



Holocene emergence in the Cook Islands, South Pacific

C. D. Woodroffe¹, D. R. Stoddart², T. Spencer³, T. P. Scoffin⁴ and A. W. Tudhope⁴

¹ Department of Geography, University of Wollongong, Wollongong, NSW 2500, Australia

² Department of Geography, University of California, Berkeley, California 94720, USA

³ Department of Geography, University of Cambridge, Cambridge CB2 3EN, UK

⁴ Department of Geology, University of Edinburgh, Edinburgh EH9 3HG, UK

Accepted 15 March 1989

Abstract. There is evidence of Holocene emergence on several of the Cook Islands. On Suvarrow Atoll there are extensive outcrops of emergent, but truncated, reef on the northern atoll rim, radiocarbon-dated 4680–4310 years B.P., overlain by younger cemented boulder conglomerates. On the northeast of the atoll there are fossil algal ridges indicating up to 1 m of emergence; the landward-most has been dated 4220 years B.P., the intermediate one 3420 years B.P. and the present one 1250 years B.P. On Mitiaro, a makatea island in the Southern Cooks, there are emergent reefal deposits in the centre of the reef flat dated 5140–3620 years B.P. Similar though poorly preserved deposits occur on Mauke, and an erosional bench and notch occurs on Atiu. Emergence on all islands appears synchronous with that reported on Mangaia, where a relative fall of sea level of at least 1.7 m in the last 3400 years has been reported. The evidence for emergence is broadly similar to that described from French Polynesia, though timing of emergence appears to differ.

Introduction

Sea level and the pattern of Holocene sea-level change have been important constraints on the development of modern coral reefs (Davies and Montaggioni 1985). Lithified reefal deposits at around high tide level or slightly above, have been widely reported from throughout the Indo-Pacific reef province. These were initially interpreted to indicate a Holocene sea level higher than present (Gardiner 1903; David and Sweet 1904; Daly 1920). Their origin, however, is not unambiguous. In some cases detailed examinations of these deposits have failed to reveal unequivocal evidence of emergence, and they appear to be lithified storm deposits (Newell 1961; Shepard et al. 1967). Elsewhere survey, radiometric dating and petrography of coral conglomerate platforms does indicate that they have formed while mean sea level has been higher than present (Buddemeier et al. 1975; Montaggioni and Pirazzoli 1984; Pirazzoli et

al. 1985; Pirazzoli and Montaggioni 1986; Pirazzoli et al. 1987a; Pirazzoli and Montaggioni 1988).

There is now convincing evidence that the pattern of Quaternary sea-level change has varied relative to different points on the globe. Geophysical modelling of the response of a viscoelastic earth to post-glacial melting of polar ice-caps predicts that the record of Holocene sea-level change will differ not only between different oceanic regions, but also between individual islands in the Pacific (Clark et al. 1978; Nakiboglu et al. 1983; Hopley 1987; Nakada and Lambeck 1988). In addition to the regional trends predicted by such modelling, individual tectonic histories, related to plate tectonic location, and individual island geometries, resulting in local hydro-isostatic compensation, contribute to further discrepancies between islands (Bloom 1980; Nakada 1986).

Accurate observations on relative sea-level history of particular islands provide important constraints on geophysical modelling, and allow testing of competing model formulations. Where detailed elevational data on emergent reefs are available, such as the work summarised by Pirazzoli and Montaggioni (1988), flexural trends within island groups may even be differentiated from the Holocene sea-level record.

The Cook Islands are a diverse group of 15 islands lying between 8° S and 23° S, 167° W and 156° W in the southern Pacific Ocean. They comprise coral atolls, an almost-atoll, a Pleistocene volcanic island with fringing reef, elevated "makatea" islands, and sand cays. Individual descriptions of islands within the Cooks either record evidence for a late Holocene sea level slightly higher than present, or suggest that islands have developed under conditions of gradual submergence and that the sea has not been higher than its present level during the Holocene. Thus, on Aitutaki, Shepard (1961) and Wood and Hay (1970) describe presumably Holocene emergent reef or shoreline, up to 1 m above present, while Stoddart (1975) and Yonekura et al. (1984) found no evidence that Holocene deposits had formed under a sea level higher than present. Similarly on Rarotonga, Schofield (1967, 1970) and Wood and Hay (1970) describe features at

around 1 m above sea level, but Yonekura et al. (1984) report that there are no emergent reefs. Recently an emergent Holocene reef has been described on Suvarrow Atoll (Scoffin et al. 1985), and emergent Holocene corals have been reported on Mangaia (Yonekura et al. 1984; Stoddart et al. 1985). A detailed chronology of late Holocene sea-level fluctuation, based upon a cliff-foot notch, emergent coral, and drilling of the reef flat, has been reported from Mangaia (Yonekura et al. 1986, 1988).

In this paper evidence for Holocene emergence on Suvarrow Atoll in the northern Cooks, and on the makatea islands of Atiu, Mauke and Mitiaro is described. The timing of emergence appears similar between several of these islands and is broadly synchronous with the record from Mangaia.

The Cook Islands

The Cook Islands comprise a northern group and a southern group (Fig. 1). The northern group consists principally of atolls (Penrhyn, Rakahanga, Manihiki, Pukapuka, Palmerston and Suvarrow), though also including Nassau, a sand cay on a reef platform. The southern group consists of an atoll (Manuae), a sand cay (Taku-

tea), an almost-atoll (Aitutaki), a Pleistocene volcanic island with fringing reef (Rarotonga) and four "makatea" islands, islands with a subdued volcanic core and peripheral emergent limestones of both Tertiary and Pleistocene age (Atiu, Mitiaro, Mauke and Mangaia). Several of the southern Cook Islands and many of the Austral Islands are aligned in one or more lines northwest to southeast. This alignment superficially suggests the development of islands over a hot spot at or close to the MacDonald Seamount, and subsequent migration with Pacific plate motion to the northwest. A volcanic propagation rate of 11.4 ± 2.3 cm/yr has been suggested (Brousse 1985). However, potassium-argon dating of island basalts (Dalrymple et al. 1975; Turner and Jarrard 1982) indicates that although Mangaia, on which basalts have been dated 16.6–19.4 Ma B.P. obeys the expected age-distance relationship, the other islands in the southern Cooks (Mitiaro > 12.3 Ma, Atiu 8–10 Ma, Mauke > 6 Ma, Aitutaki 8.1 and 0.7–1.9 Ma and Rarotonga > 1.6–2.3 Ma B.P.) are younger than expected (Stoddart and Spencer 1987; Spencer et al. 1988).

