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Pleistocene sea levels and tectonic uplift based on dating of corals from Sumba Island, Indonesia

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Abstract. We collected and dated fossil corals from the uplifted reef tracts of Sumba Island. Mass spectrometry (TIMS and AMS) was used to obtain reliable and precise radiochronological results. It is possible to identify outcrops corresponding to major sea level high stands: isotope stage 1 (starting at 7.1 kyr BP), 5a (*c.a.* 86 kyr BP), 5c (*c.a.* 105 kyr BP), 5e (between 119 and 132 kyr BP) and 9 (*c.a.* 305 kyr BP). The radiochronological data are thus broadly consistent with the timing of sea level fluctuations predicted by the astronomical theory of paleoclimates. Comparison with similar data from other terrace sequences and from benthic $\delta^{18}\text{O}$ records indicates that the average tectonic uplift rate at Cape Laundi, Sumba, is on the order of 0.2-0.5m/kyr. The lowest values (<0.3m/kyr) lead to the build-up of polycyclic topographic terraces in which it is possible to find corals grown during different interstadial or even interglacial times.

Introduction

The astronomical theory of paleoclimates [Milankovitch, 1941] was revived in the late sixties by the development of U-series dating by α -counting applied to fossil corals and deep sea sediments [Broecker *et al.*, 1968]. It was shown that the topographic terraces exposed at Barbados [Mesollela *et al.*, 1969] and Huon Peninsula of Papua New-Guinea [Bloom *et al.*, 1974] correspond to major sea level highs predicted by the astronomical theory [Berger, 1978; Imbrie *et al.* 1984]. Recently, it was demonstrated that mass spectrometry provides more reliability and precision on $^{230}\text{Th}/^{234}\text{U}$ determinations [Edwards, 1988]. This new technique has been applied successively to the reference series from Barbados [Edwards, 1988, Bard *et al.*, 1990a, 1991, Gallup *et al.*, 1993], and New-Guinea [Stein *et al.*, 1993]. However, these two sequences are found on islands located in tectonically active subduction zones. The uplift rate at Barbados is also variable in space: *e.g.* about 0.25 m/kyr in the southern part and 0.45 m/kyr in the eastern part [Bender *et al.*, 1979]. The Huon Peninsula has a very high rate of tectonic uplift, *c.a.* 1.9

m/kyr during the last 120 kyr. Moreover, it was demonstrated that the movement is discontinuous, due to stepping motions [Pandolfi *et al.*, 1994]. Numerous topographic features are thus the consequence of episodic coseismic uplift [Ota *et al.*, 1993]. These inherent problems illustrate the crucial need of identifying and studying new terrace sequences in different tectonic settings. In August 1991, we thus organized a field expedition to study and collect fossil corals from the sequence recently surveyed on Sumba Island [Jouannic *et al.*, 1988; Hantoro *et al.*, 1989; Pirazzoli *et al.*, 1991, 1993].

Methods and accuracy of radiochronometry

$^{230}\text{Th}/^{234}\text{U}$ and ^{14}C mass spectrometric techniques [Edwards, 1988; Bard *et al.*, 1990b] were used to date the lower fossil reefs from the uplifted sequence of Cape Laundi. The radiochronological data are shown in Fig. 1 and Table 1 available on microfiche. ^{14}C ages were measured by means of the Tandetron accelerator (CFR/Gif). All samples were leached with acid to remove surface contaminants [Bard *et al.*, 1990b]. $^{230}\text{Th}/^{234}\text{U}$ ages were measured with a VG-54-30 mass spectrometer fitted with an ion-counting Daly detector (CEREGE/Aix). The techniques are basically similar to those previously described [Bard *et al.*, 1990b] and more details can be found in the legend of Table 1. $^{234}\text{U}/^{238}\text{U}$ ratios were measured in ion counting Daly-Faraday dynamic multicollection mode. The external 2σ precision on individual values of $\delta^{234}\text{U}_i$ ($=[\text{initial } ^{234}\text{U}/^{238}\text{U}-1]\times 1000$) is on the order of 2 ‰. We measured the $^{234}\text{U}/^{238}\text{U}$ ratios of two sub-modern (<0.4 kyr) corals from Bermuda and of forty Holocene corals from Tahiti boreholes [Bard *et al.* in prep]. The individual $\delta^{234}\text{U}_i$ are 149 ± 2 ‰ for both Bermuda samples and average 147 ‰ for Tahiti corals (st. dev. of 1.5 ‰ on 40 meas.). These values agree very well with those measured on present sea water (av.=144, s.d.= 4 ‰ on 4 meas.; *cf.* Chen *et al.*, 1986) and on modern and recent corals (averages ranging between 145 and 150 ‰; *cf.* Bard *et al.*, 1990b, Edwards *et al.*, 1993, Szabo *et al.*, 1994, Stirling *et al.*, 1994).

