ELSEVIER

Earth and Planetary Science Letters 193 (2001) 579–587

EPSL

www.elsevier.com/locate/epsl

Coupled climate and sea-level changes deduced from Huon Peninsula coral terraces of the last ice age

Yusuke Yokoyama [a], Tezer M. Esat [a,b,*], Kurt Lambeck [a]

[a] *Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200 Australia*
[b] *Department of Geology, The Australian National University, Canberra, ACT 0200 Australia*

Received 10 May 2001; received in revised form 31 August 2001; accepted 13 September 2001

Abstract

Huon Peninsula, Papua New Guinea, is a tectonically unstable, uplifting shoreline ringed by emergent coral terraces. The terraces were formed during episodes of rapid sea-level rise when corals constructed large, discrete coral platforms that were subsequently uplifted. Uranium series ages of four prominent Huon Peninsula last glacial (OIS 3) coral terraces coincide with the timing of major North Atlantic climate reversals at intervals of 6000–7000 yr between 30 000 yr and 60 000 yr ago. Terrace elevations, when combined with uplift, indicate 10–15-m high sea-level excursions at these times. We attribute the growth of the terraces directly to sea-level rises arising from ice-calving episodes from major North Atlantic ice-sheets and the Antarctic ice-sheet that precipitated extremes of cold climate called Heinrich events. These periods are associated with major discharges of land-based ice and enhanced concentrations of ice-rafted debris in deep-sea cores. Sea-levels at this time were 60–90 m lower than present.

Keywords: uranium disequilibrium; absolute age; Anthozoa; sea-level changes; Heinrich events

1. Introduction

Huon Peninsula (Fig. 1) is a tectonically uplifting site with an uplift rate that varies from 0.5 m/kyr in the northwest to nearly 4 m/kyr to the southeast along a coastline over 80 km long [1,2]. At a given location the uplift rate, when averaged over periods of 1000 yr or longer, appears to have been uniform for the past 130 000 yr [3,4]. The high uplift rates have exposed a record of Late Quaternary interglacial and interstadial sea-level high stands. In particular, terraces corresponding to oxygen isotope stage 3 (OIS 3), older than about 30 ka, are exposed above the present sea-level. Well developed monolithic terrace structures dated approximately as 80 ka, 100 ka, and 130 ka old (OIS 5) are situated above the OIS 3 terraces. There is a clear, visual distinction between these older terraces and OIS 3 terraces. The latter are not as well developed, they are more numerous, and have complex sub-structures corresponding to relatively shallow sea-level excursions. Some of these sub-terraces have been identified as regressive configurations, that may

* Corresponding author. Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200 Australia. Tel.: +61-2-61-25-51-81.

E-mail address: tezer.esat@anu.edu.au (T.M. Esat).

0012-821X/01/$ – see front matter
PII: S0012-821X(01)00515-5

be due to meter-scale discrete uplift events or possibly due to rapid falls in sea-level [4,5]. The qualitative visual difference between the OIS 3 and OIS 5 terraces mirrors the oxygen isotope climate and sea-level curve from deep-sea cores and the climate signature from oxygen isotope ice core records, where the former period is associated with numerous fluctuations in climate in contrast to the major interstadials of the OIS 5 period.

Coral terraces at tectonically active sites are constructed when rising sea-levels overtake uplift and encourage corals to grow upward, forming keep-up reefs. In this sense, terraces at Huon Peninsula can be directly related to past episodes of sea-level high-stands. A prominent feature of OIS 3 climate is the evidence from ice cores and deep-ocean cores that indicate rapid and severe climate fluctuations over time scales ranging from millennial to decadal [6,7]. Relatively minor Dansgard–Oeschger (D–O) and major Heinrich events that correspond to periodic partial break-up of Northern Hemisphere ice-sheets, alternate in cyclic periods of intense cold and warm interstadials [8]. An unanswered question of this ice age period concerns the exact timing of the Heinrich ice-rafting events and the magnitude of the resultant sea-level changes.

