Variable rates of Late Quaternary surface uplift along the Banda Arc–Australian plate collision zone, eastern Indonesia

DOROTHY MERRITTS[1], REBECCA EBY[2], RON HARRIS[3],
R. LAWRENCE EDWARDS[4] & HAI CHANG[4]

[1] *Department of Geosciences, Franklin and Marshall College,*
Lancaster, PA, 17604-3003, USA (e-mail: D_Merritts@acad.fandm.edu)
[2] *Department of Earth and Planetary Sciences, Washington University,*
St Louis, MO 63130-4899, USA
[3] *Department of Geology, Brigham Young, Provo, UT 84602, USA*
[4] *Department of Geology and Geophysics, University of Minnesota,*
Minneapolis, MN 55455, USA

Abstract: Radiometrically dated emergent coral terraces from southeastern Indonesia provide estimates of differential vertical strain in the Banda Arc–continent collision complex. At Semau island, two samples from the lowest emergent reef (5–7 m) yield ^{230}Th dates that correspond to the 5a (*c.* 83 ka) sea-level highstand and a low surface uplift rate of 0.2–0.3 m per 1000 years. At Rote island, samples from the lowest emergent reef (*c.* 1–2 m) on both north and south sides of the island yield late Holocene ages and an average short-term uplift rate of *c.* 1–1.5 m per 1000 years. Similarity of ages from different samples on the north coast of Rote suggests possible coseismic emergence. Survey data from nine emergent reefs and marine notches up to 170 m in altitude on the south side of Rote indicate that uplift rates may have been *c.* 1–1.5 m per 1000 years for *c.* 120 000–130 000 years. Combined with previous studies, these results indicate that late Quaternary surface uplift rates vary an order of magnitude along the strike of the Banda orogen. Vertical displacement rates are greatest in young parts of the orogen where the shelf-slope break recently has been underthrust beneath the orogenic wedge, as at Rote, and in older parts of the orogen where retroarc thrust faulting occurs, as at Alor island.

This paper presents new ^{230}Th ages and associated surface uplift rates for emergent coral reefs on two islands near West Timor in southeastern Indonesia (Fig. 1). On Rote island, no previous work has been done on emergent corals. On Semau island, only one coral sample has yielded a previous age estimate (Jouannic *et al.* 1988). Both islands are located in an important zone of transition from subduction to collision along the plate boundary between the Indian–Australian and Eurasian plates. Whereas the transition from subduction to collision is poorly preserved in most other collision zones, it is well preserved in the Timor region. Many lines of evidence indicate that both horizontal and vertical rates of deformation are greater in this area than elsewhere in the orogen. This paper also compiles all previous estimates of surface uplift rates from coral dating on islands throughout southeastern Indonesia. We use this compilation to consider regional variability in vertical strain rates in relation to recent models of tectonic processes in the Banda Arc–Australian continental margin collision zone.

Cenozoic deformation in the Banda Arc–Australian continental plate collision zone

The Indonesian region contains an active subduction zone, accretionary arc, volcanic island arc, and emergent collision zone. In western Indonesia, oceanic crust of the Indian–Australian plate is subducting northward beneath the Eurasian plate along the Java trench, forming the Sunda volcanic arc and accretionary wedge, which includes the volcanic islands of Sumatra and Java (Fig. 1). In eastern Indonesia, where oceanic crust has been subducted completely, underthrusting of buoyant Australian continental lithosphere since about 3 Ma changes the Java Trench into a collisional foredeep and the locally inactive Banda Arc into an arc–continent collision zone along the Timor Trough (Hamilton 1979; Bowin *et al.* 1980; Silver *et al.* 1983; Breen *et al.* 1986; Karig *et al.* 1987). Underthrusting of the mature Australian continental margin significantly increases the influx of accretionary material and the frictional resistance to slip along the plate boundary (Harris 1991). Collisional strain

MERRITTS, D., EBY, R., HARRIS, R., EDWARDS, R. L. & CHANG, H. 1998. Variable rates of Late Quaternary surface uplift along the Banda Arc–Australian plate collision zone, eastern Indonesia. *In:* STEWART, I. S. & VITA-FINZI, C. (eds) *Coastal Tectonics*. Geological Society, London, Special Publications, **146**, 213–224.

