Rapid Pliocene uplift of Timor

N. Nguyen[1], B. Duffy[2], J. Shulmeister[1], and M. Quigley[2]
[1]School of Geography, Planning and Environmental Management, University of Queensland, St Lucia, 4072 QLD, Australia
[2]Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

ABSTRACT

Palynology of exhumed Pliocene marine turbidites and marl beds on the island of Timor provide insights into crustal deformation in the Indonesian region. Between ca. 4.5 and ca. 3 Ma, palynomorphs were sourced primarily from Australia and New Guinea, with increasing swamp and mangrove elements sourced from an emerging proto-Timor. Following ca. 3.1 Ma, pollen and charcoal evidence track the rapid uplift of Timor to a high island, with the progressive appearance of montane and dry, lee-side floristic elements. Early- to mid-Pliocene uplift rates of 0.5–0.6 mm yr^{-1} increased to 2–5 mm yr^{-1} in the latest Pliocene. The rapid topographic development of Timor-Leste initiated earlier but followed a pattern similar to that of more westerly localities in the Timor sector of the Banda Arc. Timor's emergence from the marine environment is closely correlated with the timing of closure of the Indonesian seaway to deep-dwelling foraminfera.

INTRODUCTION

The island of Timor in the Banda Arc, Indonesia (Fig. 1), is a product of the ongoing oblique collision of the Australian passive margin with the Banda Arc (Audley-Charles, 1968). Understanding the timing, rates, and styles of Timor's uplift and subaerial emergence from the Indonesian seaway is important for understanding the nature of the collision between the Australian and Eurasian plates, and for global climate history, because the collision is believed to play an important role in the development of modern circulation patterns in the tropical Pacific and Indian Oceans (Cane and Molnar, 2001). The timing of phases of the collision of Australia with the Banda Arc and associated uplift is still controversial (Carter et al., 1976; Haig and McCartain, 2007; Harris, 2011; Spakman and Hall, 2010).

Several studies have used uplifted shorelines along the Banda Arc, including Timor-Leste, to determine late Pleistocene to Holocene uplift rates (see Harris, 2011, p. 199, and references therein). However, documenting longer-term (e.g., pre–late Quaternary) surface uplift is challenging. Depth-versus-time estimates have been used to derive Plio-Quaternary bathymetric surface uplift rates west of Timor-Leste (Roosmawati and Harris, 2009; van Marle, 1991) but similar estimates have not been published for Timor-Leste. Apart from evidence of minor clastic deposition between 4.2 Ma and 3.35 Ma (Haig and McCartain, 2007) that suggests that parts of Timor emerged during the Pliocene (e.g., Audley-Charles, 1968), the rate(s) and timing of surface uplift of Timor-Leste are presently unconstrained.

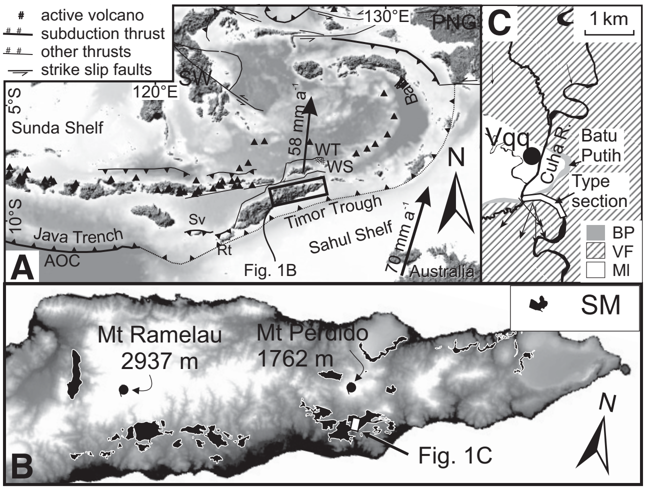

Figure 1. A: Plate boundary setting of the island of Timor. Faults follow Hinschberger et al. (2005), modified after Rigg and Hall (2012) and Watkinson et al. (2011). Convergence vectors after Nugroho et al. (2009). AOC—Australian ocean crust; PNG—Papua New Guinea; Rt—Rote; Sv—Savu; SW—Sulawesi; WT—Wetar thrust; WS—Wetar suture. B: Topography and distribution of the Synorogenic Megasequence (SM) in Timor-Leste. C: Viqueque (Vqq) area, showing location of the type section of the Viqueque Formation and orientation of paleocurrent indicators (arrows). BP—Batu Putih Formation; VF—Viqueque Formation; MI—melange.

