Geology and geomorphology of the Timor Trough and relevance to Timor-Leste’s maritime boundary

Brendan Duffy

Mike Sandiford

The University of Melbourne

Author Note

Duffy and Sandiford received no payment from the Government of Timor-Leste for this submission

Duffy, B., Sandiford, M., 2017, *Geology and geomorphology of the Timor Trough and relevance to Timor-Leste’s maritime boundary*. Submission to the Conciliation Commission of the United Nations Permanent Court of Arbitration.

Contents

1 Executive Summary

This submission presents a review of scientific evidence and interpretations concerning the geology of Timor and the islands of the Banda Arc, and the geology of the Timor Trough. It explores the tectonic plate boundary significance of the Timor Trough relevant to certain territorial claims in the Timor Sea. We begin by explaining the general tectonics and geomorphology of the Banda region, focusing on the evolving nature of the plate boundary in the adjacent Savu region, as an analogue for a young Timor. We explain how the Timor Trough south of Savu does not mark the trace of a subduction zone, and that the trace of the old subduction zone is presently buried under a rapidly developing fold and thrust belt. We point out how the rocks on Savu are rocks that are equivalent to the NW shelf, from where they were sourced.

We then consider Timor, outlining similar lines of evidence, but with the addition of geophysical insights including paleomagnetism, gravity and seismic reflection surveys. Each ties the rocks of Timor back to the NW shelf. The seismic reflection surveys show that unlike the true continental shelf edge of the Exmouth Plateau, the Timor Trough is not a shelf edge at all, but a down-warp in the continental shelf that results from the load of the Timor fold and thrust belt.

We conclude that the Timor trough is best explained as a foredeep located within the Australian continent, rather than a continuation of the active subduction zone along the plate boundary that defines the northern limit of the Australian Plate. Geological contrasts, geodetic data, and the distribution of natural seismicity all place the active boundary of the plate as a diffuse zone that begins close to the Timor Trough in Savu and progressively transfers northwards to lie predominantly along the Wetar Thrust, to the north of Timor Leste.

In sum, we do not see a tenable geological case for considering that the Timor Trough is a fundamental northern boundary of Australian continental crust.

2 Background

The maritime boundary dispute between the governments of Timor-Leste and Australia hinges in part on the scientific interpretation of the Timor Trough, a linear bathymetric low that extends from south of Sumba, eastwards between Timor and Australia before curving north towards Papua New Guinea (Figure 1). The Timor Trough has generated major questions about the timing of its formation, its present-day activity, and its importance (if any) as a plate boundary structure. Whilst many questions remain, particularly about its seismic potential, a wealth of data has accumulated since the late 1970s that provide insight into its plate boundary significance and this can be brought to bear in the present case.

The Australian government argue that the Timor Trough constitutes a break in the continental shelf, thus situating the countries of Timor-Leste and Australia on separate continental shelves. Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS) states that

> *"the continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin".*

By asserting that the Timor Trough separates two continental shelves, the Australian argument implies that the Timor Trough marks (i) the outer edge of the Australian continental shelf in the Timor Sea, as defined under Article 76, and (ii) that the Timor Trough is a tectonic plate boundary between two separate continental shelves that delimits the northern edge of the Autralian plate. The alternative is that the Timor Trough is not a plate boundary, but is entirely contained within, and superposed on the Australian continent, having formed in response to the collision process. In this submission, we present evidence concerning 1) the nature and evolution of the Australian plate boundary in the vicinity of Timor, and 2) the plate boundary significance of the Timor Trough.

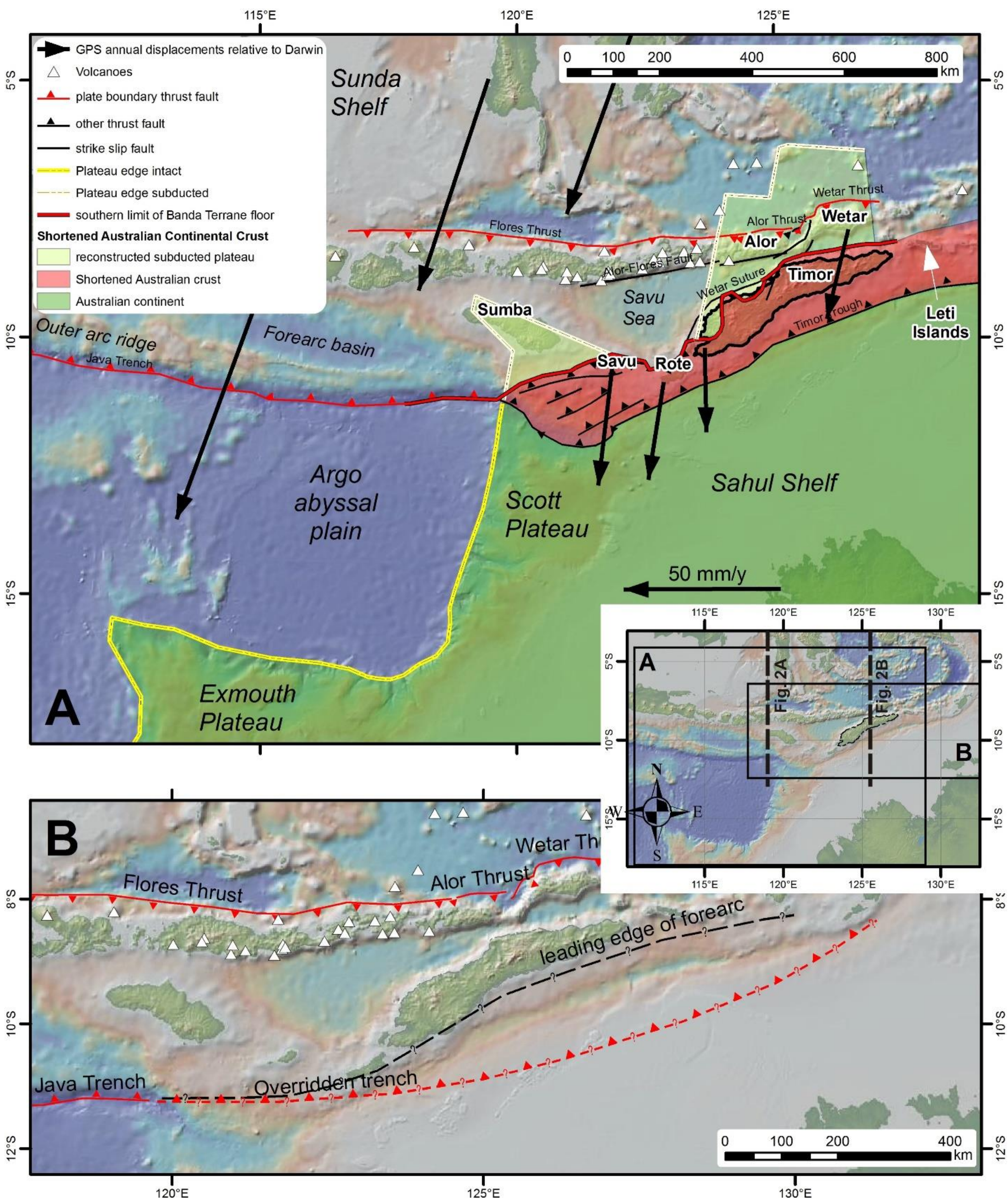
GPS annual displacements relative to Darwin
Volcanoes
plate boundary thrust fault
other thrust fault
strike slip fault
Plateau edge intact
Plateau edge subducted
southern limit of Banda Terrane floor
Shortened Australian Continental Crust
reconstructed subducted plateau
Shortened Australian crust
Australian continent
Sunda Shelf
Flores Thrust
Alor-Flores Fault
Alor Thrust
Wetar Thrust
Wetar
Alor
Wetar Suture
Timor
Timor Trough
Leti Islands
Savu Sea
Sumba
Savu
Rote
Outer arc ridge
Java Trench
Forearc basin
Argo abyssal plain
Scott Plateau
Sahul Shelf
Exmouth Plateau
50 mm/y
A
Fig. 2A
Fig. 2B
B
B
Flores Thrust
Alor Thrust
leading edge of forearc
Java Trench
Overridden trench
0 100 200 400 km
0 100 200 400 600 800 km