The variety of islands within the southern Cooks represents several of the types described by Scott and Rondono (1983) in a general model of Pacific island development. The makatea islands have evidently been uplifted since the deposition of Tertiary limestones. Uplift may have occurred as a result of flexure of the lithosphere beneath the weight of a composite volcanic load of Rarotonga-Aitutaki-Manuae (McNutt and Menard 1978) or simply as an adjustment on the emplacement of the Pleistocene island of Rarotonga (Lambeck 1981). Such loads theoretically produce compensatory up-arching of the lithosphere at predictable radii from the volcanic mass. In the southern Cooks, the makatea islands appear to be positioned on this arch, and thus to have been uplifted. Modelling of the flexural response, using several values for the rigidity of lithosphere, and adopting either an elastic deformation (McNutt and Menard 1978; Watts and Ribe 1984; Calmant and Cazenave 1986) or a viscoelastic deformation (Lambeck 1981) predicts some of the differences in elevation of limestones on the islands. However it is clear that geophysical modelling cannot explain the disparate heights of all limestone units, and particularly of contemporaneous interglacial reefal limestones on different islands (Spencer et al. 1987; 1988; Stoddart et al. in press).

The nature of the isostatic adjustments which have occurred on the makatea islands in response to altered loading of either volcanic load, sediment infill in the moat or changes in ocean volumes are not fully understood. It is possible that this scale of compensation may explain some of the discrepancies that remain with the pattern of Holocene sea-level history between islands.

Methods

The geomorphology of each of the islands was examined and topographic profiles were surveyed. Elevations were determined using a Kern automatic level, and have been referred to an approximate mean low water datum using the ordinary crest of the algal ridge at the reef edge. Tidal range has not been established on all islands; it

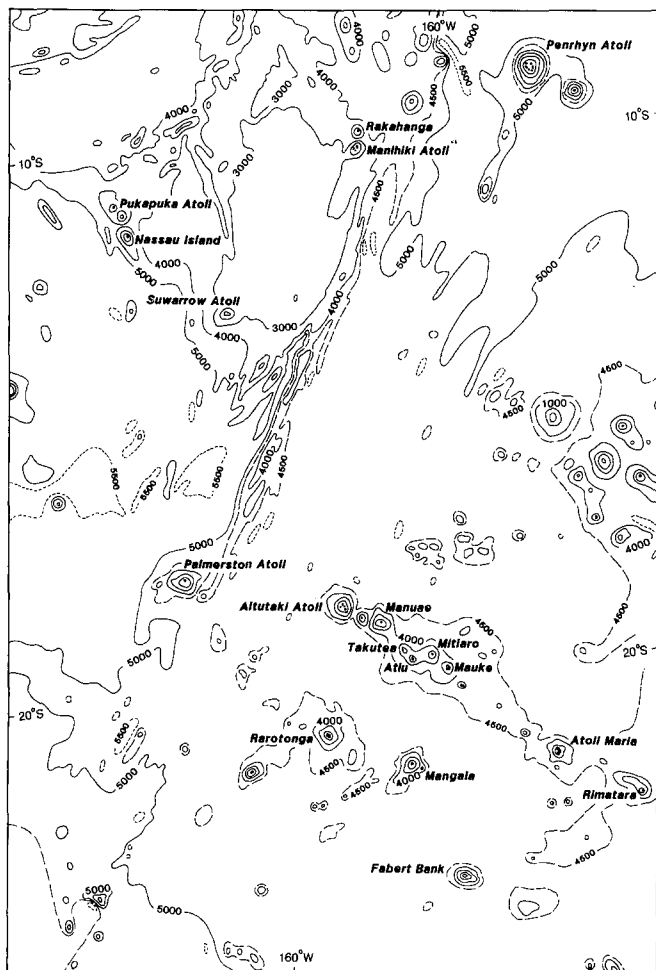


Fig. 1. Location and bathymetry of the Cook Islands

is about 67 cm on Rarotonga and 43 cm on Aitutaki (NOAA Tide Tables), and is likely to be similar on the other islands. Detailed profiles of Atiu, Mauke and Mitiaro are presented in Stoddart et al. (in press).

Samples for radiocarbon-dating were collected from lithified units in the field. Samples of coral and encrusting algae from Suvarrow Atoll were submitted to the Radiocarbon Dating Laboratory, Institute of Nuclear Sciences, D. S. I. R., New Zealand. Ages, based on ^{14}C half-life of 5568 ± 30 years and reported in Scoffin et al. (1985), are corrected for isotopic fractionation, and incorporate an environmental-correction for ocean ^{14}C reservoir effect of -412 ± 40 years based on Fiji shell standard.

Samples of coral and giant clam, *Tridacna*, from Mauke and Mitiaro were radiocarbon-dated at the Radiocarbon Dating Laboratory of the Australian National University using methods described by Gupta and Polach (1985). The ages are reported initially as conventional radiocarbon ages, and then an environmental-correction of 450 ± 35 years is subtracted from the age. This value is used for marine shells in Australia (Gillespie and Polach 1979), and has recently been shown to be appropriate in Tonga (Poulsen 1987). The different environmental-correction adopted by ANU and NZ labs means that a New Zealand date should appear about 38 years older than an ANU date on the same sample.

Recently Pirazzoli and others have indicated that corals from enclosed atoll lagoons may not require environmental correction because the ^{14}C activity of water in the lagoon is in equilibrium with that of the atmosphere, rather than being similar to open ocean water. Based on dating of modern corals from Reao Atoll in the Tuamotus, they have suggested that corrections need only be applied to open water corals (Pirazzoli et al. 1987a, b). We are unable to assess the degree of exchange between the lagoon of Suvarrow Atoll and open water, or whether the corals dated grew under predominantly lagoonal or open water conditions, and consequently do not further adjust our dates.

Radiocarbon dates reported by Yonekura et al. (1984, 1986, 1988), determined at the Japanese Geological Survey, have not been corrected for either isotopic fractionation or environmental correction (H. Kayanne personal communication). The isotopic fractionation is likely to be around $+400$ years, and the environmental correction is likely to be around -400 years. Thus with some caution those dates from the JGS lab reported from Mangaia can be compared with the dates that are reported here.

Suvarrow Atoll

Suvarrow ($13^\circ 15' \text{S}$, $163^\circ 30' \text{W}$) is an isolated atoll in the northern Cooks. It is 15 km wide and consists of a continuous atoll rim 0.5–1.0 km wide, broken only at the narrow entrance on the northern side. The lagoon is up to 80 m deep and is studded with patch reefs. There are more than 20 reef islands, concentrated on the northern atoll rim, each sited around an emergent reefal limestone core. Although Wood and Hay (1970) implied that some exposures of limestone on Anchorage Island on Suvarrow appeared to be Pleistocene, all exposed limestones examined by us are Holocene in age (Scoffin et al. 1985).

A truncated emergent Holocene reef is prominent along much of the northern atoll rim, and remnants represent anchors upon which unconsolidated sediments have accumulated. Within the fossil reef, *Porites*, *Pocillopora*, *Acropora*, *Millepora*, faviid corals and *Tridacna* are abundant in their position of growth. The upper surface occurs at about 50 cm above low water level and 40 cm above the upper limit to coral growth. Radiocarbon dates of 4680 ± 50 and 4650 ± 60 years B.P. have been obtained from this unit on Manu Island, and 4310 ± 50 years B.P.

