Tectonic post-collision processes in Timor

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Abstract: Indian Ocean crust subducted northwards at the Banda Trench from about 12 to 4 Ma. The Australian continental margin collided with the Asian fore-arc at about 4 Ma. Gradually the Banda Trench was transformed into the fold and thrust mountains of Timor Island. Tectonic collision processes developed when all ocean crust had been subducted and Australian continental crust was refused entry to the subduction path below the Asian fore-arc. The Banda Trench was then gradually converted into a Tectonic Collision Zone (TCZ) progressively filled by two highly deformed Australian continental upper crust mega-sequences. Slowing subduction of Australian sub-crustal lithosphere after *c*. 2.5 Ma led to uplift of the TCZ that raised Timor 3 km above sea level. Asian Banda fore-arc deformation is linked to *c*. 30 km southeastwards rollback of the subducting Australian mantle lithosphere. Two Asian fore-arc nappes were thrust southwards from the Banda fore-arc onto the older of two highly deformed Australian continental margin upper crust mega-sequences. The Wetar Suture was created as a thrust at the base of Australian partially detached continental lower crust propagated into the Asian fore-arc. Re-interpretation of BIRPS seismic and gravity data for the Timor region supports this collision model.

This paper discusses the key geological processes associated with the Timor tectonic collision. Timor Island has mountains up to 3 km high, is over 475 km long and has a width of 75–100 km (150 km wide with its submarine southern slope). Without including the volcanic islands, East and West Timor are together larger than the 280 × 100 km Swiss Alps. The Banda Arcs are 2300 km long, a length equivalent to the European Alps in France, Italy, Switzerland and Austria as well as the Carpathian Mountains. Timor is not an accretionary wedge of a volcanic fore-arc, nor a fore-arc as some geological maps show, although its rocks include parts of the older volcanic fore-arc. It is comprised mainly of the Australian continental margin deformed by collision with the Banda volcanic fore-arc. After collision, none of the continental crust was subducted although subduction of Australian sub-crustal mantle lithosphere continued.

The Banda subduction trench began to develop between about 15 to 12 Ma from the eastern part of the Sunda–Java Trench (Fig. 1) to form the Banda volcanic arc (Hall 2002). This trench has been assumed by many writers to have been located in what is now the Timor Trough south of the rocks that now form Timor Island (e.g. Hamilton 1979; Rangin *et al.* 1999), although the Timor Trough is now underlain by about 26 km of Australian continental crust (e.g. Richardson & Blundell 1996; Snyder *et al.* 1996). Audley-Charles (2004) attempted to explain how the Benioff zone must always have lain north of almost all the rocks that gave rise to Timor and the other islands of the southern part of the Outer Banda Arc (Fig. 1). Audley-Charles (1986*b*) and others (e.g. Lorenzo *et al.* 1998; Tandon *et al.* 2000; Hall 2002; Londono & Lorenzo 2004; Woodcock 2004) recognized that the Timor Trough is a foreland basin and could never have been a Benioff subduction trench. Audley-Charles (2004) showed how the Banda Trench had been destroyed in the tectonic collision but he did not recognize how the subduction passage below the fore-arc had been partially blocked by the inability of Australian continental crust to subduct from about 4 Ma.

Tectonic collision of the Australian continental margin with the Asian Banda fore-arc in Timor can be defined as beginning when the Australian continental crust was first unable to enter the existing subduction passage below the volcanic fore-arc. At 4 Ma the Banda Trench was *c*. 6 km deep and 30 wide (Audley-Charles 2004). Following collision, rollback of the subducting lithosphere continued by *c*. 30 km with separation of Australian continental lower crust by delamination from the subducting mantle lithosphere. The former trench became filled by thrust stacking of the Australian continental crust, and Asian nappes that were thrust southwards during rollback, and these rocks now form a region about 35 km in thickness and 110–150 km in length from NW to SE. There were two important decollements in the Australian continental upper crust; this thickening since 4 Ma was crucial to the orogenic processes. This paper discusses the

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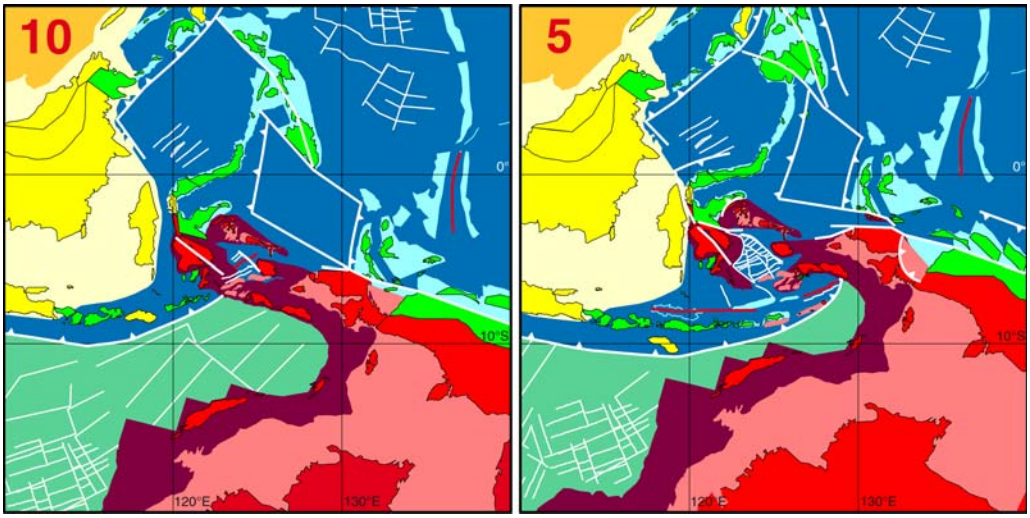

Fig. 1. Plate tectonic reconstruction of part of the Indian Ocean, Banda Trench and NW Australian continental shelf and margin at 10 and 5 Ma based on Hall (2002), and Spakman & Hall (2010). Note position of active Banda Trench north of Timor. Tectonic collision of the Australian continental margin with the Banda volcanic fore-arc proposed by Keep & Haigh (2010) between 10.8 and 9.8 Ma is not tenable.

fundamental roles of rollback, continuing subduction of sub-crustal lithosphere, five major decollements, and the movement of the lower crust creating the Wetar Suture, and how these key processes led to the tectonic evolution of Timor Island.

Summary of geological field studies and regional mapping programmes in Timor

Before World War 2 (WW2) geological field studies were focused separately in either Dutch (now Indonesian) Timor, being the western part of the island, or Portuguese (now Timor Leste), being the eastern part of Timor. By far the most important were the studies in West Timor under the direction of Brouwer, at Amsterdam University in 1937. This produced four volumes of papers in 1942 that reported in detail on the geology of many of the key areas of West Timor and some of the adjacent islands of the Banda Volcanic Arc. After the end of WW2 geological investigations in Timor from 1954 to 1969 continued to be conducted separately in West (Indonesian) Timor and in East (Portuguese) Timor. In West Timor de Waard made significant contributions focused on and around the metamorphic massifs of the Mutis Metamorphic Complex and other key stratigraphical targets producing very useful papers: de Waard (1954*a*, *b*, 1955, 1956, 1957). Work in East Timor by Escher and Grunau (Grunau 1953, 1956, 1957) and Gageonnet & Lemoine (1958) advanced the regional stratigraphical and structural geology of East Timor, including the first geological sketch map of all East Timor on a scale of 1:500 000. Van Bemmelen (1949) and Hamilton (1979) in their compendious studies of the geology of the whole of Indonesia produced summaries of the geology of Timor. Lacking plate tectonic ideas before the late 1960s limited the understanding of the tectonics to the geosyncline hypothesis.

From 1959 until 2009 UK geologists and their research students based in London University (some of whom continued after completion of their PhD when they moved to other universities, notably Harris and students) worked in both East Timor and West Timor. However, from late 1975 to the 1990s access to East Timor was limited to Bachri and Situmorang only, who were allowed to work there in 1994. Hunter (MSc thesis at West Virginia University 1993) and Reed *et al.* (1996) had worked in East Timor during the 1990s. Between 1959 and 2009 Audley-Charles, Barber, Carter, Charlton, Giani, Harris, Kenyon and Tobing worked at various times in both East and West Timor. These London-based geologists produced over 60 papers dealing the geology of both parts of Timor, and 14 PhD and MPhil theses were published on the geology of both parts of Timor by the University of London.

In 1968 Audley-Charles had published a reconnaissance geological map of Portuguese Timor on a scale of 1:250 000. In 1979 the Geological Survey of Indonesia published a geological map of

Indonesian Timor also on the scale of 1:250 000. This includes the Kupang quadrangle and the islands of Raijua, Savu and Roti as well as the most western part of west Timor. It is based on the geological mapping of Suwitodirjo & Tjokrosapoetro (1996) and Rosidi *et al.* (1996). These geological maps of Indonesian Timor employ a very similar stratigraphical scheme and nomenclature to that used in the geological map of Portuguese Timor (Audley-Charles 1968). Together these published maps represent a joint account of the reconnaissance geology of all Timor and of the three adjacent islands of the Outer Banda Arc to the west of Timor.

Since about 2003 Haig and Keep and their students, including McCartain and Logan Barber, all based at the University of Western Australia, have carried out geological field work in parts of East Timor, and their papers are referred to below.

Brief geological history of Timor

Geologically, Timor and all the islands of the non-volcanic, Outer Banda Arc are part of the Australian continental margin (Figs 1–3). Their oldest exposed sedimentary rocks are Early Permian in age and associated with Triassic and Jurassic strata. These rocks were deposited in a large Gondwana cratonic basin that underlies much of what is now the continental shelf of northern Australia. The northeastern part of eastern Gondwana was rifted from Australia and New Guinea at about 200 Ma (Pigram & Panggabean 1984). This cratonic basin extended below what are now the islands of the Outer Banda Arc, into that part of Eastern Gondwanaland that rifted from NW Australia at 155 Ma (Audley-Charles 1988; Metcalfe 1988; Powell *et al.* 1988). Thus, the younger sequence of rocks, of what is now Timor Island, began to be deposited after about 155 Ma on the NW Australian rifted continental margin above the Australian Gondwana cratonic basin. What was to become Timor remained a submarine part of that margin until it emerged as an island in the Late Pliocene following the tectonic collision with the fore-arc of the southern Banda volcanic islands in the Mid-Late Pliocene (Hall 2002).

Two mega-sequences can be recognized in the para-autochthon of Timor. The older mega-sequence crops out in the northern three-quarters of the island, whereas the younger is exposed almost entirely in the southern quarter of Timor Island, and it contributes numerous exotic blocks and clay matrix to tectonic melanges exposed with the older mega-sequence and with the Asian Banda Terrane. The older mega-sequence is the pre-rift or Gondwana mega-sequence. This includes the oldest Australian continental margin sedimentary rocks exposed in Timor and all other islands of the Outer Banda Arc, ranging from Early Permian to late Middle Jurassic stratified, mainly sedimentary, rocks. They are now highly deformed and all other rock sequences overlie them. The younger mega-sequence is referred to as the post-155 Ma rift mega-sequence. This ranges in age from Late Jurassic to Pliocene. It is strongly deformed with large-scale recumbent folds, thrusts, with some strong to intense imbrication and pressure solution cleavage, all well exposed in the Kolbano region of SW Timor. The evidence of multiple deformation, and the presence of large-scale flat-lying overthrusts distinguish this mega-sequence of younger rocks from the pre-Late Jurassic rocks of the Gondwana pre-rift mega-sequence. In a structurally high position on Timor are rocks with an Asian affinity forming thrust sheets called the Banda Terrane (Audley-Charles & Harris 1990; Harris 1991). This rests on the highly deformed para-autochthonous part of the Gondwana mega-sequence of Early Permian to Mid-Jurassic age. The basement rocks of the Banda Terrane are known as the Mutis Metamorphic Complex in West Timor and are correlated with the Lolotoi Metamorphic Complex in East Timor.

Banda Trench subduction seems to have been initiated at the easternmost limit of the Sunda–Java Trench and propagated eastwards (Fig. 1) so that it perhaps reached as far east as Seram (Hall & Wilson 2000; Hall 2002; Spakman & Hall 2010). Following collision at about 4 Ma Timor Island was created about 2 Ma by uplift, probably at least partly isostatic, by the Neogene collision between the NW Australian continental margin crust and the fore-arc of the Banda volcanic islands of Wetar, Atauro, Pantar, Lomblen, Adonara and the eastern part of Flores. The collision was associated with the inability of the lower density and thicker Australian upper continental crust and the thinner crystalline lower crust to be subducted with the sub-crustal mantle lithosphere. The sub-crustal mantle lithosphere continued to subduct below the former Banda volcanic arc. Rollback continued southwards after 4 Ma by about 30 km creating a large space that opened southeastwards progressively filled by the stacked upper crust.

