

Stratigraphy and Chronology of Late Pleistocene Reefs in the Southern Cook Islands, South Pacific

COLIN D. WOODROFFE

Department of Geography, University of Wollongong, Wollongong, New South Wales 2500, Australia

STEPHEN A. SHORT

Australian Nuclear Science and Technology Organisation, Lucas Heights, New South Wales 2234, Australia

DAVID R. STODDART

Department of Geography, University of California Berkeley, California 94720

TOM SPENCER

Department of Geography, University of Cambridge, Cambridge CB2 3EN, United Kingdom

AND

RUSSELL S. HARMON

NERC Isotope Geosciences Laboratory, Keyworth, NG12 5GG, United Kingdom

Received February 20, 1990

The Makatea Islands in the southern Cook Islands consist of a degraded volcanic core surrounded by emergent "makatea" limestones. While much of this reefal limestone is of Tertiary age, the seawardmost reefs are late Pleistocene. Last-interglacial reefs (oxygen isotope substage 5e) identified by U-series dating reach 12.2 m on Atiu (mean age of three samples $126,000 \pm 5000$ yr B.P.), 9.8 m on Mitiaro (mean age of five samples $119,000 \pm 3000$ yr B.P.), 10.0–12.7 m on Mauke (mean age of four samples $128,000 \pm 5000$, $-4,000$ yr B.P.), and 14.5–20.0 m on Mangaia (mean age of four samples $115,000 \pm 7000$ yr B.P.). On Atiu, Mauke, and Mitiaro a lower reef unit has been identified, and is separated from the overlying substage 5e reef by a sharp discontinuity, often with a crust of coralline algae. U-series dating from Atiu and Mauke indicates that this is a stage 7 reef formed in the penultimate interglaciation. The Makatea Islands have emerged as a result of flexure of the lithosphere in response to loading by the Pleistocene volcanic island of Rarotonga. Isolated outcrops of makatea limestone on Rarotonga reach 3.5 m and are probably of substage 5e age. Elastic and viscoelastic models of lithospheric flexure predict that much of the compensatory movement should occur shortly after the emplacement of the load. However, the age and elevation of late Quaternary reefs on the southern Cook Islands, where a Pleistocene volcanic island has loaded relatively old ocean floor (>80 myr), indicate that differential uplift has been continuing over the last 250,000 yr. © 1991 University of Washington.

INTRODUCTION

Oceanic islands have frequently been used as geological "dipsticks" to record past changes of sea level (Bloom, 1967). The most detailed interpretations of Quaternary sea-level fluctuations have been derived from flights of coral reef terraces on uplifted islands on tectonically active plate

margins (e.g., Barbados (Mesolella *et al.*, 1969); New Guinea (Bloom *et al.*, 1974; Chappell, 1974); Ryukyu Islands (Konishi *et al.*, 1974); Timor (Chappell and Veeh, 1978; Jouannic *et al.*, 1988); Haiti (Dodge *et al.*, 1983)). The rate of uplift of these shorelines has been determined by comparison of the height of a dated shoreline (usually the last interglaciation, oxygen isotope sub-

stage 5e) with the height of contemporaneous shorelines on mid-plate islands which were considered stable.

In a pioneering study on the application of uranium-series disequilibrium dating of corals on oceanic islands, Veeh (1966) demonstrated that limestones of last-interglacial age (ca. 120,000 yr B.P.) reach several meters above present sea level on a number of mid-plate islands. These observations have subsequently been used to support a widely held belief that global sea level at the peak of the last interglaciation was about 6–7 m above its present level.

However, it is now clear that few, if any, mid-plate oceanic islands, and little of the ocean floor, can be considered stable over geological time (Menard, 1986; Marty and Cazenave, 1989). The dominant trend is one of subsidence. Darwin proposed a theory of coral reef development linking together fringing reefs, barrier reefs, and coral atolls into an evolutionary sequence that he envisaged to be driven by the processes of gradual subsidence of the volcanic basement and vertical reef growth (Darwin, 1842). This picture of reef development was essentially confirmed by deep drilling which encountered basalts at depths of up to 1400 m below sea level on several atolls in the Pacific (i.e., Eniwetok (Ladd *et al.*, 1953); Mururoa (Lalou *et al.*, 1966)). More recently a further mechanism for subsidence has been proposed in association with plate tectonics. Oceanic lithospheric plates cool and contract with age and distance from the mid-ocean ridge (Parsons and Sclater, 1977). Consequently plate motion results in the movement of islands into progressively deeper water (Scott and Rotondo, 1983). Linear chains of islands, such as the Hawaiian-Emperor seamount chain, generated over hotspots, demonstrate in lateral succession the various stages in the classic Darwinian sequence (Grigg and Epp, 1989).

While subsidence is the dominant trend, there is evidence that several oceanic islands have undergone uplift. McNutt and

Menard (1978) pointed out that many uplifted mid-plate islands, known as “Makatea Islands,” are located in close proximity to young (Pleistocene) volcanic islands. They attributed emergence of these islands to their position on the uplifted arch resulting from regional lithospheric flexure in compensation of the mass of the young volcanic island. These authors also drew attention to the fact that many of the islands, from which Veeh (1966) had dated emergent reefs of last interglacial age, appear to be located on such an uplifted arch (i.e., Oahu in the Hawaiian Islands, Makatea in French Polynesia, and Mangaia in the Cook Islands).

In this paper we examine late Pleistocene reefal limestones on the Makatea Islands of the southern Cook Islands (Atiu, Mitiaro, Mauke, and Mangaia). Geological accounts of Mangaia and Atiu were published by Marshall (1927, 1930), and more recent descriptions of the entire Cook Island group were made by Wood and Hay (1970). We have undertaken detailed topographic surveys of each of the four Makatea Islands in the southern Cooks, Mangaia (Stoddart *et al.*, 1985), Atiu, Mitiaro, and Mauke (Stoddart *et al.*, 1990). We concentrate upon recognition of individual reef units within the late Pleistocene makatea limestones, and dating of corals from them by U-series disequilibrium dating. We demonstrate variability in the elevation of contemporaneous reefs on each of the islands, implying that differential movement of the islands has been continuing over the last 250,000 years. These results in turn place major constraints upon geophysical modeling of properties of the lithosphere.

THE SOUTHERN COOK ISLANDS

The southern Cook Islands include Rarotonga, a dissected young volcanic island rising to 653 m; Aitutaki, an almost-atoll with a residual volcanic island 124 m high to the north of the lagoon; Takutea, a large isolated sand cay; Manuae, a small

atoll comprising two sandy islands; and four Makatea Islands, Atiu, Mitiaro, Mauke, and Mangaia (Fig. 1). Makatea Islands, named after Makatea in French Polynesia, generally consist of a degraded volcanic interior of Cenozoic age, partially or entirely surrounded by highly karstified and dissected Cenozoic reefal limestones, known as "makatea." The volcanic core and the peripheral limestones are often separated by swampy footslopes and swamp-filled depressions. The emergence of the reefal limestones, often tens of meters above present sea level, indicates past uplift, and these islands have posed a particular problem in the interpretation of coral

reef development. Mangaia in the southern Cook Islands is one Makatea Island that has received particular attention in the literature. Marshall (1927, 1930) and Davis (1928) considered that the depression between the volcanic and limestone units represented preservation of the constructional form of an uplifted barrier reef. Hoffmeister and Ladd (1935) challenged this constructional view of the topography and proposed that it was an erosional topography, with an inland cliff of limestone undergoing retreat through karst erosion, a view recently confirmed by Stoddart *et al.* (1985).

The southern islands of the Cook Islands rise from a sea floor more than 4000 m deep