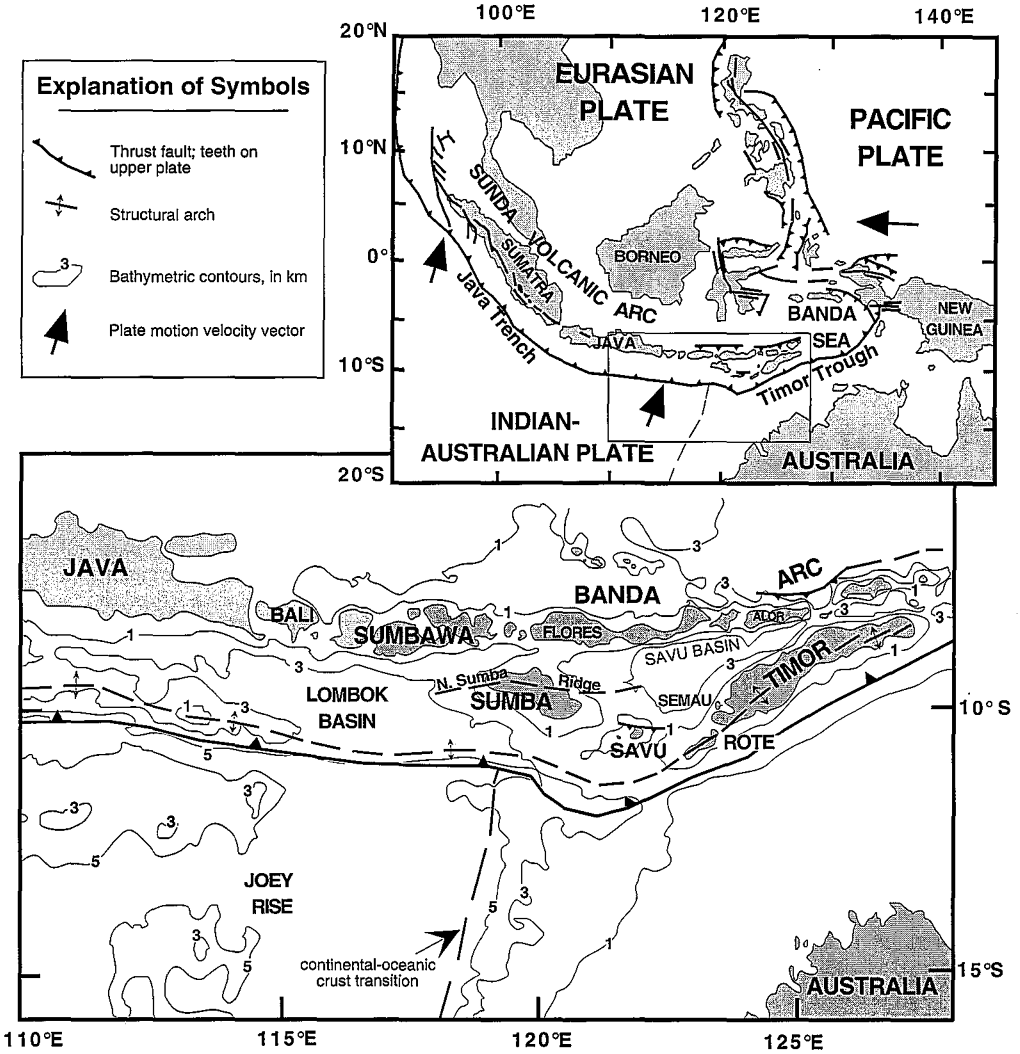


Fig. 1. Plate tectonic map of the Banda Arc orogen (upper right) and enlarged view of eastern Indonesia (lower panel). Rote and Semau are accretionary islands situated in the collision complex. The Timor Trough separates the Indian–Australian plate from the Eurasian plate. Arrows in upper panel represent relative motion of the Indian–Australian plate. Bathymetric contour interval in lower diagram is 1000 m.

in this region is increasingly distributed away from the deformational front as continental underthrusting progresses (Harris 1991). Because of the obliquity of convergence, the transition from subduction to collision propagates to the southwest along the plate boundary at an estimated rate of 110 km/10^6 years (Harris 1991) and currently is south of the island of Sumba at about 120°E longitude (Breen *et al.* 1986).

Recent work in the Banda Arc–continent collision complex has focused on estimating late Cenozoic deformation rates in response to plate collision and shortening (see Bowin *et al.* 1980; Audley-Charles 1986; Karig *et al.* 1987; DeSmet *et al.* 1989). Geologists have used structural and stratigraphic data, in particular from seismic reflection profiles, in conjunction with biostratigraphic data to estimate rates of horizontal and vertical displacement of rock. Few reliable quantitative estimates of vertical strain rates have been made, however, because of lack of precise indicators of depositional depths of uplifted strata.

In addition, it is difficult to estimate surface uplift rates from elevated columns of rock and sediment unless the amount of material exhumed (eroded) during uplift also is known (England & Molnar 1990). Global positioning system (GPS) surveys have yielded short-term (years) velocity vectors of horizontal displacement throughout the region (Genrich *et al.* 1996), but again these do not provide rates of vertical surface uplift, which commonly are an order of magnitude smaller than horizontal rates of plate motion and thus are more difficult to measure over short periods of time.

From previous work, it is known that rates and styles of horizontal and vertical deformation vary markedly along the Indonesian archipelago as the nature of the plate boundary changes from a zone of subduction to collision. Near 120°E longitude, where subduction is nearly perpendicular to the orientation of the trench (Genrich *et al.* 1996), little to no horizontal shortening occurs along the Java Trench (Fig. 1). Net surface uplift along the outer edge of the upper plate, as indicated by late Quaternary coral reefs, is minimal and Holocene rates of emergence are less than 1 m per 1000 years (Vita-Finzi & Situmorang 1989). To the east, in contrast, collision-induced changes along the Timor Trough result in increased rates of horizontal shortening and vertical displacement, as well as greater distribution of strain away from the deformation front into a broad, mountainous orogenic zone.

Offshore seismic-reflection and bathymetric profiles examined in the Timor collision zone by Karig *et al.* (1987) show that relative rates of late Cenozoic horizontal deformation vary markedly throughout the orogenic complex. In addition, Karig *et al.* qualitatively assessed the relation between horizontal and vertical displacement rates, noting that the vertical component is much smaller than the former, but still substantial. Using structural and depositional information from Pliocene to Quaternary age sediments, they concluded that the most intense horizontal shortening, caused by accretion and thrusting, has occurred along the inner slope of the Timor Trough, referred to as the deformation front. Cumulative horizontal and vertical deformation are greatest between the deformation front and an arch known as the outer arc high that forms the central spines of Savu, Rote, and Timor islands (Fig. 1). Karig *et al.* estimated that as much as 3–5 km of rock uplift has occurred in parts of the outer arc high since late Miocene time, and DeSmet *et al.* (1990) determined that rapid uplift in West Timor began about the time that subduction ceased, about 200 000 years ago. Northward from this region of emergence of bathyal sediments, rates of deformation decrease rapidly.

Seismic data from the forearc basin region north of the Timor collision zone show that the sedimentary cover is mostly undeformed and tilted to the north, which Karig *et al.* (1987) interpreted as evidence for no shortening between the forearc ridge and volcanic arc (with exception of a small arch known as the North Sumba Ridge; Fig. 1). However, offshore seismic reflection profiles presented by Silver *et al.* (1983) and Breen *et al.* (1986) and onshore field studies conducted by Harris (1991) indicate northward displacement of the accretionary wedge along the Savu thrust and other south-dipping thrusts at the rear, or northern front of the accretionary wedge (Fig. 1). Balanced sections indicate that back-arc convergence may account for as much as 25–30% of the total convergence in the collision zone (Harris 1991). These observations are consistent with regional GPS measurements which indicate that parts of Timor are moving essentially northward with the Australian plate relative to parts of the Banda Arc (Genrich *et al.* 1996).

Emergent coral reef terraces, sea-level change, and crustal uplift

Some coral species grow close to sea level, providing precise markers from which to estimate the amount of surface uplift that has occurred since coral death (Bloom *et al.* 1974; Chappell 1974; Taylor & Jouannic 1985; Chappell & Shackleton 1986; Lajoie 1986; Ota *et al.* 1993). Coral reefs grow upwards in response to a relative rise in sea level, and are abandoned during times of relative sea-level fall. Reef crests indicate the approximate height of each transgression (Chappell 1974). As a result, flights of reefs formed during periodic sea-level highstands are stranded above sea level in areas where net land mass uplift is occurring. Relative sea-level transgressions and regressions comprise two components of change: eustatic sea-level fluctuation (caused primarily by changing glacial ice volume) and vertical crustal displacement as a result of tectonism. If the former is known, the latter can be deduced from the present altitudes and ages of emergent reefs in a given area.