The $\delta^{234}\text{U}_i$ measured in Sumba Pleistocene corals range between 146 and 267 ‰. As previously observed [Bard *et al.*, 1991; Hamelin *et al.*, 1991; Stein *et al.*, 1993; Gallup *et al.*, 1994], the $\delta^{234}\text{U}_i$ of old (>50kyr) corals are often higher than for modern seawater. This suggests minor diagenetic remobilisation of U and/or Th although there is a lack of understanding of the mechanism generating these anomalies which are barely detectable by α -counting, thus justifying the use of TIMS. If these isotopic changes occur gradually or late after coral growth, the $^{230}\text{Th}/^{234}\text{U}$ ages may be biased by a few

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kyr [Hamelin et al., 1991; Gallup et al., 1994]. By contrast, ages are truly accurate within statistical errors if these isotopic anomalies are due to isotopic exchanges occurring rapidly after coral death and/or to long term sea water $\delta^{234}\text{U}$ variations. Indeed, box modelling studies have shown that small ($<10\text{‰}$) variations of sea water $\delta^{234}\text{U}$ are possible over time scales on the order of 100 kyr [Hamelin et al., 1991, Richter & Turekian, 1993]. Therefore, the strict constancy of sea water $\delta^{234}\text{U}$ through time may only be a first approximation and it may well have been c.a. 155-160 ‰ some 120 kyr ago.

Based on corals from Hateruma Island, Japan, Henderson et al. [1993] suggested that sea water $\delta^{234}\text{U}$ remained strictly constant through time. However, the only young coral reported in their study gave an anomalously low $\delta^{234}\text{U}_i$ ($135.5 \pm 2\text{‰}$ at 1.6 kyr), and the $\delta^{234}\text{U}_i$ obtained on slightly weathered Hateruma corals gave very low $\delta^{234}\text{U}_i$ values (av. 132.5‰ , s.d.= 10‰ , for 9 corals with ages between 125 and 133 kyr). Moreover, the best preserved coral from the Last Interglacial ($\delta^{234}\text{U}_i = 148 \pm 3\text{‰}$) gave an anomalously old age of c.a. 153 kyr. Following Gallup et al. [1994] we consider that Hateruma corals underwent a different diagenesis process from those observed in other environments studied so far.

By contrast with the results obtained on the Caribbean corals [Bard et al., 1992, Gallup et al., 1994], the $\delta^{234}\text{U}_i$ index does not show a trend vs age for Sumba corals belonging to stage 5e (Fig. 2). These data support those of Stein et al. [1993] and suggest that diagenetic processes are more complex than a simple assumption of linear gain of ^{230}Th and ^{234}U [Gallup et al., 1994]. For practical purpose and following other authors, we use a simple $\delta^{234}\text{U}_i$ criterion to discriminate *a posteriori* among samples. We consider that U-Th coral ages

