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To cite this article: B. L. Wood (1967) Geology of the Cook Islands, New Zealand Journal of Geology and Geophysics, 10:6, 1429-1445, DOI: [10.1080/00288306.1967.10423227](https://doi.org/10.1080/00288306.1967.10423227)

To link to this article: <https://doi.org/10.1080/00288306.1967.10423227>



Published online: 05 Jan 2012.



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GEOLOGY OF THE COOK ISLANDS

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(Received for publication 13 June 1967)

ABSTRACT

The geology of the 15 Cook Islands in the south-central Pacific is briefly described and their geological history outlined. All are the summit portions of extinct Tertiary volcanoes; six of the seven Northern Group islands are atolls, four of the Southern Group are makatea-type islands, and the others include a high mountainous volcanic island, a hilly near-atoll, an atoll, and a sand cay. Radiometric ages from Rarotonga are Late Pliocene, foraminifera from the makatea (raised coral reef) of Mangaia are Oligocene or Miocene, and much of the limestone underlying the atolls is probably middle Tertiary.

INTRODUCTION

The Cook Islands of which there are 15 (Fig. 1), have a total land area of 93 square miles scattered over 850,000 square miles of the South Pacific Ocean. They form a widely spread Northern Group, north of but excluding Aitutaki Island, and a more compact Southern Group. They lie between 8° and 23° south latitude and between 156° and 167° west longitude.

Previous geological observations in the islands include short reports on Aitutaki by Agassiz (1900, 1903), on Aitutaki and Rarotonga by Marshall (1908, 1909), and on the coral reefs and volcanic rocks (Marshall, 1912a, b, c, d). More detailed descriptions of Mangaia are given by Marshall (1927), and of Rarotonga and Atiu, Marshall (1930). General remarks on subsidence and elevation of the islands have been made by several observers such as Cook (1784), Hoffmeister (1930), and Chubb (1927, a and b, 1934, 1957). A detailed geological account of the entire group, on which this paper is based, is given by Wood and Hay (in press).

The islands of the Southern Group differ widely in form, structure, and relief, so that it is difficult to deduce a geological history consistent for the whole group. They include a high mountainous island, Rarotonga, four raised coral islands with volcanic cores, Mangaia, Mauke, Mitiaro, and Atiu, one atoll, Manuae, one near-atoll with a volcanic core, Aitutaki, and a sand cay on a coral foundation, Takutea.

Islands of the Northern Group are atolls, with one exception, Nassau, which is a sand cay on a coral reef foundation.

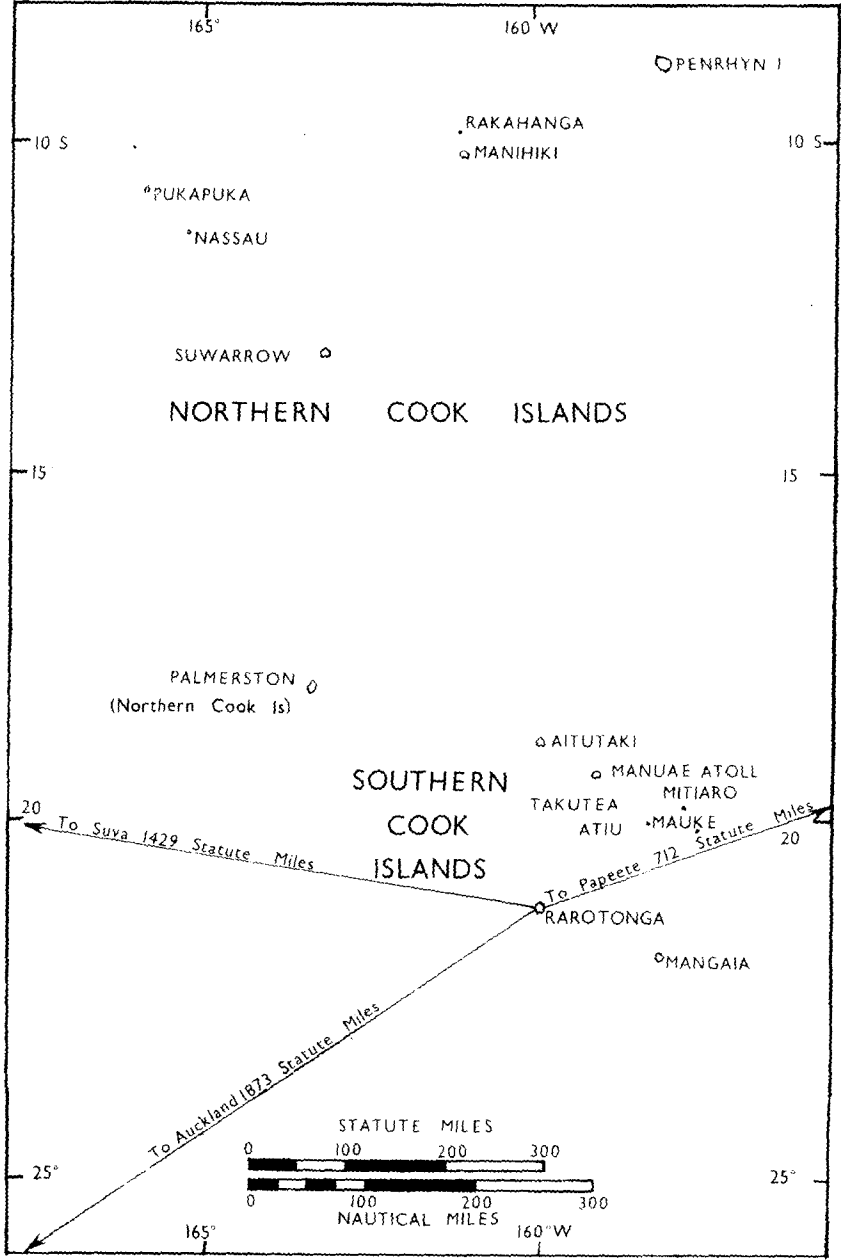


FIG. 1.—Map of the Cook Islands.

