

# Geochronology and subsurface stratigraphy of Pukapuka and Rakahanga atolls, Cook Islands: Late Quaternary reef growth and sea level history

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## ABSTRACT

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Eustatic sea-level cycles superposed on thermal subsidence of an atoll produce layers of high sea-level reefs separated by erosional unconformities. Coral samples from these reefs from cores drilled to 50 m beneath the lagoons of Pukapuka and Rakahanga atolls, northern Cook Islands give electron spin resonance (ESR) and U-series ages ranging from the Holocene to 600,000 yr B.P. Subgroups of these ages and the stratigraphic position of their bounding unconformities define at least 5 periods of reef growth and high sea-level (0–9000 yr B.P., 125,000–180,000 yr B.P., 180,000–230,000 yr B.P., 300,000–460,000 yr B.P., 460,000–650,000 yr B.P.). Only two ages fall within error of the last interglacial high sea-level stand (~125,000–135,000 yr B.P.). This paucity of ages may result from extensive erosion of the last interglacial reef. In addition, post-depositional isotope exchange may have altered the time ages of three coral samples to apparent ages that fall within glacial stage 6.

For the record to be preserved, vertical accretion during rising sea-level must compensate for surface lowering from erosion during sea-level lowstands and subsidence of the atoll; erosion rates (6–63 cm/1000 yr) can therefore be calculated from reef accretion rates (100–400 cm/1000 yr), subsidence rates (2–6 cm/1000 yr), and the duration of island submergence (8–15% of the last 600,000 yr). The stratigraphy of coral ages indicates island subsidence rates of  $4.5 \pm 2.8$  cm/1000 yr for both islands. A model of reef growth and erosion based on the stratigraphy of the Cook Islands atolls suggests average subsidence and erosion rates of between 3–6 and 15–20 cm/1000 yr, respectively.

## Introduction

The history of sea-level change, plate subsidence, erosion, and reef accretion is recorded in the stratigraphy of mid-ocean atolls. Eustatic sea-level cycles superposed on thermal subsidence of an atoll produce layers of high sea-level reefs separated by erosional unconformities (e.g. Perkins, 1977; Schlanger, 1963). When rising sea level floods the volcanic or carbonate platform, reef growth is initiated and reef sediments rapidly accumulate. Sea level lowering exposes the platform to erosion and subaerial diagenesis. The older reefs then form the foundation for subsequent reef growth (Fig. 1).

The timing of periods of rising and high sea-level can be directly determined by dating these layered limestone deposits and correcting their present depth for the thermal subsidence and lithospheric flexure that occurred since deposition (e.g., Lincoln and Schlanger, 1991). The potential of mid-ocean atolls to provide sea-level “dipsticks” for calibration with sea-level curves derived from continental margin (Haq et al., 1987) and oxygen isotope-based (e.g., Matthews and Poore, 1980) sea-level curves, has long been recognized (Bloom, 1967). However, the accuracy of atoll sea-level curves is limited by uncertainties in (1) subsidence history, (2) geochronology, (3) erosion rates, and

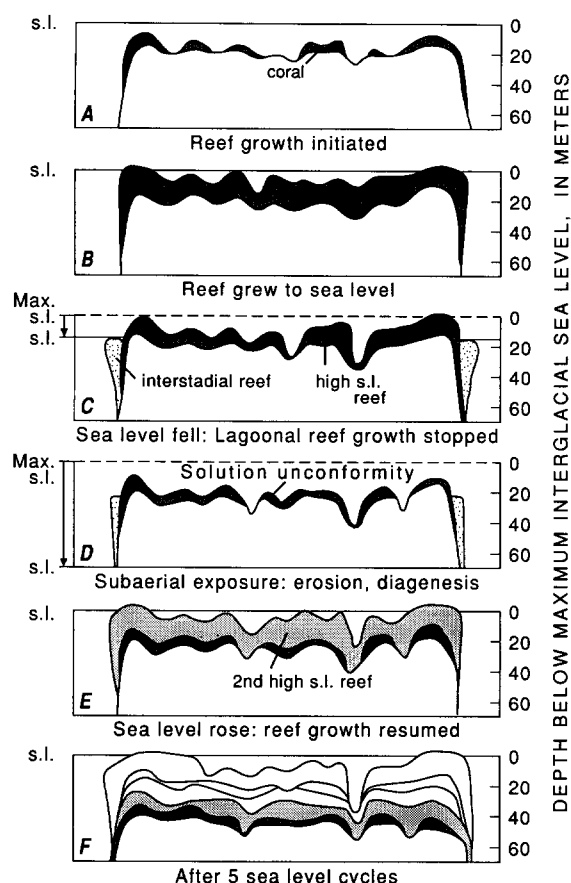


Fig. 1. Schematic diagram showing reef growth in response to glacio-eustatic sea-level cycles. A. Rapidly rising sea-level flooded a pre-existing island platform and reef growth was initiated. B. The outer reef reached sea-level and a thick (10–30 m) sedimentary pile accumulated in the lagoon. C. Lowering of sea level cut off the lagoon from open-ocean circulation. Reef growth on the outer flanks of the atoll continued. D. Sea-level fall exposed the reef platform to subaerial diagenesis during glacial epochs ( $\sim 100,000$  yr) and the elevation of the reef platform relative to sea level was reduced by erosion ( $< \sim 15$  m) and subsidence (2–7 m). E. With subsequent deglaciation, sea water again inundated the platform, and reef sediments accumulated atop the remnants of the former high sea-level reef. F. Layers of high sea-level reefs separated by solution unconformities resulted from five cycles of reef growth and erosion upon the slowly subsiding island platform. After 500,000 yr, the original reef (A) subsided between 15–35 m. (Vertical exaggeration is approximately  $\times 100$ ).

(4) depositional paleodepth (Lincoln and Schlanger, 1991).

Atoll stratigraphy has primarily been used to develop long-term, relatively lower resolution (Eocene to Quaternary) records of sea-level change

(e.g. Ludwig et al., 1988; Schlanger, 1963; Saller and Koepnick, 1990; Tracy and Ladd, 1974; Labeyrie et al., 1969; Aïssaouri et al., 1990; Lincoln and Schlanger, 1991; Quinn and Matthews, 1990; Quinn, 1991). Higher-resolution late Quaternary glacio-eustatic sea-level cycles have largely been inferred from the marine oxygen isotope record (e.g. Shackleton and Opdyke, 1973; Imbrie et al., 1984; Martinson et al., 1987; Williams et al., 1988) and from radiometric dating of corals on tectonically uplifted terraces on continental margins (e.g. Moore, 1982; Chappell and Veeh, 1978). One of the primary limitations to these reef sea-level studies has been the reliability of assumptions about the reef's tectonic history, which must be calculated from sea-level data established in tectonically stable locations (e.g. Ku et al., 1974; Harmon et al., 1983).

For this study the “dipstick approach” is applied to unravel the late Quaternary geologic history of Rakahanga and Pukapuka—two tectonically stable atolls in the Cook Islands, central south Pacific (Fig. 2). The objectives of this study are to determine, the history of reef growth in two atoll lagoons for the past 600,000 yr; show how the growth history is related to the timing of late Quaternary high sea-level stands; and demonstrate how atoll stratigraphy can be used to test models of mid-plate subsidence, reef erosion, and accretion. Pukapuka and Rakahanga atolls are far enough from Rarotonga and Aitutaki to be unaffected by lithospheric loading and flexure associated with Pleistocene to Holocene volcanism on those islands (Scoffin et al., 1985; Spencer et al., 1988). Comparison of reef growth records from these two geographically separated atolls should enable eustatic signals to be separated from relative sea-level signals arising from local tectonics.