Periodic iceberg discharges in the North Atlantic, during the last glacial, are likely accompanied by rapid rises in sea-levels [9,10]. Therefore, ages of major reefs of this period at Huon Peninsula and timing of iceberg discharges should be correlated. Of course, coral growth also occurs during stable periods of sea-level, when at uplifting sites, the relative sea-level is falling. However, growth during these times tends to be patchy, not as well preserved, and does not result in the formation of terraces [4]. In particular, OIS 3 terraces at Huon Peninsula, labelled as terrace complexes II and III, each of which include a number of sub-reefs, can be associated with discrete periods of prolific coral growth and sea-level high stands. Major individual reefs consist of 5–10-m high vertical risers and 10–20-m wide steps at the top, which then merge into the preceding reef riser. Persistence of such structures over tens of kilometers provides an indication of the magnitude of coral productivity, at favorable locations, during times of major sea-level rise. At Bobongara, terrace complexes II and III are over 110 m in vertical extent, and at Kanzarua they are over 80 m in size (Figs. 1 and 2), reflecting the spatially variable uplift rates along the Huon Peninsula coast [11]. Corals forming a terrace are in general paced by the rate of sea-level rise. Alternatively, if sea-level rose rapidly and then stabilized, coral growth may have lagged in time, and will not accurately reflect the rate of sea-level rise, but rather, the rate of coral growth. The latter scenario may better reflect the circumstances corresponding to an ice-discharge event. Regardless of such complicating factors, the prominent OIS III terraces at Huon Peninsula represent successive episodes of sea-level rise.

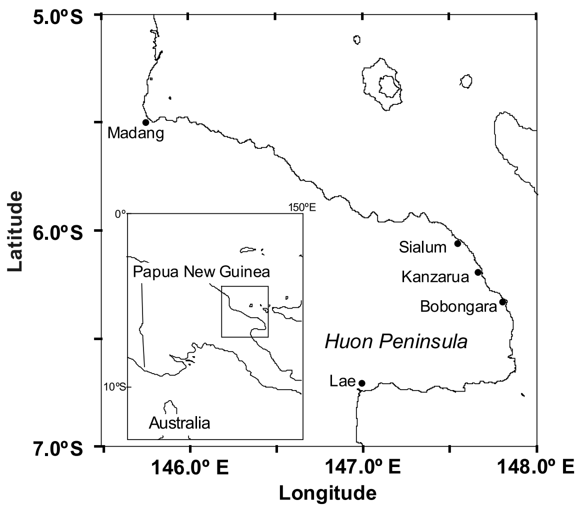

Fig. 1. Location of Kanzarua and Bobongara reef sections at Huon Peninsula, Papua New Guinea. Uplift rates for both Kanzarua (2.8 m/kyr) and Bobongara (3.3m/kyr) were determined previously [4,11].

2. Samples and methods

We have U–Th-dated 23 coral samples collected from terrace complexes II and III at Bobongara and Kanzarua (Table 1; Fig. 2). These ages, when combined with sample locations and mean uplift rates, provide a record of relative sea-levels during OIS 3. Absolute or ice-equivalent sea-levels can then be derived through calculations that take

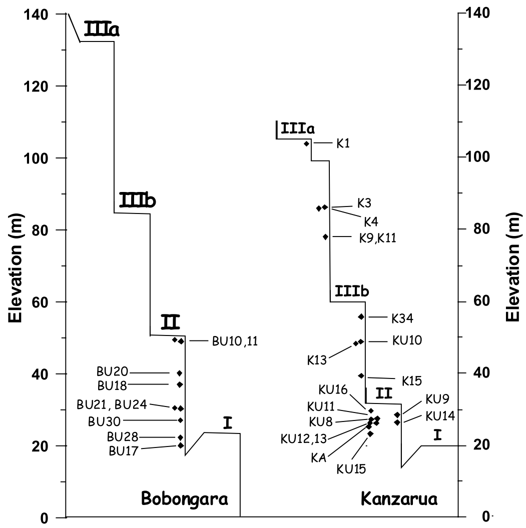

Fig. 2. Bobongara and Kanzarua reef profiles [11] and sample locations relative to major reefs I, II and III including sub-reef sections labelled as 'a' and 'b'. B and K refer to Bobo and Kanz as listed in Table 1. Ages of samples K1, K3 and K34 were reported previously [11].

account of isostatic effects [12,13]. Detailed consideration of the present data leads to an identification of the origin of OIS 3 Huon Peninsula terraces: in particular, that these terraces were built in response to sea-level rises initiated by periodic discharges of icebergs into the North and South Atlantic [14].