GEOLOGY OF ISLANDS IN THE SOUTHERN COOK GROUP

Rarotonga

(21° 12' S, 159° 46' W)

The island is roughly kidney-shaped in plan, some 7 miles from east to west, and 5 miles from north to south. A coastal fringe of low land borders a densely forested hill interior with peaks rising to over 2,000 ft above sea level. The relief and steepness of the interior is considerable with many razor-backed ridges separating deep valleys. Most hill slopes have a moderate thickness of red soil resting on weathered volcanic rocks, but near the crests of the ridges, boulders and pebbles are common, and the ridge crests are chiefly masses of broken rock held together by tree roots. Such steep relief is characteristic of many Pacific islands, both tropical and subtropical, in wet or dry climates, and is found in some parts of New Zealand; although such exaggerated forms have been attributed to the action of violent tropical rainfall, the causes are not clearly understood.

The present stream systems are obviously inherited from those consequent on the original volcanic form of the island, with the Takuvaine and Avatiu streams formerly draining the crater area, and the exterior streams draining the outer slopes of the cone. No remnants of the original main cone slopes have survived and erosion has reduced the volcano to a residual mountain (Kear, 1957, p. 673). A few hills such as Te Kou and Raemaru are eroded remnants of small cones and flow sheets that were thrown up by late eruptions from centres both within and outside the main crater.

The coastal fringe of Rarotonga consists of fans and partly cliffed terraces of strongly weathered volcanic alluvium, separated in places from a narrow strip of beach deposits and coral debris up to 25 ft high, by narrow low-lying swamps. The swamp depressions are not part of the original beach structure, but appear to be solution features caused by fresh water percolating and flowing down the near-surface layers of the relatively impermeable fan gravels.

Volcanic Rocks

The volcanic rocks fall into two main divisions, based on composition, mode of occurrence, and age. These are the Basaltic Eruptives and the younger Phonolitic Eruptives. Marshall (1930) quoted observations that pointed to a recurring sequence of basaltic and phonolitic eruptions. Re-examination of the field evidence given by Marshall has shown that this is not so, and the Basaltic and Phonolitic Eruptives mark two separate but possibly overlapping phases of volcanic activity.

Basaltic Eruptives: The basaltic rocks exhibit a wide variety of textures, occur as dikes, flows, and pyroclastics, and have a common basaltic composition. They could probably be subdivided into a number of lesser units, but much more field work would be necessary.

At present two major divisions are recognised, the Te Manga Group—rocks of the main cone structure, and the Avatiu Caldera Complex—rocks of the central caldera. A formation, the Pue Ash, is mapped within the Te Manga

Group. The Te Manga Group consists of olivine basalt, olivine-free basalt, limburgite, ankaramite, analcime basalt, separated most commonly by beds of rubbly scoria, red, brown, or yellow cinders, and ash, all invaded by few, steeply dipping dikes of basalt. Characteristic flow structures are present with dense strongly jointed rock having few or no vesicles, passing up through a more vesicular type to blacky scoriaceous material (aa lava) overlain by broken vesicular slag and true scoria.

The total thickness of the Te Manga Group is not less than the maximum height of the island (2,140 ft), and is merely the upper part of a very great pile of volcanic rocks rising more than 15,000 ft above the bed of the ocean. The angles of dip of the flows in Oroenga, Te Tanga, and at other places on the outer slopes of the island indicate that the original height (and thickness) before dissection and erosion by streams may have been at least 3,000 ft. At a still earlier stage in its history, before collapse of the centre of the volcano, the height may have been even greater.

The amount of erosion of the Te Manga rocks before the phonolitic eruptions was fairly considerable, but the cone probably did not reach the planeze stage (Kear, 1957) for there is no evidence of inversion of relief by the later eruptions. The difference in altitude between the highest Te Manga rocks of Te Manga and of Maungaroa is approximately 600 ft and this is believed to have been the order of variation in height of the former caldera rim.

The rocks of the Avatiu Caldera Complex are restricted to the central part of the island, where they form the lower slopes of the main divide from Maungaroa to Ikurangi, and the hill-flanks about Maungatea. They consist of much the same basaltic flows and pyroclastic rocks as those of the Te Manga Group, and in general chemical composition, degree of weathering, stability, and soil-forming characteristics are probably little different. Many were the upper correlatives of the Te Manga rocks before collapse of the centre of the cone to form the caldera. They are distinguished by their much more complicated faulted structure and by the presence of very numerous basalt dikes of all sizes. The rocks are olivine basalt, oceanite ankaramite, and alkali olivine basalt. The thickness of Avatiu rocks occurring above present sea level is approximately 1,100 ft. The more disturbed parts of the group have been so faulted and displaced by dikes rising from below, that they have lost most of their original structure although the beds still show their initial radial dips to some extent. The only generalisation possible is that they show consistent downward internal displacement towards a centre of collapse beneath Maungatea.

