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Last glacial sea-level change deduced from uplifted coral terraces of Huon Peninsula, Papua New Guinea

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Abstract

We have dated corals sampled from the uplifted terraces of Huon Peninsula, Papua New Guinea, that grew during the Marine Isotope Stage 3, to reconstruct sea-levels of the last glacial period from 30 to 55 ka (kiloannum). Mass spectrometric U-series dating methods resulted in high precision dates and could also be used to recognize diagenetically altered samples. The only quantitative test of open-system behaviour of both uranium and thorium isotopes involves the comparison of $^{234}\text{U}/^{238}\text{U}$ ratios, at the time of coral growth, with present sea-water values. Additional tests included checks for systematic variations in stable isotopes, X-ray diffraction to detect calcification and petrographic examination. Sea-levels were corrected for glacio-hydro-isostatic variations and also for the depth range of coral growth habitat. Sea-levels from 30 to 55 ka were approximately 80 m lower than present. Superimposed on this general trend, four periodic sea-level high-stands were found, at 6–8 ka intervals, approximately at 30, 38, 44 and 52 ka, that appear to be synchronous with rapid climate variations previously observed in ice cores and in deep sea sediments. © 2001 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

Spatial and temporal differences in sea-level variations arise from localized deformations of the Earth's mantle due to reciprocal variations in ice sheet and hence ocean volumes as a direct result of climate change. Therefore, studies of past sea-level variations provide input and constraints both for geophysical and climate models. Holocene and Last interglacial sea-levels have been extensively investigated using various sea-level indicators. Among these, corals are of particular interest because they grow at or close to prevailing sea-levels, have a wide-spread habitat, and can be dated using high-precision uranium-series methods (Edwards et al., 1986; Stirling et al., 1995, 1998). Dating is reliable provided samples can be verified to have remained closed systems for the nuclides in question. Uranium and thorium

abundances in coral samples can be influenced by diagenesis resulting in erroneous measured ages. The problem has been investigated (Bard et al., 1991, 1992; Bar-Matthews et al., 1993; Stein et al., 1993; Henderson et al., 1993) and the results reveal a systematic trend where the measured ages tend to be older in approximate proportion to the apparent ^{234}U concentration of the sample at the time the coral grew (Gallup et al., 1994; Stirling et al., 1998). Although, there are no guarantees that every altered sample would behave in this way, it appears to be the predominant trend in samples from diverse locations subjected to variable climatic conditions. Due to reduced sample size requirement for thermal ion mass spectrometric (TIMS) measurements, compared with traditional alpha counting methods, it is easier to select relatively unaltered portions from bulk samples that often are of variable quality. For example, open pore spaces and septa tend to accumulate extraneous material and react with pore fluids easily, whereas thick wall sections tend to be relatively pristine (Stirling et al., 1995).

Coral studies of last glacial sea-level variations have been largely limited to samples from major stadials such as those from the 80 and 105 ka, stages 5a and c (Ludwig

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et al., 1996; Toscano and Lundberg, 1999). These corals and those from interglacials grew close to present sea-levels and can easily be sampled. However, most corals that grew during the last glacial from 20 to 60 ka are situated well below present sea-levels and are difficult to sample. The tectonically active Huon Peninsula is one of the exceptions due to sustained relatively high uplift rates over the late Quaternary period and coral terraces of the last glacial, onward from about 30 ka, are above the present sea-level (Chappell, 1974). Corals do not provide a continuous record of past sea-levels, but they can complement other palaeo data such as oxygen isotopes from deep-sea sediments (Shackleton, 1987) which do provide a continuous record but are difficult to date directly.

A long-standing problem of up to 40 m discrepancy between sea-levels derived from deep sea cores and Huon Peninsula terraces over the period from 30 to 60 ka was resolved by Chappell et al. (1996) following resurvey of terraces at two localities and new high precision TIMS and alpha counting dates. Deep-sea isotope data, based on benthic and planktonic foraminifera, were reconciled with sea-levels derived from Huon terraces. In this paper we report new dates and sea-level data deduced from Huon Peninsula corals combined with glacio-hydro-isostatic modelling. The data comprise 23 new high precision TIMS measurements (Table 1), significantly extending the earlier work by Chappell et al. (1996) which included 5 TIMS and 8 alpha spectrometric determinations over the 30–62 ka time interval. The present and previous samples are from the same set of corals collected during an expedition to Huon Peninsula in 1992 (Pandolfi and Chappell, 1994). We have also included a detailed discussion of mass spectrometric procedures for uranium-series dating and criteria used in screening for altered corals.