Figure 1. Previous page – A) Regional geology of the Banda Arc and Timor Sea area. GPS vectors[1] shown relative to Darwin. Northern extent of the Timor Plateau is a minimum estimate based on balanced geological sections of Tate and others (Tate 2014; Tate et al. 2015), drawn to adhere to the rectilinear passive margin geometry of the Scott and Exmouth Plateaus. The subducted Scott Plateau and generalized geology of the Sumba-Savu-Rote area is based on surficial geology and well interpretation (Harris 1991; Fortuin et al. 1997; Harris et al. 2009; Roosmawati & Harris 2009), and seismic investigations of the Savu Sea (Rigg & Hall 2012) and Java Trench-Timor Trough transition (Shulgin et al. 2009; Planert et al. 2010). The southern limit of the [contiguous] Banda Terrane (Asian basement and cover rocks) on Timor [excluding structurally isolated klippe] is based on numerous onshore maps of the island including but not limited to Indonesian maps of West Timor (Rosidi et al. 1981) and the 1968 map of Audley-Charles (1968) supplemented by more recent mapping by many parties including The University of Melbourne (Ely et al. 2011; Duffy et al. 2013; Ely et al. 2014; Boger et al. 2016). The extent of shortened Australian continental crust east of Timor and the Leti Islands is based on maps included with studies of the metamorphic rocks in that region (Ishikawa et al. 2007; Kaneko et al. 2007; Kadarusman et al. 2010), and references therein. B) Detail of the Timor area, showing the probable pre-collisional trace of the [now overridden] trench. The trace is drawn to link active subduction at the Java Trench with the subduction east of Timor, with minimum curvature. The leading edge of the forearc would have originally been close to the position of the trench but has been driven northwards as the Australian Timor Plateau and Sahul Shelf collided with the trench (Audley-Charles 2004). ***This map shows that the Timor Trough does not coincide with the leading edge of the Asian forearc, or with the original location of the trench. It passes between the two, and is the trace of an intracontinental thrust located >300 km inboard of the Australian continental margin.***

3 The evolution of the plate boundary in the Timor region

3.1 General geology and tectonics

The geology of the Timor region is a complex and globally important geological example of an early stage continent–arc "collision (Harris 1991; Nugroho et al. 2009; Shulgin et al. 2009; Ely & Sandiford 2010; Planert et al. 2010; Harris 2011; Porritt et al. 2016). To the west of Sumba, at about 120°E, the boundary between Australian and Asian plates in Indonesia is marked by a subduction zone where the Argo abyssal plain of the subducting Australian Plate slides under Indonesia at the Java Trench (Figure 1A). As the Australian plate ocean crust sinks (or subducts) into the mantle, it releases water that causes partial melting of the upper plate and gives rise to the Indonesian volcanic arc, ~300 km north of the Java subduction trench (Wheller et al. 1987).

To the west of Sumba, the Java trench and the Indonesian volcanic arc are separated by several clear bathymetric features that are characteristic of subduction complexes. The trace of the plate boundary is marked by the line of active subduction along the deepest part of the Java trench. To the south of the trench, the Argo abyssal plain is underlain by old oceanic crust with a crustal thickness of about 8-9 kilometres (Planert et al. 2010). Between the trench and the volcanic arc, the outer arc ridge marks the northern limit of the accretionary prism. This accretionary prism is a geological domain formed from mostly sedimentary material scraped off the leading edge of the Australian plate as it subducts, and accreted to the overriding Asian tectonic plate. The accretionary complex reaches a thickness of about 15 km beneath the outer arc rise (Shulgin et al. 2009; Planert et al. 2010). Between the outer arc high and the volcanic arc lies a deep basin, known as a forearc basin, formed by the accumulation of sediments eroded primarily off the volcanic arc. The crustal thickness beneath the forearc basin is about 20-30 kms thick, including both basement and cover sediments.

The Java trench ends south of Sumba. At that point the bathymetry shallows rapidly. A distinct bathymetric depth anomaly deflects 120 km southeast before connecting to the NE-trending Timor Trough. The line of volcanoes continues eastwards (Figure 1) as the Banda Arc and includes the active volcanoes of Flores, Pantar and western Alor, to the north of West Timor, and the extinct volcanic islands of central and eastern Alor, Atauro and Wetar immediately north of Timor Leste. East from Sumba, a topographic high is associated with a second, outer, non-volcanic arc of continental material, including Timor, that occupies a forearc position between the volcanic arc and the Timor Trough (Von Der Borch 1979). The Savu sea forearc basin is terminated to the south by the ridge segment that runs between the islands of Sumba and Rote (the Sumba-Savu-Rote Ridge).

This ridge marks a complex transition, and its south side marks the start of the Timor Trough. The crustal thickness of the subducting Australian Plate in this area increases eastward by nearly 4 km, from about 9 km thick to about 13 km thick (Planert et al. 2010), as the ocean crust of the Argo abyssal plain gives way to the continental crust of the Scott Plateau.

The nature of the Scott plateau is important. It consists of hyper-extended continental crust that subsided after breakup in the Jurassic/Cretaceous and was subsequently modified by deposition of sediments sourced from Australia and from open ocean (pelagic) sedimentation (Falvey & Veevers 1974; Stagg et al. 2004). Its shape, and that of the adjoining Exmouth Plateau is greatly influenced by the pattern of rifts and transform (linking fault) offsets that developed during the breakup. The shape of the continental margin and the relative motion of Australia and Asia (Fig.1) result in oblique convergence of the leading edge of the Australian continental crust. This means that, with progressive convergence, the transition zone in the vicinity of Sumba is progressively moving westwards (Harris 1991). This important insight allows us to use the manifestation of progressive westward younging of collision as a proxy for the sequence of events in any specific, older location, such as in Timor. This notion has been promoted in several interpretations, including those of Harris, who proposed that the Scott Plateau had been partly subducted in order to explain the timing of island emergence in the forearc region between Timor and Sumba (1991). Harris' interpretation is supported by further surface mapping in Savu and Rote (Harris et al. 2009; Roosmawati & Harris 2009), deep crustal seismic investigations across the Java trench transition to the Timor Trough (Shulgin et al. 2009; Planert et al. 2010) and upper crustal seismic investigations in the Savu Sea and over the Sumba-Rote Ridge (Karig et al. 1987; Rigg & Hall 2012). Consequently, the Savu region provides an appropriate analogue for what happened in the early stages of collision between a continental plateau of the Australian NW shelf and the Banda forearc in the vicinity of Timor.

GPS data provide a key insight into the active kinematics in complex regions where plate boundaries are diffuse, such as the region across the Savu Sea and Timor. The change from subduction to collision is reflected in the velocities of GPS stations in the region. The Sunda Shelf in eastern Indonesia is currently moving SSW at rates of ~70 mm/yr relative to the Australian continent (Nugroho et al. 2009; DeMets et al. 2010). Where Australia collides with the forearc, it drives the arc northward along the backarc Wetar Thrust (Silver et al. 1983; Breen et al. 1989; Genrich et al. 1996; Snyder et al. 1996b) and the movement of the volcanic arc relative to Australia slows to less than 20 mm/yr across the Timor-Leste region. This GPS data shows that the outer and inner arc islands of Timor, Wetar and Alor are now strongly coupled to Australia (Figure 1) (Genrich et al. 1997; Kreemer et al. 2000; Bock et al. 2003; Nugroho et al. 2009), with everything south of the Wetar Thrust more effectively travelling with Australia. The coupling of Australia with the volcanic arc declines westward toward the subduction-collision transition (Nugroho et al. 2009), and reduces to background convergence rates west of Sumba. In essence, the GPS data reveal a diffuse plate boundary that is not a single linear feature but a progressive zone of strain transfer, from the Java Trench to the Wetar Thrust. This is common to many plate boundaries, such as the Marlborough fault system of the South Island of New Zealand (Little & Roberts 1997; Little & Jones 1998). The November 2016 M_W7.8 Kaikoura earthquake ruptured a mesh of faults across a plate boundary zone more than 100 km wide (Hamling et al. 2017). Some of those faults slip very rarely, while others slip every century and a half. We envisage a similar situation in the Timor region, with some localized strain on major faults and much distributed strain on a mesh of less active faults.

The argument above implies that seismicity provides another important guide to the nature of structure that accommodates the ongoing deformation between the Australian and Asian plates. Tectonic plate boundaries typically display clear patterns of seismicity that reveal the structure of the interacting plates, and the shape of any subducting plates.