This study focuses on the reef growth history as it is preserved in the lagoon, rather than the outer-reef rim of the atoll. During the late Quaternary, periods of reef growth are frequent enough such that reef growth resumes and fills accommodation space before the platform has subsided or eroded more than about 20–30 m. Lagoonal coral growth will only occur when sea level has risen higher than the outer reef rim and flooded the island platform (Fig. 1A). After the outer reef rim of the

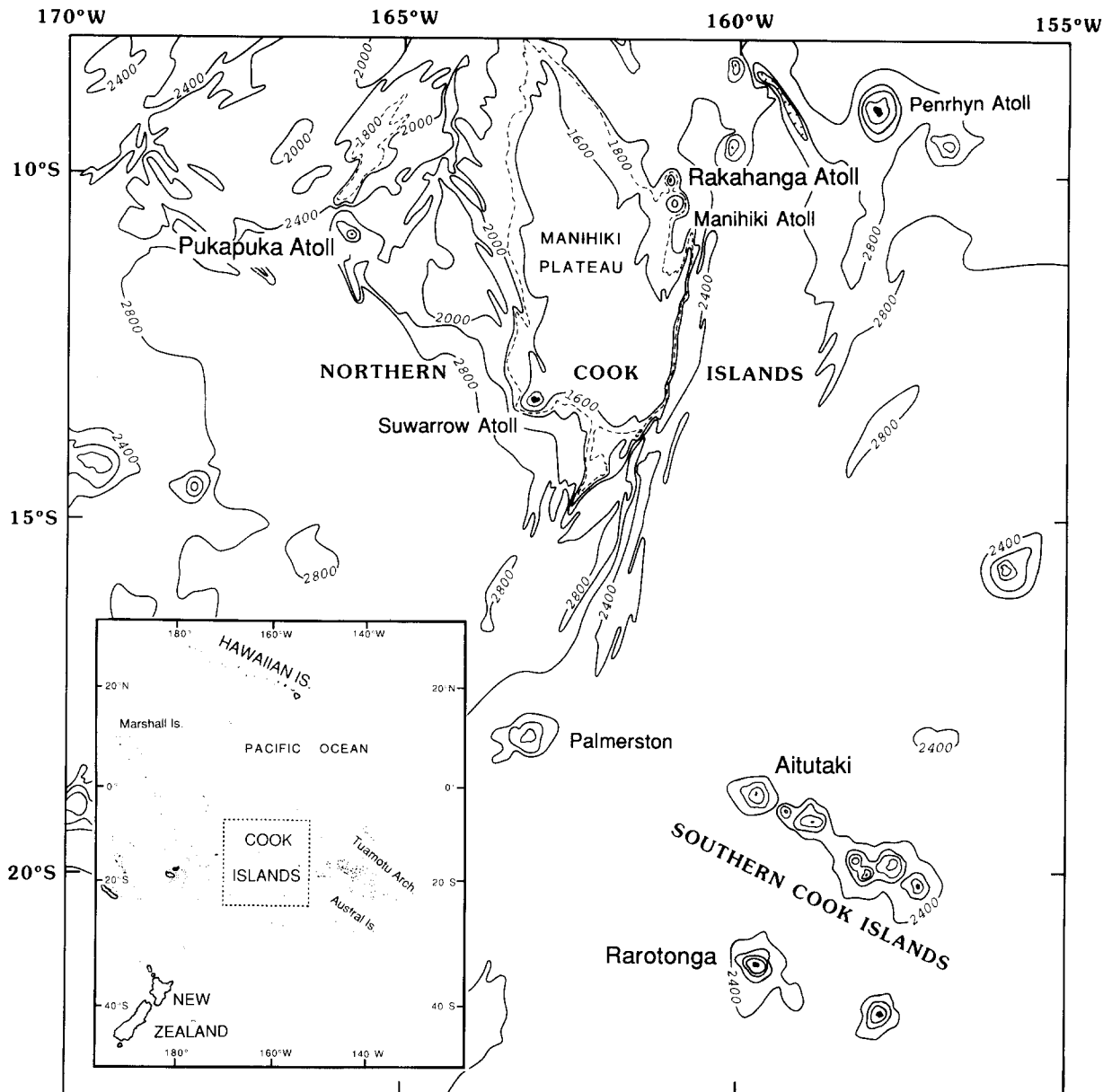


Fig. 2. Bathymetric map of the Cook Islands region showing the Pukapuka and Rakahanga atolls and the Manihiki Plateau with inset of the central Pacific showing the location of the Cook Islands.

atoll has grown to sea-level (Fig. 1B)—which occurs within a few thousand years following platform flooding (Davies and Montaggioni, 1985)—any subsequent sea-level lowering will cut off the lagoon from open ocean circulation, killing off lagoonal corals (Fig. 1C). Therefore, ages of in-place lagoonal corals give the timing of the highest sea-level stands (and the final transgres-

sions to those stands). Thus, it is not necessary to know the paleo-water depth of coral growth within the lagoon. In the outer reef environment, however, reef growth tracks sea-level change, making it necessary to know the paleowater depth of the coral in order to estimate the position of sea level (Fig. 1C). This may be problematic where coral terraces are not well developed or sea-level indica-

tor corals (for example, *Acropora palmata*) are not recovered.

This is the first study of the late Pleistocene reef-growth history of Pukapuka and Rakahanga. Previous geologic studies of the Cook Islands have included: the Holocene geological history of the southern Cook Islands (Yonekura et al., 1984, 1986, 1988) and Suvarrow (Woodroffe et al., 1990); the late Pleistocene geologic history of the southern Cook Islands (Woodroffe et al., 1991); evidence for volcanic loading and flexuring of the Southern Cook Islands (Spencer et al., 1988; Scoffin et al., 1985); and geologic surveys (Stoddart and Gibbs, 1975; Wood and Hay, 1970; Wood, 1967).

### The Cook Islands

The Cook Islands, which extend from 8° to 23° south latitude and 167° to 156° west longitude comprise an aggregate land area of 241 km<sup>2</sup> and are divided into the northern and southern groups (Fig. 2). The southern Cook Islands are thought to comprise two parallel hot-spot traces extending from the Austral Islands to the southeast (Fig. 2). However, island ages (Dalrymple et al., 1975; Matsuda et al., 1984; Turner and Jarrard, 1982), elevation of raised reefs (Spencer et al., 1988), structural trends (Diament and Baudry, 1987), and regional geophysical anomalies (Calmant and Cazenave, 1987; Smith et al., 1989) argue for a more complex volcanic and tectonic history than would be expected from a simple hot-spot model.

Pukapuka (10°51'30" S; 165°51'20" W) and Rakahanga (10°02'20" S; 161°04'40" W) atolls are part of the northern group, which consists of six atolls and a reef island capping seamounts on or around the Manihiki Plateau. The Manihiki plateau is a 600,000 km<sup>2</sup> area of anomalously shallow water and thick crust (Mahoney 1987) (Fig. 2). Rakahanga rises from a water depth of less than 3500 m on the northeastern edge of the High Plateau whereas Pukapuka caps a steep volcano with a 4 km deep base on a Western Plateau (Fig. 2).

The volcanic edifices of Pukapuka and Rakahanga islands have not been sampled or dated, but their origin is probably related to that of Manihiki Plateau. The plateau is thought to have

formed in the Early Cretaceous (Heezen et al., 1966; Winterer et al., 1974; Jenkyns, 1976; Mahoney, 1987) during a period of rapid, widespread seafloor volcanism associated with an ancient spreading ridge or migrating triple junction. Isotopic composition of the plateau basalts indicate a mixture of ocean-island and MORB basalts, perhaps originating from a hot spot situated near a ridge, similar to modern Galapagos and Iceland (Mahoney, 1987).

Pukapuka is a three-lobed atoll with a triangular-shaped lagoon (Fig. 3A) of variable depth dotted with large patch reefs. Rakahanga is a smaller

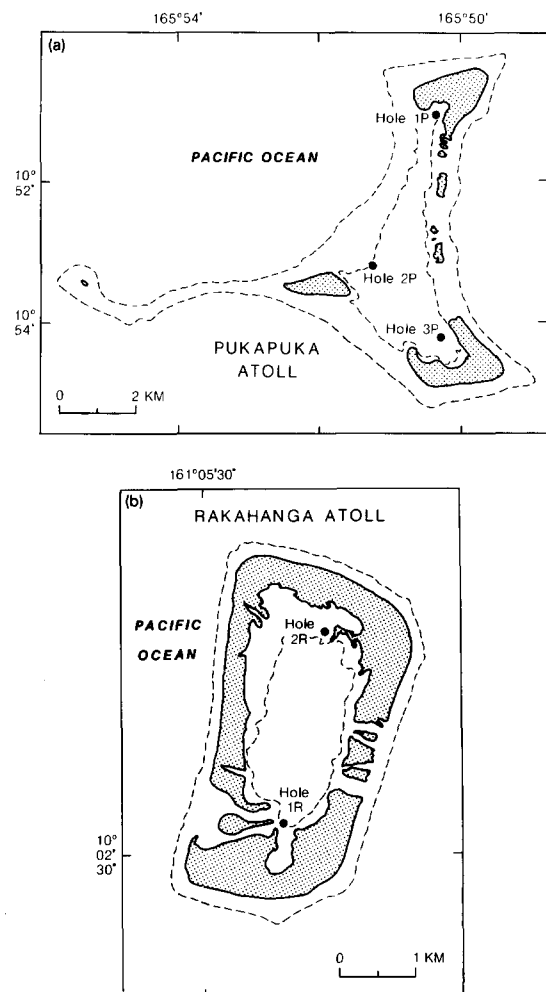


Fig. 3. General morphology and drill hole locations in (A) Pukapuka Atoll and (B) Rakahanga Atoll. Stippled pattern represents islands; dashed lines mark the inner sand flat and outer reef rim.

rectangular shaped atoll that is almost entirely enclosed (Fig. 3B). Rakahanga's bathymetry is highly variable, characterized by numerous (30–60 m deep) karst basins. Rakahanga lagoon is now depauperate of living corals, except near the channels that connect the lagoon with the open ocean. However, cores containing a diverse coral fauna were recovered from the lagoon. This suggests either the cessation of patch reef growth during the Holocene or migration of Rakahanga's reef rim.