Diagenetic alteration in corals can influence U–Th ages. A quantitative test of reliability involves the comparison of the $^{234}U/^{238}U$ ratio, at the time of coral growth [15–21], with that found in modern corals ($\delta^{234}U_{modern} = 149 \pm 1$‰ [15,17,19]) assuming that past seawater uranium values were similar to present. Existing coral data show an approximate correlation between $\delta^{234}U$, that ranges from 149‰ to higher values, and older U–Th ages independent of local conditions and climate [16–21]. Such a correlation can only result from continuous addition of both ^{234}U and ^{230}Th, at a uniform rate [17], but without addition of significant amounts of ^{232}Th as most samples have less than 0.5 ppb of this isotope. The present data represent the first systematic analysis of a significant number of corals that grew during glacial times. In contrast, most previous work involved corals that grew during interglacials, major interstadials, or during glacial to interglacial transitions with only a few isolated analyses of glacial era corals. The present samples have $\delta^{234}U$ values that are systematically lower than 149‰ (Table 1). The possibility that the low $\delta^{234}U$ values represent variations between interglacial and glacial ocean $^{234}U/^{238}U$ isotope ratios will be discussed elsewhere. However, it is possible to estimate the maximum magnitude of diagenetic alteration in typical 35 000-yr-old corals in comparison with 130 000-yr-old interglacial corals from Huon Peninsula [18] by adopting the continuous U–Th addition model [17]. Data from 130 000-yr-old Last Interglacial Huon corals show a maximal spread in $\delta^{234}U$ that are within about +55‰ of the standard 149‰ value [18]. Assuming a similar intensity of diagenetic alteration over the past 30 000 yr as for the last 130 000 yr, the corresponding spread in 30 000-yr-old corals would be 10‰ and is equivalent to an age uncertainty of about 2000 yr. We adopt these extreme values for screening the present data set, almost all of which are within the 149 ± 10‰ band. Other studies have adopted values ranging from ± 4‰ [15] to ± 8‰ [21]. Narrowing the range of acceptability from ± 10‰ to ± 8‰ does not alter the conclusions inferred from the present data. A tighter band, within ± 4‰, would exclude about half of the samples but the timing of the sea-level rises and the mean ages of the terraces would not be significantly altered. On this basis, we have retained the analytical error estimates in ages shown in Table 1. Other methods of sample selection were also applied, including textural investigation of thin sections under a petrographic microscope and X-ray diffraction analysis for calcite [22]. Detrital ^{232}Th concentrations were required to be below 0.5 ppb and U concentrations were between 2 and 4 ppm. Samples that passed all these tests are considered to be reliable.

3. Last ice age climate and Heinrich events

Periodic groupings of several D–O cycles followed by a Heinrich event are called Bond cycles [7,8]. Here we define the relative sequence of

Table 1
U/Th results and relative sea-levels

Sample[a]	U/Th age (k cal yr BP)	$\delta^{234}U(T)$[b] (‰)	Reef[c]	Height (m)	RSL[d] (m)	Calcite[e] (%)
Kanzarua						
Kanz 1[T]	61.4 ± 0.6	139 ± 2	IIIa	105	−67	0.9
Kanz 3[aP]	51.8 ± 0.8	136 ± 9	IIIa	96	−49	0.9
Kanz 4	51.5 ± 1.6	137 ± 1.7	IIIa	86	−60	0
Kanz 4[α]	51.2 ± 0.8					
Kanz 9	53.4 ± 0.3	139 ± 1.4	IIIa	78	−72	1.0
Kanz 9[T]	54.6 ± 0.7					
Kanz 11[p]	51.3 ± 0.3	139 ± 1.1	IIIa	78	−65	3.3,1.5
Kanz 13[p]	38.3 ± 0.5	132 ± 12.9	IIIb	48	−59.2	0.9
Kanz 34[aP]	44.5 ± 0.7	132 ± 9	IIIb	56	−69	0.9
Kanz 15[p]	42.0 ± 0.6	143 ± 2.4	IIIc	39	−79	0
Kanz U8[p]	37.0 ± 0.6	144 ± 4.1	IIa	27	−77	1.9
Kanz U9	42.3 ± 0.2	141 ± 1.1	IIa	28	−91	4.5,1.8
Kanz U9[α]	41.8 ± 0.6					
Kanz U9[T]	42.2 ± 0.3					
Kanz U10[p]	43.7 ± 0.3	137 ± 1.4	IIIc	49	−73	2.2
Kanz U11	37.9 ± 0.3	142 ± 3.3	IIa	27	−79	0
Kanz U12	37.5 ± 0.7	136 ± 3.4	IIa	26	−79	0.5
Kanz U13	35.8 ± 0.4	142 ± 9.1	IIa	26	−74	0.9
Kanz U14[T]	34.8 ± 0.8	139 ± 2.0	IIa	26	−72	2.5
Kanz U15	33.4 ± 0.2	132 ± 1.3	II	23	−71	0.1
Kanz U16[p]	30.4 ± 0.4	142 ± 3.5	II	29	−56	3.2
Kanz A	37.5 ± 0.2	138 ± 1.5	II	25	−80	1.0
Bobongara						
Bobo U10	37.2 ± 0.2	142 ± 1.3	IIa	49	−79	0
Bobo U11	37.9 ± 0.3	143 ± 1.9	IIa	49	−76	7.5,2.9
Bobo U17	32.0 ± 0.2	141 ± 2.8	IIc	20	−86	5.1,2.4
Bobo U18	42.4 ± 0.2	143 ± 1.9	IIb	37	−103	0
Bobo U20	37.6 ± 0.2	141 ± 1.3	IIb	40	−84	0
Bobo U21	29.7 ± 0.2	140 ± 2.6	IIc	30	−68	1.0
Bobo U21[α]	33.4 ± 0.6					
Bobo U24	32.2 ± 0.2	144 ± 1.4	IIc	30	−76	1.0
Bobo U24[α]	33.0 ± 0.5					
Bobo U28	32.3 ± 0.5	140 ± 1.8	IIc	22	−84	1.0
Bobo U30	31.5 ± 0.2	143 ± 1.3	IIc	27	−77	1.0