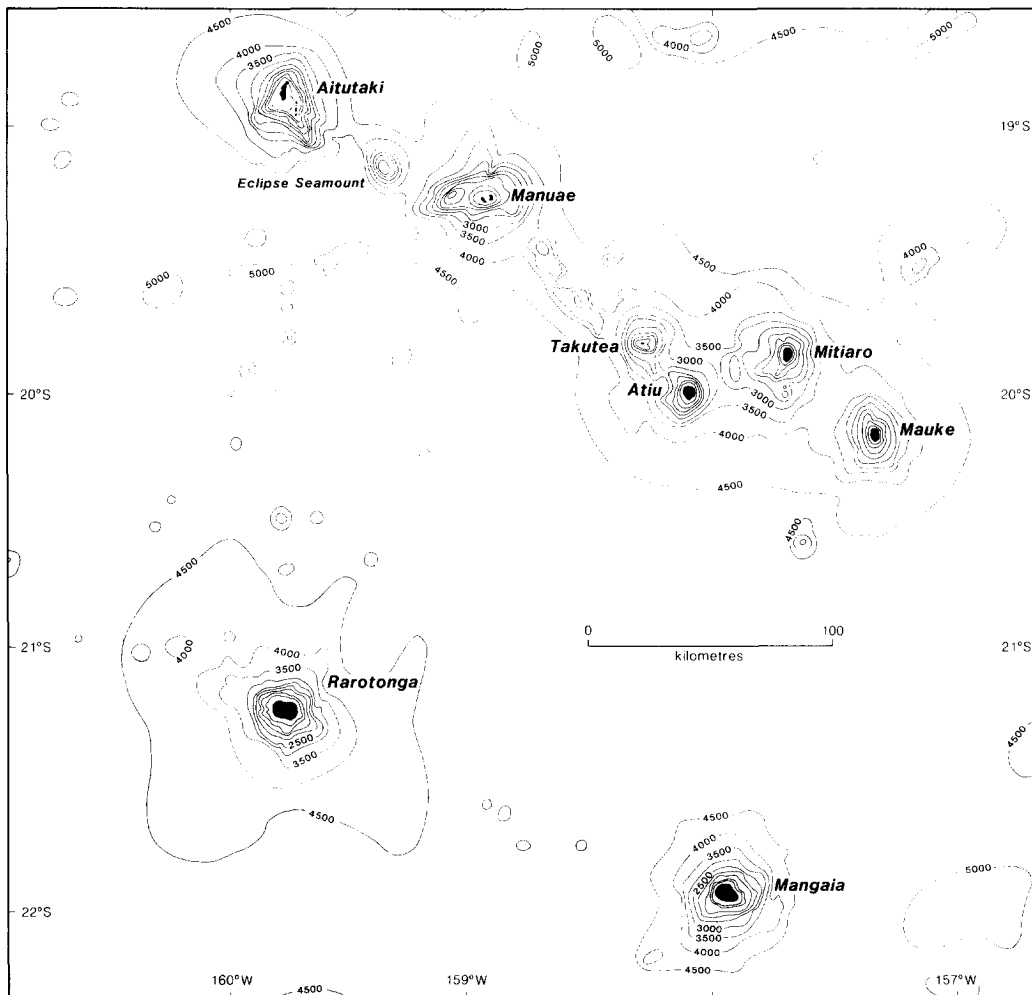


FIG. 1. Map showing bathymetry of southern Cook Islands (depth in meters).

(Fig. 1), estimated to be more than 80 myr old (Calmant and Cazenave, 1986), and form part of two linear chains that continue through the Austral Islands. Both island groups fall within the region of low elastic thickness lithosphere between 10 and 30° S and 120 and 160° W (Calmant and Cazenave, 1987) related to large-scale patterns of mantle convection (Cazenave *et al.*, 1989). These linear chains appear to have developed over hot spots in the vicinity of MacDonald Seamount. However, within the southern Cooks, only Mangaia, on which volcanism has been K–Ar dated at 18.9–16.6 myr (Dalrymple *et al.*, 1975; Turner and Jarrard, 1982), is consistent with such propagation (Jarrard and Clague, 1977; Stoddart and Spencer, 1987). Dates on basalts of 10–8 myr on Atiu, >6.0 myr on Mauke, and >12.3 myr on Mitiaro are considerably younger than would be expected. Rarotonga is formed largely of Pleistocene volcanic rocks formed 2.8–1.2 myr ago.

McNutt and Menard (1978) proposed that the uplift of the Makatea Islands in the southern Cook Islands occurred as a flexural response to loading of the ocean floor by Rarotonga, Aitutaki, and Manuae. While lithospheric flexure in response to volcanic loading has become widely recognized, the exact modeling of the compensatory uplift is compounded because flexure is a function of (a) the density distribution of the load, (b) the degree of moat in-fill, and (c) the (age-related) rigidity of the lithosphere. Details of the flexural response, particularly in the southern Cook Islands, have been the subject of several controversial revisions (Jarrard and Turner, 1979; Lambeck, 1981a, 1981b; Spencer *et al.*, 1987, 1988).

The limestones comprising the makatea on the Makatea Islands are shallow water reefal limestones. The upper surface has been eroded into tortuous pinnacles. Near-vertical cliffs dominate the seaward margin of each of the islands, and the landward margin is typically also a vertical cliff with

swampy water undercutting the base of the cliff in many places. There are extensive cave systems, particularly on the higher islands of Mangaia and Atiu (Marshall, 1927, 1930).

METHODS

Islands in the southern Cook Islands have been visited by several of us on a number of occasions since 1969. Topographic surveys of coastal morphology have been undertaken using a Kern automatic level. Surveys have been related where possible to the ordinary crests of the algal rim of the fringing reef. This level corresponds closely with the upper limit to coral growth on the reef flat and the lower limit of sand in pocket beaches, and is approximately mean low water (Stoddart *et al.*, 1990). Tidal range is approximately 80 cm for each island.

A number of coral samples were collected from Pleistocene reefs. Samples which could clearly be seen to be in their position of growth were sampled preferentially. Visual examination revealed that many of the fossil corals contained calcite crystals implying recrystallization and many samples were rejected on this basis. Mineralogy of samples thought potentially datable was determined by X-ray diffraction, and thin-sections of selected samples were also prepared. Only corals comprising 98% or more of aragonite were selected for U-series dating after ultrasonic cleaning (Table 1). Corals from Mangaia were dated at Southern Methodist University; these dates (Table 1) have already been reported separately by Spencer *et al.* (1988). Corals from Atiu, Mitiaro, and Mauke were dated at the Environmental Laboratory, Australian Nuclear Science and Technology Organisation. Samples were powdered and ultrasonically dispersed in water to which ^{236}U and ^{229}Th tracers had been added. Dissolution was effected by slowly adding nitric acid (under ultrasonic agitation) until a stable pH <2 was obtained. The solution was then boiled with a little 30% hydrogen

TABLE 1. SAMPLE MATERIAL, ELEVATION, AND U-SERIES AGES (± 1 STANDARD DEVIATION BASED ON COUNTING STATISTICS ONLY), SOUTHERN COOK ISLANDS

Sample no.	Material	Elevation (m)	Location	Aragonite (%)	Stratigraphic detail	Lab no.	U (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{234}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	Age (10^3 yr B.P.)
Atiu											
AT1	Coralline algae	2.65	Matai Landing		Encrusting surface of lower unit	LH 0717	0.49 $\pm$ 0.02	1.11 $\pm$ 0.05	0.869 $\pm$ 0.045	38.5 $\pm$ 8.4	205 $\pm$ 26, -22
AT2	Massive coral	c2.0	Matai Landing	>99	<i>In situ</i> in lower reef	LH 0635	3.64 $\pm$ 0.07	1.11 $\pm$ 0.02	0.839 $\pm$ 0.023	553 $\pm$ 139	187 $\pm$ 12, -11
AT8	<i>Porites</i>	<2.7	Taukaroa	>99	<i>In situ</i> on erosional bench	LH 0644	2.63 $\pm$ 0.08	1.07 $\pm$ 0.03	0.712 $\pm$ 0.029	722 $\pm$ 418	224 $\pm$ 21, -18
						LH 0644'	2.57 $\pm$ 0.07	1.17 $\pm$ 0.04	0.654 $\pm$ 0.026		132 $\pm$ 10, -9
											111 $\pm$ 7
AT9	<i>Porites</i>	>2.7	Taukaroa	>98	Encrusting upper unit	LH 0640	2.78 $\pm$ 0.08	1.06 $\pm$ 0.03	0.717 $\pm$ 0.030	457 $\pm$ 205	135 $\pm$ 10
						LH 0640'	2.78 $\pm$ 0.09	1.03 $\pm$ 0.03	0.756 $\pm$ 0.031		151 $\pm$ 12, -11
AT11	Massive coral	10-12	Beside airstrip	>99	<i>In situ</i> on cliff top	LH 0632	2.64 $\pm$ 0.06	1.13 $\pm$ 0.02	0.651 $\pm$ 0.023	280 $\pm$ 78	111 $\pm$ 6
						LH 0632'	2.64 $\pm$ 0.11	1.12 $\pm$ 0.04	0.657 $\pm$ 0.031		113 $\pm$ 9, -8
Mitiaro											
MT1	Faviid	>4	Te Unu	>99	<i>In situ</i> in upper unit	LH 0634	2.43 $\pm$ 0.06	1.16 $\pm$ 0.03	0.708 $\pm$ 0.022	126 $\pm$ 22	128 $\pm$ 6
						LH 0634'	2.24 $\pm$ 0.07	1.12 $\pm$ 0.04	0.738 $\pm$ 0.031		140 $\pm$ 10, -9
						HAR 6235	2.48 $\pm$ 0.05	1.06 $\pm$ 0.02	0.600 $\pm$ 0.020	>1000	98.1 $\pm$ 5.4, -5.1
MT2	Faviid	<4	Te Unu	>99	<i>In situ</i> in top of lower unit	LH 0639	2.26 $\pm$ 0.06	1.13 $\pm$ 0.03	0.652 $\pm$ 0.026	312 $\pm$ 111	112 $\pm$ 7
						LH 0639'	2.25 $\pm$ 0.07	1.14 $\pm$ 0.04	0.719 $\pm$ 0.030		132 $\pm$ 9
MT9	<i>Plesiastrea</i>	>4	North Coast	>98	Inverted in groove	LH 0647	2.35 $\pm$ 0.04	1.14 $\pm$ 0.02	0.682 $\pm$ 0.020	392 $\pm$ 196	120 $\pm$ 6
						LH 0647'	2.42 $\pm$ 0.07	1.10 $\pm$ 0.04	0.713 $\pm$ 0.028		132 $\pm$ 9, -8
MT13	<i>Porites</i>	>2	Village	>99	Encrusting upper unit	LH 0642	2.55 $\pm$ 0.06	1.16 $\pm$ 0.03	0.669 $\pm$ 0.028	362 $\pm$ 181	116 $\pm$ 8
						LH 0642'	2.55 $\pm$ 0.08	1.08 $\pm$ 0.03	0.745 $\pm$ 0.026		144 $\pm$ 9, -8
						HAR 6237	2.64 $\pm$ 0.05	1.13 $\pm$ 0.02	0.634 $\pm$ 0.019	>1000	106.3 $\pm$ 5.4, -5.1
MT15	<i>Porites</i>	>3	Vaikoua	>98	<i>In situ</i> in upper unit	LH 0643	2.55 $\pm$ 0.08	1.08 $\pm$ 0.03	0.670 $\pm$ 0.025	768 $\pm$ 543	118 $\pm$ 7
						LH 0643'	2.55 $\pm$ 0.08	1.08 $\pm$ 0.04	0.670 $\pm$ 0.025		118 $\pm$ 7