## Methods

Pukapuka, Rakahanga, and Aitutaki atolls (Fig. 2) were chosen by the Committee for the Coordination of Joint Prospecting for Mineral Resources in the South Pacific (CCOP/SOPAC) and the USGS to study their geologic history and to explore for lagoonal phosphorite using a comprehensive program of drilling, geophysical surveys, and sampling of islands, atolls, and lagoons. A portable floating hydraulic drill rig anchored to the floor of the lagoons drilled 2.69 and 4.67 cm diameter cores from 11 holes in the lagoon floors. The holes ended at 40–70 m sub-bottom depths. Here we report dating results from the northern two atolls, Pukapuka and Rakahanga. No datable Pleistocene material was recovered from Aitutaki because the Pleistocene reef has been pervasively recrystallized (Hein et al., 1988a, b) and dolomitized (Hein et al., in press). Three holes were drilled in the lagoon of Pukapuka and two in Rakahanga to sub-bottom depths between 40–50 m (Figs. 3A, B). Of 230 m drilled, 46 m were recovered, giving an overall 20% recovery. The abundance of unconsolidated and poorly consolidated sediment that were washed by the drilling process, as well as the presence of ubiquitous small caves were largely responsible for the poor recovery. Spot coring using a hammer corer also helped to define the lithology of these zones.

Cores were initially logged and described in the field and later reexamined in the laboratory to identify biological, textural, and diagenetic characteristics. Mineralogic changes down-core were determined using X-ray diffraction, and select samples were examined petrographically and by

SEM. Strontium and magnesium contents were determined at the USGS by inductively coupled plasma atomic emission spectroscopy.

Aragonitic corals that grew in place within the lagoon and showed no evident diagenetic alteration [ $<3\%$  calcite and unaltered Sr and Mg concentrations (Cross and Cross, 1983; Kinsman, 1969)] were submitted to the University of Köln for U-series analysis and the University of Düsseldorf for ESR analysis.

The procedure used in the separation of U and Th isotopes is described in Hennig (1979). Thin sources of U and Th were electroplated onto stainless-steel planchettes. The alpha activities of decay-series of isotopes were counted for  $\sim 48$  hours. Sample ages and ppm of U and Th concentrations were calculated by iteration from the measured  $^{230}\text{Th}/^{234}\text{U}$  and  $^{234}\text{U}/^{238}\text{U}$  activity ratios using the age equations given in Kaufman and Broecker (1965) with decay constants for  $^{238}\text{U}$ ,  $^{234}\text{U}$ , and  $^{230}\text{Th}$  of  $1.551 \times 10^{-10}$ ,  $2.841 \times 10^{-6}$ , and  $9.002 \times 10^{-6}$  years, respectively. Errors in the calculated ages arise from addition or leaching of non-authigenic U or Th, alpha counting errors (Geyh, 1980), and the loss of U or Th during chemical separation.

For ESR dating, sieved samples (100–200  $\mu\text{m}$ ) were divided into 15 aliquots and irradiated stepwise with defined gamma doses of a  $^{60}\text{Co}$  source (0, 20, 40, 60, 80, 100, 125, 150, 175, 200, 250, 300, 350, 400, and 500 Gy). The ESR spectra were recorded with a Bruker 200 tt ESR spectrometer with a frequency of 9.5 GHz and a magnetic field strength of about 340 mT. The microwave power was 4 MW, modulation amplitude was 0.1 mT<sub>pp</sub>, and the scan time 1 mT/min. The peak at  $g = 2.0007$  in the ESR-spectra was used for determining the AD. The dose rate was derived from analysis of the U concentration by  $\alpha$ -spectrometry and neutron activation analysis (NAA) and by adding a value assumed for the component of cosmic rays. The alpha-efficiency ("k-value") was 0.06 (Radtke and Grün, 1988). Non-linear fitting of the AD-curve was done by the computer program "REGRESS", and age calculation by the program "DATA IV" (both by R. Grün).

Presently, the exact precision of individual ESR dates is not known. Analytical uncertainty, arising

primarily from uncertainties in the AD determination, ranges between 10–20% (Grün, 1989). Repeated ESR analyses of corals give standard deviations less than 10–15% (Radtke and Grün, 1988). We therefore, estimate an age uncertainty of 15%.

### Data base

The cores consist of aragonite coral and coral gravel interbedded with unconsolidated biogenic sand, recrystallized coralline limestone, grainstone, packstone, and wackestone (Fig. 4). Large massive *Porites* was the predominant coral recovered. Diagenetic alteration in the Rakahanga and Pukapuka cores is sparse and localized and, where present, petrographic textures suggest that diagenesis

occurred in the vadose zone (e.g. Pingitore, 1976; Steinen, 1974; Matthews, 1974; Longman, 1980). However, corals between these visibly altered zones are mineralogically and petrographically pristine. Individual massive coral heads, the most common coral type in the cores, are very impermeable and diagenesis is commonly restricted to their outer margins.

Coral ages range from the Holocene to almost 600,000 yr old (Tables 1 and 2; Fig. 4). These ages are consistent with ages of 40–60 m deep atoll strata at other locations such as Mururoa (Aïssaouri et al., 1990) and Enewetak (Szabo et al., 1985). There is good agreement between ESR and U-series results (Table 2) where the ranges of the two dating methods overlap (0–300,000 yr B.P.). All ages are stratigraphically consistent

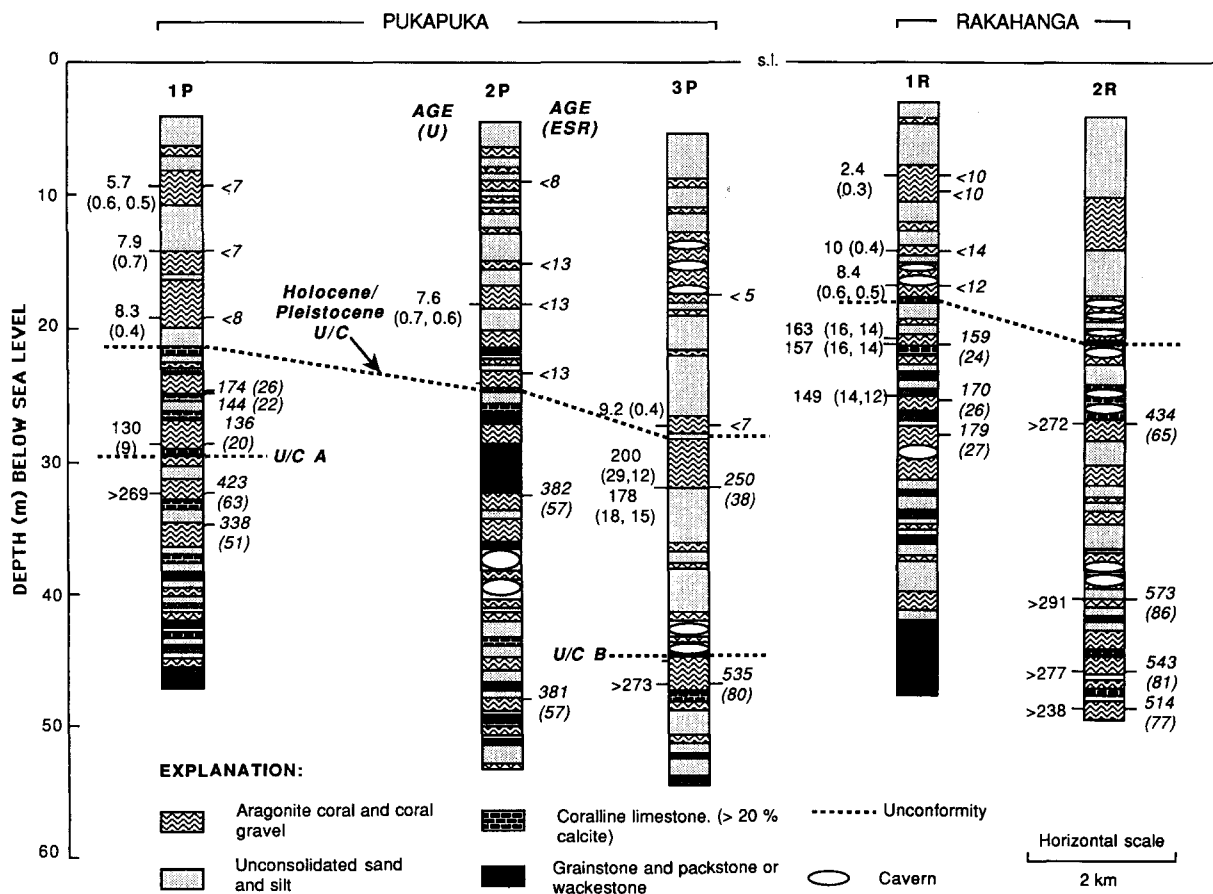


Fig. 4. Interpretive stratigraphic section from drill cores showing lithology, diagenesis, and geochronology of cores. ESR ages in thousands of years are shown on the right side and U-series ages on the left side of each core, with dating uncertainty in parentheses (Tables 1 and 2). Dashed lines mark the position of unconformities.