The age of the collision continues to be a source of controversy. This partly reflects the shape of the pre-collisional Australian margin and the different times at which different parts of this margin came into contact with the Asian margin (Fig. 1; see reconstructions in Hall 2002 and Spakman & Hall 2010). In this paper the collision refers to the time at which the fore-arc of the Banda volcanic arc made first contact with the distal parts of the Australian passive continental margin in the Timor region.

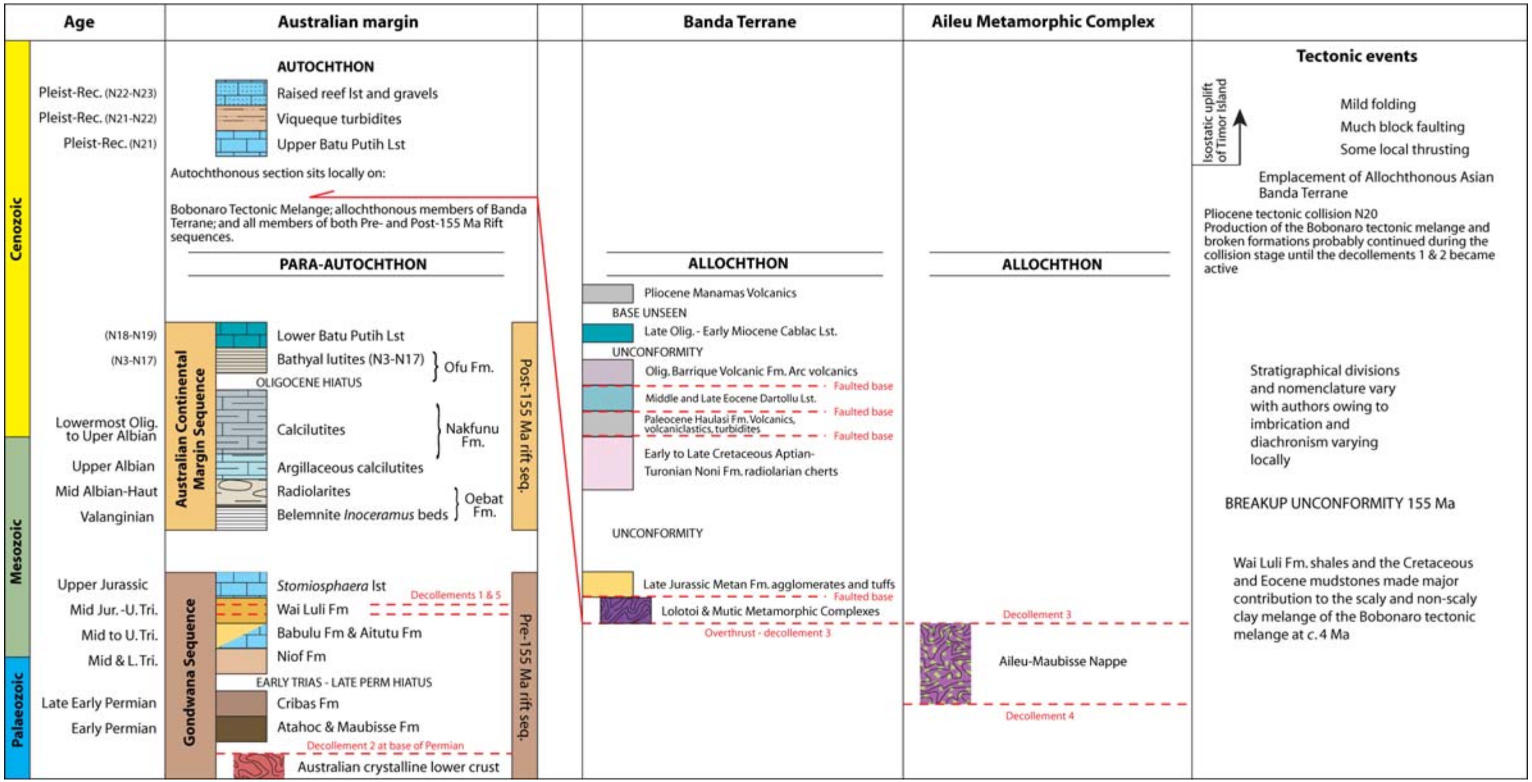

Fig. 2. Summary of Timor autochthonous, para-autochthonous and allochthonous stratigraphy. The allochthonous stratigraphy is found only in the Asian Banda Terrane and its cover rocks, and in the amphibolites of the Aileu Complex. Tectonic collision was N20, although locally N20 strata have been reported in the Australian autochthon. This may indicate diachronous deposition and deformation. See text for discussion.

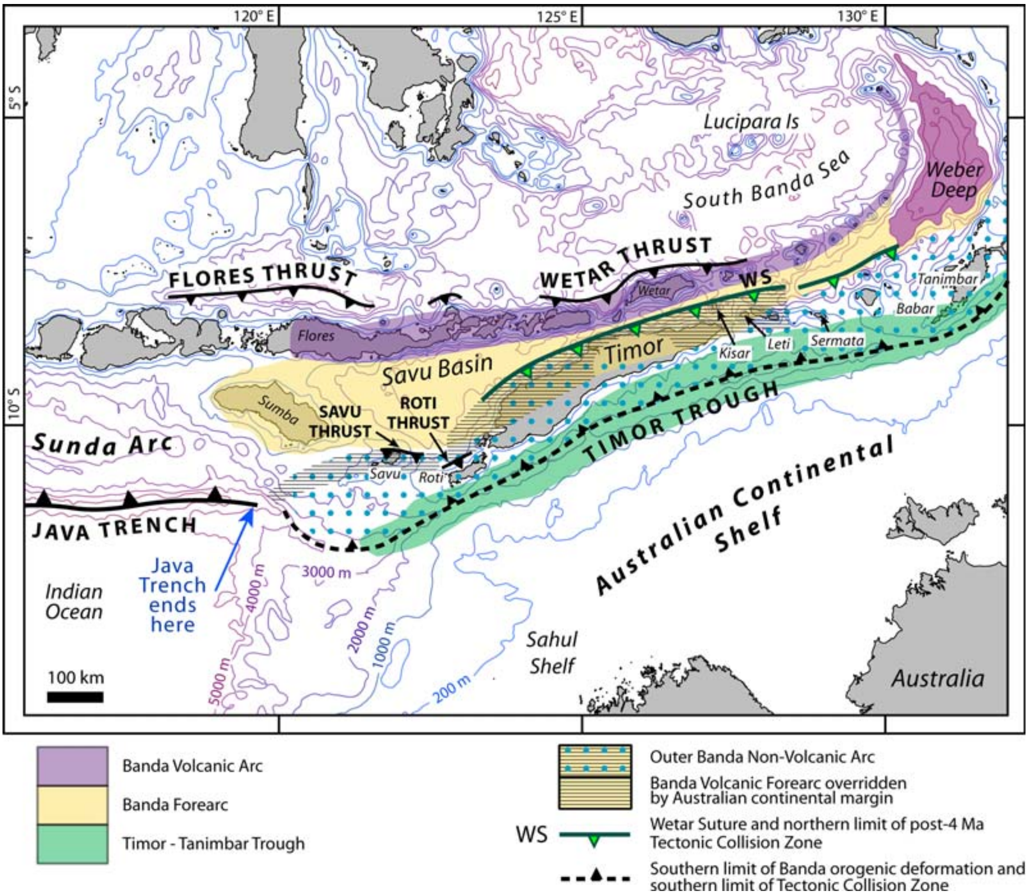

Fig. 3. The now invisible Banda Trench became filled with Australian continental crust and two Asian nappes that evolved into the TCZ that became Timor Island and its submarine southern slope. Note filling and overriding of the eastern end of the Java Trench by rocks of the Australian continental margin. The NNE–SSW strike-slip faults that help shape the northern margin of the Australian continent in the Timor region (Audley-Charles 2004, fig. 1) are omitted here as their precise location is unknown.

Dating the Neogene tectonic collision

In this paper geological events have been described in terms of their biostratigraphical age, such as Late Pliocene or Early Miocene, with numerical ages based on Gradstein *et al.* (2005), and/or in terms of the foraminiferal zones of Blow (1969), slightly modified by D. J. Carter for his use in the Banda Arc islands; updated where necessary (Fig. 4) by BouDagher-Fadel (2008). The planktonic foraminifera zonation scheme of Blow (1969) was modified by D. J. Carter in Audley-Charles *et al.* (1979) and in Audley-Charles (1986*a*, Fig. 4), and in this paper. The key geological sections for dating the Neogene tectonic-stratigraphical event are in West Timor. One reason for this may be the greater uplift in East Timor, with the greater depth of exhumation that has removed key sections, and the somewhat greater degree of deformation seen in East Timor.

Micropalaeontological dating in the Kolbano region

The Kolbano region of SW Timor (Figs 3–5) has the key exposures by which to date the collision. Here the para-autochthonous sequences from Permian to Early Pliocene reveal that these rocks have been notably indurated. A thin layer of the mixed matrix facies of the Bobonaro Melange has intruded the Neogene section. Above this is the Lower Batu Putih Limestone composed of foraminiferal (Fig. 2) calcilutites, vitric tuffs, and

Local zonation (D. J. Carter)	Planktonic zonation (Blow 1969)	Age	Important Benthonic species
Not differentiated on plank-tonics	N23	Holocene	*Hyalinea baltica*, *Bolivinita quadrilatera*, *Hoeglundina elegans*, *Valvulineria jauana*, *Ceratobulimina pacifica*, *Cassidulinoides inflatus*, *Burseolina sp. 2*, *Favocassidulina favus*
Gl. truncatulinoides Zone	N22	Pleistocene and Holocene	
Up. *Gl. oides quadrilobatus fistulosus* Zone	N21	Late Pliocene	
Lr			
Sphaeoridinellopsis-Sphaeroidinella Zone	Late N19 (? + N20)	Early (and Mid-) Pliocene	
G. nepenthes-Sphaeroidinella Zone	Early N19	Early Pliocene	
G. nepenthes-Sphaeroidinellopsis Zone	N18	Late Miocene Early Pliocene	

G., *Globigerina; Gl.*, *Globorotalia; Gl. oides*, *Globigerinoides;* Up., Upper; Lr, Lower

Fig. 4. Biostratigraphic zonation used by D. J. Carter who used the scheme of Blow (1969) as his framework. Carter modified this scheme for the local zonation as outlined in Audley-Charles (1986*a*).

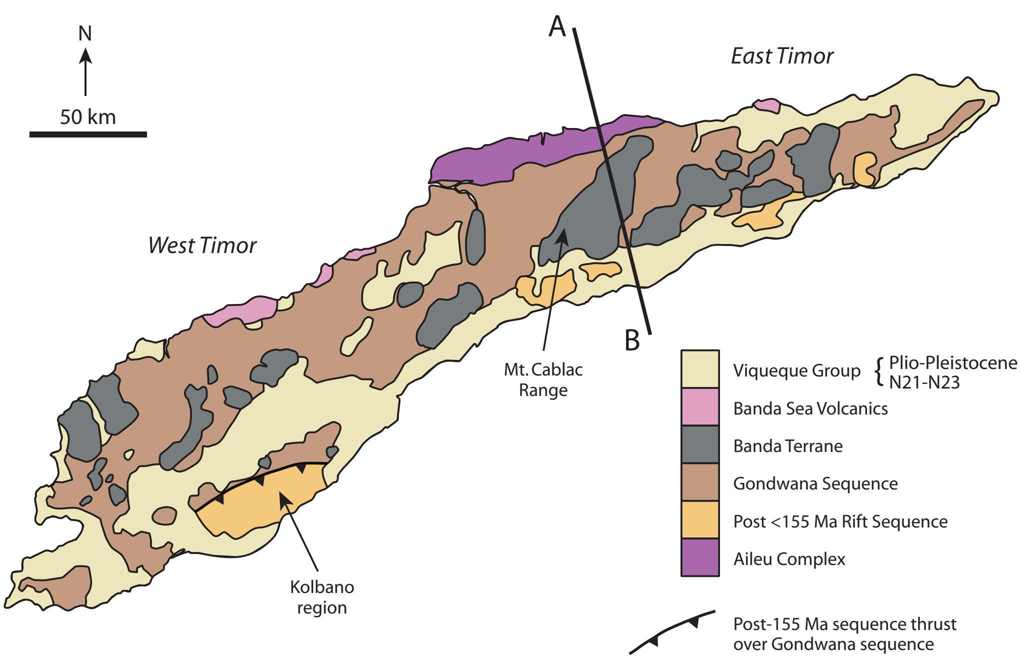

Fig. 5. Principal features of Timor geology simplified after Standley & Harris (2009). Line AB is shown on Figure 8. Banda Sea volcanic rocks are part of the Banda Terrane. The Gondwana mega-sequence shown here includes the Bobonaro Melange, its related broken formation facies, matrix mixed facies and a mixed block in clay facies. These contain some the post-rift mega-sequence blocks and some of its shales and mudstones.

occasional turbiditic arenites (Kenyon 1974). These were dated by D. J. Carter as zones N18–N19 (in Audley-Charles *et al.* 1979) which correspond to an age of 5.6 to 3.8 Ma. Microfossils in the Lower Batu Putih Limestone dated by D. J. Carter (in Kenyon 1974; in Audley-Charles 1986*a*) from more than 50 samples as zones N18 to N19 were: *Globorotalia cultrata*, *cultrata*, *Gt. menardii*, *G. tumida tumida (sinistral)*, *Globigerina nepenthes*, *Pulleniatina primalis*, *Globigerinoides gomitulus*, *Gdes des ruber*, *Gdes conglobatus*, *Gdes quadrilobatus* sp., *Gdes obliquus obliquus*, *Sphaeroidinellopsis seminulina knocki* and *Sphaeroidinellopsis subdehiscens paenedehiscens*; Benthonics: *Textularia* spp., *Cibicides* spp., *Spiroplectammmina* spp., *Uvigerina*, spp., Miliolacea, *Bulimina* spp., Nodosariacea, *Planularia* spp. and *Oridorsalis* spp.

