2,740 fathoms about 200 miles southwest of Rarotonga. These few soundings merely indicate that there is deep water around the islands. There are no soundings recorded between the different islands. Dana (12, p. 37), represents the islands as situated on a "Polynesian chain" and Gregory (17, p. 278) places them on a "South Pacific chain," but these ideas are based merely on the general alignment of the islands in relation to neighboring groups.

Existing knowledge is sufficient to indicate the probable nature and extent of earth movements in the southeast Pacific during Tertiary time. The evidence for the place and the amount of the movements is derived mainly from physiographical observations supplemented somewhat by lithological studies.

The age of the movements has been determined by a fortunate paleontological discovery.

It is now known that several islands in these seas have more or less well defined plateaus at the summit of the volcanic mass which forms their nucleus. Such a platform on Mangaia Island at an altitude of 554 feet above sea level has already been described (25, p. 36).

A similar but far better preserved structure on Atiu Island has an altitude of only 270 feet and on the neighboring island of Mauke there seems to be a plateau only 100 feet above sea level. On Aitutaki Island the greater part of the volcanic ground appears to be a plateau which slopes from about 100 feet at the northwest to perhaps 30 feet at the southeast. However, in the north part of the island two small rocky peaks rise to the height of 300 and 450 feet respectively.

Chubb (6, p. 304) has described the remnants of a plateau on Rurutu Island, which lies nearly 400 miles east of Mangaia. In this island the plateau has an elevation of 800 feet above sea level and the highest point of the island (Manureva) is 1,400 feet. His description of Rimatara suggests a similar plateau on that island, at an altitude of only 315 feet. On the high mountainous islands of Rarotonga and Rapa, no plateaus are found though both of them have been closely examined. The other islands of the Austral group have not been described but it is known that Tubuai and Ravaivai have about the same altitude as Rurutu, and that Sands Island (Hull Island) is relatively low and consists of limestone. Of the other islands in the Cook group Mitiaro is a low limestone mass, Takutea merely a bank of coral sand, and Manuae a small atoll. For the Society Islands, 900 miles to the northeast, no plateaus cut in volcanic material have yet been described.

Thus, so far as known, plateaus of marine erosion exist in four islands of the Cook Islands and in one, perhaps two, of the Austral Islands. The height of the plateaus above present sea level is, however, different in all of the islands. It is highest in the southeast and decreases in altitude to the west and north. In Mangaia Island alone has the age of the plateau been determined and even that without exactitude. As previously shown (25, p. 42) the rim of raised limestone rock on Mangaia was deposited long subsequent to the formation of the plateau and a species of *Lepidocyclus* in the limestone proves that it is not younger than the middle Miocene. The formation of the plateau on Mangaia is, therefore, assigned to pre-Miocene times. No similar evidence has been discovered in the raised reefs of the other islands of the Cook group. Smith and Chubb (32) seem not to have made microscopical examinations of the limestones which they describe as continuous around Rurutu Island, attaining an altitude of 300 feet at Arei, and at even greater heights on the slopes of the central volcanic hill. This is clearly a reef lime-

stone and is quite different from the small outcrop of detrital limestone that was found by Chubb on Rapa Island.

In the light of present knowledge it seems probable that the plateaus in the volcanic rock of all of these islands were formed at the same period of relative depression, but, of course, such a statement cannot be made with assurance. In any event they probably are not strictly contemporaneous. It would appear that the downward movement of the ocean floor that permitted the formation of these plateaus had its maximum amount (800 feet) at Rurutu, and diminished in a northwesterly direction to 554 feet at Mangaia and only 270 feet at Atiu. Eastward at Rapa there is no trace of this movement, nor westward at Rarotonga, and though a plateau is found at about 100 feet on Aitutaki, there is no trace of it in Tahiti or elsewhere in the Society Islands. It is, of course, possible though the physiographic evidence makes it highly improbable, that the Society Islands were not in existence when this downward flexing of the ocean floor took place.

The plateau of erosion at a relatively low level in Mangaia is pre-Miocene in age and in the lack of other evidence—a corresponding antiquity may be assumed for the plateaus on the other islands. There is no indication that folding or faulting was associated with this movement of the ocean floor. There seems to have been a slight tilting movement, which was perhaps greater at Aitutaki than elsewhere.

The next indication of movement of the sea floor is afforded by raised coral reefs found on many of the islands. Assuming that these structures began as fringing reefs that were actually united with the coast, the sea level was lower, or the ocean floor in this region had warped upward to a varying extent above its present position. Apparently, however, this difference was only slight, for everywhere the base of the inner edge of the raised coral is but little below the present sea level. At Rurutu it is actually above that level. At Mangaia this relatively high level was in the early Miocene, but this condition did not last long and was succeeded by a slow downward movement. The level fell 100 feet at Rapa, 300 feet at Rurutu, 216 feet at Mangaia, 70 feet at Atiu, about 70 feet at Mitiaro and Mauke, and only 15 feet at Rarotonga. There is no evidence of a fall at Manuae and Aitutaki seems not to have been affected. The Society Islands were outside of the area that was flexed. At Mangaia this movement ceased before the end of the Miocene period. Since this time there has been a gradual upward movement in all the islands until the present level has been attained. This at first was slow and nearly uniform though afterwards the uprise was less regular and at times rapid, as shown by the shore terraces at Mangaia. The general wide extent of the present fringing reefs is taken to indicate that the islands have remained with an unchanged elevation for a long period. The atoll of Manuae and the

considerable barrier reef of Aitutaki indicate a different movement. In my opinion these structures indicate a depression in the northern part of Cook Islands. The atolls of Palmerston and Suvarov islands and the barrier reefs of the Society Islands show that the conditions of the ocean floor at Aitutaki extended also to these more northern islands.

RAROTONGA

GENERAL FEATURES

The island of Rarotonga is elliptical in shape and almost exactly 20 miles in circuit. Its longer axis is nearly seven miles in length; its shorter axis, northeast to southwest, only five miles. The island lies in latitude $21^{\circ} 12' S$. and longitude $158^{\circ} 46' W$. (See map, fig. 2.)

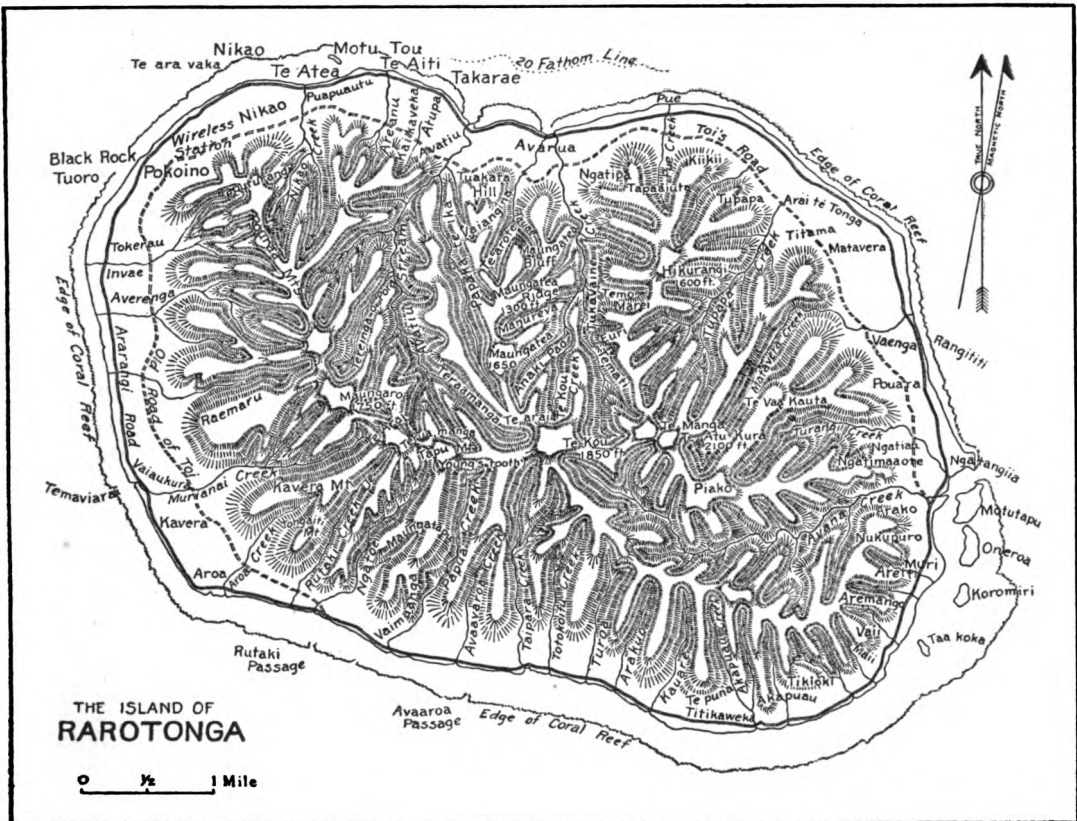


FIGURE 2.—Map of Rarotonga, outline based on a survey by H. M. Connal (1913). Physiographic and geologic features by Patrick Marshall (1925, 1926, 1927). Drawn by G. S. Druhot.

Like the other islands of the Cook group, Rarotonga is surrounded by a coral reef which fringes a low lying coast but the land soon rises rapidly into lofty hills with flanks that in many places are precipitous. The culminating point, Te Manga, has an elevation of 2,100 feet; the sharp and prominent peak of Hikurangi, close to the anchorage of Avarua, reaches a height of 1,600 feet; and several peaks with altitudes between 1,600 and 2,000 feet com-

bine to give the island an appearance of ruggedness and grandeur that is not quite warranted by the actual height of the mountains. (See Pl. I, II, figs. 3-6.) The impression of grandeur is probably emphasized by the loneliness of the island, which is generally sighted only after several days have been passed at sea. Everywhere the island is covered with vegetation which, except in a few small areas, is most luxuriant and effectually hides the rock surface of even the most abrupt precipices. On the lowlands the coconut palm is most conspicuous but many other lordly trees are interspersed with it. Almost all of the hillsides are clothed with trees though a few places are covered only with ferns above which a few feathery toas (*Casuarina*) rise conspicuously. The bare hillsides coated with red clay which are conspicuous at Mangaia and Atiu, are absent from Rarotonga and the area of fern-clad hills is relatively far smaller than at Tahiti.

HISTORICAL SKETCH

John Williams, the well known missionary, often called "the martyr of Erromanga," was the European discoverer of Rarotonga so far as actual historical records are concerned. He first heard of the island from the natives of Raiatea, where he was stationed from 1817-1822. In 1822 he was told that on the island of Aitutaki were some natives of Rarotonga who had been placed there by a passing trading vessel. He at once visited Aitutaki, on which he had previously landed some Christian natives from Raiatea. He found the Rarotongans still there and from them he ascertained the position of their homeland. His first search for the island resulted in failure, but his second attempt after visiting Mangaia and Atiu was successful, when actually at the end of his resources. Williams was evidently much impressed by the appearance of Rarotonga. He writes (38, pp. 204-205):

The high mountains, the rocky eminences, and the luxuriant valleys called forth our admiration. We were astonished to see the taro and kape, the ti and sugar cane growing luxuriantly nearly down to the edge of the sea. The whole island was also in a high state of cultivation, and I do not remember having seen anything more beautiful than the scene presented to me, when standing on the side of one of the hills looking towards the sea shore. In the first place there are rows of superb chestnut trees (*Inocarpus*), planted at equal distances, and stretching from the mountain's base to the sea, with a space between each row of half a mile wide. This space is divided into small taro beds which are dug four feet deep and can be irrigated at pleasure. These average about half an acre each. The embankments around each bed are thrown up with a slope leaving a flat surface upon the top of six or eight feet in width. The lowest parts are planted with taro and the sides of the embankment with kape or gigantic taro, while on the top are placed at regular intervals, small beautifully shaped breadfruit trees. The pea green leaves of the taro, the extraordinary size and deep colour of the kape lining the sloping embankment, together with the stately breadfruit trees on the top present a contrast which produces a most pleasing effect. . . . There is a good road round the island which the natives call "ara medua" or parent path, both sides of which are lined with bananas and mountain plantains; and these with the Barringtonias, chestnut and other trees of wide spreading foliage protect you from the rays of the tropical sun and afford

even in midday the luxury of cool shady walks of several miles in length. The houses of the inhabitants are situated from ten to thirty yards or more from this pathway and some of them were exceedingly pretty. The path leading up to the house was invariably strewn with white and black pebbles; and on either side were planted the tufted-top ti tree or dracoena, which bears a chaste and beautiful blossom, interspersed alternately with the gigantic taro. Six or eight stone seats were ranged in front of the premises by the side of the "parent pathway." These were relics of antiquity, some of which were regarded with much veneration by the people; who, while they pointed to them, would say, "Here my father, grandfather, or the great chief so-and-so would sit." They were generally formed of two smooth stones, the one serving as a seat, the other sunk in the earth to form a back. Here in the cool of the evening, after the labors of the day, with a wreath of flowers on their brow, anointed with a sweet scented oil, and wearing a new tiputa or shining pakaku, sat the inmates of the house to chat with any loquacious passenger about the events of their own little world. . .

Their wars, I think, may also be considered sanguinary. In the one that raged just prior to our first visit, the king informed me that four score and ten were slain on the side of the conquerors and five score on that of the conquered. . . At Rarotonga there was not such an equality of rank as at Tahiti, but a man was great according to the number of his kaingas or farms, which contain from one to four or five acres each. These are let to tenants, who, like the vassals in the feudal system, obey the orders of their superior, assist him in the erection of his house, in building a canoe, making fishing nets, besides bringing him a certain portion of the products of his lands. This gives to the chiefs a degree of respectability.

Gill (15, p. 4), one of the first missionaries, gives some details of earlier visits of vessels to Rarotonga. He says that soon after the islanders had heard from the occupants of a drifted canoe about Captain Cook's visit to Tahiti, a vessel arrived off their coast. One of the Rarotongans who ventured on board the ship said that it was a floating island with breadfruit and other trees on board. This statement suggests that the vessel was the *Bounty*, which may have sighted the island in 1789, when the mutineers were bringing the captured vessel from Tonga to Tahiti. It is probable, however, that confusion has arisen with Aitutaki Island which was actually visited by the *Bounty* before the mutiny. Williams states that Rarotonga was probably visited by the *Bounty*. Meinicke (27, p. 139) says that the *Bounty* actually visited the island but quotes no authority for his statement. He also states that the island was sighted by the ship *Seringapatam* in 1814.

According to Gill the next visit (in 1820) was that of an unidentified merchant ship in charge of Captain Goodenough. A boat's crew was sent ashore at Ngatangia but the natives there appearing hostile, the ship went to the northern side of the island, where it was received less boisterously. Finally the visitors removed to a little harbor to the east, where they stayed for three months. Before long their licentious and ruthless conduct with the natives led to slaughter of both natives and visitors, and Captain Goodenough found it advisable to leave the island, but he took with him some Rarotongan women whom he afterwards landed at Aitutaki. These were the natives whose presence in Aitutaki attracted the attention of Williams.

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The earlier native history of Rarotonga, briefly outlined by Williams (38, p. 192), has been given with full details by Smith (33, p. 109). According to Smith the island was first settled by Apopo, who hailed from Haapai about the year 875. At much the same time other voyagers came from the Marquesas but did not settle permanently.

The two important sources from which the island was populated were expeditions of Tangiia from Tahiti and of Karika from Samoa—both expeditions reaching Rarotonga in the year 1250. The descendants of these two pioneers are now the leading chiefs of the island. When Europeans first visited the island the most important chief was Makea of Avarua, the lineal descendant of Karika; but Pa, the descendant of Tangiia, was the most powerful military leader. Pa lived in the village of Ngatangia, named after his ancestor. Another influential chief, though of less authority, was Tinomana, who lived at Arorangi on the west side of the island.

FLORA

Rarotonga has a far more varied flora than the other islands of the Cook group. This is a natural result of its greater altitude, wider diversity of soil, and greater variation of station. The high rainfall, which averages 78 inches annually and is generally distributed throughout the year, assures an abundance of moisture even in the lightest coral sands which everywhere fringe the coast. On the southern coasts, where the slopes are cooled by the frequent trade winds, the climate is hardly tropical even at the sea level, and here the coconut palm does not bear freely. On the mountain sides the climate is of the warm temperate zone and at an altitude of 2,000 feet moderately temperate conditions prevail. At Avarua the mean annual temperature is 75 degrees; the rainfall averages 78 inches annually, but within ten years has ranged from 116 to 61 inches. Any of the wet months, November to May, may have a fall of 15 inches.

A list of the Rarotongan plants was made by Cheeseman (5) in 1903. This work was the fruit of two months stay in the island during which all its mountainous portion as well as the lowland were traversed. He identified 235 species of plants which he considered to be indigenous, 80 species that he thought had been introduced by Europeans, and 19 which were supposed to have been brought by Polynesian voyagers from other islands. The plants introduced by Polynesians include, of course, the principal food plants, among them the breadfruit tree but not the coconut. Of the 235 indigenous Rarotongan plants 167 have been recorded in the Tahitian flora, 129 in the Tongan flora, and 103 as common to both groups. Only 18 species are considered by Cheeseman to be endemic. The likeness to the Tahitian flora is to be expected because of the similarity of soil, station, and climate, and from the comparative proximity of the two islands. It is particularly noticeable



that the genera *Fitchia* and *Sclerotheca* are restricted to the Cook Islands and the Society Islands. No endemic genera have been discovered in Rarotonga.

In general features the distribution of the plants in Rarotonga is precisely that of Tahiti and other high islands of the Pacific. On the coastal strip *Ipomaea* and *Triumfetta* are prominent, while the first trees to be encountered are *Pandanus* and *Casuarina*. The widely distributed *Hibiscus* soon succeeds them and with it the coconut palm. At a short distance from the sea front are noble trees of *Barringtonia*. Their swelling trunks, as much as eight feet in diameter, give rise to spreading branches with many leaves, as much as a half square foot in expanse. An extensive area is shaded by a single tree. Here, too, grows the *tamanu* (*Calophyllum inophyllum*) used generally for canoe making, the banyan, orange trees, and many coffee bushes. There is a thick undergrowth of ferns and *Asplenium nidus* grows everywhere on the trees. In the damper ground and in the stream courses the "chestnut" (*Inocarpus edulis*) with its picturesque buttressed trunk is abundant. On the hills the candlenut (*Aleurites mollucana*) is everywhere conspicuous. Other genera well known in New Zealand are found here: *Metrosideros*, *Weinmannia*, *Myrsine*, *Elaeocarpus*, and *Coprosma*. In the deep and shaded valleys the native banana still finds a home. The curious genus *Fitchia*, which is represented by only one species, grows at sea level on the southern side of the island but not below 1,000 feet on the northern side. The great liana, *Entada scandens*, is everywhere and laces the foliage together, while in all the valleys *Hibiscus tiliaceus* forms almost impenetrable thickets, especially where it is associated with the gigantic fern *Angiopteris evecta*, which has fronds 15 feet in length. A characteristic plant of many of the ridges is an unidentified species of *Freycinetia*, its trailing and hanging branches greatly impeding progress.

Ferns are abundant. The species *Gleichenia dichotoma* covers those patches on the hills that are devoid of trees and as its interlacing wiry stipes reach a height of six feet it renders progress almost impossible. The three species of tree fern are far more abundant on the southern than on the northern side of the island. There are conspicuous species of *Pteris*, *Nephrodium*, and *Asplenium*, of which *A. nidus* is the most striking.

Of plants of recent introduction the papaw (*Carica papaya*) springs up in plentiful abundance in all cleared land, orange trees are numerous in all the valleys, and the guava (*Psidium*) readily spreads where the thickets are not too dense. The lantana has not spread in Rarotonga or elsewhere in Cook Islands to such an extent as to constitute the menace to agriculture that it has become in many tropical islands.

NATURAL DIVISIONS

THE REEF

The island of Rarotonga comprises four natural divisions, or geographic provinces here described as the reef, the beach and strand, the swamp, and the volcanic ground.

In Rarotonga, as in other reef-girt islands, a sharp distinction can be made between the raised outer edge of the reef or Lithothamnium ridge, which is above sea level at low water, and the reef flat which lies between this ridge and the beach and is covered by water at all states of the tide.

The reef is continuous round the whole circumference of the island, but it varies considerably in width. Along the northeast coast between Avarua and Ngatangia its outer edge is close to the shore, especially near Ngatangia village, but along the south and the southeast coasts it is nearly half a mile in width over a distance of five or six miles. The rise and fall of the tide is small. The reef flat is covered by a very shallow sheet of water even at high tide and at low water the Lithothamnium ridge is exposed but slightly between the surges. The seaward edge of the reef on the north side of the island is not so steep as in most places. Opposite Avarua a platform at a depth of less than 20 fathoms extends seaward for a third of a mile and along the coast for more than a mile—the entire area over which soundings have been made. The passes through the reef are few and narrow; the one most used is at Avarua, where lighters ply between the shore and vessels at anchor outside the reef. At Avatiu is a similar pass. Inside both these passes schooners are often moored but the shelter is poor. The pass at Ngatangia is wider but the prevailing winds make it less accessible. The small passes at Arorangi and those on the south side of the island are seldom used because they are exposed to the prevailing ocean swell, and are dangerous because of the outward rush of water at the entrance. The floor of the entrance of the pass at Avarua at a depth of $5\frac{3}{4}$ fathoms is covered with large rounded boulders of coral rock, but careful inspection through a water glass failed to show any heads of growing coral on the bottom of this pass.

The edge of the reef is of the usual irregular form with projecting bosses, some above and some just below the surface of the water at low tide. Deep channels, narrow as crevasses, extend here and there far into the reef itself and on their sides coral heads of many kinds are growing freely. Corals grow in luxuriance on the flanks and round the base of the bosses of rock which extend seawards from the edge of the reef. On the edge of the reef itself where the thundering surf breaks eternally into foam there is little or no coral growth. The few heads that were seen do not develop a branching form; they lie flat on the surface of the reef. Here as at Mangaia, Atiu, and Aitutaki, the edge of the reef supports mainly a growth of various kinds of alga the most abun-

dant of which are maroon colored members of the Floridiae, especially species of *Lithothamnium* and *Corallina* (or a related genus) which secrete a large amount of calcium carbonate in their cell walls. When the floor of the sea outside the reef is viewed through a water glass the edge of the reef is seen to slope down almost precipitously, but irregularly, to a depth of 4 to 5 fathoms. At this depth the surface of the rocks is generally covered with a growth of *Lithothamnium* and other calcareous algae. The principal species is maroon color, probably *Porolithon onkodes*. On the sides and in the crevices of these rocks corals of many species grow luxuriantly. From about the 5-fathom line, the sea floor slopes steeply outward and is covered with coral growth. At a distance of 50 yards from the reef are patches of sand from which many heads of coral rise. Here and there, however, the bottom is covered with large rounded boulders of coral rock among which no organic growth is present, owing presumably to the movement of the boulders during rough weather. These boulders are probably sinkers which are tied by native fishermen to their lines in such manner as to become detached when a fish is hooked. In the mouth of the pass which leads to the wharf at Avarua the boulders cover the whole of the floor at a depth of 5 fathoms. Proceeding outwards from the reef the sandy patches become more numerous and larger and the coral heads become smaller. This change continues until the limit of visibility is reached, a depth of 15 fathoms. No *Halimeda* was seen on any part of the sea floor.