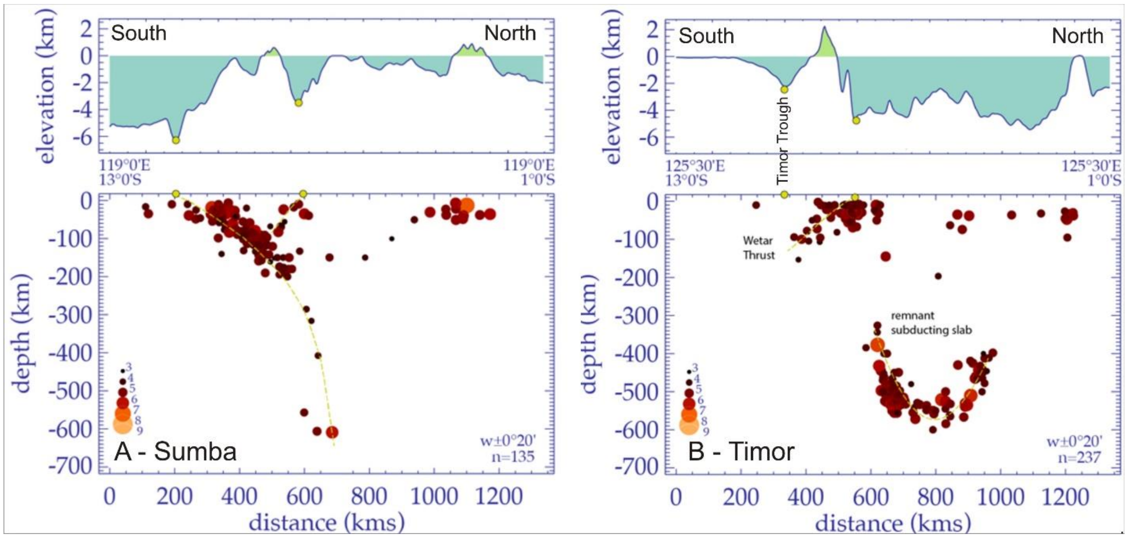

Figure 2. N–S sections using 0.8°-wide bins across segments of the Indonesian slabs using the CIR catalogue. Sections compare the distribution of seismicity at A) Sumba (young collision) and B) Timor (old collision). Top figures show topography profiles along the seismicity sections. The Sumba section shows near continuous seismicity down to the base of the slab, and a high level of activity in the outer arc ridge. The Timor section highlights a lack of intermediate depth seismicity and a clustering of shallow seismicity on the Wetar Thrust. Note the lack of a north dipping cluster of earthquakes associated with the Timor Trough.

Historical catalogues show the Sumba to Timor region to be very heterogeneous in its seismicity. A relatively typical pattern is observed in the Sumba region (Fig. 2A), which features a zone of seismicity that is located on the subduction interface beneath the forearc, and a subducting slab that is seismically active to depths >600 km. In the Timor region (Fig. 2B) intermediate depth seismicity is largely absent beneath the extinct Wetar volcano. Relatively infrequent shallow seismicity occurs mostly on reverse faults such as the Wetar Thrust in the back-arc region. The gap in intermediate seismicity is consistent with rupture (tearing) of the subducting slab (Sandiford 2008; Ely & Sandiford 2010). If the slab is ruptured, the pull of the slab is negated and any convergence across the Timor Trough must slow and stop and there certainly appears to be little ongoing convergence based on GPS surveys (Genrich et al. 1996; Kreemer et al. 2000; Bock et al. 2003; Simons et al. 2007; Nugroho et al. 2009; Koulali et al. 2016). This is consistent with seismic reflection studies that indicate that the plate boundary in Timor has largely been transferred to the Wetar Thrust (Silver et al. 1983; Breen et al. 1989; Masson et al. 1991; Snyder et al. 1996b).

3.2 The Savu Region as an example of a young Timor Trough

Recent work in Timor (Duffy et al. 2017) supports earlier suggestions (Harris 1991) that the Savu region is a good analogue for how early Timor would have evolved. The islands of Savu and Rote are formed of weak sandstones and mudstones of the Babulu and Wai Luli Formations (Harris et al. 2009) that are equivalent to and correlated with Mesozoic rift-related units of the Australian continental margin (Charlton 1989). These Australian continental rocks are thrusting northward over the forearc crust, forming an elevated southern boundary to the Savu Sea forearc basin, where young sediments are accumulating on Banda forearc crust (Harris et al. 2009; Rigg & Hall 2012). A drill hole on Savu intersected the forearc crust about1.2 km below the surface (Harris et al. 2009).

Triassic/Jurassic rocks overlying the Savu-Rote forearc are older than the eruption age of the youngest metamorphosed igneous rocks of the Banda Terrane (Harris 2006; Standley & Harris 2009), and were therefore not simply deposited on top of the Banda Terrane. In fact, biogeographic affinities of Jurassic radiolarians of the Wai Luli Formation shales on Rote suggest that during that time, Rote was probably located in a low latitude realm on the southern margin of the Tethyan Ocean (Sashida et al. 1999), a position occupied by the northern edge of the Australian continent.

The Mesozoic rocks on Rote (Roosmawati & Harris 2009) and possibly also on Savu (Harris et al. 2009) are intercalated by faulting with Cretaceous and

Tertiary rocks of the manganiferous, cherty Nakfunu/Ofu Formations. Sawyer (1993) considered the Nakfunu Formation of West Timor to be correlative with elements of the Bonaparte Basin Darwin Formation, and Roosmawati and Harris (2009) suggested that the Rote equivalents accumulated on the Australian continental slope. These young, Australian-affinity rocks, which are generally equivalent to the world-class manganiferous rocks of Groote Eylandt, are found only on the north side of Rote, because they have been overthrust from the south by Australian rift basin rocks. This virtually precludes the possibility that the Mesozoic rocks were on the north side of the rift and collided with Asia much earlier, and reinforces their origin on the Australian side of the Tethys Ocean.

The Australian rocks exposed on Savu and Rote have been emplaced northwards over the top of the forearc basement. Superficially, this resembles an accretionary prism, for which the Timor Trough would be the trench. However, the overthrust rocks are not the thin sediments that are scraped off the oceanic crust further west, but rocks of the continental crust of the Australian northwest shelf. In contrast, the rocks exposed on Sumba are forearc rocks (Fortuin et al. 1997), lifted up above the partly subducted Scott Plateau (Figure 1). The same Cretaceous clastic units are present below Savu as are exposed on Sumba (Harris et al. 2009), indicating that forearc basement is present below Savu and that the present surface trace of the boundary between Australian and Banda crust lies between Sumba and Savu (Figure 1).

Mud volcanoes provide insight to what lies beneath that forearc basement. Savu mud volcanos contain blocks of limestone with a distinctive fauna of crinoids from the Carboniferous to Permian (Paleozoic) Maubisse Formation (Harris et al. 2009). The Maubisse Formation was formerly assigned to the Asian margin of the Tethys Ocean (Audley-Charles 1968; Carter et al. 1976), but subsequently reassigned to the Gondwanan margin on the basis of its brachiopod fauna (Bird & Cook 1991). The Maubisse Formation was not found in the drill hole, or in the surface geology, so must lie below the forearc, from whence it is carried by mud volcano fluids.

The observations above indicate that the feather edge of the Indonesian forearc has sliced into the Australian continent, subducting the lower levels of the stratigraphy and allowing the uppermost continental crust to thrust northwards over the forearc. This situation is shown in a sandbox model available online (Harris et al. 2009) and illustrates the complexity of a plate boundary in a collision zone, even at early stages. The stacking of thrust sheets of Carboniferous to Triassic Australian rocks below the forearc, the draping of the forearc over these, and the thrust stacking of Mesozoic to Cenozoic Australian rocks above the forearc, creates a substantial topographic load and bends down the northern edge of Australia. The Timor Trough in the Savu region is simply a bathymetric divide between the bent down, relatively undeformed Australian Sahul Shelf and the topographically elevated piles of stacked rocks that form Savu and Rote. The Timor Trough south of Savu evolved from a subduction plate boundary, but is not a subduction zone plate boundary (Audley-Charles 2004).

3.3 The Australian affinity of the Timor fold and thrust belt

Timor differs from Savu-Rote in several key ways that are largely a matter of temporal and spatial scale. Rote island only emerged above sea level about 0.3 Ma (Roosmawati & Harris 2009) and Savu less than 1 Ma, following the initiation of plateau collision prior to 1.6-1.7 Ma (Harris et al. 2009). In contrast the collision in Timor began prior to 4.5 Ma, when Timor first emerged as an island, and may have begun as early as 8 Ma (Berry & McDougall 1986; Keep & Haig 2010; Tate et al. 2015). The age of collision is reflected in the geological complexity of Timor, which is greater than that of Savu or Rote. Timor's complexity is partly a result of the magnitude of uplift since the onset of collision (Nguyen et al. 2013). Rapid and prolonged uplift has resulted in prolonged erosion that has exposed the underplated Australian continent throughout much of the island (Figure 3), and landsliding has obscured much of the structural context. Few places remain where contiguous Banda Terrane is preserved on shore in Timor, and those are primarily in the western part of the island. In Timor-Leste, only isolated exposures of Banda Terrane remain south of the Wetar Strait (Figure 1A). These occur as one contiguous thrust sheet in the Ocussi enclave in West Timor, and a few examples of both klippe (Harris 1991; Tate et al. 2015) and horst blocks (Duffy et al. 2013).