Overlying these rocks with a disconformity is the notably different, soft and friable Upper Pliocene, Fatu Laob Member of the Upper Batu Putih Limestone that is overlain by the Sabaoe Calcarenite. The Fatu Laob Member was dated by D. J. Carter (in Audley-Charles *et al.* 1979; in Audley-Charles 1986*b*) as zone N21, which correlates with about 3.0 to 1.81 Ma, by a microfauna including *Globoquadrina dehiscens dehiscens*, *Sphaeroidinellopsis seminula seminula*, *Globigerina decoraperta* and *Pulleniatina obliquilocata praecursor*.

By using the lower Batu Putih sequence from the Kolbano imbricate zone, that is part of the Australian upper crust (para-autochthon) and the post-rift mega-sequence, below which is the Gondwana mega-sequence, one is sampling the youngest rocks in the strongly deformed part of the orogenic pile. The youngest rocks involved in the deformation indicate the closest we can date the onset of collision, but obviously this date is older than the beginning of the deformation owing to the erosion associated with onset of deformation. The oldest rocks that sit here with a disconformity (the zone N20 being locally absent) on the youngest member of the deformed sequence, namely the upper part of the Batu Putih Limestone, date the rocks deposited after the strong deformation phase. This section, younger than N20, is the oldest part of the Australian autochthonous sequence belonging to the Viqueque Group. Together these two dates, below and above the N20 disconformity, bracket the onset of collision interpreted as the strong deformation in the Tectonic Collision Zone that replaced the Banda Trench, where Australian continental crustal rocks were blocked from subducting below the Banda volcanic fore-arc.

It is notable that no N20 zone deposit has been found in the para-autochthonous sequence of the Kolbano region in contrast to its reported presence in the softer and friable autochthonous Viqueque Group of the Central Basin of West Timor (de Smet *et al.* 1990) some 40 km or more to the north. This local absence of N20 zone microfossils and the presence of diagnostic foraminifera for N21 suggest that the strong structural processes that deformed the para-autochthonous sequence in Timor had begun about 4 Ma and ceased about 2.5 Ma in the post-155 Ma rift Australian upper crust autochthonous sequence of the Viqueque Group of Kenyon (1974).

The microfauna identified by D. J. Carter (in Kenyon 1974; in Audley-Charles *et al.* 1979; Audley-Charles 1986*a*) from the Noele Marl turbidite facies that overlie the Upper Batu Putih Limestone range from Late Pliocene to Recent, N21 to N23 zones, on the basis of *Globorotalia truncatulinoides* and *Gt. tosaensis.* Benthonics *Hyalina baltica*, *Bolivinita quadrilera*, *Hoeglundina elegans* are also present. This Viqueque turbidite facies in the Kolbano region therefore ranges from about 3.0 to 0.63 Ma. This correlates with the uplift and subaerial erosion of the emerging Timor Island that appear to have begun by about 2 Ma in some places. The main collision deformation could have been over in the Kolbano region of Timor in about 1 million years during the mid-Pliocene, although some mild folding continued into the Late Pliocene and Pleistocene N22 and N23 in places referred to as the Mataian folding phase (Audley-Charles 1968, 1986*a*; Kenyon 1974).

Relative dating of the collision by the degree of induration and deformation

All the stratified para-autochthonous rocks of Timor, ranging in age from Early Permian to Early Pliocene, are indurated, strongly folded, faulted and thrust, and the younger post-155 Ma rift mega-sequence rocks are locally imbricated. The sedimentary rocks that belong to the autochthon and range from Middle Pliocene to Pleistocene are not indurated. These folded post-Middle Pliocene–Pleistocene (N22–23) rocks lack strong deformation. These differences clearly distinguish those that were deposited before the Neogene onset of the *c*. N20 tectonic collision.

Dating the Bobonaro Melange: pre-decollement activation

The Sonnebaitserie of Tappenbeck (1940) and other earlier workers in West Timor was mapped in East Timor by Audley-Charles (1965, 1968) as the Bobonaro Scaly Clay, regarded as an olistostrome emplaced in the Middle Miocene on the basis of relative stratigraphic relationships. Later Harris *et al.* (1998) renamed this the Bobonaro Melange.

They also noted three end member subdivisions of the Bobonaro Melange which are broken formation facies, matrix mixed facies, and a mixed block-in-clay facies. One can now consider that the Bobonaro Scaly Clay exposures without exotic blocks are matrix mixed facies. Locally this facies, widely exposed in Timor, contains a N22 Pleistocene foraminiferal assemblage identified by Carter as *Globorotalia truncatulinoides*, *Pulleniatina obliquilocata*, *Sphaeroidinella dehiscens* and *'Globigerina' subcretacea* (Audley-Charles 1986*a*). This indicates that the Bobonaro Melange matrix mixed facies with Pleistocene foraminifera derived from the soft strata of the Viqueque Group exposed upslope, is locally a younger reworked version of the Bobonaro Melange and is often associated with landslips.

In an unpublished report D. J. Carter (1970, in Audley-Charles 1986*a*) noted that, despite the intensive study of hundreds of samples, no species of Oligocene or Miocene age (except those in exotic fragments of allochthonous Cablac Limestone) has been found in the Bobonaro Melange. However, Middle Eocene planktonic assemblages are abundant: *Globorotalia centralis, Globigerina ampliapertura, Globigerina parva*, *Globigerina venezuelana*, *Globigerinatheka barri*, *Catapsydrax echinatus*, *Hantkenina dumblei*, *Hantkenina alabamensis*, *'Globigerapsis index'*, *Globorotaloides suteri*, *Truncorotaloides topilensis*, *Hastigerina micra*, *Globigerina yeguaensis* and *Chiloguembelina martini.*

It is likely that the Bobonaro Melange, that is mud-dominated and in many places in a scaly clay facies, as well as the broken formation facies would have been generated early in the collision process where there was some chaotic crushing and shearing of stratigraphic sequences that were trapped in the vice between the volcanic fore-arc basement and the top of the Australian crystalline lower crust. This seems likely to have preceded the activation of the two important Australian upper crust mega-sequence decollements, D1 moving the post-155 Ma rift and the D2 decollement moving the pre-rift Australian mega-sequence (Figs 2 & 5). These Australian continental upper crust rocks were crushed and sheared so that the Jurassic clay shales and the Eocene clay sequences make a notable contribution to the Bobonaro Melange and to the broken formation.

The age of the Bobonaro Melange is not easy to determine. Its age of emplacement is not known precisely. D. J. Carter (pers. comm. 1980) commented that the microfauna found in the Bobonaro Melange does not assist us in this matter, as all taxa are derived and reworked and range in age locally from Permian to Quaternary (Audley-Charles 1968; Giani 1971; Kenyon 1974; Hamilton 1979). Carter *et al.* (1976) found the youngest Kolbano strata underlying the Bobonaro Melange were N17 and that N18 faunas of 5 Ma age are found in the overlying Viqueque Group. This suggests that the Bobonaro Melange is not older than 5 Ma.

Standley & Harris (2009) and Harris *et al.* (1998) pointed out that the Bobonaro Melange is closely associated with the allochthonous Banda Terrane, and they noted that it is present below the base of the Lolotoi and Mutis Metamorphic Complexes that form the base of this terrane. It seems likely that the Bobonaro Melange may have acted as, or with, the decollement on which the terrane moved, thus facilitating the terrane's transfer upwards and southwards from the Banda fore-arc before its emplacement on top of the Australian para-autochthon. Harris *et al.* (1998) interpreted the Bobonaro Melange as 'having formed along the suture between the Asian-affinity fore-arc thrust sheets above and thrust duplex of Australian continental margin units below'. They also interpreted the maximum age of the injection of Bobonaro Melange into the Kolbano sequence with its Viqueque Group cover to be 5 Ma.

Offshore bathyal continental terrace

Haig & McCartain (2007) suggested that 'a middle bathyal continental terrace setting continued in this region, at least on the southern side of Timor, from Cretaceous–Palaeogene to the Late Miocene and Early Pliocene'. This means that from 140 to 4.5 Ma the Timor region, or at least its southern part, was in a medium to deep water setting. This makes a strong contrast with the shallow marine cover rocks, such as the Eocene Dartollu Limestone thrust onto, and the Upper Oligocene to Lower Miocene Cablac Limestone found unconformable upon, the metamorphic basement of the Banda Terrane (Audley-Charles 1968; Carter *et al.* 1976).

Volcanic activity

When continental margins collide with volcanic fore-arcs the volcanoes cease their activity. To the north of Timor is the longest and most obvious extinct sector of the entire Sunda–Banda volcanic arc (Wheller *et al.* 1987) in the islands of Alor, Atauro, Wetar and Romang. All these volcanic islands are less than 50 km from the Australian continental margin that has overthrust the Banda fore-arc, and Atauro is only 25 km from the Australian continental margin. The four islands are no longer volcanically active and activity ceased at about 3 Ma (Abbott & Chamalaun 1981). Scotney *et al.* (2005) studied massive sulphide and barite-gold mineralization of Wetar Island triggered by Banda Arc–Australian continental margin collision.

They obtained Ar–Ar ages of 4.7 ± 0.16 Ma from biotite and 4.93 ± 0.21 Ma from illite in altered footwall volcanic rocks associated with mineral deposits that formed on the flanks of a volcanic edifice at water depths of *c*. 2 km. These are covered by post-mineralization cherts, gypsum, *Globigerina*-bearing limestone, lahars, subaqueous debris flows and pyroclastic rocks. The youngest dated volcanic rock is a dacite of 2.39 ± 0.14 Ma. Scotney *et al.* (2005) interpret the volcanic stratigraphy and dating to indicate that the Wetar edifice formed at around 12 Ma by extensive rifting and associated volcanism within oceanic crust. Bimodal volcanism and a basement of basalts and basaltic andesite most likely formed around 5 Ma, with mineralization between 4.9 and 4.7 Ma. Post-mineralization dacite flows indicates that volcanism continued until at least 2.4 Ma.

A similar history is recorded on Sumba where breakup of a carbonate platform began in the early Middle Miocene leading to rapid subsidence from about 16 Ma (Fortuin *et al.* 1994). There was a significant increase in volcanic activity in the Middle Miocene, and a change to volcaniclastic turbidites deposited on Sumba and in the Savu Basin (Fortuin *et al.* 1992, 1994) from NN5 (14.8–13.5 Ma) to NN11 (8.3–5.5 Ma). The very young age of collision west of Timor is indicated by the still active, or only recently inactive, volcanic arc in western Flores (Wheller *et al.* 1987), ongoing deformation at the margins of the Savu Basin (Rigg & Hall 2011), and recent emergence of the islands of Roti and Savu (Roosmawati & Harris 2009).