Phonolitic Eruptions: Two main divisions are recognised (intra-caldera and extra-caldera), partly on differences of composition and structure, and partly on distribution. The same sequence was observed in both divisions—flow rocks, explosion breccias, then further flows—and it seems likely that the corresponding rocks of each division were contemporaneous.

Phonolitic formations mapped outside the central caldera include the Muri flows—sodalite phonolite and possible soda trachyte occupying the south-east sector of the island and forming the lagoon islet of Taa Koka; the Te Kou Complex—an incompletely dissected cone complex of sodalite phonolite and trachytic flows and pyroclastics perched on the Avatiu caldera

rim; the Maungatapu Breccia—phonolitic breccia occupying a number of vents or conduits on the outer mountain slopes; and the Raemaru Flows—an extensive series of phonolites on the western side of the island. Formations inside the central caldera are the Tuakata Flows—a small area of phonolite south of Avarua; the Maungatea Breccia—phonolitic tuff and breccia occupying a dissected explosion conduit at Maungatea Bluff and near Ngatipa; and the Manureva Flows—a phonolitic cap restricted to the summit of Maungatea Hill in the centre of the caldera. In addition to phonolitic components, the breccias also include much angular basaltic debris derived from the Te Manga rocks in the walls of the conduits.

Age of the Volcanic Rocks: No internal evidence of age of the volcanic rocks was found, and the main evidence is that given by the degree of dissection. This is fairly considerable, is somewhat greater than that of Tahiti, less than that of Moorea (both high islands in the Society group), and is similar to that of Oahu (Hawaii), Tutuila Island, and the eastern part of Upolu Island of Samoa. The basaltic cone is entering the residual mountain stage of erosion described by Kear (1957) and in New Zealand would probably be considered late Pliocene. The phonolitic volcano forms (Te Kou and Maungatea) are incompletely dissected and are probably late Pliocene and early Pleistocene. Radiometric dates obtained by Tarling (1967) for samples of phonolitic rocks from Avatiu Valley and Black Rock, are 2.30 ± 0.24 m.y. and 2.80 ± 0.13 m.y. respectively. These correspond to late Pliocene, and are in accordance with the physiographic evidence.

Sedimentary Rocks

Two divisions of the coastal sedimentary deposits are the Nikao Gravels and Aroa Sands. Soils on the Nikao Gravels were divided into four types by Grange and Fox (1953), and show variations in weathering depending on whether they are on low terraces (younger Nikao), higher terraces (older Nikao), or fans. The Nikao and Tikioki Clay Loams of Grange and Fox occur on older fans and terraces, the Pouara and Matavera Clay Loams on the younger fans and terraces.

Both the older and younger Nikao Gravels were cliffed in places by marine erosion before deposition of the Aroa Sands (*see below*), and the older gravels were cut back either by the sea, or by stream erosion before deposition of the younger. They are obviously of different ages and, from the degree of weathering, are for the most part at least as old as the Last Glaciation (15,000+ years).

Although the upper sandy parts are generally the most conspicuous, the Aroa Sands include a variety of cemented and uncemented coralline sediments. The most prominent is cemented reef rock debris. It forms the rocky banks backing a few of the beaches but does not crop out everywhere. Much of the coral is definitely not in the position of growth but appears to have been debris similar to that accumulating on the present reef flats. Lithified beach rock also forms ledges and pavements on a few beaches, up to 5 ft above high tide level.

At Matavera, at Ngatangia, and the small islets to the south, a well preserved prominent ledge of older reef stands 10 ft above the present reef.

This appears to be a remnant of a formerly continuous reef that lay outside the Aroa Sands. A raised reef associated with Aroa Sands is found about 3 ft above low tide level opposite the U.I.T. Store, Avarua. Abundant corals apparently in growth positions seem to extend inland beneath beach sands lying 12–14 ft above high tide level and might represent an earlier sea level 3–5 ft above the present. A sample from this reef gave a radiocarbon date of 2,030 years (J. C. Schofield, pers. comm.).

At the east and west ends of the airfield, an old reef with corals in position of growth extends in eroded pinnacles up to 6 ft above low tide level. A radiocarbon date for this reef is 43,000 years (+) (J. C. Schofield, pers. comm.).

These occurrences of reef rock above sea level may be evidence for higher stands of the sea at 3 ft, 6 ft, and 10 ft, and the association with the Aroa Sands implies a post-glacial age for some of them. Corresponding levels were reported on the Australia coast by Fairbridge (1952) with an inferred age of 4,000 years for the oldest. A number have been described in New Zealand by Schofield, of which the oldest was 7 ft above present mean sea level 3,900 years ago (1960, p. 478).

However, further work in the field of radiometric dating of carbonate deposits has shown that many raised reefs are much older than previously thought, and at present the Rarotongan raised reefs can only be inferred to lie between late Pleistocene and Holocene.

Indistinct remnants of rock platforms occur at Black Rock, at 70–75 ft, 40 ft, 20 ft, and 3 ft above low tide level and probably mark several Pleistocene high sea levels. Beach ridges formed on Aroa Sands are common around Rarotonga, occur up to at least 25 ft above low tide level, and stand well above the obvious storm ridges that back the present beaches. Similar higher beach ridges have been attributed in some parts of the world to higher post-glacial stands of the sea, but on Rarotonga they are more probably deposits of hurricane seas and tsunamis (earthquake sea-waves). They are also present on others of the Cook Islands, particularly the atolls, and appear to have a common origin throughout the Group.