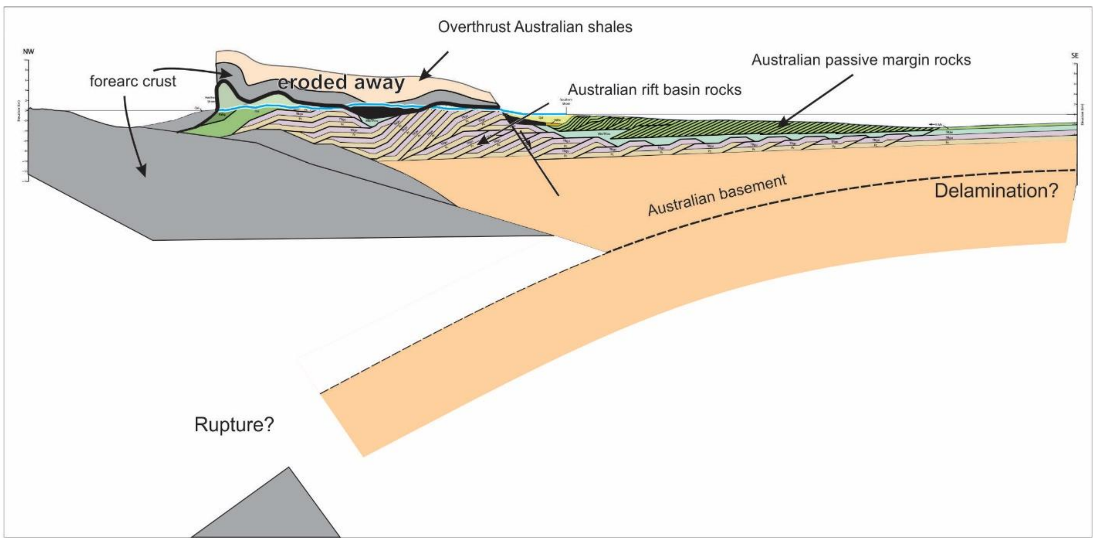

Figure 3. Section across Timor modified from Tate et al. (2015). The black shows areas of uneroded forearc remaining on Timor Leste. Blue line is topography. This section highlights the extent of Australian rift basin rocks on Timor. Presently anything below 15 km is speculative; Slab rupture, delamination and continental subduction have all been proposed.

Despite these differences, and despite its relative complexity, Timor's geology can also be best explained if the feather edge of the Indonesian forearc has sliced into the Australian continent (Duffy et al. 2017), subducting the lower levels of the stratigraphy and allowing the uppermost continental crust to thrust northwards over the forearc. Banda Terrane rocks are present at >1 km depth below Australian rocks in the Cota Taci-1 exploration well off the south coast of Timor (Charlton 2002) (Figure 3), where it has not been uplifted and eroded. The remaining scraps of forearc in the orogenic wedge make up a very small part of its volume. The bulk of Timor's rocks are similar to Savu-Rote in that they consist of Paleozoic to Cenozoic rocks that display a strong affinity with the rocks of the NW shelf. The interpretation of Timor's geology as equivalent to a shortened Australian outlying plateau is supported by multiple lines of evidence, and has influenced the naming of the large-scale rock sequences on Timor (the Gondwana and Australian Passive Margin Megasequences (Haig & McCartain 2007)). Some of the strongest evidence is detailed below.

A pre-collisional association between the Banda Terrane and the Gondwanan rocks can be reliably discounted. Firstly, as stated above, the Banda Terrane is too young to be Australian basement (Harris 2006; Standley & Harris 2009). Secondly, the Banda Terrane on Timor displays a history of exhumation (coming to the surface as a result of erosion or faulting) that is quite incompatible with the Cenozoic history of the Gondwana Megasequence over the last 40 Myr (Harris 2006; Tate et al. 2014). The Gondwanan rocks cannot therefore have been part of the Banda Terrane during that period of time and must therefore have been part of the NW Shelf.

In 1989, Charlton (1989) presented a stratigraphic correlation across the Timor Trough for the express purpose of demonstrating that southern Timor (the Kolbano area of West Timor) had been attached to the Australian continent. The correlation, and thus the period of attachment, encompassed the entire period between the intracratonic rifting of Gondwana that began in the Permian and ultimately led to the opening of the NeoTethys, and the post-rift sequence that accumulated following rifting and continued accumulating right up to the time of the Neogene closure of the Tethys and collision with the forearc of the Indonesian volcanic arc.

No reconstructions since 1989 have placed the entirety of Timor anywhere other than on the northern margin of Australia, (e.g. Fig. 4) (Metcalfe 2013). Its position there is borne out by the thickness and facies-age relationships of the

Timor stratigraphy (Charlton 1987,1989; Charlton & Suharsono 1990; Charlton et al. 1991; Charlton & Wall 1994; Charlton 2000; Charlton 2001; Charlton et al. 2002; Haig & McCartain 2007; Charlton et al. 2009; Tate 2014; Benincasa 2015; Tate et al. 2015), which are consistent with equivalent units on the NW shelf (Petkovic et al. 2000) and Exmouth Plateau (Mutter & Larson 1989; Exon et al. 1994; Stagg et al. 2004), but completely inconsistent with the stratigraphy of the Banda Terrane.

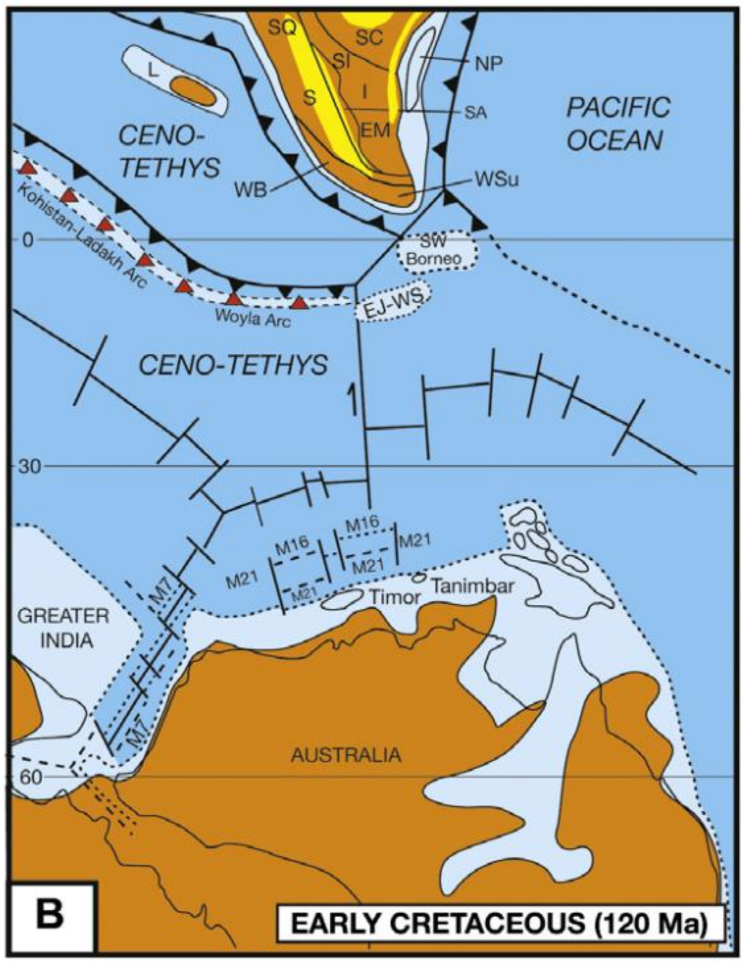

Fig. 4. 2013 reconstruction of the Early Cretaceous Paleogeography of Australia (Metcalfe 2013), showing the position of Timor in the shallow seas (light blue) of Australia's continental shelf.

The robustness of the correlation between Timor and the NW shelf goes beyond correlating rock types and ages. Paleo-environments suggest that Timorese Gondwanan rocks were part of an outlying continental plateau of the NW Shelf. The Exmouth Plateau and the Mesozoic rocks of Timor show comparable deepening of their paleobathymetry as a result of subsidence during the Cretaceous (Keep & Haig 2010). Shales exposed onshore in Timor also contain a molluscan fauna that is not otherwise found outside the contiguous Australian shelf. Until the biogeography of these organisms is rewritten, these rocks must be considered part of the Australian continental shelf (Haig & McCartain 2007; Keep & Haig 2010).

Geophysical data also support consideration of Timor as an extension of the NW Shelf. Paleomagnetism of Permian rocks on Timor show close agreement with equivalent age rocks in Australia (Chamalaun 1977), suggesting that they were stratigraphically continuous with the Australian NW shelf prior to collision (Chamalaun & Grady 1978), rather than on the opposing rift margin as would be required if they were part of Asia during the Cenozoic.