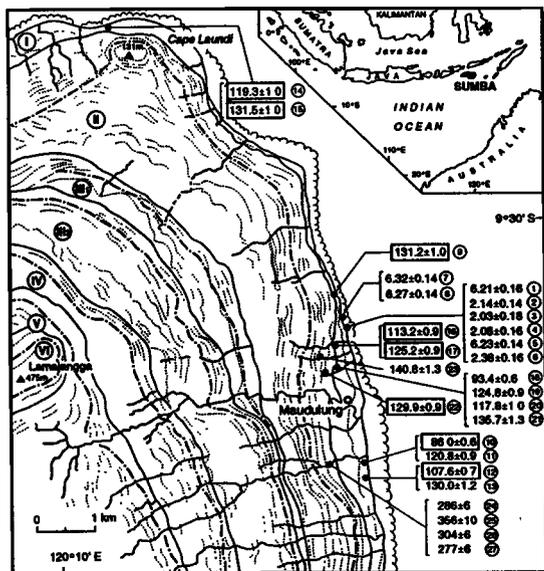


Figure 1. Location and physiography of terraces of Cape Laundi, Sumba Island. Major terraces are numbered following Jouannic et al. [1988]. Dashed-dotted lines = main reef fronts, continuous lines = base of main terraces, dotted lines = subterraces, wiggly line = limit of modern reef flat. Samples SBA1 to SBA8 are dated by ^{14}C , others by U-Th (errors at 2 sigma). Framed U-Th ages are considered the most reliable since their $\delta^{234}\text{U}_i$ is compatible with the range 145-165 ‰ (cf. text and Table 1 available on microfiche)

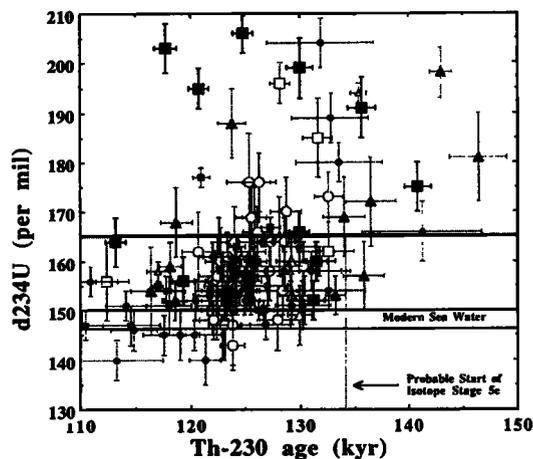


Figure 2. $\delta^{234}\text{U}_i$ vs age for corals corresponding to stage 5e. Black squares stand for Sumba corals. Open symbols are for Caribbean corals (triangles: Edwards [1988], squares: Hamelin et al. [1991], dots: Chen et al. [1991], small triangles: Gallup et al. [1994]). Closed symbols are for Pacific corals (triangles: Stein et al. [1993], small dots: Szabo et al. [1994], small squares: Stirling et al. [1995]).

are the most reliable when $\delta^{234}\text{U}_i$ is compatible with the range 145-165 ‰ (framed ages in Fig. 1). Nevertheless, ages of all samples should be accurate enough to associate Sumba terraces with interglacial periods, which is the main purpose of our study. The immediate consequences of this $\delta^{234}\text{U}_i$ criterion are that stage 5e started between 130 and 135 kyr BP and that it lasted for 15-20 kyr (Fig. 2). These two observations are not in full agreement with the viewpoint classically adopted for constructing the SPECMAP time scale. It is indeed puzzling that the 65°N June-July insolation maximum (128-127 kyr BP) seems to lag the first sea level maxima of stage 5e (135-130 kyr BP) whereas for the present interglacial the 65°N June-July insolation maximum (11-10 kyr BP) clearly leads the first sea level maxima of stage 1 (about 7 kyr BP).

