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Coral Reefs

Quaternary uplifted coral reef terraces on Alor Island, East Indonesia

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Abstract. A flight of six major coral reef terraces, up to 700 m in altitude, occurs along the eastern and northern sides of Kabola Peninsula, Alor Island, Indonesia. Some radiometric dates have been obtained from unrecrystallized coral samples collected in growth position by three different methods (^{14}C, $^{230}Th/^{234}U$, ESR). This enabled the identification of the terraces corresponding to the Holocene and to oxygen-isotope stages 5c, 5e and 7. According to the present elevation of the dated terraces, a 1.0–1.2 mm/y mean rate of uplift can be discerned. Extrapolation of this trend to the whole sequence of terraces reveals a good correlation between the development of major terraces and interglacial or interstadial stages corresponding to astronomically calibrated oxygen isotope records, up to stage 13. The relatively rapid uplift rate in this region minimized the possibility of polycyclic sea-level stands at the same levels and contributed to the good preservation of some morphological reef features. Two superimposed marine notches are visible near the present shoreline, with retreat points at about 5.0 m and 8.6 m respectively above the present MLWST level. They can be interpreted as corresponding to a glacial interstadial (the upper notch) and to the Holocene sea-level peak (the lower one). As Holocene emergence has been less than what could be expected from a 1 mm/y rate of uplift, a major coseismic vertical displacement may occur in the future.

This work is a contribution to the IGCP Project 367 "Late Quaternary coastal records of rapid change" and to the activities of the INQUA Commissions "Neotectonics" and "Shorelines", the task group "Paleoseismicity of the Late Holocene" of the Inter-Union Commission on the Lithosphere, and the UNESCO-IUGS cooperative programme "Earth Processes in Global Change" (CLIP Pilot Project)

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Introduction

Sequences of superimposed raised marine terraces have been reported from many coastal areas in the world. In several cases dating methods have provided age estimations of middle- to late-Quaternary marine episodes. The best known examples are those reported from the Huon Peninsula, Papua New Guinea (Bloom et al. 1974), Barbados, West Indies (Mesolella et al. 1969; Radtke et al. 1988; Bard et al. 1990) and the northern New Hebrides (Taylor et al. 1985).

In the Indonesian region, Chappell and Veeh (1978) studied reefal terraces on Atauro Island where they dated fossil corals belonging to the last interglacial period. They attempted to correlate by extrapolation the oxygen isotope records and upper marine terraces back to about 700 ka, on the assumption that uplift movements remained linear, at rates in the range of 0.43–0.5 mm/y. On Sumba Island, coral-reef terraces corresponding to oxygen-isotope Stages 15 (about 600 ka) and 9 (ca. 330 ka) have been dated using the electron spin resonance (ESR) method (Pirazzoli et al. 1991, 1993; Hantoro 1992). The resulting uplift rate of 0.49 mm/y, extrapolated to a one million-year sequence of spectacular terraces, strongly suggests a polycyclic geomorphic development for some of these terraces.

In the present study, a sequence of coral-reef terraces on Alor Island is described, which may have been the result of uplift rates about twice as fast as those for Atauro and Sumba, thus enabling the emergence and preservation of individual fossil shorelines corresponding to sea-level peaks during interstadials of the last glacial cycle.

Study area

Alor is located north of central Timor (Fig. 1), on the volcanic chain of the Banda island arc. Most of the island

