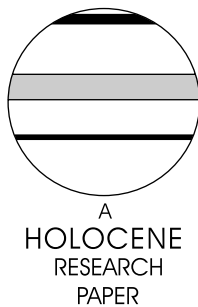


# Holocene changes in sea level and coastal environments on Rarotonga, Cook Islands, South Pacific Ocean

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Received 6 July 2004; revised manuscript accepted 28 March 2006



**Abstract:** The Holocene coastal plain of the island of Rarotonga, characterized by beach ridges and swamps, is the best developed of the Cook Islands group which lies in eastern Polynesia. Using geomorphic mapping, excavation and coring, and <sup>14</sup>C dating of these coastal deposits, we have reconstructed a sea-level curve and drawn maps of shoreline development for the middle to late Holocene. Our sea-level curve shows that sea level attained a position similar to that at present by 6000–6500 cal. BP, then gradually rose to a level of *c.* +1.5 m above present sea level by *c.* 4500 cal. BP. Highstands, possibly with fluctuations to lower levels, occurred during the interval *c.* 4500 to *c.* 800–500 cal. BP. Sea level has fallen to its present level since *c.* 800–500 cal. BP. The sea-level curve is similar to curves obtained elsewhere in Polynesia. Hydro-isostatic movement may have been responsible for the relative sea-level change before *c.* 800–500 cal. BP, whereas the sea-level fall since then is in agreement with records from western Polynesia that attribute such a fall to climatic change. The coastal plain of Rarotonga began to emerge *c.* 4500 cal. BP, and prograded to the present coastline, most conspicuously on the northeastern coast. The formation of such a flat area on the coast associated with these mid- to late Holocene shoreline developments is likely to have influenced the pattern of human settlement in Rarotonga.

**Key words:** Coastal plain, sea-level change, coastal environmental change, Rarotonga, Cook Islands, Holocene, South Pacific.

## Introduction

### Purpose

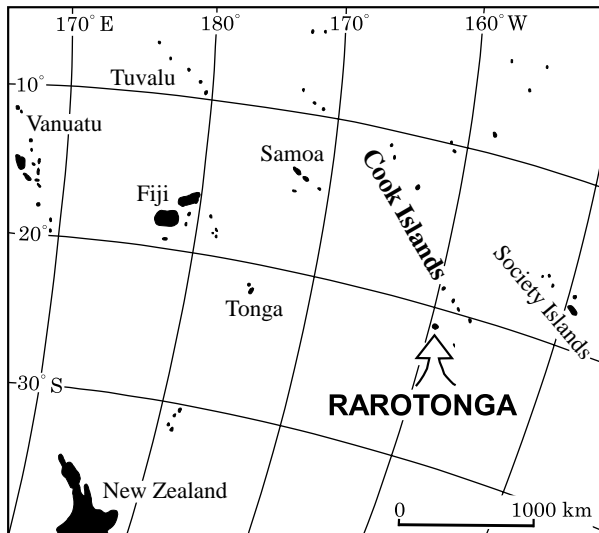
Coastal plains comprising beach ridges and swamps have excellent potential for measuring sea-level and shoreline changes. Rarotonga, situated in the southern Cook Islands, South Pacific Ocean, at 21°13'S latitude and 159°47'W longitude, lies in the western part of Polynesia (Figure 1). The largest of the Cook Islands group, Rarotonga is an oval-shaped island 11 km long and 7 km wide, on which the coastal plains are among the best developed in Polynesia. The island is fringed on all sides with a coastal lowland 1 km wide and an associated coral reef *c.* 1 km wide (Figure 2). A detailed study

of Rarotonga's beach ridges and swamps, together with a chronology based on radiocarbon dating, provides new data that document high-resolution sea-level and shoreline change for this part of the southern Cook Islands.

Marshall (1930) initially recognized four landform units on Rarotonga (reef, beach and strand, swamp, volcanic ground). Further work was undertaken by Schofield (1970), Wood and Hay (1970), Peters (1994), Yonekura (1994), Chikamori (1995, 2001) and Woodroffe *et al.* (1990, 1991) but in little detail. Consequently, we aim to document past sea levels and coastal environments since the middle Holocene from a detailed chronological study of the coastal plains of Rarotonga.

Our study is important for the wider study of sea-level change in the south-central Pacific and for assessing hydro-isostatic effects (Dickinson, 2001). In addition, it is important

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**Figure 1** Location of Rarotonga

in helping to understand the relation of coastal environmental change to the migration and settlement of the earliest people in the Pacific, a subject of controversy (Kirch and Ellison, 1994; Dickinson, 2003). The Cook Islands lie in a key position to examine settlement from western Polynesia (Fiji, Tonga, Samoa), which were colonized around 3000 years ago (Figure 1; Allen, 1998). Rarotonga, in eastern Polynesia, has much potential for early human occupation because of its wide and continuous coastal plain and because the adjacent volcanic mountains supply reliable water resources. Polynesians typically established their settlements in coastal environments (Allen, 1998; Nunn, 1998) and so such areas are likely locations for early archaeological sites (Dickinson *et al.*, 1999).

### Methods

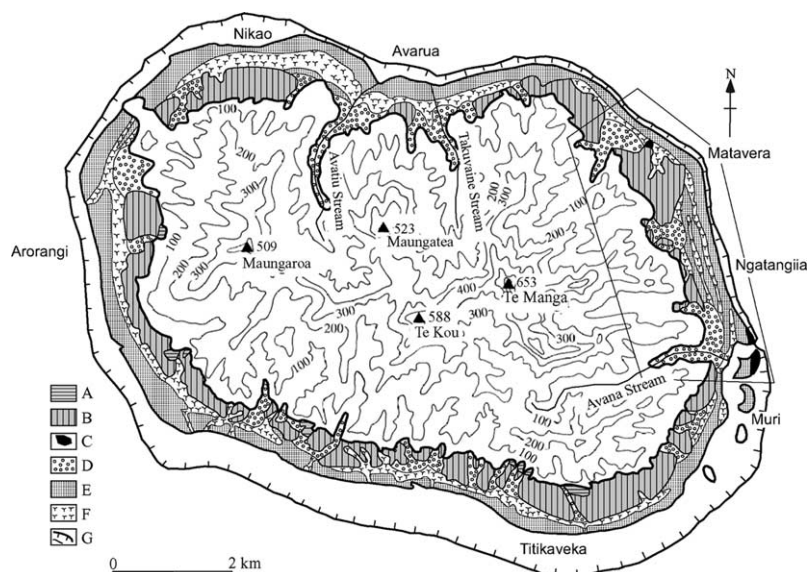
We made a detailed landform map of the coastal plain (Figure 2) using air-photographs at 1:10 000 scale, and our own geomorphic and geologic field surveys. It was refined by comparison with the soil map (Department of Scientific and Industrial Research, Wellington, New Zealand, 1980). The most intensive investigations of landforms and surface deposits