MK6	Favid	c1	Utua	>99	<i>In situ</i> in lower unit	Mauke	LH 0636	2.63 ± 0.06	1.08 ± 0.03	0.877 ± 0.026	231 ± 41	215 ± 15, -13
							LH 0636'	2.64 ± 0.10	0.96 ± 0.04	0.900 ± 0.045	>1000	261 ± 52, -37
							HAR 6236	2.44 ± 0.05	1.11 ± 0.02	0.740 ± 0.023		141.3 ± 9.2, -8.5
MK9	<i>Porites</i>	7-8	Anaaura	>98	From perched reef block		LH 0645	2.65 ± 0.07	1.07 ± 0.02	0.722 ± 0.028	562 ± 325	136 ± 10, -9
							LH 0645'	2.65 ± 0.07	1.06 ± 0.03	0.727 ± 0.028		138 ± 10, -9
MK10	Favid	c1.5	Aanga	>99	<i>In situ</i> in lower unit		LH 0641	2.56 ± 0.07	1.06 ± 0.03	0.857 ± 0.031	1740 ± 1230	204 ± 19, -17
							LH 0641'	2.54 ± 0.07	1.07 ± 0.03	0.785 ± 0.030		162 ± 12, -11
MK14	Favid	<2	South of Taunganui	>99	<i>In situ</i> in lower unit		LH 0633	2.44 ± 0.06	1.10 ± 0.03	0.914 ± 0.031	666 ± 272	243 ± 24, -20
							LH 0633'	2.44 ± 0.10	1.09 ± 0.04	0.842 ± 0.036		190 ± 19, -17
							HAR 6238	2.41 ± 0.05	1.10 ± 0.02	0.828 ± 0.025	>1000	181.2 ± 14.6, -13.0
MK15	Encrusting coral	>2	South of Taunganui	>98	Encrusting upper unit		LH 0637	2.79 ± 0.06	1.15 ± 0.02	0.690 ± 0.025	1250 ± 890	123 ± 8, -7
							LH 0637'	2.80 ± 0.08	1.10 ± 0.03	0.731 ± 0.034		138 ± 12, -11
MK16	<i>Porites</i>	5	South of Taunganui	>99	Encrusting upper unit		LH 0638	2.51 ± 0.07	1.04 ± 0.03	0.717 ± 0.032	404 ± 203	136 ± 11
							LH 0638'	2.54 ± 0.06	1.09 ± 0.02	0.748 ± 0.026		145 ± 10, -9
MK18	<i>Porites</i>	6	South of Taunganui	>98	Boulder in upper unit		LH 0646	2.81 ± 0.08	1.11 ± 0.02	0.675 ± 0.026	600 ± 146	119 ± 8, -7
							LH 0646'	2.87 ± 0.08	1.09 ± 0.03	0.674 ± 0.026		119 ± 7
							Mangaia					
M2	<i>Porites</i>	15		>99	Encrusting wall of groove		SMU	2.5	1.106 ± 0.051	0.671 ± 0.043	1683	118 ± 12
M3	<i>Porites</i>	11	North of Karanga	>99	Encrusting wall of groove		SMU	2.4	1.085 ± 0.053	0.624 ± 0.062	331	107 ± 18
M47	<i>Porites</i>	3		>99	Encrusting wall of groove		SMU	2.8	1.091 ± 0.034	0.610 ± 0.041	109	101 ± 12
M54	<i>Porites</i>	13		>99	Encrusting wall of groove		SMU	2.3	1.136 ± 0.042	0.738 ± 0.052	26	135 ± 15

peroxide to oxidize organics and U and Th isotopes collected by coprecipitation on an iron hydroxide precipitate at pH 7–9. U and Th fractions were purified by several anion exchange column separations before electrodeposition onto mirror-finish stainless planchets for high-resolution alpha spectrometry.

Four check samples (MT1, MT13, MK6, and MK14) were analyzed in duplicate at ANSTO (LH 0634 and 0634', 0642 and 0642', 0636 and 0636', 0633 and 0633' in Table 1). They were also dated by M. Ivanovich at the Harwell Laboratory (HAR6235-6238 in Table 1). These check dates did not agree as closely as we had hoped. In particular, sample MK6 yielded a considerably younger age when dated at Harwell, than when dated in duplicate at Lucas Heights. There appears to be no field attribute which can explain the degree of variability which was observed between some Lucas Heights duplicates and between the two different laboratories. Thin sections revealed little or no contamination in the corals dated. A trace of acicular cements was seen in the older samples (MK14 and MK6), and some blocky calcite was also found infilling pores in AT2. We believe that some degree of short-range variability may be ascribed to disturbances of the isotopic systems during early diagenesis, as has been seen in other recent detailed U-series dating programs on interglacial corals (Ku *et al.*, 1990). In interpreting the dates in Table 1 we have used the complete suite of Lucas Heights analyses (LH0632-0647), on the basis of which, together with stratigraphic setting, we believe we can unambiguously ascribe corals to individual interglacial oxygen isotope stages.

LATE PLEISTOCENE LIMESTONES

Atiu

The degraded volcanic interior of Atiu reaches a maximum elevation of 72 m; basalt is not exposed, but the rounded slopes

are veneered by deep red weathered soils. Makatea limestones have an average width of 1100 m, and rise up to at least 22.1 m; on the 1:7920 photogrammetrically produced topographic map (Hunt, 1969) there are several spot heights of 23 m. The makatea limestones are highest to the northwest and to the east, but rarely rise above 15 m in the south and southeast of the island. Seaward cliffs, 6 m high or more occur around most of the island. Landward cliffs to the makatea reach a maximum height of 20 m at Kurekure. The upper surface of the makatea has local labyrinth karst with a relief of 4–5 m, and with isolated pinnacles up to 6 m high. There are caves 500 m long or more through the limestone, with abundant flowstone and speleothems. Around the perimeter of the island there is a reef flat, generally 90 m wide or more; this is absent on the northern shore and is replaced by a surf bench cut into the base of the cliff (Fig. 2).

William Anderson, ship's surgeon on Cook's voyage in 1777, commented on the freshness of corals in the limestones of the seaward cliffs of Atiu (Beaglehole, 1967, p. 842). Marshall observed that, whereas the inland makatea limestones on Atiu were dolomitized, those on the coast were still composed of aragonite and calcite (Marshall, 1930). He suggested, on the basis of the absence of *Lepidocyclus* (foraminifera), that the limestones were Pliocene and younger in age, but did not realize the significance of the mineralogical trends, namely that there were a series of late Pleistocene reef units plastered onto the older makatea limestones.

It is not always possible in the field to differentiate late Pleistocene reef limestones from the older makatea because of similarities in composition, and presumably because the older makatea limestones have themselves developed through the superincumbent lateral addition of reef units through the early and middle Pleistocene. The contact between the late Pleistocene and the older limestones is often veneered by surficial sands. However, for several

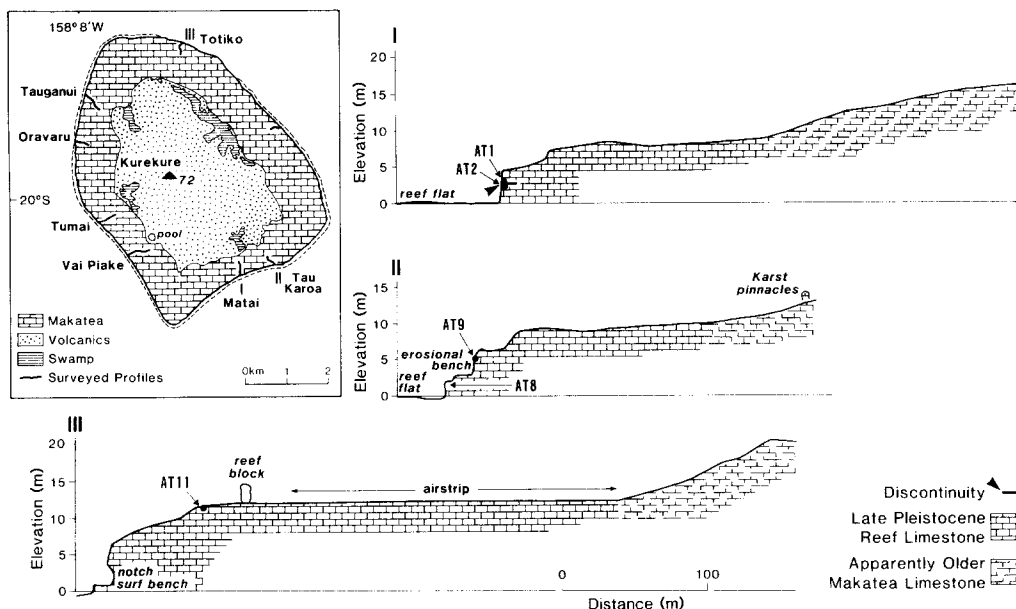


FIG. 2. Map of Atiu, showing selected profiles and location of samples dated.

profiles on Atiu the contact appears to coincide with the landward edge of a slight topographic bench. This occurs at an elevation of 8.6 m to the south at Matai, 10 m to the southwest at Tumai and Vai Piake, and 12.2 m to the north at Totiko (Stoddart *et al.*, 1990).