LITHOTHAMNIUM RIDGE

The outer edge of the reef is a little higher than the reef flat interior to it, but on its exterior side it slopes outward between tide levels at an angle of 6 degrees. At Avarua this edge is less pronounced than usual but it may still be dubbed the "Lithothamnium ridge." It has the appearance of similar structure in Mangaia and other neighboring islands. It seems quite smooth in a general view but is extremely rough in detail. Its surface is very irregular and knobby and is everywhere perforated by deeply penetrating crevices which branch and reunite to form a structure which may be compared to a gigantic stony sponge. On the surface is a dense growth of various kinds of algae among which species of *Lithothamnium* have preeminence though mossy species of *Corallina* are common.

Corals, of course, are rare in this situation and when present lack the well known elegant branching forms which render them so attractive. They have a flattened corallum which adheres closely to the surface of the rock. In the various crevices corals grow in some profusion. The small importance of the Lithothamnium ridge on the north side of Rarotonga is probably related to the insignificant surf action there. The surface of the Lithothamnium ridge is about 18 inches above the level of the low water but the wash of the surf

keeps it constantly wet at all stages of the tide. At high water the rush and force of the surf are great. The rough surface of this ridge does much to reduce the force of the surf without greatly opposing its violence at any one point. The ridge thus largely escapes damage.

A month before this shore was visited an unusually severe hurricane had been experienced, the force of the sea falling almost directly on the portion of the reef that was examined. It was found that although a number of new boulders (nigger heads) had been lifted onto the reef by the violence of the surf, none of these had been derived from any part of the *Lithothamnium* ridge which was intact throughout. At the part of the reef examined these nigger heads consist almost entirely of large masses of *Porites* which seem to grow beyond the steep outer edge. Likewise the nigger heads, which, judging from their appearance had lain on the reef for a long period, were almost exclusively formed of *Porites*. It thus appears that although the surf is sufficiently violent to break off and cast onto the reef large masses of coral that were growing outside it, the *Lithothamnium* ridge itself, which bears the brunt of the attack of the surf, is strong enough to resist its force without damage. Under normal conditions the sea floor outside the edge of the reef is quite free from disturbance by the surf, but during the occasional severe hurricanes, when waves of huge size break on the reef, this outside floor becomes subject to the most violent action. It is here that the giant waves recoil and fall headlong. The coral growths are formed during long periods of quiet conditions and develop a structure and anchorage which are unable to resist the strenuous wave action during hurricanes. They may be broken off in large masses and be thrown onto the surface of the reef.

REEF FLAT

The surface of the reef on the south side of Rarotonga has relatively few nigger heads on the reef flat though here the prevailing ocean swell breaks with greatest violence. The explanation is perhaps to be found in these considerations: the surf is here so constantly heavy that any coral that is thrown onto the reef is at once washed farther, and onto the beach; the exceptional hurricanes which afflict Rarotonga only once in twenty years bring the heavy and destructive sea from the north, the surf on the south side of the island being little more violent than usual.

The reef flat at Rarotonga is relatively narrow. On the west and north it has an average width of 200 yards; on the northeast 50 yards; and on the south and southeast 500 yards. The water that covers it is generally shallow especially on the north and west sides of the island, but is far deeper on the south side.

Corals grow freely in all the deeper portions of the water that covers the reef flat, but throughout its extent erosion appears to balance growth. Near

Avarua it is possible to cross the reef flat dry foot at low water. Even on the south side of the island the depth of the water on the reef flat is not great enough to produce the impression of a lagoon between the coral reef and the shore.

BEACH AND STRAND

For almost the complete circuit of Rarotonga the coast has a dazzling white sandy beach formed of fragments of the various organisms that grow on the reef and in the water outside of it. On the south side a considerable variety of molluscan shells can be obtained; elsewhere they are rare. Tests of Foraminifera make up a very small portion of the sand and in only a few places is there any typical beach rock (coquina). For a short distance near Matavera, the beach is formed of cobbles of coral rock. Here the reef is narrow and in ordinary weather the heavy seas at high water break full onto the surface of the beach. It is noticeable that here the beach rises in two terraces of cobbles, both of them far above the limit reached by the waves in ordinary weather. The terraces are only five feet wide and are composed of rather heavier cobbles than those on the lower part of the beach. The lower of these terraces, about six feet above the limit of ordinary storm waves, was reached by the hurricane of March, 1926, said to have been the most severe in twenty years. During this storm, which ruined the banana crop for the year, the waves swept over the beach at Avarua and Arorangi and destroyed some buildings.

The upper of these two small terraces is much the older. Its surface and also the slope between the two terraces is crossed by a trail formed by the natives in going down to the reef. Along this trail in the upper terrace the surface of the cobbles is worn smooth by the bare feet of the natives though on the lower terrace no such wearing can be seen. It is possible that this upper terrace was formed by the waves during the violent hurricane of December 22, 1831 recorded by Williams (38, p.390).

The beach of Rarotonga appears to maintain its form and size with a good deal of constancy but during hurricanes portions may be swept away, and the material removed may extend the coast where it is sheltered from the hurricane seas. The places where such changes take place naturally depend upon the direction of the striking force of each particular hurricane. During the storm of March, 1926 the beach between Arorangi and Avatiu suffered most. The beach rises with a uniform slope to a height of 10 to 12 feet and its summit is strewn with rough loose blocks of coral on the west and north sides of the island. The ground maintains this height of 12 feet above high water mark for a distance averaging 100 yards when it sinks down again almost to the sea level. This 12-foot strand extends nearly around the island. The only interruption is between Ngatangiia and Titikaweka, where the reef

flat has its greatest width and four small islands stand on it. These islands stand a quarter mile from the beach, near the edge of the reef and form a line which continues the curve of the coast lying to the north of Ngatangia. They seem to be remnants of a former coast line and it is possible that a hurricane of unusual power broke through an older coast line to the low ground beyond it and left its separated remnants as islands. This idea is supported by the fact that at Te Muri, opposite the islands, there is now no flattened ridge nor swamp behind it; the volcanic rock extends to the beach. The only similar occurrence is at Black Rock (Tuoru) where the tongue of a phonolite lava flow actually reaches the sea. Here, however, the lava flow projects out so far as to invade the region of the coral beach on the rounded curve that is naturally developed under the influence of marine action. This flat-topped strand, as displayed in low cliffs near Ngatangia, has the structure of a coral reef and is not a mere accumulation of reef debris deposited in this position by heavy storms. The coral rocks contain an abundance of coral heads in the position of growth. It is, therefore, reasonable to consider this flat strand as an old reef which was separated from the shore by a shallow lagoon which has become the swampy area that separates the coral rock from the rising ground of volcanic origin.

SWAMP

The swampy ground is variable in extent, but in most places not more than 200 to 300 yards wide. Most of it is drained by channels that pass through the raised coral strand which separates the swamp from the reef flat. The streams that drain the highlands do not take the overflow from the swamp; they build fans over which they pass at a level higher than the floor of the swamps. In times of heavy rainfall the swollen streams may give part of their water to the swamps. The Tupapa, however, has a subterranean outlet.

In this swampy ground the greater part of the taro, the staple food of the natives, is grown. The old road of Toi (Ara Medua), which was the highway before the advent of Europeans, marks the inner limit of the swampy ground. At the Black Rock (Tuoru), however, the old road lies somewhat to the landward of the edge of the volcanic ground and crosses some of it. At Te Muri, where there is no swampy ground, the old road is not to be seen.

VOLCANIC GROUND

From the inner side of the swampy ground the volcanic slope rises quickly and in many places abruptly. Most of the spur ends which radiate from the high country have truncated terminations due in all probability to marine erosion before the growth of the coral reef began. The hills rise with great steepness from the valley floors and the dividing ridges between adja-

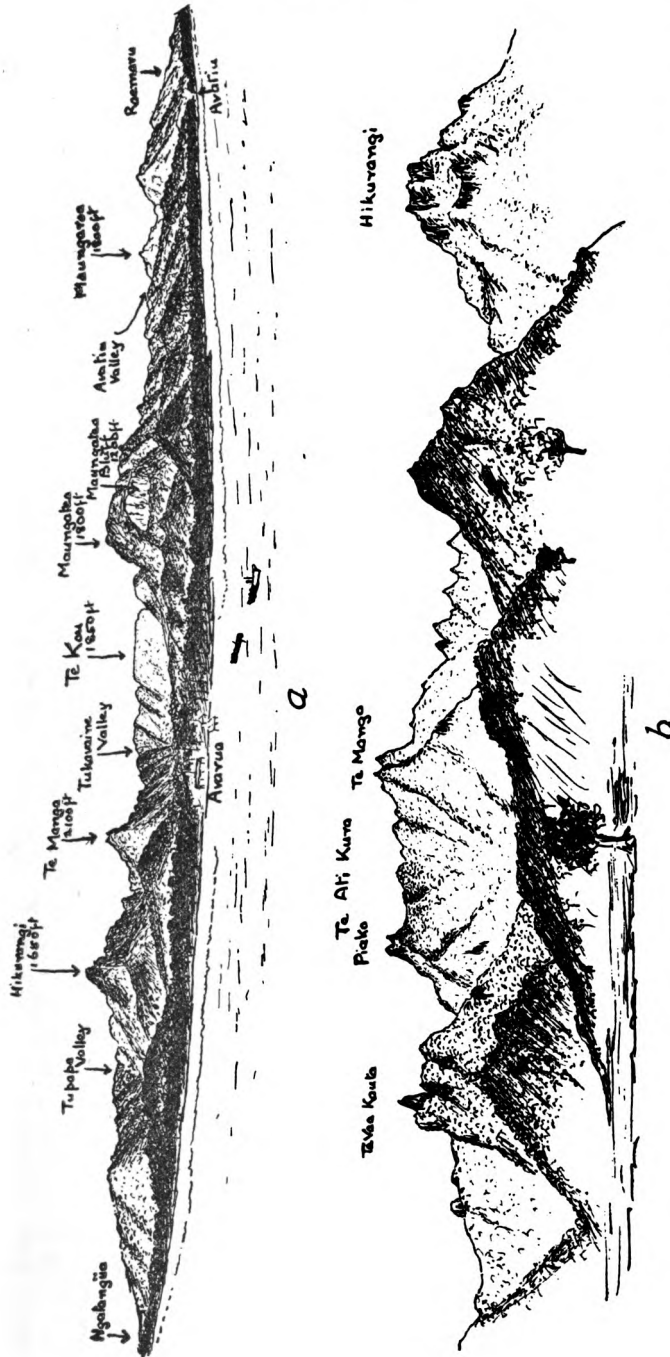


FIGURE 3.—Sketches showing topographic features of Rarotonga: *a*, view from the anchorage at Avarua; *b*, view of highest peaks from coast line near Matavera.

cent valleys are extremely sharp and in consequence the surface of the island is rugged and craggy. In spite of this the peaks and ridges reach no great heights; the summits have altitudes between 1,600 and 2,100 feet. (See map, fig. 2.)

Except for the peaks of Hikurangi and Maungatea the main heights of the island lie along a well defined ridge running west to east from Maungaroa to Piako, a distance of three miles. Branching from this main rampart three ridges with high points extend in a northerly direction and a long ridge without prominent peaks runs southeast.

The prominent hill called Raemaru is a relatively flat-topped mass with a slight westerly slope and bordered by a steep scarp which marks the edge of a flow of sodalite-phonolite lava. The conical hill of Tongoitia, a little to the southeast of Raemaru, is composed of basalt. Raemaru is particularly noticeable because its surface is covered with a carpet of fern (*Gleichenia dichotoma*) with a few toa (*Casuarina*) trees rising through it, while all the surrounding hills are covered with the mixed forest which gives the whole island such an attractive appearance. A smaller flat-topped hill, which rises directly behind the village of Arorangi, also is covered with a growth of fern and toa, and is capped with sodalite-phonolite lava.

On the western side of the island all the spurs rise to a sharp ridge trending 10 degrees west of north and terminating on the coast near Black Rock (Tuoru), but on the south end of this ridge the peak of Maungaroa marks the turning point to the east-west main mountain line of Rarotonga. On its northern side this westerly ridge falls steeply and in many places precipitously to Avatiu Valley. The peak of Maungaroa, which attains an altitude of 1,750 feet, occupies the commanding position in the center of the island, and forms an excellent viewpoint (fig. 6, a).

The main island axis, when followed eastward from Maungaroa, at first falls sharply, but soon becomes more even. A half mile from Maungaroa an extremely sharp aiguille known as Maunga Tapu ("Youngs Tooth") forms a conspicuous object from the sea off Avatiu (fig. 6, c). A little to the southwest of Maunga Tapu are several lesser but rather similar needles called Te Maunga Rua. They are clearly visible from the coast near Papua on the south side of the island. A mile and a half from Maungaroa the mountain axis rises sharply to the summit of Te Kou (1,850 feet) a flat-topped mountain capped with trachytoid phonolite and covered with a forest of the usual Pacific island type. In the center of its flat top is a small spring. From Te Kou a prominent ridge extending north-northwestward descends steeply then rises to a small, unnamed peak, north of which a pass (Te Arai) leads from Tukavaine Valley to Avatiu Valley. Farther north rises the sharp peak of Maungatea (1,750 feet), beyond which the ridge gradually descends (fig. 4, a); its main axis ends in the steep Maungatea Bluff (fig. 6, b), but a

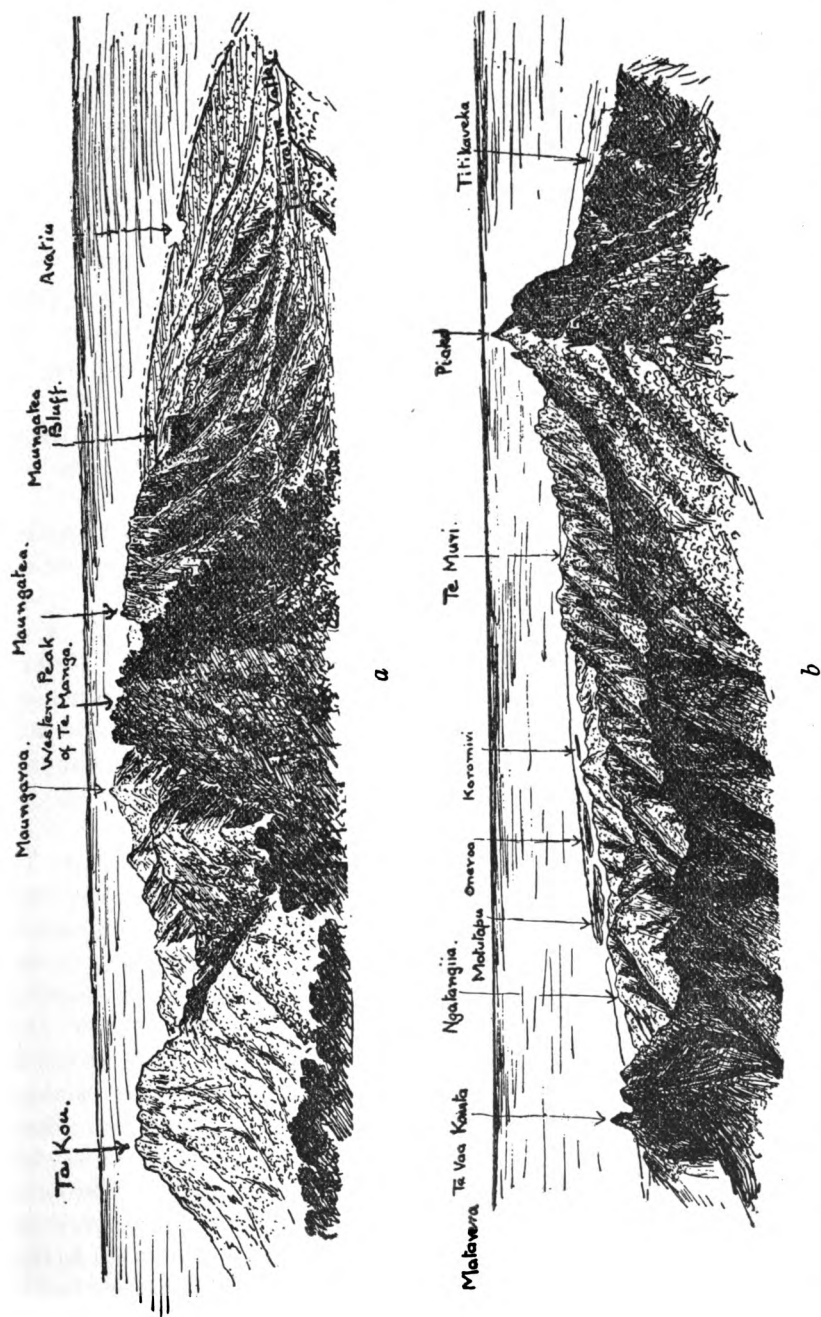


FIGURE 4.—Sketches showing topographic features of Rarotonga as seen from the summit of Te Manga: *a*, view looking west; *b*, view looking east.

small branch descends more gradually and terminates in the sharp pointed Tuakata Hill almost at the village of Avarua. Most of Maungatea ridge is formed of sodalite-phonolite, but the highest summit consists of coarse basalt. The descent of the ridge to the Tukavaine Valley is extremely steep (fig. 5, *b*). On the northern side of Maungatea a basalt which contains no olivine forms a lava flow beneath the phonolite, but the distance over which it extends could not be ascertained.

From Te Kou the main ridge of the island (fig. 3, *a*) continues in an easterly direction at a high altitude to Te Manga (2,100 feet), the culminating point of Rarotonga. This part of the ridge forms the divide between the Tukavaine and the Avana drainage basins. From its double-peaked top Te Manga descends steeply on all sides, but particularly on the south, where it falls almost sheer to the valley of Avana River, which, rising on Te Kou, enters the sea at Ngatangia, four miles distant—the longest stream on the island (fig. 4, *a*).

From Te Manga northward a prominent ridge descends almost precipitously, but at an altitude of 1,300 feet the slope flattens and except for several small aiguilles the ridge maintains a uniform height for two miles (fig. 5, *a*). It then curves slightly from north-northwest to north-northeast, rises abruptly, and terminates in the spear-shaped peak of Hikurangi. Viewed from the anchorage at Avarua, Hikurangi is the most conspicuous feature on the island (fig. 3, *a*). It rises to a height of 1,650 feet within a mile of the sea-coast (a slope of 1:3) and as the upper 300 feet are abrupt the mountain presents an appearance of height and grandeur, not altogether warranted by its actual elevation.

The most outstanding ridge on the island extends southeast from Te Manga and for a distance of a half mile maintains a height of more than 1,900 feet (fig. 3, *b*). Both its sides are so extremely steep that vegetation has difficulty in finding a station for growth. The ridge terminates in the sharp pinnacle of Piako, from which point it descends abruptly and, turning sharply to the east, rises steeply in an unnamed hill 1,600 feet in height, and finally slopes down to sea level near Ngatangia. Another ridge trending northeast from Piako is far less prominent, but it bears on its crest halfway to the coast the striking crag of Te Vaa Kauta (fig. 4, *b*). These two ridges with their serrated crests and with the commanding summits of Te Manga and Piako behind them give a vivid impression of rugged grandeur when seen from Ngatangia. A ridge of relatively low elevation trending northeast from Te Manga separates the Tupapa and Matavera valleys. A final ridge strikes southeast from Te Kou and terminates near Ngatangia. It nowhere rises to any great height.