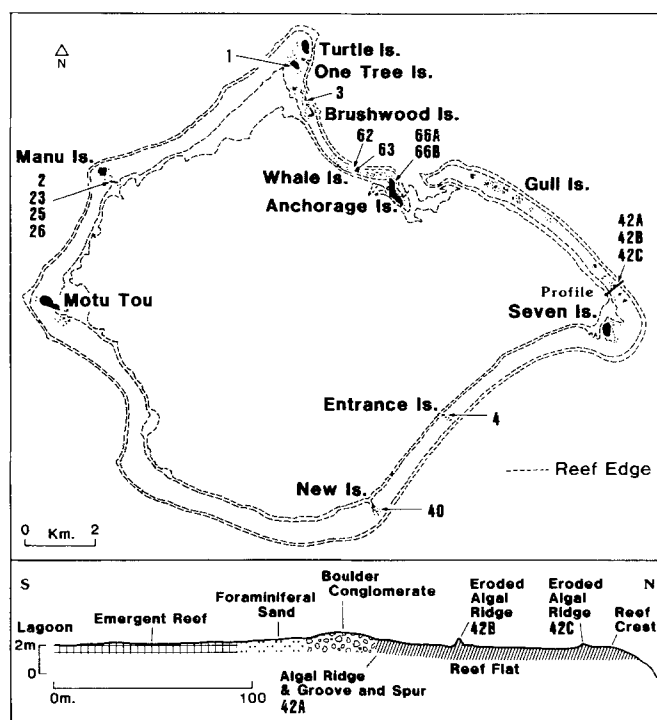


Fig. 2. Suvarrow Atoll, Northern Cooks, showing location of radiocarbon-dated samples, and a profile of the fossil algal ridges

on Whale Island, where the reef is especially extensive, more than 1000 m long and 200 m wide.

Lithologically similar emergent reefal limestone is found on both New Island and Entrance Island on the southern atoll rim, and corals from this limestone have been dated 2400 ± 50 on New and 2400 ± 60 years B.P. on Entrance. An in situ microatoll on Anchorage Island has been dated 3670 ± 50 years B.P.; it lies immediately adjacent to cemented boulder deposits from which a coral has been dated with a similar age of 3630 ± 50 years B.P. The microatoll may be emergent; alternatively it may have grown in a moated situation behind a storm rampart. A microatoll on One Tree Island, dated 1695 ± 35 years B.P., is presently a considerable distance from the modern reef flat, and it is difficult to decide whether this coral indicates a higher sea level or whether it grew moated behind seaward storm ramparts.

Seaward of and overlying the emergent reef on the north coast of Suvarrow is a boulder conglomerate (Fig. 2). This is composed of coral fragments, 5–50 cm in diameter, with interstitial foraminiferal sand. It occurs about 1.6 m above the emergent reef and 2 m above the upper limit to coral growth, and is the highest unit on the atoll. Radiocarbon ages on coral clasts range from 4460 ± 50 to 2000 ± 60 years B.P. (Table 1). The oldest ages are from the boulder conglomerate on Manu Island where the deposit is phosphatised (Scoffin et al. 1985). The wide range of ages may represent a prolonged period of episodic storm activity, or it may result from the reworking of older corals in one or several storm events.

There are additional boulder strewn fields over the reef flat, and individual reef blocks 4 m or more wide. Kaplin (1981) reported radiocarbon ages of 1225 ± 170

Table 1. Radiocarbon-dating results from Suvarrow Atoll

Lab No.	Sample no.	Reef island	Sample description	Genus	Environmentally-corrected age ^a years B.P.
NZ 6099	2	Manu Island	In situ within emergent reef, 50 cm above upper limit to live coral	Faviid	4650 ± 60
NZ 6102	23	Manu Island	Boulder in boulder conglomerate	<i>Porites</i>	2000 ± 60
NZ 6103	25	Manu Island	In situ 7 cm below surface of emergent reef	<i>Porites</i>	4680 ± 50
NZ 6104	26	Manu Island	Boulder in boulder conglomerate, 50 cm above surface of emergent reef	<i>Porites</i>	4460 ± 50
NZ 6098	1	One Tree Island	In situ emergent microatoll, slightly-above upper limit to live coral	<i>Porites</i>	1695 ± 35
NZ 6100	3	Brushwood Island	Boulder in boulder conglomerate	<i>Porites</i>	3560 ± 50
NZ 6109	62	Whale Island	Boulder in boulder conglomerate	<i>Porites</i>	2620 ± 50
NZ 6110	63	Whale Island	Coral from emergent reef, approx. 50 cm above upper limit to live coral	<i>Porites</i>	4310 ± 50
NZ 6111	66A	Anchorage Island	Boulder in boulder conglomerate	Unidentified	3630 ± 50
NZ 6112	66B	Anchorage Island	In situ emergent microatoll	Faviid	3670 ± 50
NZ 6106	42A	Seven Island	Sample from within emergent algal ridge, which rises to 1.5 m above mean low water	Encrustate algae	4220 ± 60
NZ 6107	42B	Seven Island	Emergent algal ridge	Encrustate algae	3420 ± 40
NZ 6108	42C	Seven Island	Present algal ridge	Encrustate algae	1250 ± 35
NZ 6105	4	Entrance Island	In situ corals in emergent reef, above upper limit to live coral	<i>Porites</i> + Faviid	2400 ± 60
NZ 6101	40	New Island	In situ coral in emergent reef above upper limit to live coral	Faviid	2400 ± 60

^a Radiocarbon ages incorporate an environmental correction, using Fiji shell standard, of 412 ± 40 years

years B.P. for a boulder in the centre of Motu Tou on the western rim of the atoll, and of 3045 ± 116 years B.P. on a boulder on the reef flat near this same island.

On the northeastern atoll rim, in the vicinity of the Seven Islands there are several fossil algal rims which can be identified running parallel to the reef crest. The oldest, landwardmost of these, about 180 m from the reef crest, forms a part of the reef islands and the form of former spur and groove patterns can be seen. It is at an elevation of about 1.5 m above the reef flat and a radiocarbon date of 4220 ± 60 years B.P. on encrustate algal material was obtained. The second algal rim, is a narrow ridge, 100 m in from the reef crest. It rises to about 1.5 m above the reef flat, or less where it has been eroded, and has been dated 3420 ± 40 years B.P. The modern algal ridge, capped by a veneer of live calcareous algae, with fringing live coral, and with foraminifera and serpulids, cemented by pelleted Mg calcite and fibrous aragonite (Scoffin et al. 1985), was found to have a radiocarbon age of 1250 ± 35 years B.P. This sequence of algal ridges indicates emergence, and episodic reef crest progradation.

The difference in age of emergent reef on the northern and southern rims of the atoll, together with distinct fractures on the modern reef flat, parallel to the reef crest, and tilted patch reefs in the lagoon, indicate that there may have been Holocene tectonic disturbance of Suvarrow Atoll (Scoffin et al. 1985).