Within the late Pleistocene limestones, two units can be discriminated: a lower *in situ* reef and an upper coral rubble unit. A discontinuity between the lower and upper unit, though not as clearly marked as on Mitiaro and Mauke, was observed at 2.65 m at Matai and 1.76 m at Oravaru.

Lower unit. The lower unit consists of a reef in which corals are found in growth position. Massive corals dominate, particularly faviid corals, with lesser finer-branching corals, *Halimeda*, and molluscan fragments as infill. At Matai the lower unit is veneered by a crust of calcareous algae. A massive coral from this lower unit at Matai (AT2, in which there is some blocky calcite detectable in thin-section) has been dated $187,000 \pm 12,000$, $-11,000$ yr B.P. (Table 1; profile I, Fig. 2). A sample of the algal material (AT1), though with considerably lower uranium content, has been dated

$205,000 \pm 26,000$, $-22,000$ yr B.P. These ages imply that this reef grew during oxygen isotope stage 7.

An intermediate sand unit is found separating the upper and lower unit at a few isolated places on the coast of Atiu, i.e., north of Taunganui landing and at Oravaru. Sands are bedded, dipping principally seaward, but occasionally landward, sometimes with beds distinctly truncated. Vertical columnar structures up to 3 cm wide, interpreted as burrows, were observed at Taunganui. *Halimeda* blades up to 8 mm in diameter suggest that this is a bedded beach, rather than dune, deposit. The sand unit overlies an *in situ* reef deposit, interpreted as the lower unit, at Oravaru.

Upper unit. The upper unit on Atiu is usually composed of disoriented coral boulders. *In situ* corals are rare, although some large heads of *Porites*, and some encrusting corals, especially those in grooves, are preserved in what is probably growth position. Several *in situ* corals from the surface of the upper unit were sampled for dating. No material free of recrystallization, and therefore datable, could be found in the upper unit at Matai. At Taukaroa a slight bench is dis-

cernible at a height of 2.78 m; an *in situ* *Porites* (AT8) from within this bench dated $132,000 \pm 10,000$, $-9,000$ yr B.P., whereas in the limestone above this bench a second coral (AT9) dated $135,000 \pm 10,000$ yr B.P. (profile II, Fig. 2). The erosional bench thus appears to be eroded into a reef that was formed during the last interglaciation (oxygen isotope substage 5e). Corals clearly in growth position on the clifftop to the north of the island, and the highest such *in situ* corals seen on the island, at an elevation of 10–12 m (AT11), have been dated at $111,000 \pm 6000$ yr B.P. (profile III, Fig. 2).

The outer makatea has conspicuous groove and spur patterns around its cliffed coastline. Grooves are typically 6–8 m across and run tens of meters inland, occasionally ending in enclosed depressions or blind gullies. The inner walls of grooves are encrusted by fossil platy corals. These groove and spur patterns appear to run

through both the lower unit (stage 7) and the upper unit (substage 5e).

Mitiaro

Mitiaro is the lowest lying of the makatea islands in the southern Cook Islands. It is surrounded by a fringing reef; the reef flat is up to 120 m wide, with much of it emergent at low tide, in places reaching up to 1.23 m above mean low water (Woodroffe *et al.*, 1990). In the center of the island is a swamp, with a shallow lake (Te Rotonui) at the eastern end (Fig. 3). There are four degraded volcanic outcrops in the center of the island, locally termed “foodlands,” rising to elevations of 4–9 m and covered by deeply weathered red and brown clays. The highest point (10.9 m) observed by us on the island is on the makatea between Omutu and Atai on the east of the island (Stoddart *et al.*, 1990). Late Pleistocene reefs can be seen around the coast; a lower and an

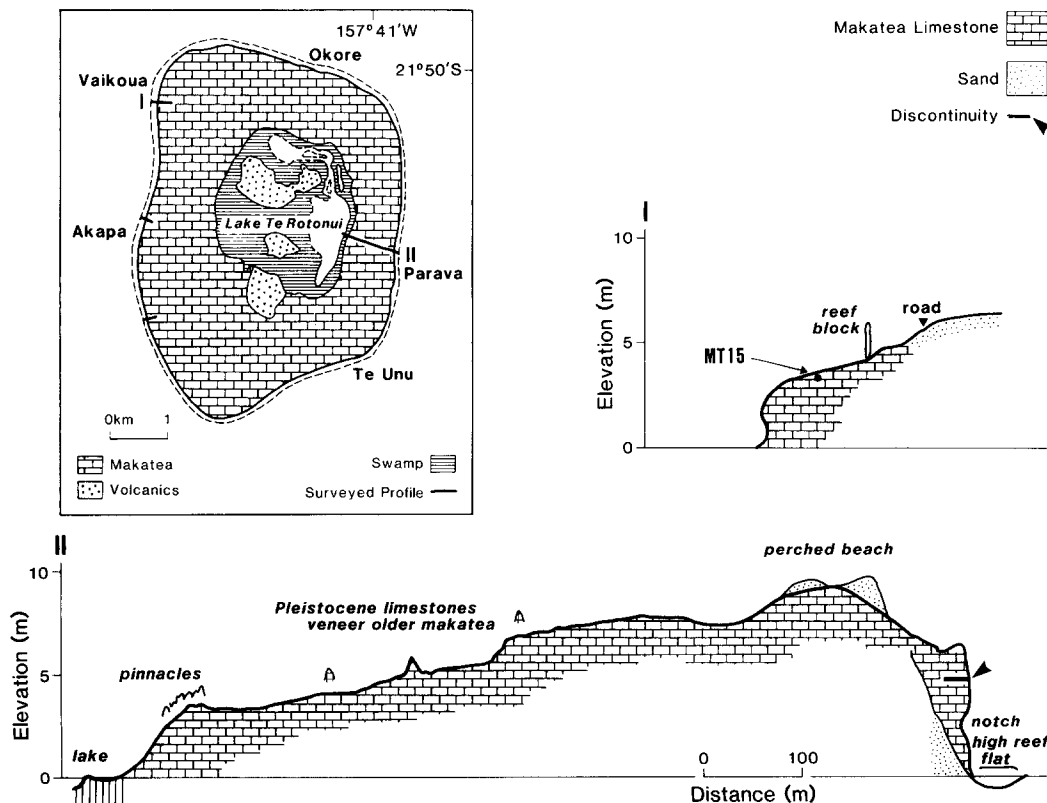


FIG. 3. Map of Mitiaro, showing selected profiles and location of samples dated.

upper unit are discernible, separated by a sharp discontinuity. The Pleistocene limestones, though not always clearly differentiable from older makatea, were observed up to 9 m in the Parava area, with one outcrop up to 9.8 m. The discontinuity is often subhorizontal and the lower unit has a smooth upper surface, without the pronounced karstification so characteristic of much of the modern limestone surface. On occasion, a calcareous algal crust is associated with the discontinuity. Corals, particularly faviid corals, *Fungia* and *Porites*, are found in growth position within both upper and lower unit.

There is a pronounced groove and spur pattern, similar to that on Atiu around the coast. The Pleistocene grooves appear to be far more widely spaced than are equivalent ones on the modern reef flat and reef front. Grooves also continue through the upper unit down into the lower unit, and contain encrusting corals flanking their interior walls. A number of large reef blocks, up to 2 m high, are perched on top of the limestone cliffs.

Corals from the lower unit are especially recrystallized on Mitiaro. Two samples of faviid corals were collected at Te Unu, one from above (MT1) and one apparently from below (MT2) the discontinuity. The upper sample dates to $128,000 \pm 6000$ yr B.P., while the lower gave a date of $112,000 \pm 7000$ yr B.P. Both ages appear to belong to oxygen isotope stage 5. The sample from the lower unit (MT2) was at the top of that unit, right at the contact. In view of its age, it is interpreted as coral growing on the surface of the lower unit during the substage 5e sea-level high, but not having been a part of the earlier reef. All other U-series dates from this island are very similar; they include an *in situ* coral from within the upper unit (MT15) with an age of $118,000 \pm 7000$ yr B.P. (profile I, Fig. 3); a *Porites* encrusting the upper unit (MT13) dated at $116,000 \pm 8000$ yr B.P.; and an inverted surficial coral from within a shallow groove on the upper surface of the upper unit (MT9)

which has an age of $120,000 \pm 6000$ yr B.P. Fields of acroporiid corals form a shallow veneer over older makatea in several places on Mitiaro. This is shown in profile II (Fig. 3) where such corals occur on the older limestone. It implies that the upper unit was laid down when much of the surface of the makatea was inundated beneath a sea level at least 9 m above the present; little if any of the island would have been above water at that time, and such a stand of sea level may have truncated part of the upper surface of the makatea.