were made on the eastern coast (Figure 3), where the suite of coastal landforms made it possible to reconstruct mid- to late Holocene changes in coastal environment in detail. The landforms comprise a wide sand ridge and swale plain, a relatively low flat alluvial lowland at the mouth of the longest stream in Rarotonga, Holocene emergent micro-atolls attached to coastal erosional features formed in Pleistocene coral limestone and a wetland comprising thick peat. Deposits were excavated using a power shovel as well as hand shovels and borers. The elevations and landform profiles were surveyed using precise levelling equipment based on the bench marks fixed by the Cook Islands Government. The chronology of coastal evolution is based on 21 radiocarbon ages obtained from Nagoya University Center for Chronological Research, Japan, and Beta Analytic Radiocarbon Dating Laboratory, USA.

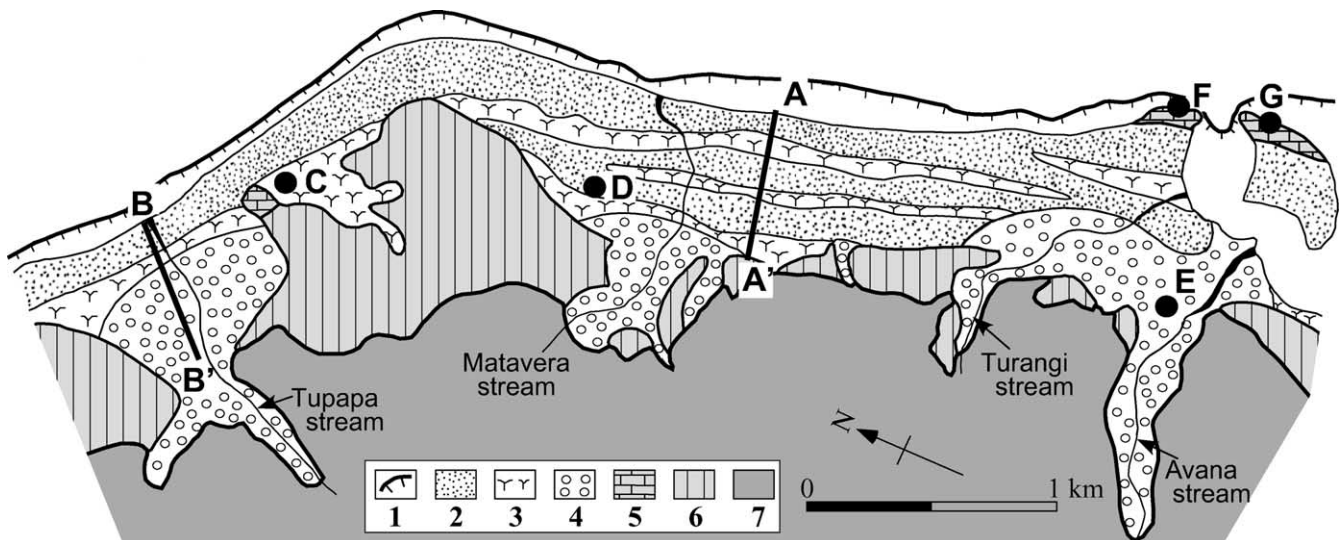
### General geology and geomorphology

The basement of Rarotonga consists of a volcanic complex built by effusive and pyroclastic deposits, mainly mafic in origin, and of late Pliocene to early Pleistocene age erupted within the Cook-Austral Island volcanic chain (Thompson *et al.*, 1998). Most of the island comprises the tip of a large volcanic edifice rising from *c.* 4000 m depth. Rarotonga is composed of three major landform units: mountains, coastal plains and a Holocene coral reef that fringes the coastal plain (Figure 2). Mountains and associated high ridges are extensive in Rarotonga and generate large drainage systems with permanent water courses. The major ridge and drainage systems on Rarotonga are dominated by the central depression which opens to the north with a sole ridge (Maungatea) in its centre and surrounding subcircular mountain ridges (Figure 2). These features are interpreted as either the remnants of an extinct caldera collapse system (Wood and Hay, 1970) or simply as erosional features (Thompson *et al.*, 1998). The main peaks, including the highest (Te Manga) at 653 m above sea level, generally attain 500 to 600 m elevation.

Drainage is dominated by three major rivers with relatively low gradients: Avana Stream, which occupies the southeastern side of the island, and Avatiu and Takuvaine streams, which flow from the central depression (Figure 2). Other streams, almost all of which rise from the main ridges, follow relatively straight courses with steep gradients.



**Figure 2** Geomorphologic map of Rarotonga. A, Pleistocene upper terrace; B, Pleistocene lower terrace; C, Pleistocene coral reef; D, alluvial fan; E, sand ridge; F, swale and swamp; G, present coral reef. The pentagonal area on the east coast indicates Figure 3. Figures in the mountain area indicate elevation in metres



**Figure 3** Geomorphologic map and investigation sites on the eastern coast of Rarotonga. 1, Present coral reef; 2, sand ridge; 3, swale and swamp; 4, alluvial fan; 5, Pleistocene coral reef; 6, Pleistocene alluvial fan; 7, mountain. See Figure 2 for location

## Landforms of the coastal area

The coastal area consists of emergent alluvial fans, the Holocene coastal plain and the present coral reef, in belts from inland to seaward (Figure 2). There are two emergent alluvial fans, an upper and lower. The upper fan with a height of around 20 m is poorly preserved and occurs along the south to southeastern foot of the mountains. The lower one, with an elevation 20 m or less, is more extensive, flanking the entire base of the mountains and bordered by sea-cliffs cut by the Holocene high sea level. The fans consist of comparatively weathered basaltic gravels of likely Pleistocene age (Nikao Gravels: Wood and Hay, 1970).