Surface uplift rates for late Quaternary time can be obtained from emergent, unrecrystallized aragonitic corals dated by methods of ^{230}Th isotope analysis. This basic procedure has been applied in different parts of the world with much success (see Bloom *et al.* 1974; Chappell 1974; Taylor & Jouannic 1985), but early work was hindered by the difficulty of obtaining sufficient amounts of unrecrystallized aragonite, which readily converts to calcite in the presence of diagenetic fluids in porous coral structures. Until recently, ^{230}Th dating relied on alpha-counting techniques that required sizeable samples and yielded dates with substantial uncertainties. Because late Quaternary sea level has oscillated at cycles as short as 20 000 years, the dating uncertainties limited correlation of certain age reefs with specific sea-level highstands. Recent improvements in methods of ^{230}Th dating that utilize thermal ionization mass spectrometric techniques require only small sample sizes and have improved analytical error, so that uncertainties in final age estimates are smaller (Edwards *et al.* 1987; Chen *et al.* 1991). As a consequence, the timing and altitudes of global sea-level highstands now are well constrained for about the past 200 000 years (Edwards *et al.* 1987; Gallup *et al.* 1994).

Previous estimates of late quaternary surface uplift in the Banda Arc collision zone

The first to analyse emergent coral reefs in the Timor region were Chappell & Veeh (1978), who worked at four sites along the north coast of East Timor, as well as along the southern coast of a small island to its north, Atauro (Fig. 2). Their U–Th ages (alpha counting) of coral samples indicated that late Pleistocene surface uplift rates along the northeast coast of East Timor are 0.5 m per 1000 years, but decrease westward to less than 0.03 m per 1000 years near central Timor. The sites in northeastern Timor are close to the axis of the outer arc high, or structural culmination zone where DeSmet *et al.* (1989) determined that substantial structural relief has developed in Quaternary time. In contrast, the central Timor site is well north of the arch's axis, at the edge of a zone of subsidence known as the Savu Basin (Fig. 1).

Along the north coast of West Timor, Chappell & Veeh noted that no emergent reefs occur, and other workers have inferred that little to no net uplift, and instead possibly even subsidence, is occurring in this area (e.g. Karig *et al.* 1987; Vita-Finzi & Hidayat 1991). West of the city of Kupang, U–Th dating (alpha counting) of one coral head in growth position on a reef 44 m above sea level yielded an age of 152 ± 10 ka BP and a surface uplift rate of 0.3 m per 1000 years (Jouannic *et al.* 1988). Radiocarbon dating of shell material from a low, wave-abraded beach sand deposit 1.3 m above sea level just east of Kupang yielded a mid-Holocene age, and indicates possible local and slight emergence since

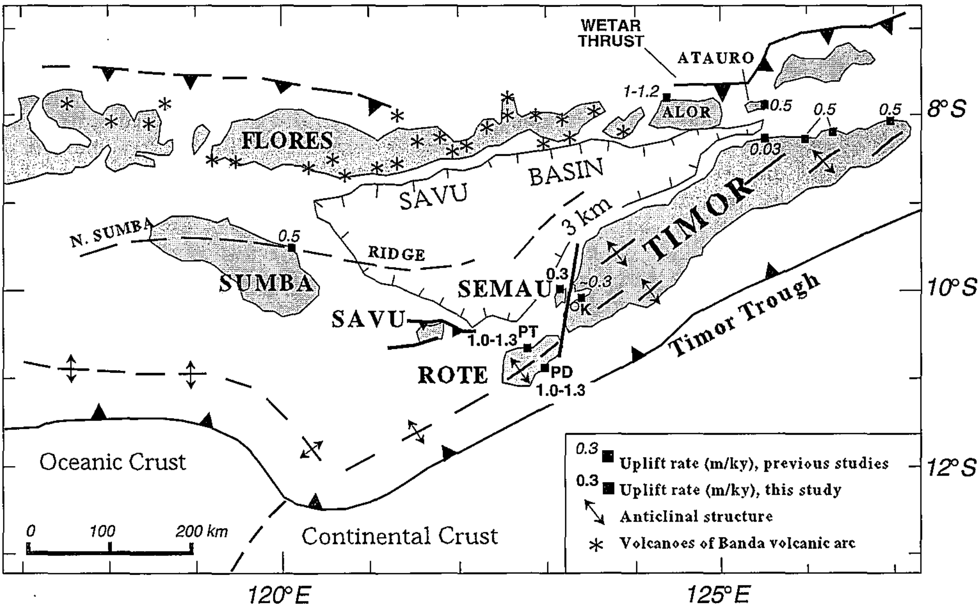


Fig. 2. Generalized tectonic map of Timor region, showing compilation of surface uplift rates from this study (bold) and previous work (italics) on emergent coral reefs (see text for references to sources of uplift rate data). K, Kupang; PD, Point Dombo; PT, Point Termanu.

that time if sea level has not risen since then (Vita-Finzi & Hidayat 1991). However, if sea level was higher during mid-Holocene time, the deposit could indicate crustal stability since then. Northwest of Kupang, on the island of Semau, Jouannic *et al.* (1988) dated a fossil coral from a terrace on the southeast coast at an altitude of about 7 m and obtained a U–Th age estimate of 124^{+8}_{-7} ka BP. If this terrace represents oxygen-isotope stage 5e, the average late Pleistocene uplift rate in southern Semau is <0.2 m per 1000 years.

Chappell & Veeh (1978) also studied a flight of emergent reefs to the north of the Savu forearc basin, on Atauro island (Figs 1 and 2). This island is part of an inactive segment of the Banda Arc that is surrounded by active faults. Sonar mapping of the sea floor in this region by Breen *et al.* (1986) revealed that some horizontal shortening and possible vertical deformation are occurring. Indeed, Chappell & Veeh (1978) determined from coral dating that late Pleistocene surface uplift rates are ~ 0.5 m per 1000 years at Atauro.

More recently, others have investigated emergent reefs on Sumba island, which is an uplifted segment of the Savu forearc basin, and on the volcanic island of Alor, west of Atauro (Fig. 1). A flight of six major reefs with many subterraces and notches spans the coastline from sea level to nearly 500 m on the north coast of Sumba, where the North Sumba Ridge crosses the island (Figs 1 and 2). Uranium-series and electron spin resonance dating methods yielded a late Quaternary surface uplift rate of 0.5 m per 1000 years (Pirazzoli *et al.* 1991, 1993), the same as that obtained by Chappell & Veeh (1978) for the outer-arc high in East Timor (Fig. 2). On the north coast of Alor, which is bounded by a well-developed back-arc thrust zone to the north (Silver *et al.* 1983), six major reefs with many subterraces and notches up to 700 m in altitude were dated with carbon-14, uranium-series, and electron spin resonance methods, and yielded a late Pleistocene surface uplift rate of 1–1.2 m per 1000 years (Hantoro *et al.* 1994).