Mitiaro

Mitiaro ($19^{\circ} 01' S$, $157^{\circ} 03' W$) is one of the smaller of the makatea islands and the lowest-lying; it is 6.4 km long by

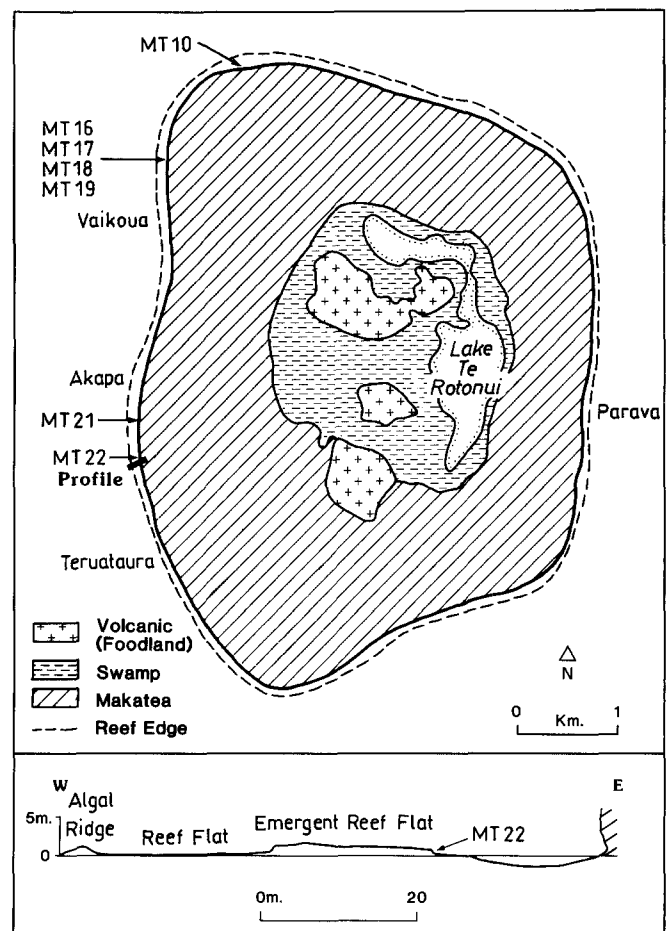


Fig. 3. Mitiaro, Southern Cooks, showing location of radiocarbon-dated samples

Table 2. Radiocarbon-dating results from Mitiaro and Mauke

Lab no.	Sample no.	Location	Sample description	Genus	Conventional age years B.P.	Environmentally-corrected age ^a years B.P.
<i>Mitiaro</i>						
ANU 4863	MT10	North coast	Emergent microatoll on reef flat, 20–30 cm above upper limit to live coral	? <i>Porites</i>	34 500 ± 1740	34 050 ± 1740
ANU 4864	MT17	Vaikoua	Emergent coral on reef flat, < 30 cm above upper limit to live coral	Faviid	4850 ± 90	4400 ± 95
ANU 4865	MT16	Vaikoua	Emergent coral on reef flat, < 30 cm above upper limit to live coral	Faviid	4350 ± 90	3900 ± 95
ANU 4866	MT18	Vaikoua	Emergent coral on reef flat, < 30 cm above upper limit to live coral	<i>Porites</i>	4070 ± 80	3620 ± 85
ANU 4867	MT19	Vaikoua	Emergent coral on reef flat, < 30 cm above upper limit to live coral	<i>Porites</i>	5590 ± 90	5140 ± 95
ANU 4868	MT21	Akapa	In situ on limestone ramp, < 20 cm above upper limit to live coral	<i>Tridacna</i>	33 230 ± 1220 1050	32 780 ± 1220 1050
ANU 4869	MT22	Akapa	Emergent coral on reef flat, 20–40 cm above upper limit to live coral in pitted surface that rises to 1.23 m above mean low water	<i>Porites</i>	4450 ± 80	4000 ± 85
<i>Mauke</i>						
ANU 4860	MK11	Tukume	Emergent microatoll on reef flat, < 30 cm above upper limit to live coral	? <i>Porites</i>	31 600 ± 800	31 150 ± 800
ANU 4861	MK12	Tukume	On limestone ramp, < 25 cm above upper limit to live coral	<i>Tridacna</i>	39 020 ± 2000	38 570 ± 2000
ANU 4862	MK13	North of Taunganui	Emergent coral on reef crest, < 20 cm above upper limit to live coral	<i>Porites</i>	3350 ± 80	2900 ± 85

^a Environmentally-corrected using the correction adopted for Australian marine shells, 450 ± 35 years, also found to be valid for Tonga (Gillespie and Polach 1979; Poulsen 1987)

4.4 km wide. The volcanic core is degraded, and remains as four discrete low “foodland” areas of deeply weathered volcanic soil reaching a maximum elevation of 8.9 m. Much of the interior is swampy, and a large lake Te Rotonui occupies the eastern interior. Makatea limestones reach 10.9 m. There is very little or no reef flat along the north coast but the reef flat averages 90 m wide on the west of the island and 120 m on the east and south-eastern sides.

Much of the reef flat on Mitiaro is of eroded limestone, barren of live coral with little sediment cover and emergent at low water. On the southwestern side of the island this surface rises as an eroded and pitted platform in the middle of the reef flat up to 1.23 m above mean low water and 1.1 m above the present upper limit to coral growth (Stoddart et al. in press). Fossil corals within this rugged portion of the reef flat, but generally not clearly in growth position, include *Porites*, *Acropora* and faviid corals. A sample of *Porites* from the transect shown in Fig. 3 has been dated 4000 ± 85 years B.P. Several radiocarbon dates have been obtained on corals from the landward side of similar emergent reef flat at Vaikoua, 5140 ± 95, 4400 ± 95, 3900 ± 95 and 3620 ± 85 years B.P. (Table 2).

A specimen of *Tridacna* in growth position on a ramp at Akapa and a microatoll at the landward margin of the reef flat at the north of the island were also dated as they were thought to be in an analogous position to Holocene

microatolls on the ramp of the emergent notch on Mangaia. Both samples from Mitiaro were entirely aragonitic, however they yielded late Pleistocene ages (Table 2).

There are a number of erosional coastal features on Mitiaro which also indicate Holocene emergence. On the northeast coast there is a conspicuous cliff-foot notch at a height of 0.5–1.0 m above mean low water. Near Parava on the east coast there is a higher notch, with a floor at 1.79 m and its deepest part 2.27 m.

Mauke

Mauke (20° 08' S, 157° 21' W) is a similar size to Mitiaro; it is 6.4 km long and 4 km wide. The volcanic core rises to 24.4 m high, and the makatea limestones reach 14.6 m. The reef flat averages 75 m wide on the northern coast, 95 m wide on the eastern coast and 165 m wide on the western coast (Fig. 4). The base of the limestone cliff is conspicuously notched at 0.6–1.5 m above mean low water. A cliff-foot bench at an elevation of 2.7 m is found at Anaraura, and in some places anomalously high beachrock was observed (Stoddart et al. in press).