Mangaia

(21° 54' S, 157° 58' W)

The central volcanic hills of Mangaia, 3 miles in diameter, rise to a distinct common level at about 550 ft. Ridge crests near the highest point (Rangimotia, 554 ft) have wide gentle slopes or near-flat surfaces, in contrast to the steeper slopes of the valleys and the sharp crests of ridges further from the summit. The total area of flat surfaces is, however, very small compared to the area occupied by ridges with accordant crest levels, and although Marshall and others have described a Central Plateau (cut by marine erosion during high sea level), air photographs reveal only a small triangular residual area at Rangimotia, and several other small flat areas on ridge crests. Because so little of the old surface is preserved, the original form cannot definitely be designated a plateau, and may simply have been a very rounded, subdued hill rising above the shoreline at which the makatea reef grew.

Around the volcanic core, a series of irregular swampy depressions up to 1,200 ft wide lie along the inland base of a more or less continuous near-vertical limestone escarpment up to 200 ft high. Immediately below the escarpment where streams flow into the limestone, the swampy flats are 20 ft or less above sea level and they rise inland to heights of more than 40 ft in the stream valleys. All the streams on the island drain through underground channels and caves in the makatea. They flow close to present sea level, and many discharge at the coast as springs. The surface of Lake Tiriara is at sea level and sea water may be driven in through the outlet in stormy weather.

The stream and swamp deposits consist of fine sand, silt, and clay derived from the weathered volcanic hills, mixed with organic debris. In the taro swamps the material is grey in colour from prolonged waterlogging.

The inner cliff of the makatea is continuous for long distances but at a few places spurs of limestone lie against volcanic rock on the lower volcanic slopes. At the northern and eastern corners of the island, the eroded inner fringe of the makatea distinctly overlaps on to a rising surface of volcanic rocks. The basal contact undoubtedly resembles that seen on Atiu Island which is sharp, slightly irregular and underlain by deeply weathered yellow and red volcanic clays.

The upper surface of the makatea is an extremely intricate and rugged karrenfeld of eroded limestone, between the jagged 15 ft pinnacles of which are flat-lying pockets and larger areas of red volcanically derived lateritic soil. Inferred by Marshall to have been transported from the hills to the makatea by birds, the soil was more probably deposited in the pockets of the makatea by streams flowing from the volcanic centre. This is presently occurring on the makatea surrounding the volcanic hill of Takuae Foodland on Mitiaro Island.

The upper surface of the makatea of Mangaia rises to between 180 ft and 230 ft above sea level and has a number of raised marine-cut benches and cliffs on its outer parts. These are with few exceptions closely parallel to the coast. Benches formed by Pleistocene high sea levels occur at altitudes of 170–180 ft, 110–125 ft, 75 ft, 40–50 ft, 15 ft, and less obviously at 10 ft and 3–4 ft. These benches are in part cut into older reef limestone by each high stand of the sea, and in part built up and outward by increments of reefs that grew during the periods of warm climate of each eustatic high sea level. The inferred sequence of events leading to formation of these benches is set out in Table 1.

The deep weathering and scarcity of outcrops on the volcanic hills of Mangaia obscure most of the volcanic structure. The rocks are mainly basalt, commonly ankaramite; a few outcrops of fine-grained type occur on the south and western slopes of the central hills, and in the Vau Roa valley there is a coarsely porphyritic type. Both were described petrographically by Marshall (1927, p. 37). The Vau Roa stream crosses a dike of basalt just before reaching the taro flats, and there are undoubtedly many more dikes elsewhere forming the numerous rectilinear alignments of minor ridges crossing the sharp watershed crests and presenting a distinct appearance on aerial photographs.

The dense fine-grained limestone forming the makatea rarely shows details

Epoch and Age m.y. = millions, t.y. = thousands of years	Rarotonga	Mangala	Atiu	Nauka	Mitharo	Aitutaki	Atolls		
TERTIARY	Oligocene or older (30m.y.)	Extinct volcanoes, undergoing erosion					Extinct volcanoes slowly subsiding, with continuously growing platform reef crowns		
	Miocene (7-30 m.y.)	Basaltic eruptions	Subsidence of island and growth of platform reefs		40 ft(-)	Basaltic eruptions through reefs			
	Pliocene (2-7 m.y.)		230 ft (+)	235 ft(+)	90 ft(+)				
	Late Pliocene (ca.2 m.y.)	Phonolitic eruptions, landsliding	Probable uplift of islands with erosion commencing on upper parts of reef limestones			Phonolitic eruptions (?)			
	Early Pleist. (or Pliocene)		Continued subaerial erosion of emergent parts, becoming strongly differential on raised reef limestones as underlying volcanic hills emerged, to form makatea, and taro swamps.						
	Antepenultimate Interglacial								
PLEISTOCENE		800 ft ± 500 ft (?) bench-remnants	550 ft	235 ft plateau		250 ft (approx.) terrace (?)	Alternating erosion, and reef growth with changes of sea level, modifying platform reefs to atoll forms		
			230 ft level top of makatea						
			170-180 ft bench		90 ft plateau				
		Older Nikao Gravels	110-125 ft benches						
	Penultimate Interglacial			100 ft top of makatea (N.)		115 ft terrace			
Last Interglacial		Younger 75 ft (Nikao 40 ft) Gravels 20 ft	70 ft top of makatea (S.)	40 ft top of makatea	60-70 ft terrace	Erosion of lagoon floors to -200 ft and less			
		Buried 10 ft reef and some Atoll sands	40-50 ft bench	40 ft bench					
	(ca.110 t.y.)		15 ft reef and bench	15 ft bench	30 ft top of makatea		40 ft terrace		
HOLOCENE	Last Glaciation (100-6 t.y.)	Sea level lowered to probable maximum of -400 ft about 18,000 years ago, rose intermittently forming flights of submarine benches, known only at -60 ft on Rarotonga, but probably well-developed around most islands.					Erosion of older post-glacial		
	Post-glacial	Gradual rise of sea almost to present level at a diminishing rate; growth of coral reefs both on seaward edges and on upper surfaces; aggradation of larger stream mouths and taro swamps.							
	Late Holocene (3-0 t.y.)	Deposition of Atoll Sands on Rarotonga and similar deposits on other islands, limited marine planation eroding older post-glacial cemented beach deposits, continued reef growth around seaward edges of modern reef flats.							