[a] Except where indicated, all samples are from the Faviidae family; the superscript p denotes *Porites* corals. Analyses of *Faviidae* corals are for wall fractions only. The superscripts α and T indicate previously reported analyses by α-counting and TIMS, respectively [11].

[b] $\delta^{234}U = \{[(^{234}U/^{238}U)/(^{234}U/^{238}U)_{eq}]-1\}\times10^3$. $(^{234}U/^{238}U)_{eq}$ is the atomic ratio at secular equilibrium and is equal to $\lambda_{238}/\lambda_{234} = 5.472\times10^{-5}$ where λ_{238} and λ_{234} are the decay constants for ^{238}U and ^{234}U, respectively. $\delta^{234}U(0)$ is the measured value, the initial value is given by $\delta^{234}U(T) = \delta^{234}U(0)e^{\lambda 234T}$, where T is the age in yr. Twenty runs of the secular equilibrium standard HU-1, measured in-between sample runs, gave $\delta^{234}U = 0.6 \pm 1$ ‰.

[c] Reef numbering is described in [11].

[d] Relative sea-level obtained using the height of corals asl and uplift rates for Kanzarua (2.8 m/kyr) and Bobongara (3.3 m/kyr) sections reported by [11].

[e] XRD analyses for bulk samples. Where two entries are given the second corresponds to wall fractions following mechanical cleaning [22].

events in a Bond cycle to help identify the likely timing of sea-level rises due to iceberg-calving episodes in the North Atlantic. Evidence for rapid climate change around the North Atlantic region over the past 60 000 yr are present in various records, for example, in oxygen isotopes in Greenland ice [23] and in foraminifera in North Atlantic deep-sea cores [24,25]. The abundance of a species of foraminifera (*pachyderma*) is sensitive to ambient sea temperatures and their relative numbers closely match variations in oxygen isotopes. Cold periods in the North Atlantic correlate with layers of debris in deep-sea cores deposited by melting icebergs. A variety of locations have been identified as the source regions of ice-rafted debris (IRD), however, the thickets and most rapidly deposited layers are close to Hudson Bay, pointing to the Laurentide ice-sheet as a major source [26]. Two distinct long and short period cycles appear to link rapid climate changes and surges of North Atlantic ice-sheets to oscillations in North Atlantic Deep Water (NADW) formation. High frequency D–O cycles of 1000–1500 yr duration alternate between periods of cold dry climate and abrupt warm transitions that occur within decades, or shorter time intervals, with magnitude over half of that between the last glacial maximum and the Holocene [8]. The cold climate is associated with fresh North Atlantic waters presumably diluted by melt water and weakening or shutdown of the NADW formation. Progressively cooler stadials over several D–O cycles lead to a particularly cold stadial, termed a Heinrich event marked by IRD-rich layers in deep-sea cores. The following interstadial is unusually warm and presumably corresponds to the resumption of the NADW formation. A Bond cycle repeats at intervals of 6000–7000 yr. These climate oscillations are not only restricted to the North Atlantic region but appear to have global reach, influencing regions in the Pacific and as far south as Antarctica [14].

There is no established direct link between iceberg-calving in the North Atlantic and sea-level rises, although there are estimates of sea-level rises of up to a few meters for the very large discharge events [8–10]. Icebergs released into the ocean need not melt rapidly, however, their effect on sea-level, once they are no longer land bound or grounded, is immediate. It is likely that both D–O cycles and Heinrich events lead to sea-level oscillations. In the above scenario, a Heinrich event provides the largest perturbation in which sea-level rises at the start of each Heinrich event. After about a 1000 yr, the ensuing warm interstadial appears as a peak in the oxygen isotope record that indicates a warming in climate, rather than a significant change in sea-level as is usually assumed for major glacial–interglacial transitions with a similar oxygen isotope signature. The warming also leads to increased precipitation at northern latitudes and to a re-growth of the ice-sheets and a fall in sea-level. This is the framework we will use to interpret the present results.