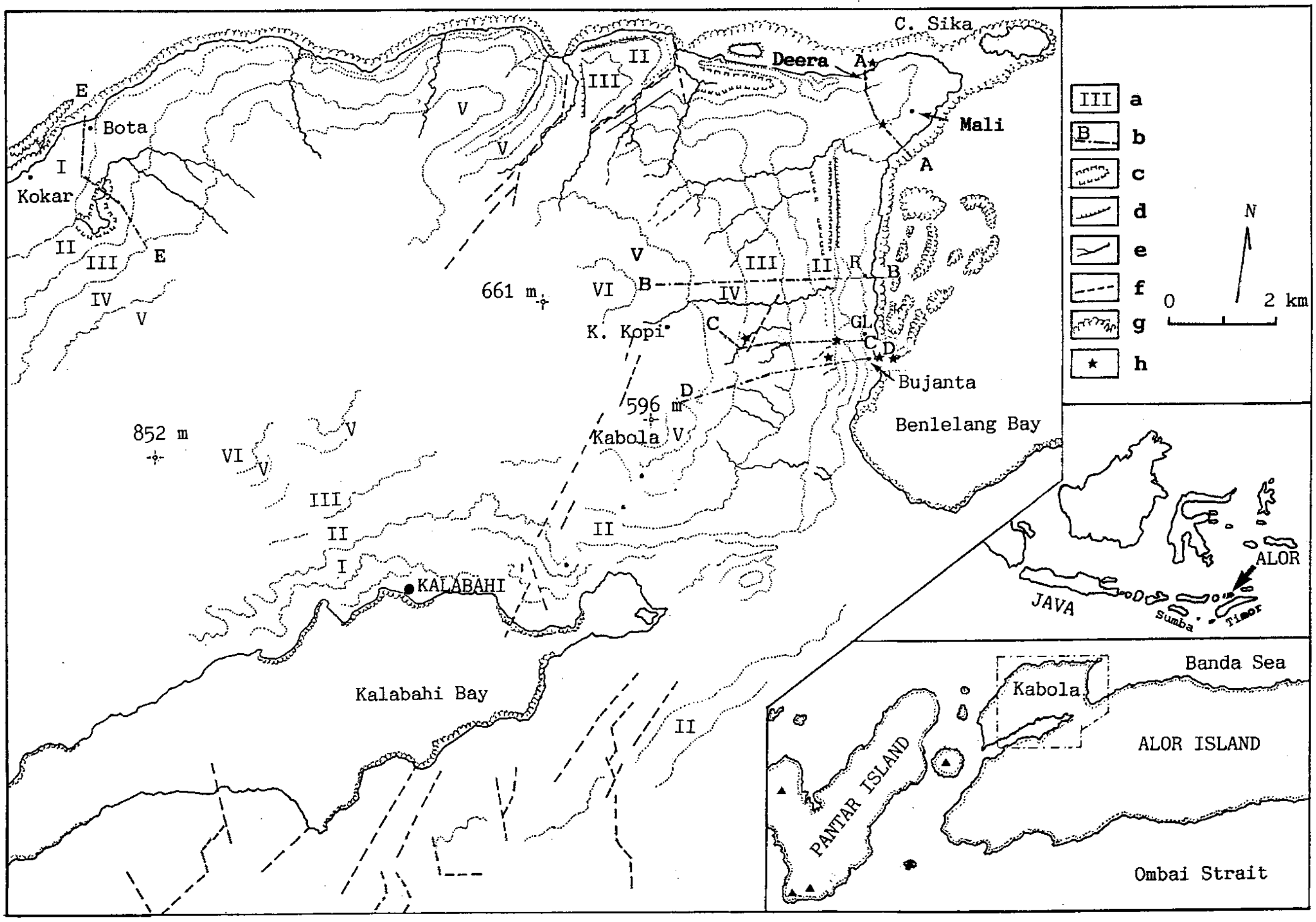

Fig. 1. Location map and morphological analysis of coral reef terraces in the Kabola Peninsula area, Alor Island. *a*, main terrace identification; *b*, transect studied; *c*, lagoon morphology; *d*, cliff; *e*, canyon; *f*, structural line; *g*, modern reef flat; *h* location of dated sample

consists of submarine effusive rocks, interbedded with calcareous tufs and marls containing *Globigerinidae*. As for the nearby Atauro and Wetar islands, volcanism in Alor has been inactive for about 3 Ma (Abbott and Chamalaun 1981). This seems to correspond to a deceleration and virtual interruption of the subduction of the Australian continental crust beneath the Banda arc (Johnston and Bowin 1981; McCaffrey and Nabalek 1984). On the other hand, this sector of the volcanic chain (from Alor to Wetar) is affected by presently active back-arc thrusting, in which the ocean crust of the South Banda Basin underthrusts the arc southwards (Silver et al. 1983).

A detailed geological description of Alor was provided by Van Bemmelen (1949). Raised coral reefs are common in Kabola Peninsula, which is connected to the main island in its northwestern part by a 3 km-wide isthmus, consisting of a small volcanic outcrop, rising up to 50 m above present sea level. Limestones occur as nearly horizontal strata that dip gently seawards. Early authors reported five terraces, up to 700 m in altitude, from the Kabola Peninsula, eight terraces up to 700 m from the south coast of Alor and the highest occurrence of marine sediments was reported at 1200 m in the middle of the island (for a review of early studies, see Hantoro 1992, pp 294–297).

Material and methods

Before field work, the areas to be investigated were studied on the multispectral Landsat satellite scene E-30187-01254 of September 8, 1978, in which the main terraces around Kabola Peninsula appear clearly (Hantoro 1992), as well as on the aerial photographs of Bakosurtanal Indonesia. This led to the identification of six major terraces and of some subterraces on the northern and eastern parts of Kabola Peninsula, where their frontal crest or the cliff edge appears to be marked by a slightly clearer line. The major terraces are numbered I to VI in Fig. 1. Higher terraces may exist inland, above 600 m in altitude.

A one-week field survey was carried out by three of us (WSH, PAP and CJ) in August 1988, mainly along five transects. It was generally not possible to walk straight across the terraces and we had to take winding paths, often between two walls of vegetation, with little or no lateral visibility. It was possible to have a wide view only on the outer scarps of the terraces (Fig. 2). This was essential in order to localize observations and evaluate horizontal distances.