TABLE 1—Tertiary and Later Events, Terraces, Benches, and Plateaus

of structure in hand-specimens, and much of it seems to be cemented coral sand. Analyses given by Marshall (1927, p. 29) show that it is a remarkably pure calcareous limestone, over 93% CaCO_3 , with virtually no magnesium carbonate, in contrast to dolomitic limestones of more northerly islands. This lack of dolomitisation may be due to the greater age (mid-Tertiary) of the main part of the makatea, and to the more southerly location of the island (almost 22° south), possibly beyond the southern limits of conditions favourable to dolomitisation in the Tertiary.

Fossils in the limestone include common calcareous algae such as *Lithothamnion*, *Lithophyllum*, *Halimeda*, and corals and encrusting foraminifera of the normal reef assemblage. Specimens collected by Marshall from the inner parts of the makatea contain *Lepidocyclus* (op. cit. 1927, p. 27, and confirmed by Mr N. de B. Hornibrook, N.Z. Geological Survey), which indicates a mid-Tertiary age; the outer parts contain no *Lepidocyclus* and are probably late Tertiary.

The low-level cliffs and benches around Mangaia are cut in Pleistocene reef rock, for corals *in situ* from two localities 6 ft above low tide level gave Th230 ages of $90,000 \pm 20,000$ years and $110,000 \pm 20,000$ years and a U234 age of $110,000 \pm 50,000$ years (Veeh, 1966). The localities are about 1,000 ft south of Oneroa landing in the low cliff adjacent to the beach and present reef flat.

Atiu

($19^\circ 59' \text{S}$, $158^\circ 06' \text{W}$)

Atiu is roughly quadrilateral in shape and about 4 miles long by $3\frac{1}{4}$ miles wide. It consists of a central, flat-topped hill of volcanic rock 235 ft high, incised by sharp-edge gullies and surrounded by a makatea over half a mile wide, 100 ft high. The volcanic rock is rarely found unweathered, is mainly tuff, basaltic breccia, and olivine basalt, and is commonly deeply weathered to a red clay containing limonitic nodules and black manganiferous veins up to 3 in. thick. The makatea has a convex surface standing generally about 70 ft above sea level and rising at the northern end of the island to 100 ft. The surface itself is rough and uneven with sink holes, caves, underground drainage, and many closely spaced craggy limestone pinnacles several feet high; along its inner edge is a mantle of red volcanic soil and pebbles making the pinnacled surface much less rough. Between the makatea and the central plateau is a well-defined topographic depression, occupied in part by narrow sinuous swamps about 600 ft in width and about 20–30 ft above sea level. Drainage from the plateau to the depression is radial; in their lower reaches the streams are fringed with narrow alluvial flats.

A fringing reef and an intertidal reef flat about 300 ft wide encircle the makatea. The reef is pierced in several places and these channels allow surf boats to pass through into the calmer waters of the reef flat.

Mitiaro

($19^\circ 51' \text{S}$, $157^\circ 43' \text{W}$)

Mitiaro is a low makatea-type island, roughly quadrilateral in shape, 4 miles long and almost 3 miles wide. Like Atiu and Mauke, it has a

makatea, swamp land, central volcanic core, and fringing reef but, whereas, the central volcanics of Mauke and Atiu consist of a single volcanic mass those of Mitiaro consist of four low-lying "islands" in an area of swamp land and lake. These "islands", known as the Atai and Auta Foodland, Taurangi Foodland, Mangarei Foodland, and Takaue Foodland, rise between 10 ft and 40 ft above sea level and consist of deeply weathered rock, probably basalt. Coral blocks lying on the highest parts of these "islands" and at the margins of the swamp lands surrounding them, indicate that the makatea originally covered the whole of Mitiaro, and that either the "islands" were originally separate masses, or that the dissection of a central mass into four hills preceded the formation of the makatea. The makatea is mainly about 20 ft above sea level, and reaches a maximum height of approximately 30 ft; it is about a quarter of a mile wide on the east, but reaches a width of half a mile on the north-west and south-west corners of the island.

The makatea, swamp land, and fringing reef are similar in origin and appearance to those of Atiu and Mauke. The surface of the makatea has more rounded pinnacles of limestone, almost no karrenfeld, and is much less rugged especially near Takaue Foodland, around which brown volcanic soil has spread.

A strong sulphurous smell at the locally named "Sulphur Spring" half a mile from Omutu Landing, is reminiscent of that from volcanic springs in New Zealand and suggests that some residual volcanic source may be involved. However, the probable late Tertiary age of the island renders this unlikely, nor is it supported by results of chemical analysis of the water.