2. Methods

2.1. Huon Peninsula

Corals used in the present study were collected from Bobongara (Bobo) and Kanzarua (Kanz) sections at Huon Peninsula, Papua New Guinea (Fig. 1). Descriptions of the local area and cross-sections of Bobo and Kanz sections can be found in Chappell et al. (1996). Sea-level at the time of growth of each sample can be determined from its present height above sea-level after adjusting for the estimated living water depth range of the sample plus the total uplift since that time. Over short, less than a thousand year time-scales, uplift at Huon Peninsula occurs through discrete, meter-scale, coseismic events (Ota et al., 1993; Ota and Chappell, 1996). However, uplift rate over several thousand years

Table 1
U/Th Results

Sample ^a	U/Th age (ka)	Reef ^b	Height (m) ^c
<i>Bobongara</i>			
Bobo U10	37.2±0.2	IIa	49
Bobo U11	37.9±0.3	IIa	49
Bobo U17	32.0±0.2	IIc	20
Bobo U18	42.4±0.2	IIb	37
Bobo U20	37.6±0.2	IIb	40
Bobo U21	29.7±0.2	IIc	30
Bobo U21 ^d	33.4±0.2		
Bobo U24	32.2±0.2	IIc	30
Bobo U24 ^d	33.0±0.5		
Bobo U28	32.3±0.5	IIc	22
Bobo U30	31.5±0.2	IIc	27
<i>Kanzarua</i>			
Kanz 4	51.5±1.6	IIIa	86
Kanz 4 ^d	51.2±0.8		
Kanz 9	53.4±0.3	IIIa	78
Kanz 9 ^e	54.6±0.7		
Kanz 11 ^f	51.3±0.3	IIIa	78
Kanz 13 ^f	38.3±0.5	IIIb	48
Kanz 15 ^f	42.0±0.6	IIIc	39
Kanz U8 ^f	37.0±0.6	IIa	27
Kanz U9	42.3±0.2	IIa	28
Kanz U9 ^d	41.8±0.6		
Kanz U9 ^e	42.2±0.3		
Kanz U10 ^f	43.7±0.3	IIIc	49
Kanz U11	37.9±0.3	IIa	27
Kanz U12	37.5±0.7	IIa	26
Kanz U13	35.8±0.4	IIa	26
Kanz U14 ^e	34.8±0.8	IIa	26
Kanz U15	33.4±0.2	II	23
Kanz U16 ^f	30.4±0.4	II	29
Kanz A	37.5±0.2	II	25
<i>Others</i>			
SEN(N)8 ^f	52.4±1.3	IIIc	nA
GBR-A	17.0±0.1		-175
GBR-A ^d	17.0±1.0		

^a Except where indicated, all samples are from the Faviidae family.

^b Reef numbering is described in Ota et al. (1993), Chappell et al. (1996).

^c Sea-levels obtained using both the height of corals as shown in brackets and uplift rates for both Kanzarua (2.8 m/kyr) and Bobongara (3.3 m/kyr) reported by (Chappell et al., 1996).

^d Indicates previously reported values using α -counting (Chappell et al., 1996).

^e Indicates previously reported TIMS measurements (Chappell et al., 1996).

^f Denotes Porites corals. Analyses of Faviidae corals are for the wall fractions only.

appears to be uniform. The average uplift rate has been determined at numerous locations along the Huon coast from both Holocene and Last Interglacial terraces. There is general agreement between the two estimates (Bloom et al., 1974; Chappell and Shackleton, 1986). At each location, the current height and age (124 ± 4 kyr) of the easily recognizable Last Interglacial terrace, when

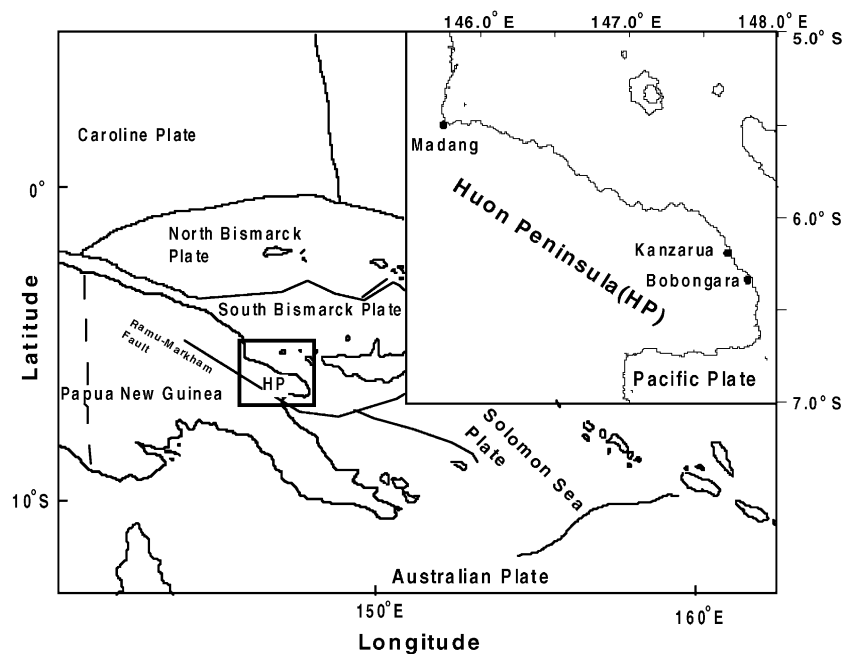


Fig. 1. Map showing the location of Kanzarua and Bobongara sections at Huon Peninsula, Papua New Guinea. Coral terraces at these locations are estimated to have been uplifting at rates of 2.8 ± 0.1 and 3.3 ± 0.1 m/ka respectively (Chappell et al., 1996).

sea-levels were 5 ± 2 m above present, were used to estimate the local uplift rate. The uncertainty in the estimated depth of coral growth can be as much as 15 m and is included in the total uncertainty in sea-level estimate. Chappell et al. (1996) determined mean uplift-rates of 2.8 m/kyr for Kanz and 3.3 m/kyr for Bobo sections. We adopt these rates in the present study.