The discontinuity between upper and lower units at Parava on the east coast occurs at 5–6 m, and at Okore on the northeast coast it occurs at 4.1–4.7 m. Several coastal features apparently are related to a higher sea level around the island. Much of the modern reef flat is emergent at low water because it is inherited from a reef flat that formed up to 1.2 m above the present one over an interval of at least 5140–3620 yr B.P. (Woodroffe *et al.*, 1990). Several samples were taken from the present intertidal bench, which were thought to relate to Holocene higher sea levels, but which gave Pleistocene radiocarbon ages. A microatoll on the inner reef flat on the north coast was dated $34,050 \pm 1740$ yr B.P., and a *Tridacna* from Akapa on the west coast gave an age of $32,780 \pm 1120$, – 1050 yr B.P.

Mauke

The volcanic core of this island rises up to an elevation of 24.4 m, and the makatea limestone forms a marginal feature 0.8–1.6 km wide around the island (Fig. 4). The makatea limestones rise up to 10 m around much of the island, reaching 8.1–8.7 m in the south, 9.5 m in the northwest, and 9.6–10.0 m on the eastern side; a maximum of 14.7 m was observed at Uriaata to the northeast (Stoddart *et al.*, 1990). Much of the surface of the older makatea is also at 8–10 m, and may have been bevelled during the same late Pleistocene sea-level stand as deposited the reef. The reef flat around Mauke is up to 190 m wide, and much of it

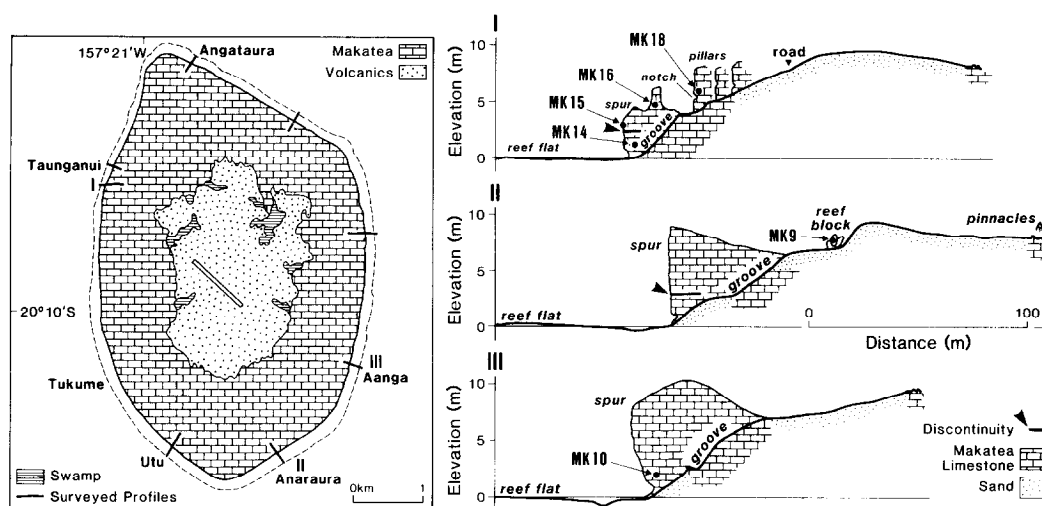


FIG. 4. Map of Mauke, showing selected profiles and location of samples dated.

dries at low tide, as on Mitiaro, implying some late-Holocene emergence (Woodroffe *et al.*, 1990).

An upper and lower unit within the late Pleistocene reefs are clearly discernible at several points around the island. These are usually separated by a sharp discontinuity which occurs at 1.8–2.4 m at Utu on the southwest coast, 2.7 m at Anaraura to the southeast, 1.5 m at Angataura on the north coast, and 2.75 m north of Taunganui on the northwest coast (Fig. 4). A bedded sand unit was seen exposed at an elevation of about 2 m in a groove at Taunganui; it is not widespread but may be equivalent to the bedded sand unit recorded on Atiu. Beds dip seaward at angles of up to 28°, and landward at up to 6°. U-series dates from the lower unit on Mauke are (MK6) 215,000 + 15,000, –13,000 yr B.P., (MK14) 243,000 + 24,000, –20,000 yr B.P., and (MK10) 204,000 + 19,000, –17,000 yr B.P. Corals from the upper unit are (MK16) 136,000 ± 11,000 yr B.P., (MK15) 123,000 + 8000, –7000 yr B.P., and (MK18) 119,000 + 8000, –7000 yr B.P.

A profile from the west coast (profile I, Fig. 4) demonstrates what appear to have been multiple events within the deposition and cementation of the upper unit. While the lower unit has abundant *in situ* corals, much of the upper unit contains coral boulders. A notch is cut into this upper unit. A

reef block at Anaraura is perched on volcanic rocks at 7–8 m; the top of the reef block is at 8.4 m. A sample of *Porites* from within the block (MK9) has an age of 136,000 + 10,000, –9000 yr B.P., indicating that it is also of last interglacial age.

Several coastal features indicate that there has been a mid-Holocene high stand of sea level on Mauke and one coral from an emergent part of the reef flat has been radiocarbon-dated to 2900 ± 85 yr B.P. However, a further coral, considered Holocene, from the coastal ramp at Tukume dated 31,350 ± 800 yr B.P. and a *Tridacna* nearby dated 38,570 ± 2000 yr B.P. (Woodroffe *et al.*, 1990).

Mangaia

Mangaia is the largest of the makatea islands in the southern Cook Islands; it is 9.6 km long, with a volcanic core rising to a height of 169 m. The modern reef flat is ≥130 m wide, and there is evidence of up to 1.7 m of Holocene emergence (Stoddart *et al.*, 1985; Yonekura *et al.*, 1988). The makatea limestones rise up to 70 m, although to a lesser height in the southeast. The inner makatea limestones were considered by Marshall to be possibly Lower Miocene to Oligocene in age (Marshall, 1927). Yonekura *et al.* (1988) suggest on the basis of foraminifera that they are up to 17

myr old. If so, then because the K–Ar dates on the volcanic rocks range from 18.9–16.6 myr, it would imply that limestones began to form soon after volcanism ceased. The makatea limestones of Mangaia have been reinterpreted by Stoddart *et al.* (1985) who identify Pleistocene limestones on the seawardmost part of the limestone margin, up to an elevation of 14.5 m (Fig. 5). These formed when sea level was probably about 20 m above its present level.

Veih (1966) initially collected corals from Mangaia, and reported U-series ages of $90,000 \pm 20,000$ and $110,000 \pm 20,000$ yr B.P. (and a confirmatory $^{234}\text{U}/^{238}\text{U}$ age of $110,000 \pm 40,000$ yr B.P.). These samples came from 2 m above sea level. Samples of *Porites* encrusting the walls of grooves up to an elevation of 15 m yielded ages shown in Table 1 and reported by Spencer *et al.* (1988). The mean of the four ages is $115,000 \pm 7000$ yr B.P.

DISCUSSION

Most of the makatea limestone on Atiu, Mitiaro, Mauke, and Mangaia is Tertiary in age, having formed as sequential fringing reefs around the eroded volcanic core. Foraminiferal evidence from Mangaia implies that fringing reefs were initiated shortly after, if not even before, volcanism ceased on

that island (Yonekura *et al.*, 1988). Indeed, on the Makatea Island of Rurutu, Australs group, a basal conglomerate with mangiferous clays indicates the contemporaneity of volcanism and reef growth (Bardintzeff *et al.*, 1985). In the southern Cook Islands these Tertiary limestones have subsequently been uplifted, largely in response to loading of the lithosphere by the volcanic mass of Rarotonga. K–Ar dating of basalts on Rarotonga give ages of 2.8–1.2 myr, with a mean age of 1.65 myr (Dalrymple *et al.*, 1975). Maximum elevation of makatea limestones should give an indication of uplift since formation of Rarotonga (McNutt and Menard, 1978; Spencer *et al.*, 1988). However, as the absolute height of the sea at 1.65 myr ago and the amount of erosion that has occurred on the makatea limestone are unknown, but presumed similar for each island, the best comparative measures are differential rates of uplift (Lambeck, 1981a, 1981b).