Palynoflora have been used to derive estimates of surface uplift in other orogens (Dupont-Nivet et al., 2008). This has potential in Timor where a range of ecotones are found in the modern island from lowland swamp forest to montane podocarp forest. Here we report a palynological investigation of synorogenic sediments in Timor-Leste that quantifies the timing and rates of surface uplift. We statistically define five vegetation communities leading to identification of four paleoelevation zones, changing pollen sources, and a fire history. Using published bio- and chronostratigraphy, we define a geohistory curve for the surface uplift of Timor-Leste. This study provides insight into the topographic development of the Timor arc-continent collision zone and the bathymetry of the Indonesian seaway.

SETTING

Geology

Subduction north of Australia led to development of the Banda volcanic arc north of Timor, which was active from 12 to 3 Ma (Abbott and Chamalaun, 1981). The Australian continental shelf presently travels NNE at ~70 mm yr^{-1} relative to the Sunda Shelf (Nugroho et al., 2009) (Fig. 1A) and collides with the Banda Arc. The oblique collisional geometry results in a westward propagation of collision at ~100 km m.y.$^{-1}$ (Harris, 1991). Australian continental material is thought to have contaminated Banda Arc volcanism prior to ca. 3 Ma (Elburg et al., 2005) but interpretations of the timing of arc-continent collision in Timor vary from ca. 3.5 Ma (Carter et al., 1976) to 5.5–9.8 Ma (Haig and McCartain, 2007). Continued shortening of the Timor orogen continues at ~20 mm yr^{-1} (Nugroho et al., 2009) and supports a modern relief that locally exceeds 2900 m (Fig. 1B).

The syncollisional uplift and erosion of proto-Timor was recorded by deposition of the Synorogenic Megasequence (Haig and McCartain, 2007), including the pelagic chalk/marl Batu Putih Formation and the turbiditic Viqueque Formation of Timor-Leste. These are now widely exposed on the south side of Timor (Audley-Charles, 1968) (Fig. 1B). The samples reported here are taken from the type section of the Viqueque Formation in the Cuha River downstream of 8°51.9′ S, 126°21.844′ E (Fig. 1C).

In the type section of the Viqueque Formation (Fig. 2A), the thin basal Batu Putih Formation chalk (foraminiferal zone N18–N19) grades up to a marl (~N20), which is overlain by a 200-m-thick Viqueque Formation sandstone/mudstone turbidite package (N21) (Haig and McCartain, 2007). These changes record an exponential increase in sedimentation rates, from ~3.3 m m.y.$^{-1}$ in N18–N19 (Batu Putih Formation chalk) to ~27 m m.y.$^{-1}$ in N20 (Batu Putih Formation marl), and <490 m m.y.$^{-1}$ in N21 (Fig. DR6 in the GSA Data Repository[1]).