4. Coupled climate and sea-level changes

Variations in sea-level during the OIS 3 from about 30 ka to 55 ka are shown in Fig. 3 plotted together with the reef profile at Kanzarua [3,4,11] where reef elevations are displayed along the time axis after re-scaling to convert the horizontal distance scale using the measured ages of corals (Fig. 3A). We have included data obtained by Bond et al. [7] on the abundance of *Neogloboquadrina pachyderma* (*s*) from the North Atlantic core V23-81, which provides a good example of the timing and signature of Heinrich events and for which radiocarbon ages have been converted to calendar ages [25]. Peaks in the abundance of foraminifera correspond to cold stadials and coincide with episodes of IRD deposits in the North Atlantic (Fig. 3B). Variations in IRD abundances in two South Atlantic cores are in excellent agreement with the North Atlantic events except for the additional IRD peak at about 37.5 ka in the South Atlantic record which matches the age of the prominent Huon Peninsula terrace riser IIa (Fig. 3C). This South Atlantic IRD-rich layer has not been labelled as a Heinrich event in the Northern Hemisphere records, but there is a sharp enhancement in *pachyderma* abundances in core V23-81 at this time (Fig. 3B). Although there are some uncertainties in the radiocarbon age of the various Heinrich episodes, an assessment of data from