Pleistocene coral limestones found in places on the east coast are probably contemporaneous with the lower Pleistocene emergent alluvial fans, judging from the similarity of the elevations between the emerged reef surfaces and the trimlines along the seaward edge of the fans. The limestones at Ngatangia reach 3.5 m in elevation, which is among the lowest in the southern Cook Islands (Woodroffe *et al.*, 1991). Although the radiocarbon ages on those limestones are 30 000 to 50 000 years BP. (Schofield, 1970), they are considered to be of last interglacial age (Oxygen Isotope Stage [OIS] 5e) (Berryman, 1987; Woodroffe *et al.*, 1991; Nakada, 1996). Thus, Woodroffe *et al.*, (1991) reported that slight subsidence with an average rate of 0.02 mm/yr might have occurred over the last 120 000 years, if the sea level stood 6 m above present at the peak of the last interglaciation.

The Holocene coastal plain is characterized by a stretch of sand ridges, swales and swamps, which are associated with alluvial fans at most stream outlets (Figure 2). On the sand ridge and swale plain, there generally occurs a single row of sand ridges associated with a relatively wide swamp on the mountain (inland) side, except along the eastern coast (Ngatangia-Matavera district), in which Pleistocene terraces are poorly developed. Instead, multiple rows of sand ridges and swales occur here as described below. Sand deposits constituting these ridges classified as the Aroa Sand (Wood and Hay, 1970).

The elevation of the sand ridge is higher on the north to northeast coast, fringing a narrower reef flat, than on the south coast where the fringing reef flat is wider. Higher ridges, the highest of which is 4 m above mean sea level, consist of coral

gravels deposited by storm-wave action, whereas lower ridges are sand-dominated, deposited by smaller waves running across the wide reef flat. Although considerable quantities of basalt gravels are supplied to the coast, the widely distributed beach ridges do not contain these gravels but instead comprise coral sands and gravels, suggesting that the production of coral sediments on the reef and reef flat and their supply to the shore has been dominant, as reported by Dickinson (2000) for a similar location in the Mariana islands.

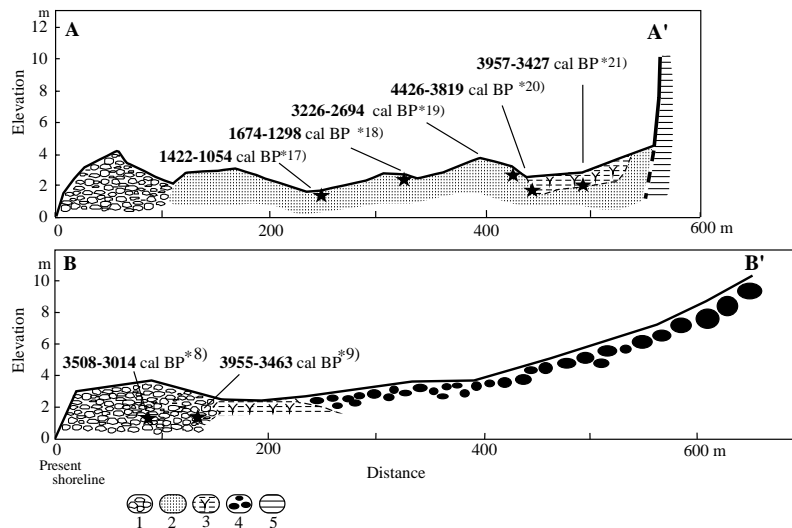
Most swamps occur in a single elongate belt between the sand ridges and the Pleistocene or Holocene alluvial fans. The widest wetlands occur at Nikao and Arorangi. Much of the water in these wetlands is groundwater derived from a stream that crosses the alluvial fans. However, most alluvial fans have no permanent surface streams because of their steep gradients.

The modern fringing reef is characteristically wider on the southern (windward) coast compared with the reefs of other coasts (Figure 2). The reef flat on the southern coast is ~1 km wide, but those fringing the other coasts are less than a few hundred metres in extent. That the Holocene coastal plains are narrow on the southern coast suggests a scarcer supply of sediment to the reef flat during the Holocene, whereas elsewhere there was enough sediment supplied to the reef flat to form a wide coastal plain. The total width of the coastal plain and modern reef flat is nearly equal (~1 km) around the entire coast. The differences in origin are probably due to different strengths of wave action and current flow, which are influenced by the dominant southeast trade winds. The broadest reef flat and coastal plain lie on the southeast of the islands, which is expected in the tropical South Pacific (Nunn, 1994).

## Landforms, deposits and radiocarbon ages on the eastern coast

### Landforms

The coastal landforms containing the multiple beach ridge and swales, best developed in the eastern part of the island, provide the clearest indication of shoreline and sea-level change since the mid-Holocene (Figure 3). More than three rows of ridges and swales, ~1 km wide, associated with alluvial fans occur in



**Figure 4** Topographic and surface geologic cross-section, and radiocarbon ages on the east coastal plain. 1, Coral gravel; 2, sand; 3, peaty clay and silt; 4, basalt gravel; 5, Pleistocene basement. Star shows a site where <sup>14</sup>C dated samples were collected. See Figure 3 for the position of the sections. Asterisk numbers relate to reference number in Table 1.

Ngatangia and Matavera districts. As each row of ridges is wider than a normal single beach ridge, rows are considered to consist of compound beach ridges. Geomorphic and surface geologic sections (Figure 4) show that landward ridges are low in relief, whereas the ridges along the present shore are high. This difference reflects the difference in grain size of beach ridge materials. The most seaward ridge conspicuously consists of coral cobbles and boulders, with a maximum grain size of ~20 to 30 cm.

No beach-ridge plain occurs on the coast adjacent to Avana stream. Instead, a low-gradient alluvial fan slopes directly to the sea shore. However, the offshore island of Motutapu has beach ridges along its coast. It is likely that a former beach ridge plain here has been destroyed by current erosion (Marshall, 1930). Two other fans formed by Matavera and Tupapa streams, to the north of Avana do not reach the present shoreline. Instead, they form swampy lowlands sourced by groundwater flow alone.