(Tables 1 and 2; Fig. 4), except sample 956, which has an old U-series age of 10,300 ( $\pm 400$ ) (Table 1), very close to the age of the underlying sample. The cause of this inconsistency is unknown.

In spite of the aragonitic mineralogy of the dated samples, several of these U/Th isotopic ratios are inconsistent with a closed system model because the  $^{230}\text{Th}/^{234}\text{U}$  and  $^{234}\text{U}/^{238}\text{U}$  ratios are greater than expected concordia in a closed system (Table 1). Anomalously high  $^{230}\text{Th}/^{234}\text{U}$  and  $^{234}\text{U}/^{238}\text{U}$  may result from addition of exogenous U. The magnitude of age deviations resulting from isotopic exchange is unknown. For some ages, the precision of the thorium analyses has also been affected by low yields (Table 1). In spite of these effects, the geochronologic evidence is still permissive of our separation of samples into 5 general groupings (reef growth periods).

Hiatuses are indicated by age gaps that are in places marked by lithologic features indicative of subaerial diagenesis/exposure. The stratigraphic position of the Holocene–Pleistocene unconformity (15–22 m, subbottom) is unequivocal in all holes from both lithologic characteristics and from dating (Fig. 4). Two additional hiatuses/unconformities suggested by age gaps and solution unconformities occur in the Pleistocene section (Fig. 4: U/C A and U/C B).

The stratigraphic position of the Holocene–Pleistocene boundary (15–22 m) (Fig. 4) corresponds to the shallowest occurrence of secondary calcite and an age gap between the oldest Holocene age of 9200 ( $\pm 400$ ) yr B.P. (Hole 3P) and the youngest Pleistocene age of 130,100 ( $+8900/-8100$ ) yr B.P. (Hole 1P). The Holocene–Pleistocene boundary given by these ages is slightly deeper than it is at other atolls. For example, at Aitutaki, in the southern Cook Islands, this unconformity is between 7–12 m (Hein et al., 1988a); at Enewetak: <15 m (Szabo et al., 1985), 7–8 m and 10 m (Folger, 1986), and 10 m subbottom in hole 00R-7 (Quinn and Matthews, 1990); at Tarawa, Kiribati: 12–17 m (Marshall and Jacobson, 1985); and at Mururoa, French Polynesia: 3–9 m (Trichet et al., 1984). However, most of these studies were conducted on the outer reef, where one would expect a Pleistocene foundation shallower than the lagoon.

Corals of approximately 130,000–170,000 and 200,000 yr B.P. underlie the Holocene–Pleistocene boundary in holes 1P and 1R, and 3P, respectively (Table 1; Fig. 4). The youngest dated Pleistocene corals in holes 2P and 2R, which occur between 5–10 m below the Holocene–Pleistocene boundary are approximately 380,000 and 430,000 yr B.P., respectively. No coral ages fall between 226,000 and 325,000 yr B.P. on either atoll and between 200,000 yr B.P. and 360,000 yr B.P. on Rakahanga (Fig. 4), which is similar to a gap in coral ages reported for Mururoa (Trichet et al., 1984).

## Discussion

### *Reef growth periods and sea-level history*

The grouping of sample ages broadly describes the timing and stratigraphic position of past periods of reef growth and thus high sea-level (Figs 5 and 6; Table 3). However, these groupings become less distinct with age due to large dating errors and therefore older reef growth intervals may encompass more than a single period of assumed reef growth.

Holocene reef growth in the northern Cook Islands started 9200 ( $\pm 400$ ) yr B.P. –about the same time as in other locations (7500–9000 yr B.P.) (Pirazzoli and Montaggioni, 1988; Marshall and Jacobson, 1985; Marshall and Davies, 1984; Szabo et al., 1985; Shinn et al., 1989). At this time sea-level was high enough to flood the islands' lagoons, which were 15–22 m below present sea level.

The most recent period of lagoonal reef growth prior to the Holocene occurred during the last interglacial ( $\sim 122,000$ – $135,000$  yr B.P.). The last interglacial was a period of widespread reef development worldwide (Moore, 1982; Marshall and Davies, 1984; Marshall and Jacobson, 1985; Shinn et al., 1989) when sea-level was +4–7 m higher than modern levels (Hattin and Warren, 1989; Jones and Hunter, 1990; Ku et al., 1974; Marshall and Thom, 1976; Thomson and Walton, 1977).

Given how widespread these last interglacial reef deposits were, it is surprising that only two (one U-series and one ESR) Cook Islands ages (samples 951 and 991: Tables 1 and 2) fall within error of

TABLE 1

Table 1. Composition of corals and U-series data for Pukapuka and Rakahanga Atolls.