Mauke

(20° 09' S, 157° 21' W)

Mauke Island is oval in plan with a central plateau 2 miles by $1\frac{1}{4}$ miles, surrounded by a makatea up to 1 mile wide. The makatea rises to 60 ft above sea level with indistinct benches at 15 ft and 40 ft and the plateau reaches 90 ft. The intervening swamp land between the makatea and the plateau is only irregularly developed and is confined in patches to the east, west, and north. A narrow fringing reef and reef flat encircles the makatea and is pierced in six places by passages. These passages, like the patches of swamp land, are confined to the north, east, and west.

Over the central plateau the volcanic rock, presumably basalt, has weathered to a red friable soil. Red and brown muddy sediments of the swampland are derived from the volcanic hillslopes nearby, as is the similar material lying in the crevices between limestone pinnacles on the surface of the inner part of the makatea.

At the north-east side of the central volcanic hill, the makatea limestone rests directly against volcanic rock, and partly encircles a small volcanic hill. The basal surface of the limestone was obscured by soil cover, but is obviously a surface of moderate relief on the weathered volcanic core. The relief was probably formed by normal subaerial erosion before subsidence of the volcanic foundation and growth and deposition of the coral. This would require a long period of time before submergence. The upper surface of the nearby

makatea continues across the top of this small outlier of limestone, and terminates against the slopes of the volcanic hill. It shows the former relationship between the rest of the makatea and the volcanic cone before erosion by limestone solution of the circular depression now occupied by swamp lands, and it confirms the mode of origin of the volcanic sediments lying on the makatea surface of this and similar islands.

Aitutaki

(18° 52' S, 159° 48' W)

Aitutaki consists of a low hilly volcanic island on a 'near atoll'. The reef, which is about 25 miles in circumference, is studded with 13 sand islands (motus). Within the lagoon are the volcanic islands of Aitutaki, Rapota, and Moturakau. Aitutaki is by far the largest, being 5 miles from north to south and $1\frac{3}{4}$ miles at its widest part from east to west. Flat terraces occupy most of it, but the north is comparatively steep, with Mount Maungapu (390 ft) on the western edge of a crater-like feature $\frac{3}{4}$ mile in diameter. Fairly extensive areas of coral sand adjoin the island in the north and south; elsewhere there is generally a narrow coastal strip.

The reef is very close to the volcanic island in the north, but to the south it flares away and in the south-east extremity it is as much as 5 miles away from the southernmost tip of the main island. Within the reef is a lagoon not of uniform depth and studded with coral heads.

Two main varieties of volcanic rocks are present—basic alkaline basalts as represented by weathered scoria and agglomerate of Tangorutu and Moturakau, and more highly alkaline and nepheline basalts as found at Maungapu, together with phonolite and trachyte of Rapota Island. Like those of Rarotonga, they probably represent two main phases and types of volcanic activity during build-up of the primitive island.

There is no makatea or raised reef on Aitutaki, but benches at 40 ft, 60–70 ft, 115 ft, and undoubtedly at 250 ft are veneered with much-weathered pebbly volcanic alluvium.

Beach deposits such as coral sand, partly cemented conglomerate, and lithified beach rock, form two levels 2–3 ft and 7–9 ft above high tide level around Aitutaki, but are in places eroded and removed by present seas. Shepard (1961) reports a raised reef 2 ft above sea level, but it was not found by the writer.

Coral heads are prominent in the leeward reef and the lagoon floor is thickly studded with coral knolls that show up as a pattern of fine dark spots on vertical air photographs. In the south-west, these coalesce to form a peculiar branching pattern of ridges. Submarine fans of coral sand occupy the south-east and south-west corners of the lagoon.

Manuae (or Hervey Islands)

(19° 15' S, 158° 55' W)

Manuae (29 ft high) and Auotu (or Te Au O Tu) are the names of the two islands on the only atoll in the Southern Group. A lagoon 2 miles in

diameter separates the two islets, and prominent sand spits extend from both islets into the lagoon. The islands consist of coral sand and rubble, with three or four low ridges parallel to the sea beaches, ledges, or flats of cemented coral rubble and lithified coral sand (beach rock), and low-lying flats and swamps underlain by shelly coral sand. Prominent ledges at 15 ft and 5 ft are probably not older than Holocene and the materials may have been thrown up by storm waves from present sea level.

Takutea

(19° 48' S, 158° 18' W)

Takutea is a small, oval uninhabited sand island elongated east-west, a little more than 1 mile long by $\frac{3}{4}$ mile across. It consists entirely of coral sand with lithified beach rock on the northern beach. Nowhere does the land rise more than 20 ft above high water level, and no indications were seen of coastal benches such as occur on some of the larger islands of the Cook Group.

The sand island is surrounded by an apparently living coral reef a short distance offshore, and this grows around a narrow elongated curved submarine ridge between depths of 18 and 60 ft, presumably also coral, which trends west-north-west.

GEOLOGY OF ISLANDS OF THE NORTHERN GROUP

Penrhyn (Tongareva)

(8° 59' S, 158° 02' W)

The lagoon of Penrhyn is about 108 square miles in extent (13 miles by 7) and is enclosed by 40 miles of reef.

The prominently concave outline of the reef, a result of Pleistocene sea sliding of the foundations of the atoll, has deep reef passages at the salients that may have formed by stream drainage during Pleistocene lowered sea levels.