Gravity measurements across the Timor Trough reinforce this message (Snyder et al. 1996a). A strong negative gravity feature is associated with the southern slopes of the Timor orogen that is not compatible with a subduction trench. The gravity low suggests that the thin young sediments on the Timor slope are underlain by anomalously thick older sediments or continental crust, rather than dense forearc basement (Figure 3). This geophysical evidence for anomalously thick and buoyant crust was interpreted to imply that a

> *"local promontory in the irregular boundary of the Australian craton was underthrust beneath the volcanic arc and forearc, to a depth of 50-70 km, or a Paleozoic basin similar to the nearby Bonaparte Basin was underthrust and its former crustal structure inverted and thickened to form buoyant continental crust. (Snyder et al. 1996a)"*

This interpretation echoed that of Harris (1992) and presaged several subsequent interpretations (Charlton 2000; Keep & Haig 2010; Duffy et al. 2013). Recent balanced sections have reinforced the concept of a 300 km wide subducted plateau, off which the top 4 km (the thickness of the Exmouth Plateau) has been scraped (Tate 2014; Tate et al. 2015) (Figure 3). The reconstructed extent of that plateau is shown in Figure 1A, and shows that the Timor orogen is equivalent to folding and thrusting the entire distance from the Timor Trough to the Australian coastline. The length of the plateau requires that it should have reached magma generation depths, and thus be recorded in the geochemistry of the extinct volcanoes. This is consistent with several studies that report continental influence on the geochemistry of lavas on Wetar and Atauro (Wheller et al. 1987; Elburg et al. 2005; Ely et al. 2011; Herrington et al. 2011) since prior to 3Ma.

Even the syn-collisional sediments attest to the 'Australianness' of Timor. The provenance of synorogenic sedimentary rocks suggests that Australian-affinity shales have been the dominant contributor to syn-collisional sedimentary basins since at least 4.5 Ma (Duffy et al. 2017).

4 Does the Timor Trough mark the edge of the NW shelf?

If the Timor Trough is considered to be a continental shelf edge, it should conform to similar settings on the NW Shelf, such as the edge of the Exmouth Plateau. Fig. 5 compares seismic transects across the Timor Trough (Petkovic et al. 2000) (Fig. 5A&C) and across the Exmouth Plateau (Mutter & Larson 1989; Stagg et al. 2004) (Fig. 5B). The Timor Trough transect shows that the strata of the NW shelf are bent down into the trough, whereas no such bending is observed in the Exmouth Plateau survey. Fig. 5C shows that the bent down NW shelf strata can be traced across the trough into the fold and thrust belt that forms the Timor slope on the northern side of the trough (Karig et al. 1987).

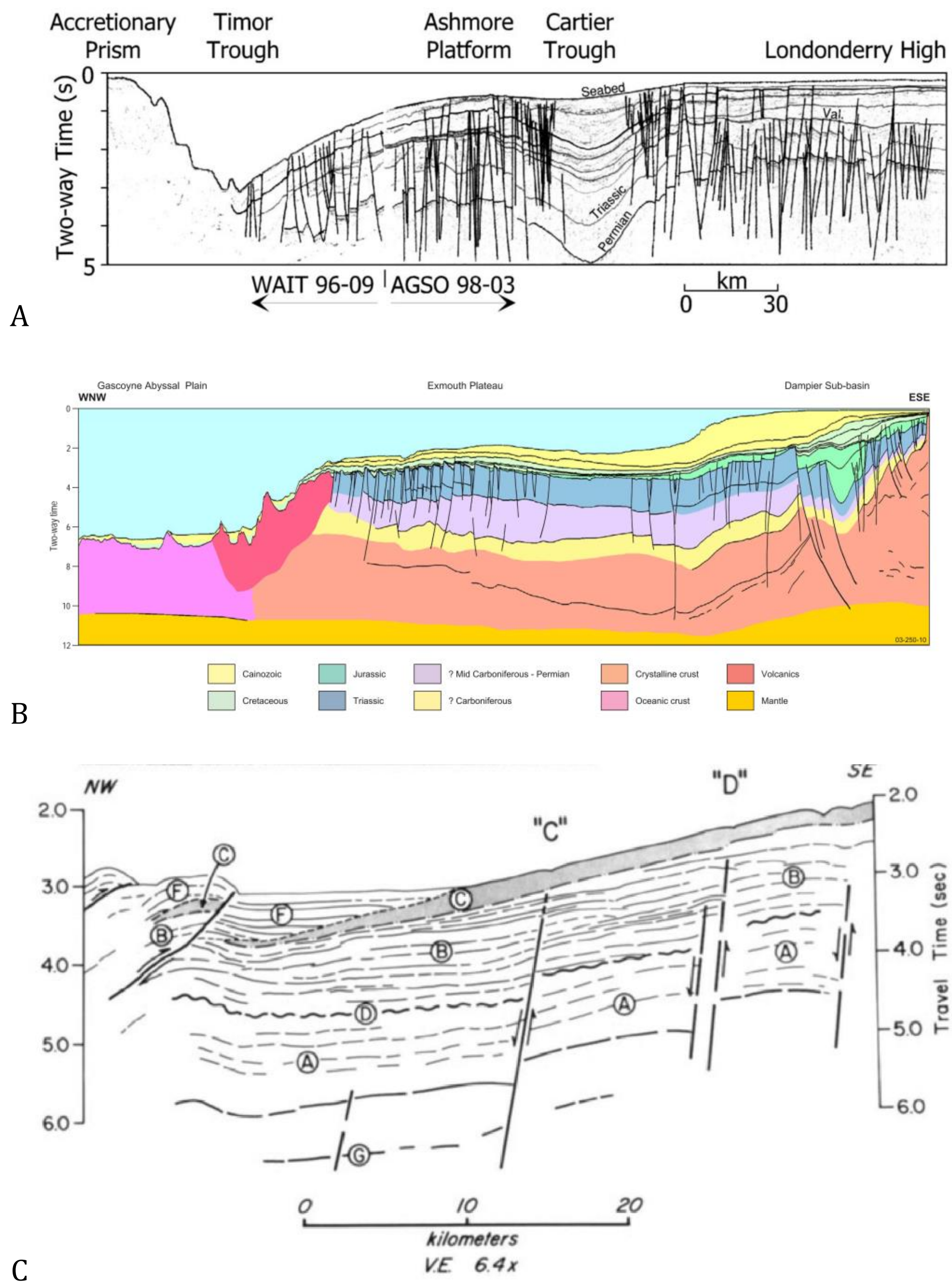

Fig. 5. A) A seismic transect across the Timor Trough (Petkovic et al. 2000), showing bending down of formerly horizontal strata into the trough. B) Seismic transects through the Exmouth Plateau by authors including Mr Mark Alcock of Geoscience Australia provide a counterpoint that shows show no evidence of such bending (Mutter & Larson 1989; Stagg et al. 2004). C) The bent down strata in A can be traced right into the slope on the northern (Timor) side of the trough (Karig et al. 1987).

This interpretation is supported by evidence from the DSDP262 drill hole located a few hundred meters south of the axis of the Timor Trough, and at close to the maximum depth of the trough (Heirtzler et al. 1974). The hole contains three facies (types) of sediment; the **basal** facies is a **shallow** shelf calcarenite (limey sandstone) that extends from 414 m to 442 m down the hole. The upper two facies accumulated at progressively greater depths. Like Fig. 5A&C, seismic reflection surveys acquired across the drill site show that the Australian continental shelf is bent down (Veevers et al. 1978). Based on the distinctive facies transition from shallow marine at the base of the hole to deep marine at the top, and on the evidence provided by the seismic survey, Veevers et al. (1978) interpreted the sequence of lithologies and micro-fossil paleo-environments represented in the hole as resulting from progressive depression of the continental shelf from shallow (continental shelf) to bathyal (Timor Trough) depths. In other words, the sloping northern 'edge' of the NW Shelf is not an edge at all but a bend of the continental crust caused by the weight of the Timor mountain belt, which has progressively built up as the continental shelf has shortened. In this context, the Timor Trough is best considered as a foredeep, the deepest part of a foreland basin that forms during loading of an elastic continental lithosphere. Such basins are not necessarily plate boundaries, and may occur within continents, either on land (Menegazzo et al. 2016) or in a marine setting (Critelli et al. 2007).

5 Where is the old plate boundary between Timor and Australia?

With the exception of Bird (2003), who drew Timor as a separate plate, few people have ever regarded the Timor Trough as a plate boundary. Bird's definition was based on a neotectonics view of a plate, which is better referred to as a block, and should be seen in the context of his breaking the earth down into 52 plates (blocks) rather than the traditional eight. The difference is best explained for a country like New Zealand, where the Australian and Pacific Plates can be broken down to >10 blocks that rotate relative to each other, depending on the model (Nicol & Wallace 2007; Wallace et al. 2007; Wallace et al. 2012). In this context, the Timor "block" is a similar size to the Canterbury block in New Zealand. Other GPS studies of Indonesia have similarly broken the Banda Orogen down into separate blocks (e.g., Bock et al. 2003; Nugroho et al. 2009).