Sea level variations and tectonic uplift

The structure and coral diversity of the modern reef platform on the NE coast of Sumba clearly suggest that uplift persisted during the modern period. Abundant living colonies are found only in the outer reef, while the back reef is characterized by a rather low number of living corals ($<10\%$) and abundant species resistant to episodic emersion and/or relatively high water turbidity (e.g. *Goniastrea retiformis*, *Acropora digitifera*). A level of fossil microatolls of *Porites*, discovered *in situ* during the expedition, gives an age of 7.1 kyr BP (mean calibrated ^{14}C age for samples SBA7 and SBA8). This precise sea level marker [Scoffin & Stoddart, 1978] may correspond to the post-glacial isostatic rebound optimum for Sumba Island [Lambeck, 1993; Peltier, 1994]. The altitude of this *Porites* level (c.a. 1.5-2m above mean low water spring MLWS) implies that the Holocene uplift rates were $<0.3\text{ m/kyr}$ (less than 2m in 7.1 kyr). This upper-bound value for the Holocene uplift is lower than the average long-term uplift rate (0.5m/kyr) reconstructed for the last million years by Pirazzoli et al. [1991; 1993]. An apparent deceleration of the uplift rate during the Holocene has also been observed at Alor

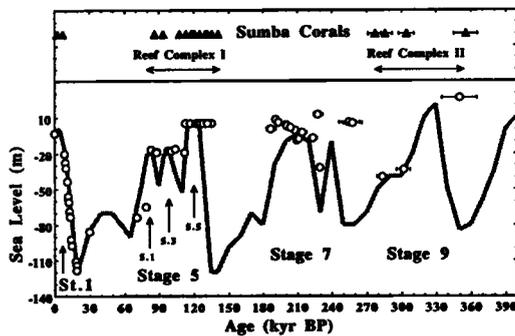


Figure 3. Sea level vs time for the last 400 kyr. On the upper panel black triangles correspond to Sumba corals (cf. Fig. 1). On the lower panel, open dots show sea level reconstructions based on TIMS $^{230}\text{Th}/^{234}\text{U}$ dating of individual corals from Barbados island (cf. text for references). The thick curve represents a simplified sea level history based on several benthic foraminifera $\delta^{18}\text{O}$ curves.

Island [Hantoro *et al.*, 1994]. It may correspond either to a recent decrease in the long-term tectonic strain, if the uplift rate at Sumba is continuous, or to increased strain accumulation preceding coseismic uplift of metric order, if the movement is discontinuous like in New-Guinea [Ota *et al.* 1993; Pandolfi *et al.*, 1994].

Our ^{230}Th - ^{234}U radiometric results show that the first uplifted terrace (complex I; crests altitudes at *c.a.* 3 and 20m above MLWS) was formed during isotope stage 5 (Fig. 3). However, this construction includes corals which grew during the main three high sea levels: 5a at *c.a.* 86kyr BP, 5c at *c.a.* 105 kyr BP and 5e at *c.a.* 125 kyr BP (Figs. 1 and 3). The occurrence of well preserved corals of these ages in the same topographic feature is an argument for the polycyclic nature of reef complex I. Moreover, the presence of corals contemporaneous with interstadials 5a and 5c places another constraint on the uplift rate at Cape Laundi which, on average, must be $> 0.2\text{m/kyr}$ since eustatic sea levels were about 20m below present during stages 5a and 5c (Fig. 3).

Well preserved outcrops discovered on the internal part of complex I, correspond to stage 5e (*c.a.* 125 kyr BP). The biological assemblages are typical of low-energy, lagoonal environments with abundant genera and species such as: *Echinophyllia*, *Lobophyllia*, *Heliopora coerulea*, *Strylaphora*, *Seriatopora*, *Porites nigrescens*, *Pachyseris speciosa*, *Mycedium elephantotus*, *Fungia sp.* [cf. Faure, 1982]. Furthermore, the bioclastic limestone facies and the relative positions of these outcrops on terrace I (Fig. 1; samples SBA16, SBA17 and SBA18 to 21) suggest that they are similar to those of modern lagoons and/or outer slopes of sheltered reefs at depths on the order of 5 to 15m.