Pleistocene limestones flanking the older makatea limestones provide evidence of both late Quaternary sea-level fluctuations and the continued differential uplift of the islands. Our stratigraphic observations have indicated that on at least three of the islands (Atiu, Mitiaro, and Mauke) there are two prominent Pleistocene reefal units separated by a pronounced discontinuity. It

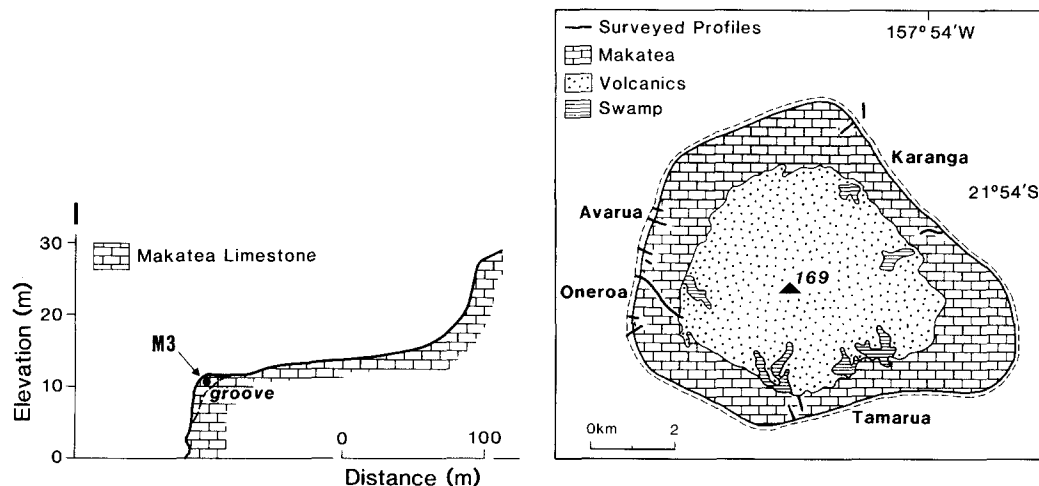


FIG. 5. Map of Mangaia, showing selected profiles and location of samples dated.

seems highly likely that a similar break exists on Mangaia, but the island is generally inaccessible and the break is harder to detect on that island. Reefal limestones considered older than substage 5e crop out at Ivirua, where corals are predominantly calcitic, and 700 m south of Oneroa (Stoddart *et al.*, 1985).

The lower unit contains abundant *in situ* corals, although most are recrystallized and undatable. U-series ages indicate that this is a reef probably dating from oxygen isotope stage 7, i.e., the penultimate interglaciation. Sample MT2 from Mitiaro is excluded on the grounds that it was only superficial to the lower reef unit and that its U-series age appears to fall unambiguously within the range of ages of the upper unit.

The upper reef unit on these makatea islands corresponds to the last interglaciation, oxygen isotope substage 5e. On Mitiaro, Mauke, and Mangaia this unit contains many corals in growth position and it is clearly a major constructional reef. However, on Atiu much of the upper unit is composed of coral boulders; on this island it appears to be an accumulation of forereef rubble. Isolated outcrops of makatea occur on Rarotonga, reaching 3.5 m at Ngatangaia. Schofield (1970) reported two radiocarbon ages from this limestone of 28,200 and 43,400 yr B.P. These ages are approaching the limit of radiocarbon dating, and it has been suggested that the limestones are most likely of last interglacial age (Berryman, 1987).

Several studies of substage 5e reefs around the world imply that there were two periods of high sea level during the last interglaciation separated by a period of lower sea level (i.e., Veeh, 1966; Chappell, 1974; Ku *et al.*, 1974; Moore and Somayajulu, 1974; Chappell and Veeh, 1978; Aharon *et al.*, 1980; Moore, 1982). No such double peak is predicted by the Milankovich theory of orbital change, nor is there evidence of it in the deep sea ^{18}O foraminiferal record even where these permit good time resolution. Kaufman (1986) concluded, based

upon selected sampling of published dates from "stable" islands, that the dates either represent one event which lasted for less than 12,000 yr, or two events separated by no more than 7500 yr. We are unable to detect a bimodal distribution in the spread of dates from the Cook Islands (Fig. 6).

Although there is no field evidence to support two major reef units in the Cook Islands during the last interglaciation, there are several stratigraphic features that indicate fluctuations of sea level during or shortly after substage 5e. Erosional benches (i.e., the bench on profile II at Taukaroa, Atiu, Fig. 2) and notches (i.e., on profile I on Mauke, Fig. 4) have been formed in the emergent substage 5e reef. There also are encrusting corals, particularly encrusting specimens of *Porites*, which appear plastered onto the lithified substage 5e reef. However, U-series dates of these corals indicate they are indistinguishable in age from the bulk of the reef unit that they encrust (Fig. 6).

On several other islands a reef of apparent stage 7 age has been observed to underlie one of substage 5e age. On Bermuda, the Belmont Formation reaches 2 m elevation and gives stage 7 ages; it underlies the Rocky Bay (Devonshire) Formation which dates from substage 5e (Harmon *et al.*, 1983). Similarly, on Tongatapu in Tonga, Taylor and Bloom (1977) reported a U-series age of $205,000 \pm 40,000$ yr B.P. for coral from a lower, presumably stage 7, reef termed the Niutoua Formation, which reaches an elevation of 3.5 m and underlies extensive substage 5e reefs that reach 6 m elevation. A reef at 2.5 m elevation in the Loyalty Islands has an age of ca. 225,000 yr (Bourrouilh-Le Jan, 1985); a discontinuity at a similar elevation occurs on Makatea (Veeh, 1966; Montaggioni *et al.*, 1985).

The upper and lower reefal units on the Makatea Islands are separated by a discontinuity. In most places this takes the form of a sharp break, and the upper surface of the lower unit is conspicuously subhorizontal and regular; it does not have pinnacles or

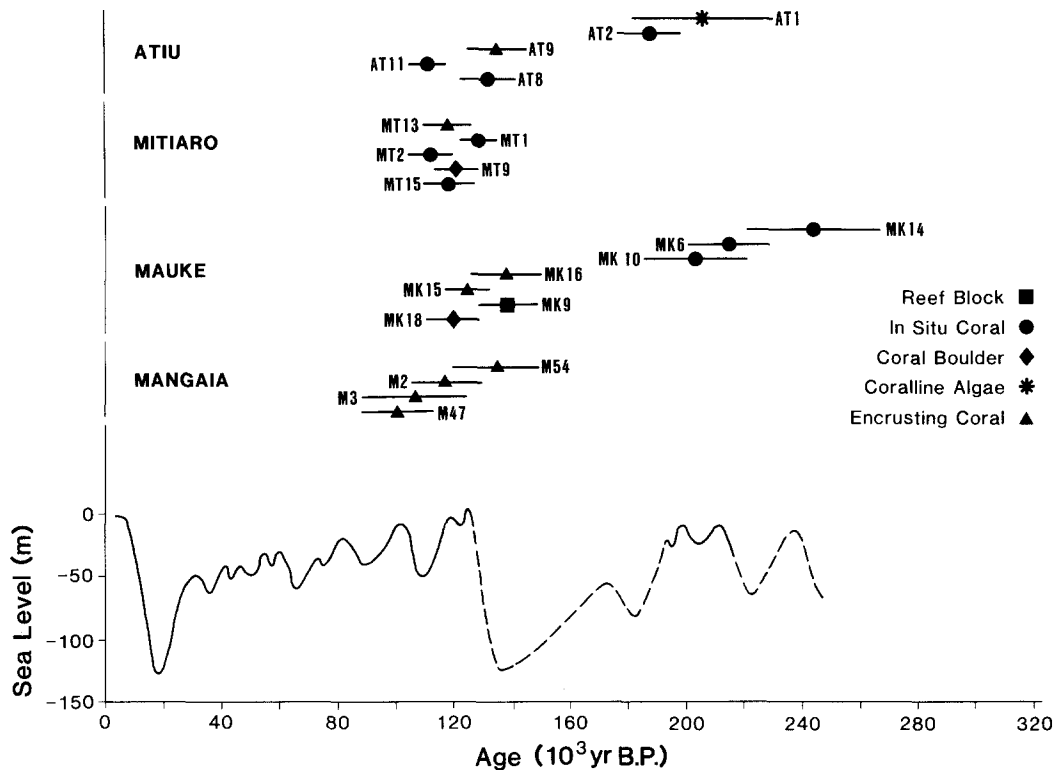


FIG. 6. Uranium-series ages (± 1 standard error) on corals from southern Cook Islands, and comparison with late Quaternary sea-level curve of Chappell and Shackleton (1986).

the other karst forms that characterize the upper surface of the makatea limestones in general. In a few places (such as at Taungani and Oravaru on Atiu, and at Taungani on Mauke), a bedded sand unit overlies the lower reefal unit. The sand unit is interpreted as a beach sand deposit formed on top of the lower unit. However, it is not clear when it was deposited, nor under what conditions this deposit was formed (the environment of deposition evidently differed from the tiny modern pocket beaches). The U-series age of $205,000 \pm 26,000$, $-22,000$ yr B.P. on the coralline algal crust at Matai, Atiu (AT1) implies that the smooth upper surface of the lower unit is a feature that dates from stage 7, and it may represent a cemented reef flat surface formed during the high stand of sea level during the penultimate interglaciation. Perhaps the sand unit formed as sand cays on a slightly emergent reef flat surface, rather

similar to modern islands that have accumulated on an emergent, truncated mid-Holocene reef flat on Suvarrow Atoll, northern Cook Islands (Scoffin *et al.*, 1985).