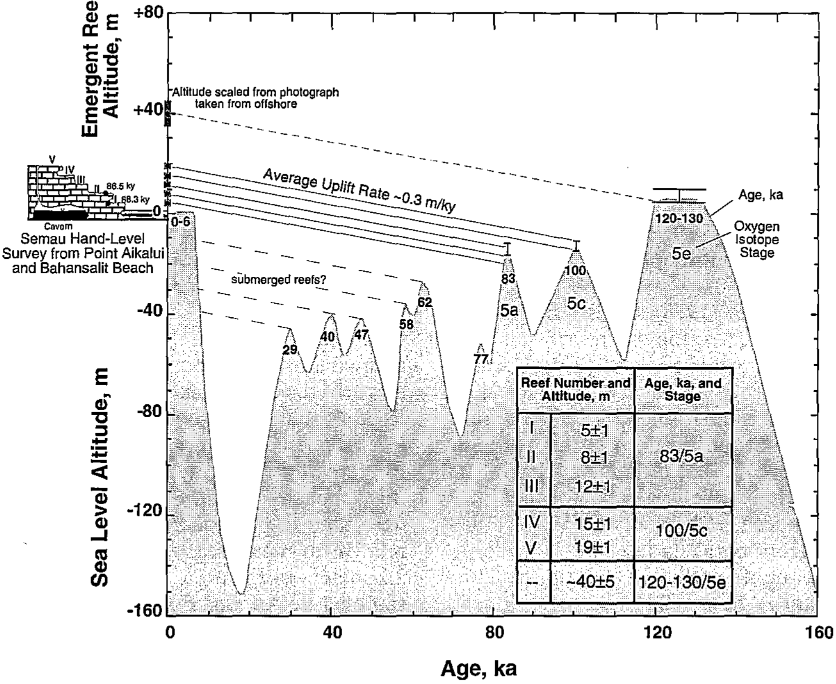
Results of this study

Site descriptions and survey methods

Until the work described in this paper, no studies of Pleistocene reefs had been carried out on islands between West Timor and Sumba, with exception of a single coral sample from Semau dated by Jouannic *et al.* (1988). These islands are located at the important transition zone along the Indian-Australian and Eurasian plate boundary, where subduction ceases and collision begins. We worked on Semau and Rote islands offshore of West Timor to assess flights of emergent reefs for evidence of vertical displacement.

Semau is located within the Banda Arc–Australian plate collision zone just west of Timor, north of the axis of the outer arc high (Figs 1 and 2). Emergent reefs are ubiquitous along the northeastern coast of Semau. Reefs commonly encircle mud diapirs capped by mud volcanoes associated with localized release of fluid over-pressure in the collision zone. Sites are accessible only by boat, as few dirt roads and motorized vehicles exist on this remote island. Reef altitudes were obtained using a Lietz hand level mounted on a bracket fixed to a telescoping rod (cumulative errors ± 1 m). Indicators of high tide, such as the zone of highest green algae, were used to provide an absolute vertical datum relative to mean sea level. Tidal range is about 2.2 meters in the area. Reefs were surveyed and sampled at Aikalui Point as well as Bahansalit Beach (Fig. 3), where reefs occur at similar altitudes, but only those from Aikalui Point yielded unrecrystallized aragonite (Table 1). At Aikalui, sample A4 was collected from a coral (genus Faviidae) exposed in a prominent marine notch 2–3 m below a reef crest at *c.* 8 m above mean sea level. Sample A5 (genus Faviidae) was collected from the reef crest.

Flights of emergent reefs are prominent on most of the island of Rote, the southernmost island in Indonesia (Figs 1 and 2). Rote is located along the axis of the outer arc high, closer to the deformation front than any other island. Warped reefs arch upwards over the island's central ridge, rising to altitudes of nearly 400 m. Quaternary bathyal sediments from deep in the accretionary prism are exposed just below the capping of coral limestone, indicating substantial amounts of vertical displacement. An extensive flight of reefs was surveyed on the southern coast of the island, at Point Dombo (Fig. 4), using a US Paulin System Altimeter (range of 0–5000 feet, or 0–1524 m), with supplemental hand-level surveying as described for Semau. A base camp near sea level was used to monitor barometric changes over the duration of the survey period (4 days) and to correct altimeter readings for diurnal fluctuations. Hand-level surveys were used in addition to altimeter readings to assess the uncertainty of the latter, which was determined to be ±3–5 m. As on Semau, the zone of highest green algae was used to provide an absolute vertical datum relative to mean sea level. Only samples from the



Reef Number and Altitude, m		Age, ka, and Stage
I	5±1	83/5a
II	8±1	
III	12±1	
IV	15±1	100/5c
V	19±1	
--	~40±5	120-130/5e

Fig. 3. Eustatic sea-level curve from Huon Peninsula, Papua New Guinea (Chappell & Shackleton 1986; Gallup *et al.* 1994) and correlation of interglacial and interstadial sea-level highstands with emergent coral terraces on Semau. Combined topographical transect from Aikalui Point and Bahansalit Beach was obtained with a hand level (see text); horizontal distances are shown diagramatically. The total horizontal distance shown is about 400 m. Vertical error bars for survey altitudes are ±1 m. Two samples dated from reef II correlate with stage 5a (83 ka), and are used to estimate an uplift rate of 0.2–0.3 m per 1000 years.

lowest reefs immediately along the coast yielded unrecrystallized aragonite. Aragonite was obtained from the lowest reef at Point Dombo, just below a prominent marine notch, as well as from a broad reef in an embayment on the north coast of the island, at Point Termanu (Fig. 2; Table 1).

X-ray diffraction and petrographic analysis

Each sample was divided into four parts: one for archival purposes, a second for X-ray diffraction (XRD) analysis, a third for thin section preparation, and a fourth for U–Th dating. For XRD analysis, samples were submersed in acetone and ground with a mortar and pestle, then sieved through 230 mesh to eliminate particle-size effects during X-ray diffraction. A cavity mount of the sample was prepared and a full scan from 2° to 60° 2θ was conducted. To determine the per cent aragonite in each sample, we used the Gibbs (1971) working curve of the ratio of the height of the calcite fundamental peak to the height of the aragonite fundamental peak ($h_{3.40}/h_{3.03}$) v. per cent aragonite. Those samples which indicated large amounts of aragonite (Table 1) then were used for further petrographic analysis and radiometric dating.

Standard thin sections were prepared using a clear epoxy resin. The thin sections were etched in 1% hydrochloric acid and stained with an alizarin red S and potassium ferricyanide stain to aid in identification of carbonate minerals (Dickson 1966). Thin sections were examined under a petrographic microscope to characterize the state of preservation, the mineralogy as indicated by the stain, and the crystal form and degree of neomorphism.