The plate boundary at the onset of collision would have been the contact between the Indonesian forearc and the Australian ocean crust. Once the leading edge of the Australian continent began to split, with part going below and part above the forearc, the original plate boundary trench would have been buried below the collisional deformation, and the plate boundary would have become the contact between the forearc and the overthrust rocks, until such time as deformation was transferred northwards.

The original position of the plate boundary trench can be approximated by joining the ends across the length of the Timor orogen. The arc-trench gap along the Java trench is very regular and is about 270 km at the longitude of Sumba. East of Sumba, the arc is younger and therefore likely to be a little narrower (Dickinson 1973), but east of Tanimbar it reaches about 250 km. The gap between Atauro volcanic island and the Timor Trough is only ~170 km. On this basis, the original location of the trench probably lies below the NW shelf (Figure 1B) and does not coincide with the Timor Trough.

The key points made here are that 1) the original plate boundary – the subduction thrust between Banda Terrane and Australian rocks – is now dismembered and mainly preserved as fragments along the north coast of Timor; 2) the original location of the plate boundary is probably buried under the Australian basement of the NW shelf; 3) the Timor Trough coincides with neither the original position or the final postion of the subduction thrust; 4) the Timor

Trough evolved from a subduction thrust but has not been a subduction thrust since the early to middle Pliocene; 5) Timor is underlain by Australian continental basement; and 6) the modern plate boundary is largely transferred to the north of Wetar (Silver et al. 1983; Masson et al. 1991; Snyder et al. 1996b). These points render it difficult to envisage a geological case for interpretation of the Timor Trough as a maritime boundary marking the northernmost extent of Australian continental crust.

6 Summary

The Timor plate boundary system remains relatively poorly understood. However, the available evidence, summarized in points 1-6 of the preceding paragraph, leads us to consider that the Timor trough is not presently a tectonic plate boundary. Rather it is a foredeep of the Timor fold and thrust belt, developed as a result of attempted continental subduction at a Pliocene plate boundary, and presently located within the Australian continent. Critically, Timor is largely made of the very same rocks that lie beneath the sea floor on Australia's own north-west shelf, albeit broken up and interleaved with bits of the Indonesian forearc in great thrust stacks that pushed the island from the sea a few million years ago. The old plate boundary is not a single line but rather a dismembered, locally emergent, substantially overrun collection of features, none of which coincide with the Timor Trough. If Timor is made from the same shelf, there can be no continental "shelf edge" between Timor and Australia and that conclusion is supported by seismic surveys that should highlight the difference between a shelf edge and a foredeep. We see no geological case for varying the maritime boundary from the international norm defined Article 76.

7 References

Audley-Charles, MG 1968, *The Geology of Portugese Timor*, Geological Society of London, London.

Audley-Charles, MG 2004, 'Ocean trench blocked and obliterated by Banda forearc collision with Australian proximal continental slope', *Tectonophysics,* vol. 389, no. 1-2, pp. 65-79.

Benincasa, A 2015, *The 'fatus' of East Timor: stratigraphy and structure*, PhD Thesis, University of Western Australia.

Berry, RF & McDougall, I 1986, 'Interpretation of ^{40}Ar/^{39}Ar and K/Ar dating evidence from the Aileu Formation, East Timor, Indonesia', *Chemical Geology (Isotope Geoscience Section),* vol. 59, pp. 43-58.

Bird, P 2003, 'An updated digital model of plate boundaries', *Geochemistry, Geophysics, Geosystems,* vol. 4, no. 3, p. 1027. DOI:10.1029/2001GC000252

Bird, PR & Cook, SE 1991, 'Permo-Triassic successions of the Kekneno area, West Timor: implications for palaeogeography and basin evolution', *Journal of Southeast Asian Earth Sciences,* vol. 6, no. 3–4, pp. 359-71. Retrieved 1991/11//, from. DOI:http://dx.doi.org/10.1016/0743-9547(91)90081-8

Bock, Y, Prawirodirdjo, L, Genrich, JF, Stevens, CW, McCaffrey, R, Subarya, C, Puntodewo, SSO & Calais, E 2003, 'Crustal motion in Indonesia from Global Positioning System measurements', *Journal of Geophysical Research B: Solid Earth,* vol. 108, no. 8.

Boger, SD, Spelbrink, LG, Lee, RI, Sandiford, M, Maas, R & Woodhead, JD 2016, 'Constraints on the origins of the Aileu and Gondwana sequences of Timor from geochemical, Nd isotope, and U-Pb detrital zircon data', *Journal of Asian Earth Sciences,* vol. 134, pp. 330-51.

Breen, NA, Silver, EA & Roof, S 1989, 'The Wetar back arc thrust belt, eastern Indonesia: the effect of accretion against an irregularly shaped arc', *Tectonics,* vol. 8, no. 1, pp. 85-98. Retrieved 27 November 2011, from Scopus database.

Carter, DJ, Audley-Charles, MG & Barber, AJ 1976, 'Stratigraphical analysis of island arc-continental margin collision in eastern Indonesia', *Journal of the Geological Society of London,* vol. 132, pp. 179-98.

Chamalaun, FH 1977, 'Paleomagnetic evidence for the relative positions of Timor and Australia in the Permian', *Earth and Planetary Science Letters,* vol. 34, no. 1, pp. 107-12. DOI:http://dx.doi.org/10.1016/0012-821X(77)90111-X

Chamalaun, FH & Grady, AE 1978, 'Tectonic Development of Timor: A New Model and its Implications for Petroleum Exploration', *APEA Journal,* vol. 18, no. pt 1, pp. 102-8.

Charlton, TR 1987, *The tectonic evolution of the Kolbano-Timor trough accretionary complex, Timor, Indonesia.*, PhD Thesis, University of London.

Charlton, TR 1989, 'Stratigraphic correlation across an arc-continent collision zone: Timor and the Australian Northwest Shelf', *Australian Journal of Earth Sciences,* vol. 36, no. 2, pp. 263-74. Retrieved 7 September 2012, from Scopus database.

Charlton, TR 2000, 'Tertiary evolution of the Eastern Indonesia Collision Complex', *Journal of Asian Earth Sciences,* vol. 18, pp. 603-31.

Charlton, TR 2001, 'Permo-triassic evolution of gondwanan Eastern Indonesia, and the final mesozoic separation of SE Asia from Australia', *Journal of Asian Earth Sciences,* vol. 19, no. 5, pp. 595-617.

Charlton, TR 2002, 'The Petroleum Potential of East Timor', *APPEA Journal,* vol. 42, pp. 351-69.

Charlton, TR, Barber, AJ & Barkham, ST 1991, 'The structural evolution of the Timor collision complex, eastern Indonesia', *Journal of Structural Geology,* vol. 13, no. 5, pp. 489-500.

Charlton, TR, Barber, AJ, Harris, RA, Barkham, ST, Bird, PR, Archbold, NW, Morris, NJ, Nicoll, RS, Owen, HG, Owens, RM, Sorauf, JE, Taylor, PD, Webster, GD & Whittaker, JE 2002, 'The Permian of Timor: Stratigraphy, palaeontology and palaeogeography', *Journal of Asian Earth Sciences,* vol. 20, no. 6, pp. 719-74.

Charlton, TR, Barber, AJ, McGowan, AJ, Nicoll, RS, Roniewicz, E, Cook, SE, Barkham, ST & Bird, PR 2009, 'The Triassic of Timor: Lithostratigraphy, chronostratigraphy and palaeogeography', *Journal of Asian Earth Sciences,* vol. 36, no. 4-5, pp. 341-63.

Charlton, TR & Suharsono 1990, 'Mesozoic-Tertiary stratigraphy of the Kolbano area, Southern West Timor', *Bulletin of the Geological Research Development Centre,* vol. 14, pp. 38-58.

Charlton, TR & Wall, D 1994, 'New biostratigraphic results from the Kolbano area, southern West Timor: Implications for the Mesozoic-Tertiary stratigraphy of Timor', *Journal of Southeast Asian Earth Sciences,* vol. 9, no. 1-2, pp. 113-22.

Critelli, S, Le Pera, E, Galluzzo, F, Milli, S, Moscatelli, M, Perrotta, S & Santantonio, M 2007, 'Interpreting siliciclastic-carbonate detrital modes in foreland basin systems: An example from Upper Miocene arenites of the central Apennines, Italy', *Geological Society of America Special Papers,* vol. 420, pp. 107-33. DOI:10.1130/2006.2420(08)

DeMets, C, Gordon, RG & Argus, DF 2010, 'Geologically current plate motions', *Geophysical Journal International,* vol. 181, no. 1, pp. 1-80. Retrieved 8 June 2011, from Scopus database.