Uplift and erosion

The obvious has too often not been mentioned in the debate about the age of Timor collision, and one important issue is the timing of uplift and erosion expected as the Australian margin collided with the volcanic arc. In East Timor uplift seems to have began at about 4 Ma (Audley-Charles 1986*a*) with estimated average rates of uplift of 1.5 km/Ma. For West Timor de Smet *et al.* (1990) found that significant uplift began at about 2.2 Ma, and that emergence from water depths of 1 km to elevations of 0.5 km above sea level occurred in the last 0.2 Ma at average rates of 0.75 to 1.0 km/Ma. Haig & McCartain (2007) state that proximal turbidite deposition from the rising island of Timor began at about 3.35 Ma. Quaternary limestones are mapped in West Timor at elevations above 1 km (Suwitodirjo & Tjokrosapoetro 1996). Roosmawati & Harris (2009) show that for the islands of Savu and Roti significant and rapid uplift from water depths of more than 2 km to emergence began at about 2 Ma. On Sumba there was uplift from depths of more than 5 km to emergence of up to 1 km above sea level since 4 Ma (Fortuin *et al.* 1997). The uplift of Timor over the last 2 Ma was at least 4 km in places (Audley-Charles 1986*a*). Furthermore, the production of clastic sediment from Timor over the last *c*. 2 Ma has built the sedimentary slope, aided by the young D5 decollement, that extends from the 3 km deep axis of the Timor Trough to many metres above sea level along the south coast of Timor for about 480 km length and over a width of 50 km.

Orogeny-engendered stratigraphic diachronism

Some of the Pliocene para-autochthonous and autochthonous strata of Timor and other islands of the Outer Banda Arc are diachronous. Harris *et al.* (2009) and Roosmawati & Harris (2009) have noted that in East Timor the Batu Putih Formation (lower or upper parts not indicated) is overlain by N19/N20 Noele Marl clastic deposits (Kenyon 1974). In the Central Basin of West Timor the upper sections of Batu Putih Formation (lower or upper parts not indicated) are dated as N20 by de Smet (1990). In Roti (immediately SW of Timor) the youngest Upper Batu Putih Formation is late N23 (Roosmawati & Harris 2009); further west in Savu Island the youngest Upper Batu Putih Formation is N22/23. This represents an age range of 4 to 0.5 Ma for the Upper Batu Putih Formation.

Diachronism is further illustrated by the significantly different results obtained for Neogene–Quaternary vertical movements in the Central Basin of Timor (de Smet *et al.* 1990) and those obtained in West Timor outside the Central Basin by Audley-Charles (1986*a*). The Central Basin of West Timor, that was at times subsiding and at other times rising, is located between the Kolbano younger mega-sequence imbricate zone in the south and the Banda Terrane in the north (Audley-Charles 1986*a*). In the Batu Putih Limestone (lower or upper part not indicated) of the Central Basin Viqueque Group Australian autochthon de Smet *et al.* (1990) found N20 foraminifera, but *c*. 40 km south, located above the Kolbano imbricate succession of the post-rift mega-sequence, underlain by the Gondwana mega-sequence, Carter (in Audley-Charles 1986*a*, *b*) reported that the N20 zone was absent below the N21 Upper Batu Putih Limestone.

This orogeny-related diachronism could be the result of several factors: the irregular shape of the Australian continental margin, different times during the collision at which different parts of the post-155 Ma rift mega-sequence were deformed in the Banda Trench, and continual stacking of the deforming Australian continental margin mega-sequences in the TCZ; equally there is also a range in age of uplift in different parts of the 480 km long, 75–100 km wide Timor Island.

Discussion of collision ages

In the Banda region, notably in Timor, interpretation of ages has led to confusion and also claims of multiple or pre-Pliocene collisions. As pointed out above, some of the variation in ages may be the consequence of diachroneity reflecting the irregular shape of the Australian margin, or an oblique collision (e.g. Harris 1991). Nonetheless, all the ages are consistent with a collision beginning at about 4 Ma or slightly later. Deep-water sedimentation continued into the Pliocene with a succession of Plio-Pleistocene Viqueque Group friable chalks deposited in lower to middle bathyal water depths with a quiet tectonic interval. Proximal turbidite sedimentation in southern Timor was dated by Carter (in Audley-Charles *et al.* 1979) at 3 Ma, and by Haig & McCartain (2007) at 3.35 Ma.

However, some authors have followed Berry & Grady (1981) and Berry & McDougall (1986) in interpreting high grade metamorphosed rocks with cooling ages of 8 Ma as marking initial collision of Australian crust with the Asian margin. Based on deformation, principally fault reactivation, of NW Shelf sequences in the Timor Sea south of the Timor Trough (i.e. more than 100 km south of the southernmost deformation front located at the axis of the Timor Trough, Fig. 3), an 8 Ma collision age has been suggested in the Sumba region by Keep *et al.* (2002, 2003). An even older age has been suggested by Keep & Haig (2010) for Timor, where they proposed that tectonic collision began between 10.8 to 9.8 Ma.

Pre-Pliocene collision ages are very improbable in the light of the evidence summarized above, and ages of initial collision of about 10 Ma are untenable. Much of the Banda volcanic arc is significantly younger than 10 Ma. North of Timor the age of initiation of volcanic activity is uncertain but there are few volcanic rocks anywhere in the arc with ages greater than 12 Ma (Abbott & Chamalaun 1981; Macpherson & Hall 2002). The oldest volcanic rocks on Flores, NW of Timor are 16 Ma (Fleury *et al.* 2009), based on unpublished K–Ar ages from Hendaryono (1998), and volcanic rocks there fall into two age groups, with ages from 16 to 8.4 Ma and 6.7 to 1.2 Ma. On Wetar volcanic activity began at about 12 Ma and continued until at least 2.4 Ma (Scotney *et al.* 2005). In the South Banda Sea back-arc spreading occurred between 6.5 and 3.5 Ma (Hinschberger *et al.* 2001). A continuation of volcanic arc activity for a period after initial contact between the fore-arc and Australian margin is plausible, but advocates of a Miocene 10 to 8 Ma collision fail to explain why arc volcanic activity continued until after 3 Ma in Flores and Wetar.

In fact, Keep & Haig (2010) make little attempt to explain events outside Timor and show only an unscaled diagram which displays elongate promontories projecting northwards in the regions of East Timor and Sumba. Even a brief consideration of rates of subduction show that these narrow promontories would have to extend several hundred kilometres northwards to cause collision at 10 or 8 Ma. Reconstructions of the Banda region (Hall 2002; Spakman & Hall 2011) suggest that about 10 Ma the Banda Trench was located *c.* 600 km north of its position at 4 Ma. There is no evidence for the Australian continental margin having extended significantly north of what is now Timor, even allowing for the overthrusting of the Banda volcanic fore-arc and shortening of the Australian margin, although there probably were offsets in the continental margin (Harris 1991; Hall 2002).

All the evidence discussed above rules out (Fig. 1) a tectonic collision between the continental margin of Australia and the Banda volcanic fore-arc at about 10.8 to 9.8 Ma, as claimed by Keep & Haig (2010). Other explanations of the 8 Ma metamorphic event are discussed below.

Composition and origin of the Banda Terrane basement

Metamorphic rocks and sedimentary cover sequence with an Asian affinity, derived from the fore-arc of the Banda Volcanic Arc, were emplaced on what was to become Timor during the Neogene, in structurally high positions as thrust sheets called the Banda Terrane (Audley-Charles & Harris 1990; Harris 1991). They are found sitting on the highly deformed para-autochthonous part of the Australian Gondwana mega-sequence of Early Permian to mid-Jurassic age (Figs 2 & 5). The basement rocks of the Banda Terrane are known as the Mutis Metamorphic Complex in West Timor (Earle 1981; Brown & Earle 1983) and are correlated with the Lolotoi Metamorphic Complex in East Timor (Audley-Charles 1968; Barber & Audley-Charles 1976; Standley & Harris 2009).

Allochthonous Asian status of metamorphic complexes

The truly allochthonous nature of the Mutis and Lolotoi Metamorphic Complexes has now been further confirmed by Standley & Harris (2009) in their petrological study of the Lolotoi Metamorphic Complex. They presented data indicating that one sample from the Lolotoi has ‘a Late Cretaceous sedimentary protolith deposited after 82 Ma', and the 'Lolotoi Complex has a metamorphic age of 46 Ma. It has cooling ages of 39–35 Ma. The detrital zircon grains in the Lolotoi are as young as 82 Ma within the core of the Bebe Susu Nappe of East Timor'. The Eocene metamorphic age for the Lolotoi and Mutis Complexes are incompatible with these complexes having been a part of the Australian continental basement of Timor Island, as suggested by some authors (Grady 1975; Chamalaun & Grady 1978; Charlton 2002). Standley & Harris (2009) also reported that 'the Lolotoi Complex records all the deformation events reported from the Mutis Complex'. The postulated correlation of the Alieu with Lolotoi metamorphics (Kaneko *et al.* 2007) is also incompatible with the detailed work of Standley & Harris (2009), for example, no zircon grains younger than Permian are found in the Aileu Complex. Apatite grains in the Aileu are highly annealed yielding exhumation fission track ages of <2 Ma whereas in the Lolotoi Complex apatite grains have model ages of <23 Ma. The Lolotoi and Mutis Complexes are also overlain by a Late Oligocene unconformity.

Significance of Aileu Formation metamorphism for the age of tectonic collision

Keep & Haig (2010), citing the work of Berry & McDougall (1986) on the 8 Ma cooling ages of the Aileu Formation, claim that this implies 'that the earliest collision of some part of the Australian margin occurred prior to this time, and that the rocks were subducted, metamorphosed and exhumed by 8 Ma'. Another view (Standley & Harris 2009) is that the metamorphism of the Aileu with cooling ages of 8 to 4 Ma indicate these rocks were present at *c.* 8 Ma about 35 km below the Banda Trench. That means they were located in the fore-arc basement of the Banda Volcanic Arc before *c.* 8 Ma and would have been already metamorphosed at that depth.

Keep & Haig's (2010) suggestion of an 8 Ma collision conflicts with the evidence presented above, and it requires, as does the Standley & Harris (2009) model, that the Australian continental crust had been subducted to about 35 km depth below the Banda fore-arc where it was metamorphosed to amphibolite grade between *c.* 8 to 4 Ma. Tectonic collision is defined here as contemporaneous with the blocking of Australian continental crust in the trench from subducting below the fore-arc. There is no evidence that any Australian continental crust was subducted in the Banda Trench system, quite the contrary, evidence suggests that much of the upper and lower crust were rejected by the subduction system. The upper crust was stacked to fill the trench, while the crystalline lower crust seems to have been thrust northwards from the base of the Banda Trench over the downward-flexing, northward-dipping, subducting mantle lithospheric slab, thus blocking the subduction system against any continental crust (Figs 6–8). The suggestion of an 8 Ma tectonic collision anywhere in the southern part of the Banda Arc finds no foundation in field observations or laboratory science.

Another way of thinking about the 8 Ma cooling ages and the first and second deformation phases of the Aileu amphibolites in the narrow, Timor north coast strip and adjacent small islands seems to fit all the evidence. These cooling ages and deformation can be regarded as the product of metamorphism of a part of the fore-arc basement associated with thermal conditions in the fore-arc adjacent to the active volcanism in Alor, Atauro and Wetar Islands. Harris & Long (2000) reported that fission tracks in apatite grains in the Aileu Formation are, highly to completely annealed, indicating an exhumation age of <2 Ma. This Late Pliocene exhumation age would correspond with upward movement of the Aileu amphibolites facilitated by the extension in the Banda fore-arc, associated with its subsidence into the trench, caused by rollback of the subducting sub-crustal lithospheric slab, and result from the upward movements along the Wetar Suture (Fig. 8). These Aileu amphibolites were taken from the fore-arc basement by the moving Wetar Suture and lower crust and carried upwards where they were moved together with the Aileu glossy slates and phyllites (Fig. 8). These slates and phyllites could have formed deep in the TCZ but some distance above the lower crust. From there the decollement, at the base of the Gondwana mega-sequence, moving upwards associated with the lower crust and Wetar Suture, late in the collision process, could have delivered these rocks to where we find them today (Fig. 8). 'The structure of the Aileu is characterized by a very distinct layer and foliation parallel shortening that forms a layer normal cleavage and foliation' (Standley & Harris 2009). This is different from the structure of the rest of the Gondwana mega-sequence, and may have resulted from it having occupied a deeper position in the TCZ before its transfer upwards to its present position (Fig. 8).