**Matavera swamp**

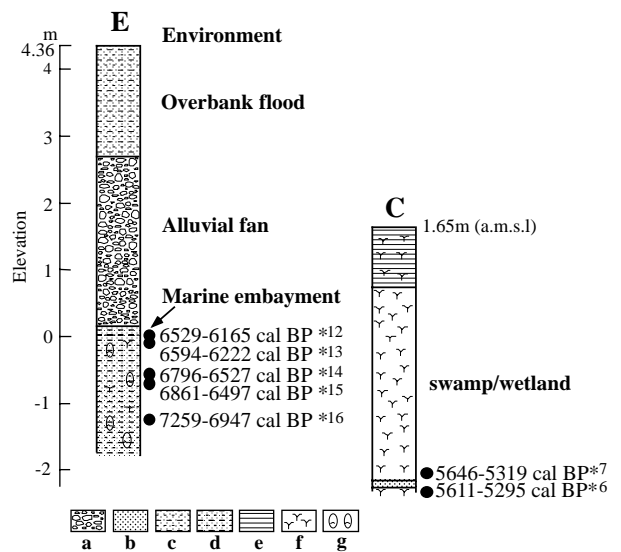
This wetland, located east of Tupapa stream, is extensive and contrasts with all other wetlands that are narrow and linear in shape (Figure 3). Its inland side is marked by an emergent Pleistocene fan (consisting of Nikao gravel) and a limestone ridge, while its seaward side is bordered by Holocene beach ridges. This suggests that Matavera swamp originated as a lagoon at the time of the Holocene transgression. However, Sutton *et al.* (1991) did not encounter any coral marine sand in a core taken to a depth of 11.5 m in this swamp. In this investigation, we also obtained a core 4 m deep by hand boring, which showed no distinct marine sediments. Terrestrial peat dominated the core although very thin fine coral sands are intercalated at its base, giving an age of *c.* 5500 cal. BP (Figure 3, Figure 5, location C). This stratigraphic evidence indicates that the swamp was not subjected to invasion by seawater through rising Holocene sea levels. We conclude therefore that the wetland formed in a solution depression, such as a doline, and formed under lower sea-level conditions, as suggested originally by Sutton *et al.* (1991). The seaward side of the swamp was probably blocked by low-lying Pleistocene limestone, now overlain by beach ridge gravels, as inferred from both the occurrence of low-lying Pleistocene

limestones along the northwestern rim of the swamp and from those exposed in places within beach ridge deposits along the present coast (Figure 3).

The fine-grained coral sands (*c.* 5500 cal. BP) thinly intercalated with the peat suggest that occasionally seawater managed to wash over the beach ridge deposits during mid-Holocene times. Although the sand ridge barrier at this stage was probably low and narrow, the overwash events may have been mitigated by the presence of a contemporary reef flat.

**Radiocarbon ages relevant to past sea-level and shoreline changes**

Radiocarbon samples relevant to past sea levels and shorelines were collected from (1) the Avana alluvial fan area (Figure 3, location E), (2) the sand ridge and swale area (section A–A’, B–B’, location D) and (3) the emergent Pleistocene limestone area (location F) on the eastern coastal plain.



**Figure 5** Stratigraphic sections with <sup>14</sup>C ages at locations E and C on the eastern coast of Rarotonga. a, Gravel; b, sand; c, sandy silt; d, silty sand; e, clay; f, peat or organic material; g, shell. See Figure 3 for the locations. Numbers with asterisks relate to reference numbers in Table 1.

### Alluvial fan area

We excavated the sediments on the Avana alluvial fan in Ngatangia using a power shovel in order to detect evidence of the Holocene transgression (location E, Figure 3). The excavation attained a depth of *c.* 6 m (Figure 5, E). We recognized sandy silt deposits, underlying alluvial fan gravels 2.5 m thick that are capped by overbank flood deposits (brown sandy silts).

The silty deposits, more than 2 m thick, are dark grey in colour and contain numerous organic fragments and marine shells. The dominant species of the shells are *Tellina palatam*, *Strombus* sp., *Neritina* sp., *Natica* sp., *Nassarius* sp., *Pyramidella* sp. and *Aliculastrum* sp. Those silty deposits and the marine shells indicate that the palaeoenvironment was a shallow marine sea to intertidal zone in an embayment or moat. We obtained ages of between *c.* 7000 and 6000 cal. BP for the shells (Table 1; Nos. 12–16). The top of the marine deposits is at  $\sim 0$  m elevation.

### Sand ridge and swale area

The wetlands occurring in most inland areas are attached to the Matavera alluvial fan supplying water to much of the swamp in section A–A' (Figure 3). Systematic sampling was conducted using a peat sampler in the swales and shovel on the sand ridges, along the section A–A' crossing the coastal plain in the Matavera district (Figure 3). The ages obtained, though the shell samples are not *in situ*, are consistent with the seaward movement of sand ridge formation (Figure 4, Table 1), suggesting there was little time between death and deposition of these samples, and hence the ages are likely to represent those of the formation of the sand ridges.

Radiocarbon ages of coral and shell samples (Table 1, Nos 10 and 11) obtained at most inland sand ridge sites (Figure 3, location D) indicate that the coastal plain began to prograde at *c.* 4500 cal. BP. As these samples were from the beach ridge crest, derived from storm deposits, their elevation at +270.8 cm is likely to be somewhat higher than the former sea level. Schofield (1970) reports an age of  $3510 \pm 50$  yr BP from coral sand collected at a site close to the innermost beach ridge on Kavera district in the southwestern coast of Rarotonga.

Some boreholes in the inland swales show a bed of beach sand with a highest elevation of +1.5 to +2.0 m, underlying peaty mud with a thickness of *c.* 1 m. Two radiocarbon ages on shell fragments obtained at +1.9 m and +1.47 m in elevation (Figure 4; Table 1, Nos 21 and 20), which are nearly at the top of the beach sand, were 3957–3427 cal. BP and 4426–3819 cal. BP, respectively.