Dickinson, WR 1973, 'Widths of modern arc-trench gaps proportional to past duration of igneous activity in associated magmatic arcs', *Journal of Geophysical Research,* vol. 78, no. 17, pp. 3376-89. DOI:10.1029/JB078i017p03376

Duffy, B, Kalansky, J, Bassett, K, Harris, R, Quigley, M, van Hinsbergen, DJ, Strachan, LJ & Rosenthal, Y 2017, 'Mélange versus forearc contributions to sedimentation and uplift, during rapid denudation of a young Banda forearc-continent collisional belt', *Journal of Asian Earth Sciences,* vol. 138, pp. 186-210. DOI:10.1016/j.jseaes.2017.02.008

Duffy, B, Quigley, MC, Harris, R & Ring, U 2013, 'Arc-parallel extrusion of the Timor sector of the Banda arc-continent collision', *Tectonics,* vol. 32, no. 3, pp. 641-60. DOI:10.1002/tect.20048

Elburg, MA, Foden, JD, van Bergen, MJ & Zulkarnain, I 2005, 'Australia and Indonesia in collision: Geochemical sources of magmatism', *Journal of Volcanology and Geothermal Research,* vol. 140, no. 1-3, pp. 25-47. Retrieved 6 July 2012, from Scopus database.

Ely, KS & Sandiford, M 2010, 'Seismic response to slab rupture and variation in lithospheric structure beneath the Savu Sea, Indonesia', *Tectonophysics,* vol. 483, no. 1-2, pp. 112-24.

Ely, KS, Sandiford, M, Hawke, ML, Phillips, D, Quigley, MC & Reis, JEd 2011, 'Evolution of Ataúro Island: Temporal constraints on subduction processes beneath the Wetar zone, Banda Arc', *Journal of Asian Earth Sciences,* vol. 41, no. 6, pp. 477-93. DOI:10.1016/j.jseaes.2011.01.019

Ely, KS, Sandiford, M, Phillips, D & Boger, SD 2014, 'Detrital zircon U–Pb and 40Ar/39Ar hornblende ages from the Aileu Complex, Timor-Leste: provenance and metamorphic cooling history', *Journal of the Geological Society,* vol. 171, no. 2, pp. 299-309. DOI:10.1144/jgs2012-065

Exon, NF, Haq, BU & von Rad, U 1994, 'Exmouth Plateau revisited: Scientific drilling and geological framework', *Proceedings of the Ocean Drilling Program, Scientific Results,* vol. 122, pp. 3-20.

Falvey, DA & Veevers, JJ 1974, 'Physiography of the Exmouth and Scott Plateaus, Western Australia, and adjacent northeast Wharton Basin', *Marine Geology,* vol. 17, no. 2, pp. 21-59. DOI:http://dx.doi.org/10.1016/0025-3227(74)90046-2

Fortuin, AR, van der Werff, W & Wensink, H 1997, 'Neogene basin history and paleomagnetism of a rifted and inverted forearc region, on- and offshore Sumba, Eastern Indonesia', *Journal of Asian Earth Sciences,* vol. 15, pp. 61-88.

Genrich, JF, Bock, Y & Mason, RG 1997, 'Crustal deformation across the Imperial Fault: Results from kinematic GPS surveys and trilateration of a densely spaced, small-aperture network', *Journal of Geophysical Research B: Solid Earth,* vol. 102, no. B3, pp. 4985-5004.

Genrich, JF, Bock, Y, McCaffrey, R, Calais, E, Stevens, CW & Subarya, C 1996, 'Accretion of the southern banda arc to the Australian plate margin determined by global positioning system measurements', *Tectonics,* vol. 15, no. 2, pp. 288-95.

Haig, DW & McCartain, E 2007, 'Carbonate pelagites in the post-Gondwana succession (Cretaceous - Neogene) of East Timor', *Australian Journal of Earth Sciences,* vol. 54, no. 6, pp. 875-97.

Hamling, IJ, Hreinsdóttir, S, Clark, K, Elliott, J, Liang, C, Fielding, E, Litchfield, N, Villamor, P, Wallace, L & Wright, TJ 2017, 'Complex multifault rupture during the 2016 Mw 7.8 Kaikōura earthquake, New Zealand', *Science*. DOI:10.1126/science.aam7194

Harris, RA 1991, 'Temporal distribution of strain in the active Banda orogen: a reconciliation of rival hypotheses', *Journal of Southeast Asian Earth Sciences,* vol. 6, no. 3-4, pp. 373-86.

Harris, RA 1992, 'Peri-collisional extension and the formation of Oman-type ophiolites in the Banda arc and Brooks Range', in LM Parson, BJ Murton & P Browning (eds), *Ophiolites and their modern oceanic analogues*, Geological Society of London Special Publication 60, Bath, England, pp. 301-25.

Harris, RA 2006, 'Rise and fall of the Eastern Great Indonesian arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor', *Gondwana Research,* vol. 10, no. 3-4, pp. 207-31.

Harris, RA 2011, 'The Nature of the Banda Arc–Continent Collision in the Timor Region', in D Brown & PD Ryan (eds), *Arc-Continent Collision*, vol. 1, Springer Heidelberg, Berlin, pp. 163-211.

Harris, RA, Vorkink, MW, Prasetyadi, C, Zobell, E, Roosmawati, N & Apthorpe, M 2009, 'Transition from subduction to arc-continent collision: Geologic and neotectonic evolution of Savu Island, Indonesia', *Geosphere,* vol. 5, pp. 152-71.

Heirtzler, JR, Veevers, JJ, Bolli, HM, Carter, AN, Cook, PJ, Krasheninnikov, V, McKnight, BK, Proto-Decima, F, Renz, GW, Robinson, PT, Rocker(Jr), K & Thayer, PA 1974, 'Site 262', *Initial Reports on the Deep Sea Drilling Project 27*, pp. 193-278.

Herrington, RJ, Scotney, PM, Roberts, S, Boyce, AJ & Harrison, D 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,* vol. 19, no. 3, pp. 583-93. DOI:10.1016/j.gr.2010.10.011

Ishikawa, A, Kaneko, Y, Kadarusman, A & Ota, T 2007, 'Multiple generations of forearc mafic-ultramafic rocks in the Timor-Tanimbar ophiolite, eastern Indonesia', *Gondwana Research,* vol. 11, no. 1-2, pp. 200-17.

Kadarusman, A, Maruyama, S, Kaneko, Y, Ota, T, Ishikawa, A, Sopaheluwakan, J & Omori, S 2010, 'World's youngest blueschist belt from Leti Island in the non-volcanic Banda outer arc of Eastern Indonesia', *Gondwana Research,* vol. 18, no. 1, pp. 189-204. DOI:http://dx.doi.org/10.1016/j.gr.2010.02.009

Kaneko, Y, Maruyama, S, Kadarusman, A, Ota, T, Ishikawa, M, Tsujimori, T, Ishikawa, A & Okamoto, K 2007, 'On-going orogeny in the outer-arc of the Timor-Tanimbar region, eastern Indonesia', *Gondwana Research,* vol. 11, no. 1-2, pp. 218-33.

Karig, DE, Barber, AJ, Charlton, TR, Klemperer, S & Hussong, DM 1987, 'Nature and distribution of deformation across the Banda Arc - Australian collision zone at Timor', *Geological Society of America Bulletin,* vol. 98, no. 1, pp. 18-32.

Keep, M & Haig, DW 2010, 'Deformation and exhumation in Timor: Distinct stages of a young orogeny', *Tectonophysics,* vol. 483, no. 1-2, pp. 93-111. DOI:10.1016/j.tecto.2009.11.018

Koulali, A, Susilo, S, McClusky, S, Meilano, I, Cummins, P, Tregoning, P, Lister, G, Efendi, J & Syafi'i, MA 2016, 'Crustal strain partitioning and the associated earthquake hazard in the eastern Sunda-Banda Arc', *Geophysical Research Letters,* vol. 43, no. 5, pp. 1943-9. DOI:10.1002/2016GL067941

Kreemer, C, Holt, WE, Goes, S & Govers, R 2000, 'Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data', *Journal of Geophysical Research B: Solid Earth,* vol. 105, no. B1, pp. 663-80.

Little, TA & Jones, A 1998, 'Seven million years of strike-slip and related off-fault deformation, northeastern Marlborough fault system, South Island, New Zealand', *Tectonics,* vol. 17, no. 2, pp. 285-302. DOI:10.1029/97tc03148

Little, TA & Roberts, AP 1997, 'Distribution and mechanism of Neogene to present-day vertical axis rotations, Pacific-Australian plate boundary zone, South Island, New Zealand', *Journal of Geophysical Research B: Solid Earth,* vol. 102, no. B9, pp. 20447-68.

Masson, DG, Milsom, J, Barber, AJ, Sikumbang, N & Dwiyanto, B 1991, 'Recent tectonics around the island of Timor, eastern Indonesia', *Marine and Petroleum Geology,* vol. 8, no. 1, pp. 35-49.