Another explanation for Australian continental basement in the Banda fore-arc is offered by Hall (2002, 2011) and Spakman & Hall (2010). The Banda Terrane in Timor appears to be a complex that includes continental crust, arc and fore-arc that formed part of the Early Cenozoic Asian margin together with their overlying sedimentary rocks. The Banda fore-arc also included Australian

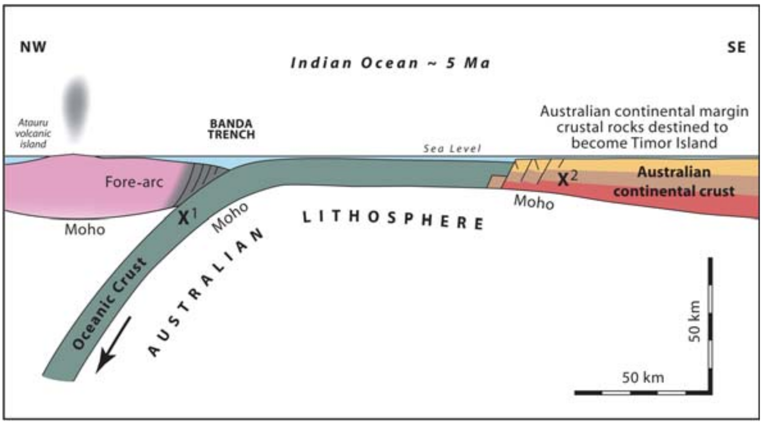

Fig. 6. Cartoon cross section of 5 Ma pre-collision. Note no Australian crust was subducted with sub-crustal mantle lithosphere. When X2 arrived at X1 (4 Ma) all ocean crust had been subducted and the Australian continental crust was refused entry to the subduction passage. This tectonic collision of the Asian fore-arc with the Australian continental margin began at the Banda Trench which was to gradually become the Tectonic Collision Zone shown in Figure 8.

continental crust from the Sula Spur that collided in the Early Miocene with Asian Neogene arc and was then extended during the Late Miocene during roll-back (Spakman & Hall 2010). The first contact of the Australian and Asian margins was collision of the Australian Sula Spur soon after 25 Ma (Spakman & Hall 2010) and recorded by metamorphic rocks in Asian Sulawesi (e.g. Parkinson 1998*a*, *b*; van Leeuwen *et al.* 2007) and dredged samples from the Banda Ridges (Silver *et al.* 1985). A 24 Ma age is recorded in Timor (Berry & McDougall 1986) although this has not previously been explained. During the Neogene Australian-origin crust added to the Asian margin by collision was extended by rollback in the Banda Embayment (Spakman & Hall 2010). Extension was discontinuous, indicated amongst other evidence by oceanic spreading in the North Banda Sea from 12.5 to 7.2 Ma and South Banda Sea from 6.5 to 3.5 Ma (Hinschberger *et al.* 2000, 2001), and an episode

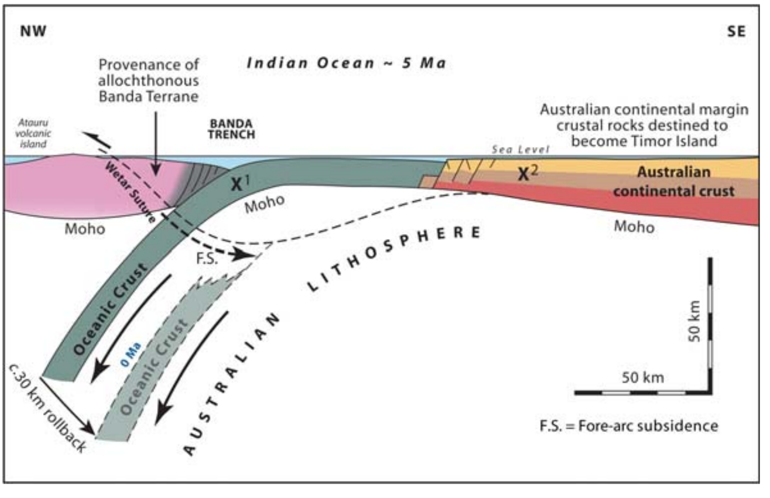

Fig. 7. Cartoon cross section of pre-collision 5 Ma repeating the configuration of Figure 6. The pecked line shows bottom of the Banda Trench profile after the X1–X2 tectonic collision. It shows that there has been no subduction of continental crust. It also shows the subsequent rollback and subduction of sub-crustal mantle lithosphere. Note subsidence of Banda Trench-TCZ after 30 km of southeastwards rollback from 4 to 0 Ma, and accompanying northwards subduction of sub-crustal mantle lithosphere. Note also subsidence of fore-arc (F.S.) linked with the rollback.

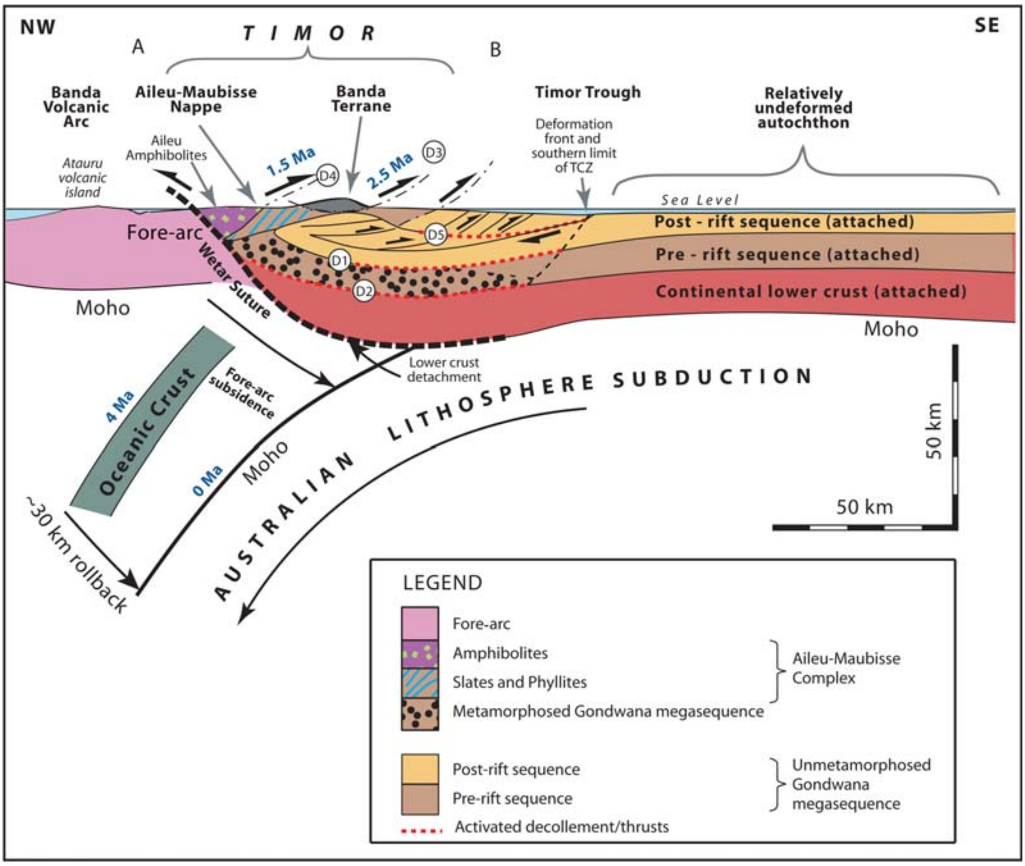

Fig. 8. Cartoon cross section of Timor today, (cf. Richardson & Blundell 1996, their BIRPS figs 3b, 4b & 7; and their fig. 6 gravity model 2 after Woodside *et al.* 1989; and Snyder *et al.* 1996 their fig. 6a). Dimensions of the filled 40 km deep present-day Timor Tectonic Collision Zone are based on BIRPS seismic, earthquake seismicity and gravity data all re-interpreted here from Richardson & Blundell (1996) and from Snyder *et al.* (1996). NB. The Bobonaro Melange, its broken formation and other facies are not indicated, but they are included with the Gondwana mega-sequence. Note defunct Banda Trench, now the Timor TCZ, filled with Australian continental crust and Asian nappes that occupy all space between Wetar Suture and the 2–3 km deep deformation front north of the axis of the Timor Trough. Note the much younger decollement D5 used exactly the same part of the Jurassic lithology of the Gondwana mega-sequence in the older D1 decollement that produced what appears to be much stronger deformation.

of arc volcanism from 8 to 3 Ma is recorded in the North Banda region (e.g. Honthaas *et al.* 1998) and the Banda Ridges (Silver *et al.* 1985). All these rocks record metamorphic cooling ages associated with the Neogene extension. Similar complex Australian crust is known from several of the small islands east of Timor from Leti to Babar, and Bowin *et al.* (1980) commented on the anomalous pre-collision position of these rocks within the Banda Outer Arc. Hall (2011) suggests the assumption that metamorphic ages mark contractional deformation that accompanied an early collision is wrong – the ages simply record cooling, which in most cases resulted from extension. The ages do not record the time of collision at the place the rocks are now found, because they have been moved to their present positions by extension of the upper plate above the retreating subduction hinge, and the Neogene metamorphic ages record extension of this complex upper plate (Spakman & Hall 2010; Hall 2011).

Asian cover rock sequences of the Banda Terrane

The Banda Terrane (Fig. 5) is now found occupying high ground, usually as gently folded thrust sheets, with much post-emplacement steep faulting. The metamorphic rocks are covered in places by several different, mainly sedimentary sequences, and some basic volcanic and volcaniclastic rocks. Tappenbeck (1940) explained the stratigraphy of some of these rocks overlying the Mutis Metamorphic Complex in terms of three distinct sequences, all of which have been found in the equivalent stratigraphical and structural position in East Timor (Audley-Charles & Carter 1972; Carter *et al.* 1976; Standley & Harris 2009).

What makes these stratigraphic sequences, which are unconformable or thrust onto the Mutis and Lolotoi Metamorphic Complexes, so important is that some of these supra-metamorphic sequences are of Asian affinity, and the others seem likely to be Gondwana mega-sequence thrust slices emplaced after the Banda Terrane arrived in Timor (Fig. 2). Here the key features of the cover rock sequences are first summarized, and then some controversies concerning their status and significance are discussed.

Triassic sequences

Mapping on a 1:25 000 scale by Tappenbeck (1940) shows exotic blocks of Upper Triassic Bahamian limestones, mainly on the slopes of Mt Mollo in West Timor, associated with exotic blocks of Permian crinoidal limestones, as part of the Sonnebaitserie (which today would be referred to as Bobonaro Melange). His map strongly suggests that the Bobonaro Melange with various exotic blocks once covered the whole of Mt Mollo which is a massif of the Mutis Metamorphic Complex. Keep *et al.* (2009) reported similar Bahamian-type limestones of Upper Triassic age in a thrust stack high on Mt Cablac. They might be Australian, or perhaps Asian and truly allochthonous.

Upper Jurassic and Cretaceous Palelo Group sequences

The lowest sequence of the Palelo Group rocks, referred to as the Metan Formation, is comprised of mainly agglomerates and tuffs. It is thought to be of Late Jurassic age because it is found below Lower Cretaceous cherts, dated as Aptian–Turonian with radiolaria (Haile *et al.* 1979) of the Cretaceous Noni Formation (Earle 1983). These rocks are commonly in fault contact with the Mutis and Lolotoi Metamorphic Complexes and are often associated with the Bobonaro Melange. This is shown by Tappenbeck (1940) on his 1:25 000 map of Mt Mollo.

Paleocene Palelo Group sequences

A Paleocene sequence of volcanic rocks and volcaniclastics, known as the Haulasi Formation, is found with angular unconformity on the Cretaceous Noni Formation in West Timor (see Tappenbeck's map). This Mesozoic–Paleocene sequence is discussed by Tappenbeck (1940), Audley-Charles & Carter (1972), Audley-Charles *et al.* (1974), Rosidi *et al.* (1996), and Earle (1983).

Middle and Upper Eocene

The Eocene Dartollu Limestone (Audley-Charles & Carter 1972; Carter *et al.* 1976) is found resting with a faulted base on the Lolotoi and Mutis Metamorphic Complexes in both West and East Timor. It is possible that these Eocene rocks are locally unconformable on the metamorphic complexes. One importance of this limestone is the palaeontological evidence of its Asian origin (Lunt 2003), as this supports the allochthonous status of the metamorphic complexes of the Banda Terrane (see Tappenbeck's map).