The outstanding physiographic features of Rarotonga are clearly not

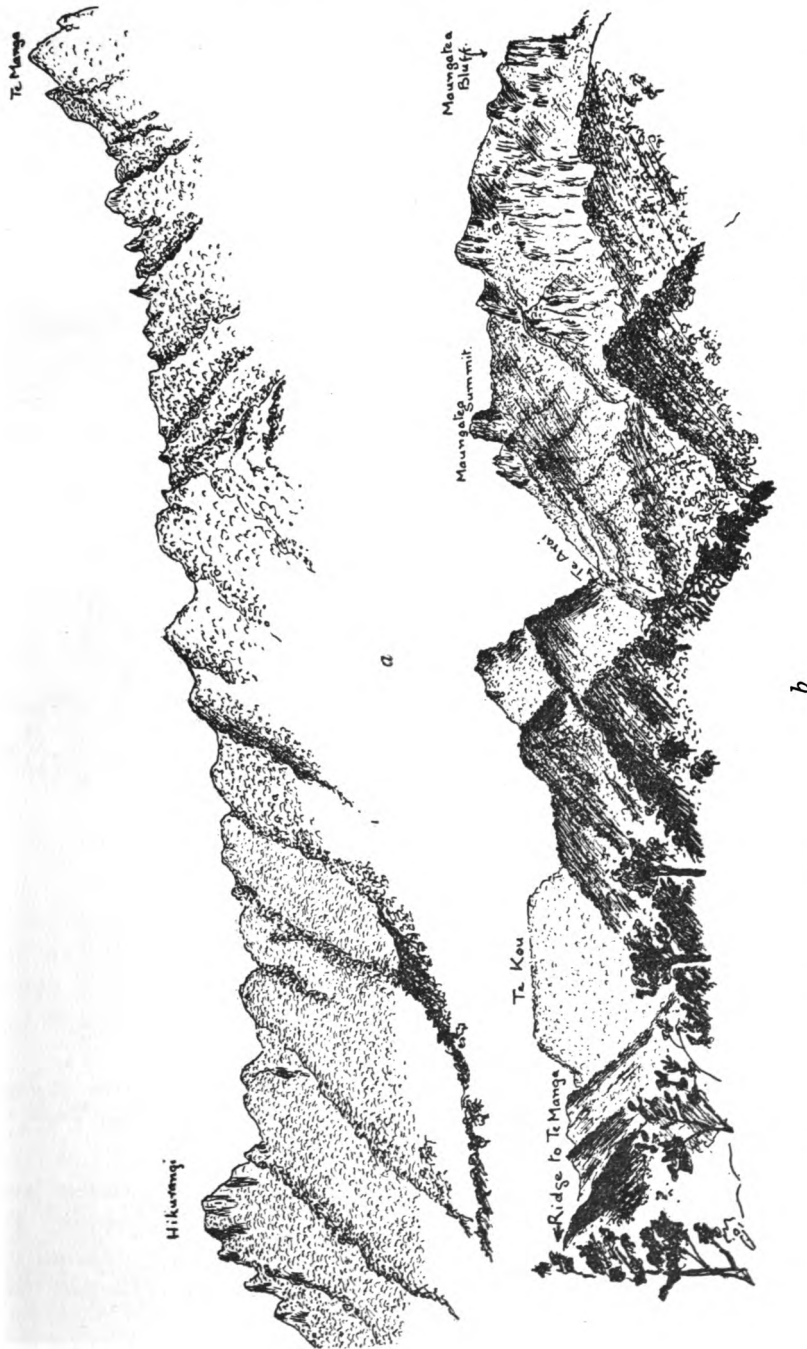


FIGURE 5.—Sketches of Tukavaine Valley: *a*, view of east side from Upper Tukavaine; *b*, view of head and west side.

original; they are not directly due to the volcanic activity to which the island owes its origin. Apart from the evidence offered by the lithology of the rocks (pp. 28-31) a mere inspection of the relief map of the island (fig. 2) shows that the rugged profile and prominent peaks are due to subaerial erosion. In very few places, such as the sloping summit of Raemaru and the

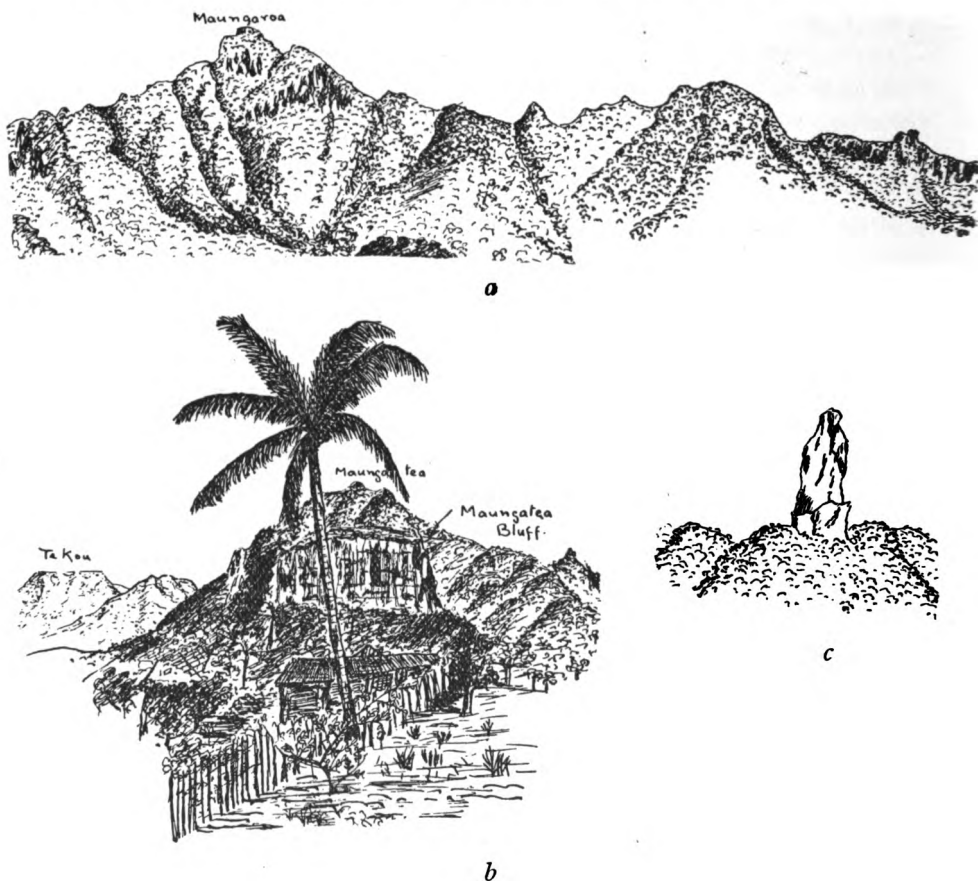


FIGURE 6.—Sketches showing topographic features of Rarotonga: *a*, view of west side of Avatiu Valley; *b*, Maungatea looking south from Avarua; *c*, Youngs Tooth as seen from Upper Avatiu.

relatively flat-top of Te Kou, do the original surfaces of the massive lava flows remain. Most of the hill summits are remnants of beds of scoria. Te Manga and Tapu are survivals of erosion which removed large masses of material. Hikurangi and Te Vaa Kauta owe their prominence to the fact that they are the outcrop of dykes.

The ridges have the "razor back" form, common to tropical islands of

volcanic origin. The cause of this exaggerated physiographic form is not clearly understood. It generally has been ascribed to the effect of violent tropical rainfall on land areas which had an initial slope of great steepness. Observations in Rarotonga led to the opinion that this peculiar form of ridge is due in part at least to the protection afforded by the tropical growth of vegetation. Trees growing near the summit of one of the ridges have roots that extend over it and become fixed in the rock on the further side. The bracing of these roots combined with the lacing of climbing plants give the crest of the ridge a resistance and solidity not possessed by the flanks. There is thus developed a tendency for the flanks to flake away in severe weather while the crest of the ridge remains relatively secure. It seems, however, that other causes must operate perhaps in equal degree, as ridges in regions of light rainfall are said to have a "razor edge" form as exaggerated as those on other tropical islands. It is noticeable that on Mangaia and other islands of the Cook group the "razor back" type of ridge has not been developed. However, the altitude of these islands is small and the denudation far less extensive than in Rarotonga.

It was noticeable in Rarotonga after the hurricane of March, 1926, that considerable areas of the steep flanks of the mountains had been completely stripped of vegetation and that the trees had carried with them the skin of rocky material in which the roots had anchored. So far as observed, none of the ridge crests were stripped.

IGNEOUS ROCKS

CLASSIFICATION

The structure of the volcanic ground could not be studied in detail though a large amount of information was obtained. The precipitous nature of the hills, the absence of trails over the greater part of the island, the thick covering of interlaced tropical vegetation, the frequent heavy rains all combine to hinder geological work and in some places effectually prevent it. The rock masses comprise four main types:

1. Basaltic tuffs and scoria
2. Basaltic lavas and dikes.
3. Phonolitic tuffs.
4. Phonolite lavas.

In general it may be said that basaltic tuffs and scoria constitute the more prominent peaks of the island, and phonolitic tuffs the most striking physical features. Phonolite lavas have a somewhat wider extent than the other rocks. Basaltic lavas and dikes are relatively small in amount.

BASALTIC TUFFS AND SCORIA

The basaltic tuffs of Rarotonga are composed of large fragments of coarse-grained, black, basaltic material embedded in finer grained tuffaceous matter. The boulders of basalt contain large idiomorphic crystals of augite of typical form and also large anhedral olivine. These tuffs are thought to constitute the greater part of the slopes extending from near shore to the tops of the highest hills though in places they are covered with phonolitic material. Along the shore they are represented by red clay soil, the product of deep weathering and oxidation.

In its unoxidized state, the tuff is well exposed in the middle part of Tuka-vaine Valley, where a huge landslide in the distant past descended from the ridge which connects Hikurangi and Te Manga. The presence of this rock at high levels in the center of the island and its very wide extent beneath other volcanic rocks along the coastal slopes of the volcanic hills justify the opinion that the tuff is the oldest rock in the island. Its thickness must have amounted at least to the height of the island (2,000 feet). Because of its weathered surface and the dense cover of vegetation, outcrops of the rock are rare. The largest observed are behind Avarua and on the outer slopes of the hills farther east. Typical material may be seen in the grounds of the Church Mission at Avarua.

The structure of the tuff clearly indicates that the earliest eruptions of which there is any record in Rarotonga were violent explosions. The finer matrix in which the boulders of coarse basalt are embedded is red and the oxidation to which this color is due appears to be original and indicates that these early eruptions were subaerial.

The finer material of this scoria contains a number of sharp angled augite crystals as much as 20 mm. in length. They show the crystal faces usual in basaltic augite, but many of them show the orthodome (p. -101). Several crystals are twinned in the usual manner with the orthopinacoid, the twinning and composition plane. In this scoria there are a few fragments of phonolite—a proof that eruptions of alkaline rock had preceded the formation of these scorias, which are the lowest rocks now exposed. It suggests the condition at Otago Harbor where in the long series of eruptions alkaline lavas, principally phonolites, preceded and succeeded outflows of basalt (24, pp. 382-408).

BASALTIC LAVAS AND DIKES

No coarse-grained basaltic lavas were found in place. In many streams boulders of this rock are plentiful, but observations made it seem probable that they were all derived from the scoria beds or, to a far less extent, from dikes. Lava flows of fine grained basalts do not seem to be common. There

are, however, two flows beneath the phonolite of Maungatea; the upper a medium grained lava, the other finer grained with no phenocrysts of augite or olivine.

Dikes are rather more common. A coarse-grained dike seen at the point where the Avatiu enters its mountain gorge is 10 feet wide and strikes 60° . Another of similar texture at the entrance of the gorge of the Tauae, near Avârua, is 8 feet wide and strikes 50° . Still another dike, 9 to 12 inches wide on the cliff face of Maungatea Bluff, penetrates the breccia as well as a mass of coarse basalt 5 feet wide striking 60° . That numerous dikes traverse the rocks of the island cannot be doubted but the thick covering of vegetation conceals them so effectually that few were distinguished. The summit of Hikurangi seems to owe its resistance to a dike and it is possible Te Vaa Kauta is the outcrop of another dike.

PHONOLITIC TUFFS

The exposure of phonolitic tuffs are in steep cliffs at Maungatea Bluff, Youngs Tooth, and on the west side of the Avatiu Valley. The rocks are light gray in color and contain fragments of many kinds of lava as much as a foot in diameter. The pebbles collected include basalts of various types.

This breccia is a solid rock mass almost free from joints of all kinds but it is roughly stratified. On the west side of Avatiu Valley unequal weathering of the different strata has produced an irregular cliff with projecting ledges and sheltered recesses in which the "bosun" bird makes its nests. Like some of the other more abrupt features of the island the bluff at the northern end of the Maungatea Ridge, which has a cliff face some 300 feet in height, owes its steepness to the physical characters of the breccia. Maunga Tapu (Youngs Tooth), the conspicuous aiguille at the head of the Avatiu Valley (fig. 6, *c*) and the other aiguilles, which show up so conspicuously from Papua when looking towards the north, are also formed of this material.

At Maungatea Bluff the phonolitic breccia seems to rest on highly weathered basaltic breccia, and on the east side of the bluff near its summit, there are some basaltic lava flows. These facts lead to the opinion that at this place the breccia fills an explosion cavity and is, in fact, an agglomerate. It may be that these basaltic lavas are of a later period and flowed round a denuded remnant of the breccia. The presence of basaltic dikes on the eastern side of the bluff gives support to this suggestion and makes it necessary to assume two periods of basaltic eruption, one preceding, the other succeeding the phonolitic eruptions. That this is not an improbable assumption is shown by the fact that in Dunedin eruptions of basic material occurred both before and after those of alkaline lavas more than once in the history of a single volcanic area.

PHONOLITE LAVAS

A great emission of alkaline lavas succeeded the scattering of the tuffaceous phonolitic matter. The area covered by these lavas is considerable though, judging by the absence of pebbles of this material in the stream

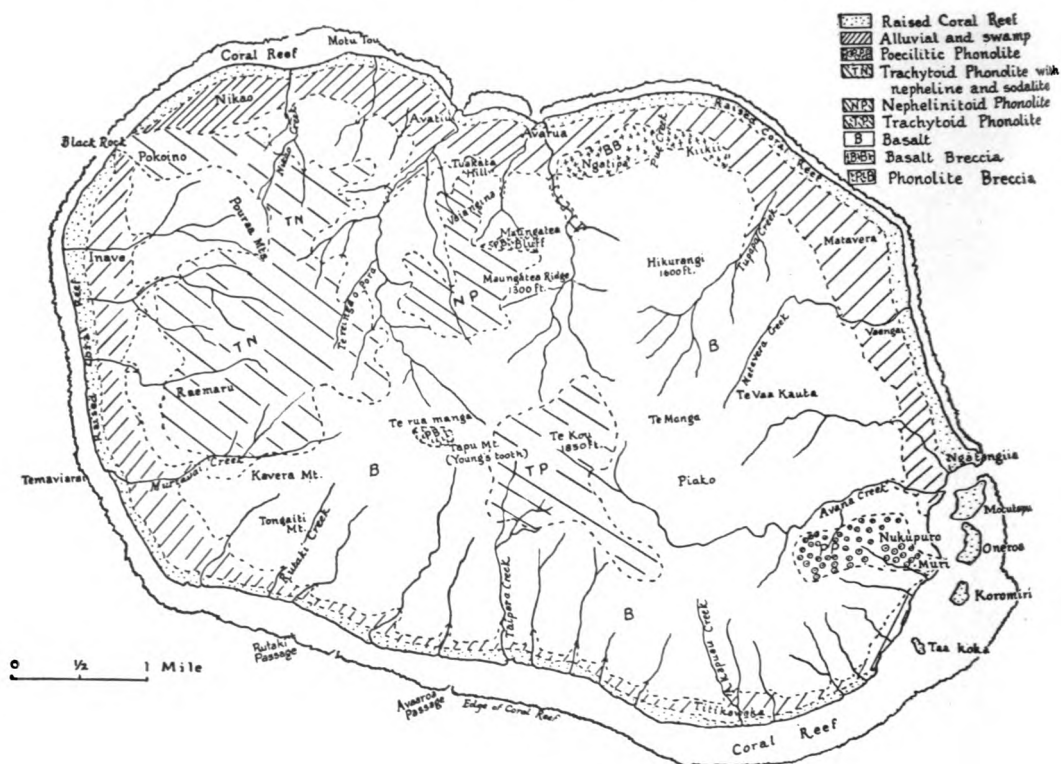


FIGURE 7.—Geological map of Rarotonga.

courses, none of it is to be found in Tupapa or Matavera valleys and very little in Avana Valley. The points from which the alkaline lavas were erupted could not be located, though it is important to record that lavas of this type reach sea level at Te Muri and Black Point and also at Tuakata, near Avarua. The summit of Raemaru is formed of a lava flow with a pronounced tilt southwesterly. Much of the summit of Maungatea Ridge and seemingly all

of the flat top of Maungatea Bluff consist of alkaline material though of a slightly different composition. On the other hand no outcrop of alkaline lava was seen on the floors of any of the valleys which at many places cut through the volcanic material almost to sea level.

The conclusion is obvious that the alkaline lavas were emitted from elevated positions within the island and flowed outwards from what are even now the high lands. Te Kou may well have been one of the points of eruption but the existence of many others is suggested by the distribution of the rocks and their composition (fig. 7).

The ridge of Maungatea appears at first sight to be a continuous lava flow that extended outwards from Te Kou. These two elevations, however, are composed of different materials and actually the alkaline rock is by no means continuous along the summit of the ridge; in several places on it basaltic rock occurs. Even the small outcrop at Tuakata Hill is probably an independent mass derived from a local eruption or intrusion.

On the ridge extending north from Maungaroa is a dike of phonolite, 11 feet wide, trending east-west. It is the only one seen on the island. The mantling of the coast of the island with a covering of coral rock prevents the structure of the volcanic rocks from being displayed by marine erosion.

PETROGRAPHIC DESCRIPTIONS

PHONOLITES

Several types of phonolites can be distinguished in Rarotonga, but the centers from which they were erupted cannot be located, owing to the large amount of denudation that has taken place.

Microscopically these phonolites are dense rocks with a dark greenish tint. Some fresh surfaces have the greasy luster often associated with abundant nepheline.

A trachytoid type, which comes from the top and southern slopes of Te Kou, consists mainly of microlites of sanidine or soda-orthoclase but these are mixed plentifully with somewhat irregular prisms of aegerine (Pl. III, *F*). Iron ore, apparently magnetite, is not uncommon in well formed, but minute, crystals. There are no phenocrysts in the rock. Between the feldspar and aegerine microlites is a good deal of a perfectly transparent colorless mineral with a very low refractive index and an extremely low birefringence. This mineral could not be identified with certainty. The choice lay between such a zeolite as analcite or chabazite and sodalite, determined by Smith and Chubb (32, p. 324) as the interstitial mineral of the sodalite-phonolite of Rapa Island. The same or at least a similar material has evidently a wide occurrence in rocks of this nature. It is clearly the constituent of the base of phonolites that was called a glass by Rosenbusch (28, p. 970) and by Zirkel (40, p. 442).

Both of these authors remark that the substance (glass) dissolves readily in acid. Zirkel quotes several analyses of this soluble portion of the rock as well as the residue after treatment with acid. Most such analyses have little value for this portion of the rock may contain such minerals as nepheline and sodalite as well as the isotropic glass of the base, all of which are soluble in acid.

Microscopic study of the interstitial material in the phonolite from Te Kou showed that nepheline and sodalite are absent. It was found that 27.12 per cent of the rock was dissolved in hydrolic hydrochloric acid in the dilute state and just raised to the boiling point. When acid of different strengths was used and the temperature not raised to the boiling point the same amount of material was dissolved. The dissolved matter consisted of the following ingredients:

	Percentage	Molecular Proportions
SiO ₂	34.10	5.68 12
Al ₂ O ₃	29.53	2.90 6
Fe ₂ O ₃	1.20	
TiO ₂	.96	
CaO	4.44*	.68 }
K ₂ O	3.63	.38 }
Na ₂ O	16.00	0.55+2.63 }
P ₂ O ₅	.66	
H ₂ O	7.49	
Cl	1.10	.55

*Part of the CaO is calculated to make apatite with P₂O₅ and sphene with TiO₂.

These analytical results lead to the conclusion that the dissolved substance is a definite mineral with the composition 7 (Na₂O, K₂O, CaO) 6Al₂O₃, 12SiO₂+NaCl closely related to sodalite which has the composition 3 Na₂O 3 Al₂O₃ 6 SiO₂+NaCl. The question, however, arises as to whether the water that is present in the rock is a constituent of the mineral but as it is not affected by a high temperature water is not likely to be present. Subsequent tests showed that dilute silver nitrate stains the mineral. The chlorine is obviously very loosely held. Zirkel (40, p. 147) comments on the relatively low silication of the dissolved portion of phonolitic rocks compared with the insoluble portion and the surprising amount of lime that passes into solution and notes that it is not accompanied by a corresponding amount of magnesia. In the analyses given by him the rock from Messid Gharian is the only one in which chlorine is estimated in the soluble portion and in this rock recognizable sodalite is present. The fact that the chlorine of the Rarotongan rock seems to be concentrated in the soluble portion appears to support the view that the substance is a definite mineral, not merely a glass. The name ameleite is proposed for the mineral (αμελής, overlooked). A more definite occurrence of this mineral recently found at Dunedin, New Zealand, is described in the "Mineralogical Magazine" (Vol. 22, No. 127, 1929).

It was found that the sodalite-phonolite on the top of the Maungatea Bluff (Pl. III, C) contains as much as 62 per cent of material soluble in dilute hydrochloric acid. This is a higher percentage of soluble matter than that in any of the rocks quoted by Zirkel. This soluble portion has the following composition:

SiO ₂	41.30
Al ₂ O ₃	29.67
CaO	3.87
K ₂ O	2.87
Na ₂ O	11.74
H ₂ O	8.71
Cl	2.10
	100.26

Zirkel (40) notes that the composition of the soluble portion of these rocks approaches that of nepheline. This is true for the rock from Maungatea Bluff though the presence of water and lime introduces a complicating feature. Because this rock contains sodalite and nepheline as well as some zeolitic matter attempts to determine the composition of its interstitial matter from this analysis would not be satisfactory.

The phonolite from Black Rock (Tuoru), which forms a large lava flow on the northerly extension of Maungaroa, is also trachytoid but its feldspar microlites are smaller and no magnetite is present. It contains many minute nepheline crystals as well as some of larger size and also crystals of sodalite but in less abundance than in other rocks of this type in the island. Isotropic matter between the feldspar microlites is common. The rock which forms the prominent flat summit of Raemaru covers the greater part of its western slopes and extends northward for a considerable distance along the hill slopes towards Tuoru, is yet more alkaline in composition (Pl. III, A). Though microlites of feldspar are still abundant nepheline is more common: but the minute crystals of this mineral tend to become localized in well defined areas especially in association with patches of aegerine. Sodalite too is more abundant and the interstitial matter here called ameleite, supposed to be a mineral allied to sodalite, has a general distribution through the rock. A few crystals of sphene are present.

A highly alkaline phonolite occurs at Te Muri, extending from sea level to the top of the ridge between that place and Avana Valley. It contains no microlites of feldspar but the mineral is present in the form of small plates, with highly irregular boundaries, which include, in poecillitic manner, crystals of nepheline, aegerine, and sodalite. The nepheline also includes microlites of aegerine which are also molded around many small crystals of sodalite. A few crystals of sphene are present. As in most rocks of this group there is no iron ore. The order of crystallization is clearly: sodalite, aegerine, nepheline, feldspar.

The nature of this rock was not fully understood when previously described by me (22, p.99). It is rather a more coarsely crystalline type than the other phonolites, and the high percentage of water shown in the analysis indicates that a considerable amount of zeolite mineral is present. Some spaces in the rock are filled with these minerals. This is the type of Lacroix' rock species, murite (19, p.32).

A somewhat similar type of phonolite comes from a lava flow at the top of the Maungatea Bluff and the ridge south of it. Here the nepheline crystals are large and contain abundant zonally arranged microlites of aegerine. The sodalite is more distinct and contains the same dusty brown material in the center as at Te Muri. There is very little feldspar but the zeolitic mineral seems to be more plentiful.

The rock that forms a precipice near the southern end of the Maungatea ridge is perhaps the most interesting of the Rarotongan phonolites. In hand specimens the rock is a dark green color and has a number of vacuoles partly or wholly filled with white zeolites. (See Pl. III, B).

In microscopic slices it is found to be extremely dense and to consist mainly of a network of small aegerine needles, in the meshes of which are a few small crystals of nepheline and sodalite. Here and there roundish spaces filled with isotropic matter can be distinguished. These contain large numbers of concentrically arranged needles of aegerine. The whole combination closely resembles that described by me (21, p.405) in a somewhat similar rock from Puketeraki near Dunedin, New Zealand, which was identified as leucite. The meshes of the aegerine net in the Maungatea rock are generally filled with a colorless mineral that has feebly birefringent properties which seem almost certain to be a zeolite, perhaps chabazite. The vacuoles which are filled with zeolites proved to be of great interest. In many places needles of aegerine augite project into the cavities and some are suspended in the zeolitic matter and have no apparent connection with the walls of the cavity (Pl. IV, A). This striking feature affords convincing proof that the zeolites that fill the space are primary constituents of the rock. Several different species of zeolite are found in each of the cavities (Pl. IV, B). Most of the cavities are lined with an isotropic mineral of low refractive index, probably analcite. Inside this border in many cavities are two distinct types of radiating crystal groups: one having strikingly long fibers; the other, which is far more common, consisting of shorter, wider crystals with pyramidal terminations and a relatively high refractive index. Another mineral has small crystals so arranged in a feathery form that it is difficult to distinguish the individuals. The more central part of the larger spaces is filled with a zeolite having a low refractive index, and arranged as relatively large interlocking plates. It is thought that the zeolite in coarsely radiating groups is natrolite, that the finely radiating species may be scolecite, and that the species in the center are

perhaps chabazite. When a section is treated with silver nitrate and subsequently with potassium chromate the species in the mass of the rock and that in the central portion of the vacuoles stain in a conspicuous manner.