2.2. Glacio-hydro-isostatic modelling

Glacial isostatic modelling was undertaken for both the Bobo and Kanz sections. The rheological model employed here is a nominal 3-layer construct found to be representative for many locations (Lambeck et al., 1998). It consists of a 65 km elastic lithosphere, 4×10^{20} Pa s upper mantle viscosity and 1×10^{22} Pa s lower mantle viscosity. Details of the computations can be found in Nakada and Lambeck, 1987; Johnston 1993; Lambeck and Johnston (1998) and Lambeck et al., 1998.

2.3. Uranium series-dating

The method relies on the presence of excess ^{234}U in the system, thus ^{230}Th is produced by both the decay of ^{234}U in secular equilibrium with ^{238}U and by the decay of the excess ^{234}U . The half life of ^{234}U to ^{230}Th decay is $\approx 10^5$ yr, and within the age range for dating suitable Pleistocene samples. Uranium content of sea-water is high, whereas the very low Th content is due to its absorption and fixation into sediments. Thus, living corals have negligible thorium abundances; the subsequent $^{230}\text{Th}/^{238}\text{U}$ ratio is the result of ^{234}U decay after

the coral has died, provided there is no exchange of U and Th through diagenesis (closed system requirement).

The ^{230}Th age is derived from the equation defined by Kaufman and Broecker, 1965; and Edwards et al., 1986 and $\delta^{234}\text{U}$ is a reformulation of the $^{234}\text{U}/^{238}\text{U}$ ratio introduced by Edwards et al., 1986:

$$\delta^{234}\text{U}(0) = \left\{ \left[\frac{^{234}\text{U}/^{238}\text{U}}{(^{234}\text{U}/^{238}\text{U})_{\text{eq}}} \right] - 1 \right\} \times 10^3 \quad (1)$$

where $(^{234}\text{U}/^{238}\text{U})_{\text{eq}} = \lambda_{238}/\lambda_{234} = 5.472 \times 10^{-5}$ is the atomic ratio at secular equilibrium.

If there were no initial ^{230}Th present in the coral, the age, T , can be calculated using the measured $^{234}\text{U}/^{238}\text{U}$ ratio ($\delta^{234}\text{U}(0)$), and assuming that the $^{234}\text{U}/^{238}\text{U}$ ratio at the time of coral growth ($\delta^{234}\text{U}(T)$) was the same as the present day sea-water value:

$$\delta^{234}\text{U}(T) = \delta^{234}\text{U}(0)e^{\lambda_{234}T} \quad (2)$$

However, by measuring both ^{234}U and ^{230}Th abundances, no assumptions need to be made about the $^{234}\text{U}/^{238}\text{U}$ sea-water ratio at the time of coral growth (Eq. 2). This parameter can then be used to assess the closed system history of the sample or, if systematic variations can be established, investigate the past sea-water concentrations of ^{234}U .

Over the last decade, the traditional α -counting methods (Veeh, 1966) have been superseded by direct measurement of the abundances of U and Th isotopes using thermal ionisation mass spectrometry TIMS (Chen et al., 1986).

The first measurements of coral Uranium and Thorium isotopes by TIMS was performed by Edwards

et al. (1986) using the Caltech Lunatic-1 single-collector mass spectrometer. In the present study, uranium isotopes were measured using a Finigan MAT 261 multi-collector mass spectrometer equipped with an electron multiplier operated in analogue mode for ^{234}U . The other U isotopes were measured in Faraday cups, simultaneously with ^{234}U . Thorium isotopes were measured using the 61-cm radius 180° sector TIMS in multi-cup charge collection mode (Esat, 1995).

2.4. Physical and chemical sample preparation

The $^{230}\text{Th}/^{238}\text{U}$ relative abundance and the $^{234}\text{U}/^{238}\text{U}$ isotope ratio are measured using TIMS and methods of isotope dilution. The pre-cleaning of samples follows techniques developed by Stirling et al. (1995) and chemical procedures for the extraction, separation, and purification of U and Th in the coral samples are based on methods similar to those described by Edwards et al. (1986).

2.5. Pre-cleaning of samples

Coral samples were first inspected in sunlight for traces of “glitter” from low magnesian calcite and then broken to cm-sized pieces to expose additional surfaces. We have established that samples with greater than 4% calcite can be visually identified in this way and eliminated from further consideration. Selected pieces were then physically cleaned using a hand held diamond abrasive wheel under a magnifying lens to remove delicate lattice structures and septa that are presumably easier to alter or fill with extraneous material compared with solid wall sections. This is possible for Favid species corals, which have solid wall sections but not for Porites corals. It has previously been established that samples cleaned in this way yield $^{234}\text{U}/^{238}\text{U}$ ratios closer to present sea-water value (Stirling et al., 1995). Therefore, favids are preferred whenever available. The physically cleaned coral pieces were then rinsed in acetone, alcohol and de-ionised water in an ultrasonic bath.