Oligocene

The Oligocene Barrique Volcanic Formation that is found widely in East Timor where it is locally found thrust on the Lolotoi Metamorphic Complex. The Barrique Formation is overlain unconformably by the Cablac Limestone of Late Oligocene to Early Miocene age (Audley-Charles 1968; Standley & Harris 2009). These Oligocene volcanic rocks have been shown to be typical of volcanic arcs and are incompatible with Australian continental margin igneous rocks (Standley & Harris 2009).

Upper Oligocene–Lower Miocene

The Upper Oligocene–Lower Miocene Cablac Limestone sits with eroded unconformity on the Mutis Metamorphic Complex of West Timor, in places with a cobble–pebble basal conglomerate, (Tappenbeck 1940, 1:50 000 map of Mt Booi) in West Timor, and is also present on Mt Mata Bia in East Timor (Standley & Harris 2009). Its presence on the lower slopes of Mt Cablac was reported by Audley-Charles (1968) and Carter *et al.* (1976). Standley & Harris (2009) also reported it sitting unconformably on the Lolotoi Metamorphic Complex on Mt Cablac. In contrast, Haig *et al.* (2008) claim that 'No Upper Oligocene to Lower Miocene stratigraphic unit has been found on Cablac Mountain'. This contradiction is discussed below.

Pliocene Manamas Volcanic rocks

Standley & Harris (2009) reported that these typical arc volcanic rocks are the youngest members of the Banda Terrane found locally on the north coast of Timor, having been derived from the basement of the Banda volcanic fore-arc. This discovery provides further support for Pliocene tectonic collision and late emplacement of this allochthonous terrane.

Stratigraphic and tectonic significance of the Mt Cablac Range, East Timor

The Mt Cablac Range (Fig. 5) is 15 km long. Its base is a thrust sheet of the Lolotoi Metamorphic Complex that functions as the base of the Banda Terrane throughout East and West Timor (Fig. 5) where it is usually overlain unconformably by the Cablac Limestone.

Mesozoic sequences

Triassic limestones on Mt Cablac, which occur in a Bahamian facies on the upper slopes, were not mapped by Audley-Charles (1968) because Mt Cablac was then considered sacred by local people and investigation of the upper slopes in 1959–1962 was prohibited.

Upper Triassic–Lower Jurassic limestones are now known from the higher levels of Mt Cablac, thanks to the more recent investigations reported by Haig & McCartain (2007), Haig *et al.* (2008) and Keep *et al.* (2009). Keep *et al.* (2009) published a geological sketch map at a scale of 1:100 000 concerned with the geology of part of the Mt Cablac Range. This map is described by Keep *et al.* (2009, p. 151) as 'detailed geological mapping', whereas on page 155 they describe it in their figure 5 caption as a 'generalized geological map of the Cablac Mountain Range'. It includes some discoveries, including an Upper Triassic Bahamian limestone, that appears to be similar to that mapped on Mt Mollo in West Timor by Tappenbeck (1940). The variety of lithology and age of sedimentary rocks and the igneous cover rocks reported by Haig & McCartain (2007), Haig *et al.* (2008) and Keep *et al.* (2009) on the Mt Cablac Range are all very similar to rocks reported from diverse Lolotoi and Mutis metamorphic massifs (where the unconformable Upper Oligocene to Lower Miocene Cablac Limestones are also found) in East and West Timor.

The Mesozoic and younger limestones reported by Haig *et al.* (2008) on the higher slopes of Mt Cablac appear likely to be either: (i) the remnants of a more extensive overthrusting of the Mesozoic and other rocks onto the upper slopes of Mt Cablac in a post-2.5 Ma event, or (ii) as on Mts Mollo, Booi, Mata Bia, and many other massifs in East and West Timor, exotic blocks that are part of the Bobonaro Melange. Earlier, Carter *et al.* (1976), had mapped Triassic limestones and Jurassic lithologies belonging to the para-autochthonous pre-155 Ma Gondwana rift sequence overthrust onto the Oligocene–Lower Miocene Cablac Limestone on the lower slopes of Mt Cablac.

Upper Oligocene–Lower Miocene Cablac Limestones

Audley-Charles (1968), as part of his mapping of East Timor at a scale of 1:250 000, described the variety of limestones he found cropping out on the lower slopes of the Mt Cablac Range as hard, massive calcilutites and calcarenites. Samples of these rock types were dated by D. J. Belford (of the Australian BMR) in 1960, reported in Audley-Charles (1968) as Te, Early Miocene. In 1963 D. J. Carter (reported in Audley-Charles 1968) studied samples from these lower slopes collected by Audley-Charles and confirmed their Te status and Early Miocene age. Later, Carter *et al.* (1976) visited the same lower slopes of Mt Cablac Range, which Carter sampled and confirmed their age as N3 to N8 (zonation of Blow 1969) which is Late Oligocene to Early Miocene.

What Audley-Charles (1967) identified on Mt Cablac as a brecciated, polymict intracalcirudite belonging to Upper Oligocene–Lower Miocene Cablac Limestone has since been interpreted by Haig *et al.* (2008) as a Pleistocene crush breccia in a local fault zone. On the basis of that revision Haig *et al.* (2008, p. 10) stated 'No Upper Oligocene to Lower Miocene shallow marine stratigraphic unit has been found on Cablac Mountain'.

This claim that no Upper Oligocene to Lower Miocene shallow marine limestones are present unconformably on the Lolotoi Metamorphic Complex contradicts the micropalaeontological and petrological analyses by D. J. Belford in 1960, and those by D. J. Carter in 1963 reported by Audley-Charles (1968), and Carter *et al.* (1976) when Carter re-confirmed his earlier finding. The claims by Haig *et al.* and Keep & Haig (2010) cited above, appear to imply that two very experienced micropalaeontologists, Belford and Carter, must have mistaken Triassic or other Mesozoic foraminifera for all the Late Oligocene and Early Miocene foraminifera in every limestone sample they reported on from Mt Cablac. This seems extremely improbable (Marcelle K. BouDagher-Fadel, pers. comm. 2009). Moreover, more recently, Standley & Harris (2009, p. 85) also reported finding Oligocene to Miocene Cablac Limestones, very similar to those reported by Audley-Charles (1968) and by Carter *et al.* (1976), on the lower slopes of the Mt Cablac Range where they can be seen sitting unconformably on the Lolotoi Metamorphic Complex.

Tectonic processes associated with the Australian para-autochthon and Asian allochthon

The collision was associated with the rejection of Australian continental crust by the Timor subduction system when it met the Banda volcanic fore-arc at the Banda Trench. Maybe the low density and the increasing thickness in the proximal slope of the submarine terrace or plateau led to its rejection. In contrast, Australian sub-crustal mantle lithosphere appears to have subducted normally. Audley-Charles (1988, fig. 14), Haig *et al.* (2008) and Roosmawati & Harris (2009) considered this Australian upper crust sequence similar to the Exmouth, Scott and related plateaux. The great differences in structural style between the younger post-155 Ma rift mega-sequence and the older pre-rift mega-sequence can be largely attributed to the significant differences in the sedimentary lithologies that characterize the different Australian mega-sequences. It is not known whether two mega-sequences, each with their own principal decollement, were activated simultaneously or not.

Tectonics of the Australian continental upper crust para-autochthon and its two mega-sequences

The mechanical solution, that nature exploited, while the subcrustal part of the lithosphere continued subducting, was to provoke the continental upper crust, of mainly stratified sedimentary rocks, that remained in the trench to activate decollements at the base of the two mega-sequences: namely D1 at the base of post-rift mega-sequence ranging in age from Late Jurassic to Neogene, and D2 at the base of the Gondwana mega-sequence ranging from Lower Permian to Middle Jurassic (Figs 2 & 8). The two mega-sequences remained attached to each other south of the subducting slab, where the lower mega-sequence remained attached to the Australian lower crust and thus to the continental mantle lithosphere. This caused the Australian upper crust to be pulled northwards into the trench where the compressive and related stresses must have increased significantly, as the Australian crust began to be packed ever more tightly. Eventually the two principal decollements were activated. This allowed the movement of the two mega-sequences in a coherent and discrete manner. In this way, each of them developed its own very different deformation style related to the very different lithologies comprising the two mega-sequences. Another important consequence of the activation of these two decollements was that, after the initial chaotic crushing phase, each mega-sequence then seems to have been deformed separately in the collision complex. The initial chaotic phase seems likely to have been responsible for the origin of the Bobonaro Melange and its facies.

Australian continental margin upper crust sub-late Jurassic decollement D1

Once the Middle Jurassic part of the Wai Luli Formation (Audley-Charles 1968), comprising considerable thicknesses of shales, acted as a decollement, this must have allowed the younger, Late Jurassic to Neogene post-rift mega-sequence to be strongly deformed with large-scale recumbent folds, thrusts, and with some strong to intense imbrication, as is well exposed in the Kolbano region of SW Timor. Extensive development of pressure solution cleavage and inversion of strata, evidence of multiple deformation, and the presence of large-scale flat-lying overthrusts distinguish this post-155 Ma rift sequence (Barber *et al.* 1977) from the structures in the older Australian mega-sequence comprised of the pre-rift part of the para-autochthon. This younger of the two mega-sequences is exposed almost only in the southern quarter of Timor Island, although it contributes numerous exotic blocks and clay matrix to the Bobonaro Melange, while the older Gondwana mega-sequence crops out in the northern three-quarters of the island. The widespread Bobonaro Melange and the associated broken formation facies suggest that without these two great decollements, D1 and D2, most of the two pre-collision sequences would have made Timor, as Fitch & Hamilton (1974) wrongly claimed it is, an island of mainly chaotic melange.

The Australian continental margin upper crust sub-Permian decollement D2

The oldest Australian continental margin sedimentary rocks of the Gondwana mega-sequence are Early Permian to late Middle Jurassic rocks that are highly deformed and exposed throughout Timor where all other rock sequences overlie the Gondwana mega-sequence. This distribution serves to emphasize the effectiveness of the decollements in the TCZ where they separated the mega-sequences tectonically.

The folds of this older mega-sequence range from ‘large scale culminations and depressions up to *c.* 10 km wavelength, with limbs often broken, and in thinner bedded sequences crumpled into smaller folds of 10 m or less in amplitude with axial planes vertical or steeply dipping southwards. Many overturned folds are towards the south but some are overturned northwards. Hinges are mostly broken and all rocks extensively affected by later faulting' (Barber *et al.* 1977).

Asian fore-arc basement, sub-allochthonous Banda Terrane decollement D3

The Lolotoi (East Timor) and Mutis (West Timor) metamorphic complexes are found at the base of the Banda Terrane throughout Timor. For the most part, the Banda Terrane is underlain by the Bobonaro Melange wherever the base of these metamorphic thrust sheets can be seen (Standley & Harris 2009). The Bobonaro Melange was produced from the Jurassic shales of the Gondwana mega-sequence and from the clay-rich zones of the Eocene rocks of the younger post-rift mega-sequence. They could have contributed to the lubricant for the decollement that facilitated the transport of the Banda Terrane. The structurally high position of this terrane above the deeply eroded Gondwana mega-sequence, indicates it must have been emplaced relatively late in the collision process (Figs 2, 5–8) following the deep erosion of para-autochthon. The Bobonaro Melange is also often found on slopes of the allochthonous Banda Terrane.

The Australian Aileu–Maubisse Gondwana mega-sequence sub-Permian decollement D4

The sub-Permian decollement at the base of the Gondwana mega-sequence must be present at the base of the Aileu Complex, that is only found in north part of East Timor (Figs 2 & 8) and in some of the very small islands north and east of Timor including Kisar, Leti and Sermata (Kaneko *et al.* 2007). The Aileu Complex lithologies range from amphibolite facies metamorphic rocks to unmetamorphosed sedimentary rocks of Permo-Triassic age. This complex is found in the most southerly part of its crop to interdigitate with the para-autochthonous rocks of Maubisse Formation of Permo-Triassic age (Barber & Audley-Charles 1976; Prasetyadi & Harris 1996). The most northerly, highly metamorphosed part of the Aileu Complex is exposed only along a narrow north coast strip and in some small islands a few kilometres north and east of Timor. This part of the Aileu Complex reaches amphibolite facies grade (Berry & Grady 1981). The metamorphic grade declines southwards in a relatively short distance from the north coast of Timor, with slates and phyllites that interdigitate in the southernmost part of the crop with the Maubisse Formation. It thus appears that, except for the amphibolites, the Aileu Complex is a part of the Australian Gondwana sequence. These amphibolites must have been metamorphosed to the north of Timor, and their last provenance must have been at about 35 km depth in the fore-arc basement of the Banda Volcanic Islands. This metamorphism can be attributed to the heat associated in the fore-arc basement when the Banda volcanic islands of Alor, Wetar and possibly Atauro were active.