Schofield (1970) reported an age of  $2030 \pm 60$   $^{14}\text{C}$  yr BP on a raised reef 0.9 m above low tide level at Avarua on the northern coast, and Wood and Hay (1970) also reported evidence for a higher sea level. Woodroffe *et al.* (1990) and Yonekura *et al.* (1988) found no emergent reefs on Rarotonga. However, Chikamori (1995, 2001) found microatolls dated between 4000 and 3000 yr BP, 0.9 m above low-tide level on the former reef flat underlying coral gravels and sands *c.* 1 m thick in Ngatangia. Yonekura (1994) drew a Holocene sea-level curve higher than the present according to this information. This evidence allows us to estimate the occurrence of a sea level higher than the present, likely +1.5 m in elevation at around 4000 to 3000 cal. BP. A radiocarbon age from the central part of the sand ridge plain in the Matavera district shows it possibly emerged around *c.* 1000 cal. BP (Figure 4; Table 1,

**Table 1**  $^{14}\text{C}$  dates on the Holocene coastal plain of Rarotonga

No.	Locality	$^{14}\text{C}$ age (conventional) (yr BP)	Calibrated age (cal BP) ( $2\sigma$ probability distribution: %) <sup>1</sup>	Sample material	Landform	Past sea-level elevation (cm, a.m.s.l.)	Lab. No <sup>2</sup>
1	Ngatangia	1020 $\pm$ 90	816–493 (100)	Coral	Bench	135	NUTA-5687
2	Ngatangia	950 $\pm$ 30	649–518 (100)	Coral	Bench	135	NUTA2-9364
3	Ngatangia	1340 $\pm$ 30	1046–837 (100)	Coral	Bench	20	NUTA2-9363
4	Ngatangia	1340 $\pm$ 30	1046–837 (100)	Coral	Bench	50	NUTA2-9365
5	Matavera	300 $\pm$ 80	446–239 (72.0)	Peat	Swamp	?	NUTA-5506
6	Tupapa	4780 $\pm$ 80	5611–5295 (99.8)	Peat	Swamp	?	NUTA-5387
7	Tupapa	4830 $\pm$ 80	5646–5319 (100)	Peat	Swamp	?	NUTA-5388
8	Tupapa	3360 $\pm$ 90	3508–3014 (100)	Coral	Beach ridge	?	NUTA-5688
9	Tupapa	3720 $\pm$ 90	3955–3463 (100)	Coral	Beach ridge	?	NUTA-5689
10	Matabera	4210 $\pm$ 90	4638–4084 (100)	Coral	Beach ridge	270.8 $\geq$	NUTA-5694
11	Matavera	4370 $\pm$ 90	4826–4355 (100)	Shell	Beach ridge	270.8 $\geq$	NUTA-5680
12	Ngatangia	5860 $\pm$ 80	6529–6165 (100)	Shell	Fossil lagoon	$\approx 0$	NUTA-5352
13	Ngatangia	5920 $\pm$ 80	6594–6222 (100)	Shell	Fossil lagoon	$\approx 0$	NUTA-5372
14	Ngatangia	5920 $\pm$ 50	6796–6527 (98.3) <sup>3</sup>	Wood	Fossil lagoon	$\approx -50$	BETA-105083
15	Ngatangia	5930 $\pm$ 70	6861–6497 (98.9) <sup>3</sup>	Wood	Fossil lagoon	$\approx -50$	BETA-100723
16	Ngatangia	6260 $\pm$ 60	7259–6947 (100) <sup>3</sup>	Wood	Fossil lagoon	$\approx -120$	BETA-105084
17	Matavera	1650 $\pm$ 80	1422–1054 (100)	Shell	Swale	150 $\geq$	NUTA-5729
18	Matavera	1870 $\pm$ 80	1674–1298 (100)	Coral	Beach ridge	250 $\geq$	NUTA-5730
19	Matavera	3070 $\pm$ 110	3226–2694 (100)	Coral	Beach ridge	250 $\geq$	NUTA-5861
20	Matavera	4030 $\pm$ 110	4426–3819 (100)	Shell	Swale	$\approx 150$	NUTA-5860
21	Matavera	3700 $\pm$ 100	3957–3427 (100)	Shell	Swale	$\approx 190$	NUTA-5862

All samples were measured by accelerator mass spectrometry.

No. 1 and No. 2 are from the same sample. Each was analysed by a different machine.

<sup>1</sup>Calendar year was calibrated by a computer program CALIB 5.0 (Stuiver and Reimer, 1993). Calibrated data sets are SHCal04 (McCormac *et al.*, 2004) for terrestrial samples and Marine04 (Hughen *et al.*, 2004) for marine samples. Regional marine reservoir correction  $\Delta R = -52 \pm 27$  yr at Rarotonga (21°14'S, 159°49'W; Guilderson *et al.*, 2000) was used.

<sup>2</sup>NUTA and BETA are laboratory numbers of Tandeton AMS  $^{14}\text{C}$  Dating Laboratory, Center for Chronological Research, Nagoya University, and Beta Analytic Radiocarbon Dating Laboratory in USA, respectively.

<sup>3</sup>Calculated age is based on conventional age after Chikamori (2001).

No. 14). Based on the heights of swale surfaces, the elevation of sea level at this time is estimated to be less than +1.50 m.

Two samples of coral gravels collected from an exposure in the channel of the Tupapa stream where it crosses the single row of beach ridges adjacent to the present shoreline (Figure 3, section B–B') give comparatively old radiocarbon ages, ie, 3508–3014 cal. BP and 3955–3463 cal. BP (Figure 4; Table 1, Nos 8 and 9). These ages are similar to those from farther inland in the wide coastal plain of Matavera district (Figure 4, section A–A'), which is located to the southeast of the section B–B' (Figures 3 and 4). These facts indicate that the shoreline in the Tupapa district has stayed at a location adjacent to the present shoreline throughout the late Holocene, whereas it has advanced toward the present shoreline in the Matavera district.

#### *Emergent Pleistocene coral area*

Evidence of more recent sea-level change was found on the present sea shore at Ngatangia (Figure 3, locations F and G). On this coast, a Pleistocene-emerged coral limestone, overlain by Holocene beach deposits, is exposed as a low erosional terrace with an elevation of ~2 m along the shore. A notch associated with a Holocene sea-level highstand has been cut into the remnant. We found some Holocene emergent corals attached to the Pleistocene coral limestone. Among these corals, the highest one is at 1.35 m above the present mean sea level (Figure 3, location F; Figure 6). Judging from the

present tidal range (0.6 m–National Tidal Facility, the Flinders University of South Australia, 1996), the sea level at that time would have been ~ 1.5 m above the present.

