T51A-2305

The rise and fall of an arc-continent collisional orogen: insights from synorogenic sediments in Timor Leste

Brendan Duffy[1]*, Mark Quigley[1], Ngoc Nguyen[2], James Shulmeister[2]

[1] University of Canterbury, Christchurch, New Zealand
*structure and sedimentology (brendan.duffy@pg.canterbury.ac.nz)

MARSDEN FUND
TE PŪTEA RANGAHAU A MARSDEN

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Background

Timor Leste, the eastern part of the island of Timor, consists in part of synorogenic, late Miocene to Pleistocene mid-bathyal marine sequences that record the rates (**Panel 1**) and timing of uplift (**Panel 2**) and the subsequent extension (**Panel 3**) of the collisional orogen between the northern Australian continental margin and the Banda arc. Timor is located east of the transition from subduction of Australian oceanic crust beneath the Sunda Shelf to collision of Australian continental crust with the Banda Arc . Australian continental crust moves NNE toward the Banda Arc at ~70 km/Ma relative to the Sunda Shelf. The volcanic arc north of Timor is presently strongly coupled to the Australian plate (Nugroho et al., 2009) and most of the compression is taken up on the young Wetar Thrust (Fig. B1). Nevertheless, uplift over the last 100 ka has been spatially variable (Fig. B2) which has been ascribed to a combination of isostatic rebound, folding and block faulting . In particular, a late phase of extensional faulting, especially obvious within the synorogenic Viqueque Megasequence, has typically been attributed to isostatic rebound over a ruptured slab (e.g. Price and Audley-Charles, 1987).

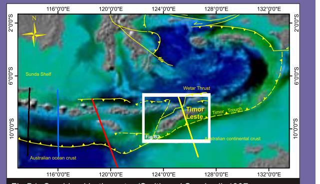
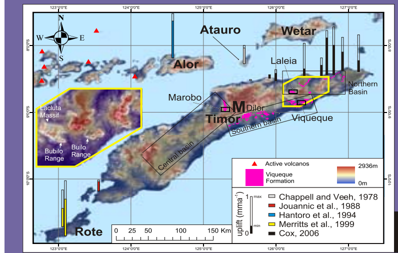


Fig.B1: Combined bathymetry (Smith and Sandwell, 1997 - greener is shallower) and gravity map of the Banda Arc (Sandwell and Smith, 2009 - bluer is more positive). Green areas show thick low gravity sediments, blue areas show deep ocean crust. Turquoise is continental crust.



A number of distinctive fault bounded mountain ranges dominate the topography in eastern Timor Leste (Inset Fig. B2). We investigate the structure and sediments of two synorogenic sedimentary basins abutting the Lacluta Massif to look for clues to the factors governing the topographic development (**Panel 1)**, unroofing (**Panel 2**) and late extension (**Panel 3**) of the Timor orogen. The **Viqueque Basin** lies south of the linear escarpments of the Bibilu and Builo Ranges. The former is a contiguous part of the Lacluta Massif. The Lacluta Massif is bounded to the north by the **Laleia Basin**. We also investigated the **Marobo Basin** in western Timor Leste.

Fig.B2: Digital elevation model showing distribution of topography, Quaternary uplift and the Viqueque Formation in Timor Leste.

1 - Pliocene surface uplift

Vertical zonation of palynology has been used to document uplift of the Tibetan Plateau (eg Dupont-Nivet et al., 2008). We sampled the basal carbonate pelagites and hemipelagic muds of the Viqueque type section for palynomorphs. The floral zonation of these rocks records the surface elevations of the source area (Fig.1.1).

Although turbidite sedimentation does not begin until foraminiferal zone N21, charcoal and pollen concentrations increase right from the base of the sequence, whilst concentrations of lithogenic elements (predominantly Si and Fe) increase at the expense of Calcium (Figure 1.1 - summary concentrations). This suggests that the a landmass was already emergent by 5.53 Ma (Fig.1.2)

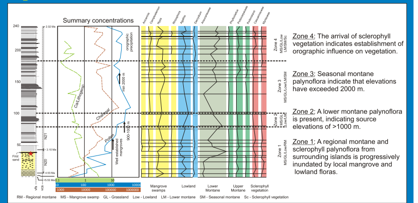


Figure 1.1: Palyno-stratigraphy and zonation of the Viqueque type section

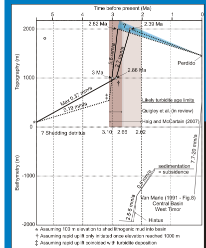


Figure 1.2: Paleotopographic geohistory diagram for the Viqueque type section, compared with paleobathymetric uplift rates for the Central basin of West Timor. Perdido represents modern (0 Ma) maximum elevations in the source direction.