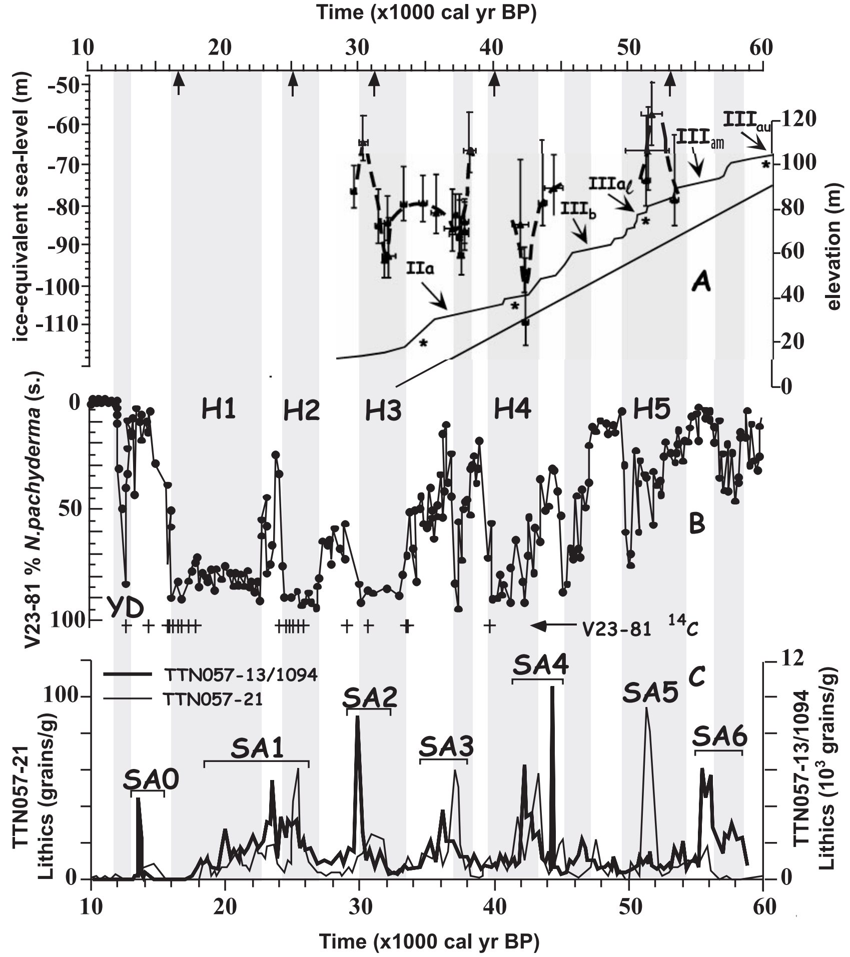

Fig. 3. Sea-level reconstruction for OIS 3 from uplifted coral reefs at Huon Peninsula, Papua New Guinea (A). The coral height data were corrected for glacio-hydro-isostatic effects using rigorous modeling. Uncertainties in the sea-level are dominated by the possible range in coral growth habitat which may range up to 15 m of water depth. Age uncertainties are 2σ 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 of 10–15 m in magnitude spaced by 7000–10 000-yr intervals. The heavy dashed line is drawn to guide the eye. Since uplift is uniform, the horizontal distance axis of the reef profile can be re-scaled to linearly match the measured ages of various terraces. Scaling points are marked by (*). Terrace III has two major sections labelled as (a) and (b). Sub-terrace a is further divided into three components u (upper), m (middle) and l (lower). There is a good correlation between specific terraces and sea-level high stands. The abundance of *N. pachyderma* (sinistral) from the North Atlantic core V23-81 [25], plotted across a common time scale (B). The timeline for V23-81 was established by ^{14}C dating at points shown by (+) and then converted to calendar ages [7,25]. The major cold periods are identified with Heinrich events H1–H5 and the Younger Dryas, shown within shaded bands, other prominent cold periods are unlabelled. The ≈38-ka band has not been labelled as a Heinrich event although there is a sharp increase in *pachyderma* abundances at this time. The arrows on the upper time axis point to mean ages for Heinrich events as determined by Chapman et al. [27]. IRD from South Atlantic deep-sea cores [14], (C). Each peak matches one of the shaded bands indicating an excellent correlation between North and South Atlantic debris horizons in deep-sea cores. The South Atlantic IRD is probably related to periodic iceberg discharges from Antarctica. The correlation between Northern and Southern Hemisphere events suggest periodic partial break-up of major Northern Hemisphere ice-sheets that result in sea-level rises of sufficient magnitude to destabilize the Antarctic ice-sheet. Removal of ice-shelves pinned below the sea-level presumably lead to an outflow of inland ice.

deep-sea core SU90-03, and several others from mid- to high-latitude North Atlantic by Chapman et al., [27] indicate a consistent and synchronous timing among the various North Atlantic IRD records. The positions of these are indicated by arrows along the time axis in Fig. 3 and fall within the shaded bands that represent periods of intense cold. There is a good correlation between all of the records, both from North and South Atlantic. Dated sea-level high stands, synonymous with major terrace steps at Huon Peninsula, appear to be directly correlated with enhanced concentrations of IRD and hence Heinrich episodes. Our sample collection is not extensive enough to cover all of the terrace risers shown in Fig. 3A. There is a break in data from about 39 ka to 42 ka with a hint of a sea-level peak that coincides with H4 and with terrace IIIb. Another break occurs from 45 ka to 50 ka and coincides with terrace IIIa-lower, including an increase in *pachyderma* abundance at about 46 ka between H4 and H5.

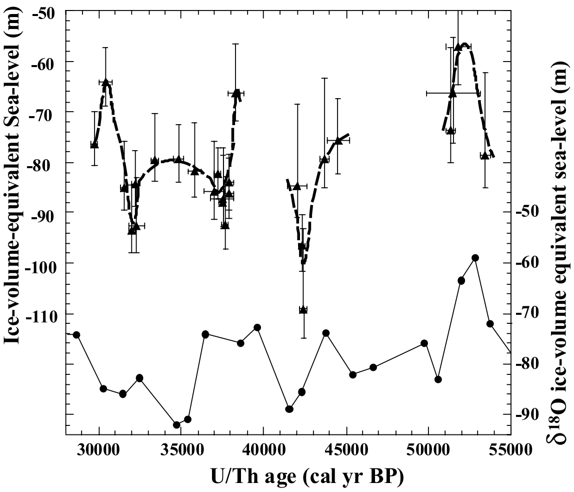

Fig. 4. IVE sea-level curve derived by glacio-hydro-isostatic modeling [13] using relative sea-level data obtained from the heights of dated coral samples and uplift rate. This correction amounts to about −10 m; it has not been included in previous studies [4,11,30]. Error estimates include an allowance for uncertainty in the range of habitable water depth for various coral species (0–8 m; [11,31]), uncertainty in uplift rate (±0.2 m/kyr), and in glacio-hydro-isostatic modeling (±2 m). The dashed line has been drawn to guide the eye. The solid line is the sea-level curve from oxygen isotope analysis of benthic and planktonic foraminifera [28].

In Fig. 4 we compare the ice-volume-equivalent (IVE) sea-levels [12,13] with a sea-level curve derived from benthic and planktic deep-sea core oxygen isotope data [28,29]. The IVE sea-level curve was derived from glacio-hydro-isostatic modeling using relative sea-levels calculated from the heights of dated coral samples and the mean uplift rates at specified HP locations. The error bars are mainly due to the variable depth range that corals can grow in, and may range up to −15 meters. There is a good agreement between the two curves, in particular, where there are prominent peaks in sea-level.