The ages determined for corals from the lower part of reef complex II (crests altitudes at *c.a.* 50m and 60m above MLWS) indicate a bimodal distribution: ages close to 130 kyr BP belonging to stage 5e and ages between 280 and 355 kyr BP which correspond to stage 9. By contrast with the Barbados sequence, there is a lack of stage 7 corals, *i.e.* between 190 and 240 kyr BP (Fig. 2). This absence could be accidental since Pirazzoli *et al.* [1991; 1993] reported two samples with ages compatible with stage 7: $240\pm 60/-50$ kyr BP and $230\pm 70/-50$ kyr BP (U-Th by α -counting). However, these two samples could have equally grown during stage 9 if one takes into

account the rather large statistical errors. Indeed, a third sample from complex II gave a lower-bound age of 300 kyr BP [Pirazzoli *et al.*, 1991; 1993].

An alternative explanation could be proposed for the absence of a clear terrace corresponding to stage 7: this construction could be partly covered by a younger one grown during stage 5e. This explanation requires that the uplift rate was $< 0.5\text{m/kyr}$ for a significant period during the late Pleistocene. We used a numerical model in order to better understand the interplay of coral growth, eustatic sea level changes and tectonic uplift, and to illustrate the polycyclic phenomenon. The model uses similar growth equations as listed by Bosscher & Schlager [1992]. If the uplift rate is $< 0.3\text{m/kyr}$, the computations show that a particular topographic terrace can be the result of superimposed constructions which occurred during different interstadials or even interglacials (cf. legend and three upper panels of Fig. 4). The topographic

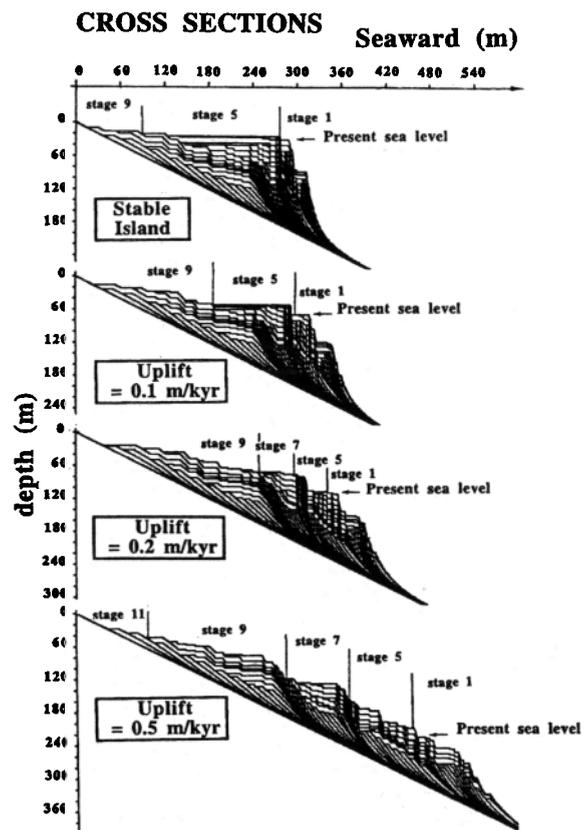


Figure 4. 2D cross-sections of reefs accreted on a simple topography during the last 400 kyr. The input sea level curve is the simplified curve of Fig. 3 with a slightly longer stage 5e to take into account the coral results. Curves within the cross-sections represent isochron topographies (drawn every 5 kyr). Simulations have been obtained with the following parameters: growth rate 2m/kyr , radiation extinction coefficient $= 0.05\text{m}^{-1}$, light saturation at 12% of the surface value. Above each cross-section are indicated the rough age of the outcrop (isotopic stages only). Note that for the 2nd panel (0.1m/kyr), the stage 7 reef does not outcrop since it has been covered by younger constructions during stage 5e. On the 3rd panel (0.2m/kyr) the highest topographic terrace is polycyclic since it includes outcrops belonging to different sea level highs (isotopic stages 9, 7 and 5e).

terraces have thus a polycyclic origin which renders extremely difficult an age assignment based on stratigraphic or morphologic grounds only.

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