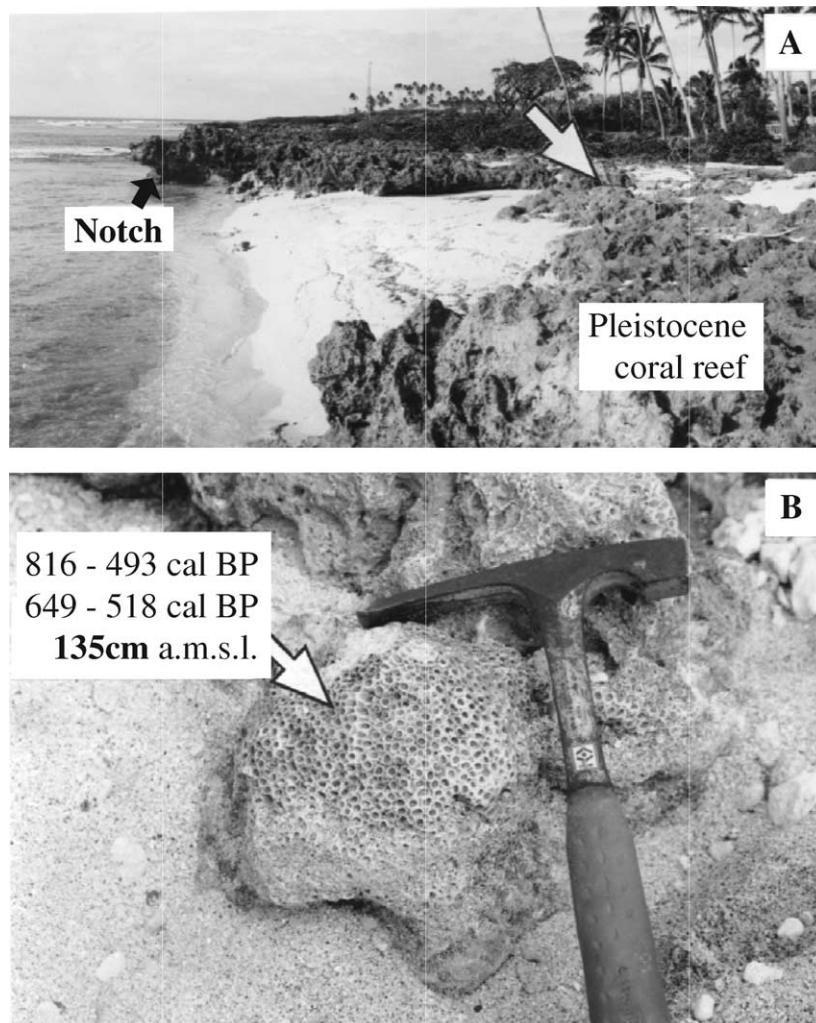
The Holocene corals at this location are very thin and small in size, suggesting that they formed over a short time span. We obtained two radiocarbon dates for the same sample using different AMS machines at Nagoya University: 816–493 cal. BP (AD 1134–1457 cal.) and 649–518 cal. BP (AD 1301–1432 cal.) (Table 1, Nos 1 and 2).

Two other emergent corals are dated from a Pleistocene coral limestone, exposed on the beach close to the present reef flat on Motutapu Island (Figure 3, location G). They are 0.2 m and 0.5 m in elevation above the present mean sea level and dated 1046–837 cal. BP (AD 904–1113 cal.) and 1046–837 cal. BP (AD 904–1113 cal.), respectively (Table 1).

Those findings indicate that the relative mean sea level was higher than the present mean sea level around 500–1000 years ago on Rarotonga.

### Sea-level change

Yonekura (1994) derived reliable sea-level data for *c.* 8000–7000 cal. BP based on the corals excavated on the present reef flat of Rarotonga. The sea-level records for the past 7000 cal. BP obtained from our investigations represent a sea-level curve since *c.* 8000 cal. BP on Rarotonga and are summarized as



**Figure 6** Holocene emerged corals attached at Pleistocene coral reef at location F on the eastern coast. The white arrow indicates the sampling position (A) and sample (B) for  $^{14}\text{C}$  dates of No. 1 and No. 2 (Table 1). See Figure 3 for location F, and Table 1 for details of  $^{14}\text{C}$  dates

follows. Following early Holocene rapid sea-level rise, which attained  $\sim 1.2$  m *c.* below present 7000 cal. BP, slight and gradual sea-level rise occurred until around 4500 cal. BP, when sea level reached its Holocene maximum height,  $\sim 1.5$  m above present sea level (Figure 7). In the course of the gradual sea-level rise, sea level attained its present level around 6000–6500 cal. BP on Rarotonga. It was essentially stable from *c.* 4500 to *c.* 800–500 cal. BP, when sea level was  $\sim 1.5$  m higher than today, though shortly before *c.* 800–500 cal. BP it might have fallen slightly; then it fell to the present-day level, although the course is not clear from this investigation. Evidence of sea-level fall approximately 600–700 cal. BP is recognized in many parts of the tropical Pacific (Nunn, 2000a,b; Nunn and Britton, 2001); sea level fell during the AD 1300 Event below its present level, where it remained for much of the ‘Little Ice Age’ (approximately 600–150 cal. BP) at the end of which it began rising.

Poorly developed microatolls and the absence of long stillstand remnants correlated to the coral dated at 800–500 cal. BP, such as emergent notches and wave-cut terraces on the eastern coast of Rarotonga, suggest that the high sea-level stand around 800–500 cal. BP was of short duration.

From Mangaia, Yonekura *et al.* (1988) reported that rapid emergence occurred between 3400 and 2900 yr BP. Woodroffe *et al.* (1990) reported that most ages for emergent Holocene features in the Cook Islands fall in the range 5100–3400 yr BP. Thus, evidence of emergence in the past 3000 years has been previously reported from the Cook Islands. However, Yonekura *et al.* (1988) recognized an emergent microatoll on Aitutaki Island dated at  $1530 \pm 210$  yr BP, which suggests that the sea was slightly ( $+0.4$ – $+0.5$  m) higher in the latest Holocene. This is similar to the evidence on Rarotonga. The relative sea-level trend obtained for Rarotonga is essentially the same as that in sea-level curves from French Polynesia (Pirazzoli and Montaggioni, 1988; Pirazzoli, 1991).