5. Conclusions

The presence of last glacial age, discrete coral terraces at Huon Peninsula necessarily imply repeat episodes of sea-level high stands. The present coral dates place the timing and interval of these events synchronous with major North Atlantic glacial age climate reversals. Sea-levels at this time were 60–90 m lower than present. At tectonically stable locations, similar coral terraces are currently below present sea-levels. They occur above present sea-levels only in exceptional circumstances, when at tectonically unstable locations the mean uplift rate is greater than about 2.5 m/1000 yr. At Huon Peninsula Kanzarua and Bobongara sections they reach total elevations up to 100–130 m respectively. Prolific coral growth at uplifting sites is stimulated by sea-level rise and results in terrace-shaped coral assemblies. The periodic nature of sea-level rise during OSI 3 is evident from the regular structure of terraces within Huon reef sections II and III. The most prominent of these terraces have ages that correspond to periods of severe climate shifts in the North Atlantic and specifically correlate with the timing of Heinrich events. It appears that Huon Peninsula OIS 3 coral terraces were constructed in response to sea-level high stands initiated by partial collapse of North Atlantic ice-sheets followed by iceberg discharges from Antarctica. Magnitude of the sea-level rises, within uncertainties in the range of coral growth habitat, is of the order of 10–15 m. Therefore, Heinrich events can be associated with very major discharge events of land-based ice. Assuming that the Laurentide Ice-Sheet is the major source, each surge amounts to 10–15% of its total volume. The present U–Th dates provide the most accurate timing for Heinrich events. We have labelled the previously unidentified Heinrich event at ~38 ka as Heinrich event H3.5. The timing of the major sea-level high stands and the corresponding Heinrich event designations are as follows: H3 (30.4 ka); H3.5 (38.3 ka); H4 (43.7); H5 (51.5 ka).

Acknowledgements

We thank John Chappell for his interest in this project and for sharing his encyclopedic knowledge of Huon Peninsula coral reefs. Malcolm McCulloch took part in the arduous task of collecting quality coral samples under difficult circumstances. Comments from Dr. Laurent Labeyrie and an anonymous referee helped correct and improve the manuscript.*[AC]*