Long after their metamorphism the Aileu amphibolites were carried upwards from this fore-arc lower crust in the Wetar Suture that emplaced them in the northern part of East Timor at about 2 Ma (Standley & Harris 2009; Spakman & Hall 2010). These metamorphosed sedimentary rocks seem likely to have been stacked in a deeper part of the TCZ than the unmetamorphosed Gondwana sequence (Fig. 8).

The Australian sub late–Jurassic post-rift mega-sequence decollement D5

The sub-Late Jurassic D5 decollement, mapped by Hughes *et al.* (1996) with BIRPS deep reflection seismic, was active in same Middle Jurassic Wai Luli Formation shales that function as the D1 decollement provoked by the collision event of about 4 Ma. However, the D5 decollement was a notably younger event than that involved in the D1 decollement. This D5 decollement is only present and active north of the deformation front located in the deep axis of the Timor Trough. South of the deformation front there is no D5 decollement, but of course the same Middle Jurassic shales continue to be present, where they are part of the undeformed Australian autochthon that occurs south of the bathymetric axis of the Timor Trough (Fig. 12). This D5 decollement thus marks a sharp transition from the Timor foreland, represented in the Timor Trough and Australian Shelf, and the collision zone north of the deformation front (Figs 8 & 12).

An additional contrast (cf. Figs 8 with 12) is the lack of any indication of a decollement or deformation below the two undeformed mega-sequences that Hughes *et al.* (1996) mapped in the Australian autochthon south of the deformation front in the Timor Trough. This is another piece of evidence that conflicts with the suggestions that the Timor Trough is or has been a Benioff subduction zone.

Tectonic processes associated with the Banda Trench, Wetar Suture and Timor Trough

The Wetar Strait is part of the Banda volcanic fore-arc and separates the volcanic islands Alor, Atauro and Wetar from Timor. The strait drops precipitously to more than 3 km depth and varies in width between about 25 km (Atauro), 35–75 km (Alor) and 50 km (Wetar). In these islands most of the volcanic activity ceased in the Pliocene (Abbott & Chamalaun 1981). The Wetar Strait opens westward into a 200 km wide fore-arc basin of the Savu Sea that also descends steeply from the north coast of Timor, and from the submarine margin of the Roti-Savu Ridge (Audley-Charles 2004, Fig. 1).

The downward flexing Australian plate comprising only mantle lithospheric slab and ocean crust (Snyder *et al.* 1996) is subducting below northern Timor, the Wetar Strait and the islands of the Banda Volcanic Arc. This subducted slab is traceable by earthquake seismology (Figs 8 & 9) to depths beyond 600 km (Engdahl *et al.* 1998).

The Banda Trench and the Wetar Suture

The Banda Trench was the morphological *c.* 6 km deep trench to the east of 120°E that continued the Sunda–Java Trench from about 12 to 4 Ma. It was located east of 120°E and south of 6°S, where the subduction zone refused to subduct the Australian continental crust at *c.* 4 Ma. This is called the Banda Trench because its subduction of Indian Ocean crust gave rise to the Banda Volcanic Arc from *c.* 12 Ma. The Wetar Suture has carried northwards the Timor tectonic collision zone (TCZ), with the stacked *c.* 40 km thickness of Australian continental crust and allochthonous Asian nappes, over the Banda volcanic fore-arc. All those islands of the Banda Volcanic Arc that are now less than 50 km from the Australian continental margin have been dormant for over 2 Ma. This part of the Australian continental margin correlates positively with the North Timor–Wetar aseismic triangle, an area in which there are almost no hypocentres between 75 and 300 km depth (Engdahl *et al.* 1998).

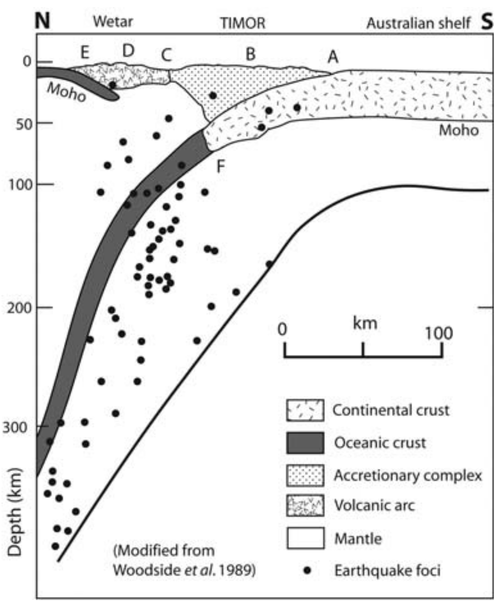

Fig. 9. BIRPS profile and earthquake seismology from Snyder *et al.* (1996, fig. 6a) with annotations by the present author: A is bathymetric deep axis of Timor Trough; B is Banda Trench now defunct and 40 km deep Timor TCZ, cf. Figure 8 of this paper. C is fore-arc basin, note steep, south-dipping slope of Banda Trench, now TCZ, corresponds to Wetar Suture on Figure 8. D is Banda volcanic fore-arc, E is Banda volcanic arc. F indicates that interpreted Australian continental crust extends only 6 km below the Banda Trench in the Snyder *et al.* interpretation (cf. Fig. 8).

The Wetar Suture (Fig. 8) can be interpreted as a major thrust zone developed early in the collision phase, intimately associated with the lower crust whose response to the deforming forces was very different from the much softer, well stratified Australian upper crust Gondwana mega-sequence. The Australian continental lower crust in the Wetar Suture carried the Gondwana mega-sequence nappes. This is also implied by the BIRPS data (Richardson & Blundell 1996), and the gravity data of Woodside *et al.* (1989), re-interpreted in this paper. It is indicated by regional geology and the extraordinary amount of impingement of the Australian continental margin on the Banda fore-arc to the north of central and eastern Timor (Audley-Charles 1986*a*, *b*; Hall & Wilson 2000). The continental margin post-rift mega-sequence may also have been carried northwards over the Banda volcanic fore-arc, but these younger rocks have been eroded from most of the northern part of Timor.

The Wetar Suture and associated Australian lower crust

The elevation difference between the bottom of the Wetar Strait and the north Timor coastal zone approaches 4 km in places. The exceptional steepness of the gradient between them suggests faulting, on what was postulated (Audley-Charles 1981; Audley-Charles 1986*a*, *b*) as the southward-dipping Wetar Suture (Figs 7 & 8). Richardson & Blundell (1996) mapped multiple south-dipping thrusts from BIRPS seismic data in the Banda fore-arc immediately east of Wetar and Kisar islands (Figs 10 & 11) that correspond closely with the postulated position of the Wetar Suture. Moreover, Masson *et al.* (1991) and Snyder *et al.* (1996) found a south-dipping thrust near the north coast of Kisar, but none of these authors noticed any connection with the postulated Wetar Suture. Breen

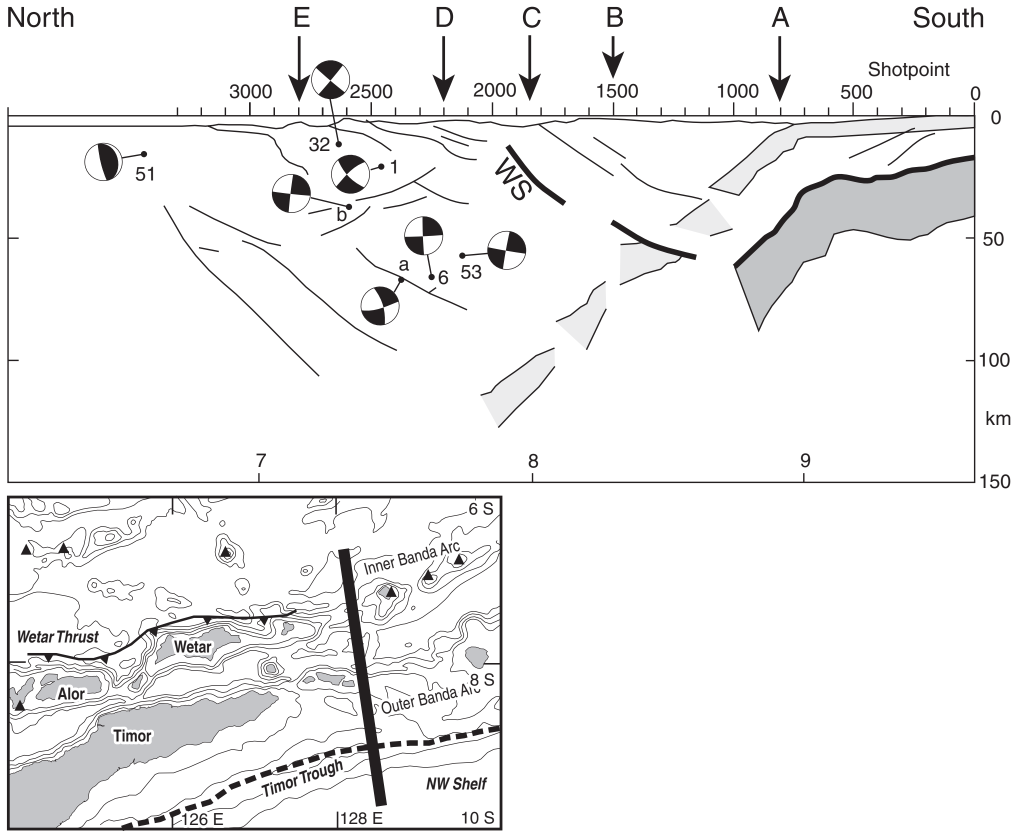

Fig. 10. BIRPS seismic profile of 'Damar Line' from Richardson & Blundell (1996) with geological re-interpretation by the present author. A is the bathymetric 2–3 km deep axis of Timor Trough; B is eastward continuation of submarine ridge of Timor Island 130 km east of Timor; C is fore-arc basin between Timor and Wetar east of those islands. D is Banda volcanic fore-arc; E is dormant Banda volcanoes. WS reflector is Wetar Suture and Australian lower crust (cf. Fig. 8).

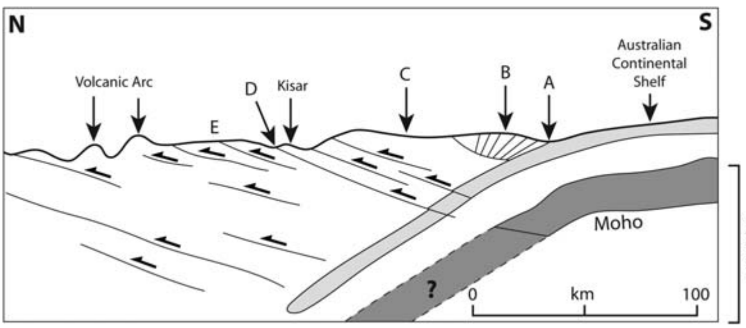

Fig. 11. Cartoon of BIRPS deep seismic profiles immediately east of Timor Island summarized and interpreted by Richardson & Blundell (1996) and re-interpreted by the present author. A is 2–3 km bathymetric deep axis of Timor Trough coincident with southern limit of deformation and southern limit of Banda Trench now the Timor TCZ filled with Australian continental crust and Asian nappes. B is the Hughes *et al.* (1996) BIRPS profile as interpreted by Richardson & Blundell 1996 in their figure 7 (cf. Figs 8 & 12 of this paper). C is Timor Island. D is northern limit of northward overthrust of Australian continental margin (represented by former Banda Trench, now the Timor TCZ) that was carried over 50 km of Banda fore-arc driven by lower crust in Wetar Suture. Note Wetar Suture principal reflector immediately north of Kisar Island. E is reflectors associated with Wetar Suture located in the Banda fore-arc.

et al. (1989), Harris (1991) and Prasetyadi & Harris (1996) also found south-dipping thrusts close to the north coast of East Timor.

Harris *et al.* (2009) mapping Savu Island (150 km SW of Timor) found a major south-dipping fault zone in North Savu that carries the Australian para-autochthon and the Bobonaro Melange, that is a part of this para-autotochthon, northwards over the Banda fore-arc basement. This Savu Thrust Zone is structurally similar to the Wetar Suture, but the two have no physical connection although they may have the same effect as the Wetar Suture, as shown by Rigg & Hall (2011).