Altitudes were measured with a spirit level and a folding ruler for Holocene samples and estimated using three pocket altimeters for higher terraces. Since interpolated corrections for barometric changes were often not possible, altitudes above 100 m are accurate only to ± 10 m.

Regarding the analytical procedures for the U-series method, the inner part of each clean coral sample was taken for isotopic analysis. The samples were broken into small fragments which were scrubbed

Fig. 2. View from Terrace V_1 of transect D towards Cape Sika (all the photos are by P.A. Pirazzoli)

by ultrasonic vibration, dried at 100 °C and then ground to a fine powder. An aliquot of each powder sample was taken for the determination of the relative abundance of calcite by X-ray diffraction. Only samples with $\leqslant$3–4% calcite were chosen for analysis. The radiochemical procedure used is described in Causse and Hillaire-Marcel (1989) and Hoang and Hearty (1989). Uncertainty ranges of U-series data correspond to 1σ counting errors. The U-series data obtained display values of uranium concentration and $^{234}U/^{238}U$ activity ratios within the range of those generally observed in reliable fossil corals. The initial $(^{234}U/^{238}U)_i$ values of 1.13 ± 0.03 and 1.18 ± 0.04 are consistent, within experimental errors, with the present-day seawater value of 1.15 ± 0.03. The ^{232}Th isotope level is below or very close to the detection limit.

The ESR method was applied to splits of three samples used for U-series dating, i.e. MLI. 4.3.b, GDL.7.1 and BJT.7.1. ^{230}Th and ESR dates are in agreement within the margin of experimental error. Sample preparation, ESR measurement and age calculation were carried out following Grün (1989). Uncertainty ranges of ESR dates have been estimated at 15%. U-migration (perhaps due to recrystallization) cannot be entirely excluded, but in general this will at worst require the addition of an 5–10% error.

Results

The modern reef flat is 50 to 200 m wide. Its innermost part is generally covered with sands, carbonate muds and algae. Seaward, live branching and massive corals occur immediately below the mean low water spring tide (MLWST) level (the local tidal range is of the order of 2.2 m). A strip of sand beach or mangrove patches are usually found landwards.

The main data concerning the fossil samples dated are summarized in Table 1. Discontinuous remnants of a fossil reef flat capped by coral debris appear at some places at about 3 m above the present-day counterpart (Fig. 3). Near Deera, a *Porites* coral collected in growth position, 3.1 m above the MLWST level, was dated 6370 ± 170 y BP by ^{14}C. Near Bujanta, a large *Porites* microatoll reaching about 2 m above the present MLWST level had a ^{14}C date of 6240 ± 150 yr BP (Fig. 4). Along the road, near the same place, a well-developed double notch shows retreat points at about 5.0 m and 8.6 m above the MLWST level (Fig. 5), i.e. emergence of 3.9 m and 7.5 m respectively in relation to the mean sea level (MSL), where modern notches are forming (Pirazzoli 1986).

Topographical transects measured across the raised terraces of Kabola Peninsula are summarized in Fig. 6. The width of Terrace I_1 at +5/+10 m elevation increases from 25–50 m near Deera and Bota to 50–100 m near Mali and to 300–500 m at Bujanta. This terrace has a reefal

Table 1. List of coral samples analyzed from the reef series of Kabola Peninsula, Alor Island: sample codes, taxonomy, radiochemistry, and estimated ages

Terrace number sample code	Latitude S	Longitude E	Sample altitude (m)	Coral species	Calcite (%)	U (ppm)	$^{234}U/^{238}U$	$(^{234}U/^{238}U)^f$	$^{230}Th/^{234}U$	U-Th age (ka)	ESR age[e] (ka)	^{14}C age (y BP)
0, BJT.0.1.1	08°11′44″	124°33′15″	2[a]	*P*	0.6							6240 ± 150
0, KBL.0.1.1	08°08′53″	124°33′24″	3.1[a]	*P*	0.4							6370 ± 170
II_4, GDL.7.1	08°11′20″	124°32′15″	115	*Fc*	3.0	2.03 ± 0.05	1.14 ± 0.03	1.18 ± 0.04	0.60 ± 0.02	98 ± 7[c]		
						2.31 ± 0.14[b]					111 ± 17	
II_5, MLI.4.3b	08°09′32″	124°33′16″	85	*Cm*	3.8	2.32 ± 0.06	1.13 ± 0.03	1.18 ± 0.04	0.67 ± 0.02	118 ± 9[c]		
						2.49 ± 0.15[b]					131 ± 23	
II_6?. BJT.7.1	08°11′20″	124°31′56″	150	*Gp*	2.3	2.49 ± 0.07	1.09 ± 0.02	1.13 ± 0.03	0.72 ± 0.02	134 + 9/− 7[d]		
						2.17 ± 0.13[b]					117 ± 15	
IV_1, GDL.11.1	08°11′20″	124°31′56″	280	*Pls*	8.5	2.40 ± 0.14[b]					192 ± 48	