| Lab no. | Hole no. | Depth (cm) | sub-bottom | Coral genus   | % Arag | Mg (ppm) | Sr (ppm) | U (ppm) | error Th (+/-1σ) (ppm) | Th (ppm) | error Th (+/-1σ) (ppm) | U-234/U-238 (+/-1σ) (activity) | error U-234/U-238 (+/-1σ) (activity) | Th-234/U-238 (+/-1σ) (activity) | error Th-234/U-238 (+/-1σ) (activity) | Th-232/Th-234 (+/-1σ) (activity) | error Th-232/Th-234 (+/-1σ) (activity) | Uncorrected error U-series Age (1000 yrs B.P.) | Corrected error U-series Age (1000 yrs B.P.) | error (+1σ) (1000 yrs) | error (-1σ) (1000 yrs) |      |
|---------|----------|------------|------------|---------------|--------|----------|----------|---------|------------------------|----------|------------------------|--------------------------------|--------------------------------------|---------------------------------|---------------------------------------|----------------------------------|----------------------------------------|------------------------------------------------|----------------------------------------------|------------------------|------------------------|------|
| 947     | 1P       | 518        |            | FAVIA         | 99     | 130      | 7100     | 3.17    | 0.14                   | 0.09     | 0.02                   | 1.098                          | 0.038                                | 0.059                           | 0.005                                 | 7                                | 2                                      | 6.6                                            | 0.6                                          | 5.7                    | 0.6                    | 0.5  |
| 948     | 1P       | 1053       |            | PORITES       | 97     | #        | #        | 3.16    | 0.09                   | 0.09     | 0.04                   | 1.136                          | 0.029                                | 0.078                           | 0.006                                 | 10                               | 4                                      | 8.8                                            | 0.8                                          | 7.9                    | 0.7                    | 0.7  |
| 949     | 1P       | 1562       |            | DIPLOASTREA   | 100    | #        | #        | 2.43    | 0.06                   | 0.01     | 0.01                   | 1.155                          | 0.024                                | 0.075                           | 0.004                                 | 54                               | 28                                     | 8.5                                            | 0.5                                          | 8.3                    | 0.4                    | 0.4  |
| 951     | 1P       | 2485       |            | PORITES       | 100    | #        | #        | 2.62    | 0.05                   | 0.09     | 0.02                   | 1.111                          | 0.017                                | 0.713                           | 0.023                                 | 72                               | 15                                     | 131.2                                          | 8.9                                          | 130.1                  | 8.9                    | 8.1  |
| 952     | 1P       | 2853       |            | FAVIA         | 97     | 140      | 6900     | 2.58    | 0.07                   | 0.14     | 0.04                   | 1.113                          | 0.026                                | 1.089                           | 0.045                                 | 67                               | 19                                     | >269                                           | #                                            | >269                   | #                      | #    |
| 963     | 2P       | 1424       |            | PORITES       | 99     | #        | #        | 2.84    | 0.04                   | 0.06     | 0.03                   | 1.141                          | 0.013                                | 0.074                           | 0.005                                 | 12                               | 5                                      | 8.3                                            | 0.7                                          | 7.6                    | 0.7                    | 0.6  |
| 975     | 3P       | 2251       |            | PORITES       | 100    | #        | #        | 2.93    | 0.05                   | 0.05     | 0.01                   | 1.141                          | 0.013                                | 0.086                           | 0.004                                 | 17                               | 4                                      | 9.7                                            | 0.5                                          | 9.2                    | 0.4                    | 0.4  |
| 976a*   | 3P       | 2575       |            | PORITES       | 100    | 190      | 7200     | 2.37    | 0.04                   | n.d.     | #                      | 1.089                          | 0.022                                | 0.857                           | 0.018                                 | >250                             | #                                      | 199.8                                          | 29.5                                         | 12.4                   | #                      | #    |
| 976b*   | 3P       | 2575       |            | PORITES       | 100    | 190      | 7200     | 2.34    | 0.03                   | n.d.     | #                      | 1.137                          | 0.019                                | 0.827                           | 0.016                                 | >250                             | #                                      | 178.3                                          | 18.6                                         | 15.2                   | #                      | #    |
| 977     | 3P       | 4149       |            | PORITES       | 100    | 140      | 7400     | 3.23    | 0.09                   | 0.10     | 0.03                   | 1.077                          | 0.026                                | 0.988                           | 0.041                                 | 109                              | 29                                     | >273                                           | #                                            | >273                   | #                      | #    |
| 954     | IR       | 542        |            | ECHINOPHYLLIA | 98     | #        | #        | 4.59    | 0.11                   | 0.04     | 0.03                   | 1.151                          | 0.018                                | 0.024                           | 0.003                                 | 11                               | 9                                      | 2.6                                            | 0.3                                          | 2.4                    | 0.3                    | 0.3  |
| 956     | IR       | 1129       |            | PORITES       | 98     | #        | #        | 2.99    | 0.06                   | 0.03     | 0.01                   | 1.137                          | 0.017                                | 0.093                           | 0.004                                 | 35                               | 16                                     | 10.5                                           | 0.5                                          | 10.3                   | 0.4                    | 0.4  |
| 957     | IR       | 1449       |            | PORITES       | 99     | 130      | 7700     | 2.91    | 0.09                   | 0.06     | 0.02                   | 1.085                          | 0.027                                | 0.080                           | 0.005                                 | 14                               | 4                                      | 9.00                                           | 0.6                                          | 8.4                    | 0.6                    | 0.5  |
| 988     | IR       | 1719       |            | PORITES       | 98     | #        | #        | 2.88    | 0.05                   | 0.18     | 0.04                   | 1.126                          | 0.013                                | 0.799                           | 0.031                                 | 44                               | 9                                      | 165.2                                          | 16.3                                         | 14.1                   | 16.3                   | 13.9 |
| 958     | IR       | 1811       |            | PORITES       | 99     | #        | #        | 3.33    | 0.08                   | 0.07     | 0.03                   | 1.130                          | 0.021                                | 0.784                           | 0.031                                 | 121                              | 43                                     | 157.9                                          | 16.0                                         | 13.7                   | 15.7                   | 13.6 |
| 989     | IR       | 2214       |            | PORITES       | 100    | #        | #        | 2.52    | 0.04                   | 0.08     | 0.03                   | 1.121                          | 0.012                                | 0.764                           | 0.031                                 | 79                               | 24                                     | 150.1                                          | 14.2                                         | 149.1                  | 14.0                   | 12.3 |
| 969     | 2R       | 2372       |            | PORITES       | 99     | 130      | 7500     | 3.66    | 0.11                   | 0.19     | 0.03                   | 1.123                          | 0.029                                | 1.056                           | 0.044                                 | 69                               | 12                                     | >272                                           | #                                            | >272                   | #                      | #    |
| 971     | 2R       | 3642       |            | PORITES       | 99     | #        | #        | 4.40    | 0.11                   | 0.11     | 0.02                   | 1.094                          | 0.024                                | 1.042                           | 0.036                                 | 146                              | 38                                     | >291                                           | #                                            | >291                   | #                      | #    |
| 972     | 2R       | 4184       |            | PORITES       | 100    | #        | #        | 6.57    | 0.16                   | 0.25     | 0.07                   | 1.089                          | 0.021                                | 1.103                           | 0.041                                 | 95                               | 24                                     | >277                                           | #                                            | >277                   | #                      | #    |
| 973     | 2R       | 4458       |            | PORITES       | 100    | 120      | 7600     | 4.07    | 0.12                   | 0.15     | 0.05                   | 1.053                          | 0.024                                | 1.138                           | 0.056                                 | 97                               | 29                                     | >238                                           | #                                            | >238                   | #                      | #    |

\*Two splits of coral sample 976 were dated at UCSC.

#, not determined

TABLE 2

Table 2. Composition of Corals and ESR dating results for Pukapuka and Rakahanga Atolls.

| Lab # | Hole | Depth (cm) sub-bottom | Coral genus    | % Arag. | Mg (ppm) | Sr (ppm) | U (ppm) | error (+/-1σ) (ppm) | Accum. Dose (Gy) | Annual Dose (m Gy/a) a | ESR Age (1000 yrs B.P.) | ESR error (+/- 15%) (1000 yrs) | ESR Range (+/- 15%) (1000 yrs) | U-series Age Range (1000 yrs B.P.) |
|-------|------|-----------------------|----------------|---------|----------|----------|---------|---------------------|------------------|------------------------|-------------------------|--------------------------------|--------------------------------|------------------------------------|
| 947   | 1P   | 518                   | FAVIA          | 99      | 130      | 7100     | 3.17    | 0.14                | 2.9              | 0.4042                 | <7.3                    | #                              | <7.3                           | 5.2-6.3                            |
| 948   | 1P   | 1053                  | PORITES        | 97      | #        | #        | 3.16    | 0.09                | 2.7              | 0.4025                 | <6.8                    | #                              | <6.8                           | 7.2-8.6                            |
| 949   | 1P   | 1562                  | DIPLOASTREA    | 100     | #        | #        | 2.43    | 0.06                | 2.5              | 0.3257                 | <7.7                    | #                              | <7.7                           | 7.9-8.7                            |
| 990   | 1P   | 2153                  | PORITES        | 99      | #        | #        | 2.29    | 0.06                | 124.1            | 0.7159                 | 174                     | 26                             | 148-200                        | #                                  |
| 991   | 1P   | 2177                  | PORITES        | 100     | #        | #        | 2.47    | 0.07                | 103.4            | 0.7167                 | 144                     | 22                             | 122-166                        | #                                  |
| 951   | 1P   | 2485                  | PORITES        | 100     | #        | #        | 2.62    | 0.05                | 98.9             | 0.7304                 | 136                     | 20                             | 116-156                        | 122-139                            |
| 952   | 1P   | 2853                  | FAVIA          | 97      | 140      | 6900     | 2.58    | 0.07                | 423.0            | #                      | 423                     | 63                             | 360-486                        | >269                               |
| 953   | 1P   | 3082                  | FAVIA          | 98      | #        | #        | 2.60 c  | #                   | 330.6            | 0.9787                 | 338                     | 51                             | 287-389                        | #                                  |
| 961   | 2P   | 452                   | PORITES        | 100     | #        | #        | 2.93    | 0.06                | 3.5              | 0.4328                 | <8.1                    | #                              | <8.1                           | #                                  |
| 962   | 2P   | 1123                  | PORITES        | 100     | #        | #        | 2.61    | 0.08                | 4.6              | #                      | <12.6                   | #                              | <12.6                          | #                                  |
| 963   | 2P   | 1424                  | PORITES        | 99      | #        | #        | 2.84    | 0.04                | 5.2              | 0.4005                 | <13.2                   | #                              | <13.2                          | 7.0-8.3                            |
| 964   | 2P   | 1908                  | PORITES        | 100     | #        | #        | 2.43    | 0.04                | 4.5              | 0.3493                 | <13.0                   | #                              | <13.0                          | #                                  |
| 965   | 2P   | 2882                  | PORITES        | 100     | #        | #        | 2.79    | 0.07                | 399.5            | 1.0471                 | 382                     | 57                             | 325-439                        | #                                  |
| 966   | 2P   | 4386                  | STYLOCOENIELLA | 100     | #        | #        | 4.34    | 0.15                | 582.3            | 1.5297                 | 381                     | 57                             | 324-438                        | #                                  |
| 974   | 3P   | 1264                  | PORITES        | 100     | 150      | 7800     | 4.62    | 0.18                | 3.2              | 0.5935                 | <5.4                    | #                              | <5.4                           | #                                  |
| 975   | 3P   | 2251                  | PORITES        | 100     | #        | #        | 2.93    | 0.05                | 2.8              | 0.4267                 | <6.6                    | #                              | <6.6                           | 8.8-9.6                            |
| 976   | 3P   | 2575                  | PORITES        | 100     | 190      | 7200     | 2.39    | 0.04                | 205.1            | 0.8204                 | 250                     | 38                             | 212-284                        | 163-229                            |
| 977   | 3P   | 4149                  | PORITES        | 100     | 140      | 7400     | 3.23    | 0.09                | 666.4            | 1.2469                 | 535                     | 80                             | 455-615                        | >273                               |
| 954   | 1R   | 542                   | ECHINOPHYLLIA  | 98      | #        | #        | 4.59    | 0.11                | 5.5              | 0.5856                 | <9.5                    | #                              | <9.5                           | 2.1-2.7                            |
| 955   | 1R   | 642                   | FAVID          | 98      | #        | #        | 3.58    | 0.09                | 4.3              | #                      | <9.7                    | #                              | <9.7                           | #                                  |
| 956   | 1R   | 1129                  | PORITES        | 98      | #        | #        | 2.99    | 0.06                | 5.9              | 0.4187                 | <14.1                   | #                              | <14.1                          | 9.9-10.7                           |
| 957   | 1R   | 1449                  | PORITES        | 99      | 130      | 7700     | 2.91    | 0.09                | 4.9              | 0.3947                 | <12.4                   | #                              | <12.4                          | 7.9-9.0                            |
| 958   | 1R   | 1811                  | PORITES        | 99      | #        | #        | 3.33    | 0.08                | 154.7            | #                      | 159                     | 24                             | 135-183                        | 144-173                            |
| 959   | 1R   | 2258                  | PORITES        | 97      | 100      | 8200     | 2.79    | 0.09                | 140.2            | 0.8224                 | 170                     | 26                             | 144-196                        | #                                  |
| 960   | 1R   | 2497                  | PORITES        | 99      | #        | #        | 3.34    | 0.08                | 181.2            | 1.0152                 | 179                     | 27                             | 152-206                        | #                                  |
| 969   | 2R   | 2372                  | PORITES        | 99      | 130      | 7500     | 3.66    | 0.11                | 611.6            | 1.4112                 | 434                     | 65                             | 369-499                        | >272                               |
| 971   | 2R   | 3642                  | PORITES        | 99      | #        | #        | 4.40    | 0.11                | 984.0            | 1.7173                 | 573                     | 86                             | 487-659                        | >291                               |
| 972   | 2R   | 4184                  | PORITES        | 100     | #        | #        | 6.57    | 0.16                | 1063.8           | 2.4373                 | 437(543) c              | 81                             | 462-624                        | >277                               |
| 973   | 2R   | 4458                  | PORITES        | 100     | 120      | 7600     | 4.07    | 0.12                | 791.8            | 1.5495                 | 514                     | 77                             | 437-591                        | >238                               |