Palynological zones were discriminated by principal component analysis and are illustrated in **Figure 1.1.** Between 91m and 173m above the base of the Viqueque type section, Timor has increased in elevation from c. 1000m to 2000m. From this we calculate surface uplift rates in the hinterland source area of the turbidites.

All calculated uplift rates (Fig. 1.2) assume constant turbidite sedimentation rates. Minimum uplift rates assume deposition of the turbidites across the full time interval of N21 (3.1-2.02 Ma, e.g. Keep and Haig, 2010). The higher uplift rates are based on adopting a U/Pb coral age of 2.66 Ma from the top of the Northern Cuha section as the younger age limit for the type section (**Panel 2**).

Calculated uplift rates vary from 2.7-5.6 mm/a, which is exceptionally fast compared with modern uplift rates of 0-1.6 mm/a determined on the north coast for the last 150kyr (Cox, 2009). It is, however, very much in keeping though slightly earlier than uplift rates calculated for the Central Basin (Van Marle, 1991)

2 - Chronostratigraphic constraints

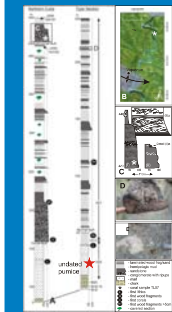


Fig.2.1: (A) stratigraphy of the Northern Cuha and Type Sections of the Viqueque Megasequence in the Cuha River, Viqueque. (B) Location of measured sections (see Fig.3.1 on Panel 3). (C) Vertical and lateral grainsize and thickness variation of the upper conglomerate. Note rapid transition from conglomerate into sandy turbidite with laminated woody fragments at its base. (D) Fossil tree trunk near top of the type section. (E) Insitu Platygyra sample, showing exceptional preservation and setting within coarse lithic dominated conglomerate.

Debris flow deposits in the Viqueque area contain pristine detrital Platygyra corals (Fig. 2.1) that we have dated. A coral from the upper part of the sequence yielded a $^{238}U/^{206}Pb$-$^{207}Pb/^{206}Pb$ concordia age of 2.66 ± 0.14 (2σ) Ma (Fig.2.2A) that is supported by coral $^{87}Sr/^{86}Sr$ chemostratigraphy (Fig2.2D) and foraminiferal biostratigraphy from bounding strata (Fig.2.1A). The ability to date corals beyond the limits of ^{14}C and U/Th techniques improve the resolution of collisional marine chronostratigraphy

Fig.2.3: Pumice sample found just below first lithics. A sample of this size may have floated for <10 years and originated in Mexico, but geochronologically, it provides an instantaneous age control on the host sediment. Age pending....

Our age provides an upper bound of 2.66 Ma on the initiation of turbide deposition at the study site. We are in the process of dating further corals from the basal conglomerate of the Northern Cuha section as well as a pumice from below the first turbidite in the type section (Fig.2.3). These dates will further refine timing and rates of important geodynamic events **(Panel 1).**

Provenance of the turbidite and conglomerate beds in the Northern Cuha section appears to change up-section. Basement clasts in the lowest conglomerate are 100% mafic volcanics, schists and quartz, probably from the Banda Terrane. Clasts in the upper conglomerate, however, although dominantly similar to lower conglomerates (68%), also contain sandstones and mudstones (~20%) and limestone clasts that are faunally consistent with elements of the Gondwana Megasequence (~12%) (David Haig pers comm.). We are presently attempting to substantiate this using detrital zircon geochronology.

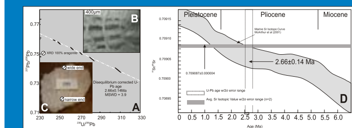


Figure 3: (A) U/Pb isochron for TL07. (B) SEM image of well-preserved primary aragonitic coral skeleton. (C) TL07 sample indicating locations of XRD screening. (D) Marine Sr isotopic curve for the last 6.5 Ma . Horizontal thick grey line represents the average Sr-isotopic ratio obtained from four Platygyra subsamples with 2σ error. Vertical dashed lines denote 2σ uncertainty about the U/Pb age obtained from our sample.

3 - Strike slip and extension

Structural analysis of sediments in the Viqueque, Laleia and Marobo Basins of Timor Leste reveals that the post-collisional phase is dominated by extensional and strike slip deformation.