Samples selected for ^{230}Th age dating exhibited excellent preservation of the original coral skeleton and yielded less than 5–10% calcite during XRD analysis. Unique petrographic features include pore spaces that essentially are void of cement and sediment, and aragonite needle cements along primary pore edges. In addition, thin rims of intermediate iron calcite were noted on several samples, indicating that

Table 1. *^{230}Th age determinations completed by University of Minnesota*

Sample No.	Island	Site name	Altitude (level and tape)	Site description	XRD results*	^{238}U (ppb)	^{232}Th (‰)	δ^{234}U measured†	^{230}Th/^{238}U (activity)‡	Age (years BP)§	δ^{234}U Initial†	Corrected age (years BP)‖	Corrected δ^{234}U initial†
A4	Semau	Aikalui Point	8 ± 1 m above mean sea level	Head coral in growth position on reef crest	Aw/C	2865 ± 2	1291 ± 8	127.0 ± 1.2	0.6266 ± 0.0019	86 500 ± 400	162.3 ± 1.6	86 500 ± 400	182.3 ± 2.1
A5	Semau	Aikalui Point	5 ± 1 m above mean sea level	Coral head in growth position from notch below reef crest	Aw/C	2521 ± 2	1059 ± 6	123.3 ± 1.2	0.6326 ± 0.0020	88 300 ± 500	158.4 ± 1.8	88 300 ± 500	168.4 ± 2.1
N4 (a)¶	Rote	Nomodali	~1.5 m above mean sea level	Small coral head in growth position(?) with beach rubble matrix below prominent notch of next higher reef	A	2709 ± 3	3107 ± 9	147.0 ± 1.3	0.01460 ± 0.00007	1 348 ± 7	147.6 ± 1.3	1 319 ± 17	147.6 ± 2.3
N4 (b)¶	Rote	Nomodali	~1.5 m above mean sea level	Small coral head in growth position(?) with beach rubble matrix below prominent notch of next higher reef	A	2704 ± 2	2577 ± 12	148.9 ± 1.2	0.01437 ± 0.00010	1 315 ± 10	149.5 ± 1.2	1 300 ± 16	149.5 ± 1.7
T3	Rote	Point Termanu	<1.5 m above mean sea level	Coral head in growth position on stratified beach rock (coral rubble matrix)	A	2467 ± 2	2111 ± 10	149.9 ± 1.2	0.01131 ± 0.00007	1 030 ± 7	150.4 ± 1.2	1 008 ± 13	150.4 ± 1.6
T2	Rote	Point Termanu	<1.5 m above mean sea level	Coral head in growth position on stratified beach rock (coral rubble matrix)	A	2358 ± 2	981 ± 7	148.9 ± 1.4	0.01146 ± 0.00006	1 045 ± 6	149.3 ± 1.4	1 035 ± 8	149.3 ± 2.0

* Aw/C, aragonite with some (<5–10%) calcite; A, aragonite.

† $\delta^{234}U = [\{(^{234}U/^{238}U)/(^{234}U/^{238}U)_{eq}\} - 1] \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ is the atomic ratio at secular equilibrium and is equal to 5.472×10^{-5}. $\delta^{234}U(0)$ is the measured value. $\delta^{234}U(T)$ is the initial value and is equal to $\delta^{234}U(0)\ (e^{\lambda_{234}T})$. Values of decay constants are $\lambda_{238} = 1.551 \times 10^{-10}$ years^{-1}, $\lambda_{234} = 2.835 \times 10^{-6}$ years^{-1}, and $\lambda_{230} = 9.195 \times 10^{-6}$ years^{-1}.

† Activity ratio is calculated from the atomic ^{230}Th/^{238}U ratio by multiplying by $\lambda_{230}/\lambda_{238}$.

§ Ages are calculated using $[^{230}Th/^{238}U]act - 1 = -e^{-\lambda_{230}T} + (\delta^{234}U(0)/1000)\ [\lambda_{230}/(\lambda_{230} - \lambda_{234}))(1 - e^{-(\lambda_{230}-\lambda_{234}T)})]$ where T is the age in years.

‖ Corrected ages assume an initial ^{230}Th/^{232}Th atomic ratio of 4.4 ± 2.2 × 10^6. This is the value for a material at secular equilibrium, with a crustal ^{232}Th/^{238}U value of 3.8. The error is arbitrarily assumed to be 50%.

¶ (a) and (b) are duplicate analyses of the same sample.

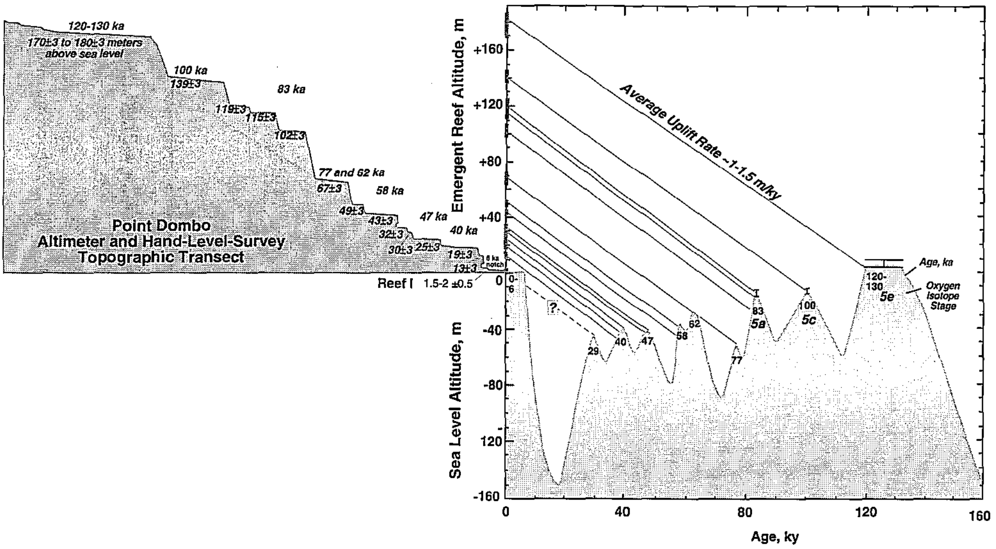


Fig. 4. Eustatic sea-level curve from Huon Peninsula, Papua New Guinea (Chappell & Shackleton 1986; Gallup *et al.* 1994) and preliminary correlation of interglacial and interstadial sea-level high stands with emergent reefs at Point Dombo, southern Rote. A sample dated from reef I was used to estimate an uplift rate of 1–1.2 m per 1000 years. However, different uplift rates were used to test the degree of fit between older reefs and the times and altitudes of sea-level highstands. That shown here is the most consistent with all reefs surveyed. It should be noted that reefs correlate with times of sea-level peaks, but steps and notches continue to form even as sea level regresses. A similar process is occurring today. As the lowest reef at Point Dombo is raised above a relatively stable sea level, a broad surface is formed, with notches and steps that span several metres in altitude. At the time of the next eustatic sea-level regression, more notches and steps might form before a subsequent sea-level highstand.

reducing and oxidizing pore fluids passed through the system and some neomorphism occurred (Aikalui 4 and 5 Termanu 2). The diagenetic environment may have been in the deep sea or on a shallow-water platform; however, given the geological context, the most likely scenario involves a shallow platform with storm waves carrying marine waters into the supratidal regime.