2.6. Chemical procedures

For samples up to 50,000 yr old, we have used approximately 2–3 g of cleaned coral, which contain 25–35 pg of ^{230}Th and 5–8 μg of Uranium. The cleaned samples were dried in a laminar air-flow chamber and weighed. The samples were then covered with distilled water and slowly dissolved by adding concentrated HNO_3 . Weighed, mixed-spikes (^{229}Th – ^{233}U – ^{236}U) were then added after first drying the spike to remove trace amounts of HF which help to keep enriched Th tracer in solution. To eliminate any remaining organic matter, concentrated H_2O_2 was added. The solution was then

slowly dried, usually overnight, to drive off CO_2 and to ensure complete sample-spike equilibration.

In corals, both U and Th exist only in relatively small amounts (parts per million and parts per billion, respectively). A small amount of FeCl_3 was added to the sample as carrier of U and Th. The sample solution now includes Fe, Ca, Sr, and Mg as major elements and U and Th as trace elements. The U and Th were then co-precipitated with Fe by adding NH_4OH . The solution changes colour from clear to yellow and a brown deposit containing ferric hydroxide forms that includes oxides and hydroxides of U and Th. The mixture was then centrifuged and the supernatant containing Ca was discarded. The remaining ferric hydroxide precipitate was washed several times in de-ionised water and dissolved in 7N HNO_3 .

Chemical separation of U and Th was by anion exchange resin using standard methods. Pre-cleaned 2 ml columns were used for this step and Fe was eluted with 7N HNO_3 . Then, Th was eluted by adding 2 ml (3 times) of 8N HCl followed by U with 2 ml (twice) of 0.5N HCl. Both Th and U fractions were dried, then re-dissolved in 7N HNO_3 and loaded separately onto small anion exchange columns (0.15 ml). Any remaining Fe was cleaned by 7N HNO_3 and U and Th were recovered using 0.5 HCl and dried on a hotplate. They were stored as small dried residues ready for mass spectrometry.

2.7. Measurement of uranium and thorium isotopes

Uranium isotopes were measured using a Finnigan MAT 261 mass spectrometer with a multi-collector Faraday cup system and a secondary electron multiplier (SEM) with an overall gain of ≈ 100 which allows the measurement of low level currents (from 10^{-16} to 10^{-13} A), in analogue mode, and can be operated simultaneously with the Faraday cups.

Approximately 1 μg of total uranium was loaded onto Re double filaments. Uranium isotopes, ^{238}U , ^{235}U , and ^{233}U , were measured in the Faraday cups and ^{234}U ($^{238}\text{U}/^{234}\text{U} \approx 13800$) was measured with the SEM at the same time. Fifteen blocks of data, corresponding to 150 sets of ratios, were acquired over a 40 min interval at evaporation filament temperatures ranging from 1050°C to 1150°C and ionisation filament temperatures of 2000°C .

Measured U isotope ratios, $^{234}\text{U}/^{235}\text{U}$ and $^{233}\text{U}/^{235}\text{U}$, were corrected for isotopic mass fractionation, using the measured $^{235}\text{U}/^{238}\text{U}$ ratio normalised to the natural value (137.88), with appropriate corrections for the contributions of various isotopes in the spikes. The uncertainty of each run was typically 1–2% ($2\sigma_M$). Each run was preceded and followed by measurement of a U standard (HU-1, a Precambrian uraninite that has been shown to be in secular equilibrium, Ludwig et al., 1992). These results are shown in Fig. 2 together with

measurements of NIST standard SRM 960. The external reproducibility for $\delta^{234}\text{U}$ is about $\pm 1\%$.

Th isotope ratios were measured with the 61-cm TIMS in charge collection mode (CCTIMS; Esat, 1995). Previous methods employed peak hopping using a single electron multiplier (Edwards et al., 1986) or a Daley detector (Bard et al., 1990) which enabled measurement of very low intensity ion beams ($< \text{ca. } 10^{-15} \text{ A}$). However, the precision obtainable was limited due to beam intensity variations and poor duty cycle in data-acquisition.

In the present work, internal statistical precision for a 45 min data acquisition period is typically 0.6‰ and is better than what has been achieved in other laboratories by about a factor of three (Esat, 1995; Stirling et al., 1995).

Thorium sample fractions were dissolved with 1N HNO_3 and loaded onto a zone-refined Re “dimple” filaments (Esat et al., 1979) between two layers of graphite. No evidence for interferences have been found in the vicinity of the Th isotopes. Peak scanning of Th isotopes in the Faraday cups shows flat topped peaks

with widths less than one-third of the Faraday cup slits. For focussing and centring of the ions beams the electrometers were switched to resistor mode, with $10^{12} \Omega$ resistors, when the beam intensity increased to approximately $6 \times 10^{-15} \text{ A}$.