References

[1] R.W. Fairbridge, The changing level of the sea, Sci. Am. 202 (1960) 7079–7084.
[2] J. Chappell, Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea-level changes, Bull. Geol. Soc. Am. 85 (1974) 553–570.
[3] Y. Ota, J. Chappell, R. Kelley, N. Yonekura, E. Matsumoto, T. Nishimura, J. Head, Holocene coral terraces and coseismic uplift of Huon Peninsula, Papua New Guinea, Q. Res. 40 (1993) 177–188.
[4] J. Chappell, Y. Ota, K. Berryman, Late Quaternary coseismic uplift history of Huon Peninsula, Q. Sci. Rev. 15 (1996) 7–22.
[5] Y. Ota, J. Chappell, Late Quaternary coseismic uplift events on the Huon Peninsula, Papua New Guinea, deduced from coral terrace data, J. Geophys. Res. 101 (1996) 6071–6082.
[6] M. Bender, T. Sowers, M.L. Dickson, J. Orchardo, P. Grootes, P.A. Mayewski, D.A. Meese, Climate correlations between Greenland and Antarctica during the past 100,000 years, Nature 372 (1994) 663–666.
[7] G. Bond, W. Broecker, S. Johnsen, J. Mcmanus, L. Labeyrie, J. Jouzel, G. Bonani, Correlations between climate records from North Atlantic sediments and Greenland ice, Nature 365 (1993) 143–147.
[8] R.B. Alley, Icing the North Atlantic, Nature 392 (1998) 335–337.
[9] D.R. MacAyeal, A low-order model of the Heinrich event cycle, Paleoceanography 8 (1993) 767–773.
[10] D.R. MacAyeal, Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantics Heinrich events, Paleoceanography 8 (1993) 775–784.
[11] J. Chappell, A. Omura, T. Esat, M. McCulloch, J. Pandolfi, Y. Ota, B. Pillans, Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records, Earth Planet. Sci. Lett. 141 (1996) 227–236.
[12] M. Nakada, K. Lambeck, Glacial rebound and relative sea-level variations a new appraisal, Geophys. J. Int. 90 (1987) 171–224.
[13] K. Lambeck, Y. Yokoyama, P. Johnston, A. Purcell, Global ice volumes at the Last Glacial Maximum and early Late glacial, Earth Planet. Sci. Lett. 181 (2000) 513–527.
[14] S.L. Kanfoush, D.A. Hodell, C.D. Charles, T.P. Guilderson, P.G. Mortyn, U.S. Ninnemann, Millenial-Scale Instability of the Antarctic Ice Sheet During the Last Glaciation, Science 288 (2000) 1815–1818.
[15] C.H. Stirling, T.M. Esat, M.T. McCulloch, K. Lambeck, High-precision U-series dating of corals from Western Australia and implications for the timing and duration of the Last Interglacial, Earth Planet. Sci. Lett. 135 (1995) 115–130.
[16] E. Bard, R.G. Fairbanks, B. Hamelin, in: G.J. Kukla, E. Wendt (Eds.), How accurate are the U–Th ages obtained by mass spectrometry on coral terraces, NATO ASI Ser. 13. Springer-Verlag, Berlin, 1992.
[17] C.D. Gallup, R.L. Edwards, R.G. Johnson, The timing of high sea levels over the past 200,000 years, Science 263 (1994) 796–800.
[18] M. Stein, G.J. Wasserburg, P. Aharon, J.H. Chen, Z.R. Zhu, A. Bloom, J.M.A. Chappell, TIMS U-series dating and stable isotopes of the last interglacial event in Papua New Guinea, Geochim. Cosmochim. Acta 57 (1993) 2541–2554.
[19] C.H. Stirling, T.M. Esat, K. Lambeck, M.T. McCulloch, Timing and duration of the Last Interglacial evidence for a restricted interval of widespread coral reef growth, Earth Planet. Sci. Lett. 160 (1998) 745–762.
[20] B. Hamelin, E. Bard, A. Zindler, R.G. Fairbanks, $^{234}U/^{238}U$ mass spectrometry of corals: How accurate is the U–Th age of the last interglacial period?, Earth Planet. Sci. Lett. 106 (1991) 169–180.
[21] C.H. Stirling, T.M. Esat, K. Lambeck, M.T. McCulloch, S.G. Blake, D.C. Lee, A.N. Halliday, Orbital forcing of the Stage 9 Interglacial: Evidence from U-series dating of Henderson Island corals, Science 291 (2001) 290–293.
[22] Y. Yokoyama, T.M. Esat, K. Lambeck, L.K. Fifield, Last ice age millennial scale climate changes recorded in Huon Peninsula corals, Radiocarbon 42 (2000) 383–401.
[23] P.M. Grootes, M. Stuvier, J.W.C. White, S. Johnsen, J. Jouzel, Comparison of oxygen isotope records from the

GISP2 and GRIP Greenland ice cores, Nature 366 (1993) 552–554.
[24] D.W. Oppo, S.J. Lehman, Suborbital timescale variability of North Atlantic Deep Water during the past 200,000 years, Paleoceanography 10 (1995) 901–910.
[25] D.C. Lund, A.C. Mix, Millennial-scale deep water oscillations: Reflections of the North Atlantic in the deep Pacific from 10 to 60 ka, Paleoceanography 13 (1998) 10–19.
[26] J.F. McManus, R.F. Anderson, W.S. Broecker, M.Q. Fleisher, S.M. Higgins, Radiometrically determined sedimentary fluxes in the sub-polar North Atlantic during the last 140,000 years, Earth Planet. Sci. Lett. 155 (1998) 29–43.
[27] M.R. Chapman, N.J. Shackleton, J-C. Duplessy, Sea surface temperature variability during the last glacial–interglacial cycle assessing the magnitude and pattern of climate change in the North Atlantic, Palaeogeogr. Palaeoclimatol. Palaeoecol. 157 (2000) 1–25.
[28] N.J. Shackleton, Oxygen isotopes, ice volume and sea level, Q. Sci. Rev. 6 (1987) 183–190.
[29] J. Chappell, N.J. Shackleton, Oxygen isotopes and sea level, Nature 324 (1986) 137–140.
[30] J. Chappell, H.A. Polach, Post-glacial sea-level rise from a coral record at Huon Peninsula, Papua New Guinea, Nature 349 (1991) 147–149.
[31] J. Pandolfi, J. Chappell, Stratigraphy and relative sea-level changes at the Kanzarua and Bobongara sections, Huon Peninsula, Papua New Guinea, in: Y. Ota (Ed.), Study on Coral Reef terraces of the Huon Peninsula, Papua New Guinea. Yokohama Natl. Univ., Yokohama, 1994, pp. 119–139.