Menegazzo, MC, Catuneanu, O & Chang, HK 2016, 'The South American retroarc foreland system: The development of the Bauru Basin in the back-bulge province', *Marine and Petroleum Geology,* vol. 73, pp. 131-56. DOI:http://dx.doi.org/10.1016/j.marpetgeo.2016.02.027

Metcalfe, I 2013, 'Gondwana dispersion and Asian accretion: Tectonic and palaeogeographic evolution of eastern Tethys', *Journal of Asian Earth Sciences,* vol. 66, pp. 1-33. DOI:http://dx.doi.org/10.1016/j.jseaes.2012.12.020

Mutter, JC & Larson, RL 1989, 'Extension of the Exmouth Plateau, offshore northwestern Australia: Deep seismic reflection/refraction evidence for simple and pure shear mechanisms', *Geology,* vol. 17, no. 1, pp. 15-8. DOI:10.1130/0091-7613(1989)017<0015:eotepo>2.3.co;2

Nguyen, N, Duffy, B, Shulmeister, J & Quigley, MC 2013, 'Rapid Pliocene uplift of Timor', *Geology,* vol. 41, no. 2, pp. 179-82. DOI:10.1130/G33420.1

Nicol, A & Wallace, LM 2007, 'Temporal stability of deformation rates: Comparison of geological and geodetic observations, Hikurangi subduction margin, New Zealand', *Earth and Planetary Science Letters,* vol. 258, no. 3-4, pp. 397-413.

Nugroho, H, Harris, RA, Lestariya, AW & Maruf, B 2009, 'Plate Boundary Reorganization in the Active Banda Arc-Continent Collision: Insights from New GPS Measurements', *Tectonophysics,* vol. 479, no. 1-2, pp. 52-65.

Petkovic, P, Collins, CDN & Finlayson, DM 2000, 'A crustal transect between precambrian Australia and the Timor trough across the Vulcan sub-basin', *Tectonophysics,* vol. 329, no. 1-4, pp. 23-38.

Planert, L, Kopp, H, Lueschen, E, Mueller, C, Flueh, ER, Shulgin, A, Djajadihardja, Y & Krabbenhoeft, A 2010, 'Lower plate structure and upper plate deformational segmentation at the Sunda-Banda arc transition, Indonesia', *J. Geophys. Res.,* vol. 115, no. B8, p. B08107. DOI:10.1029/2009jb006713

Porritt, RW, Miller, MS, O'Driscoll, LJ, Harris, CW, Roosmawati, N & Teofilo da Costa, L 2016, 'Continent–arc collision in the Banda Arc imaged by ambient noise tomography', *Earth and Planetary Science Letters,* vol. 449, pp. 246-58. DOI:http://dx.doi.org/10.1016/j.epsl.2016.06.011

Rigg, JWD & Hall, R 2012, 'Neogene development of the Savu Forearc Basin, Indonesia', *Marine and Petroleum Geology,* vol. 32, pp. 76-94.

Roosmawati, N & Harris, RA 2009, 'Surface uplift history of the incipient Banda arc-continent collision: Geology and synorogenic foraminifera of Rote and Savu Islands, Indonesia', *Tectonophysics,* vol. 479, no. 1-2, pp. 95-110. DOI:10.1016/j.tecto.2009.04.009

Rosidi, HMD, Suwitodirdjo, K & Tjokosaproetro, S 1981, 'Geologic map of the Kupang-Atambua quadrangles, Timor'. Geological Research and Development Centre, Bandung, Indonesia

Sandiford, M 2008, 'Seismic moment release during slab rupture beneath the Banda Sea', *Geophysical Journal International,* vol. 174, no. 2, pp. 659-71.

Sashida, K, Munasri, Adachi, S & Kamata, Y 1999, 'Middle Jurassic radiolarian fauna from Rotti Island, Indonesia', *Journal of Asian Earth Sciences,* vol. 17, no. 4, pp. 561-72. DOI:http://dx.doi.org/10.1016/S1367-9120(99)00002-4

Sawyer, RK, Sani, K & Brown, S 1993, 'The stratigraphy and sedimentology of West Timor, Indonesia', *Proceedings of the Indonesian Petroleum Association, Twenty Second Annual Convention*, pp. 533-74.

Shulgin, A, Kopp, H, Mueller, C, Lueschen, E, Planert, L, Engels, M, Flueh, ER, Krabbenhoeft, A & Djajadihardja, Y 2009, 'Sunda-Banda arc transition: Incipient continent-island arc collision (northwest Australia)', *Geophys. Res. Lett.,* vol. 36, no. 10, p. L10304. DOI:10.1029/2009gl037533

Silver, EA, Reed, D, McCaffrey, R & Joyodiwiryo, Y 1983, 'Back arc thrusting in the eastern Sunda arc, Indonesia: a consequence of arc-continent collision', *Journal of Geophysical Research,* vol. 88, no. B9, pp. 7429-48

Simons, WJF, Socquet, A, Vigny, C, Ambrosius, BAC, Haji Abu, S, Promthong, C, Subarya, C, Sarsito, DA, Matheussen, S, Morgan, P & Spakman, W 2007, 'A decade of GPS in Southeast Asia: Resolving Sundaland motion and boundaries', *J. Geophys. Res.,* vol. 112, no. B6, p. B06420. DOI:10.1029/2005jb003868

Snyder, DB, Milsom, J & Prasetyo, H 1996a, 'Geophysical evidence for local indentor tectonics in the Banda Arc east of Timor', in R Hall & DJ Blundell (eds), *Tectonic evolution of Southeast Asia*, Geological Society of London Special Publication 106, Bath, England, pp. 61-73.

Snyder, DB, Prasetyo, H, Blundell, DJ, Pigram, CJ, Barber, AJ, Richardson, A & Tjokosaproetro, S 1996b, 'A dual doubly vergent orogen in the Banda Arc continent-arc collision zone as observed on deep seismic reflection profiles', *Tectonics,* vol. 15, no. 1, pp. 34-53.

Stagg, HMJ, Alcock, MB, Bernardel, G, Moore, A, Symonds, PA & Exon, NF 2004, 'Geological framework of the outer Exmouth Plateau and adjacent ocean basins', *Geoscience Australia Record 2004/13*.

Standley, CE & Harris, RA 2009, 'Tectonic Evolution of Forearc Nappes of the Active Banda Arc-Continent Collision: Origin, Age, Metamorphic History and

Structure of the Lolotoi Complex, East Timor', *Tectonophysics,* vol. doi:10.1016/j.tecto.2009.01.034.

Tate, GW 2014, *Structural deformation, exhumation, and uplift of the Timor fold-thrust belt*, PhD Thesis, Princeton University.

Tate, GW, McQuarrie, N, Hinsbergen, DJJv, Bakker, RR, Harris, R, Willet, S, Reiners, P, Fellin, MG, Ganerød, M & Zachariasse, JW 2014, 'Resolving spatial heterogeneities in exhumation and surface uplift in East Timor: constraints of deformation processes in young orogens', *Tectonics*. DOI:10.1002/2013TC003436

Tate, GW, McQuarrie, N, van Hinsbergen, DJJ, Bakker, RR, Harris, R & Jiang, H 2015, 'Australia going down under: Quantifying continental subduction during arc-continent accretion in Timor-Leste', *Geosphere*. DOI:10.1130/ges01144.1

Veevers, JJ, Falvey, DA & Robins, S 1978, 'Timor trough and australia: Facies show topographic wave migrated 80 km during the past 3 m.y', *Tectonophysics,* vol. 45, no. 2-3, pp. 217-27.

Von Der Borch, CC 1979, 'Continent - Island arc collision in the Banda Arc', *Tectonophysics,* vol. 54, no. 3-4, pp. 169-93.

Wallace, LM, Barnes, P, Beavan, J, Van Dissen, R, Litchfield, N, Mountjoy, J, Langridge, R, Lamarche, G & Pondard, N 2012, 'The kinematics of a transition from subduction to strike-slip: An example from the central New Zealand plate boundary', *J. Geophys. Res.,* vol. 117, no. B2, p. B02405. DOI:10.1029/2011jb008640

Wallace, LM, Beavan, J, McCaffrey, R, Berryman, K & Denys, P 2007, 'Balancing the plate motion budget in the South Island, New Zealand using GPS, geological and seismological datas', *Geophysical Journal International,* vol. 168, no. 1, pp. 332-52.

Wheller, GE, Varne, R, Foden, JD & Abbott, MJ 1987, 'Geochemistry of quaternary volcanism in the Sunda-Banda arc, Indonesia, and three-component genesis of island-arc basaltic magmas', *Journal of Volcanology and Geothermal Research,* vol. 32, no. 1-3, pp. 137-60.