Two long motus (islands) lie on the south-west side, but those on the south and east sides have been cut up by hurricane seas. Dark brown strongly cemented limestone probably of Pleistocene age forms craggy ledges up to 10 ft a.s.l. at Motu Kasi. It has been thrown up into great bouldery scrub-covered ridges along the western side of the airstrip, and is present on several of the north-eastern motus. On Paniko it is partly covered with an irregular slabby armour of probably younger beach conglomerate. Slabby boulder beaches extend around most of the atoll, extensive rubble tracts occur along the southern reef, and several swampy brackish lagoons are present on eastern and northern motus. These lagoons are partly due to shifting dune and beach sands enclosing hurricane-eroded embayments. Beach rock forms narrow pavements at many places but rarely lies above high tide level.

Rakahanga

(10° 02' S, 161° 05' W)

The rectangular atoll of Rakahanga has a small lagoon (2 miles by 1), almost completely encircled by islets totalling 1.6 square miles. The few passages are so shallow that they can barely be negotiated by canoe.

Wide sandy beaches lie along the north-east coast, but most of the west coast is either slabby boulder-beach, or rubble tract on a wide flat of beach rock overlying old reef rock at sea level. At the seaward edge, more than a mile of the rubble tract is bordered by seaward-dipping (15°–20°) ramp-like ridges 3.5 ft high of cemented beach conglomerate containing boulders up to 1 ft long. Along the shallow passage at Te Kainga, craggy undercut ledges overlie older reef rock at high tide level.

The width and continuity of the motus around the lagoon suggest that they are relatively long lived and stable, and probably most of the atoll is underlain at shallow depth by older Pleistocene reef rock. The lagoon possesses no coral heads at the surface, is virtually land-locked and obviously has poor circulation of sea water and unfavourable conditions for coral growth.

Manihiki

(10° 25' S, 161° 01' W)

Manihiki has a large triangular lagoon, 6½ miles by 5½, with no ship passages, and the two main motus are among the largest and oldest of the Northern Group. Tauhunu is underlain at the south end by yellow-brown phosphatic limestone probably of Pleistocene age, as is probably the other motu—Te Pae Roa Ngake e Tukao.

Three broad, shallow coastal re-entrants (probably formed by collapse of parts of the older reef foundations during the Pleistocene) have only very narrow reef flats with conglomerate ramparts. An eroded old reef at sea level (probably Pleistocene) extends underwater offshore from Tauhunu village and is eroded into lines of buttresses reaching to within 2 ft of low tide level. Further offshore the 9-ft-deep clefts merge into an irregular sandy floor about 20 ft deep, with eroded pinnacles and pedestals rising almost to sea level; towards the reef edge these are covered and often joined together by vigorous new coral to form a living reef. This shallow submarine erosion of the old reef probably occurred during a low stand of the sea at the end of the Pleistocene or beginning of the Holocene.

The bathymetry of the lagoon has been studied by Bullivant (1962), whose chart shows a system of ridges rising from a floor 180–240 ft deep in the central area, and a number of small islets scattered on the higher ridges.

The thickness of coral cover in the middle part of the motu Te Pae Roa Ngake e Tukao, was determined seismically by Hochstein (1967) to be only about 100–130 ft. A maximum thickness of about 1,470 ft was measured at the motu Atimoono and a similar thickness was inferred to underlie Tukao village.

Pukapuka

(10° 53' S, 165° 49' W)

The outline of the atoll of Pukapuka (also known as Danger Island) is more three-lobed than triangular, extends $6\frac{1}{2}$ miles by $6\frac{1}{2}$, and is probably a very shrunken remnant of a formerly larger structure that has been extensively reduced by collapse and sea-sliding of the foundations. The relatively small shallow lagoon has passages a few feet deep at the north-west end, but is otherwise inaccessible to boats. A long reef extends west for $3\frac{1}{2}$ miles from Motu Kotawa and has on its far end a treeless sand bank.

The three motus consist of unconsolidated coral debris, with coarse slabby boulders towards the outer coasts, finer coral fragments in the interior beneath the dark humic soil of the coconut plantations, and fine sand with, in places, a thin skin of carbonate cement along lagoon shores. A few wave-worn boulders and ledges of cemented beach conglomerate outcrop on the sea beach of Motu Kotawa, but are much more common on Pukapuka just south of Ngake Village where old reef rock of probable Pleistocene age rises irregularly to 2–3 ft above high tide level.

Palmerston

(18° 04' S, 163° 10' W)

The lagoon (6 miles by $4\frac{1}{2}$) is not accessible to sea-going ships, but, north of the village, several small tortuous passages across the reef allow access for boats. The reef outline possesses several broadly concave segments, the reefs of which probably grew on the edges of old scarps remaining from partial collapse of the foundations in sea-side. No old reef rock and almost no cemented deposits were found on Palmerston atoll, but, because of insufficient time, only the inhabited motu was visited. It consists of unconsolidated sand with slabby coral boulders around the seaward side, and a storm ridge of boulders up to 5 ft a.s.l. The lagoon has many uncharted coral banks and heads, and the motus are small and scattered widely on the reef. It seems probable that the atoll has had a greater land area in the past and has been eroded by hurricane seas.

Suvarrow

(13° 14' S, 163° 06' W)

The reef of Suvarrow (or Suvarov), $9\frac{1}{2}$ miles by 8, has three major concavities, to the north-east, south-east, and south-west respectively, each of which undoubtedly corresponds to an old sea-slide at depth.