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[1] GSA Data Repository item 2013044, palynology and geochemistry data and methods, and section age model, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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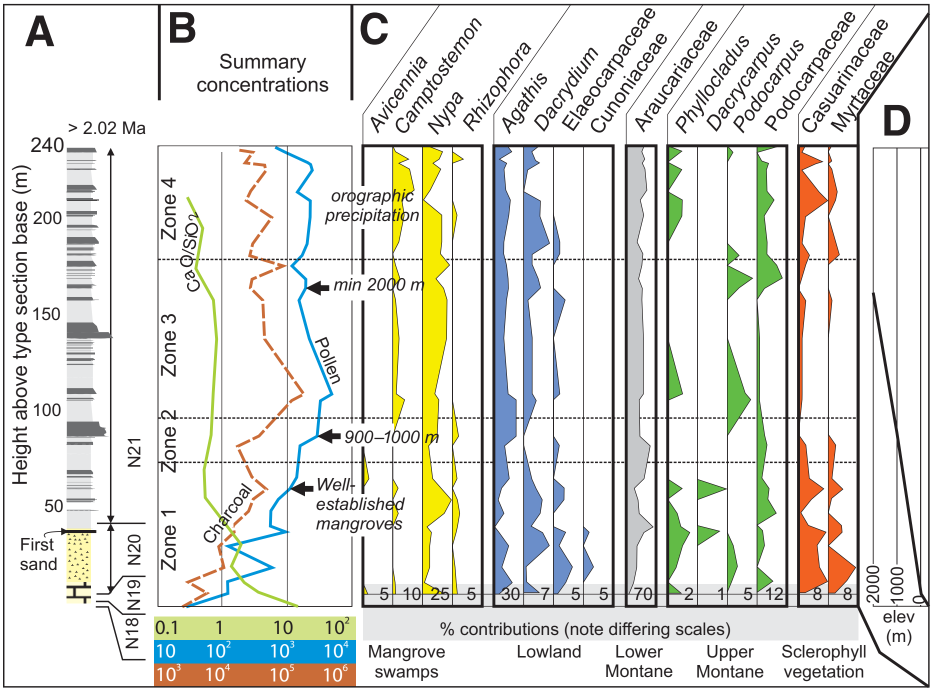

Figure 2. Palynostratigraphy and zonation of the Viqueque type section. A: Stratigraphic column showing carbonate base overlain by marls then interbedded turbidites (dark gray) and hemipelagic muds (light gray). B: Summary per-gram concentrations of pollen (blue) and charcoal (brown). CaO/SiO_2 (green) reflect increasing terrigenous sediment. Black arrows represent estimated elevation in meters above sea level of proto-Timor at the respective points in the stratigraphy. C: Pollen diagram for taxa that define elevation zones. D: Plot showing upsection increase in paleoelevation.

Botany

Timor's southern landscape is dominated by patches of tropical lowland evergreen rainforests and larger areas of lowland monsoonal rainforests below 1000 m above sea level (asl). On the northern side, semi-evergreen rainforests occur due to lower rainfall and drier soil conditions (Monk et al., 1997). Timor's lowland rainforest merges into seasonal mixed montane or upper montane forests that are capped by grasslands on mountain peaks. Above 1000–1200 m asl, seasonal montane forests are commonly composed of fire-tolerant tree species such as *Casuarina junghuhniana, Eucalyptus urophylla*, and *E. alba,* and evergreen non–fire-resistant species including *Dacrycarpus imbricatus, Palaquium* sp., and *Planchonella* sp. In drier areas and higher regions, lowland semi-evergreen rainforests merge into upper montane forests that are composed mostly of *Podocarpus neriifolius* (Podocarpaceae), *Ficus drupacea* (Moraceae), and *Mischocarpus sundaicus*, with an understory of ferns including *Gleichenia neariz* (Monk et al., 1997).

METHODS

We analyzed the palynology of 34 samples from the type section of the Viqueque Formation, between the base of the Batu Putih Formation and the top of the outcrop of the Viqueque Formation (Fig. 2). Samples from the hemipelagic muds were extracted from immediately below sandstone beds to avoid sampling reworked material. We also analyzed the major-element geochemistry and X-ray diffraction (XRD) mineralogy of separate samples previously taken from the same section to quantify changes in terriginous sedimentation. Methodological details and complete results (including taxa not mentioned below) are provided in the Data Repository.

PALEOVEGETATION RECONSTRUCTION OF THE VIQUEQUE TYPE SECTION

Four palynological zones encompass the principal components of variability in the pollen record (Fig. 2). The basal zone (Zone 1) contains a palynoflora from a range of ecotones, the contributions of which evolve through the zone. Initially low pollen concentrations (minimum of <50 grains g^{-1}, mean of 630 grains g^{-1}) increase by two orders of magnitude from the base of the section upward to the start of Zone 2 at 77 m above the type section base (ab). Charcoal concentration increases by an order of magnitude from initial values of ~4000 grains g^{-1}. As pollen concentrations increase, mangrove taxa such as *Nypa* maintain their percentage contributions. The lower montane family Araucariaceae (excluding *Agathis*) rises gradually to a peak, alongside the lowland taxa *Agathis*, Cunoniaceae, and Elaeocarpaceae. Mirroring this trend, Podocarpaceae (southern conifer) genera including the lowland/lower-montane *Dacrydium* (van Steenis, 1985), as well as the montane genera *Dacrycarpus*, *Phyllocladus*, and *Podocarpus* (Morley, 2000), decline with increasing pollen concentrations.