Uncertainty ranges of U-series data correspond to 1σ error. Coral species are as follows: *Cm*, Coeloseris mayeri (Vaughan); *Fc*, *Favites chinensis* (Verrill); *Gp*, *Goniastrea pectinata* (Ehrenberg); *P*, *Porites* sp.; *Pl s*, *Platygyra sinensis* (Chevalier)

[a] above the low tide level

[b] analyzed at INAA, Neutron test analysis, Hamilton, Ontario; uncertainty range estimated at 6%

[c] analyzed by C.C. at the Laboratoire de Géologie du Quaternaire, Marseille

[d] analyzed at Centre des Faibles Radioactivités, Gif-sur-Yvette

[e] uncertainty range estimated at about ±15% (at about ±25% for the sample, GDL.11.1)

[f] initial $^{234}U/^{238}U$ ratio corrected for ^{230}Th age

Fig. 3. Remnants of a fossil reef flat at about 3 m above the present low tide level between Cape Sika and Deera

Fig. 4. *Porites* microatoll reaching 2 m above the MLWST level near Bujanta

origin, though corals are rare (generally limited to its inner part) and recrystallized. The front of I_1 is most often sandy, and the back part, locally capped by grainstones, appears to be paleo-dunes.

Subterraces I_2, I_3, II_1, II_2 and II_3 correspond to narrow, undated flat steps, less than 100 m wide, often bounded outwards by a reef crest made up of corals, mainly recrystallized. In transect E, the II_4 level corresponds to the shores of a former lagoon, delimited by a barrier reef and a fringing reef reaching about +115 m elevation. This reef level can be correlated with a reef dated 98 $\pm$7 ka (U-Th) and 111 $\pm$ 17 ka (ESR) in transect C (Terrace II_4, probably corresponding to oxygen-isotope substage 5c).

The last Interglacial peak 5e is represented by the well-developed complex of Terraces II_5 and/or II_6, which is dated 118 $\pm$ 9 and 134 + 9/−7 ka (U-Th) and 131 $\pm$ 23 and 117 $\pm$ 15 (ESR). Two different morphological steps appear to correspond to the 5e peak in some transects of Alor, as on the nearby Atauro Island (Chappell and Veeh 1978). Unfortunately, no calcite-free coral samples could be found in both the steps in the same transect to confirm this interpretation with radiometric ages.

The morphology of raised lagoons associated with the terraces formed during the last Interglacial has been identified near Kokar and Deera on the north coast, and between Mali and Rawa on the east coast (Fig. 1). In the

Fig. 5. Double notch at 5.0 m and 8.6 m respectively above the MLWST level near Bujanta. Scale is 2 m