This rock clearly belongs to the sodalite phonolite series of Rarotonga. The conclusion reached from a study of the walls of the cavities that the zeolite minerals which fill them are primary is supported by the consideration of the possible origin of the minerals. The nepheline and sodalite of the rock are quite fresh in the section, and therefore, cannot be the source of the zeolite. The feldspar also is unweathered.

Another type of sodalite phonolite, represented by boulders from the bed of the Tukavaine stream shows the extreme form of nephelinitoid development. In it nepheline is notably the most prominent and well developed mineral (Pl. III, *D, E*). The crystals have the usual hexagonal or rectangular sections and are crowded with microlites of aegerine arranged in concentric zones. The largest ones measure 0.5 mm. in length. There is little feldspar but an abundance of aegerine. A few crystals of a greenish brown hornblende with a moderate resorption border and a few crystals of sphene of an extremely pale brown tint are present. Between the nepheline and aegerine crystals there is a good deal of a platy feebly birefringent zeolite. The exact place from which this specimen was derived is not known but it is almost certain that it came from some part of the Maungatea Ridge.

A still more peculiar form of rock is represented only by a boulder found in the bed of the Tukavaine. The plentiful feldspar in this rock is apparently soda orthoclase in somewhat irregular crystals 3 mm. long and 0.5 mm. wide. The aegerine too is in rather coarser grains than usual. No nepheline or sodalite is to be seen but there is a great abundance of well crystallized and perfectly transparent zeolites. Many of them are arranged round the feldspar crystals and none display an arrangement or outline that suggests that they have been formed from any preexisting mineral such as nepheline or sodalite.

However, the rock contains no crystals of these minerals. Quite unaltered aegerine projects into the mineral aggregations in a manner that suggests the same period of formation as the zeolites. This rock is light grey in color and shows on a fractured surface conspicuous cleavage planes of feldspar.

Examination of these types of alkaline volcanic rocks from Rarotonga produces a strong impression that the several species of zeolite which occur in them are primary. It is generally recognized that analcite occurs in many volcanic rocks. In New South Wales natrolite is regarded as a primary constituent of some rocks.

Table 1 shows how widely the phonolitic rocks are distributed in the south central Pacific Ocean. The composition of the basic rocks here presented or of the much fuller series given by Lacroix studied in conjunction with that of the phonolites so often associated with them shows that the lavas in these

TABLE 1. COMPARATIVE ANALYSES OF PHONOLITES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO ₂	47.52	54.60	49.20	50.80	52.40	52.00	54.15	53.80	56.12	57.00	59.00	57.60	56.40	58.91	60.50	60.46	62.44	56.78
Al ₂ O ₃	15.18	17.48	22.15	22.96	20.19	21.09	16.09	18.72	21.32	18.56	17.09	20.78	15.84	17.20	18.20	19.17	18.87	18.29
Fe ₂ O ₃	5.98	5.72	4.21	3.84	4.01	3.21	7.35	4.99	2.59	4.58	5.30	4.00	6.48	1.99	1.34	1.81	1.87	5.01
FeO.....	3.17	1.02	2.07	1.62	1.70	1.63	4.90	3.59	3.29	2.76	3.25	3.50	3.54	4.86	1.89	1.95	0.87	1.23
MgO.....	1.61	1.44	0.15	0.21	0.24	0.14	1.61	0.86	0.56	0.41	0.21	0.35	0.21	0.44	1.18	0.16	0.62	1.31
CaO.....	7.42	3.10	2.95	2.75	3.20	4.15	3.86	2.80	2.30	1.05	1.46	1.98	1.52	3.33	1.75	1.44	1.35	2.42
Na ₂ O.....	8.11	9.32	7.80	8.45	8.33	8.23	5.94	8.82	5.79	6.43	7.47	6.05	5.80	7.28	7.25	7.46	7.29	5.35
K ₂ O.....	3.84	5.61	3.58	4.12	4.08	4.28	4.41	5.20	4.81	6.34	5.39	4.67	5.78	4.50	4.45	4.68	5.66	4.24
NO ₃	1.92	0.80	1.20	1.14	1.08	1.20	0.41	0.30	.....	.....	0.41	0.52	.....	0.43	0.92	0.12	0.62	0.59
P ₂ O ₅	0.63	.....	0.45	0.70	0.14	0.31	0.42	.....	.....	.....	0.42	.....	0.13	0.09	.....	0.06	0.09	0.11
H ₂ O.....	3.62	1.56	5.20	1.46	2.00	5.86	1.40	1.90	1.54	2.96	2.32	2.60	3.96	0.72	.....	1.32	0.32	2.34
H ₂ O.....	1.25	.....	.....	1.14	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.20	.....	0.56	0.17	2.33
MnO.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.18	.....	0.25	0.21	.....
Cl.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.16	.....	0.26	.....	0.08

1. Murite from Te Muri Point, Rarotonga: Lacroix (19, p. 32).
2. Nephelinitoid phonolite from Maungatea, Rarotonga: Marshall (26, p. 98).
3. Nephelinitoid phonolite from Maungatea Bluff, Rarotonga: Marshall (this paper).
4. Trachytoid phonolite from Maungaroa, Rarotonga: Marshall (this paper).
5. Trachytoid phonolite from Te Kou mountain, Rarotonga: Marshall (this paper).
6. "Zeolitic phonolite," from a boulder in Tukavaine Valley, Rarotonga: Marshall (this paper).
7. Trachytoid phonolite from Signal Hill, Dunedin, New Zealand: Cotton (9, p. 120).
8. Nephelinitoid phonolite from Signal Hill, Dunedin, New Zealand: Cotton (9, p. 121).
9. Trachytoid phonolite from Mount Cargill, Dunedin, New Zealand: Bartrum (3, p. 173).
10. Trachytoid phonolite from Logan's Point, Dunedin, New Zealand: Cotton (9, p. 118).
11. Trachytoid phonolite from North Head, Dunedin, New Zealand: Marshall (21, p. 393).
12. Trachytoid phonolite (lava 25) from North Head, Dunedin, New Zealand: Marshall (21, p. 393).
13. Sodalite-phonolite from Mopanui, Dunedin, New Zealand: Marshall (21, p. 406).
14. Sodalite trachytoid phonolite from Rapa Island: Smith and Chubb (32, p. 325).
15. Phonolite from Vairao, Tahiti: Lacroix (18, p. 112).
16. Trachyte phonolite from Huaheine Island: Lacroix (19, p. 30).
17. Rock from Tapioi, Raiatea Island: Lacroix (18, p. 29).
18. Rock from Papetoai, Moorea Island: Lacroix (18, p. 26).

islands are derived from magmatic material in which silica was not present in sufficient quantity to form feldspar with all the alkaline bases: in other words, the magma is not saturated with silica.

It seems clear that in this magma, magnesia, lime, and iron united with silica in the proportions required for the stable minerals olivine, augite, and (or) hornblende and a few accessories. The amount of silica required in the formation of these minerals leaves an insufficient quantity to form feldspar with the large amount of alkaline oxides present; though there is usually enough silica to permit the formation of some feldspar. This sub-saturation with silica permits the formation of nepheline and sodalite molecules and these minerals crystallize before the feldspar. The obscure mineral substance ameleite is related to sodalite but has a still lower percentage of silica and crystallizes after the feldspar. The small excess of lime also enters into this compound.

The composition of the Maungatea nepheline sodalite phonolite and of the boulder from Tukavaine Valley indicate that in some rocks at least the excess of alkali and alumina is combined with silica and water in the formation of zeolite molecules and that these minerals may be original components of the igneous rock. Analcite has long been recognized as a constituent of monchiquites and teschenites and there is no reason to deny to other zeolites what is permitted to analcite.

In the natrolite-tinguaite lately described from Dunedin (26, p.533) the large spherulites of natrolite have not been derived from the alteration of either the feldspar or the nepheline of the rock for they remain quite unchanged.

No attempt is made here to account for the physical or chemical separation of that portion of the magma which solidifies into ankaramites and oceanites from that portion which solidifies into phonolites though it is thought that the difference in specific gravity (3.20 and 2.62) is significant. The separation of the two series is undoubtedly sharp though the basanitoids of Lacroix can be regarded as a connecting series. In Rarotonga the basalt flow that lies below the phonolite at Maungatea is regarded in this light. No specimen was found which showed an inclusion of phonolite in basalt or of basalt in phonolite.

NESOITE

The lava found below the phonolite at Maungatea is a close-grained rock slightly vesicular in texture and greenish grey in color. It is composed mainly of small elongated crystals of feldspar and augite quite aphyric in their arrangement. The feldspar has a maximum extinction angle of 15 degrees and appears to be an acid andesine. The small prisms of augite are of a very pale color but show a distinct violet tinge. There are a few small flakes of

a brown pleochroic biotite and some yellowish green serpentinous material which is clearly a decomposition product though it does not seem to represent olivine. Magnetite is abundant. A large part of the rock is composed of a clear colorless mineral with a low refractive index and extremely low birefringence, without cleavage or other distinguishing structures. The mineral is certainly original in the rock and it is thought to be a zeolite probably chabazite. When treated for five minutes with cold dilute hydrochloric acid 12.6 per cent of the rock dissolved. Of this 4.4 per cent was found to be alumina and 1.4 per cent, lime. Assuming that the 5.4 per cent of water found in the analysis constituted part of the dissolved matter, all the residue, 1.4 per cent, was probably soda. The alumina would represent a percentage of 22 per cent of chabazite in the rock, the lime and soda 24.2 per cent, and the water 26.3 per cent. It thus appears that about 20 per cent of the rock consists of chabazite or of some mineral similar to it. The mineral is attacked by silver nitrate and on treatment with potassium chromate a deposit of silver chromate is formed. This large amount of original zeolite is such a remarkable feature that it has been considered justifiable to give the rock a distinctive name and nesoite is proposed for it.

ANKARAMITE

A rock that is placed in the group of highly basic volcanics called ankaramites by Lacroix occurs rather widely in Rarotonga, though no mass of it was found in place. Large fragments of it are contained in a mass of breccia in Tukavaine Valley, derived from the ridge between Hikurangi and Te Manga. It is widely distributed in the basin of the Tupapa River and breccias which contain fragments are exposed on the top of Te Manga, Maungaroa, and at many places on the higher ridges of the island.

The rock is coarse-grained with idiomorphs of augite, pale brown in section, and as much as 15 cm. long. Olivine grains may be 5 cm. long (Pl. IV, C). The finer portion consists mainly of anhedral augite, a few feldspar microclites that show a low angle of extinction, and grains of magnetite, some as much as .5 cm. in diameter. Some zeolitic matter occupies the residual spaces.

BASALTS

Basalts are widely distributed in Rarotonga Island, but most outcrops of these rocks are concealed. Most of the specimens collected came from boulders in stream courses. Exceptions are the dike at Tokerau and the dikes on the eastern flank of Hikurangi. The basalt at Tokerau, at the entrance to the small Tauae Valley near Avarua, could probably be classed with the ankaramites of Lacroix. In this rock phenocrysts of augite and olivine are about equal in number. The larger crystals of augite are idiomorphic

and pale brown in color with a yellowish tint in the center and a violet tint near the margin. The crystals may be 10 mm. in length while the olivine grains do not exceed 5 mm. The ground mass is composed mainly of anhedral augite with labradorite microlites and much titaniferous iron ore, most of it in long slender crystals, but some granular. Residual patches between the feldspar microlites are mostly isotropic but many of them contain a highly refractive mineral which is also strongly birefringent. This is certainly calcite and the conditions of its occurrence convince an observer that it is original.

A boulder found in the Tukavaine stream proved to be a basalt containing large idiomorphic augites, many euhedral crystals of olivine, and a few slender and small phenocrysts of labradorite. The ground mass is mainly composed of diopside but magnetite is abundant and there is some interstitial isotropic matter.

One of the native stone axes is composed of basaltic material. In it the olivine has been completely changed to a serpentinous substance; the feldspar consists of slender, small crystals of labradorite; the augite is anhedral and of a pale greenish tint. Much fine magnetite is also present. The origin of this rock is not known.

Another basalt pebble from the Tukavaine stream is composed of the same material as the dyke that traverses the breccia at Maungatea. This rock, however, has no phenocrysts of augite nor of olivine and contains more microlites of feldspar. A few small flakes of brown mica are present.

A basaltic rock forming a dyke on the eastern flank of Hikurangi has no phenocrysts and contains no olivine. It consists of a dense intergrowth of feldspar microlites and anhedral augite with magnetite. Though the rock is quite fresh, small grains of calcite are distinct in some interstitial spaces. Since the feldspar is andesine this rock may probably be classed with the andesine andesite from Rapa, described by Smith and Chubb (32, p. 332).

A basalt pebble from the breccia of "Young's Tooth," is a slightly vesicular rock in which olivine has been replaced by serpentine and the steam pores filled with secondary materials. It contains only a few feldspar microlites, but these are quite fresh. A pale brown augite forms the greater part of the rock; though a good deal of magnetite is present. Throughout the rock, many of the augite crystals are arranged in the form of rosettes with six to twenty slender crystals. Another rock from the breccia forming Youngs Tooth is a typical basalt with abundant magnetite. In the specimen examined the olivine grains are changed to serpentine around the margins and along the fissures. Otherwise augite and labradorite feldspar appear in about equal quantities as well formed microlites.

PICRITE PORPHYRY

In Maungatea Bluff, a nearly vertical dike,—one foot thick and trending south-southeast, is composed of picrite porphyry. The rock is dense, black in color, and has a specific gravity of 2.99. It contains idiomorphic crystals of pale brown augite, and many rounded grains of olivine somewhat altered to iron oxide and serpentine. These are set in a dense fine network of diopside prisms in the meshes of which are small grains of magnetite. There are some microlites of andesine feldspar and a very small amount of brown glass.

In both mineralogical and chemical composition this rock closely resembles the peridotite of Papenoo Valley, Tahiti, described by Lacroix as “pyroxenolite” or “diopsidite à olivine” because he considered it too deficient in olivine to justify its classification as peridotite.

Another rock of an identical nature forms numerous small rounded fragments in a breccia at the north end of Aitutaki Island. These consist of crystals of diopside with olivine grains partly changed into iron oxide, and some serpentinous substance.

The basic rocks of the ankaramite-oceanite suite of Lacroix have a wide distribution in the islands that rise from the depths of the Pacific basin and as is implied from the necessity of assigning them to a special class they are practically unknown outside this area except at Madagascar which may be said to occupy a position in the Indian Ocean somewhat analogous to that of Juan Fernandez in the Pacific, and in Christmas Island which rises from the depths of the north Indian Ocean. Here the limburgite recorded by Smith (31, p. 61) clearly has the general nature of the basanitoids of Lacroix; a group well represented in Tahiti and other islands.

Lacroix (19) shows that representatives of this ultra basic series occur in Tahiti, Raiatea, Rapa, Mangareva (Gambier), Tutuila, Hawaii, and Juan Fernandez. They also appear at Mangaia and Rarotonga, though in Mangaia they occupy a small area, and in type they approach the basanitoids rather closely. In New Zealand, however, no exact equivalents have been found. The coarse dolerites and basalts of Dunedin which at first sight resemble them have actually large crystals of feldspar, and their analyses show a greater percentage of silica. Some of the basalts of Hyde 20 miles distant have a smaller amount of feldspar, but they have not yet been fully studied.

Lacroix (18, p. 44) regards the rocks of the ankaramite-oceanite series as the extreme product of differentiation, and remarks that one type of oceanite from Putua, Mangareva Island, “constitue réellement la forme d’epanchement d’une péridotite.” It would seem, however, that the complete absence of feldspar in the peridotite of Papenoo Valley, Tahiti, and in the dike equivalent at Maungatea, Rarotonga, indicates an even more extreme effect of

differentiation: but whatever its origin, the distribution of this very exceptional basic rock type justifies an inquiry into its geological significance. The analyses presented in Table 2 clearly show that the combination of extreme basic and alkaline—or nepheline-bearing rocks is an ordinary condition in the oceanic islands of the south central Pacific region, notably in Tahiti, Raiatea, Huahine, Rarotonga, Aitutaki, Rapa, and Upolu.

TABLE 2. ANALYSES OF ROCKS FROM PACIFIC ISLANDS

	1	2	3	4	5	6	7	8	9
SiO ₂	46.20	44.94	46.59	46.90	43.10	42.14	43.29	44.88	42.19
Al ₂ O ₃	16.50	17.30	15.19	16.13	8.94	8.36	9.10	10.50	9.03
Fe ₂ O ₃	3.58	4.15	3.30	4.26	4.56	7.05	6.88	1.55	3.08
FeO	6.41	5.33	8.97	7.85	9.94	6.35	7.25	9.22	9.27
MgO	3.17	3.93	4.69	4.37	15.92	16.03	16.21	15.19	13.89
CaO	8.40	8.34	8.06	7.43	10.10	12.62	10.11	10.61	11.95
Na ₂ O	4.52	5.14	3.67	5.34	1.67	1.42	1.44	1.37	1.77
K ₂ O	2.11	3.03	1.42	1.84	1.14	0.93	0.88	1.15	0.47
TiO ₂	2.62	3.20	4.01	3.56	2.40	3.12	2.84	3.03	2.72
P ₂ O ₅	0.42	0.69	0.18	1.25	0.27	0.31	0.32	0.65	0.71
H ₂ O	5.40	2.74	1.68	0.56	1.60	0.93	1.48	1.88	1.03
		0.60	1.11	0.57	.....	0.88	0.54	0.64	1.02
MnO .....	.....	.....	0.18	0.15	.....	0.10	0.14	0.16	0.19
Total	99.30	100.24	100.11	100.21	99.66	100.24	100.59	100.03	100.10

1. Basalt below nephelinitoid phonolite (basanitoid?) at Maungatea, Rarotonga Island: Marshall (this paper).
2. Basanitoid from Punaruu, Tahiti: Lacroix (18, p. 2).
3. Olivine trachybasalt from Hiri Bay, Rapa Island: Smith and Chubb (32, p. 332).
4. Olivine bearing nepheline tephrite from Rurutu Island: Smith and Chubb (32, p. 336).
5. Rock from Tupapa Valley, Rarotonga Island: Marshall (this paper).
6. Ankaramite basanitique from Tahiti: Lacroix (18, p. 29).
7. Ankaramite porphyrique from the west coast of Raiatea Island: Lacroix (18, p. 29).
8. Ultra basic basalt from Vairu, Rapa Island: Smith and Chubb (32, p. 326); basalte passant á ankaramite: Lacroix (18, p. 37).
9. Labradorite basalt from Fangaloa Bay, Samoa: Bartrum (2, p. 253).

The list of islands showing basic and alkaline rock in combination may well be extended when the relatively large islands of Tahaa, Borabora, and Mangareva are better known. Even present knowledge suggests a common nature or identity in the magma that underlies all this large portion of the Pacific Basin.

This similarity is strongly supported by the presence of the ultra basic differentiates in the three islands of Tahiti, Aitutaki, and Rarotonga. The wide distribution of the highly basic ankaramite-oceanite suite and the three-fold appearance of the diopside olivine rock justify the conclusion that this original magma was of an extremely basic nature and of high specific gravity.

GEOLOGICAL HISTORY

The geological development of the island of Rarotonga can be described in more simple terms than that of Mangaia and Atiu, two of the other islands of the Cook group, for there is far less evidence of movements of the strand line. As in the other high islands of the southern Pacific a volcanic eruption was the prelude to the first appearance of land. Rarotonga may be considered as the summit of a large volcano most of which is submarine. So far as known the base of this volcanic mountain stands 12,000 feet below the sea level and its total height is no less than 14,000 feet. It is of course, possible that the Rarotongan and Mangaian mountains are confluent at their bases and further that Cook Islands as a whole constitutes a single group of volcanic mountains.

The dissection of the volcanic mass of Rarotonga must have produced a large amount of detritus but this great quantity of waste has not built up a definite platform on any part of the coast, at least with reference to the present sea level. The larger stream valleys such as Tukavaine and Avatiu, have flat floors 200 yards wide where they emerge from the mountainous part of the island. Their gravel covered floors indicate the possibility that the valleys were at one time deeper and in consequence of a slight submergence were filled up with detritus to the new sea level. Such a movement could well account for the anchorage bank which extends off the coast opposite this part of the north side of the island for a distance of three quarters of a mile, and a quarter to a third of a mile beyond the present reef. The few soundings taken outside the reef at the north end of the island are sufficient to show this well defined platform at a depth of less than 20 fathoms. When viewed through a water glass this bank seems to be covered with small coral boulders, but in most places the covering is sand in which heads of coral are common.

It would seem that in Rarotonga, as in Mangaia, the growth of coral did not begin until the erosion had reached almost its present stage, possibly when the period of depression had commenced. It is reasonable to suppose that such a movement would decrease the amount of detritus transported to the coast and thus not check the growth of coral, so the inner edge of the coral bank or the outer edge of the taro swamp would indicate the position of the sea margin at that time. As the downward movement of the land proceeded, the upward growth of the coral would enable it to keep at the surface of the water. When a still-stand condition supervened, the reef would begin to extend outward—its growth depending upon the length of time the still-stand lasted. At Rarotonga, it continued while the reef grew outward some 200 yards. An elevation of a maximum amount of 15 feet then took place and since that time the present fringing reef has grown outward a further dis-

tance of 50 to 440 yards in different parts of the island, apparently without any variation of the sea level.

Throughout the great lapse of time during which the growth of the coral reef has been in progress stream erosion has progressed very slowly. The amount of gravel deposited on the reef by the streams is quite small. The floor of the passage through the reef at Avarua opposite the Tukavaine stream is covered with large boulders which when viewed through a water glass appear to be a foot in diameter, but as the water is $4 \frac{1}{3}$ fathoms deep, it is hard to make an estimate of the actual size. The boulders appear to consist of coral rock but they may be volcanic boulders encrusted with calcareous organisms. It is thought, however, that the movement to which these boulders are subject whenever the surf runs high might keep them clean from such growth. The amount of gravel transported by the stream has been insufficient to fill this passage.

The opinion that there has been little or no elevation since the growth of the present fringing reef began is based on the absence of stacks of limestone on the present reef, such as would be expected if elevation had taken place. On the other hand, the shallowness of the reef flat proves that no downward movement has occurred since the outward growth was initiated.

Since volcanic activity ceased in Rarotonga, the island has not been deeply submerged. On the flanks of the hills no erosion platforms, no beach deposits, and no coral growth were seen. The valley system also shows no traces of adjustment to any level markedly different from that of the present day, though the slight filling in the lower courses of the Tukavaine and the Avatiu is a consequence of a small movement of depression.