U–Th sample preparation and analytical procedures

Isotope analysis for radiometric dating was done at the University of Minnesota Isotope Laboratory. Detailed analytical procedures for measurement of Th and U isotopes have been described by Edwards *et al.* (1993) and Gallup *et al.* (1994), and are modifications of those described by Chen *et al.* (1986) and Edwards *et al.* (1987). ^{230}Th dating of corals is based on the decay of ^{238}U through a series of relatively short-lived intermediate daughters to ^{206}Pb. In this chain, ^{234}U decays to ^{230}Th with a mean life of 352 700 years, which makes these nuclides suitable for dating Quaternary corals. The initial amount of ^{230}Th in corals is extremely low and can be assumed to be zero (Edwards *et al.* 1988). If corals are assumed to represent closed systems from which no ^{230}Th, ^{234}U, or ^{238}U escapes or into which no ^{230}Th, ^{234}U, or ^{238}U enters, equations for radioactive production and decay can be used to solve for coral age as a function of the decay constants for each nuclide and the measured values of the ratios of $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ (Chen *et al.* 1986; Edwards *et al.* 1987). In addition, the initial value of $\delta^{234}U$ when the system was isolated from seawater can be calculated for each sample and compared with the present seawater value as an independent check on the assumption of closed system behaviour.

New coral ages and estimates of Late Quaternary surface uplift rates in the Banda Arc collision zone

At Aikalui Point, northeastern Semau island, two coral samples (A4 and A5) from a low emergent reef yield dates that correlate with the 5a (*c.* 83 ka BP) interstadial sea-level highstand

(86.5 ± 0.4 ka BP; 88.3 ± 0.5 ka BP; Table 1). Although these samples contain some calcite (<5–10%), the estimated initial value of δ^{234}U when the system was isolated from seawater is similar to the modern value (*c.* 150–165), indicating that diagenesis has not been extensive and the nominal age is close to the true age. At this time, there is increasing effort to re-evaluate the timing and altitude of the interstadial highstand that corresponds to oxygen isotope stage 5a. Most sea-level estimates range from as high as at present to as low as −19 ± 5 m (see review by Ludwig *et al.* (1996)). Using an altitude of formation of −13 to −18 m for the 5a highstand (Gallup *et al.* 1994) and the present reef crest altitude of *c.* 5–8 m to compute a total amount of uplift ((+5 to 8 m) to (−13 to −18 m) = 18–26 m), we estimate a very low surface uplift rate of *c.* 0.2–0.3 m per 1000 years.

On the basis of this uplift rate and estimates of sea-level highstand altitudes (Chappell & Shackleton 1986; Gallup *et al.* 1994), we predict that the 5c terrace (*c.* 100 ka BP) should be located at present altitudes of *c.* 8–18 m above sea level, and the 5e terrace (*c.* 120–130 ka BP) at *c.* 30–45 m above sea level. Many higher emergent reefs occur at Aikalui Point, including a prominent reef complex at an altitude of about 35–40 m but no higher reefs have yet been dated.

Comparison of our surveyed reef crest and marine notch altitudes (from sea-level to 19 ± 1 m) with the eustatic sea-level curve (Chappell and Shackleton 1986; Fig. 3) indicates that multiple crests and notches are associated even with single sea-level highstands, including the present highstand. This same phenomenon has been noted on the islands of Sumba (Pirazzoli *et al.* 1991, 1993) and Alor (Hantoro *et al.* 1994) in Indonesia, and on the Huon Peninsula, Papua New Guinea (Ota *et al.* 1993). Ota *et al.* (1993) argued that in Papua New Guinea the multiple benches and notches on a given reef complex are the result of episodic coseismic emergence, not just a continuously changing relative sea level. It might be possible with more detailed surveying and sampling to test this hypothesis for Semau, although it is easier at a site with higher uplift rates and younger emergent reefs, such as Rote (discussed below).

By assuming that uplift rates in northeastern Semau have been relatively constant for the past 120 000 years, we tentatively correlate reefs I, II, and III with the 5a interstadial sea-level highstand, and IV and V with the 5c interstadial sea-level highstand (Fig. 4). We propose that notches associated with surfaces I and IV formed at the end of times of interstadial highstands, as falling sea level undercut highstand surfaces. The uplift rate at Semau is low enough that all reefs from highstands younger than oxygen isotope stage 5a have been submerged by the present 0–6 ka interglacial highstand. This highstand is responsible for the prominent notch forming at the base of the 5a reef (reef I), and indicates the modern high-water mark.

On Rote island, coral samples from two sites yield late Holocene reef ages and relatively high short-term uplift rates. At Point Termanu, on the north side of Rote (Fig. 2), two samples from the lowest emergent reef (*c.* 1 ± 0.5 m above sea level) yielded ages of 1008 ± 13 yrs and 1035 ± 8 years (Table 1). An average short-term uplift rate of *c.* 1 ± 0.5 m per 1000 years is calculated for Point Termanu, assuming that sea level has changed little in altitude during that time (see discussion below). About 20 km to the south, at Point Dombo, a sample from the lowest emergent reef (*c.* 2 ± 0.5 m above sea level) yielded ages of 1319 ± 18 years and 1300 ± 17 years (duplicate analyses), and an average short-term uplift rate of *c.* 1.5 ± 0.4 m/ky (Table 1).

Based on these average short-term uplift rates, we predict that the 5a terrace would be located at present altitudes of *c.* 60–110 m above sea level. Higher emergent reefs occur in this altitudinal range on the island, but have not yet been dated. All samples collected from these terraces contained more than 5–10% calcite. Until more age control is available, it is possible to use the eustatic sea-level curve derived from Papua New Guinea (Chappell & Shackleton 1986) and elsewhere (Gallup *et al.* 1994) to infer possible ages of each reef crest and erosional marine notch surveyed with altimeter and hand level (Fig. 4). Assuming that uplift rates have been fairly constant and that the late Holocene uplift rate is a reasonable value for longer-term rates, we identified a plausible best-fit solution for reef ages. This solution matches the most prominent reef complexes at 170 ± 3 to 180 ± 3 m 139 ± 3 m and 102 ± 3 to 119 ± 3 m with the 5e, 5c, and 5a sea-level highstands, respectively. All lower reefs and notches are correlated with interstadial highstands younger than stage 5. It should be noted that uplift rates are high enough at Rote, as compared with Semau, that the 6 ka marine notch is well above sea level and is not submerged during high tide. Multiple notches and reef crests spaced closely together on each broad reef surface suggest that episodic coseismic emergence might occur on Rote, as at Papua New Guinea (Ota *et al.* 1993). Because each reef crest spans time periods of several thousands of years, the individual steps notched into them probably represent events separated by durations of several hundred to a thousand years or so.