Viqueque Basin

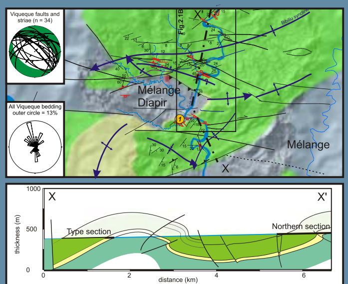


Fig.3.1: Shaded relief DEM and cross section of the Viqueque Basin showing the general distribution of the Viqueque megasequence, mapped structures and study localities.

The southern basin of Timor Leste (Fig.B2) is generally characterised by NE-SW folds with anticline cores of Bobonaro Melange and synclines cored by synorogenic sediments of the Viqueque Megasequence.

In the Viqueque basin, the NE-SW folds are cross-folded in a WNW-ESE orientation, resulting in intrusion of diapirs of the underlying melange into the syncline cores. The melange is rarely stratigraphically concordant in this situation and diapiric activity has resulted in formation of a locally overturned antiformal monocline on the NW side of the diapir. Small scale thrusting is always directed away from the diapir. Cross-folds associated with the diapir parallel the strike of late stage normal faults, suggesting that extension resulted in renewed diapirism. The late normal faults (e.g. Fig. 3.5) are mainly top-down-to-the-northeast, commonly dextral-oblique and have dextrally offset the axial traces of the NE-SW folds

Laleia Basin

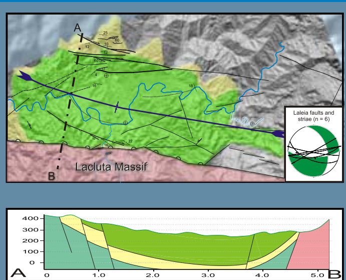
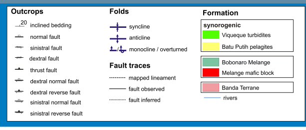


Fig.3.2: Shaded relief DEM and cross-section of the Laleia Basin showing the general distribution of the Viqueque megasequence, mapped structures and study localities.

The Bere syncline of the Laleia Basin in the Northern Basin of Timor Leste was investigated in a short reconnaissance visit. It is a canoe-shaped syncline bounded to the north and south by dextral and dextral normal faults. The southern side of the syncline is down-folded and faulted against the Lacluta massif of the overthrust, Asian-affinity Banda Terrane. Normal faults are found in the Dilor area on the opposite (southern) side of the Lacluta Massif (Fig. D2), suggesting that the massif is a horst block.

NE-SW trending faults appear to be a mix of both dextral and sinistral, which suggests that they operate as basin and range style transform faults.



Marobo Basin

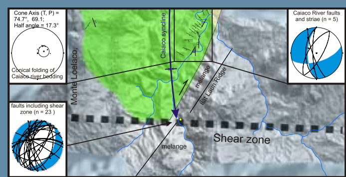


Fig.3.3: Shaded relief DEM of the Marobo Basin showing the general distribution of the Viqueque megasequence, structures and study localities.

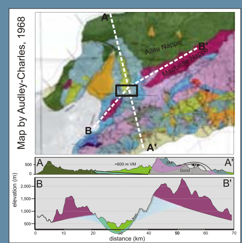


Fig.3.4: Large-scale sub-orthogonal cross-sections through the Marobo basin illustrating the magnitude of throw on the faults bounding the Marobo Basin. Sediments contain detritus of the Lolotoi Metamorphic complex, which would have been structurally above the Maubisse nappe (purple)

The Marobo Basin of western Timor Leste lies at the eastern limits of the Central Basin of West Timor. Reconnoissance of the basin shows that the Caiaco syncline plunges gently but discordantly southwards into outcrop of the Bobonaro Melange and rocks of the Gondwana Megasequence. The southern boundary of the basin, which must be a very large throw normal fault, coincides with a lineament on the DEM. This lineament hosts a dramatic shear zone within the melange that yields top-down to the NW sense normal faults that would interact in a dextral sense with the eastern boundary fault. Along strike of the shear zone to the west, the shear zone lineament appears to truncate the southern end of the Monte Loelaco strike ridge of Gondwana limestone. Eastwards, it intersects the Ilat Laun ridge. This intersection is marked by a zone of hot springs.

The eastern limb of the syncline is strongly discordant with the Ilat Laun Ridge and is conically re-folded along its eastern boundary in an manner consistent with NE-SW dextral normal shear (e.g. Alexander, 1995) parallel to the ridge. This is in agreement with dextral shear on minor oblique faults exposed in the Caiaco River. Larger scale cross sections suggest that the Marobo Basin is a deep pull-apart basin with very large throws to the east, west and south.