AGE

During the prolonged period of still-stand, since the coral growth began, the erosion due to atmospheric action has been profound; the floors of many valleys are as much as 1500 feet below the crests of the ridges on either side of them. Whether the conditions of erosion in Rarotonga were the same as in Mangaia and Atiu, neighboring islands of much less altitude, cannot be definitely stated, but there is no particular reason to suppose otherwise. In both of these islands the rate of erosion has been extremely slow for during the time that the volcanic rocks have been submitted to its action, a coral reef has formed and grown out for a distance of two-thirds of a mile from the foot of the volcanic rocks. At Mangaia the inner edge of this mass of coral rock is certainly not younger than the middle Miocene period, and since that time the island has been continuously subject to the attack of subaerial agents of erosion. Yet the original flat summit of this small island has not been completely dissected and on many of the spurs there are conspicuous flat surfaces. For Atiu, the age of the inner part of the Makatea is unfortunately

not so well known, but the island is not likely to be much younger than Mangaia (25). Small as is the dissection in Mangaia and Atiu, it seems to have been mainly, if not entirely, effected before the Miocene period. Little erosion has taken place since then for the depression between the volcanic hill and the Makatea has not been filled. In Rarotonga the coral growth has not been so extensive as in the other two islands, but the total amount of erosion is enormously greater and it would seem if the rate of erosion in Mangaia and Atiu is taken as a criterion Rarotonga must date back to the Cretaceous period.

Apart from this paleontological method, the physiographic features are of value in determining the age of the islands. By calculating the present rate of erosion, and assuming that rate to have been constant for a long geological period, the time required for the agents of denudation to produce the actual amount of dissection represented in the present land forms can be estimated by applying this method in combination with a knowledge of the rate of accumulation of volcanic material. Wentworth (36, pp.52-57; 37, p.118) estimated the age of the island of Lanai, Hawaii, as 200,000 years; of Oahu, as not less than 2,500,000 years.

When, however, consideration is given to the extremely slow rate of erosion in Mangaia these estimates for the age of the Hawaiian islands seem altogether too low. On the other hand, isolated volcanic masses in New Zealand, of Miocene or later age, such as those in the Dunedin region and the Coromandel Peninsula have suffered as much denudation as Rarotonga. On the whole, it may be stated that because Rarotonga has been denuded to much the same degree as Oahu and to a much greater extent than Mangaia, it is reasonable to state that it cannot be younger than 2,500,000 years and it may be of early Tertiary age.

ALKALINE ROCKS IN THE PACIFIC OCEAN

It is now well known that a variety of alkaline igneous rocks occurs in the islands scattered over the basin of the Pacific Ocean, and they have perhaps their most varied development in the Society Islands, as has been shown by Lacroix (18, p. 91) and by me (23, p. 196).

More recently alkaline rocks have been recorded from the islands of Rapa and Rurutu lying about 500 miles east of Rarotonga. These rocks are distributed over districts where, as Washington (34, p.341) has pointed out, there is no shore line that indicates a structure of the Atlantic type. The islands show no evidence of rapid elevation or depression that could be associated with a faulted structure of the ocean floor.

Judging from the few soundings available, there is every reason to think that in the neighborhood of these islands the ocean is 2000 to 2500 fathoms deep. At Mangaia it has been shown that the relative level of island and

ocean has varied no more than 600 feet since the early Tertiary. The island of Atiu conveys similar information. It would appear then that present knowledge of the ocean floor is in harmony with the evidence for the permanence of the islands and of the small amount of movement that they have demonstrably undergone.

On the other hand, in all of the islands in which they are known to occur, the alkaline rocks are associated with basic rocks with low silica content and of high specific gravity and are of much smaller volume than the highly basic types with which they are associated. The alkaline rocks, too, have a relatively low silica content. It would seem that these phonolites represent differentiation products of the silica unsaturated, heavy, magma by which it is thought the basin of the Pacific Ocean is underlaid. Though the phonolites have a relatively low specific gravity their volume in relation to that of the basic rocks is so small that the mean specific gravity of all of the rocks of any one of the islands would probably be high.

ATIU ISLAND

HISTORICAL SKETCH

Atiu Island, a coral rimmed volcanic mass with a circumference of 12 1/2 miles and a summit height of about 250 feet was discovered by Captain Cook on March 31, 1777. The account (8) states that Lieutenant Gore with two boats landed on the reef, taking with him Omai, a native of Huaheine. The Atiuans welcomed the visitors and carried them from the edge of the reef to the beach, a narrow stretch of sand, from which a slender defile led through jagged limestone rocks to a strand thickly covered with vegetation. The white men were then conducted to a marae (*morai*) half a mile farther on, where three chiefs were seated some distance apart, and between them lines of men armed with clubs. Lieutenant Gore found that the natives were gradually separating his men with the object, he thought, of detaining them. There were even suspicions that ovens were being prepared with sinister intentions. It seems, however, that the islanders merely wished to detain the white men ashore and entertain them in a lavish manner and that the ovens were being heated to cook pigs. Gill (15, pp. 186-187) states after questioning the natives that they would certainly have detained the visitors but for the exaggerated tales of Omai who told them that the ship's guns could easily destroy the island and kill every person living on it. He also states that during their stay on the island, the visitors were the guests of the chief Tiaputa.

Lieutenant Gore and his men were able to leave the island and embark again without molestation, but Gore complains of the crowding by the natives and the fact that his men were virtually prevented from making any observations on the geographic features of the island, or the condition of the people.

The actual point of landing was at Orovaru on the northwest side of the island (fig. 11). My native guide Ngapaku showed me the place: a small sandy beach with rugged limestone on either side crowned with toa trees (*Casuarina equisetifolia*). From the head of this small nook a defile leads with a gradually rising floor to the top of the level strand which runs round all the western part of the island. From the strand a path leads to the marae (*morai*) of Orongo where Tepaku told me the reception of Gore by the chiefs took place. This old marae is still in a good state of preservation. The walls are 2 feet 3 inches high, built in part of large stalactites taken from a cave, in part of limestone blocks, and in part of boulders of volcanic rock which must have been diligently sought and carried a considerable distance. The larger platform measures 12 by 15 feet, and the smaller, 8 feet distant, 4 by 5 feet. All the adjoining ground is covered with small limestone pebbles carried from the strand. Ngapaku said that the chiefs had their allotted positions near the marae and that the people were assembled between them and the adjoining swamp.

Lieutenant Gore seems to have been less successful than Captain Cook in dealing with the natives in most of the islands visited. On Atiu he could obtain no supplies of water or fodder both of which were urgently required and except for a few coconuts no food was purchased. However, no water could have been obtained nearer than a mile from the coast. As the weather proved rather unfavorable and the provision of supplies uncertain Cook wasted no further time at Atiu, but lay under Takutea (called by him Ota-kotaia) a small island of coral sand 12 miles north of Atiu. He found no inhabitants on the island though it is often visited by natives of Atiu to obtain a supply of fish. A considerable quantity of coconuts and fodder for the live stock was obtained, but no fresh water.

Though the language of the Atiuans is more like Maori than Tahitian, Omai, a native of Huaheine, who was in Cook's vessel was able to understand it and soon learned that three Society Islanders were living among the Atiuans. These men told Omai that they were the remnants of an expedition 20 strong which set out from Tahiti for Raiatea. Strong winds blew them out of their course and after drifting about for a number of days they came in sight of Atiu. All but three of them had succumbed to exposure, hunger, and thirst. The survivors had been well treated by the inhabitants of Atiu, they had become incorporated in the island society and refused the offer that was made to take them back to their own country. They must have been on Atiu for more than ten years for they had no knowledge of the visit of Captain Wallis to Tahiti in 1767. These Society Islanders have been so completely absorbed by the natives of Atiu that the story of their arrival is nearly lost. As a result of diligent inquiry in 1926, Mr. W. H. Scott, Resident Agent, discovered that a memory of the event still lingers and that the families of Tahitian origin are known.

After Cook's departure Atiu seems to have been unvisited until 1822, when the missionary John Williams arrived. A little before his coming a characteristic incident had occurred. A chief of Atiu named Akaina was living in Mauke, a neighboring island of small size. He became enamoured with the wife of an important chief of Mauke and at last managed to persuade the lady to live with him. Akaina was promptly killed but a native of Atiu then living on Mauke managed to paddle his small canoe to Atiu across the open ocean. As soon as he had told the relatives of the murdered chief about the events in Mauke an expedition was organized for revenge. Rongomatane, the leading chief, sallied forth with a fleet of canoes. Landing on Mauke he slaughtered the people in large numbers and not content with that he extended his voyage to Mitiaro, another little island 20 miles east of Atiu, and repeated the slaughter there. For years afterwards the miserable remnant in Mauke and Mitiaro lived in terror of their lives, for the Atiu natives from time to time descended on them and killed as many as could be found.

When Williams landed on Atiu, he found the chief Rongomatane a willing convert to Christianity, owing to the persuasion of a chief from Aitutaki who was among Williams' party. Hearing of Mauke from the natives, Williams decided to go there. Rongomatane went with him. Great consternation prevailed among the people of Mauke but it was quickly changed to the joy of unexpected deliverance when they found that the dreaded chief had come in the spirit of Christianity. Since that time there have been no inter-island conflicts.

Even on Atiu itself there were occasionally fights. At the time of Rongomatane's absence on Mauke when most of the fighting men were away, the people of the Makatea region tried to gain control. These people comprised those who had been banished from the society of the island and in daily fear of their lives were eking out a miserable existence in the impenetrable rocky fastnesses. The women who had been left behind by Rongomatane, took up arms and the Makatea people had to retreat to their hiding places.

In connection with missionary enterprises Atiu was many times visited. In 1822 Mr. J. M. Orsmond sent two native teachers from Tahiti. John Williams who arrived in December of that year found them in a most pitiable condition "having been stripped by the natives of every article of property, suffering exceedingly from hunger." Visits were paid afterwards by the missionaries of Tahiti from time to time. In 1842 Rev. E. Krause arrived from America but he was unfortunate in landing on a part of the island where no natives were living. Rev. W. Gill first went to Atiu in 1843 and soon afterwards Rev. H. Royle paid visits, some of which were several months in length. For forty years after John Williams first visited the island, missionary efforts were in charge of native teachers. Until quite recent times all the missionary effort was due to the London Missionary Society—a Methodist organization; but lately the Roman Catholic Church, Seventh Day Adventists, and the Latter Day Saints have worked on the islands with greater or less success.

For many years missionary steamers, whaling ships, and occasional stray vessels called at Atiu at rare intervals. In recent years trading steamers call for copra, and bring such supplies as are needed. During the orange season fruit steamers pay a monthly visit and sometimes a vessel of the Royal Navy calls; but usually during the summer months, the so-called "hurricane season," no vessels appear.

POPULATION

Originally most of the natives of Atiu lived in the lower ground near the taro cultivations where terraces had been excavated for houses from the sides of the radiating spurs of volcanic rock. It may be noted, however, that Cook saw buildings on the plateau. The missionaries induced the people for their

health and convenience, to live together on the plateau—the central flat part of the island which stands 280 feet above sea level.

At the present time all the people live on the plateau. The villages though quite near to one another have separate names and are subject to different chiefs of whom three are prominent at present: Ngamaru of Areora, Parua of Mapumai, and Rongomatane of Tengtangi.

The plateau is decidedly a healthy situation for Europeans and perhaps for the natives also. Certainly teaching and administration became far easier when the people were concentrated than when they were scattered in widely separated localities. The water supply, however, presented a difficult problem. The flowing springs that issue at the heads of most of the valleys are about 50 feet below the level of the plateau to which the water has to be carried. Within recent years the Government has constructed concrete tanks to store the rainwater that falls on the roofs of the village halls. As the rainfall is considerable and frequent this supply is sufficient at ordinary times for domestic wants. A curious attitude of the native mind comes to light in connection with this water supply. Those who live furthest from the tanks are jealous of those who live near them and may purposely leave the tap running so that all may fare alike in having to carry their water from the springs below the plateau rim.

Though all the natives live on the plateau most of them have small huts for temporary occupation near their cultivation grounds on the lower levels, and they spend much of their time there. Tribal boundaries are rigidly recognized in the settlements though the villages are almost continuous. As in Mangaia, Rarotonga, and probably in the other islands of the Cook group, the land is divided into sectors (*tapere*) separated from one another by radial lines proceeding from the central point of the plateau to the coast. Each family of standing has its own *tapere*. At the present time the population of Atiu comprises 925 natives and 10 Europeans.

VEGETATION

The small size of Atiu Island combined with its relatively low altitude prevent it from offering a great variety of station for plant growth. Consequently, the number of plant species is small and as would be expected, there seems to be no plant that is peculiar to this island. On the top of the low cliffs that face the sea the plant covering is that common to many Pacific islands. Proceeding inland, the species first seen are *Ipomaea lobata*, *Heliotropium anomalum*, and some hardy grasses. In most places, the first shrubby plant is *Scaevola koenigii*, commonly with *Cassytha filiformis* as a parasite, and the first tree is *Casuarina equisetifolia* (toa) associated with *Pandanus odoratissimus* (ara). The graceful foliage of the toa softens the harshness of the rocky coast. Sheltered from the blast of the salt-bearing

winds by these plants a mixed vegetation including the magnificent *Barringtonia speciosa* (*utu*), is found. On the southwest side of the island the particularly huge *Barringtonia* trees with wide spreading branches completely satisfy all preconceived ideas of tropical luxuriance. Here and there the coconut palm is found but only in situations where it appears to have been planted though it grows freely in all parts of the coastal land.

Other prominent trees are the *Hernandia peltata* (*puka*) and the *Calophyllum inophyllum* (*tamanu*), a tree much valued for its canoe making timber. With these trees is a thick spreading growth of *Hibiscus tiliaceus* (*pu-rau*), and of *Spondias dulcis* (*vi* apple). Likewise *Broussonetia papyrifera* (*aute*), and *Elaeocarpus rarotongensis* (*karaka*) are quite common. Here and there the wild banana, *Musa paradisiaca*, is growing, but it is not common in Atiu. At the inner edge of the Makatea where the ground is kept wet by the waters of the swamp the *Inocarpus edulis* (*maupe*) appears as lofty trees with their characteristic sharply buttressed trunks. The waters of the swamp are shallow and are covered with a growth of reeds and rushes.

The volcanic ground is covered with a growth of the fern, *Gleichenia dichotoma* (*tuaniu*), and with it a good deal of guava but both of these have a low growth because of the fires which often sweep across this ground. In the ravines through which the small streams run there is a varied growth from which the great *maupe* trees rear their crests but the predominant vegetation is a matted growth of hau (*au*).

On the Makatea are some plantations of coconut palms but these are more plentiful on the lower slopes of the volcanic ground. Oranges are grown on the Makatea. Taro is cultivated in the swamp near the volcanic slopes and in the lower part of the valleys. Bananas are planted on the lower parts of the volcanic slopes while many of the plantations of kumera and yams are on the volcanic plateau. Coconuts are also planted here, and there are a few oranges in the valleys.

The main industry of the natives is the production of copra, all of which is shipped in canoes at Taunganui and transported to steamers or schooners lying off and on. In July and August a few oranges are shipped to New Zealand.

BIRD LIFE

As elsewhere in Cook Islands, Atiu has few land birds. This is to be expected in view of the small size of the island, the small surface relief, the remoteness, and the large number of inhabitants who in the past have had a meagre supply of animal food.

A small swallow not found on Rarotonga or on Mangaia flits about the trees on the plateau. A woodpecker is rather common. A pigeon is to be found in most parts of the island especially in the wooded Makatea. The long

tailed cuckoo is not uncommon in May. This migratory bird is found in New Zealand from October till February. It is noteworthy that with the exception of the pigeon the birds seen on Rarotonga, Mangaia, and Atiu, are all different though on Mangaia and Atiu some of them are very common.

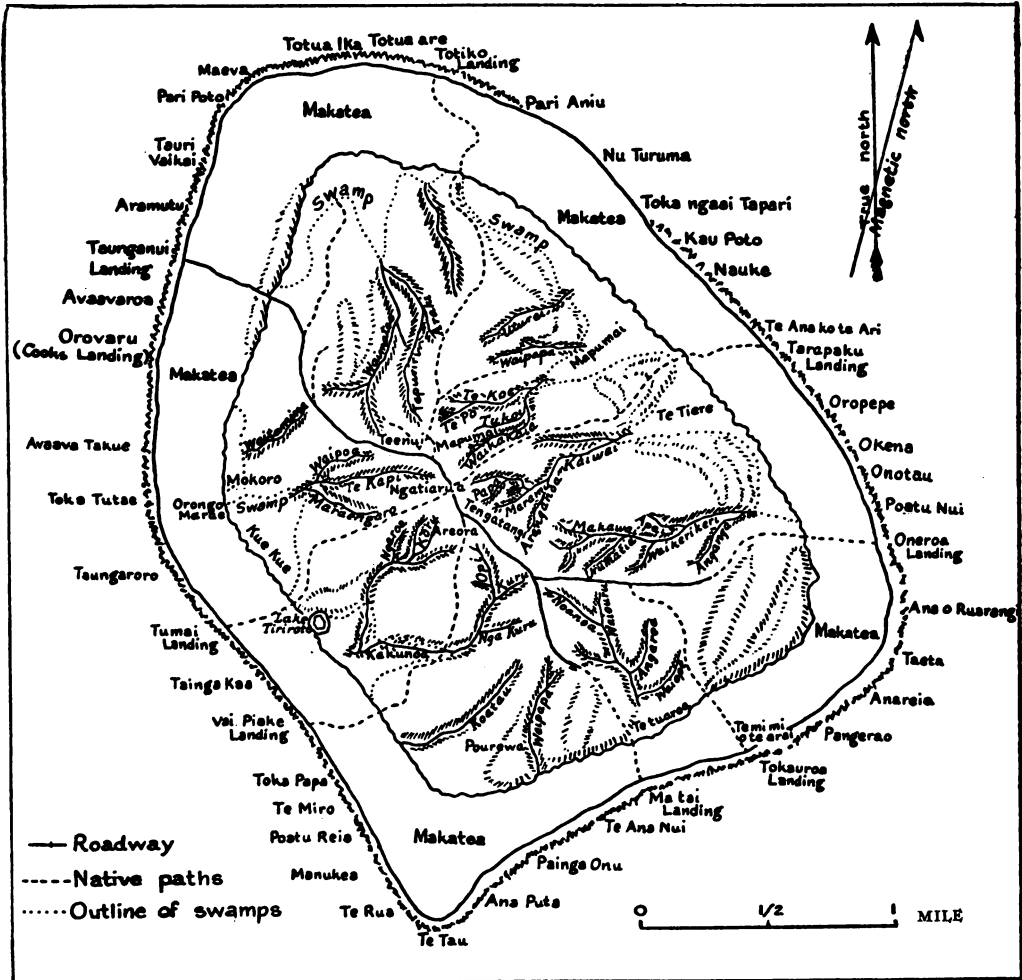


FIGURE 8.—Map of Aitu Island: Outline Survey by H. M. Connal (1911); physiographic features by Patrick Marshall (1927).

The water birds are not numerous. The duck (*Anas superciliosa*), the egret, and the blue heron of Atiu are the same as those seen throughout Cook Islands and in New Zealand. A dotterel common on Atiu, was not seen elsewhere. Only three kinds of sea birds were seen: the well known tropic birds

(*Phaethon coerulea* and *ruficaudis*) and the frigate bird. No gannets and no petrels of any kind were observed.

It is a little strange that the native names that were given me by my guide Ngapaku for the duck and longtailed cuckoo: *morerau* and *arawi tangaroa* respectively, are different from those in use by the Maoris: *parera* and *koekoea*. The names of the other birds are the same in the two dialects.

PHYSIOGRAPHIC OUTLINE

The small island of Atiu with a circuit of only 12 1/2 miles is surrounded by a reef 50 to 100 yards from the shore. (See fig. 8.) Low cliffs 10 to 20 feet high front the sea everywhere but there are many recesses in which small beaches of sand are found. From the top of the low sea cliffs the land rises gradually, but does not at first reach an elevation greater than 70 feet in a distance of 300 yards. From this point it descends gradually for 600 to 800 yards, when a swampy tract is reached. The swamp has an average width of a quarter of a mile, but is not continuous around the island. From the

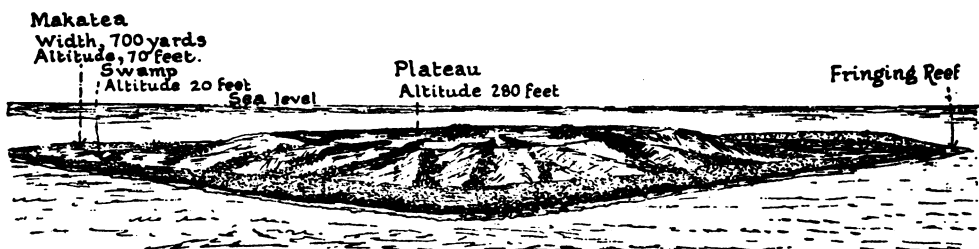


FIGURE 9.—Imaginary bird's eye view of Aitu Island.

inner edge of the swamp the land rises more steeply and at a height of 230 feet it suddenly flattens out and the center of the island is occupied by a low dome shaped plateau with a summit altitude of 270 feet.

Atiu thus has a general resemblance to Mangaia Island (fig. 9). The same main features of reef, strand, Makatea, taro ground, and central volcanic hill are present, but these features have not the same distinctness as on Mangaia. The reef in Atiu is in few places more than 50 yards wide; there is no marked line between the strand and the Makatea which rises no higher than 70 feet; the inland cliff which marks the descent from the Makatea to the taro ground is in most places hardly noticeable and the passage from one to the other involves but little change of level. The plateau which crowns the volcanic core of Atiu is much more extensive but is at a lower level than the corresponding feature at Mangaia.

THE CORAL REEF

Except for a distance of a half mile at Te Pari Aniu the island of Atiu is entirely surrounded by a coral reef. Its margin is, however, close to the shore—in few places more than 50 yards distant—and the reef flat is frequently swept by the strong currents that arise from the breaking of the surf on the reef edge.

The shore line faces the sea in cliffs 10 to 20 feet high and are somewhat undercut by the sea which at high water and in rough weather breaks with some force at their base. It is, therefore, certain that a portion of the reef flat represents a shelf of marine erosion where the seaward fringe of the Maka-

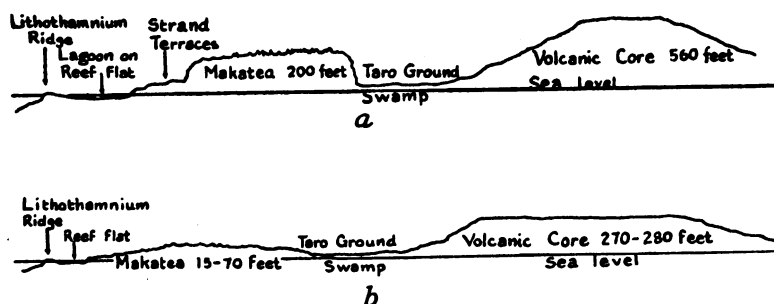


FIGURE 10.—Sketch sections showing general profiles: *a*, Mangaia Island; *b*, Atiu Island.

tea has been removed. It is probable, however, that a very small portion of the reef flat has been formed in this way, for at Te Pari Aniu, where there is no protecting reef there is no erosion shelf comparable with the reef flat in other parts of the island. At Te Pari Aniu the water is perhaps three fathoms deep at the foot of the cliff though large boulders covered with coral forming organisms can be distinguished here and there. It is probable then that nearly all of the reef flat is due to the outward growth of the reef. The edge of the reef on which the sea breaks is here as at Mangaia covered with a growth of calcareous algae, and *Polytrema* while coral is to be seen but seldom. All the specimens obtained, however, consist mainly of coral, covered with a thin coating of calcareous algae. It is possible here to obtain a measure of the rapidity of the growth of these algae. In 1910 a boat passage was blasted through the reef and since that time *Lithothamnium* has grown on the broken rock surfaces to an average thickness of half an inch. It seems, therefore, that these algae can form a crust of limestone one inch thick in 30 years.