a. from alpha, beta, gamma, and cosmic radiation

b. Uranium content assumed to be between 2.0-3.0 ppm.

c. Correction for linear uranium uptake from 2.5 ppm (assumed) to 6.5 ppm.

#. not determined

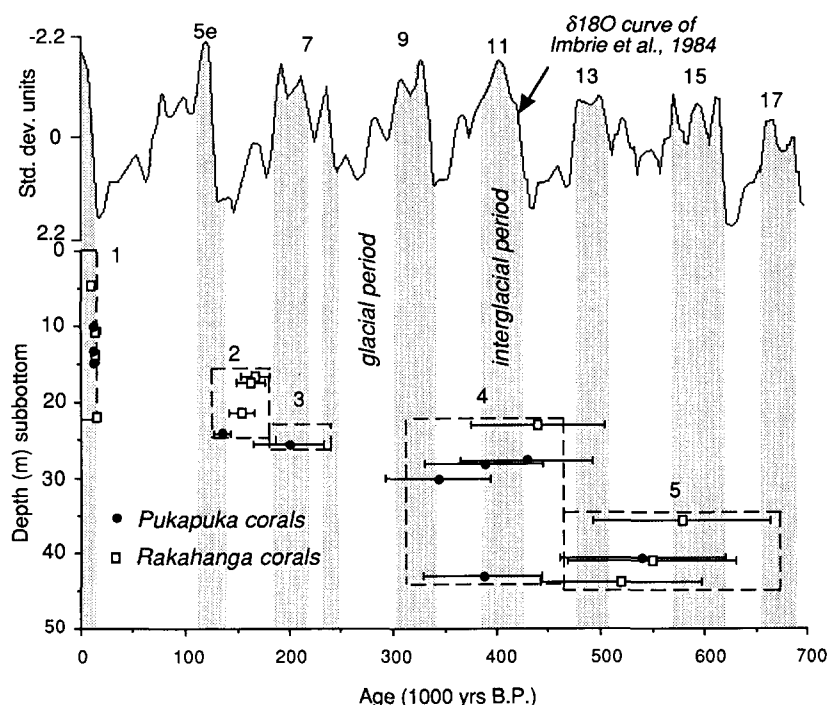


Fig. 5. Age versus depth of coral samples from Pukapuka (circles) and Rakahanga (squares) compared to the  $\delta^{18}\text{O}$  curve from five deep-sea cores that were normalized, averaged, smoothed and plotted against the SPECMAP time scale (Imbrie et al., 1984). Ages less than 300,000 yr B.P. are based on U-series analyses (dating error =  $\pm 1 \sigma$ ) and ages greater than 300,000 yr B.P. are based on ESR analyses (dating error =  $\pm 15\%$ ). Stippled areas mark the durations of interglacial periods suggested by negative excursions of  $\delta^{18}\text{O}$ .

TABLE 3

Table 3. Cook Island reef growth periods.

| REEF GROWTH PERIOD | AGE (YRS B.P.)  | DEPTH RANGE (M SUBBOTTOM) | THICKNESS (M)                             |
|--------------------|-----------------|---------------------------|-------------------------------------------|
| 1                  | 0-9000          | 0 to 22                   | 15 to 22                                  |
| 2                  | 125,000-180,000 | 15 to 25                  | 3 to 10                                   |
| 3*                 | 180,000-230,000 | 22 to 26(?)               | >4 m**                                    |
| 4                  | 300,000-460,000 | 24 to 43                  | Rakahanga: 10 to 15<br>Pukapuka: 15 to 22 |
| 5                  | 460,000-650,000 | > 36                      | >12                                       |

\*The grouping of samples #959 and #960, with ESR ages of  $170,000 \pm 26,000$  and  $179,000 \pm 27,000$  yrs B.P., respectively in period 2 or 3 is equivocal (Table 2).

\*\*The thickness of Reef 3 is difficult to determine because solution unconformities were not recovered.

this period. One explanation for the paucity of last interglacial-aged samples is that subaerial erosion during the subsequent 100,000 yr of exposure removed much of the lagoonal sediments deposited during that time.

Although some coral (e.g. Bard et al., 1990) and oxygen isotope (Imbrie et al., 1984) records indicate that the last interglacial was restricted to a short interval between  $\sim 120,000$ – $127,000$  yrs B.P., closer examination of paleoclimate records reveal

inconsistencies with respect to the precise timing and duration of this sea-level high stand. Paleoclimatic evidence from a variety of environments suggests that deglaciation may have been underway as early as 140,000 yr B.P. Evidence supporting earlier deglaciation include: (a) coral terrace dates, which suggest a double high sea-level stand (one preceding and one following) Termination 2 (Kaufman, 1986; Bloom et al., 1974; Ku et al., 1974; Newmann and Moore, 1975; Thomson and Walton, 1972); (b) speleothem dates indicating that sea-level had risen to  $-12$  m by 134,000 yr B.P. (Li et al., 1989; Lundberg et al., 1990); (c) dates of  $\sim 140,000$  yr B.P. for a negative excursion in  $\delta^{18}\text{O}$  in a terrestrial record (Winograd et al., 1988); and (d) negative  $\delta^{18}\text{O}$  excursions and faunal shifts in high latitude deep-sea cores  $\sim 140,000$  yr B.P. suggesting increased arctic meltwater (discussed in Johnson, 1991). A reduction of water-vapor input to the ice sheets driven by atmospheric circulation changes in response to a low in the insolation gradient  $\sim 140,000$  yr B.P. was proposed as a possible mechanism for this "cold climate" deglaciation (Johnson, 1991).

The Cook Islands data do not provide conclusive evidence either for or against such an earlier sea-level stand. U-series ages for Rakahanga corals (no. 988, 958, and 959, Table 1) of 150,000–163,000 yr B.P. fall 23,000–36,000 yr earlier than termination 2, during glacial stage 6 (Fig. 5). Although these corals are  $>98\%$  aragonite, their ages have likely been affected by post-depositional isotopic exchange. Discordant mass spectrometric  $^{230}\text{Th}$  and  $^{231}\text{Pa}$  ages of 100% aragonite splits of these stage 6 corals strongly support this possibility (Gray et al., 1991). A model of isotopic exchange in mineralogically unaltered corals (Ku et al., 1990) predicted age dispersions of 5–10% from the preferential gain of  $^{234}\text{U}$  through continuous exchange with groundwater uranium. An age offset of 10% ( $\pm 15,000$  yr) due to isotopic exchange could conceivably shift these ages to within error of substage 5e or the following stage 7 (Imbrie et al., 1984).