In Zone 2 (77–100 m ab), the mean pollen and charcoal concentrations (2252 grains g^{-1} and 26,460 grains g^{-1}, respectively) are higher than in Zone 1. Sclerophyll pollen declines to virtually zero, along with the dominantly upper montane Podocarpaceae, leaving the lowland to lower montane taxa *Agathis* and Araucariaceae to share dominance with mangrove taxa such as *Nypa*.

Zone 3 (100–183 m ab) has the highest charcoal values in the record, including a major peak at 112 m of over 185,000 grains g^{-1}. Upper montane Podocarpaceae reappear (18%), while mangrove and lowland taxa remain important.

Zone 4 (>183 m ab) is similar to Zone 3 except for the resurgence of sclerophyll vegetation, as represented by Myrtaceae and Casuarinaceae. All vegetation communities present at the start of the pollen record reoccur in the final zone.

GEOCHEMICAL PROVENANCE DISCRIMINATION

The gradual upsection increase in charcoal and pollen in Zone 1 is matched by a decrease of CaO/SiO_2 (Fig. 2B), which decreases by 80% between VM1 and VM2 (Table DR2), indicating a progressively more terrestrial source. All samples contained >30% carbonate. To investigate lithogenic sediment provenance, we plotted biogenically influenced discriminant functions (Roser and Korsch, 1988) for the type section samples against data from possible parent terranes, including the Gondwana (Berry and Jenner, 1982) and Banda terranes (Standley and Harris, 2009), Wetar (Elburg et al., 2005), and Atauro (Ely et al., 2011) (Fig. 3). 50% of the Banda ultramafics, and two Atauro rocks fell outside the top left of the plot in Figure 3 due to high Mg and Ca levels. The type section mudstones occupied an intermediate position between the average Banda metabasites and metapelites, and did not overlap with the dominantly felsic arc rocks. The carbonates from the base of the section showed Mg enrichment, possibly due to the presence of undetected minor dolomite. No clay minerals

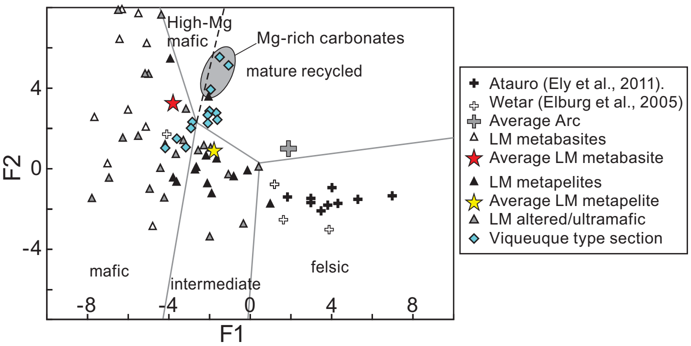

Figure 3. Major-element provenance discriminant plot (Roser and Korsch, 1988). The Viqueque type section mudstones plot on a mixing line between the average values of Lolotoi (LM) metabasites and metapelites (Standley and Harris, 2009), and are more mafic in composition than most local volcanic arc rocks. F1—discriminant function 1; F2—discriminant function 2.

were detected in the Batu Putih Formation samples by XRD analysis, and only kaolinite was present in the interbedded mudstones, which is consistent with a basement rather than volcanic source.