Evidence of possible coseismic emergence on Rote island

Preliminary evidence that episodic coseismic emergence might have occurred on Rote comes from the ^{230}Th dates of the late Holocene reef complexes. Recent estimates of late Holocene sea level for the Timor Sea indicate that sea level was about +1 m at 6 ka, but has decreased to *c.* 0 m since then (Nakada & Lambeck 1987; Hantoro *et al.* 1994). No significant sea-level change has been documented for the past 1000 years, so emergent reefs with ages of about 1000 years can be explained only by crustal deformation, be it coseismic or aseismic. If multiple dates from corals at the same site yield similar ages, then it is possible that death was sudden and widespread, as during coseismic emergence (e.g. Taylor & Jouannic 1985; Ota *et al.* 1993). At Point Termanu on Rote, two samples (T2 and T3) collected about 10 m from one another yield age estimates (±1 SD) that differ by only 6 years for samples that are more than 1000 years old (Table 1). The close similarity in ages suggests that the north coast of the island might have experienced sudden, coseismic uplift, in a manner similar to recent and historic events elsewhere in Indonesia (Vita-Finzi & Hidayat 1991; K. Sieh, unpub. data).

In contrast to Rote, the other places in Indonesia with historic coseismic emergence, or evidence of prehistoric coseismic emergence, occur to the west, where subduction of oceanic crust still is active, as along the coast of Sumatra. On the south side of Rote, at Point Dombo, a single sample yielded replicate ages that are about 300 years greater than at Point Termanu. If this reef were raised by coseismic deformation, then different earthquake sources generated uplift at different times on the north and south sides of the island.

Conclusions regarding vertical strain in the Banda Arc collision zone

Compilation of results from new ^{230}Th ages of emergent coral reefs on islands near Timor and from previous work throughout the Timor region indicates that late Quaternary surface uplift rates vary more than an order of magnitude along and across the emergent Banda Arc orogenic complex (Fig. 2). In general, vertical displacement rates are greatest near the deformation fronts in both fore- and retro-wedge parts of the orogen, where rates of horizontal shortening also are largest. Surface uplift rates decrease northward toward the forearc basin, but increase again where horizontal shortening is accommodated by back-arc thrusting in the retro-wedge region along the Banda volcanic arc, north of the forearc basin. GPS measurements indicate that rates of horizontal shortening (convergence) are low in Timor (*c.* 20 mm/year), but increase westward to 46 mm/year in Sumba (Genrich *et al.* 1996). Between these areas are the zone of transition from collision to subduction and the islands of Semau and Rote. Just as GPS results indicate that the rates of horizontal displacement increase, the results of our new dates indicate that rates of vertical strain might increase, too.

Diapirism clearly influences the pattern of deformation on Semau island, as evidenced by the circular reef fringes around Aikalui Point and many other mud diapirs on the island. Nevertheless, rates of vertical deformation from the past 125 000 years have been very low (*c.* 0.2–0.3 m per 1000 years or less) along the north and northeastern coast of the island. The diapiric zone that forms the island is located near a major lateral ramp zone that bounds the western edge of Timor and separates it from the most submerged and narrow part of the outer arc ridge to the southwest (Harris 1991); however, its structural significance is poorly constrained.

Southwest of Semau and this lateral ramp zone, near the deformation front in Rote, uplift rates are much higher, with late Holocene rates of 1–1.5 m per 1000 years. In addition, ^{230}Th dating of a reef 1 ± 0.5 m above sea level suggests that coseismic emergence might have occurred about 1008 ± 13 to 1035 ± 8 years BP. Multiple notches and reef crests on higher terraces in southern Rote indicate that episodic coseismic emergence in the area has occurred possibly for at least the past 120 000–130 000 years. It is suggested here that coseismic emergence in Rote is associated with vertical accommodation of movement along contractional faults in the collisional wedge, as documented at other convergent plate boundaries (Carver *et al.* 1994; Merritts 1996). Although coseismic emergence has occurred during historic time to the west along the Java Trench, this is the first time evidence of possible coseismic emergence has been identified for the region of arc–continental margin collision east of Sumba. Emergence near Java is associated with subduction and results in little long-term net surface uplift at the plate boundary (because of post-seismic crustal relaxation), whereas in Rote, net uplift during Quaternary time is substantial, probably as a result of underthrusting of buoyant continental lithosphere.

We are grateful for sponsorship and field support from the University Pembangunan Nasional (UPN Veteran) of Indonesia. R. O'Connell and O. O'Connell provided invaluable field assistance for collecting the coral samples. Petrographic expertise was provided by C. DeWet of Franklin and Marshall College. We also thank A. Bloom for advice regarding how to sample corals, and J. Muller for assistance with the XRD analysis. We are most appreciative of financial support from NSF grant EAR-9118151 to R. Harris and from Petroleum Research Fund grant 27865-B2 to D. Merritts.

References

Audley-Charles, M. G. 1986. Rates of Neogene and Quaternary tectonic movements in the southern Banda Arc based on micropalaeontology. *Journal of the Geological Society, London*, **143**, 161–175.

Bloom, A. L., Broecker, W. S., Chappell, J. M. A., Matthews, R. K. & Mesolella, K. J. 1974. Quaternary sea level fluctuations on a tectonic coast: New ^{230}Th/^{234}U dates from the Huon Peninsula, New Guinea, Quaternary Research, **4**, 185–205.

Bowin, C., Purdy, G. M., Johnston, C., Shor, G., Lawyer, L., Hartono, H. M. S. & Jezek, P. 1980. Arc–continent collision in the Banda Sea region. *Bulletin, American Association of Petroleum Geologists Bulletin*, **64**, 868–915.

Breen, N. A., Silver, E. A. & Hussong, D. M. 1986. Structural styles of an accretionary wedge south of the island of Sumba, Indonesia, revealed by Seamarc II side scan sonar. *Geological Society of America Bulletin*, **64**, 868–915.

Carver, G. A., Jayko, A. S., Valentine, D. W. & Li, W. H. 1994. Coastal uplift associated with the 1992 Cape Mendocino earthquake, northern California, *Geology*, **22**, 195–198.