The reef flat on Mauke, while not as clearly preserving evidence of emergence as that on Mitiaro, nevertheless is barren of live coral over much of its surface, and is exposed at low tide in several places. An emergent

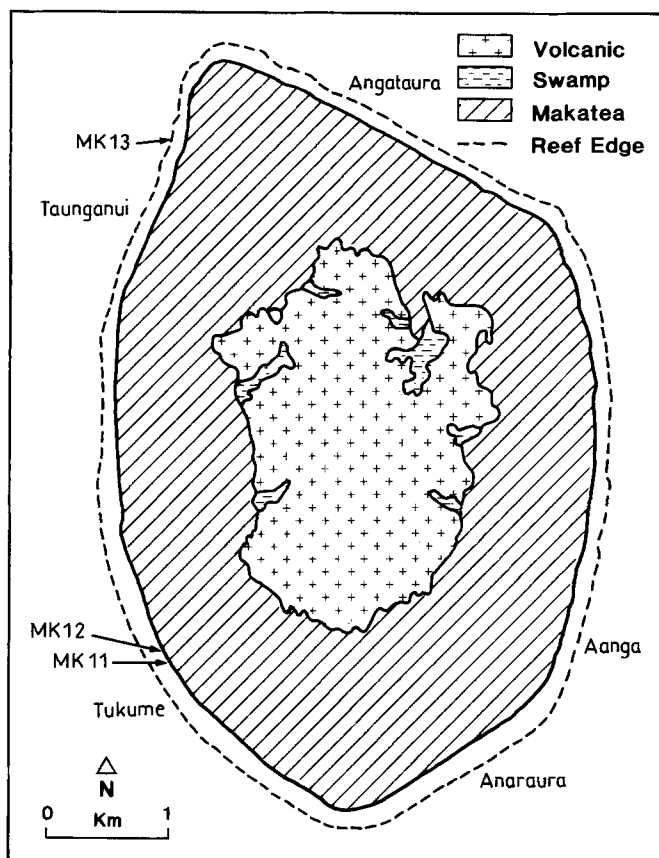


Fig. 4. Mauke, Southern Cooks, showing location of radiocarbon-dated samples

microatoll and a *Tridacna* in growth position were sampled from the ramp at the base of the cliff at Tukume landing and yielded late Pleistocene ages. The only Holocene coral to have been dated that appeared to be slightly above the present upper limit to coral growth came from the reef flat near the reef crest on the northeast of the island where the reef flat is narrowest. At this locality an emergent specimen of *Porites* dated 2900 ± 85 years B. P. (Table 2).

Atiu

Atiu ($20^{\circ} 00' S$, $158^{\circ} 10' W$) is a slightly larger makatea island; it is 7.2 km long and 6.3 km wide. The degraded volcanic core rises to 72 m and the makatea which varies up to 1 km wide, rises to 23 m, although much of the limestone to the south of the island does not exceed 15 m high. The reef flat is extremely narrow on the northeast and absent on the north coast where there is a prominent surf bench; it reaches about 100 m wide on the southeast and 140 m wide on the western shore.

The reef flat is generally barren of coral growth, except for colonies of *Porites* which occur in pools on the reef flat surface. In places the reef flat appears to be formed of large coalescing *Porites* microatolls. Elsewhere it is traversed by algal terracettes perpendicular to the algal rim. No evidence of Holocene emergence was seen on the reef flat.

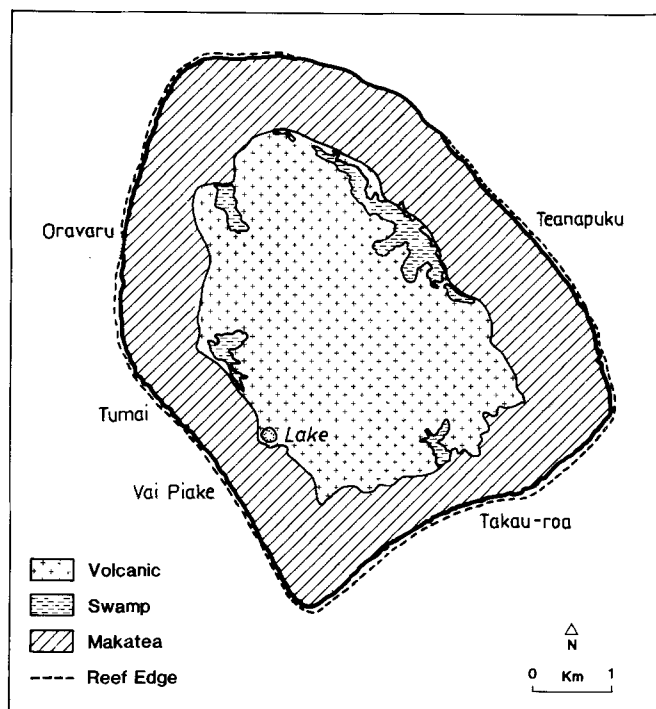


Fig. 5. Atiu, showing location of places mentioned in the text

However, there are several notches and benches around the island which may be Holocene in age. There is a bench 2.8 m above mean low water at Takau-roa, a bench and a notch at 1.8 m at Oravaru, a notch at 3.3 m at Teanapuka, a bench at 1.8 m at Turnai, and a bench and notch at 2.8–3.6 m at Vai Piake (Fig. 5). Those benches at around 2.8 m above mean sea level may represent features controlled by a contact between lower and upper Pleistocene reefal limestones (Stoddart et al. in press). The lower feature, at 1.7–1.8 m above mean low water may be indicative of Holocene emergence.

Discussion

On Mangaia, the largest of the makatea islands, 9 km long, 7.7 km wide with volcanics and makatea to altitudes of 169 m and 70 m respectively, clear evidence of Holocene emergence has been reported (Yonekura et al. 1984; Stoddart et al. 1985). Around much of the island there is a conspicuous cliff-foot erosional notch 1.5–2.5 m above the presently forming notch. Yonekura et al. have described thin microatolls (<40 cm thick) veneering the ramp of the notch, the highest of which is 1.5 m above mean sea level, has been dated 3410 ± 170 years B. P. and indicates 1.7 m of emergence. Further emergent microatolls have been dated 5020 ± 190 , 4990 ± 210 , 4370 ± 210 , 3980 ± 180 and 3540 ± 190 years B. P. In addition there is a rugged upper surface to the central reef flat from which *Acropora* have been dated 3950 ± 150 and 3640 ± 170 years B. P. (Yonekura et al. 1986). Drilling on the reef flat has revealed that the rugged central reef flat contains a former reef crest, from which coral has been dated 4070 ± 200 years B. P., while the modern reef crest dates 2290 ± 160 years B. P. Between the reef crests drill-