The outer surface of the reef was closely examined from a canoe and from the edge of the *Lithothamnium* ridge at Taunganui on the northwest

side of the island in fine weather. It descends rapidly but irregularly at first for a depth of 5 fathoms from which depth the surface of some large outlying bosses of reef extend upward about half way to the water level. The soundings increase quickly but the bottom could not be observed at a greater depth than 20 fathoms, 100 yards distant from the outer edge of the reef. The native fishermen, however, say that on all sides the sea floor slopes steeply to a depth of 100 fathoms, the limit reached by their lines. There is no anchorage for steamers.

Corals abound in all of the interstices of the outer side of the reef and among the corals there is a plentiful algal growth. On the tops of the out-



FIGURE 11.—Sketch of Captain Cook's landing, Orovaru, Atiu Island.

lying rocks as also on the surface of the reef a growth of algae alone is to be seen. Corals grow in abundance on the sea floor outside the reef but patches of sand are to be seen here and there. The sand areas become larger but coral heads are still abundant at the depth of 20 fathoms which was the limit of visibility.

THE MAKATEA

GENERAL FEATURES

The Makatea (formation of raised coral limestone) in the Atiu Island has an average breadth of 1200 yards. It faces the beach as a small cliff, highest on the southern and eastern sides of the island but nowhere exceeding 20 feet in height. From the top of this cliff the surface continues to rise gradually and in most places uniformly until at a distance of 300 to 400 yards from the beach it is 70 feet above the sea level. From that point, the surface declines gradually until the Makatea terminates abruptly at the edge of the taro swamp 10-20 feet above sea level.

As at Mangaia, the surface of the Makatea on Atiu is highly irregular but

the spaces between the projecting points of limestone rock are more completely filled in with red soil, especially on the inland side. As a whole, the Makatea on Atiu is a less formidable barrier between the coast and the interior of the island, than at Mangaia. In particular it does not rise as a cliff from the taro ground and there is no cliff on the beach side until the actual coast is reached. Though the small cliff that faces the beach is far more continuous, it is breached on the north and west sides of the island almost every hundred yards by a deep recess that offers a passage along a sandy floor, gradually rising to the surface of the Makatea. (See fig. 10.)

MINERALOGICAL COMPOSITION

In the rock at Tumai landing, which is typical of that forming the seaward edge of the Makatea, the skeleton of organisms such as the corals and *Halimeda* originally composed of aragonite, are still composed of that mineral. Some of them, however, show the kind of change as described by David (13, p. 400) and by Skeats (29, p. 106). The original cavities of the coral skeleton are in places partly or wholly filled with aragonite of secondary origin in long prismatic crystals that are optically and crystallographically continuous with the crystalline elements of the coral structure. In a closely adjacent part of the rock, or even in the same microscopic preparation the material of the coral skeleton may be changed to calcite in the form of large plates, though dark lines may still show the margin of the original coral structure (Pl. V. A, D). In the same specimen relatively large rhombohedrons of calcite may appear in the central parts of the cavities. For all specimens studied it is thought that these crystals are formed from the preexisting crystals of secondary aragonite, because in these places the aragonite crystals have rounded terminations and have lost their clear definition. Whether or not the calcite rhombohedrons start in this way, they undoubtedly grow at the expense of the secondary aragonite, and before long completely fill the cavities in the coral which is then entirely changed into calcite. It should be borne in mind that all these different conditions can be seen in a single microscopic preparation of the rock. It seems that the aragonite of the actual coral skeleton changes into calcite before the secondary aragonite which fills the cavities. In the sandy portion of the rock from this outer part of the Makatea, which in the specimens actually obtained is not abundant, the various grains, whether composed of calcite or aragonite organisms, are cemented together by a deposit of the fibrous calcite crystals of secondary origin that have previously been described as formed on the *Lithothamnium* ridge at Mangaia Island (25, p. 15, Pl. III, 3). Here, however, the individual fibers appear rather coarser than on the ridge. It is also worthy of note that in one specimen from the *Lithothamnium* ridge of Mangaia a grain of coral in the sand had its cavities partly filled with secondary aragonite. In the rock from Tumai

landing there is a large amount of *Halimeda* in the fine sand grains which form a portion of the rock. In a specimen collected from a spot 10 feet above sea level and 50 yards back from the beach, these *Halimeda* grains still retain their brownish tint. None of the specimens obtained from the Makatea at points more distant from the reef contains aragonite; all of this min-

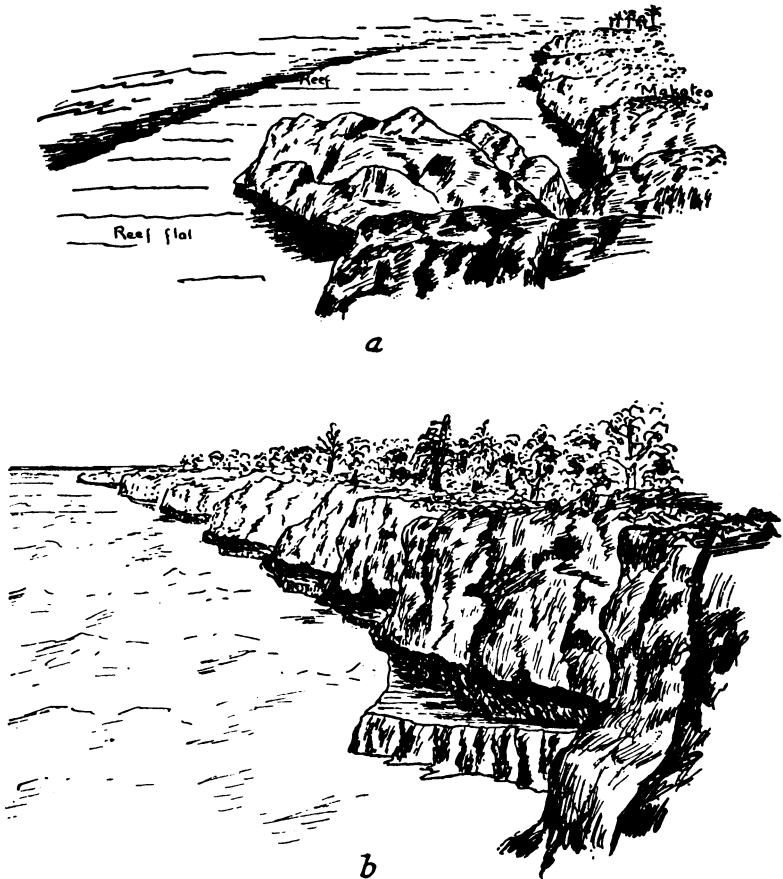


FIGURE 12.—Sketches of the coast line, Atiu Island: *a*, coast at Taunganui protected by a reef; *b*, coast at Te Pari Aniu, unprotected.

eral has been changed into calcite. As soon as the strand is left, *Halimeda* becomes far less common and the material of all the organic skeletons is recrystallised. It is hard to distinguish the fibrous growth of secondary calcite. This, on the whole, is far less distinct than in similar positions in Mangaia Island.

Soon after the highest point of the Makatea has been passed, some 400 yards from the beach, dolomitization begins. Whether this condition prevails

in all parts of the island cannot be stated with certainty but it was found in at least four places: Taunganui, Oneroa, Te Miro, and Tumai, on the routes across the Makatea. (See Pl. V, B, C).

The change to dolomite proceeds very irregularly; in a single specimen one portion may contain 85.4 per cent of calcium carbonate and another no more than 68.6 per cent. Where the proportion of calcium carbonate is large it was found that the dolomite portion consists of the skeletons or organisms that were originally aragonite and were afterwards changed to calcite. Of these the corals are the principal organisms but some of the Foraminifera though originally calcite, have also been changed to dolomite. Thus while *Amphistegina* remains as unchanged calcite, the skeletons of *Gypsina* and *Operculina* originally also calcite, have been changed to dolomite. Though the cavities in the coral skeletons are generally entirely filled with calcite, the central portion of some is filled with dolomite in the middle of the calcite filling. (See Pl. IV, D, E, F).

In those parts of the specimen where the change is most complete, *Lithothamnium* is the only unchanged organism. It retains its original structure almost without change. This is a striking fact for it is now well known that the stony part of the tissue of *Lithothamnium* and its allies contains a higher proportion of magnesium carbonate than any other organism of the reef.

So far as can be seen in the rock which is now completely recrystallized, the only other situation in which calcite is found is in some of the spaces between the original grains of sand. Even in these places the calcite occupies the center of the original spaces only. As the inner edge of the Makatea is approached, the dolomitization of the rock is more pronounced and unchanged calcite is difficult to find (Pl. V, E). The infillings in the lacunae of a few coral skeletons show alternating layers of calcite and dolomite.

There is every reason to think that all of these mineralogical changes have taken place at or near the sea level. All the various conditions of deposition of secondary calcite and dolomite have been found in rocks that are now exposed at the surface while the nature of their exposure and the study of the physiography point emphatically to the opinion that the rock has never been submerged beneath any but a slight depth of water.

COMPARISON WITH FUNAFUTI

All the mineralogical changes found in the limestone constituting the Makatea on Atiu are recorded in drill cores obtained at Funafuti atoll. It is of interest to notice the depth at which they occur. From the description by Cullis (10) the following list has been prepared:

1. 10-20 feet: the formation of fibrous calcite in the cavities was noticed in all of the bores.

2. 20-90 feet: the percentage of magnesium carbonate increases with depth to a maximum of 16 per cent but no dolomite could be detected.
3. Deposit of secondary aragonite.
4. 100 feet: secondary aragonite changes to calcite.
5. 150+ feet: primary aragonite changes to calcite.
6. 50-637 feet: the material encountered is generally unconsolidated coral sand which it is suggested might be due to the solution of the aragonite in rock originally solid.
7. 637-1117 feet: the rock is dolomite except for one or two small masses of calcite.

To account for these variations in the composition of the material, the following explanations were advanced by the writers of the Funafuti report:

1. The fibrous calcite is thought by Professor J. W. Judd to have been deposited directly from solution.

2. The increase in magnesia in the upper part of the bore is ascribed to the leaching of the more soluble CaCO_3 from the rock in which magnesia was at first present in relatively small amount. (Skeats [30, p.199] suggests that as calcium and magnesium carbonates have solubilities that vary differently with changes of pressure, it is possible that at a pressure of two or three atmospheres a compound of the two carbonates is stable and tends to form readily when calcium carbonate is in the presence of the magnesian salts of sea water and carbonic acid gas.)

3. The deposition of secondary aragonite is ascribed to direct crystallization from solution in sea water.

- 4 and 5. No special explanation is given for these mineral changes.

6. The incoherence of the sandy material is thought to be due to the solution of aragonite.

7. It is suggested by Judd that the formation of dolomite is partly due to the leaching of some of the calcium carbonate, and partly to the greater abundance of the remains of organisms that have a relatively high percentage of magnesium carbonate in their stony material. Clark (7, p.448) regards it as most probable that the process of dolomitization is partly due to leaching and partly to the replacement of calcium carbonate by magnesium carbonate.

Comparison of the results obtained at Funafuti with those obtained at Mangaia and Atiu islands shows at once, as previously suggested by Skeats (30), that for many of these chemical changes it is erroneous to regard the depth of formation as a necessary factor. With the exception of the incoherent sandy material all of the conditions of limestone that have been recorded at different depths in the Funafuti bore have been found in the surface rock of Atiu Island. The great thickness of sand found in the bore was thought by the authors of the Funafuti report to have been originally solid coral rock

and that from it aragonite had been removed by solution, leaving a mass of loose sand.

As compared with the records obtained at Funafuti a study of the materials from Atiu shows:

1. The deposit of fibrous calcite between the grains of sand takes place almost at the surface of the living reef at Atiu, also at Mangaia. In many places a thickness of only 3 mm. separates the actual surface of the reef from small cavities where the formation of this material is in progress. This portion is never more than a few seconds without a covering of water. The reef is continuously beneath water, except when the tide is at its lowest, and even then it is awash to every wave that breaks on the margin of the reef. Under these conditions concentration of calcium carbonate in solution by evaporation seems impossible, and its deposition cannot be explained in this way. It may be that the carbon dioxide required by *Lithothamnium* for its transpiration is derived from some of the calcium bicarbonate that is in solution in sea water and that the calcium carbonate thus liberated is deposited in the fibrous form. However, it would be expected that calcium carbonate formed in this manner would be deposited on the surface of the *Lithothamnium* rather than in the spaces between the small grains of sand. Calcium sulphate is, of course, present in relatively large quantities in sea water and under the conditions prevailing on a coral reef; the carbon dioxide liberated from the surface of the algae and other organisms by respiration may form calcium carbonate. The distinction between the fibrous carbonate formed in the presence of sea water and the rhombohedral form of all of the calcite that is deposited subsequently may have a large significance. The sand which is held by the algae and other organisms on the surface of the reef is surrounded by living and dead organic matter from which a great deal of carbonic acid gas is constantly being emitted. It is quite possible that as a result of the reaction between this gas and the calcium sulphate or chloride of sea water, calcium carbonate is produced and at once becomes crystallized in the fibrous form.

At Funafuti a deposit of fibrous calcium carbonate was found again in the lowest 300 feet of the bore. Nothing analogous to this was found in the dolomitic rock of Atiu Island, and no explanation of this occurrence at Funafuti is here attempted. At Mangaia and Atiu islands this fibrous form of calcite very soon changes into the irregular rhombohedral crystals and no subsequent development of the fibrous type of calcite structure was seen.

2. The higher percentage of MgCO_3 at a slight depth may be due merely to the prevalence of *Lithothamnium* and other organisms rich in MgCO_3 .

3. The origin of the secondary aragonite in the lacunae of the coral skeletons may be the same as that of the fibrous calcite but the effect of the aragonite prisms in the coral structure is sufficiently potent to cause the carbonate

to crystallize in the molecular form as aragonite instead of calcite, as elsewhere. The microscopic preparations that were made of the rock collected at Tumai landing show clearly that the aragonite of the coral skeleton changes into calcite grains of relatively large dimensions before the secondary aragonite has undergone any change (Pl. V, *D*). This observation is contrary to those made by Cullis (10) on the material from Funafuti, where the primary aragonite is more lasting than the secondary. Again in the rock examined from Atiu the calcite which fills the central portions of a few of the spaces is certainly secondary and has been formed from aragonite, whereas in the Funafuti material it is regarded as primary.

In the Funafuti report, no indication is given of the nature of the change that the fibrous calcite undergoes. It is merely stated that in various bores fibrous calcite was found at depths between 20 and 90 feet and again from 815 feet to the bottom of the bore. A study of specimens from the Makatea at Atiu proved that the fibrous calcite had undergone changes similar to those previously recorded for specimens from Mangaia. In both islands the fibrous form of the mineral rapidly changes into rhombohedral calcite. At first the rhombohedral crystals are quite small but as older and older rocks are examined the crystals are found to increase in size gradually. But even when all the elements of the rock have been recrystallized it is possible to see the limits of the original fibrous calcite for they are indicated by the slight cloudiness of the mineral where the fibrous matter has been replaced.

4 and 5. The change from aragonite both primary and secondary to calcite clearly takes place at the surface and has no relation to thickness of covering as was suggested in the Funafuti report. It seems to be simply a change from a less stable to a more stable form of calcium carbonate.

6. The unconsolidated coral sand which forms most of the Funafuti core at depths between 50 and 637 feet contains many organic remains that have become disintegrated by the solution of such substances as coral skeletons originally composed of aragonite. May it not be that this material was originally deposited as sand on the margin of a sinking reef, the actual site of which migrated slightly during long continued subsidence.

7. The development of dolomite from coral rock is, of course, a special problem on which there is still a considerable difference of opinion.

DOLOMITE IN PACIFIC ISLANDS

It is well known that dolomite is widely distributed in the raised coral rocks of Pacific islands. Dana (11, p.307) first recorded dolomite in a specimen from the island of Makatea. A second specimen, however, from the same island contained only 5 per cent of magnesium carbonate. In later years Skeats (30, p.118) showed that all the specimens collected by Agassiz from the raised coral reefs of Vatuvala, Yathala, and Kambara, were in reality dol-

omites; that the rocks from Christmas, Mango, Namuka, and Euathere islands included both limestones and dolomites; and that only limestones were found on Niue, Vavau, Tongatabu, and Guam islands. In addition to these records, Elschner (14) reports dolomites at sea level at Anybods Bay on the east side of Nauru Island and also on Ocean Island.

Information regarding the distribution of the dolomitic rock in the various islands is meager, or lacking. This is probably due to the fact that the specimens collected were not recognised as dolomites at the time. Skeats (30, pp.71, 75) gives some valuable information based on field work by E. C. Andrews in Fiji, by Agassiz in Eua, and by W. C. Andrews in Christmas Island (Indian Ocean). For these islands, however, the distribution of dolomite is considered from the vertical, rather than from the horizontal direction, as was necessarily also done at Funafuti.

CHEMICAL COMPOSITION OF MAKATEA ROCK

The following analyses were made of a number of specimens collected from the Makatea of Atiu Island:

	MgCo ₃	CaCo ₃
Crust on Lithothamnium ridge.....	73.09	14.53
Proportions in stony matter.....	83.42	16.59
Lithothamnium ridge, 3 ft. from surface	84.69	6.66
Oneroa, 1200 yds. from beach	61.30	40.10
Oneroa, 300 yds. from beach	98.80	1.42
Tarapaku, inner side of Makatea	59.10	40.20
Vai Piake, inner side of Makatea	57.51	42.86
Tumai, 700 yds. from inner side	97.73	2.15
Tumai, 1000 yds. from inner side	99.42	0.56
Te Miro, 300 yds. from inner side	85.41	13.67
Te Miro, in same specimen 10 cm. distant.....	68.64	31.12

By observing the effect of dilute hydrochloric acid and of dilute acetic acid on the specimens that had been analysed it was found that the extent to which dolomitization had proceeded could be roughly estimated without resorting to actual analysis. These tests showed that the rock on the inner side of the Makatea all around the island was generally converted into dolomite though here and there specimens were found that had undergone no change. The tests also showed a definite and gradual decrease in dolomitization from the inner towards the outer side of the Makatea, though at any one point, as shown by the analyses of a sample from Te Miro, highly magnesian limestone can be found in close association with material that is almost unaffected.

In order to study the details of this chemical change more closely a resort was made to staining. The method of staining with aluminium chloride and logwood as used by Lemberg (20) was found quite satisfactory for microscopic preparations. Staining with a deposit of silver chromate was also tried—a method which afterwards was found to have been used by Lemberg (20, p. 23) and strongly recommended by Cayeux (4, p. 183). This method

proved particularly suitable for the study of hand specimens the surface of which had been ground down smoothly before the stain was applied. Surfaces treated in this way revealed the progress of dolomitization in a surprising manner. The extent to which the remains of different kinds of organisms were effected varied to such a degree that it was thought desirable to have a confirmation of the results by some other method that also would discriminate between calcite and dolomite. Of the acids tried, dilute acetic acid gave the most satisfactory result. When a smoothed surface of a dolomitic limestone was etched with this substance the calcite was at once dissolved but the dolomite was not touched. The distinction was extremely sharp and the result confirmed in very detail that obtained from the staining.

It is found that the first material to change into dolomite is the skeleton of organisms which originally is formed of aragonite. This agrees with the results recorded by the Funafuti expedition: though the associated statement that secondary aragonite changes more easily into calcite than the primary was not confirmed by examination of the Atiu specimens; in several tests the primary aragonite changed first. The changes in the corals are the most noteworthy. In all the partly altered rock the material of the skeleton had completely changed while the coral mud that fills all of the cavities remained quite unaffected. Thus in the compact magnesian limestone, a complete coral structure is revealed by etching and it stands out in relief (Pl. IV, *D*). The *Foraminifera* are differently affected: the genera *Gypsina*, *Polytrema*, *Amphistegina*, *Operculina*, and *Rotalia* can be distinguished in the rock. The tests of *Operculina*, *Polytrema*, and *Rotalia* are soon converted into dolomite while that of the other genera remain as unaltered calcite. In the very large number of each of these genera examined no exception to the rule was seen. Exactly the opposite condition was found in regard to the calcite mud with which the small chambers have been filled. These genera in which the skeleton has been changed to dolomite have their chambers filled with unchanged calcite mud. On the other hand those genera which retain the unchanged calcite skeleton have chambers filled with dolomite which is obviously derived from original calcite mud. The acid treatment confirms this in every detail. The dolomite skeletons stand out in well defined relief while the chambers are deep pits; the walls of the calcite skeletons have dissolved out while the dolomite in filling of the chambers stands out as minute rounded bosses. (See Pl. IV, *E*, *F*.)

No explanation of this remarkable difference is attempted here. It would seem, however, that it must be due to some inherent molecular structure in the calcite of the skeleton though that would not be expected to have any effect on the calcite mud with which the chambers are filled. Comparison may perhaps be made with the materials that were obtained from a depth

greater than 850 feet in the Funafuti bore. There the deposition of calcite and dolomite alternated in the linings of many of the cavities.

CAUSE OF DOLOMITIZATION

A good historical sketch of the views held by various geologists regarding dolomitization has been given by Skeats (30, p. 186) and by Clarke (7, pp. 480-86), but the authorities that they cite were for the most part not especially concerned with this phenomenon as related to the changes that have taken place in coral reefs. In reference to this particular aspect of the question, Dana (11, p. 307) has suggested that there may be a concentration of magnesian salts in lagoon water. Judd (13, p. 386) has laid emphasis on the possibility of the leaching of calcium carbonate which would leave behind a residue rich in magnesium carbonate. Clarke (7) tentatively ascribes the change to the combined action of leaching and of the presence of the preponderance of remains of organisms that originally contained a high percentage of magnesium carbonate in their skeleton.

Before any attempt is made to solve this problem it must be recognized that before dolomitization commences the rock has already become solid and resistant by the deposition of secondary calcite, some of which is first deposited as aragonite, in all of the spaces originally vacant. Cullis (10, p. 414) particularly mentions that the rocks between the depths of 1000 and 1070 feet at Funafuti show no sign of solution.