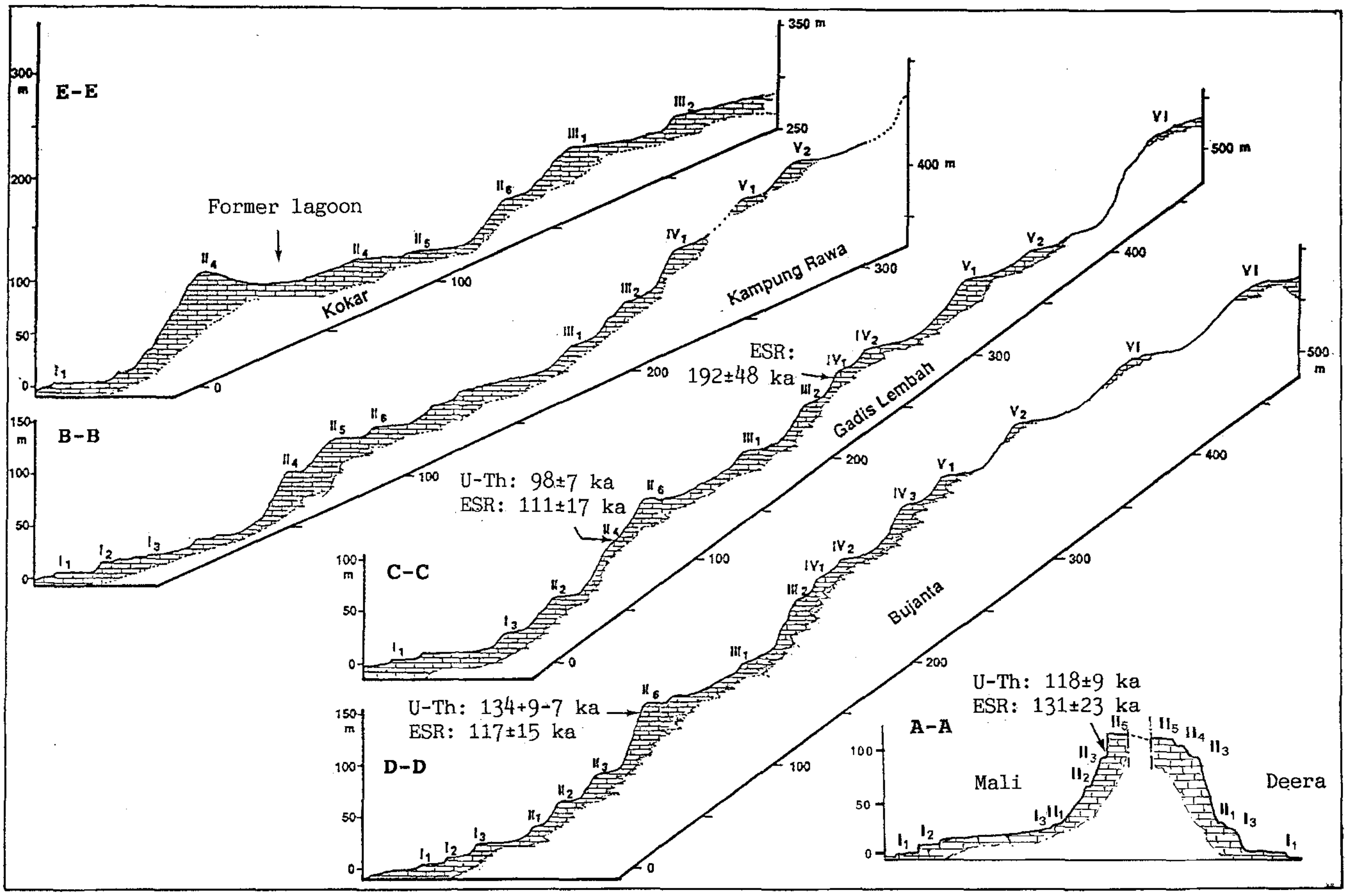

Fig. 6. Topographical transects across the raised terraces, Kabola Peninsula, Alor Island. For location of the transects, see Fig. 1

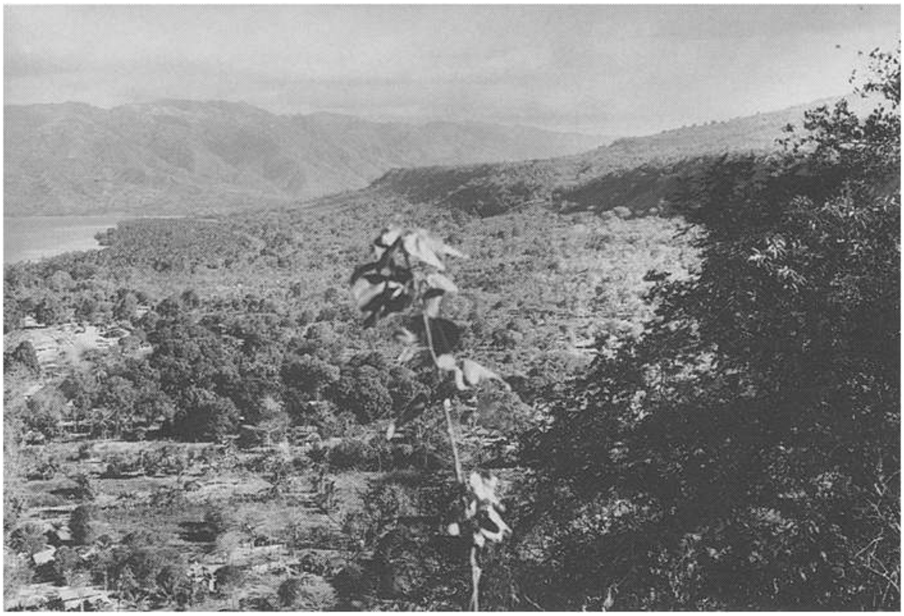

Fig. 7. The complex of terraces I and II seen from the outer last interglacial surface near Mali. The high cliff/scarp delimiting the outer edge of terraces II_5-II_6 is visible in the background

latter area, the fossil barrier reef delimiting the lagoon shows a steep fore reef scarp about 25 m high (Fig. 7).

Several coral reef terraces have been measured at higher levels, up to 580 m in altitude (Fig. 6). Former reef crests often contain dense coral assemblages, but are deeply recrystallized and hence unfit for dating. An attempt to date a *Platygyra* coral with 8.5% calcite collected in situ at about +280 m in transect C using ESR, gave an apparent age of 192 ± 48 ka. While recrystallization appears to have only limited effects on ESR results (Radtke et al. 1988), this sample seems to have been affected also by dissolution and its apparent age must be interpretated with caution.