Although the ^{230}Th current is typically $2\text{--}4 \times 10^{-15} \text{ A}$, at the beginning of a run with 15–30 pg of ^{230}Th loaded onto the filament, it grows to more than $5 \times 10^{-14} \text{ A}$. As the run proceeds, ^{230}Th intensity builds up to $6 \times 10^{-14} \text{ A}$ over 1 h. No appreciable within-run shift in the $^{229}\text{Th}/^{230}\text{Th}$ ratio has been observed during any of the runs (Fig. 3).

2.8. Calibration of the mixed spikes

In the present study, a mixed solution of ^{229}Th and ^{233}U tracer was used. Spike solutions were stored in teflon bottles with a trace amount of HF to prevent Th from precipitating out of solution. The isotopic composition of the spike is: $^{238}\text{U}/^{235}\text{U} = 2.8937$, $^{234}\text{U}/^{235}\text{U} = 2.3378$, $^{233}\text{U}/^{235}\text{U} = 1259.38$, and $^{229}\text{Th}/^{230}\text{Th} = 20,000$. Corals which are 20,000–50,000 yr old were spiked so that $^{233}\text{U}/^{235}\text{U}$ ca. 0.3–0.4 and $^{229}\text{Th}/^{230}\text{Th}$ ca. 3–5.

Uraninite standard HU-1, which is in secular equilibrium, was used to calibrate the relative abundance of the U and Th mixed spikes. Calibration using this standard has several advantages, including the elimination of uncertainty arising from gravimetric measurements of the sample and the standard, and also reduces systematic biases due to errors in the decay constants. Mass spectrometric analyses of particular mixtures of HU-1 plus the spike solutions yielded $^{233}\text{U}/^{229}\text{Th} = 53.18 \pm 0.05 (2\sigma_M)$ (Stirling et al., 1995).

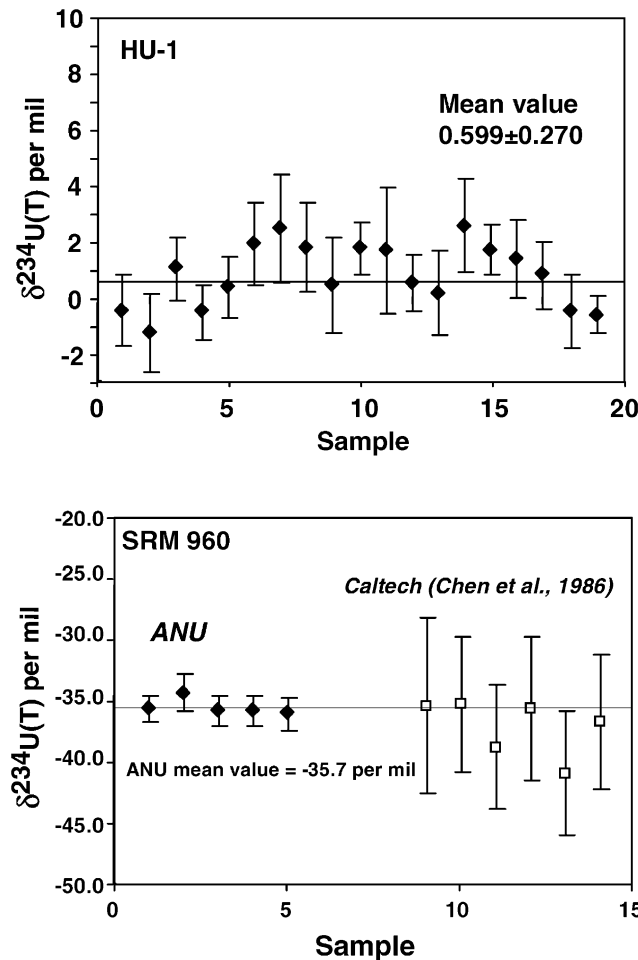


Fig. 2. Repeat measurements of $^{234}\text{U}/^{238}\text{U}$ using the HU-1 uranium standard (upper figure) and the NBS SRM 960 uranium standard (lower figure). Open symbols are results from Chen et al. (1986).

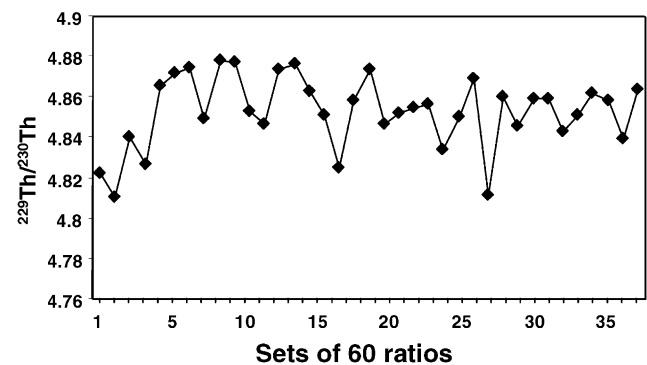


Fig. 3. Thorium isotope data for an entire run consisting 37 sets of 60 data points each. Thorium was extracted from a 32.2 ka coral in this example. At the beginning of the experiment the beam intensity was low ($^{230}\text{Th} \approx 0.6 \times 10^{-14} \text{ A}$) and the error for one set ranged from 5% to 8%. The statistical accuracy improved and dropped to 1% or less with increasing beam intensity ($^{230}\text{Th} > 3 \times 10^{-14} \text{ A}$). Within these statistical uncertainties there are no discernable systematic trends in the data with time.