The height and timing of Holocene sea-level changes in the Cook Islands can be interpreted through geophysical models. Yonekura *et al.* (1988) reported that the Holocene higher sea levels in the Pacific seemed to be harmonious with the sea-level changes predicted by Clark *et al.*’s Zone V (Clark *et al.*, 1978; Clark and Lingle, 1979), although timing of the maximum sea level known by observation is different from that of the predicted curve. Woodroffe *et al.* (1991) also reported that mid-Holocene emergence in the Cook Islands is consistent

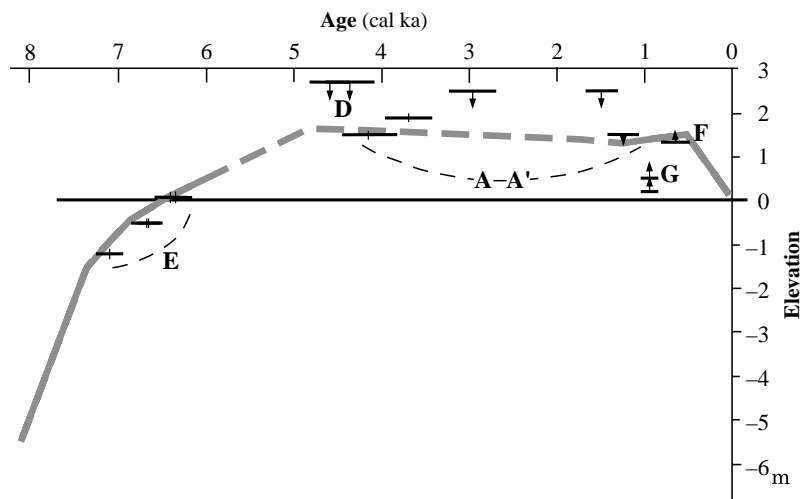
with that predicted by the geophysical models of Clark *et al.* (1978) and Lambeck and Nakada (1985). These models seem likely to explain higher Holocene sea levels on Rarotonga. In addition to hydro-isostasy, flexure of lithosphere caused by young volcanic load of Rarotonga and Aitutaki islands has been used to explain the emergence of the South Cooks (McNutt and Menard, 1978; Jarrard and Turner, 1979, Lambeck, 1981, Spencer *et al.*, 1987). Woodroffe *et al.* (1991) suggested that this flexure was responsible for the slight differences between Holocene sea-level heights across the Cook Islands. Thus, the new findings for Holocene emergence on Rarotonga reported here will provide useful data for refining the geophysical interpretations of Holocene sea-level records in the Cook Islands.

Meanwhile, the magnitude and timing of sea-level fall after around 800–500 cal. BP recognized on Rarotonga is similar to those recognized on many islands in western Polynesia and Melanesia, permitting another interpretation. According to Nunn (2000a,b, 2003) and Nunn and Britton (2001) the sea-level fall caused an environmental and societal catastrophe (the AD 1300 Event) following the Mediaeval warm stage, and corresponds to an increased frequency of El Niño.

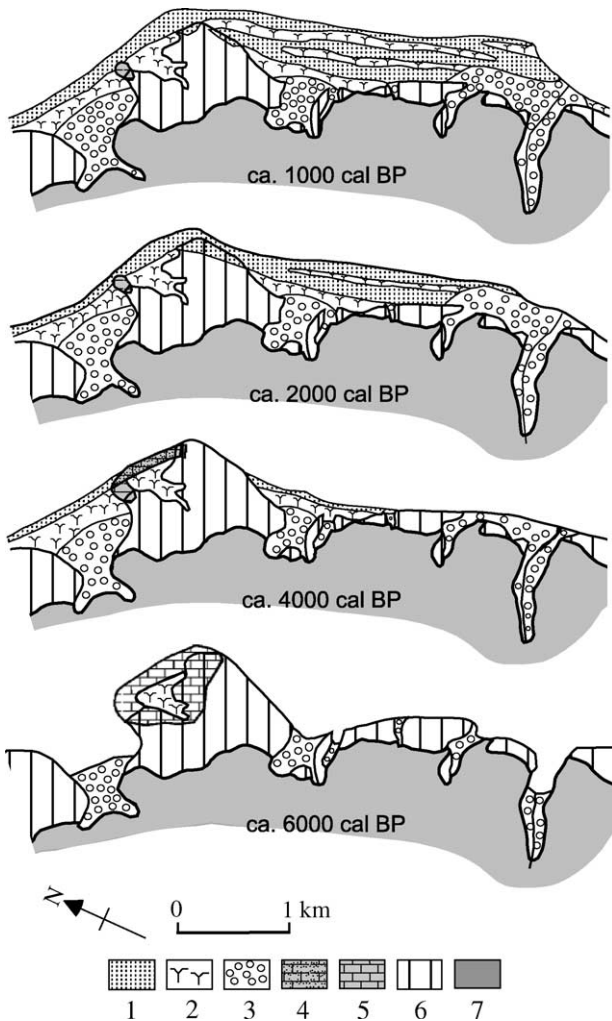
## Shoreline and environmental change

Mid- and late-Holocene changes in shoreline and environment on the coastal plain of Rarotonga have been dominantly influenced by the sea-level changes described above (Figure 8).

The marine transgression extended inland along the former stream valleys *c.* 6500 to 6000 cal. BP. In particular, conspicuous transgressions occurred in the former Takuvaine, Avatu and Avana stream valleys, which have low gradients, forming rather deep embayments or lagoons. In contrast, promontories consisting mainly of Pleistocene emergent fan terraces or limestones between stream valleys, spread farther seaward than present as shown by the sea-cliffs occurring on the seaward side of the terraces. As a result, more intricate coastal patterns than are evident on the present coast were formed at this stage (Figure 8). The deposits resulting from the transgression in the alluvial fan areas are presently overlain by fluvial gravel deposits, which result from net regression since *c.* 4500 cal. BP.



**Figure 7** Holocene sea-level change on the eastern coast of Rarotonga. Horizontal and vertical lines on sea-level data show errors and medians of calibrated ages, respectively. A–A', D, E, F and G show the locations (see Figure 3) for which sea-level data were obtained. Ages prior to 7.3 ka are after Yonekura (1994)



**Figure 8** Holocene palaeogeographic change on the eastern coast of Rarotonga. 1, Sand ridge; 2, swale and swamp; 3, alluvial fan; 4, Pleistocene coral reef overlain by Holocene beach deposit; 5, Pleistocene coral reef; 6, Pleistocene alluvial fan; 7, mountain

Around 6000–5000 cal. BP, when slight and gradual sea-level rise was experienced, the shoreline was nearly stable in the embayments at the mouths of the stream valleys, likely because slight sea-level rise, and was balanced with sediments supplied from the streams. At the same time promontories consisting of unconsolidated Pleistocene materials between embayments were being eroded by wave erosion, forming sea-cliffs parallel or subparallel to the present shoreline. Initial fringing reef developments must have resulted in moats on the landward sides of reefs in some districts, in which wide wetlands occur today.