Discussion

Correlation between Pleistocene reef terraces

The probable relation between terraces measured along the transects is given in Table 2. This is based on morphological characteristics, using aerial photographs to infer lateral continuity. Following Bloom's method (1980), applied to raised coral reef terraces on Sumba Island (Pirazzoli et al. 1991, 1993), a constant uplift rate was calculated that was consistent with most terrace levels and their ages. Correlation was attempted between sea-level positions estimated with error margins at interglacial stages, deduced

Table 2. Altitude (in m) of terraces and possible relation between transects measured around Kabola Peninsula, based on the morphology and height of the terraces

Terrace	Transect					Age		Estimated oxygen-isotope stage (Fig. 8)
	A (Mali-Deera)	B (Kampung Rava)	C (Gadis Lembah)	D (Bujanta)	E (Kokar-Bota)	U-Th (ka)	ESR (ka)	
VI	—	—	525	500–580	—			13
V_2	—	400	400–415	420	—			11
V_1	—	375	370	380	—			11?
IV_3	—	—	—	355–360	—			9
IV_2	—	310	305–310	300	300?			9
IV_1	—	290	280–285[a]	285			$\geqslant 192 \pm 48$	$\geqslant 7$
III_2	—	250	265–270	270–275	270			7
III_1	—	200–220	200–220	200–230	225			7
II_6	125	145	? 150–165	? 150–165[a]	? —	$134 + 9 - 7$	117 ± 15	5e
II_5	115[a]	130	—	—	125–130	118 ± 9	131 ± 23	5e
II_4	105	100	115[a]	—	115	98 ± 7	111 ± 17	5c
II_3	85–90	—	—	90	—			5a
II_2	50–53	—	60	60–65	—			3?
II_1	30–35	—	—	33–40	—			3
I_3	25	27–30	25	25–30	—			3
I_2	15	15	—	13–15	—			3
I_1	5–10	5–10	5–10	5–10	5–10			3 + 1?

[a] Level with dated sample, see age columns

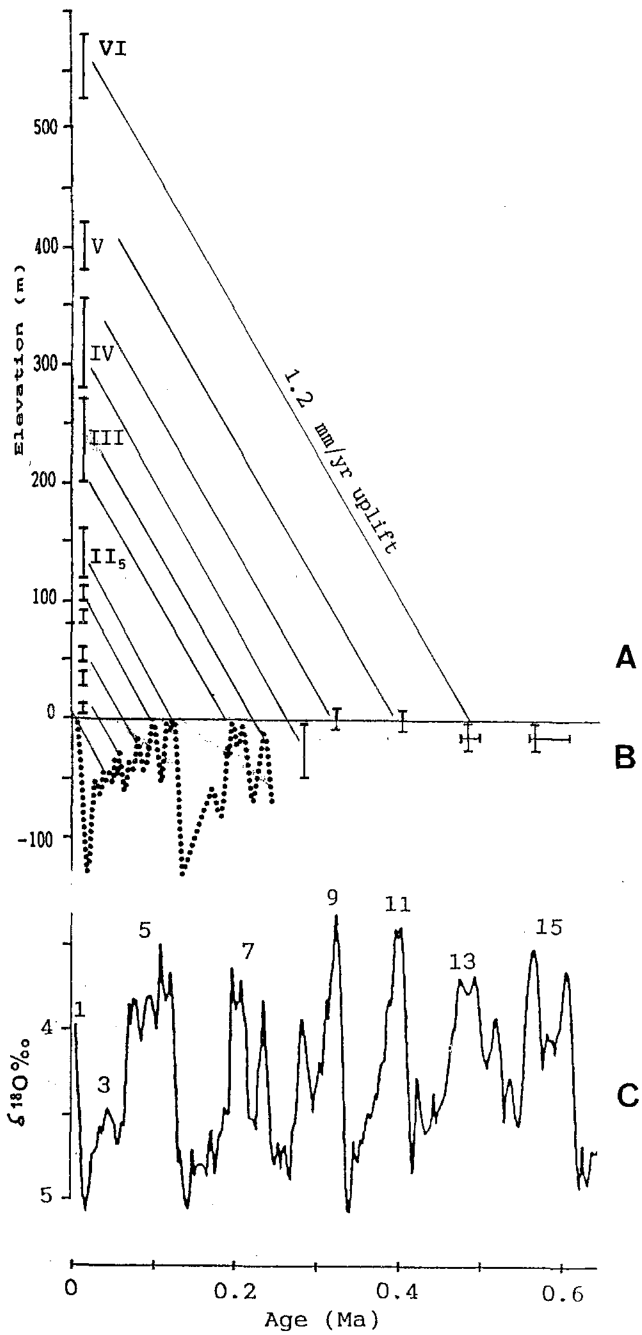

Fig. 8A–C. Correlation between uplifted coral reef terraces, sea level, and isotope stages. **A** model of uniform uplift rate; **B** possible sea-level positions since 250 ka (according to Chappell and Shackleton 1986) and at previous interglacial peaks; **C** astronomically calibrated benthonic isotope records from Ocean Drilling Program site 677 (Shackleton et al. 1990)

from the astronomically calibrated benthonic oxygen-isotope data for ODP 677 (Shackleton et al. 1990) (Fig. 8), and the elevations of the marine terraces measured along the transects.