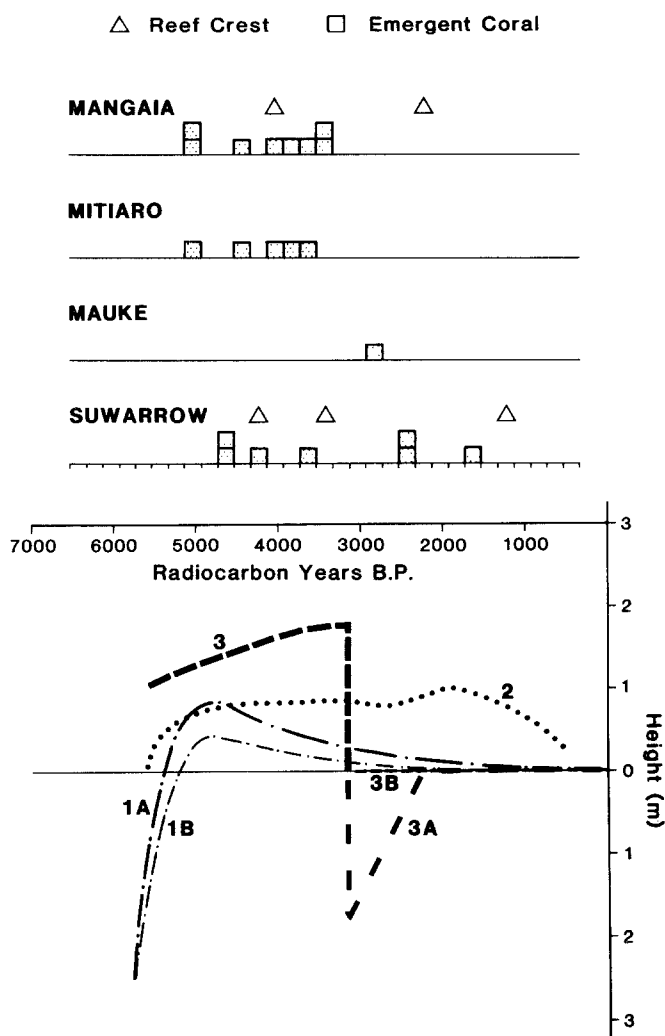


Fig. 6. Radiocarbon-dated samples of emergent deposits on reef flats and fossil reef crests from the Cook Islands, and a comparison with sea-level curves reported for the area. 1: after Clark et al. (1978), for 165° W: 1A for 22° S; 1B for 10° S; 2: after Pirazzoli and Montaggioni (1988) for French Polynesia; 3: after Yonekura et al. (1986) for Mangaia, 3A and 3B represent alternatives

ing revealed backreef sediments, indicating that the reef has advanced episodically, rather than prograding gradually. Initially Yonekura et al. (1984) interpreted the Mangaia evidence to indicate that the island had been tectonically uplifted 2 m in the last 3000 years, in the apparent absence of similar emergent features on Rarotonga and Aitutaki. Subsequently they have suggested a relative sea level history for the island in which rapid emergence has occurred soon after 3400 years ago, either followed by a period of sea level stability, or by gradual re-submergence (Yonekura et al. 1986, 1988). Their alternative sea level scenarios are shown in Fig. 6.

The data reported here from other islands in the Cooks indicate that emergence has been widespread. Furthermore radiocarbon dating of emergent evidence indicates that emergence has been broadly synchronous between islands, including Mangaia (Fig. 6). This would appear to imply that it is controlled by a regional sea-level trend. Most ages for emergent Holocene features in the Cook Islands fall in the range 5100–3400 years B.P.,

despite differing practices adopted by laboratories in reporting radiocarbon ages. Emergence at this time is consistent with that predicted by several geophysical models (i.e. Clark et al. 1978; Lambeck and Nakada 1985). This record, however, appears to differ slightly from that identified in French Polynesia (Pirazzoli et al. 1985; Pirazzoli and Montaggioni 1988) where a sea level relatively higher than present persisted until 1250 years B.P. Yonekura et al. (1988), discussing the evidence from Mangaia, have pointed out that while the scarcity of emergent features dated younger than 3400 years B.P. does not in itself negate a gradual fall of sea level since that time, rapid emergence seems more likely to explain the progradation of the reef front. The data reported here imply that this trend was widespread in the Cook Islands, but it is unclear why the pattern of relative sea-level change in the Cook Islands should differ from that in French Polynesia.

The timing of Holocene reef growth on makatea islands, on which there is a basement of last interglacial limestones for corals to colonise as sea level rose, and on which coral growth might be expected to adopt a keep-up strategy (Neumann and Macintyre 1985), has been similar to that on the atoll of Suvarrow, on which there is no pre-Holocene basement exposed and where reef growth might be expected to have lagged behind sea level (catch-up strategy). The principal anomalies in terms of age of emergent corals are a sample from Mauke dated 2900 years old only slightly postdating emergence elsewhere, and emergent reef on the southern atoll rim of Suvarrow dated 2400 years old, possibly related to tectonic tilting of the atoll. The modern reef crest on Mangaia has been dated 2200–2400 years B.P. (Yonekura et al. 1986). On Suvarrow Atoll an age of 1250 ± 35 years B.P. has been determined on the present algal rim, on which there is a live calcareous algal veneer.

The pattern of episodic build-out of the reef crest identified on Mangaia, is also shown by the fossil algal ridges on Suvarrow where three reef crests are identified. Reef flat morphology on Mitiaro (shown in the transect in Fig. 3) resembles that described by Yonekura et al. (1986) on Mangaia and may mean that the emergent, rugged reef flat on Mitiaro similarly represents a former reef crest. Similar emergent portions of the central reef flat, which may also prove to contain mid or late Holocene reef crests have been described on Reao (Pirazzoli et al. 1987b) and Makatea (Montaggioni et al. 1985).

Initial modelling of eustatic response of a viscoelastic earth to postglacial ice melt, based on Northern Hemisphere ice sheets predicted emergence of the Cook Islands. Figure 6 shows the predicted sea-level signature at 10° S (curve 1B) and 22° S (curve 1A) from Clark et al. (1978). Greater emergence was predicted to the south, a trend identified by the detailed sea-level reconstructions undertaken for many of the islands of French Polynesia by Pirazzoli and Montaggioni (1988). However more recent modelling has shown that individual island sea-level signatures are particularly dependent upon details of Antarctic deglaciation (Nakiboglu et al. 1983; Nakada and Lambeck 1988). Some patterns of Antarctic ice melt (supplementing northern Hemisphere ice melt) generate

predictions of gradual submergence for the Cook Islands (Nakada 1988), while others predict emergence (i.e. alternatives in Peltier 1988). Furthermore it can also be shown that sea-level signatures depend on the adopted lithospheric thickness, and are not unique (Peltier 1988).

Pirazzoli and Montaggioni (1988) recognise a second trend in the pattern of Holocene sea-level records for French Polynesia, which they believe corresponds to flexure of the lithosphere. They indicate that emergent Holocene reef deposits on young volcanic islands, specifically Moorea and Tahiti, plot below the general trend of Holocene sea-level evidence, whereas several other islands plot above the general trend. The latter group include islands which appear to be on the flexed arch of young volcanic islands, i.e. Makatea, or appear to have been thermally rejuvenated, i.e. Anaa (Pirazzoli et al. 1988) and Rurutu (Pirazzoli and Veeh 1987; Stoddart and Spencer 1987).