Reef-growth period 3 likely occurred during stage 7 when a sea-level stand of  $+2$  m (Harmon et al., 1983) has been reported. Exposure during glacial stage 8 may account for the gap in coral ages between Reefs 3 and 4 (226,000–325,000 yr

B.P.) (Fig. 6). Reef growth resumed following termination III at  $\sim 244,000$  yr B.P. (Williams et al., 1988).

Reef growth periods 4 and 5 are based on ESR ages only. Reef growth period 4 may have occurred during sea-level stands of oxygen isotope stage 11, ( $\sim 362,000$ – $423,000$  yr B.P.) (Imbrie et al., 1984) with the ESR age of one sample (953) overlapping stage 9. Minimum oxygen isotope excursions during this period occur at  $\sim 320,000$  and  $\sim 330,000$  yr B.P. during stage 9, at  $\sim 400,000$  yr B.P. during stage 11 (Fig. 5). Ages of reef growth period 5 corals occur during oxygen-isotope stages 13 (478,000–524,000 yr B.P.) and 15 (565,000–620,000 yr B.P.) (Imbrie et al., 1984) (Figs. 5 and 6).

### Reef accretion, erosion and subsidence

The Pleistocene development of atolls is characterized by rapid spurts of reef growth during short intervals of rising sea level, followed by long intervals of erosion on a slowly subsiding basement. Atolls will drown if they subside or erode below a critical depth (Grigg and Epp, 1989), which for the Hawaiian islands is generally less than about 30 m. Upward reef growth during a sea-level transgression should be rapid enough to fill accommodation space created by erosion and subsidence of the basement since the preceding period of high sea level. This is described by the following relation:

$$\begin{aligned} \text{Current reef accretion} \\ = \text{prior erosion of reef platform} \\ + \text{prior subsidence} \end{aligned} \quad (1)$$

Since reef accretion and erosion only occur during periods of submergence and emergence, respectively, then

$$\begin{aligned} &[(\text{actual reef accretion rate}) \\ &\times (\text{fraction of time the reef was submerged})] \\ &= [(\text{erosion rate}) \\ &\times (\text{fraction of time the reef was emerged})] \\ &+ \text{subsidence rate} \end{aligned} \quad (2)$$

Equation 2 provides a means to quantify erosion rates knowing subsidence rates, and the percentage of time that sea-level was high enough to flood the atoll platform/lagoon. Subsidence of the ocean

crust is proportional to the square root of its age (e.g. Parsons and Sclater, 1977), which, for the last 600,000 yr B.P., should approximate a straight line. Cook Island subsidence rates of  $-4.5 \pm 2.8$  cm/1000 yr B.P. ( $r^2 = 0.65$ ) are given by the regression of depth versus age. This subsidence rate is within range of thermal subsidence rates for other mid-plate islands (e.g. Schlanger, 1963; Schlanger et al., 1987).

Accretion rates in the Holocene were generally greater than 100 cm/1000 yr [e.g. Belize: 100–600 cm/1000 yr (Shinn et al., 1979); Florida: 38–485 cm/1000 yr (Shinn et al., 1977); Panama: average: 500 cm/1000 yr, maximum: 1200 cm/1000 yr (Macintyre, 1977); and offshore Barbados up to 1300 cm/1000 yr (Fairbanks, 1989)]. Accretion rates vary with the position of the reef with respect to sea-level. Accretion rates were higher (400–1000 cm/1000 yr) during periods of rising sea-level than after sea-level stabilization (100–300 cm/1000 yr) (Davies, 1983; Davies and Montaggioni, 1985; Hopley, 1982). Accretion rates in the lagoon environment are typically much less [up to 10 times (Purdy, 1974)] than in outer reef environments [e.g. <140 cm/1000 yr (Shinn et al., 1979)] (Hopley, 1982). Radiocarbon ages of the Holocene sections of Pukapuka and Rakahanga confirm this pattern and give an average Holocene reef accretion rate of 220 cm/1000 yr for these northern Cook Islands atoll lagoons (Gray and Hein, in prep.). These high accretion rates enabled reefs to grow from submerged platforms to sea-level within the short duration (5000–10,000 yr) of a Pleistocene sea-level high stand.

The percentage of time that the lagoons were submerged can be estimated from the oxygen isotope curve. Porter (1989) used the high-resolution oxygen isotope record from core V19-30 to estimate that sea-level was above present level for 6% of the past 340,000 years and Paulay and McEdward (1990) estimated that reefs grew above  $-10$  m for 15% of the Pleistocene. According to the raised reef record (summarized in Moore et al., 1982), over the last glacial–interglacial cycle, sea-levels above  $-20$  m occurred during the Holocene and oxygen isotope stages 5a ( $\sim 84,000$  yr B.P.), 5c ( $\sim 105,000$  yr B.P.) and 5e (122,000 and 135,000 yr B.P.). The oxygen isotope curve of

Imbrie et al. (1984) shows oxygen isotope excursions (in standard deviation units) less than  $-0.7$  for these time periods (Fig. 5). Values less than  $-0.7$  standard deviation units comprise 20% of the oxygen isotope record for the past 700,000 yr (Imbrie et al., 1984). Considering that lagoons should be submerged only during the transgressive and still-stand phases of a sea-level cycle, from this record, we estimate atolls were submerged for  $\sim 8$ –15% of the past 700,000 yr.

A rate of reef erosion of 20 cm/1000 yr is calculated from Eq. 2 using an average reef accretion rate of 220 cm/1000 yr (determined from  $^{14}\text{C}$  dating of Pukapuka and Rakahanga's Holocene reef), lagoon submergence for 10% of the Pleistocene, and a subsidence rate of 4 cm/1000 yr. By varying the parameters of reef growth (100–400 cm/1000 yr), subsidence (2–6 cm/1000 yr), and duration of island submergence (8–15% of the last 600,000 yr), erosion rates of 6–63 cm/1000 yr result.

These erosion rates are within range of erosion rates calculated by subtracting assumed subsidence from the position of the Holocene–Pleistocene unconformity: 1–17 cm/1000 yr (Mururoa), 8.2–20.2 cm/1000 yr (Enwetak), 1.1–14.6 cm/1000 yr (Tarawa) (Paulay and McEdward, 1990); and 7–14 cm/1000 yr (Great Barrier Reef) (Marshall and Davies, 1984).

Short-term subaerial surface-lowering rates reported for Grand Cayman Island, Caribbean Sea, (Spencer, 1985) and Aldabra Atoll, Indian Ocean (Trudgil, 1983) of 1–69 cm/1000 yr (mean: 37 cm/1000 yr), and 26 cm/1000 yr, respectively also are within range of the calculated rates. However, these measurements—made over the short-term—are highly variable and sensitive to climatic conditions and cannot be extrapolated through the Pleistocene. Furthermore, as suggested by Spencer (1985), erosion rates should decrease with the development of vegetation and calcrete surfaces on the emergent platform.

### Model of Pleistocene reef growth

The age, thickness, and stratigraphy of Cook Islands reefs provide a means to model atoll growth and erosion given Pleistocene sea-level history

TABLE 4

Table 4. Timing and amplitude of sea-level high stands inferred from the oxygen isotope record (Imbrie et al., 1984) and other sources. These high stands are used to model the late Quaternary reef growth history of Pukapuka and Rakahanga (Figure 7).

| Cook Island Reef | Oxygen isotope interglacial stage | Age (1000 yrs.)* | Periods of oxygen isotope depletion (highstands) | Approximate timing (1000 yrs.) for each highstand** | Amplitude (m) relative to modern sea level | Reference                                        |
|------------------|-----------------------------------|------------------|--------------------------------------------------|-----------------------------------------------------|--------------------------------------------|--------------------------------------------------|
| 1 (Holocene)     | 1                                 | < 10             | 1                                                | 0-10                                                | 0                                          |                                                  |
| 2                | 5                                 | 80-128           | 5e                                               | 120-135                                             | 6                                          | Ku et al. (1974)                                 |
| 3                | 7                                 | 186-245          | 7a<br>7c                                         | 200-210<br>225-235                                  | 2<br>~10                                   | Marshall and Thom (1976)<br>Harmon et al. (1983) |
| 4                | 9                                 | 303-339          | 9c                                               | 320-330                                             | 0                                          | estimated from Imbrie et al. (1984)              |
|                  | 11                                | 362-423          | 11                                               | 395-405                                             | 0                                          | assumed                                          |
| 5                | 13                                | 478-524          | 13                                               | 490-500                                             | 0                                          | assumed                                          |

\* From Imbrie et al. (1984).