Makatea limestones occur at different heights on different islands in the southern Cook Islands. They are inferred to be entirely below sea level on several islands indicating subsidence (i.e., Aitutaki and Manuae), as they are on other atolls in the Pacific (i.e., Trichet *et al.*, 1984). However, they rise up to 70 m above sea level on Mangaia. This has been attributed to differential movement of islands as a result of lithospheric flexure in response to the volcanic load of Rarotonga, and perhaps also other islands (McNutt and Menard, 1978). The lithosphere is considered to behave in an elastic manner by some geophysicists (i.e., Watts and Ribe, 1984), and in a viscoelastic manner by others (i.e., Lambeck,

1981b). Both of these models predict that much of the compensatory adjustment occurs soon after loading (of the order of 10^3 – 10^5 yr), but some processes, i.e., moat-infilling, ensure that some adjustment goes on over longer time periods. Our results indicate that differential uplift has persisted through the late Quaternary.

Table 2 summarizes data on the elevation of particular reef units from the southern Cook Islands. It should be emphasized that these elevations are minimum values, as some erosion and lowering of the surfaces may have occurred since the formation of individual reefs (Jarrard and Turner, 1979). As the absolute height of the sea surface at times in the past is not known exactly, it is difficult to calculate rates of uplift or subsidence based only on the elevation of particular reef units.

If uplift is assumed to have occurred continuously since 1.65 myr ago, the mean age for main shield-building phase (Te Manga) on Rarotonga, average rates of uplift would have been approximately 0.044 mm/yr on Mangaia, 0.011 mm/yr on Atiu, and 0.005–0.007 mm/yr on Mitiaro and Mauke (Spencer *et al.*, 1988). If sea level stood 6 m above present at the peak of the last interglaciation, average rates of uplift over the last 120,000 yr would have been approximately 0.07–0.10 mm/yr on Mangaia, 0.05

mm/yr on Atiu, 0.03 mm/yr on Mitiaro, and 0.03–0.05 mm/yr on Mauke; subsidence of as much as 0.02 mm/yr may have occurred on Rarotonga. We cannot be sure that the figure of 6–7 m above present for the height of the sea at the peak of the last interglaciation is appropriate in the Cook Islands. This figure has come primarily from mid-plate islands, including Mangaia, with reefs at about that height above sea level. Many of the so-called stable islands used to derive this figure, Mangaia included, lie on the uplifted arch of lithospheric flexure around a young volcano (McNutt and Menard, 1978). We have demonstrated that the shoreline of the last interglaciation shows more than 15 m of differential movement on islands in the Cook Islands; therefore, it is clearly unwise to base an estimate of the height of the sea at the peak of the last interglaciation on any one of the southern Cook Islands alone.

The rates of differential movement implied from Table 2 indicate that Mangaia has undergone the most rapid uplift; it has the most elevated makatea (70 m) and the most elevated substage 5e reef (14–20 m). Relatively similar patterns of uplift are implied for Atiu and Mauke on which the stage 7 reefs are 2.7–2.8 m, and the substage 5e reefs around 12 m. The stage 7 reef on Mitiaro reaches 6 m elevation, whereas

TABLE 2. ELEVATION OF FEATURES IN THE SOUTHERN COOK ISLANDS

	Highest volcanic (m)	Highest makatea (m)	Highest substage 5e (m)	Highest discontinuity (m)	Highest Holocene (m) ^a
Atiu	72	22.1	12.2	2.7	0–1
Mitiaro	8.9	10.9	9.8 ^b	6.0	1.2
Mauke	24.4	14.7	10.0 [12.7] ^c	2.8	<1
Mangaia	169	73	14.5 [20.0] ^d	?	1.7
Rarotonga	653	3.5	3.5 ^e	NA	0–1 [1.0] ^f

^a For details see Woodroffe *et al.*, (1990).

^b Highest substage 5e probably did not emerge above level of sea at peak of last interglaciation.

^c 10.0 m is general level of substage 5e; 12.7 m is highest observed (see Stoddart *et al.*, 1990).

^d 14.5 m is highest observed substage 5e; sea level at time may have been as much as 20 m above present (see Stoddart *et al.*, 1985).

^e Limestone at Ngatangaia presumed to be substage 5e (see Berryman, 1987).

^f Evidence for Holocene high sea level reported by Schofield (1970) but none seen by us.

the substage 5e reefs reach up to around 10 m, which is close to the height of the highest point on the island and is >1 m above the highest volcanic outcrop on the island. During the peak of the last interglaciation apparently none of Mitiaro was subaerially exposed; the upper surface of the substage 5e reef is, therefore, only a minimum value for sea level at that time. The rate of uplift on Mitiaro may have exceeded that on Atiu and Mauke, as implied by the higher stage 7 reef on this island.

Rates of uplift of the order suggested for the southern Cook Islands would have resulted in slight differential movements of the islands during the Holocene. There is evidence of Holocene emergence on several of the islands. A fall of sea level of at least 1.7 m in the last 3400 yr has been reported for Mangaia (Yonekura *et al.*, 1988; Spencer *et al.*, 1988). On Mitiaro, emergent fossil corals on the reef flat, radiocarbon-dated as 5140–3620 yr B.P., suggest less emergence (around 1.2 m). A similar late Holocene story is suggested for Atiu and Mauke (Woodroffe *et al.*, 1990). Evidence for a late Holocene fall of sea level on Rarotonga, reported by Schofield (1970), has not been observed by us, and we feel that this island has undergone the least, if any, emergence. These recent trends are consistent with the pattern of differential movement that we infer for the southern Cook Islands over the last 250,000 yr.

CONCLUSIONS

Reefal limestones on the makatea islands of the southern Cook Islands range in age from Tertiary to late Pleistocene. Within the late Pleistocene sequence we have identified two reef units. The lower unit was formed during the penultimate interglaciation (isotope stage 7), as indicated by U-series ages on corals (plus coralline algae) from Atiu and Mauke. The same age is presumed for a similar lower reef on Mitiaro, where it reaches up to 6 m in elevation, and a similar unit is inferred on Mangaia. The upper unit was formed during the peak of

the last interglaciation (substage 5e), has been dated on each of the four makatea islands, but reaches a different height on each island. In a few places the two units are separated by a bedded sand unit. Heights of (i) the makatea limestones, (ii) the lower reef and discontinuity between reefs, and (iii) the upper unit differ between islands situated on the uplifted arch surrounding Rarotonga. These results imply that differential movement of islands, presumably as a result of lithospheric flexure, has been continuing over the last 250,000 yr.

ACKNOWLEDGMENTS

Research in the Cook Islands was made possible by financial assistance from the Royal Society of London, the Australian National University, and the University of Manchester. We acknowledge the considerable support we received from the chief administrative officers and islanders on Atiu, Mauke, Mitiaro, and Mangaia, and from Stuart and Teriapi Kingan and Tony Utanga on Rarotonga. We thank M. Ivanovich for additional U-series dates, J. F. Marshall for examination of thin sections, and R. Miller for drawing the figures.

REFERENCES

- Aharon, P., Chappell, J., and Compston, W. (1980). Stable isotope and sea-level data from New Guinea supports Antarctic ice-surge theory of ice ages. *Nature (London)* 283, 649–651.
- Bardintzeff, J. M., Brousse, R., and Gachon, A. (1985). Conditions of building of coral reefs on a volcano: Mururoa in Tuamotu and Rurutu in Australes (French Polynesia). *Proceedings of the 5th International Coral Reef Congress. Tahiti* 6, 401–405.
- Beaglehole, J. C. (1967). "The Voyage of the *Resolution* and *Discovery* 1776–1780: The Journals of Captain James Cook on His Voyages of Discovery," Vol. 3, Part 2. Cambridge Hakluyt Society.
- Berryman, K. (1987). Tectonic processes and their impact on the recording of relative sea-level changes. In "Sea Surface Studies: A Global View" (R. J. N. Devoy, Ed.), pp. 127–161. Croom Helm, London.
- Bloom, A. L. (1967). Pleistocene shorelines: A new test of isostasy. *Geological Society of America Bulletin* 78, 1477–1494.
- Bloom, A. L., Broecker, W. S., Chappell, J., Matthews, R. K., and Mesolella, K. J. (1974). Quaternary sea level fluctuations on a tectonic coast: New Th²³⁰/U²³⁴ dates from New Guinea. *Quaternary Research* 4, 185–205.