The data from the Cook Islands appear broadly consistent with two of the trends identified in French Polynesia by Pirazzoli and Montaggioni (1988), namely that emergence increases to the south, and that young volcanic islands are less emerged, and those on an uplifted arch are more emerged than islands beyond the flexure. However, there is neither the geographical spread of data points necessary, nor sufficiently precise indicators of former sea level on the islands to satisfactorily test for either trend. The best indicators of former sea level are the emergent microatolls described from Mangaia by Yonekura et al. (1984, 1986, 1988), and the fossil algal ridges from Suvarrow. The former indicate that sea level reached a level 1.7 m higher than present on Mangaia, and the latter indicate up to 1 m of emergence on Suvarrow. Mitiaro has clear evidence of emergence, probably of around 1.0–1.2 m. Mauke appears to have emerged, though by how much is uncertain, and on Atiu the only evidence of emergence noted was cliff-foot erosional features, the age for which could not be determined. On Rarotonga and on Aitutaki evidence for emergence has been reported, but its interpretation is not unambiguous. On Rarotonga, Schofield (1967, 1970) has reported from Avarua a Holocene reef emergent by about 1 m but which is no longer exposed. Our own investigations have not revealed any evidence for Holocene emergence on the island. On Aitutaki the features described as emergent reef by Shepard (1961) do not contain clear evidence that they were formed when sea level was higher than present (Stoddart 1975). However, recently Yonekura et al. (1988) have reported a microatoll dated 1530 ± 210 years B.P. from near the airfield on Aitutaki which may indicate emergence of 0.4 m or more.

The greatest emergence, that on Mangaia, occurs on the southernmost island, which is also located on the arch of the young volcanic load of Rarotonga. Little (1 m or less) if any emergence has occurred on Rarotonga and Aitutaki; this is geophysically consistent as these islands, the former a Pleistocene volcanic island, and the latter an island that has undergone secondary Pleistocene volcanism, might be expected to still be gradually subsiding (Lambeck and Nakada 1985). Other islands on the arch, Mitiaro, Mauke and Atiu, appear to have undergone

Holocene emergence. However emergence is also indicated away from the area of flexure by the results from Suvarrow. Some Holocene tectonic movement may have occurred on the atoll to account for the greater ages for emergent reef on the northern than on the southern atoll rim (Scoffin et al. 1985). However, the similarity in timing of reef flat emergence and of reef crest progradation with that in Mangaia and other makatea islands in the Southern Cooks, suggests that the features on the northern atoll rim have undergone little disturbance as a result of any tilting that has occurred, and that Suvarrow, like those islands to the south, reflects a dominant eustatic record.

Conclusion

Holocene emergence has been widespread in the Cook Islands, similar to, but perhaps not entirely contemporaneous with, that described throughout French Polynesia. There is an extensive emergent and truncated reef on the northern atoll rim of Suvarrow dated 4680–4310 years B.P., and emergent algal ridges at 4220 and 3420 years B.P., since which time there has been build-out of the reef flat. Emergent reefal deposits on the centre of the reef flat on Mitiaro similarly date 5140–3620 years B.P., and may mark a former reef crest. The emergence of these two islands appears synchronous with that reported for Mangaia, and comparable emergence is likely for both Mauke and Atiu. While the pattern of emergence appears to reflect greater emergence towards the south, and greater emergence on the flexed arch at critical radii from the young volcanic island load of Rarotonga, there is neither the geographical coverage, nor precise enough indicators of former sea level on those islands to confirm this.

Acknowledgements. Research in the Cook Islands was made possible by financial assistance from the Royal Society of London, the Australian National University, the University of Manchester and the University of Auckland. The New Zealand Oceanographic Institute facilitated fieldwork on Suvarrow Atoll. We are grateful to Radiocarbon Laboratory of the DSIR New Zealand for dating samples, and to Henry Polach and John Head of the Australian National University Radiocarbon Dating Laboratory for further dating and for discussions on comparison of dating methods. We wish to acknowledge the considerable assistance we received from the chief administrative officers and islanders on Atiu, Mauke and Mitiaro, and from Stuart and Teriapi Kingan and Tony Utanga on Rarotonga.

References

- Bloom AL (1980) Late Quaternary sea level change on South Pacific coasts: a study in tectonic diversity. In: Morner NA (ed) Earth rheology, isostasy and eustasy. Wiley, London, pp 505–516
- Brousse R (1985) The age of the islands in the Pacific Ocean: volcanism and coral-reef build up. *Proc 5th Int Coral Reef Symp* 6:389–400
- Buddemeier RW, Smith SV, Kinzie RA (1975) Holocene windward reef-flat history, Eniwetok Atoll. *Geol Soc Am Bull* 86:1581–1584
- Calmant S, Cazenave A (1986) The effective elastic lithosphere under the Cook-Austral and Society Islands. *Earth Planet Sci Lett* 77:187–202