DISCUSSION

The only other Pliocene to early Pleistocene pollen record from near Timor is from the Deep Sea Drilling Project (DSDP) Site 262 core in the Timor Trough. Zaklinskaya (1978) found that in the earlier part of the record, there was a higher level of Indo-Malayan pollen. This is inconsistent with both regional currents and our observations, which indicate that the sparse pollen in the early part of our record has Australian affinity. Zaklinskaya suggested that Indo-Malayan pollen became less important later in the Pleistocene. We have more samples and larger pollen counts that indicate the record is dominated by Australian-affinity taxa throughout while there is a minor but persistent Indo-Malayan influence. In Zone 4, the appearance of all modern vegetation communities, including coastal and inland mangrove swamps, lowland and lower montane rainforests, lower montane Araucarian forests, upper montane Podocarpaceae-dominated conifer forests, and sclerophyll vegetation, demonstrates that the Pliocene flora of proto-Timor was very similar to modern vegetation.

The changes in the paleovegetation and geochemistry recorded in the type section provide insight into paleoelevations in the Viqueque Formation source region (Fig. 2D). The near-absence of pollen, and the geochemistry and concentration of lithogenic sediment at the base of the section, suggest that the Banda Arc was not contributing greatly to background sedimentation in the Viqueque Basin. The composition of sparse pollen in Zone 1 indicates sources that include regions with montane podocarps (requiring mountains higher than 2000 m) and many Australian elements [e.g., *Casuarina* and *Eucalyptus* (Myrtaceae)]. This sparse pollen flora probably incorporates sources from New Guinea and Northern Australia.

The timing of Timor's emergence above sea level and its initial establishment as a low-lying island is broadly constrained by the pollen record. The rapid increase of lithogenic sediment input above the base of the section suggests that proto-Timor was emergent by the base of N20 at 4.45 Ma (approximate age of sample VM2; see below). This is consistent with a rapidly increasing signal of lowland rainforest vegetation communities in Zone 1. The gradual increase in *Nypa* to its peak at 58 m ab (Fig. 2C) is interpreted to record establishment of mangrove swamps during the emergence of Timor. Collectively, the appearance of mangrove taxa such as *Avicennia*, which peaks at 50 m ab, alongside the presence of *Camptostemon* and *Rhizophora* demonstrate that mangrove swamp communities were well established by the time of the appearance of the first turbidite bed.

Araucarian forest taxa increased rapidly at ca. 3.5 Ma, before declining at ca. 3.1 Ma and recovering at the base of Zone 2 (Fig. 2C). This occurs simultaneously with minor peaks in upper montane taxa and a decline in lowland taxa. Possible explanations include a cooling event that regionally lowered the threshold elevations of vegetation zones.

Zone 2 marks the uplift of the island to lower montane elevations (minimum 1000 m asl), as recorded by the dominance of Araucarian forest taxa in the type section. On New Guinea, *Araucaria* forms an important component of lower montane forests, and naturally occurs between 1000 m and 2450 m asl (Enright, 1982). *Araucaria* thrives in drier areas (Havel, 1971; Moss and Kershaw, 2000), on steeper topography (Havel, 1971), and on rockier outcrops (Moss and Kershaw, 2000) than rainforest.

Zone 3 records the rise of Podocarpaceae pollen. *Podocarpus*, *Dacrycarpus,* and *Phyllocladus* genera are largely restricted to upper montane forests in the tropics, though they can occur infrequently in the lower montane forests of New Guinea and Sulawesi (Culmsee et al., 2011). Upper montane forests start at elevations of 2400 m asl on New Guinea to as low as 1800 m asl on Sulawesi (Culmsee et al. 2011), but in most locations in the Indonesia region, upper montane forests occur above ~2000 m asl. Thus the re-established influx of Podocarpaceae pollen indicates that the island had reached elevations greater than ~2000 m asl.

Charcoal was used as an independent indicator for environmental change in this record. Values and variability of charcoal are low at the start of the record, suggesting long-distance dispersal (Whitlock and Larsen, 2001). Rising values through the lower two zones indicate a gradual increase in fire frequency or, more probably, greater proximity to source. Charcoal increases to a marked peak after the start of Zone 3 at ca. 2.9 Ma (Fig. 2C), which coincides with the highest pollen concentration values in the record. This may reflect a higher concentration of organic material at this level, but the overall pattern of high charcoal values from this point on is robust. After the peak, charcoal fluctuates, but values remain higher than before the peak. Presently, the southeast trade winds bring orographic precipitation to the southern side of Timor-Leste, and drier conditions to the northern leeward side for much of the year. The charcoal peak is interpreted as reflecting the point at which Timor had emerged high enough to develop an incipient dry lee side, which supported burning.