The two islands, Mangaia and Atiu, offer a great contrast so far as the distribution of dolomite is concerned. In Atiu the highest portion of the Makatea is somewhat on the outer side of its median line; in Mangaia the highest part is at its inner edge (fig. 10). In my description of Mangaia (25) it was stated that judging from the composition of some 20 specimens of limestone from the Makatea no dolomite occurred on the island. Since then it has been found that dolomite is present on the outer side of the Makatea at Te Ara Toiro, in the southern part of the island, and probably at Kumukumu in the northern part, and at Opiu in the southwest part.

In Atiu Island, on the other hand, dolomitization is general and for the most part complete throughout the inner part of the Makatea. Actual determinations of the amount of lime and magnesia were made in comparatively few places and the general statement is based on tests made by placing a drop of dilute acetic acid on the surface of specimens of the rock from a number of localities. The action of the acid had first been tried on the surface of specimens in which the amount of lime and magnesia had been estimated and it was found that the activity of the reaction gave a definite indication of the amount of magnesium carbonate in the specimen. This test showed that the extent of dolomitization decreased rather rapidly as the Makatea was crossed from its inner to its outer side. When the highest point of the encircling ring

of Makatea was reached, that is, about two-thirds of its width from its inner margin, it was found that the amount of magnesia was as low as that in the material of the living reef, and that this condition extended to the outer edge of the Makatea. In other words, the outer third of the Makatea ring is formed of unchanged limestone while the inner two-thirds is formed of dolomitic limestone which is nearly pure dolomite at the inner edge of the Makatea but contains a gradually increasing percentage of calcium carbonate as the inner edge is left behind, and contains hardly any magnesium carbonate when the highest point of the Makatea has been reached.

It seems that these facts may lead the way to an understanding of the conditions that promote the change from the limestone of a coral reef to dolomite. At Mangaia, after the last movement of elevation, the base of the Makatea was for a long time subject to the wash of the sea water; until the reef had grown outward to a considerable extent. At Atiu the inner side of the Makatea was submerged for a long period which continued while the coral reef which now constitutes the Makatea grew outwards 500 yards; for at this distance from the beach it now has its greatest elevation. While the reef was growing outward a shallow lagoon was formed between the reef edge and the shore. The landward part of the reef which was formed first and afterwards became the floor of the small lagoon was subject to rapid circulation of water from the surf that broke over the reef edge which all the time was slowly extending seawards.

The dolomite at the foot of the outer edge of the Makatea at Mangaia was also subject to the circulation of sea water for a lengthened period. Here the rapid uprise of the island which was responsible for the outer cliff face of the Makatea would have raised some of the marginal growing surface of the reef from a depth of 15 fathoms to sea level. The organisms that were growing there would have been killed by the surf in their new station; the limestone of which their skeletons were formed would be subject to the constant action of the surf while the reef margin slowly grew outward at the new level.

On the other hand, since the inner edge of the Makatea is its highest part, no portion of the surface of the rising reef would be subject to the prolonged action of the circulating sea water during elevation. The lagoon separated from the sea by the gradual elevation of the Makatea would contain water almost still and of less salinity than sea water. This condition would obviously not permit the formation of dolomite from the limestone on the surface of the inner cliff of the Makatea if the circulation of sea water as suggested is the true cause of the change.

This explanation of the origin of dolomite by mere circulation of sea water at surface pressure in oceanic islands cannot be applied to the rocks studied by Skeats (29) because of the lack of accurate knowledge of distri-

bution of the rocks and of the geological history of the islands in which they are found. This remark applies also to Funafuti where nothing is known of the areal distribution of the dolomite and for which information as to the vertical distribution is restricted to the results obtained from a single bore.

SOIL

All the spaces between the projections on the rough surface of the Makatea are filled with a red earth at Atiu to the same extent as at Mangaia, forming a soil of great fertility. Its composition is shown in Table 3, which includes analyses of similar material from Mangaia and other islands.

TABLE 3. ANALYSES OF MAKATEA SOILS

	1	2	3	4	5
Si O ₂	9.80	8.84	2.23	5.0	5.0
Al ₂ O ₃	23.85	19.70	9.25	2.5	25.9
Fe ₂ O ₃	25.13	31.71	4.15		7.4
Ca O	2.75	1.60	30.36	32.5	
TiO ₂	5.42	5.10			
P ₂ O ₅	2.55	2.48	27.37	39.0	38.5
Loss on ignition	30.60	30.80	25.34	20.0	20.0
Total	100.10	100.26	98.70	99.0	96.8

1. Makatea soil from Taunganui, Atiu Island. Sample from near the road 600 yards from the beach. A sample from Vai Piae contained 4.47 per cent P₂O₅: Marshall (this paper).
2. Makatea soil from Mangaia: Marshall (25, p. 23).
3. Phosphate deposits from Walpole Island: Wright (39, p. 93).
4. Soil from Murray Hill, Christmas Island: Andrews (1, p. 291).
5. Phosphatized rock from Clipperton Island: Teall (34, p. 231).

To account for this material is difficult. The first explanation that comes to mind is that this soil has been derived from volcanic ash spread over the Makatea by volcanic action, and subsequently changed by laterization. But this explanation is unsatisfactory. In the first place the summit plateau of Atiu, the form of which is due to marine planation, must have been developed before the Makatea was in existence. If a depression sufficient to permit the planation of the summit had taken place after the Makatea had been formed, the long continued wave action would have covered the Makatea with material derived from the plateau, and would have filled all of the depression now occupied by the swamp. Again volcanic activity of an explosive nature would certainly have spread out the fine grained products unevenly, whereas the soil is distributed evenly over the Makatea though it is rather thinner on the outer than on the inner portion, especially at Oneroa. This explanation also fails to account for the high percentage of phosphoric acid.

The only explanation that seems to hold is that the soil represents the accumulated excrement of water birds, especially of duck. The widely ranging *Anas superciliosa* is found on the island and was at one time probably

abundant; for during the period while the outer third of the Makatea was being formed, a large area of brackish water stood between the Makatea and the volcanic core. As pointed out in the account of Mangaia (25) the excreta of the duck contains much inorganic matter, which in the course of ages might accumulate to form a thick deposit. It is known that the huge deposits of calcium phosphate at Nauru, Makatea, and other islands is derived from the excreta of sea birds, and it is thus reasonable to assign the red earth of the Makatea at Atiu to this source.

PALAEONTOLOGY

The general conversion of the material of the inner part of the Makatea into dolomite has naturally obscured to a great extent the characteristic features of the organisms of which it is composed. However, the outlines of many of their skeletons can still be distinguished in the thin dirt line which so persistently surrounds the "ghosts" of the fossils.

No remains of *Lepidocyclus* could be found though it is almost certain that such structures could be recognized even in the most dolomitized rock. The few pieces of relatively unaltered rock found in the inner portion of the Makatea contain a good deal of *Gypsina communis*. This species occurs also at Mangaia, but only in the outer part of the Makatea. Though a slender basis for correlation, the presence of this fossil in corresponding positions on the two islands suggests that the inner part of the Makatea at Atiu is approximately the same age as the outer part of this formation at Mangaia. At Atiu *Operculina* and *Amphistegina* are common; *Rotalia* is not rare; *Polytrema* is found everywhere; *Lithothamnium* is abundant, though less so than at Mangaia; *Halimeda* is rare. Corals make up a large portion of the rock and echinoid remains are everywhere to be seen. The material of the small cliffs on the coast is not of great age; in some places the aragonite of the corals is unchanged, and *Halimeda* retains its brownish tint in sections.

The evidence points to the probability that coral reef growth began in the early Pliocene and has continued without interruption till the present day.

CAVES

The Makatea at Atiu Island is perforated by numerous caves some of which are as much as 500 yards in length. Several of them have been used for burials, which on occasions have been disturbed by Europeans. This has annoyed the natives, who, fearing vandalism, refuse to allow visitors to enter some of the caves. It is said that at one time during local fighting, a whole tribe took refuge in one of the caves and after wandering about in it were lost, and never emerged, probably a grossly exaggerated story. In some of the caves stalactites are abundant. Huge specimens have been broken off, carried some miles and employed in building the platforms in front of the houses of

chiefs. They have been used also in the construction of the walls of some maraes. Where thus used, they have been merely piled one on top of another in horizontal positions without any attempt at shaping. Some large stalactites were seen on the central plateau in the village of Tengtangi. In transportation these huge pieces were tied to saplings and carried by large numbers of men. There is no indication that the stalactites were used in building the more elaborate structures such as those for which the basaltic columns at Kusaie Island were employed. In fact, throughout the Cook Islands no attempt was made to construct permanent buildings or fortifications except at Arorangi, Rarotonga, where some large phonolite boulders have been roughly piled together for defensive purposes.

The cave most easily accessible is Taketake, situated on the southwest side of the island near the track to the Vai Piake landing. This cave is entered from the surface of the Makatea at a point about 500 yards from its inner edge, where an irregular opening some 25 feet deep may be descended by means of a ladder. Within the cave stalactites and stalagmites are greatly developed. The roof of the cave must be near the surface of the Makatea for its highest point is not more than 75 feet above sea level. In one or two places, daylight can be seen through crevices in the roof. The floor of the cave is very uneven and in places is slightly terraced. No water flows on it. In places on the floor are a number of small rounded nodules of aragonite, $\frac{1}{4}$ to $1\frac{1}{2}$ inches in diameter, somewhat vesicular, and concentrically zoned. Their surface is slightly rough, partly due to the projecting ends of small crystals and partly to irregular intersecting crevices. These aragonite nodules are somewhat irregularly arranged and only a few are attached to the floor. They do not seem to be related to the formation of stalactites. They lie on a wet floor but at the time of my visit though wet all over, they were not wholly immersed in the water. They are all stained with iron oxide derived from the soil that covers the surface of the Makatea. The cave was visited at the end of the wet season. It is possible that its floor is dry during the dry season, and that the nodules are formed from the calcium carbonate that had been in solution in the water that covered the floor.

Taketake cave may have been an original passage in the reef. In the reef that now surrounds the island many fissures extend almost from the margin of the reef to the shore line. Though at the surface these fissures are nearly closed by the growth of reef forming organisms, at a greater depth many of them open out into large spaces. It is probable that whatever may be the origin of these fissures the growth that takes place on their floors and sides is much slower than that on the roof, or on the surface of the reef. On the whole the fissures seem to have their maximum development on those portions of the reef where the sea is heaviest.

It was expected that the caves would prove to have been formed by the

dissolving action of percolating water, or by streams, and it was a surprise to find little or no evidence for this origin. The floor of the cave seems to be a surface of deposition rather than solution, and no evidence could be found that there had at any time been a flow of water through it. The floor of the cave seems to be at a higher level than that of the water in the swamp.

At Ivirua, Mangaia, a cave 100 feet below the surface of the Makatea, seems to have been a channel through which water passed outwards from the old lagoon when the water level was 30 feet higher than now. For a considerable part of its length, it is not more than 6 feet wide and 10 feet high, but its direction changes frequently and the floor rises and falls. The rocks on the sides of the cave are rounded and there are few stalactites. It is said that this passage leads out to the beach about 5 feet above high water mark. In form and appearance this cave at Ivirua is wholly different from the cave at Taketake, which has a high roof in places broken through, an uneven floor, and sides formed of angular rock.

THE SWAMP

On Atiu, the Makatea ends abruptly at its inner edge around the whole circumference of the island. At Kuekue it terminates in a cliff about 20 feet high and 150 feet long; elsewhere it rises gently.

But though the abrupt precipice which characterizes the Makatea of Mangaia Island is lacking, the boundary between the Makatea and the swamp is everywhere well defined. Inland from the Makatea, the even surface of the swamp is maintained for varying distances to the foot of the volcanic ground, and in places extends for a quarter of a mile into the valleys of the small streams that flow from the central plateau.

In many places, especially on the south side of the island, the spurs of the volcanic ground extend to the edge of the Makatea, but even in these places they sink to the level of the swamp water before the Makatea is reached. These spur ends provide convenient routes for the native paths which lead from the volcanic ground to the Makatea, and on to the beach. In the southern part of the island, the swamp is represented only by a slight depression, in which bananas are grown. In those parts of the swampy ground where the water in the streams flows sufficiently to prevent stagnation, the conditions are favorable for taro cultivation. Some of the ground is used for that purpose, generally that on the inner side only, near the points where the streams enter the swamps. Otherwise the swampy ground is waste land, covered with a growth of rush and other water weeds. The surface of the swamp is 20 to 30 feet above sea level. In the wet season the swamp contains considerable water, but the small Lake Tiroto is the only permanent sheet of water with a surface free from growth of weeds. It is said that in

rough weather salt water is sometimes driven from the reef into the lake through subterranean passages.

There are no conspicuous sink holes by means of which the water of the swampy area can pass into channels through the Makatea. The wetness of the swampy ground shows that channels through the Makatea afford less easy passage for the outflow of water than they do at Mangaia Island.

THE VOLCANIC CORE

Only in a few places is the volcanic ground in Atiu directly connected with the limestone of the Makatea. Over most of the circuit of the island swampy ground intervenes between the two.

The summit of the volcanic ground is a nearly flat area of two square miles at an altitude of 270 feet above sea level, though its peripheral portions are 56 feet lower than the central part. This plateau is deeply dissected by valleys which radiate outwards to the coast line. The head waters of streams flowing to opposite sides of the island have left but a narrow ridge between them. Remnant lobes of the plateau of considerable size separate the middle courses of the radiating streams, and near the circumference of the plateau attain a considerable width.

As compared with Mangaia where only a small portion of the plateau remains, it is obvious that the plateau on Atiu is still in the early stages of dissection. The streams have eroded deep, steep-sided valleys. The larger valleys have flat floors which extend a quarter of a mile back from the apices of the spurs.

Notwithstanding the transporting power of the heavy tropical rainfall, the weathering of the rock has proceeded far more rapidly than its removal. The explanation of this may be the same as that which was offered for similar conditions in Mangaia: the matted rhizomes of *Gleichenia dichotoma* on the ground combined with the dense canopy of its foliage protect the soil to such an extent as to almost prevent the removal of the surface material by rainfall; at the same time the growth of the *mape* (*Calophyllum inophyllum*) in the stream valleys protects their floors so effectively with its matted roots that erosive action of streams is almost stopped.

The weathering of the basalt is apparently the same as that in Mangaia where it has produced a partial laterization of the rock.

No patches of limestone were found anywhere on the volcanic rock and their absence as well as the absence of fossil shells justifies the opinion that the uplift of the plateau from the level at which it was formed by marine erosion took place so soon after its development that no marine life had migrated to it, and no masses of limestone had been formed.

Small terraces are to be seen on the flanks of the volcanic hill. The one most strongly developed stands at the same altitude as the highest part of the Makatea (70 feet above sea level) and is more or less general on the distal portion of the spurs all around the island. A less pronounced terrace appears in places some 30 feet lower. These terraces must mark levels of marine erosion as they are far more extensive and continuous than those that have been excavated by the natives to serve as platforms for their houses. The lower terrace, which is extremely fragmentary, marks the sea level before the old fringing reef, now the Makatea, began its growth. The upper one marks the level of marine erosion at the period of maximum subsidence when, perhaps owing to relatively rapid downward movement, the reef, for the time, did not provide protection for the coast sufficient to prevent it from suffering from wave action.

The apparent absence of beach matter of organic origin on the slopes of the volcanic ground implies a considerable difference in the conditions that prevailed while the Makatea was being formed from those now existing at Huaheine and Raiatea islands, where there are fringing reefs or coral beaches as well as the barrier reefs. In parts of Tahiti, however, and on the coast of north Queensland, marginal fringing reefs are absent, and there are no coral beaches for considerable distances along the coast line. It may be that where the coast line provides much inorganic detritus there is no marginal growth of coral.

There is no indication of any eruption of the central volcano after the growth of the Makatea had begun. In no place do the volcanic spurs invade the Makatea, nor do they spread out where they reach its margin. Furthermore, the surface of the Makatea is not covered with scoriaceous volcanic matter as Chubb (6, p. 309) found at Rurutu Island. The red soil on the surface of the Makatea has quite a different origin.

As shown on the map (fig. 8), the plateau with its lobes between the stream valleys extends over all the central part of the island; it is possible to walk for a distance of two and a half miles north to south, and of two miles east to west on almost level ground. This level area was originally, and in large part still is, covered with the fern *Gleichenia dichotoma* through which rise a considerable number of toa trees; which frequent burning of the vegetation on the plateau prevents from attaining any large size. The rocks of which this plateau is composed are deeply weathered and the material has been converted into a dark red, unctuous clay which in wet weather is particularly adhesive. In the clay small nodules of ilimonite are common, and manganese oxide is also found. Here and there, particularly on the northeast slopes of the island, some roots of the *Gleichenia* fern have become silicified, but no large masses of flinty silica were found on the surface as in Mangaia Island.

In places the paths that have been made by the natives in walking from their homes to their taro patches, or to the fishing grounds, have been washed out by the rain into deep gutters. Here and there, the structure of the plateau is revealed on the high banks even though the rock has been entirely changed. All the original rock seen is fragmentary and scoriaceous and in places the same structure is shown on the sides of the steep ravines that the streams have excavated in the plateau. The heads of these valleys are abrupt and in a few places unaltered rock may be seen in dikes. A dike at the bottom of the Waikakaia, and another in the village of Teenui, at the head of the Topuriri Valley, consist of rather coarse-grained basalt. In the marae visited by Captain Cook are some blocks of a fine grained basalt but their source could not be ascertained. It seems that all of the rock of which Atiu Island is formed is basaltic. No indication was found of phonolitic rocks that have such a wide distribution in Rarotonga, nor of nepheline basalts such as are found in Aitutaki.

DESCRIPTION OF ROCKS

All of the volcanic rocks found on Atiu have proved to be basalts. The ordinary type of rock illustrated by that in the dike near the source of the Waikakaia, is coarse-grained with large idiomorphs of a brown augite, some of which are conspicuously zoned, the outer zone having the higher extinction angle. Large idiomorphs of olivine are somewhat less abundant, but most of this mineral is changed to serpentine though talc is also present. The few phenocrysts of feldspar have an extinction angle, which shows that they have the composition Ab 35 An 65. The groundmass consists mainly of colorless augite with some microlites of feldspar and many euhedrons of magnetite. There are a number of round gas pores filled with secondary minerals. The lining of many pores is hyalite, perhaps with a little chalcedony, but the central portion is filled with calcite.

This rock has a specific gravity of 3.16, but is less basic than the coarse-grained basalts of Mangaia and Rarotonga, which contain no phenocrysts of feldspar. It would appear to fall in the group of "basaltes labradoriques" of Lacroix (19, p. 61) of a less basic composition than his ankaramites and oceanites.

The fine grained rock from the Orongo Marae, the exact origin of which is not known, is still less basic and comes near the "basalte andesitique" from the Marquesas as defined by Lacroix. The structure is that called "inter-sertal" by Rosenbusch, the augite and feldspar of which the rock is almost entirely composed of equal dimensions. There are some isometric idiomorphs of magnetite. The first mineral to crystallize was the magnetite, followed in

turn by the few larger grains of augite, the feldspar laths, and the minute irregular augite, and feldspar with some minute grains and needles of magnetite.

As shown in the following analysis, the basalt from Atiu contains a relatively high percentage of silica and of lime. Similar rocks have been described by Lacroix (19) from the Marquesas and other Pacific islands.

SiO ₂	46.60	46.68
Al ₂ O ₃	14.68	15.01
Fe ₂ O ₃	9.82	6.35
FeO	4.61	5.44
MgO	5.08	4.30
CaO	10.05	9.84
Na ₂ O	2.14	3.13
K ₂ O	1.74	1.51
TiO ₂	1.42	4.20
P ₂ O ₅	0.36	0.47
H ₂ O	2.20	3.10

1. Basalt. Orongo Marae, Atiu Island: Marshall (this paper).
2. "Basalte andesitique" from Nukuhiva, Marquesas Islands: Lacroix (19, p. 42). Many other analyses of similar rocks are given in this paper by Lacroix.

GEOLOGICAL HISTORY

Like many other islands in the south central Pacific, the first appearance of Atiu Island above the surface of the water was due to volcanic action. The result of this activity was the formation of an island which measured approximately 3 miles in diameter. At a time when the level of the ocean surface was 270 feet higher than now, or the floor of the ocean 270 feet lower, the island was composed of fragmental volcanic matter. As at Mangaia, wave action soon reduced Atiu to the condition of a shoal. Slow elevation then took place until the sea level was perhaps 50 feet lower than now, and there was considerable atmospheric erosion of the platform that had been formed by marine planation.

After this had proceeded to a considerable extent, the formation of a coral reef began. At the same time the volcanic slopes became covered with a thick mat-like mantle of *Gleichenia dichotoma* which held the surface together and prevented the removal of the clay which had been derived from the action of the atmosphere on the volcanic rock. The thickness of clay thus preserved from removal, in time became considerable. The fringing reef of coral which began to develop after the erosion had produced most of the stream valleys, soon protected the shore line and gradually extended outwards.

Slow subsidence continued and as the coral reef grew outwards, each successive portion was higher than that interior to it. These relative actions continued until the reef had become 600 yards wide. The movement was then reversed, the negative condition being apparently succeeded without any in-

terval by positive, though the movement was extremely slow. The reef was able to maintain its outward extension without modification while positive movement continued. It has a surface, which, though irregular, on the average slopes seaward at a small angle.

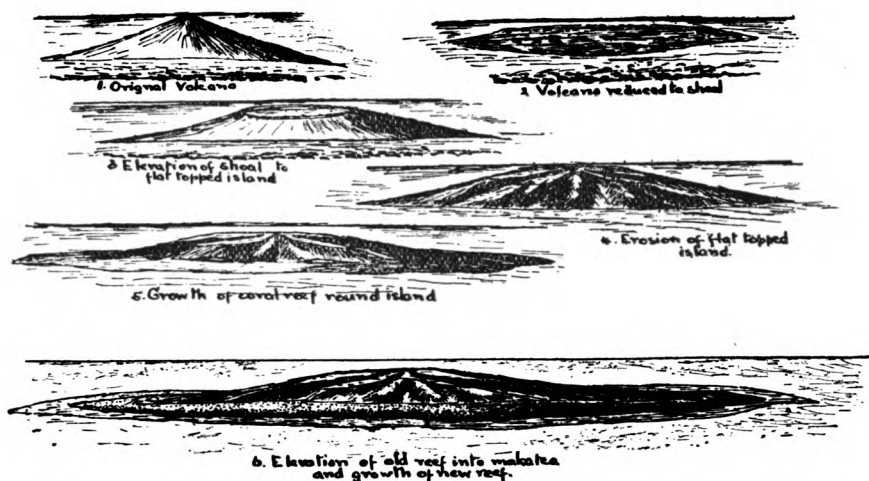


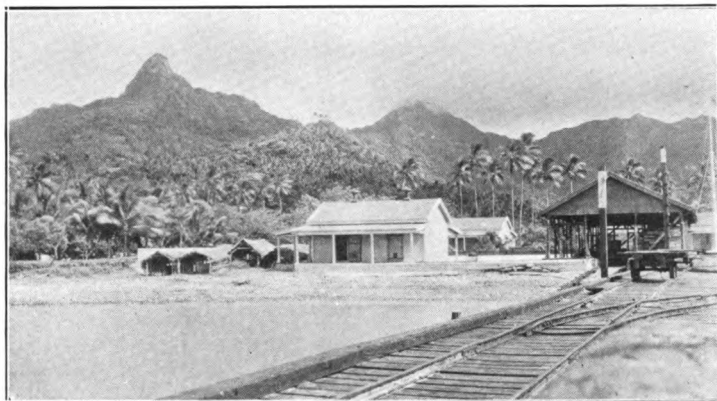
FIGURE 13.—Sketches illustrating the geological development of Atiu Island.