- Clark JA, Farrell WE, Peltier WR (1978) Global change in postglacial sea level: a numerical calculation. *Quat Res* 9:265–287
- Dalrymple GB, Jarrard RD, Clague DA (1975) K-Ar ages of some volcanic rocks from the Cook and Austral Islands. *Bull Geol Soc Am* 86:1463–1467
- Daly RA (1920) A general sinking of sea level in recent time. *Proc Natl Acad Sci* 6:246–250
- David TWE, Sweet G (1904) The geology of Funafuti. In: *The Atoll of Funafuti*. Royal Society, London, pp 61–124
- Davies PJ, Montaggioni LF (1985) Reef growth and sea-level change: the environmental signature. *Proc 5th Int Coral Reef Symp* 3:477–515
- Gardiner JS (1903) The fauna and geography of the Maldive and Laccadive Archipelagoes, Cambridge University Press, Cambridge
- Gillespie R, Polach HA (1979) The suitability of marine shells for radiocarbon dating of Australian prehistory. *Proc 9th Int Conf Radiocarbon*, pp 404–421
- Gupta SK, Polach HA (1985) Radiocarbon dating practices at ANU. Radiocarbon Dating Laboratory, ANU
- Hopley D (1987) Holocene sea-level changes in Australasia and the Southern Pacific. In: Devoy, RJN (ed) *Sea surface studies: a global review*. Croom Helm, London, pp 375–408
- Kaplin PA (1981) Relief, age and types of oceanic islands. *NZ Geogr* 37:3–12
- Lambeck K (1981) Lithospheric response to volcanic loading in the southern Cook Islands. *Earth Planet Sci Lett* 55:482–496
- Lambeck K, Nakada M (1985) Holocene fluctuations in sea level: constraints on mantle viscosity and melt-water sources. *Proc 5th Int Coral Reef Symp* 3:79–84
- McNutt M, Menard HW (1978) Lithospheric flexure and uplifted atolls. *J Geophys Res* 83:1206–1212
- Montaggioni LF, Pirazzoli PA (1984) The significance of exposed coral conglomerates from French Polynesia (Pacific Ocean) as indicators of recent relative sea-level changes. *Coral Reefs* 3:29–42
- Montaggioni LF, Richard G, Bourrouilh-Le Jan F, Gabrie C, Humbert L, Monteforte M, Naim O, Payri C, Salvat B (1985) Geology and marine biology of Makatea, an uplifted atoll, Tuamotu Archipelago, Central Pacific Ocean. *J Coastal Res* 1:165–171
- Nakada M (1986) Holocene sea levels in oceanic islands: implications for the rheological structure of the earth's mantle. *Tectonophysics* 121:263–276
- Nakada M (1988) Holocene sea-level changes and isostasy. In Yonekura, N (ed) *Sea-level changes and tectonics in the Middle Pacific*, Report of the Hipac Project, Department of Geography, University of Tokyo, Japan, pp 7–17
- Nakada M, Lambeck K (1988) The melting history of the late Pleistocene Antarctic ice sheet. *Nature* 333:36–40
- Nakiboglu SM, Lambeck K, Aharon P (1983) Postglacial sealevels in the Pacific: implications with respect to deglaciation regime and local tectonics. *Tectonophysics* 91:335–358
- Neumann AC, Macintyre IG (1985) Reef response to sea level rise: keep-up, catch-up or give-up. *Proc 5th Int Coral Reef Symp* 3:105–110
- Newell ND (1961) Recent terraces of tropical limestone shores. *Z Geomorph NF [Suppl]* 3:87–106
- Peltier WR (1988) Lithospheric thickness, Antarctic deglaciation history, and ocean basin discretization effects in a global model of postglacial sea level change: a summary of some sources of nonuniqueness. *Quat Res* 29:93–112
- Pirazzoli PA, Montaggioni LF (1986) Late Holocene sea-level changes in the northwest Tuamotu Islands, French Polynesia. *Quat Res* 25:350–368
- Pirazzoli PA, Montaggioni LF (1988) Holocene sea-level changes in French Polynesia. *Palaeogeog Palaeoclim Palaeoecol* 68:153–175
- Pirazzoli PA, Veeh HH (1987) Age $^{230}\text{Th}/^{234}\text{U}$ d'une encoche émergée et vitesses de soulèvement quaternaire à Rurutu, îles Australes. *CR Acad Sci Paris* 305:919–923
- Pirazzoli PA, Montaggioni LF, Delibrias G, Faure G, Salvat B (1985) Late Holocene sea-level changes in the Society Islands and the northwest Tuamotu atolls. *Proc 5th Int Coral Reef Symp* 3:131–136
- Pirazzoli PA, Montaggioni LF, Vergnaud-Grazzini C, Saliege JF (1987a) Late Holocene sea levels and coral reef development in Vahitahi Atoll, eastern Tuamotu Islands, Pacific Ocean. *Mar Geol* 76:105–116
- Pirazzoli PA, Delibrias G, Montaggioni LF, Saliege JF, Vergnaud-Grazzini C (1987b) Vitesse de croissance laterale des platiers et évolution morphologique récente de l'atoll de Reao, îles Tuamotu, Polynésie Française. *Ann Inst Oceanogr* 63:57–68
- Pirazzoli PA, Koba M, Montaggioni LF, Person A (1988) Anaa (Tuamotu Islands, Central Pacific): an incipient rising atoll? *Mar Geol* 82:261–269
- Poulsen J (1987) Early Tongan prehistory. *Terra Australis* (The Australian National University), vol 12
- Schofield JC (1967) 1. Post glacial sea-level maxima a function of salinity? 2. Pleistocene sea-level evidence from the Cook Islands. *J Geosci Osaka City Univ* 10:115–120
- Schofield JC (1970) Notes on late Quaternary sea levels, Fiji and Rarotonga. *NZ J Geol Geophys* 13:199–206
- Scoffin TP, Stoddart DR, Tudhope AW, Woodroffe CD (1985) Exposed limestones of Suvarrow Atoll. *Proc 5th Int Coral Reef Symp* 3:137–140
- Scott GAJ, Rotondo GM (1983) A model to explain the differences between Pacific Plate island atoll types. *Coral Reefs* 1:139–150
- Shepard FP (1961) Sea level rise during the past 20 000 years. *Z Geomorph NF [Suppl]* 3:30–38
- Shepard FP, Curray JR, Newman WA, Bloom AL, Newell ND, Tracey JI, Veeh HH (1967) Holocene changes in sea level: evidence in Micronesia. *Science* 157:542–544
- Spencer T, Stoddart DR, Woodroffe CD (1987) Island uplift and lithospheric flexure: observations and cautions from the South Pacific. *Z Geomorph NF [Suppl]* 63:87–102
- Spencer T, Stoddart DR, Woodroffe CD, Harmon RS (1988) Lithospheric flexure and raised reef limestones, S. Cooks-Austral Islands. *Proc 6th Int Coral Reef Symp* 3:485–489
- Stoddart DR (1975) Almost-atoll of Aitutaki: geomorphology of reefs and islands. *Atoll Res Bull* 190:31–57
- Stoddart DR, Spencer T (1987) Rurutu reconsidered: the development of makatea topography in the Austral Islands. *Atoll Res Bull* 297:1–19
- Stoddart DR, Spencer T, Scoffin TP (1985) Reef growth and karst erosion on Mangaia, Cook Islands: a reinterpretation. *Z Geomorph NF [Suppl]* 57:121–140
- Stoddart DR, Woodroffe CD, Spencer T (in press) Mauke, Mitiaro and Atiu: Geomorphology of makatea islands in the Southern Cooks. *Atoll Res Bull*
- Turner DL, Jarrard RD (1982) K-Ar dating of the Cook Austral Island chains: a test of the hot-spot hypothesis. *J Volc Geotherm Res* 12:187–220
- Watts AB, Ribe NM (1984) On geoid heights and flexure of the lithosphere at seamounts. *J Geophys Res* 89:11152–11170
- Wood BL, Hay RF (1970) Geology of the Cook Islands. *NZ Geol Surv Bull* 82:1–103
- Yonekura N, Matsushima Y, Maeda Y, Kayanne H (1984) Holocene sea-level changes in the southern Cook Islands. In: Sugimura A (ed) *Sea level changes and tectonics in the Middle Pacific*. Report of the Hipac Project, Department of Earth Sciences, Kobe University, Japan, pp 113–136
- Yonekura N, Ishii T, Saito Y, Matsumoto E, Kayanne H (1986) Geologic and geomorphic development of Holocene fringing reefs of Mangaia Island, the South Cooks. In: Sugimura A (ed) *Sea level changes and tectonics in the Middle Pacific*. Report of the Hipac Project, Department of Earth Sciences, Kobe University, Japan, pp 44–69
- Yonekura N, Ishii T, Saito Y, Maeda Y, Matsushima Y, Matsumoto E, Kayanne H (1988) Holocene fringing reefs and sea-level change in Mangaia Island, Southern Cook Islands. *Palaeogeog Palaeoclim Palaeoecol* 68:177–188