\*\* Ages are estimated from substages shown on the Imbrie et al., (1984) curve except for 5e, the end of which has been extended from 128,000 (from Imbrie's curve) to 135,000 years to encompass evidence for earlier high sea-level stands (summarized in Moore, 1982) associated with this substage. The duration of sea-level high stands is assumed to be 10,000 years, except for substage 5e, which is 15,000 years in duration.

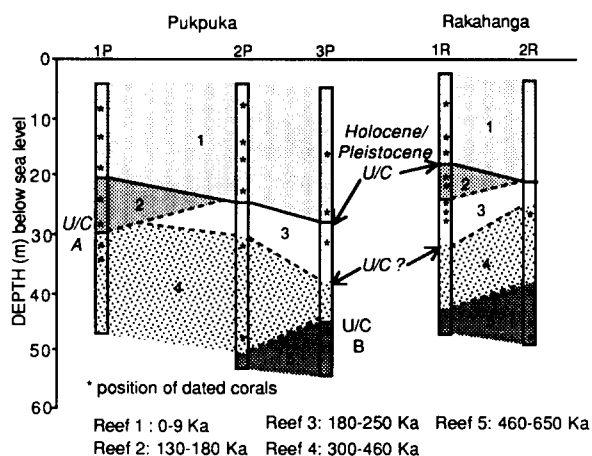


Fig. 6. Stratigraphic position of dated corals representing 5 reef growth periods separated by hiatuses/unconformities. Stars mark the position of dated corals. Solid lines indicate that the stratigraphic position of the unconformity is well constrained from radiometric ages and lithologic evidence of subaerial exposure features. Dashed lines indicate the inferred position of an unconformity.

(Table 4). The model (Fig. 7) predicts the stratigraphy that would result from subsidence rates of 2, 5, and 8 cm/1000 yr (Fig. 7). Assuming similar reef topography between reef-growth periods, erosion rates of 20, 17, and 14 cm/1000 yr for subsidence rates of 2, 5, and 8 cm/1000 yr, respectively are determined graphically from the slope of the line connecting the last interglacial high sea-level stand (+6 m) to the average depth of the Pleistocene–Holocene unconformity (19 m) (Fig. 7).

More rapid subsidence rates will result in preservation of thicker sections and a greater number of high sea-level reefs. Slower subsidence rates will result in a compressed stratigraphic section. For example, with subsidence rates of 2 cm/1000 yr, reef 2 is not preserved, reefs 3 and 4 are less than 5 m thick and reef 5 begins at -27 m (Fig. 7). With a subsidence rate of 8 cm/1000 yr, only the first four reefs are preserved in the upper 50 m of the atolls' stratigraphic section. With a slower subsidence, reef stratigraphy is compressed, reefs are

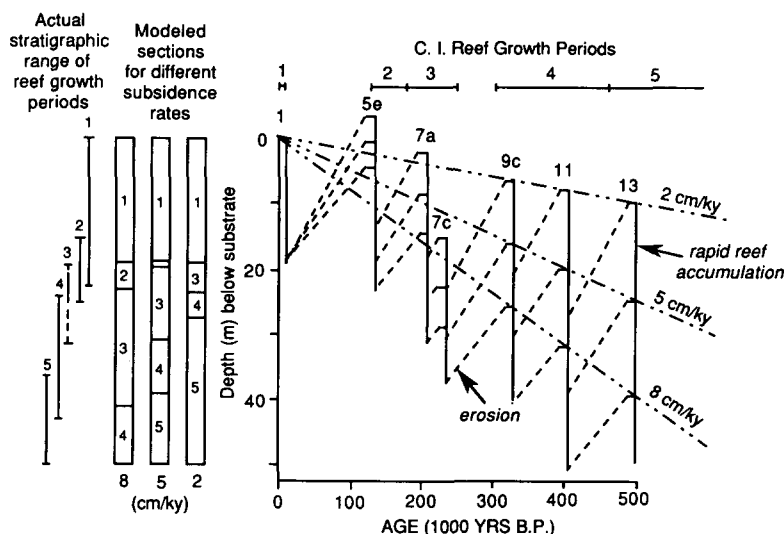


Fig. 7. Models of atoll reef growth and erosion during the late Quaternary showing the resulting stratigraphy from different rates of subsidence and erosion. Solid vertical lines (right side of diagram) mark rapid reef accretion during major sea-level high stands indicated by the oxygen isotope curve (Fig. 5; Table 4). Dashed diagonal lines represent erosion of the reef during periods of low sea-level and subaerial exposure. The erosion rates of 14, 17, and 20 cm/1000 yr for subsidence rates of 2, 5, and 8 cm/1000 yr, respectively are determined graphically. High stands of sea-level are inferred from the oxygen isotope curve and studies of Pleistocene reefs (Table 4). Stratigraphic sections resulting from modeled subsidence rates of 2, 5, and 8 cm/1000 yr are shown in the three columns on the left and compared to the observed stratigraphic position of reef growth periods from the Cook Island cores (far left). According to this model, subsidence and erosion rates of 5 and 17 cm/1000 yr, respectively, are most consistent with the observed stratigraphic section.

thinner, and fewer reefs and solution unconformities will be preserved. Higher subsidence rates promote preservation of a greater number and stratigraphically thicker reefs (Fig. 7). Comparison of the observed Cook Island stratigraphic section to the atoll stratigraphy predicted by this model suggests that subsidence and erosion rates of about 5 and 17 cm/1000 yr, respectively, can account for the stratigraphy of Pukapuka and Rakahanga. According to this model, a record of the substage 5e last interglacial high stand of sea-level (reef growth period 2), which is so well represented by reefs in tectonically active locations (e.g. Chappell and Veeh, 1978; Bender et al., 1979; Dodge et al., 1983; Marshall and Thom, 1976) may be absent, or thin on mid-plate atolls with high erosion or slow subsidence rates (Fig. 7).

The sea-level curve used for this model-based on the timing of negative oxygen isotope excursions (Imbrie et al., 1984) and dating of reefs in tectonically stable areas (Table 4)—is limited by our poor knowledge of the precise timing and amplitude of Pleistocene sea-level stands (especially prior

to the last interglacial). For substage 5e (e.g. Ku, et al., 1974; Marshall and Thom, 1976) and stage 7 (e.g. Harmon et al., 1983), the paleosea-level amplitude is inferred from dated reefs in tectonically stable locations. Because sea-level amplitudes are unknown before 200,000 yr B.P., we assume a sea-level amplitude equal to 0 m for oxygen isotope stages 9, 11, and 13. ESR dating of Barbados terraces (Radtke and Grün, 1990) showed conflicting evidence (probably because of variable uplift patterns) with respect to whether the pre-stage 7 sea-levels were generally above or below present. Although the predicted stratigraphy by this model is highly sensitive to assumptions about sea-level amplitude, it illustrates the potential for atoll stratigraphy to constrain rates of subsidence and reef erosion.

## Conclusions

At least five major periods of coral growth occurred in the lagoons of Pukapuka and Rakahanga atolls over the past 600,000 years. During

these periods, sea-level must have been high enough ( $> \sim -25$  m) to flood the lagoons. However, poor dating precision, and –for some samples–the possibility of post-depositional isotopic exchange prevents unequivocal correlation of these reef growth periods to specific negative oxygen-isotope excursions.

Similar subsidence rates of  $4.5 \pm 2.8$  cm/1000 yr occurred on the two islands. Because vertical accretion during rising sea-level must compensate for surface lowering from erosion during sea-level lowstands and subsidence of the atoll, erosion rates (6–63 cm/1000 yr) can be calculated from reef accretion rates (100–400 cm/1000 yr), subsidence rates (2–6 cm/1000 yr), and the duration of island submergence (8–15% of last 600,000 yr). A model based on the stratigraphy of the Cook Islands predicts average subsidence and erosion rates of between 3–6 and 15–20 cm/1000 yr, respectively.

Records of late Quaternary high sea-level are preserved in the subsurface sediments of mid-plate atoll lagoons. These records provide important sea-level data to compliment sea-level records from tectonically active settings. However, the application of reef-based sea-level records is limited by the range, precision, and accuracy of coral geochronology. Although the range of U-series geochronology has been extended and the precision vastly improved by mass spectrometry (Edwards et al., 1986/1987), the accuracy of coral dates ultimately depends on our ability to ensure that samples have remained closed to isotopic exchange throughout their history. These data suggest 100% aragonite mineralogy may not necessarily provide such assurance.

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