Fig.3.5: Photo towards the southeast of listric normal faults at locality 1, Fig. 3.1, near the base of the Viqueque type section. Extension direction toward the NE

References

Afonso, J. C., and S. Zlotnik (2011), The Subductability of Continental Lithosphere: The Before and After Story, in *Arc-Continent Collision*, edited by D. Brown and P. D. Ryan, pp. 53-86, Springer Berlin Heidelberg.
Bowin, C., G. M. Purdy, C. Johnston, G. Shor, L. Lawver, M. S. Hartono, and P. Jezek (1980), Arc-continent collision in the Banda Sea region, *American Association of Petroleum Geologists Bulletin*, *64*, 868-918.
Chappell, J., and H. H. Veeh (1978), Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island, *Geological Society of America Bulletin*, *89*(3), 356-368.
Cox, N. L. (2009), Variable uplift from Quaternary folding along the northern coast of East Timor, based on U-series age determinations of coral terraces, MSc thesis, 151 pp, Brigham Young University, Salt Lake City.
Dupont-Nivet, G., C. Hoom, and M. Konert (2008), Tibetan uplift prior to the Eocene-Oligocene climate transition: Evidence from pollen analysis of the Xining Basin, *Geology*, *36*(12), 987-990.
Ely, K. S., M. Sandiford, M. L. Hawke, D. Phillips, M. Quigley, and J. E. d. Reis (2011), Evolution of Ataúro Island: Temporal constraints on subduction processes beneath the Wetar zone, Banda Arc, *Journal of Asian Earth Sciences*, *41*(6), 477-493.
Hantoro, W. S., et al. (1994), Quaternary uplifted coral reef terraces on Alor Island, East Indonesia, *Coral Reefs*, *13*(4), 215-223.
Harris, R. (2011), The Nature of the Banda Arc–Continent Collision in the Timor Region, in *Arc-Continent Collision*, edited by D. Brown and P. D. Ryan, pp. 163-211, Springer Heidelberg, Berlin.
Herrington, R. J., P. M. Scotney, S. Roberts, A. J. Boyce, and D. Harrison (2011), Temporal association of arc-continent collision, progressive magma contamination in arc volcanism and formation of gold-rich massive sulphide deposits on Wetar Island (Banda arc), *Gondwana Research*, *19*(3), 583-593.
Jouannic, C., C. T. Hoang, W. Soepri Hantoro, and R. M. Delinom (1988), Uplift rate of coral reef terraces in the area of Kupang, West Timor: Preliminary results, *Palaeogeography, Palaeoclimatology, Palaeoecology*, *68*(2-4), 259-272.
Keep, M., and D. W. Haig (2010), Deformation and exhumation in Timor: Distinct stages of a young orogeny, *Tectonophysics*, *483*(1-2), 93-111.
Merritts, D., R. Eby, R. Harris, R. L. Edwards, and H. Chang (1998), Variable rates of Late Quaternary surface uplift along the Banda Arc- Australian plate collision zone, eastern Indonesia, in *Coastal tectonics*, edited by I. Stewart and C. Vita-Finzi, pp. 213-224, Geological Society Special Publication.
Nugroho, H., R. Harris, A. W. Lestariya, and B. Maruf (2009), Plate Boundary Reorganization in the Active bandA Arc-Continent Collision: Insights from New GPS Measurements, *Tectonophysics*, *479*(1-2), 52-65.
Price, N. J., and M. G. Audley-Charles (1987), Tectonic collision processes after plate rupture, *Tectonophysics*, *140*(2-4), 121-129.
Sandiford, M. (2008), Seismic moment release during slab rupture beneath the Banda Sea, *Geophysical Journal International*, *174*(2), 659-671.
van Marle, L. J. (1991), Late Cenozoic palaeobathymetry and geohistory analysis of Central West Timor, eastern Indonesia, *Marine and Petroleum Geology*, *8*(1), 22-34.

Discussion

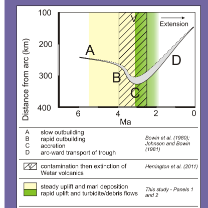


Fig. D1: Temporal changes in the position relative to the Banda Arc of the Timor Trough south of Timor Leste (modified from Bowin et al., (1980). Grey area indicates uncertainty based on Bowin et al.'s erroneous convergence vectors. Superimposed are timings of key events.