The small number and small size of the motus on the atoll rim are due to severe damage from several major hurricanes in the past 100 years. Most damage seems to have resulted from one in 1942, when more than half the land area was washed away.

Achorage Island is the only motu that could be studied in the short time available; it consists of unconsolidated broken coral, gravel, and sand, with

a lagoon beach of fine coral sand, and small areas of strongly cemented beach rock. The seaward side consists of irregular pavements, slabs, and ledges of densely cemented beach conglomerate, resting a few feet above sea level, on an irregular surface on darker fossil reef rock probably of Pleistocene age.

Nassau

(11° 33' S, 165° 25' W)

The island closely resembles Takutea of the Southern Group, is 1 mile by $\frac{1}{2}$ mile, flat with a few beach ridges and dunes rising to about 30 ft, oval in outline, and surrounded by continuous sand and gravel beaches with a narrow reef flat. There are no breaks in the reef, and landings by canoe or boat are hazardous.

The interior of the island consists of coral sand and gravel, through which shallow wells have been dug to give a good dependable water supply. Beach rock forms sloping pavements at several places, and on the north coast seaward dipping beach rock and cemented conglomerate forms low ramparts.

SUMMARY OF THE GEOLOGICAL HISTORY

The Cook Islands are the summit portions of extinct volcanic mountains that rise more than 10,000 ft above the ocean floor; the highest is Penrhyn with a relief of over 16,000 ft. Details of early volcanic stages of all but Rarotonga are almost unknown; the occurrence of apparently normal sub-aerial flow rocks and tuffs shows that at least Rarotonga, Aitutaki, Mangaia, Mauke, and probably Atiu, once stood as volcanoes above sea level. The depths to the volcanic peaks beneath the coral of the atolls is unknown, but are probably within the range of 1,100–4,600 ft discovered by drilling on the atolls of Funafati (Ellice Islands) and Eniwetok (Marshall Islands) respectively. Although so far below sea level now, the volcanic mountains beneath the Northern Group atolls are also believed to have stood high above sea level during their eruptive phase; like a vast number of atolls, submerged seamounts, and guyots elsewhere in the Pacific, they were planed by marine erosion to a broad platform that slowly subsided and developed a thick crown of coral limestone and living reef.

The first eruptions of the Cook Island volcanoes are thought to have begun during the early Tertiary, and probably to have built the submarine mountains up to sea level during the Eocene and Oligocene. Some may not have remained for long above sea level (e.g., Northern Group atolls), but may have become extinct and begun subsiding during the Eocene, in accordance with the inferred subsidence of the Darwin Rise (Menard, 1864). There seems little doubt from similarities to other atolls such as Eniwetok, at which the coral capping has been deeply drilled, that the larger atolls of the Cook Group (Penrhyn, Manihiki, and Suvarrow) are underlain by limestone at least as old as Miocene (30 million years). The recently measured thickness of coral cover at Manihiki of 1,470 ft given by Hochstein (1967) allows an order-of-magnitude estimate of the age, using the average sinking

rate of several atolls and guyots of 1–1.6 km per 50 million years determined by Menard (1964, fig. 4.23). Although not necessarily a linear function of time, this rate implies that the age of the limestone at the base of the thickest measured section is 14–22 million years, that is, mid-Miocene.

The makatea islands are probably as old, and Mangaia in particular must have become extinct and commenced subsidence well before the Miocene, for much of its emergent makatea limestone includes Oligocene or Miocene foraminifera.

Distinctive features of the Cook Island volcanic rocks include:

(a) Highly alkaline undersaturated phonolites, and trachytes are associated with basic alkaline volcanic rocks, many of which tend towards ultramafic character by virtue of a high content of ferromagnesian minerals.

(b) On Rarotonga the basic members were the first group to be erupted and the youngest flows are nepheline-sodalite phonolites.

(c) The sodic nature of the trachytic differentiates is emphasised by the regular appearance of sodalite, nepheline, analcime, and anorthoclase, though potassium-rich feldspars are notably absent; even in the largest phenocrysts of zoned soda orthoclase the Or in the crystal cores is rarely in excess of 50%.

(d) The common occurrence of limburgites and particularly the widespread ankaramites may be an indication of the importance of crystal settling in the process of differentiation. Another feature of similar nature is the striking paucity of olivine-bearing basalts and the more common distribution of olivine-free basalts.

Terraces occur to some extent on all the islands of the Group, but no island has terraces at all the levels at which they are found throughout the Group. Possibly for this reason some observers have endeavoured to correlate between islands, terraces at different levels, and from the inferred change in height of correlated levels to deduce folding and tilting of the ocean floor (Marshall 1930, p. 7; Chubb, 1934).

There are no good grounds for regarding terraces and plateaus at differing heights on the different islands as the same age, but they can most satisfactorily be correlated with the sequence of eustatic high sea levels of the later Pleistocene. The presence or absence of terraces at any particular height depends on a number of factors relevant only to each particular island, the most important of which is probably the size of the island.

The volcanic history and subsequent erosion and reef development of the islands is summarised in Table 1 to show inferred correlations between events.

ACKNOWLEDGMENTS

The petrology of the volcanic rocks was described by Dr R. N. Brothers, University of Auckland; and additional information on some of the Pleistocene benches in the Southern Group was kindly supplied by Mr J. C. Schofield, New Zealand Geological Survey. Much assistance during field work was generously given to the writer by R. F. Hay and B. E. Skinner, by the officers of the Cook Islands Administration and the Survey Department, Rarotonga, and by numerous island hosts.

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