In Zone 4, the emergence of Myrtaceae and Casuarinaceae sclerophyll vegetation at 185 m ab follows the successive emergence of lowland, lower montane, and upper montane communities. This suggests that the ecotones on the island were becoming differentiated, with dry, wet, and montane zones fully established.

Using an age model based on the published ages for the section (see the Data Repository, and Fig. DR6 therein), we developed a geohistory curve recording the surface uplift of the proto-Timor source area (Fig. 4). Sample VM2 (see Table DR2), taken from 7 m ab, lies slightly above the base of N20 (located at ~6.5 m ab) and is ca. 4.45 Ma. Sediment flux at that time was increasing rapidly suggesting that at least isolated islands were emergent. We therefore assume a conservative 0 m elevation at that time. The subsequent attainment of 1000 m elevation at 84 m ab would have occurred between 3.01 Ma and 2.59 Ma. This yields an initial uplift rate of 0.53–0.69 mm yr^{-1} over this period, or 0.44 mm yr^{-1} assuming constant uplift rates from the onset of turbidite deposition (dotted black line, Fig. 4). Elevations of 2000 m recorded at 173 m ab would have been attained between 2.79 and 2.2 Ma, yielding uplift rates of 2.56–4.55 mm yr^{-1}.

These calculated rates are faster than surface uplift rates of 0–1.6 mm yr^{-1} determined for Timor's north coast for the past 150 k.y. (Harris, 2011). However, our rates and temporal patterns are consistent with, but 0.7 m.y. earlier than, uplift rates calculated for the Central Basin of West Timor (van Marle, 1991) and ~1.2 m.y. earlier than bathymetric uplift in the vicinity of Rote and Savu west of Timor (Roosmawati and Harris, 2009) (gray lines in Fig. 4). We interpret our calculated accelerated uplift to record the arrival of the continental slope at the Viqueque sector of the Banda forearc at ca. 3.1 Ma.

Srinivasan and Sinha (1998) detected a biogeographic barrier to deep-dwelling foraminifera between the Indian and Pacific Oceans that originated

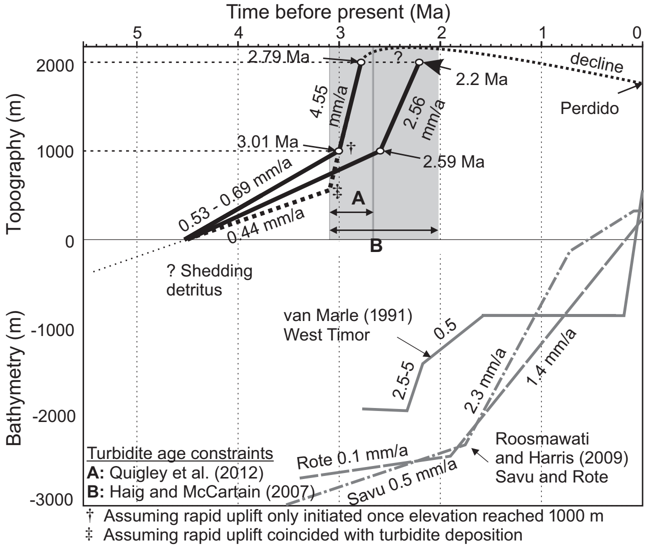

Figure 4. Paleotopographic geohistory for the Viqueque type section (left axis topography), compared with paleobathymetric uplift rates for the Central Basin of West Timor, Rote, and Savu (left axis bathymetry). Perdido—Mount Mundo Perdido (Timor-Leste), representing modern (0 Ma) maximum divide elevations in the source direction (Fig. 1B).

at ca. 5.2 Ma, marking the onset of closure of the Indonesian seaway. Our study has shown that proto-Timor was already shallowing by that time and may have been close to emergence. The uplift of the Timor orogen may therefore have played a role in the development of the Indonesian throughflow, and hence in the cooling of global climate (Cane and Molnar, 2001).

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