The best estimate uplift was between 1.0–1.2 mm/y. At this rate, the development of the upper terrace (VI) corresponds to Stage 13 and is estimated to be about 0.5 m.y. old. Most of the upper-terrace elevations are consistent with major development occurring during an interglacial stage or substage (V with Stage 11, IV with Stage 9, III with Stage 7). If this uplift rate is correct, the likely real age of sample GDL.11.1 is about 240 ka.

Although parts of the sea-level curve proposed by Chappel and Shackleton (1986) are uncertain and differ slightly from other curves proposed (e.g. Bloom and Yonekura 1985; Shackleton 1987), it is reproduced in Fig. 8B to show the correlation of terrace II_4 with substage 5c and of the lower steps in the transects with the various peaks of Stage 3. In particular, terrace I_1, at 5–10 m and the notch at +8.6 m, would be 40–50 ka old. However the shoreline dated near 30 ka obviously could not have emerged at the uplift rate of 1–1.2 mm/y.

Holocene features

The only features which are clearly related to Holocene sea levels in the northern and eastern parts of the Kabola Peninsula are remnants of a luxuriant reef flat, between 2 and 3 m above the low sea level. The lower notch at about +5 m, is also consistent with this reef flat (Fig. 9). One of the samples dated was collected from the surface of a *Porites* microatoll, i.e. approximately at the MLWST level at the time of its development (Scoffin and Stoddart 1978; Woodroffe and McLean 1990). Thus, the available data provide evidence of Holocene emergence of about 2 to 3 m since 6300 y BP.

The sea-level curve for Alor during the past 7000 y predicted by glacio-hydro-isostatic theory for a visco-elastic earth model, including second interaction corrections for the water load and the time-dependent shoreline, is given in Fig. 10 (Nakada and Lambeck 1987; Johnston 1993). This earth model assumes a lithosphere of 50 km thickness, an upper mantle (down to 670 km) viscosity of either 2×10^{20} or 4×10^{20} Pa s and a lower mantle viscosity of 10^{22} Pa s, consistent with values found previously (Lambeck and Nakada 1990). The ice model is ARC3 + ANT3, previously defined by Nakada and Lambeck (1988, 1989) and includes a small amount of on-going melting after 6000 y BP, consistent with results found in some other regions (Lambeck and Nakada 1990; Lambeck et al. 1990). The model predicts only minor regional variability ($\pm$15 cm at 6000 BP) in the highstand amplitude for the region. Figure 10 illustrates a band of sea-level predictions which corresponds to a range of earth models.

Using the calibration curve for marine samples proposed by Stuiver et al. (1986) and assuming that the reservoir effect near Alor is 400 years (instead of 250 y, as assumed by Hantoro 1992), the calibrated age of the two samples dated by radiocarbon at 6300 y BP becomes about 7070 cal. y BP. At an uplift rate of 1.0–1.2 mm/y, uplift would have been 7.8 $\pm$ 0.7 m during the last 7070 years. However, no evidence of a Holocene reef flat has been found at the level near the floor of the upper notch. All available evidence corresponds to a fossil reef (including the corals dated 7070 cal. y BP) near the floor of the lower notch (Fig. 9).

A possible interpretation (which modifies the interpretation proposed previously by Hantoro 1992) is that