For a considerable time still-stand conditions then prevailed and the attack of the sea was maintained at a constant level, and has now eroded a small marginal cliff which overlooks the reef flat.

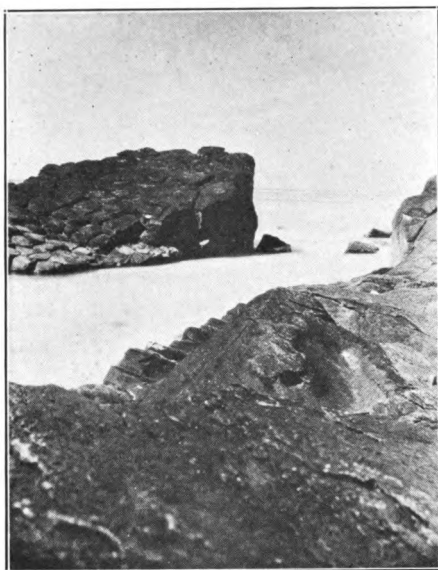
LITERATURE CITED

1. ANDREWS, W. C., A monograph on Christmas Island: British Mus. Trustees, London, 1900.
2. BARTRUM, J. A., Igneous rocks from Western Samoa: New Zealand Inst., Trans., vol. 57, pp. 254-264, 1927.
3. BARTRUM, J. A., Rocks of Mount Cargill, Dunedin: New Zealand Inst., Trans., vol. 44, pp. 163-179, 1911.
4. CAYEAUX, L., Introduction à l'étude petrographique des roches sedimentaires, Imprimerie Nationale, Paris, 1916.
5. CHEESEMAM, T. F., The flora of Rarotonga: Linnean Soc., London, Trans., 2d ser., vol. 6, pp. 261-313, 1903.
6. CHUBB, L. J., The geology of the Austral or Tubuai Islands (Southern Pacific): Quart. Jour. Geol. Soc., vol. 83, pp. 291-316, 1927.
7. CLARKE, E. W., The data of geochemistry: U. S. Geol. Surv., Bull. 330, 1908.
8. COOK, JAMES, A voyage to the Pacific Ocean . . . in the years 1776, 1777, 1778, 1779 and 1780, vol. 1, pp. 180-204, London, 1784.
9. COTTON, C. A., Geology of Signal Hill, Dunedin: New Zealand Inst., Trans., vol. 41, pp. 111-126, 1908.
10. CULLIS, C. G., The mineralogical changes observed in the cores of the Funafuti borings: in the atoll of Funafuti, pp. 392-415. (See David and others, No. 13.)
11. DANA, J. D., Corals and coral islands, New York, 1875.
12. DANA, J. D., Manual of geology, 4th ed., New York, 1894.
13. DAVID, T. E. W., and others, The atoll of Funafuti, borings into a coral reef and the results, being the report of the coral reef committee of the Royal Society: Roy. Soc. London, 1904.
14. ELSCHNER, CARL, Corallogene phosphat-inseln austral-oceaniens, Lubeck, 1913.
15. GILL, W. W., Gems from coral islands, vol. 2, London, 1856.
16. GILL, W. W., Savage life in Polynesia, Wellington, 1880.
17. GREGORY, J. W., Geography: structural, physical, and comparative, London, 1908.
18. LACROIX, A., Les roches alcalines de Tahiti: Geol. Soc. de France, Bull. 4th ser., vol. 10, pp. 91-124, 1910.
19. LACROIX, A., La constitution lithographique des îles volcanique de la Polynésie australe; Acad. des Sciences, Mem., vol. 49, pp. 1-82, 1927.
20. LEMBERG, J., Zur microchemischen untersuchung einiger minerale: Zeit. d. Deutsch. Geol. Gesell., vol. 44, 1890.
21. MARSHALL, PATRICK, Geology of Dunedin: Quart. Jour. Geol. Soc. London, vol. 62, pp. 381-424, 1906.
22. MARSHALL, PATRICK, Geology of Rarotonga and Aitutaki: New Zealand Inst., Trans., vol. 41, pp. 98-100, 1908.
23. MARSHALL, PATRICK, Alkaline rocks of the Cook and Society islands: Australasian Assoc. Adv. Sci., Rept., vol. 13, pp. 196-201, 1912.
24. MARSHALL, PATRICK, The sequence of lavas at North Head, Otago Harbour: Quart. Jour. Geol. Soc. London, vol. 70, pp. 382-408, 1914.
25. MARSHALL, PATRICK, Geology of Mangaia: B. P. Bishop Mus., Bull. 36, 1927.
26. MARSHALL, PATRICK, A natrolite tinguaita from Dunedin: New Zealand Inst., Trans., vol. 58, pp. 533-535, 1927.
27. MEINICKE, C. E., Die inseln des stillen oceans: eine geographische monographie, vol. 2, Leipzig, 1898.

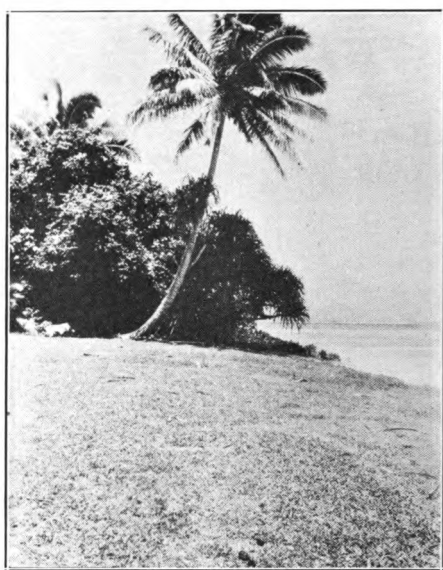
28. ROSENBUSCH, H., *Microscopische physiographie*, vol. 2, p. 970, 1908.
29. SKEATS, E. W., The chemical composition of limestones from upraised coral islands with notes on their microscopical structure: *Mus. Comp. Zool., Bull.*, vol. 42, pp. 53-126, 1903.
30. SKEATS, E. W., The formation of dolomite and its bearing on the coral reef problem: *Am. Jour. Sci.*, 4th ser., vol. 45, pp. 185-200, 1918.
31. SMITH, W. C., The volcanic rocks of Christmas Island: *Quart. Jour. Geol. Soc. London*, vol. 72, pp. 44-66, 1926.
32. SMITH, W. C., and CHUBB, L. J., The petrography of the Austral or Tubuai Islands (Southern Pacific): *Quart. Jour. Geol. Soc. London*, vol. 83, pp. 317-341, 1927.
33. SMITH, PERCY, *Hawaiki*, Wellington, 1898.
34. TEALL, J. J. H., Phosphatized trachyte from Clipperton Island: *Quart. Jour. Geol. Soc. London*, vol. 54, pp. 230-232, 1898.
35. WASHINGTON, H. S., The chemistry of the Pacific volcanos—the limitations of our knowledge: *B. P. Bishop Mus. Special Publ. no. 7*, pp. 325-345, 1921.
36. WENTWORTH, C. K., The geology of Lanai: *B. P. Bishop Mus., Bull.* 24, 1925.
37. WENTWORTH, C. K., Pyroclastic geology of Oahu: *B. P. Bishop Mus. Bull.* 30, 1926.
38. WILLIAMS, JOHN, *Missionary enterprises in the South Seas*, London, 1837.
39. WRIGHT, A. M., Phosphate from Walpole Island: *New Zealand Jour. Sci. and Tech.*, vol. 7, pp. 91-94, 1924.
40. ZIRKEL, F., *Lehrbuch der petrographie*, vol. 2, 1894.

*A**B**C*

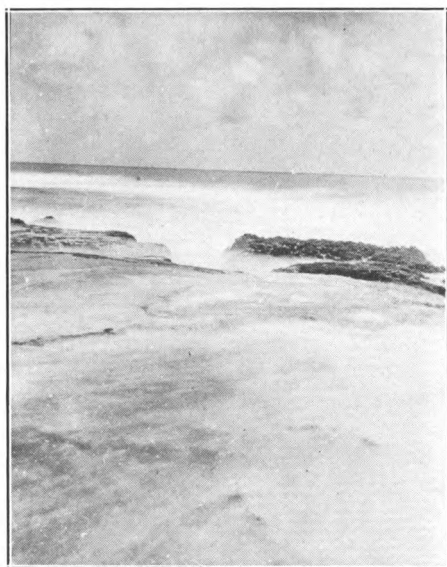
VIEWS OF RAROTONGA: *A*, WHARF AT AVARUA. HIKURANGI PEAK AND TE MANGA (CLOUD-CAPPED) IN BACKGROUND; *B*, FRINGING REEF AS SEEN FROM MAUNGATEA BLUFF (ALTITUDE 1,200 FEET); *C*, LOOKING WEST FROM MAUNGATEA BLUFF.



A



B

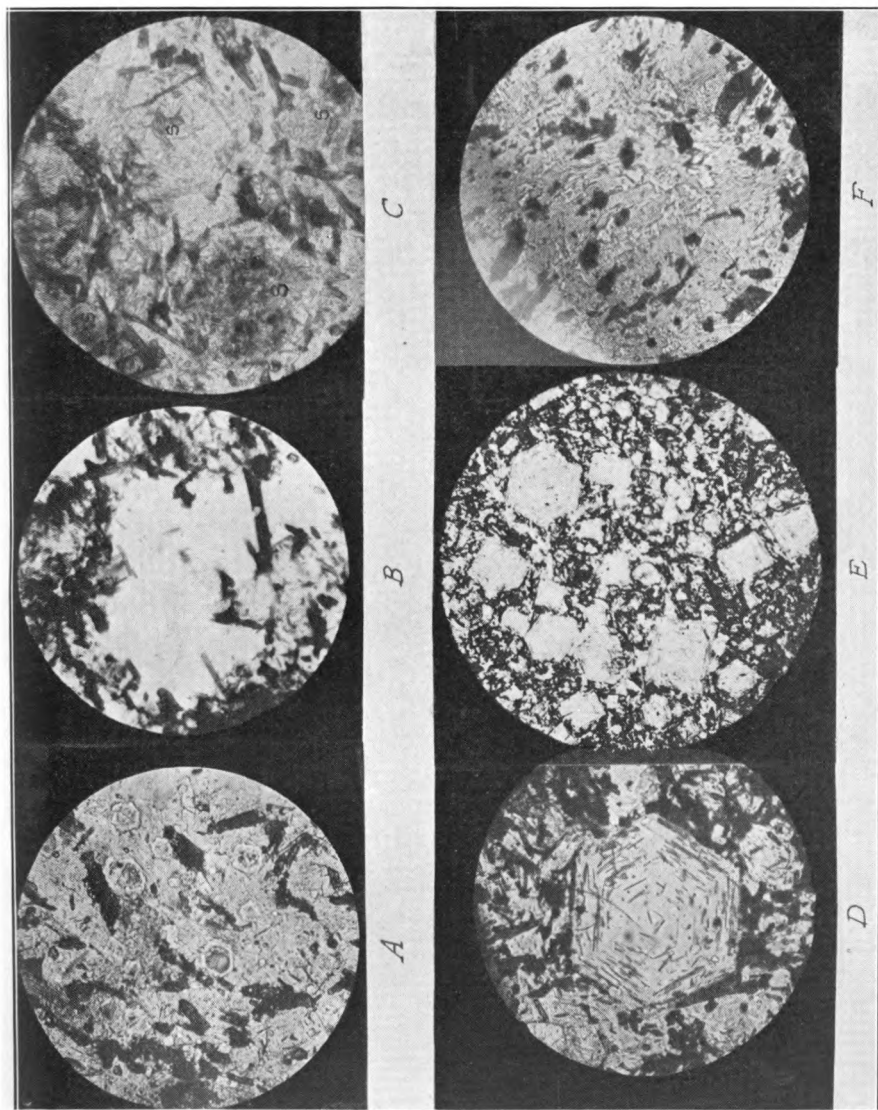


C



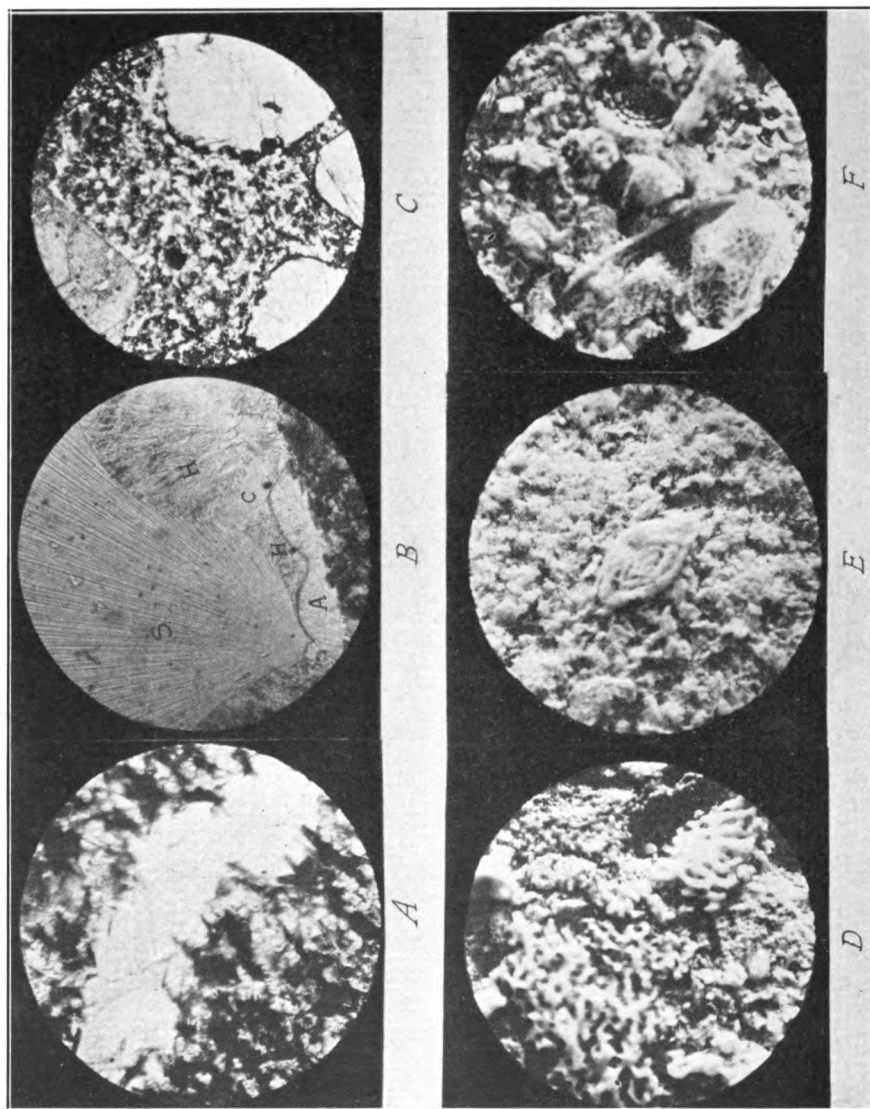
D

VIEWS OF RAROTONGA: *A*, BLACK ROCK (TUORU); *B*, BEACH AT TITIKAWEKA; *C*, EDGE OF REEF AT NGATANGIHA SHOWING LITHOTHAMNIUM RIDGE; *D*, TARO SWAMP, BREADFRUIT, AND PALM TREES WITH HIKURANGI PEAK IN BACKGROUND.



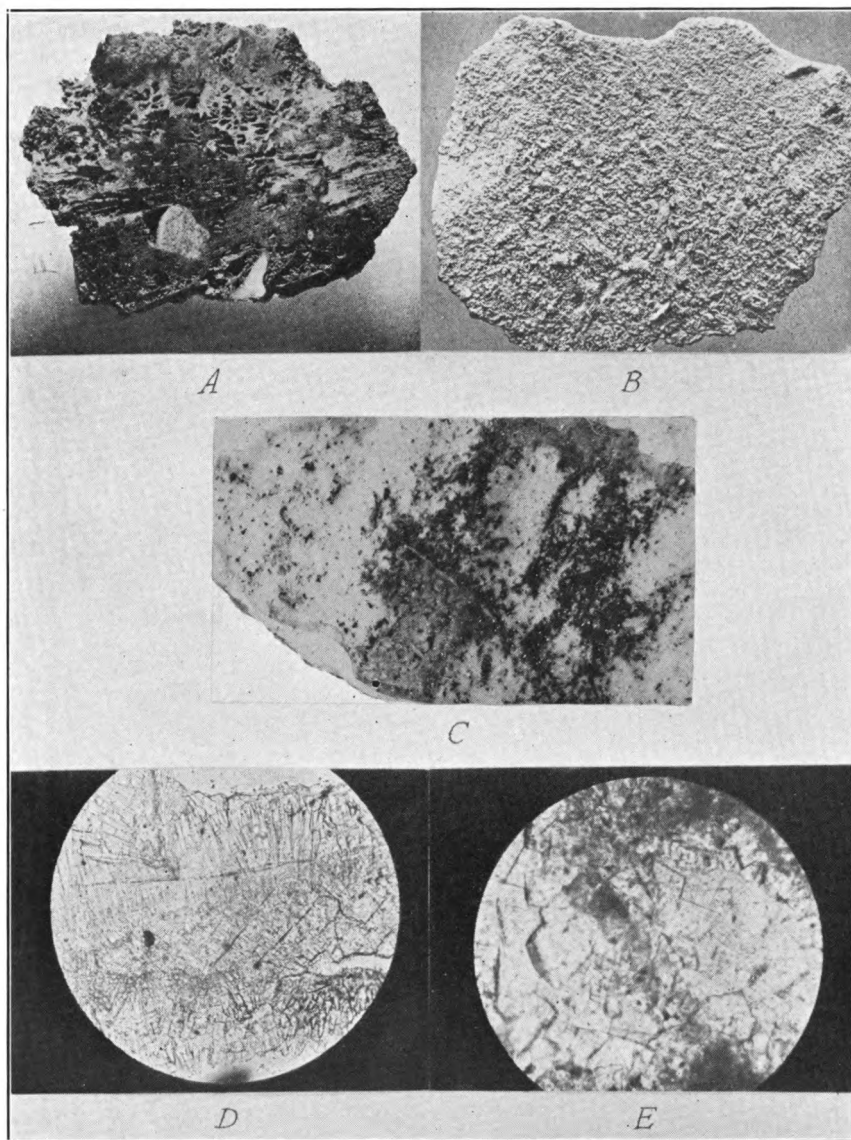
MICROPHOTOGRAPHS OF ROCKS FROM RAROTONGA: *A*, SODALITE PHONOLITE FROM RAEMARU; ISOMETRIC CRYSTALS OF SODALITE WITH LOW REFRACTIVE INDEX, NEPHELINE CRYSTALS FORM CLOUDY PATCH NEAR CENTER, DARK MINERAL IS AEGERINE, THE REMAINDER FELDSPAR, $\times 100$; *B*, SODALITE PHONOLITE FROM MAUNGATEA; WHITE PATCH IS A ZEOLITE INTO WHICH PROJECT CRYSTALS OF AEGERINE, $\times 100$; *C*, PHONOLITE FROM MAUNGATEA; BLUFF CRYSTALS OF SODALITES WITH CROWDS OF INCLUSIONS OF AEGERINE, $\times 180$; *D*, PHONOLITE FROM TUKAVAI; CRYSTAL OF NEPHELINE INCLUDING REGULARLY ARRANGED NEEDLES OF AEGERINE, $\times 100$; *E*, NEPHELINITOID PHONOLITE FROM TUKAVAI; NEPHELINE CRYSTALS CONTAINING MICROLITES OF AEGERINE, $\times 30$; *F*, TRACHYTICOID PHONOLITE FROM TAIPARA, SHOWING AREAS OF "GLASS" (AMELETITE) NEAR CENTER, DARK GRAINS AEGERINE, REMAINDER FELDSPAR, $\times 100$.

(All photographs reduced 2/5ths in reproduction)



MICROPHOTOGRAPHS OF ROCKS FROM RAROTONGA: *A*, NEPHELINE PHONOLITE FROM MOUNT MAUNGATEA, NEEDLES OF AEGERINE PROJECT INTO AREA OF ZEOLITES, X 120; *B*, ZEOPLITES IN NEPHELINE PHONOLITE FROM SUMMIT OF MAUNGATEA: *ga*, ANALCITE; *c*, CHAZARITE; *h*, HYDRONAPHELITE?; *s*, STILBITE?; *r*, ROCK, X 180; *C*, ANKARAMITE FROM TUPAPA, THREE CRYSTALS OF OLIVINE AND ONE OF AUGITE IN A GROUND MASS OF FELDSPAR AUGITE AND MAGNETITE, X 30; *D*, LIMESTONE FROM TE MIRO, ATIU ISLAND, CORAL SKELETON CONVERTED INTO DOLOMITE, FILLING REMOVED BY ACETIC ACID, X 8; *E*, LIMESTONE FROM TE MIRO, ATIU ISLAND, DOLOMITIZED OPERCULINA, CALCITE REMOVED BY ACETIC ACID, X 8; *F*, LIMESTONE FROM TE MIRO, ATIU ISLAND, CHAMBERS IN AMPHISTEGINA (*ga*) FILLED WITH DOLOMITE.

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PHOTOGRAPHS OF LIMESTONE FROM ATIU: *A*, PARTLY ALTERED CORAL ROCK FROM TUMAI LANDING, STAINED WITH COBALT NITRATE; THE BLACK PARTS ARE EMPTY SPACES IN THE CORAL; THE GRAY, PRIMARY AND SECONDARY ARAGONITE; THE WHITE CALCITE, $\times 2$; *B*, ROCK FROM THE MAKATEA 500 YARDS FROM TAUNGANUI LANDING ETCHED WITH ACETIC ACID. THE DOLOMITE STANDS OUT, $\times 2$; *C*, MAGNESIAN LIMESTONE 600 YARDS FROM TAUNGANUI LANDING, SMOOTHLY SURFACED AND STAINED WITH LEMBERG'S SOLUTION. THE CALCITE IS DARK; THE DOLOMITE, WHITE, $\times 2$; *D*, ROCK FROM TUMAI LANDING, CLEAVAGE SHOWS CENTRAL LAMINA OF CORAL TO BE CALCITE, SECONDARY ARAGONITE PROJECTS INTO THE CAVITY FROM EITHER SIDE, $\times 100$; *E*, CORAL ROCK FROM THE INNER SIDE OF THE MAKATEA. RHOMBOHEDRA OF DOLOMITE PROJECT INTO AN ORIGINAL CAVITY, $\times 100$.

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