2.9. Calibration of $^{234}\text{U}/^{238}\text{U}$

Analytical bias in the machine can be monitored and corrected using HU-1 and assuming that it is in secular equilibrium. Since the installation of a new electron multiplier (1999), the value obtained for $\delta^{234}\text{U}$ has been $0.599 \pm 0.270\%$ (Fig. 2). Previously a small bias in the SEM produced a systematically lower value of $-2.1 \pm 0.5\%$. This offset was used to correct the measured values (Stirling et al., 1995). In the present case there is no need for any correction factors for $\delta^{234}\text{U}$ data within an error of $\pm 1\%$.

2.10. Filaments

Zone-refined rhenium dimpler filaments for Th measurements with CCTIMS were first out-gassed at about 1500°C for 30 min and then loaded with graphite for a second stage of out-gassing at more than $\sim 2000^\circ\text{C}$ for 2 h. The first out-gassing is intended to remove oxygen from the filament to prevent oxidation and volatilisation of the following graphite load. Filaments were stored in high vacuum until the sample was loaded. Filaments left in air for extended periods tend to oxidise and yield poor ion currents. No ^{230}Th , ^{232}Th or U isotopic signals have been detected above background levels from blank filaments.

3. Results and discussion

3.1. Criteria for assessment of open system behaviour

Extensive efforts have previously been made to establish quantitative criteria for recognising U and Th open-system behaviour in corals (e.g., Stein et al., 1993; Bar-Matthews et al., 1993). Currently, none of the established procedures can identify altered samples with certainty. We have used a combination of criteria to select out likely samples suspected of open system behaviour.

3.2. Microscopic analysis

Alteration of primary aragonitic coral textures, in fossil coral skeletons, were studied using a petrographic microscope. Both longitudinal and latitudinal thin-sections, relative to coral growth axis, were examined for secondary void filling and alteration, including coarsening due to re-calcification (James, 1974; Bar-Matthews et al., 1993). In cases where alteration was visible in faid corals, traces of alteration were confined to the delicate lattice-work or septa in between solid wall sections. These structures are routinely removed during sample cleaning. Other samples, with extensive alteration features were not used for dating.

3.3. XRD analysis

In corals exposed to freshwater, secondary calcite can replace the original aragonite, as calcite in such environments is more stable than aragonite. Presence of calcite is indicative of U and Th exchange and can be detected by X-ray diffraction analysis. Samples with 4% or greater calcite content can be visually identified in sunlight. The sensitivity of XRD analysis is limited to $\approx 2\%$ calcite. In most cases, where calcite is detected above background levels, cleaned wall fractions were found to have significantly less or negligible amounts of calcite.

3.4. Trace elements and stable isotopes

There have been numerous attempts to establish a correlation between trace elements, stable isotopes and spurious U-Th ages (eg., Chen et al., 1991; Stein et al., 1993; Bar-Matthews et al., 1993). Trace elements and isotopes studied include Na, Mg, Sr, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. However, the results have been inconclusive. Stein et al. (1993) concluded: "Trace element and stable isotope data are insensitive to low-level leakage". In two papers, on corals from the Bahamas, Chen et al. (1991) and Bar-Matthews et al. (1993), have reported generally lower concentrations of Na, Mg, and Sr compared with modern corals. They attributed this to secondary calcite growth. However, the relationship between this and U/Th age of the corals, if any, has not been established. We have measured the oxygen and carbon isotopes in all of the present samples. If marine carbonates preserve their original composition, both isotope values should be close to zero. The data are shown in Fig. 4 and scatter within the range of acceptable values as found by Stein et al. (1993).

3.5. $\delta^{234}\text{U}(T)$

Corals that remain as closed systems with respect to U and Th exchange should have $^{234}\text{U}/^{238}\text{U}$ ratios similar to those found in modern corals where $\delta^{234}\text{U}(T) = 149 \pm 1\%$ (Gallup et al., 1994; Stirling et al., 1995), or in present sea-water where $\delta^{234}\text{U}(T) = 144 \pm 7\%$ (Chen et al., 1986) with the expectation that the sea-water value has remained unchanged over the past 400,000–600,000 yr. Stein et al. (1993) used a value of $\delta^{234}\text{U}(T)$ from 140‰ to 150‰, for acceptable Last Interglacial samples from Huon Peninsula, within an uncertainty of $\pm 9\%$. In contrast, stricter limits of $\pm 4\%$ could be applied for the majority of Last Interglacial corals from Western Australia (Stirling et al., 1995). Gallup et al. (1994) have demonstrated a direct correlation between U-Th ages and high $\delta^{234}\text{U}(T)$ values. In all cases, high $\delta^{234}\text{U}(T)$ values, outside of $149 \pm 8\%$, were approximately correlated with older apparent ages. Similar