- Bourrouilh-Le Jan, F. G. (1985). An attempt at dating by isotopic stratigraphy of Holocene and Pleistocene notches and deposits of some so-called uplifted atolls. *Proceedings of the 5th International Coral Reef Congress, Tahiti* 3, 125–130.
- Calmant, S., and Cazenave, A. (1986). The effective elastic lithosphere under the Cook-Austral and Society islands. *Earth and Planetary Science Letters* 77, 187–202.
- Calmant, S., and Cazenave, A. (1987). Anomalous elastic thickness of the oceanic lithosphere in the south-central Pacific. *Nature (London)* 328, 236–238.
- Cazenave, A., Souriau, A., and Dominh, K. (1989). Global coupling of Earth surface topography with hotspots, geoid and mantle heterogeneities. *Nature (London)* 340, 54–57.
- Chappell, J. (1974). Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea level changes. *Geological Society of America Bulletin* 85, 553–570.
- Chappell, J., and Shackleton, N. J. (1986). Oxygen isotopes and sea level. *Nature (London)* 324, 137–140.
- Chappell, J., and Veeh, H. H. (1978). Late Quaternary tectonic movements and sea level changes at Timor and Atauro Island. *Geological Society of America Bulletin* 89, 356–368.
- Dalrymple, G. B., Jarrard, R. D., and Clague, D. A. (1975). K-Ar ages of some volcanic rocks from the Cook and Austral Islands. *Geological Society of America Bulletin* 86, 1463–1467.
- Darwin, C. (1842). "The Structure and Distribution of Coral Reefs." Smith Elder, London.
- Davis, W. M. (1928). The coral reef problem. *American Geographical Society Special Publication* 9, 1–596.
- Dodge, R. E., Fairbanks, R. G., Benninger, L. K., and Maurrasse, F. (1983). Pleistocene sea levels from raised coral reefs of Haiti. *Science* 219, 1423–1425.
- Grigg, R. W., and Epp, D. (1989). Critical depth for the survival of coral islands: Effects on the Hawaiian Archipelago. *Science* 243, 638–641.
- Harmon, R. S., Mitterer, R. M., Kriasakul, N., Land, L. S., Schwarcz, H. P., Garrett, P., Larson, G. J., Vacher, H. L., and Rowe, M. (1983). U-series and amino-acid racemization geochronology of Bermuda: Implications for eustatic sea-level fluctuation over the past 250,000 years. *Palaeogeography, Palaeoclimatology and Palaeoecology* 44, 41–70.
- Hoffmeister, J. E., and Ladd, H. S. (1935). The foundations of atolls: A discussion. *Journal of Geology* 43, 653–665.
- Hunt, P. J. (1969). Atiu Island 1:7920. University of Otago, Department of Surveying (map).
- Jarrard, R. D., and Clague, D. A. (1977). Implications of Pacific island and seamount ages for the origin of volcanic chains. *Review of Geophysics and Space Physics* 15, 57–76.
- Jarrard, R. D., and Turner, D. L. (1979). Comments on 'Lithospheric flexure and uplifted atolls' by M. McNutt and H. W. Menard. *Journal of Geophysical Research* 84, 5691–5697.
- Jouannic, C., Hoang, C.-T., Hantoro, W. S., and Delinon, R. M. (1988). Uplift rate of coral reef terraces in the area of Kupang, West Timor: Preliminary results. *Palaeogeography, Palaeoclimatology, Palaeoecology* 68, 259–272.
- Kaufman, A. (1986). The distribution of $^{230}\text{Th}/^{234}\text{U}$ ages in corals and the number of last interglacial high-sea stands. *Quaternary Research* 25, 55–62.
- Konishi, K., Omura, A., and Nakamichi, O. (1974). Radiometric coral ages and sea level records from the late Quaternary reef complexes of the Ryukyu Islands. *Proceedings of the 2nd International Coral Reef Symposium* 2, 595–613.
- Ku, T.-L., Ivanovich, M., and Luo, S. (1990). U-series dating of last interglacial high sea stands: Barbados revisited. *Quaternary Research* 33, 129–147.
- Ku, T.-L., Kimmel, M. A., Easton, W. H., and O'Neil, T. J. (1974). Eustatic sea level 120,000 years ago on Oahu, Hawaii. *Science* 183, 959–961.
- Ladd, H. S., Ingerson, E., Townsend, R. C., Russel, M., and Stephenson, H. K. (1953). Drilling on Eniwetok atoll, Marshall Islands. *Bulletin of the American Association of Petroleum Geologists* 37, 2257–2280.
- Lambeck, K. (1981a). Flexure of the ocean lithosphere from island uplift, bathymetry and geoid height observations. *Geophysical Journal* 67, 91–114.
- Lambeck, K. (1981b). Lithospheric response to volcanic loading in the southern Cook Islands. *Earth and Planetary Science Letters* 55, 482–496.
- Lalou, C., Labeyrie, J., and Delibrias, G. (1966). Datation des calcaires coralliens de l'atoll de Mururoa (Archipel des Tuamotu) de l'époque actuelle jusqu'à 500,000 ans. *Compte Rendu de l'Académie des Sciences Paris série D* 263, 1946–1949.
- Marshall, P. (1927). Geology of Mangaia. *Bulletin of the Bernice P. Bishop Museum* 36, 1–48.
- Marshall, P. (1930). Geology of Rarotonga and Atiu. *Bulletin of the Bernice P. Bishop Museum* 72, 1–75.
- Marty, J. C., and Cazenave, A. (1989). Regional variations in subsidence rate of oceanic plates: A global analysis. *Earth and Planetary Science Letters* 94, 301–315.
- McNutt, M., and Menard, H. W. (1978). Lithospheric flexure and uplifted atolls. *Journal of Geophysical Research* 83, 1206–1212.
- Menard, H. W. (1986). "Islands." Scientific American Library.
- Mesolella, K. J., Mathews, P. K., Broecker, W. S., and Thurber, D. L. (1969). The astronomical theory

- of climatic change: Barbados data. *Journal of Geology* 77, 250–274.
- Montaggioni, L. F., Richard, G., Bourrouilh-Le Jan, F., Naim, O., Payri, C., and Salvat, B. (1985). Geology and marine biology of Makatea, an uplifted atoll, Tuamotu Archipelago, Central Pacific Ocean. *Journal of Coastal Research* 1, 165–171.
- Moore, W. S. (1982). Late Pleistocene sea-level history. In "Uranium Series Disequilibrium: Applications to Environmental Problems" (M. Ivanovich and R. S. Harmon, Eds.), pp. 481–496. Oxford Univ. Press, London/New York.
- Moore, W. S., and Somayajulu, B. L. K. (1974). Age determination of fossil corals using $^{230}\text{Th}/^{234}\text{Th}$ and $^{230}\text{Th}/^{227}\text{Th}$. *Journal of Geophysical Research* 79, 5065–5068.
- Parsons, B., and Sclater, J. G. (1977). An analysis of the variation of ocean floor bathymetry and heat flow with age. *Journal of Geophysical Research* 82, 803–827.
- Schofield, J. C. (1970). Notes on late Quaternary sea levels, Fiji and Rarotonga. *New Zealand Journal of Geology and Geophysics* 13, 199–206.
- Scoffin, T. P., Stoddart, D. R., Tudhope, A. W., and Woodroffe, C. D. (1985). Exposed limestones of Suwarro Atoll. *Proceedings of the 5th International Coral Reef Congress, Tahiti* 3, 137–140.
- Scott, G. A. J., and Rotondo, G. M. (1983). A model to explain the difference between Pacific plate atoll types. *Coral Reefs* 1, 139–150.
- Spencer, T., Stoddart, D. R., and Woodroffe, C. D. (1987). Island uplift and lithospheric flexure: observations and cautions from the south Pacific. *Zeitschrift für Geomorphologie, N.F., Supplement band* 63, 87–102.
- Spencer, T., Stoddart, D. R., Woodroffe, C. D., and Harmon, R. S. (1988). Lithospheric flexure and raised reef limestones, S. Cooks-Austral Islands. *Proceedings of the 6th International Coral Reef Congress* 3, 485–489.
- Stoddart, D. R., and Spencer, T. (1987). Rurutu reconsidered: The development of makatea topography in the Austral Islands. *Atoll Research Bulletin* 297, 1–19.
- Stoddart, D. R., Spencer, T., and Scoffin, T. P. (1985). Reef growth and karst erosion on Mangaia, Cook Islands: A reinterpretation. *Zeitschrift für Geomorphologie, N.F. Supplement band* 57, 121–140.
- Stoddart, D. R., Woodroffe, C. D., and Spencer, T. (1990). Mauke, Mitiaro and Atiu: Geomorphology of Makatea islands in the southern Cooks. *Atoll Research Bulletin* 341, 1–66.
- Taylor, F. W., and Bloom, A. L. (1977). Coral reefs on tectonic blocks, Tonga island arc. *Proceedings of the 3rd International Coral Reef Symposium* 2, 275–281.
- Trichet, J., Repellin, P., and Oustrière, P. (1984). Stratigraphy and subsidence of the Mururoa Atoll (French Polynesia). *Marine Geology* 36, 241–257.
- Turner, D. L., and Jarrard, R. D. (1982). K–Ar dating of the Cook-Austral chain: A test of the hot-spot hypothesis. *Journal of volcanology and geothermal research* 12, 187–226.
- Veeh, H. H. (1966). $\text{Th}^{230}/\text{U}^{238}$ and $\text{U}^{234}/\text{U}^{238}$ ages of Pleistocene high sea level stand. *Journal of Geophysical Research* 71, 3379–3386.
- Watts, A. B., and Ribe, N. M. (1984). On geoid heights and flexure of the lithosphere at seamounts. *Journal of Geophysical Research* 89, 11152–11170.
- Wood, B. L., and Hay, R. F. (1970). Geology of the Cook Islands. *New Zealand Geological Survey Bulletin, New Series* 82, 1–103.
- Woodroffe, C. D., Stoddart, D. R., Spencer, T., Scoffin, T. P., and Tudhope, A. W. (1990). Holocene emergence in the Cook Islands, South Pacific. *Coral Reefs* 9, 31–39.
- Yonekura, N., Ishii, T., Saito, Y., Maeda, Y., Matsushima, Y., Matsumoto, E., and Kayanne, H. (1988). Holocene fringing reefs and sea-level change in Mangaia Island, Southern Cook Islands. *Palaeogeography, Palaeoclimatology, Palaeoecology* 68, 177–188.