The overthrusting of the Banda fore-arc implied by gravity and BIRPS seismic data suggest the Wetar Suture was created by movements of the Australian continental lower crust. This suture (Figs 3 & 8) is found along most of the northern margin of Timor (Audley-Charles 2004) and may continue as far east as Sermata where it would have a strike length of *c*. 650 km. It has carried the Australian continental margin by as much as 50 km over the Banda fore-arc, so the suture seems likely to have had the Australian continental lower crust as its base, implying that the lower crust had become detached from the northward subducting part of the Australian continental sub-crustal mantle lithosphere by de-lamination at the Moho. The lower crust thrusts upwards and northwards from where this mantle lithospheric slab bends northwards to subduct below the northern parts of the TCZ. The lithosphere subducts below northern Timor, the Wetar Strait and the Banda volcanic fore-arc. BIRPS seismic and gravity modelling across the Inner and Outer Banda Arc east of Timor (Richardson & Blundell 1996) can be construed as supporting this interpretation of the Wetar Suture, as the Australian lower crust moving northwards on a major thrust zone over the sub-crustal lithosphere, and over the Banda volcanic fore-arc (Figs 8–13). The driving force for this must be the pulling force of the >600 km deep northward dipping Australian lithospheric mantle slab (Engdahl *et al.* 1998). It is this subducting Australian sub-crustal mantle lithosphere that is pulling all the Australian crust from south of the point where the sub-crustal lithospheric slab bends downward and northward. Thus, the Australian crust above the Wetar Suture continues to ride over the Banda fore-arc as the subduction passage has been unable to accommodate any continental crust (Figs 7 & 8). This supports the suggestion of there being no Australian continental crust subducted from Timor.

The crystalline lower crust must be present below what is now the exposed mega-sequence of Permian to Jurassic stratified, highly deformed, para-autochthon, whose base is seen nowhere. The different physical properties of the crystalline lower crust, have led to it being overridden by what seems to have been the very effective sub-Permian decollement D2 (Figs 2 & 8). These properties of the lower crust would have facilitated detachment of the well stratified, much softer rocks of the upper crust Gondwana mega-sequence from the crystalline, relatively strong and rigid Australian continental lower crust during the deformation processes in the Banda Trench, and its progressive replacement by the TCZ during fore-arc collision from *c*. 4 to *c*. 1 Ma. The deformation of the two mega-sequences suggests that the lower crust retained its discrete response to the forces involved in the 4 Ma collision at the deepest structural levels (Figs 7 & 8).

The Timor Trough

The Timor Trough is a depression 700 km long and between 30 and 75 km wide. Its depth is mainly about 2 km but reaches a maximum of 3.2 km. It is located entirely within what is now the Australian continental slope (as defined by bathymetry), its southern boundary being the shelf edge. It is underlain by Australian continental crust and lithosphere (Richardson & Blundell 1996; Snyder *et al.* 1996).

The Timor Trough, partially filled by marine sediment, has the characteristics of a foreland basin (Audley-Charles 1981; Price & Audley-Charles 1987; Lorenzo *et al.* 1998; Hall 2002; Londono & Lorenzo 2004; Woodcock 2004). It continues as a bathymetric trough north-eastwards through the 1 km deep Tanimbar Trough, and then passes south and east of Kai, from where it follows the arcuate strike of non-volcanic Outer Banda Arc islands, passing through the Seram Sea north of Seram Island where it, like the Timor Trough, has a depth of mostly 2 km, but which, in the Seram Trough, deepens locally to more than 3 km.

The Timor Trough, like the Tanimbar and Seram Troughs, are all Bally-type Ampferer subduction zones (defined by Bally 1983) because there is no ocean floor subduction linked to any of the three troughs. When the Banda Trench had an ocean floor that was subducting ocean crust from 12 to 4 Ma, that trench was north of the Australian continental margin into which the northwards-subducting slab sank into the mantle (Fig. 1). Since the blocking of that trench at 4 Ma no Australian crust has been subducted because it has been stacked in the post-trench tectonic collision zone (TCZ) in which some of that Australian continental crust has overridden the subducting sub-crustal lithosphere, and it is still overriding the Banda fore-arc (Figs 7 & 8). The morphological Banda Trench failed as a Benioff zone about 4 Ma when it was progressively converted into a TCZ. That also led to the Timor

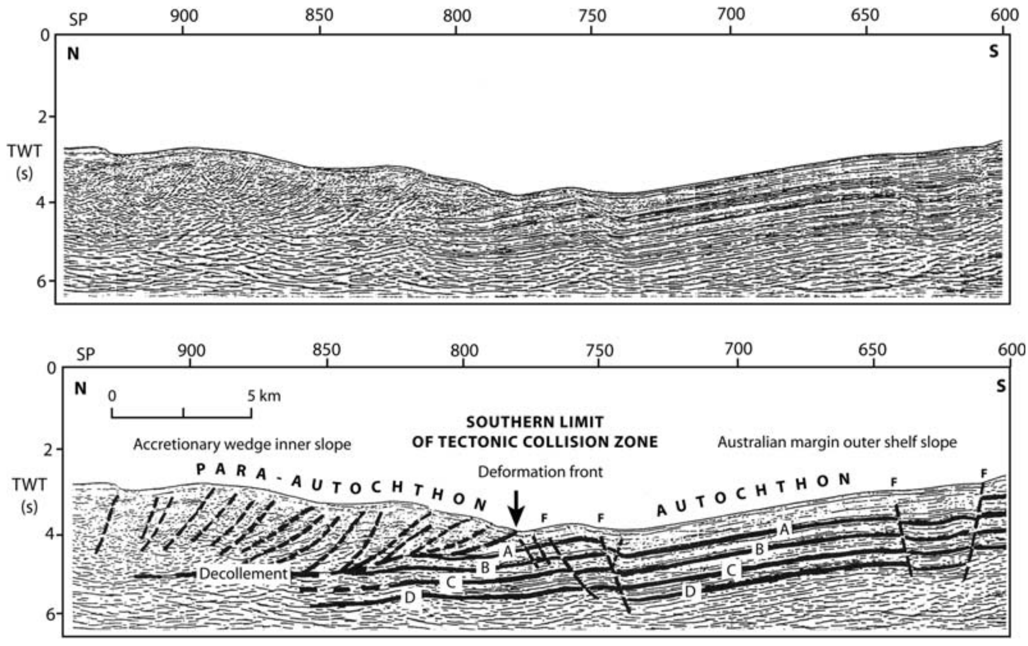

Fig. 12. A is an annotated BIRPS deep seismic profile across deep axis of Timor Trough (see also Figs 8 & 11). Reflectors identified by Hughes *et al.* (1996) as follows: A is Mid–Late Tertiary; B is Mid-Base Tertiary; C is Mid–Late Jurassic break-up unconformity; D is Top Permian? The basal decollement of the wedge is labelled.

Trough being formed as a perisutural foreland basin, and the underthrusting Australian crust moving under Timor is part of a Bally-type Ampferer subduction zone. South of the bathymetric axis of the Timor Trough is the Australian foreland to the Banda orogen.

Hughes *et al.* (1996) showed by deep seismic reflection profiling that the Jurassic shales of the Wai Luli Formation, that are below the almost entirely submarine accretionary wedge off southern Timor, are there underthrusting northwards. However, south of the deep axis of the Timor Trough, there have been no active decollements because this region is part of the Australian autochthon. The two great mega-sequences whose stratigraphy in a strongly deformed state, are present north of the deep Timor Trough axis belong to the Australian para-autochthon (Figs 2, 8 & 12).

Late orogenic block faulting and uplift: possible relation to extension linked to Wetar Suture

The timing of the uplift of Timor from a submarine position to become an island almost 3 km above sea level is indicated by the evidence of the first sub-aerial erosion provided by the siliciclastic turbidites of the Viqueque Group (Kenyon 1974), whose age can be determined from the foraminifera. The lowest Noele Marl turbidites, described by D. J. Carter as high Upper Pliocene to Pleistocene N21–N22 zone, equivalent to about 2.2 to 1.8 Ma, and widely exposed throughout Timor (Kenyon 1974), record the first erosion products produced from the emergence of northern Timor as an island undergoing sub-aerial erosion. This uplift was associated with extension of the Banda fore-arc produced by the rollback of the subducting lithosphere slab below Timor (Figs 7 & 8). Then the Wetar Suture thrust system broke through to the surface in the Wetar Strait. This could have reduced compression in the Timor tectonic collision zone that confined all the deformed Australian crust and Asian nappes until the Wetar Suture carried them to the north.

The Late Pliocene to Pleistocene turbidites of N21–N22 age are overlain by the Pleistocene fluvial gravels and fringing coral-algal reefs that are found on and around much of Timor Island today (Audley-Charles 1968; Kenyon 1974) indicating that Timor had begun to emerge as an island by the latest Pliocene or early Pleistocene at about 2.5 Ma. This uplift had been accompanied by Plio-Pleistocene faulting (Price & Audley-Charles 1987). The faulting affects the Quaternary reef limestone

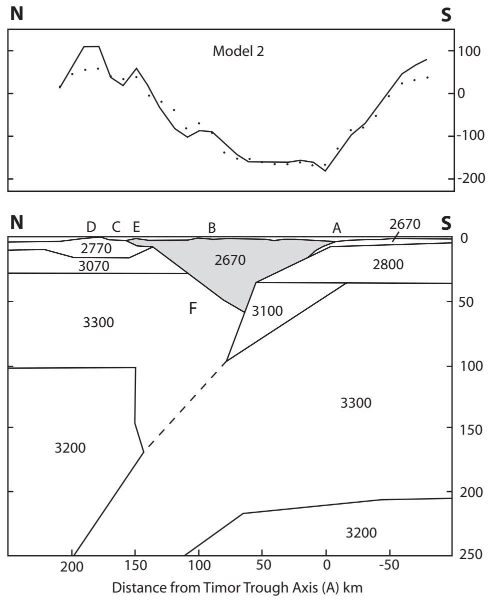

Fig. 13. Gravity data model of Timor region from Woodside *et al.* (1989) interpreted by Richardson & Blundell (1996, fig. 6). Densities of polygons are in kg m^{-3}. The model was intended to constrain crustal thicknesses in the central part of the Banda orogen. Note the grey area corresponds very closely with the defunct Banda Trench, now Timor TCZ, filled with Australian continental crust in Figure 8 of this paper. The gravity model annotations by present author are: A is bathymetric 2–3 km deep axis of Timor Trough; B is Timor; C is Banda volcanic fore-arc; D is Banda volcanic Arc; E draws attention to the overthrusting of the fore-arc by the Australian continental margin represented by the fill in Banda Trench, and later TCZ fill, moved in Wetar Suture by Australian lower crust. Note strata south of the Timor Trough axis are all horizontal, being the autochthonous Australian foreland to the non-volcanic part of the Banda Orogen represented here in grey.

plateaus (see the 1:250 000 geological maps of East and West Timor: Audley-Charles 1968; Rosidi *et al.* 1996; Suwitodirjo & Tjokrosapoetro 1996), some of which have also been gently folded (Kenyon 1974; Audley-Charles 1986*a* reported N22 and N23 gentle folding and tilting).

Conclusions: collision tectonics of the Banda Orogen–Timor region

The early evolution of the Banda Trench led first to the development of the Banda Inner Volcanic Arc from about 12 Ma, and then after the 4 Ma collision the Banda Outer Non-Volcanic Arc developed into the 2300 km long fold and thrust mountain belt reaching 3 km above sea level.

The most important tectonic event in building the Timor orogen was the blocking of the Australian continental crust from subducting at the Banda Trench. This was probably caused by the *c.* 10 km thick lower crust being driven over the subduction passage at the bottom of the northern limit of the Banda Trench where it met the Banda fore-arc at *c.* 6 km depth. This blocked any relatively low density continental crust from subducting. Another early important event was continuation of the roll-back of the sub-crustal mantle lithosphere below the Banda Trench by 30 km after 4 Ma together with the pull-down effect of the subducting sub-crustal mantle lithosphere. Many other key tectonic events followed. The continual pull of the subducting sub-crustal lithosphere was the engine for the movements of the two major decollements below the Gondwana mega-sequence and post-rift mega-sequence; and for the detachment of the Australian lower crust from the Moho above the zone where the mantle lithospheric slab continued to subduct. This enabled the lower crust to ride over the fore-arc; and was responsible for the 800 km long Wetar Suture thrust zone. The removal of the allochthonous Banda Terrane metamorphic basement with its range of Asian cover rocks including the Cablac Limestone from the fore-arc, and of the Asian allochthonous Aileu amphibolites also being removed from the fore-arc, all followed from the creation of the Wetar Suture. The range of Bobonaro Melange facies were a consequence of the initial chaotic compression and shearing of Jurassic Wai Lui shales and the Eocene clay-rich rocks present in the tectonic collision zone.

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