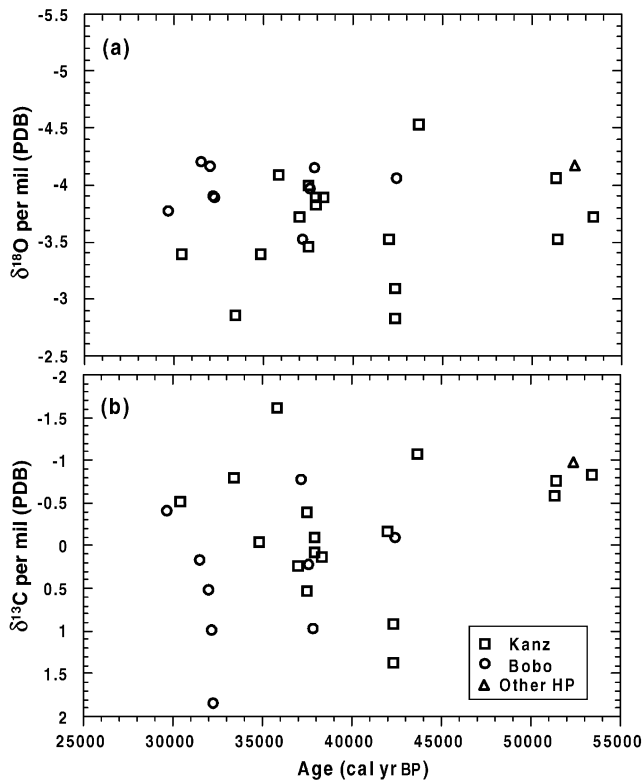


Fig. 4. Stable carbon and oxygen isotope measurement results for corals used in the present study. All the data are within acceptable ranges established by previous work (Stein et al., 1993).

trends can be seen in Last Interglacial Huon corals (Stein et al., 1993), and in Western Australian corals (Stirling et al., 1998). We consider the $\delta^{234}\text{U}(T)$ criterion to be the only quantitative indicator for U and Th open system behaviour. In the present work we have used $149 \pm 10\%$ as the acceptable range for $\delta^{234}\text{U}(T)$.

3.6. Total U and ^{232}Th concentrations

Uranium concentration in modern corals is approximately 3 ppm and is only weakly dependent on species. Fossil corals, acceptable for dating in general have 2.5–3.5 ppm of uranium.

Pristine corals from oceanic islands normally contain less than 0.5 ppb of ^{232}Th (Edwards et al., 1986; Chen et al., 1991). In continental rocks ^{232}Th is a common isotope (> 1 ppm concentration). Excess ^{232}Th in corals is indicative of external U and Th addition and results in older measured ages. The measured concentration of ^{232}Th and the expected $^{238}\text{U}/^{232}\text{Th}$ ratio can therefore be used to correct for the contribution of detrital materials. In the present study none of the dated corals had significant ^{232}Th abundances.

3.7. Sea-level change during the last glacial stage

Chappell et al. (1996) reported Uranium series ages using both conventional α -spectrometric methods, 8

samples, and TIMS dates, 5 samples. We have re-measured the α -dated samples and others using TIMS, as this method produces better precision. The previous and present sets of measurements are in good agreement within analytical errors. Overall twenty three new dates were produced (Table 1).

Glacio-hydro-isostatic effects at Huon Peninsula amount to approximately -10 m and this was included in the sea-level estimates. The results are plotted in Fig. 5 and show that the Marine Isotope Stage 3 sea-levels were lower by about 80 m compared to present. Age uncertainties are two sigma mean. The uncertainty in sea-levels can be as much as $+15$ m due to possible range of depths that particular coral species can inhabit. Smaller error bars could be assigned to some samples by utilizing depth constraints from facies analyses (Pandolfi and Chappell, 1994).

The coral based ice-equivalent sea-levels and oxygen isotope sea-level estimates (Shackleton, 1987) are in very good agreement (Fig. 5) given the uncertainties in the oxygen isotope data which are ± 10 m as deduced from oxygen isotopic variations in the Holocene when sea-levels were stable (Chappell et al., 1996). However, there are differences in detail, including four periods of apparent rapid sea-level change, recorded by corals, that are better highlighted in the present data.

The four “high stands” roughly correspond with sub-reef structures at Kanzarua and Bobongara. We attribute the ≈ 15 m sea-level excursions to periodic partial disintegration of ice sheets at high latitudes.