Proto-Timor was already emergent by 5.53 Ma (Panel 1). This early landmass probably represents the initial stages of uplift and outbuilding of the outer arc high as a thick package of continentally derived sediments entered the subduction zone (Fig. D1-A). The rate of outbuilding increased (Fig. D1-B) as large volumes of ocean sediment/continental material were subducted and accreted. Some continental material eventually reached magma-genic depths and led to a rapid geochemical change in the Wetar and Atauro volcanics at around 4.7 Ma (Ely et al., 2011; Herrington et al., 2011) (Fig. D1-V).

Uplift was not a function of thickening. Crustal thickening south of Timor Leste was virtually complete by ~3 Ma when seismic surveys indicate that convergence across the trough virtually ceased (Fig. D1-C). Surface uplift rates were low (0.2-0.3 mm/yr) during this thickening phase **(Panel 1)**. When the Timor Trough began to move with the Australian continent at ~3Ma (Fig. D1-D), terrestrial uplift rates accelerated to 2.7-5.6 mm/yr, culminating in development of a 2-3000 m mountain range northeast of the Viqueque basin and resulting in deposition of the Viqueque debris flows and turbidtes until at least 2.66 Ma **(Panel 2)**.

Uplift was probably driven by crustal delamination. Marine facies migration data (Veevers et al. 1978) suggests that convergence may have slowed by ~80% prior to accretion of the Wetar segment of the Banda Arc. Such dramatic convergence velocity reductions commonly occur due to and/or result in mechanical delamination of the lithospheric crust and mantle (e.g. Afonso et al., 2011). This results in cessation of magmatism due to subduction of dry continental lithospheric mantle. Moreover, an 80% velocity reduction is within 10% of that required to rupture the slab by necking (Afonso et al., 2011), and is likely to be even more favourable to rupture by lateral tear (eg Sandiford, 2008).

Post-collisional deformation is dominated by extensional and strike slip deformation related to the interplay between topographic and buoyancy forces and a dynamically evolving tectonic stress field.
The Banda arc and forearc have responded to collision by shortening in the convergence direction, whilst simultaneously elongating parallel to the orogen. Extension in the eastern half of Timor Leste develops as northeastwards-directed dextral oblique normal shear expressed as a basin and range style of rifting (Fig. D2). The sinistral normal Laclo Fault (Harris, 2011) appears to form the western boundary. The Lacluta massif is an isolated horst block and the other large massifs that dominate the skyline of eastern Timor Leste probably have a similar origin.

The massif distribution invites palinspastic reconstruction of a coherent massif and suggests that the areal extent of Timor is probably now signficantly larger than it was previously due to eastward extrusion. The Viqueque source area is certainly lower than the 2-3000 m that existed NE of the Viqueque basin immediately post-collision.

The Marobo Basin, and presumably its western counterpart, the Maliana Graben, developed by northwestwards extension. The two extension directions are both oriented towards the closest zones of ongoing subduction (Fig. D2), which supports a tectonic escape interpretation.

Rapid uplift rates within the proposed rift zone (Fig. B2) may result from active folding of the rift under residual compression (eg Harris, 2011), isostatic uplift of horst blocks, or possibly due to incipient or recent slab rupture (e.g. Sandiford, 2008).

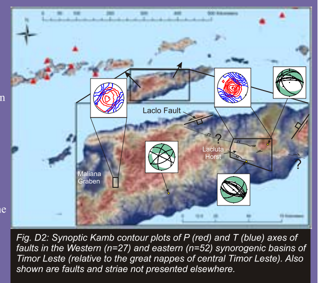


Fig. D2: Synoptic Kamb contour plots of P (red) and T (blue) axes of faults in the Western (n=27) and eastern (n=52) synorogenic basins of Timor Leste (relative to the great nappes of central Timor Leste). Also shown are faults and striae not presented elsewhere.

Acknowledgements

This work was supported by a Royal Society of New Zealand Marsden grant to Quigley and a Tertiary Education Commission Top Achiever scholarship to Duffy. B.D.'s fieldwork benefited from associations with Louise Moody, Aaron Benincasa, Ron Harris, Douwe van Hinsbergen and Richard Bakker. We thank them for their support but note that this does not imply their agreement with our findings. Thanks are due to the administration and field staff of the Timor Secretary of State for Natural Resources (SERN). The wonderful assistance of Jhony Rheis, Jhony Suares, Lamberto Fernandes, Andy Monteiro, Atino Varela and Nabe is greatly appreciated.