Chappell, J. M. 1974. Geology of coastal terraces, Huon Peninsula, New Guinea, a study of Quaternary tectonic movements and sea level changes. *Geological Society of America Bulletin*, **85**, 553–570.

—— & Shackleton, N. J. 1986. Oxygen isotopes and sea level. *Nature*, **324**, 137–140.

—— & Veeh, H. H. 1978. Late Quaternary tectonic movement and sea-level changes at Timor and Atauro Island. *Geological Society of America Bulletin*, **89**, 356–358.

Chen, J. H., Curran, H. A., White, B. & Wasserburg, G. J. 1991. Precise chronology of the last interglacial period: ^{234}U–^{230}Th data from fossil coral reefs in the Bahamas. *Geological Society of America Bulletin*, **103**, 82–97.

——, Edwards, R. L. & Wasserburg, G. J. 1986. ^{238}U, ^{234}U and ^{232}Th in sea water. *Earth and Planetary Science Letters*, **80**, 241–251.

DeSmet, M. E., Fortuin, A. R., Tjokrosapoetro, S. & Van Hinte, J. E. 1989. Late Cenozoic vertical movements of nonvolcanic islands in the Banda Arc area. *Netherland Journal of Sea Research*, **24**, 263–275.

——, ——, Troelstra, S. R., Vanmarle, L. J., Karmini, M. & Hadiwasatra, S. 1990. Detection of collision-related vertical movements in the Outer Banda Arc (Timor, Indonesia), using micropaleontological data. *Journal of Southeast Asian Earth Science*, **4**, 337–356.

Dickson, J. A. D. 1966. Carbonate identification and genesis as revealed by staining. *Journal of Sedimentary Petrology*, **36**, 491–505.

England, P. & Molnar, P. 1990. Surface uplift, uplift of rocks, and exhumation of rocks. *Geology*, **18**, 1173–1177.

Edwards, R. L., Beck, J. W., Burr, G. S., Donahue, D. J., Druffel, E. R. M. & Taylor, F. M. 1993. A large drop in atmospheric ^{14}C/^{12}C and reduced melting during the Younger Dryas documented with Th-230 dating of corals. *Science*, **260**, 962–968.

——, Chen, J. H. & Wasserburg, G. J. 1987. ^{238}U–^{234}U–^{230}Th–^{232}Th systematics and the precise measurement of time over the past 500 000 years. *Earth and Planetary Science Letters*, **81**, 175–192.

——, Taylor, F. W. & Wasserburg, G. J. 1988. Dating earthquakes with high precision Th-230 ages of young corals. *Earth and Planetary Science Letters*, **90**, 371–381.

Gallup, C. D., Edwards, R. L. & Johnson, R. G. 1994. The timing of high sea levels over the past 200,000 years. *Science*, **263**, 796–800.

Genrich, J. F., Bock, Y., McCaffrey, R., Calais, E., Stevens, C. W. & Subarya, C. 1996. Accretion of the southern Banda arc to the Australian plate margin determined by global positioning system measurements. *Tectonics*, **15**, 288–295.

Gibbs, R. D. 1971. X-ray diffraction mounts. *In*: Carver, R. E. (ed.) *Procedures in Sedimenztary Petrology*. Wiley–Interscience, New York, 552–563.

Hamilton, W. 1979. *Tectonics of the Indonesian Region*. US Geological Survey Professional Paper, **1078**.

Hantoro, W. S., Pirazzoli, P. A., Jouannic, C. *et al.* 1994. Quaternary uplifted coral reef terraces on Alor Island, East Indonesia. *Coral Reefs*, **13**, 215–223.

Harris, R. A. 1991. Temporal distribution of strain in the active Banda orogen: a reconciliation of rival hypotheses. *In*: Hall, R., Nichols, G. & Rangin, C. (eds) *Journal of Southeast Asian Earth Science*, **6**, 373–386.

Jouannic, C., Hoang, C. T., Hantoro, W. S. & Delinom, R. M. 1988. Uplift rate of coral reef terraces in the areas of Kupang, West Timor: preliminary results. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **68**, 259–272.

Karig, E. E., Barber, A. J., Charlton, T. R., Klemperer, S. & Hussong, D. M. 1987. Nature and distribution of deformation across the Banda arc–Australian collision zone at Timor. *Geological Society of America Bulletin*, **98**, 18–32.

Lajoie, K. R. 1986. Coastal tectonics. *In*: Robert & Wallace *Active Tectonics*. Studies in Geophysics. Geophys. Res. Forum. National Academy Press, Washington, DC, 95–124.

Ludwig, K. R., Muhs, D. R., Simmons, K. R., Halley, R. B. & Shinn, E. A. 1996. Sea-level records at ~80 ka from tectonically stable platforms: Florida and Bermuda. *Geology*, **24**, 211–214.

MERRITTS, D. J. 1996. The Mendocino triple junction: active faults, episodic coastal emergence, and rapid uplift. *Journal of Geophysical Research*, **101**, 6051–6070.

NAKADA, M., & LAMBECK, K. 1987. Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology. *Geophysical Journal*, **96**, 497–517.

OTA, Y., CHAPPELL, J. M., KELLEY, R., YONEKURA, N., MATSUMOTO, E., NISHIMURA, T., & HEAD, J. 1993. Holocene coral reef terraces and coseismic uplift of Huon Peninsula, Papua New Guinea. *Quaternary Research*, **40**, 177–182.

PIRAZZOLI, P. A., RADTKE, U., HANTORO, W. S., JOUANNIC, C., HOANG, C. T., CAUSSE, C. & BOREL BEST, M. 1991. Quaternary raised coral-reef terraces on Sumba Island, Indonesia, *Science*, **252**, 1834–1836.

——, ——, ——, ——, ——, —— & ——1993. A one-million-year-long sequence of marine terraces on Sumba Island, Indonesia. *Marine Geology*, **109**, 221–236.

SILVER, E. A., REED, D. R., MCCAFFREY, R. & JOYODIWIRYO, Y. 1983. Back arc thrusting in the eastern Sunda arc, Indonesia: a consequence of arc–continent collision. *Journal of Geophysical Research*, **88**, 7429–7448.

TAYLOR, F. W. & JOUANNIC, C. 1985. Quaternary uplift history of the Torres Islands, northern new Hebrides frontal arc: comparison with Santo and Malekula Islands, central New Hebrides frontal arc. *Journal of Geology*, **93**, 419–438.

VITA-FINZI, C. & HIDAYAT, S. 1991. Holocene uplift in West Timor. *Journal of Southeast Asian Earth Science*, **6**, 387–393.

—— & SITUMORANG, B. 1989. Holocene coastal deformation in Simeulue and Nias, Indonesia. *Marine Geology*, **89**, 153–161.