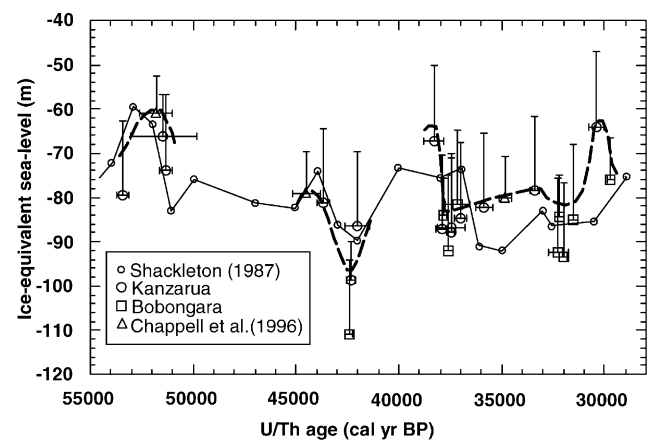


Fig. 5. Sea-level reconstruction for MIS 3 from uplifted coral reefs at Huon Peninsula, Papua New Guinea. The coral height data were corrected for glacio-hydro-isostatic effects using rigorous modelling. Uncertainties in the sea-level are dominated by the possible range in coral growth habitat which may range from 0 to 15 m of water depth. Age uncertainties are 2 sigma mean. Mean sea-levels during this period were ≈ 80 m lower than present. Superimposed on the mean level, there are four distinct sea-level high-stands (30.4, 38.3, 43.7 and 51.5 ka) of 10–15 m in magnitude spaced by 700–1000 yr intervals. The heavy dashed-line is drawn to guide the eye. The isotopic sea-level curve shown by the thin line (Shackleton, 1987) follows the trend shown here remarkably well.

Detailed oxygen isotope records from GISP and GRIP ice cores, as well as from deep-sea cores, show rapid cyclic fluctuations in climate during Marine Isotope Stage 3 known as minor Dansgaard-Oeschger events recurring approximately every 1000 yr and major Bond-cycles of 7000–10,000 yr duration (Bond et al., 1993). Each Bond-cycle ends in a major interstadial that is, in magnitude, half to two-thirds of a full glacial to interglacial transition. Each interstadial is preceded by a particularly cold stadial called a Heinrich event. In deep-sea cores, the Heinrich layers are identified by the presence of ice-rafted debris (IRD), presumably from melting icebergs discharged into North Atlantic (Broecker, 1994). The timing of “high stands” at Huon Peninsula fossil coral reefs appear to be coincident with Heinrich events. A Heinrich stadial starts by an ice calving event. Once released the effect of icebergs on sea-level is immediate. Fresh melt-water from icebergs affects salinity and causes the slow down or interruption of the thermohaline circulation resulting in a cold snap at northern latitudes. The sudden rise in sea-level is likely to stimulate coral growth and formation of terraces at Huon Peninsula. Subsequent salt build up and resumption of the thermohaline circulation leads to a warm interstadial and enhanced precipitation over the northern ice sheets and a lowering in sea-level. The corresponding oxygen isotope peak in ice and deep-sea cores is presumably a response to the warm climate rather than to a rise in sea-level, as occurs for glacial to interglacial transitions.

The present sea-level high stands at ≈ 30.4 , ≈ 43.7 and ≈ 51.5 ka can be identified with Heinrich events H3, H4 and H5. The peak at 38.3 ka is not identified as a Heinrich event. However, in many records there is a sharp transition at ≈ 38 ka similar in character to Heinrich-type events. Kanfoush et al. (2000) have identified IRD layers in several South Atlantic deep-sea cores at approximately 37–38 ka. Other peaks, correspond directly with the timing of Heinrich events in North Atlantic deep-sea cores. They attribute the South Atlantic IRD events to iceberg discharges from the Antarctic ice-sheet in response to sea-level rises initiated by ice-calving from the major North Atlantic ice sheets. Therefore, it is likely that rapid climate change and large iceberg discharges in the North Atlantic which are identified with start and stop behaviour of the thermohaline circulation (Broecker, 1994) can also be associated with sea-level rise and reef building episodes at Huon Peninsula.

4. Conclusions

The ^{238}U – ^{234}U – ^{230}Th decay system can be used for dating Pleistocene and Holocene corals, and in carefully selected samples it can be used as an indicator of varia-

tions in past sea-levels. Stringent criteria need to be applied to ensure closed system integrity in U and Th isotopes.

Development of TIMS methods has led to a reduction in sample size, faster analysis times, and higher precision. In the present study, U isotopes were measured using Faraday cups in combination with an analogue-mode electron multiplier. Thorium isotopes were measured using charge collection in multiple Faraday cups. The latter method provides higher precision relative to other methods of measurement. A multiplicity of criteria were employed to ensure the quality of the dated coral samples. In particular, the $^{234}\text{U}/^{238}\text{U}$ ratio provides the only quantitative means of ensuring closed system U and Th behaviour and the most reliable ages.

Twenty-three new high-precision TIMS dates, of selected coral samples, from the uplifted coral terraces of Huon Peninsula Marine Isotope Stage 3 complement and extend earlier work by Chappell et al. (1996). Prevailing sea-levels, at this time, were about 80 m lower than present. The sea-level curve shows four distinct sea-level excursions, up to 10–15 m in magnitude, that appear to be synchronous with rapid climate changes recorded as iceberg discharges and Heinrich events in the North Atlantic as well as in the South Atlantic. In the North Atlantic, the Laurentide ice sheet is the dominant source and during each episode, may have shed up to 15% of its volume. The consequent sea-level rise is likely to have de-stabilized the Antarctic ice sheet, resulting in iceberg discharges from land based segments. Although additional data will help fill in the gaps in the present sea-level curve, the coupled climate and sea-level fluctuations recorded in Huon Peninsula coral terraces, ice-cores and deep-sea sediments point to major periodic climate shifts during the last glacial with global consequences.

5. Uncited References

Esat, 1984.

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