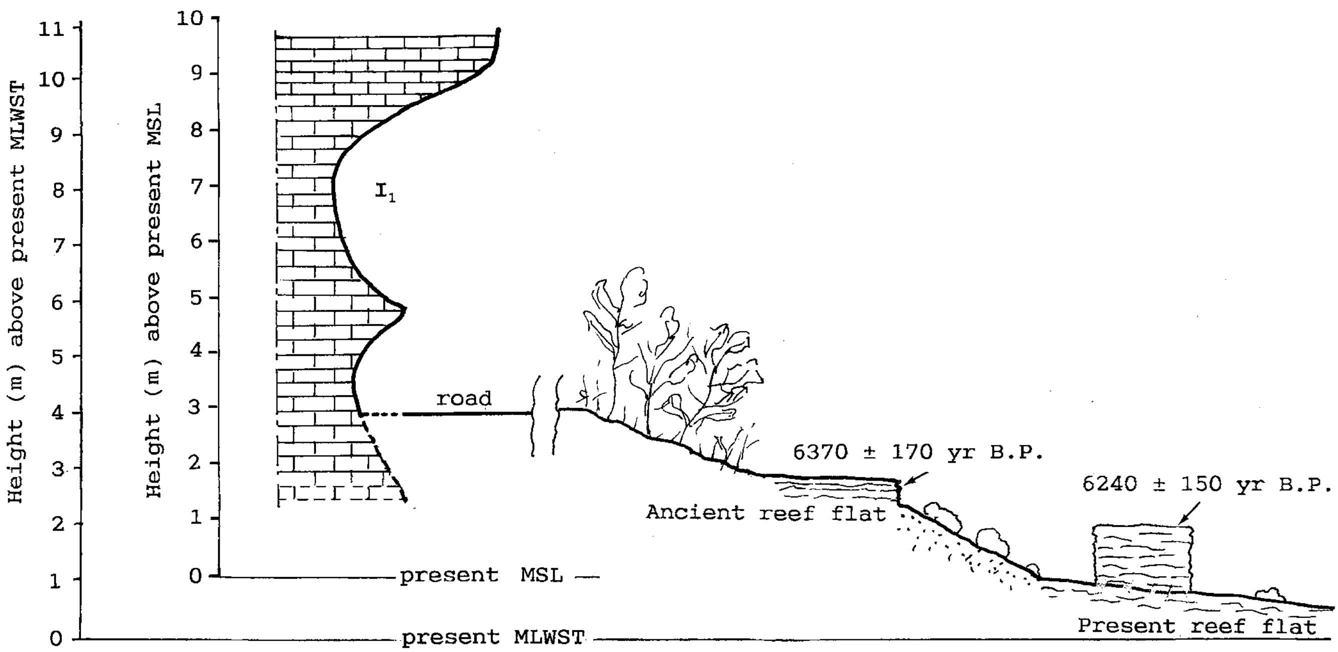

Fig. 9. Idealized transect combing the Holocene sea-level data from Alor Island

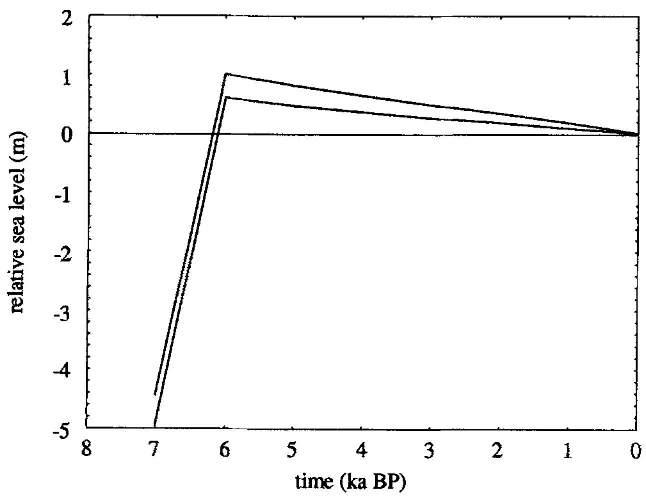

Fig. 10. Glacio-hydro-isostatic sea-level changes predicted for Alor Island. The ages are expressed in conventional ^{14}C years

(1) only the lower notch is Holocene; (2) the date of the microatoll corresponds to a period of decreasing sea-level rise, just before the Holocene relative sea-level maximum; (3) emergence since the mid-Holocene has been much less than what would be expected from an uplift rate of 1–1.2 mm/y. Either the uplift rate in the area has significantly decreased during the Holocene, or, more probably, the long term uplift rate, as in several other tectonically active areas, expresses the summation of successive coseismic vertical displacements generated by great-magnitude earthquakes. If this is the case, the period of recurrence of sudden vertical displacements would appear to be rather long in Alor; on the order of several thousand years, since no sudden uplift appears to have occurred during the last 7000 years. A coseismic uplift of up to a few metres, accompanying a great-magnitude earthquake, may therefore occur in the near future in this area. On 14 July 1991, an earthquake of $M = 6.7$ was reported from Alor. This earthquake is evidence that stress accumulation-relaxation is active in this area, suggesting a possible future event of even greater magnitude.

The upper, 8.6 m-high notch is probably correlated with the 5–10 m-high coastal plain (Terrace I_1). The relatively large extension of this plain (e.g. 300–500 m in the Bujanta area) and the poor preservation and severe recrystallization of corals present in its inner part do not favour a Holocene age. As suggested above, a 40–50 ka age seems more likely for these features (Fig. 8).

Conclusions

We reached the following conclusions concerning the evolution of geodynamic processes on Alor Island. The local long term average uplift rate appears to be 1.0–1.2 mm/y since 500 ka. This rate is twice as fast as uplift rates deduced from similar coral reef terraces on nearby Atauro and Sumba Islands, and fast enough to preserve marks corresponding to most interstadial periods.

Though the Alor data are insufficient to establish local sea-level changes since 500 ka in detail, the lower terraces presumably reflect relatively low sea level stands during glacial interstadials which can be compared with data reported from Huon Peninsula. Moreover, the higher terraces reflect a mid-Pleistocene sea-level history comparable to the longer time scale obtained from Sumba Island.

For the Holocene, available data suggest that the uplift trend may be the result of sudden upward movements occurring at the time of great-magnitude earthquakes, resulting in a gradual, continuous movement only over the long term. A sudden uplift may therefore occur in the future. A more detailed survey of the terraces dealing with morphology, chronology and paleoenvironmental reconstruction would improve our knowledge of the neotectonic evolution of the rapid trend of vertical movements presently affecting the inner Banda volcanic arc, in relation to the subduction/collision processes occurring between the Australian and Eurasian plates, including back-arc thrusting.

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