Around *c.* 4500 cal. BP, the transgression was replaced by a regression, which began to produce coastal lowlands, potentially allowing human occupation. Beach ridges and swale plains began to emerge as either single sand ridges or a wide coastal plain.

Since *c.* 4500 cal. BP, the shoreline has largely advanced seaward on the east coast, forming multiple beach ridges (Figure 8). Elsewhere, the coast, consisting of a narrow single ridge, has experienced only slight progradation or has been stable, as typically expressed on the Tupapa single ridge coast north of the wide ridge plain (Figure 2). On the western to northwestern coasts, on which have developed a single but rather wide sand or shingle ridge, rather rapid shoreline advances occurred after *c.* 4500 cal. BP. On the coast, in which wide coastal lowlands exist now, coastal lowlands have

expanded across the fringing reef flat, leaving only the narrow present reef flat. Only slight shoreline advances due to low volumes of source materials on the south coast allowed remnants of wide reef flats to remain instead of wide coastal lowlands.

As a result of post 800–500 cal. BP net sea-level fall, streams have slightly incised coastal lowlands of this island, forming low terraces. In particular, they are readily discernible on the alluvial fans along Avana, Takuvaine, Avatiu streams, in which low terrace scarps 1–2 m high represent emergent fans affected by recent slight sea-level fall, which may have influenced human occupation patterns as recognized in the Pacific islands by Nunn (2000a, 2003) and Dickinson (2003).

Human occupation of coastal lowlands in Rarotonga has likely occurred in the context of this mid- and late-Holocene coastal development. According to the orthodox model for human settlements in Polynesia based on archaeological remains (Spriggs and Anderson, 1993), those on the Cook Islands including Rarotonga were established around 1000 years ago. However, the early settlement model, theoretically deduced in terms of navigation, suggests an earlier settlement, perhaps 2500 years ago, in the Cook Islands including Rarotonga (Irwin, 1990). On the basis of this early model, Kirch and Ellison (1994) showed evidence for an increase in grass pollen and charcoal around 2500 years ago from coring in Mangaia, suggesting destruction of trees by human activity. However, such evidence for human activity may also be interpreted as having a natural cause such as climatic change (Nunn, 1997).

In the Cook Islands, ages from direct archaeological evidence are less than 1000  $^{14}\text{C}$  yr BP (Allen, 1998). Dates on archaeological excavations on the coastal plain of Rarotonga, few in numbers, have revealed only younger human settlements (Bellwood, 1978; Okajima, 1999). Of the human remains, the oldest from Motutapu island, off the Avana lowland (Figure 2), was dated to  $720 \pm 50$   $^{14}\text{C}$  yr BP (Okajima, 1999).

In Rarotonga, no conspicuous evidence of human influence on coastal landform development has been yet recognized from natural sites. However, the paucity of archaeological excavations leaves open the possibility that earlier human remains were buried by later colluvial deposits (Kirch and Ellison, 1994).

The results obtained here provide new findings to test the hypothesis proposed by Dickinson (2003) that initial human occupation on each island of remote Pacific Oceania was governed by mid-Holocene sea-level changes. Timing of the termination of the highstand, around 800–500 cal. BP obtained here, corresponding to that of initial human occupation mentioned above, seems to be in harmony with this hypothesis, although the remnants of initial human occupation in Rarotonga are not fully yet elucidated.

Studies of the coastal plain and mid- to late-Holocene coastal sites provide the most likely location for early human settlement sites (if they exist). Fluvial flood deposits would likely cover such postulated sites on the alluvial fans; swamps and swales are generally too wet for occupation but suited to taro cultivation. The optimum locations for verifying possible past settlement are on the landward beach ridges, which were suitable for contemporaneous occupation because of their low relief but dry condition. These ridges are old enough to have supported earlier human settlement, and are rarely covered with thick colluvial or alluvial deposits.

Thus, the record of coastal environmental change in Rarotonga obtained provides important data to help clarify any interrelationship between human occupation and coastal environmental change, and to possibly resolve the question of the antiquity of early human settlement.

## Conclusion

The coastal plain of Rarotonga comprises the most widely developed beach ridge and wetland system in the Cook Islands. As is the case on other tectonically stable islands of Polynesia, the mid- to late-Holocene sea-level curve obtained for Rarotonga shows an elevation of  $\sim 1.5$  m higher than at present. The highstand likely began *c.* 4500 cal. BP in Rarotonga following a gradual rise of sea level from *c.* 6500 cal. BP at which time sea level was nearly as same as that of the present day. Sea level has fallen by *c.* 1.5 m since *c.* 800–500 cal. BP, resulting in emergence of the coastal plain. The mid- to late-Holocene highstand may be largely the result of hydro-isostatic movements, as discussed elsewhere for Polynesia. However, the close agreement of the recent sea-level fall with evidence for climatic change suggests that the influence of the climatic factor is possible, and requires further examination.

The mid- to late-Holocene coastal environments, in particular the shoreline changes occurring on the present coastal plain of Rarotonga, have evolved in relation to sea-level change. The Holocene coastal plain began to prograde *c.* 4500 cal. BP. Since then, shorelines have advanced seaward during effectively stable sea levels until *c.* 800–500 cal. BP. The eastern coast has experienced the most conspicuous advance, with multiple beach ridge and swale plains being formed on the antecedent reef flat, while the lesser advance on the southern coast has resulted in the formation of only narrow single ridge and swale landforms and the development instead of a wide reef flat.

Although the coastal plain of Rarotonga has high potential for early human occupation, few archaeological remnants have been recognized. The distribution and evolution of coastal geomorphic features as described here help to properly evaluate the relationship of the coastal plain developments to human occupation history as well as the potential location of early human occupation in Rarotonga.

## Acknowledgements

We are grateful to David Lowe (University of Waikato) and Patrick Nunn (University of the South Pacific) for reviewing the manuscript, Toru Yamaguchi (Keio University), Tadashi Okajima (Tokai University), Kuchiki, Satoru Tanahashi (Tokyo Metropolitan University) and Shunji Yoshida for archaeological information and help with field survey, and Yoshiaki Matsushima for identifying molluscan shells. We thank Tony Utanga for his kind advice and for arranging our research programme. We wish to express our thanks to the government of the Cook Islands for giving us permission to carry out research in 1996 and 1997 in Rarotonga. The work was supported by a grant-in-aid for Overseas Scientific Survey of the Japanese Ministry of Education, Science and Culture, No. 07041022.

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