Chapter 7
The Nature of the Banda Arc–Continent Collision in the Timor Region

R. Harris

7.1 Introduction

Arc continent collision is one of the most fundamental tectonic processes for the formation of new land, and the preservation on land of fragments of oceanic lithosphere (ophiolites). However, the tectonic evolution of arc continent collision is commonly over-simplified in everything from introductory textbooks to complex tectonic models. Major unresolved issues include the response of the forearc during collision, controlling factors of deep continental subduction, possible slab delamination and the role of structural inheritance. Many of these issues have been addressed by detailed studies of arc continent collisions in a variety of tectonic settings and stages of development. These studies reveal many common features, such as (1) arcuate orogens surrounding young, supra-subduction zone ocean basins, (2) high pressure metamorphism, (3) thrust sheets of forearc basement structurally overlying mélange in the hinterland of a continental fold and thrust belt, (4) reversal of sedimentation into a flexural trough, (5) contamination and modification of arc volcanism (6) arc accretion and suture zone development, and (7) uplift and exhumation of the orogenic wedge.

These common features attest to similar syn-collisional processes associated with plate kinematics that controls the personality of arc continent collisions. I refer to these features as the tectonic *nurture* of the collision versus its tectonic *nature*, which is associated with pre-collisional or inherited features. For example, the arc continent collision of Taiwan displays only some of the features listed above. Upper plate nappes and high-pressure metamorphic terranes are notably lacking in Taiwan. This contrast is mostly attributable to the young *nature* of the Asian continental margin versus the old and cold *nature* of most continental margins colliding with arcs, such as the Tethyan continental margins and those involving the northern Australian margin. Does the increased positive buoyancy and reduced strength of warm continental margins resist subduction more than cold continental margins? Is a continental margin with high heat flow, as in Taiwan, more likely to thrust over the forearc versus under it to some extent as in most arc continent collisions? Deciphering the relative contribution of these inherited features versus plate kinematics in arc continent collisions is one of the most important aspects to reconstructing how continental crust is formed and shaped its *nurture* versus its *nature*.

Active collisions are key to addressing these issues. They provide both the tectonic nature and nurture of the collision at a variety of temporal and spatial scales. If the continental margin is oblique to the plate boundary then it can be analyzed in the fourth dimension of time where various phases of collision are manifest along orogenic strike. Taiwan is the most intensely studied example, but the Banda arc continent collision of the Timor region also provides a classic example of an active, oblique arc continent collision that differs in some very important aspects from Taiwan. The plate kinematics or *nurture* of each is very similar, but they are very different in *nature*.

The Timor region in many respects is more typical of arc continent collisions in general (Searle and Stevens 1984), yet it is not nearly as well constrained by geological research as Taiwan and because of this is used as a "one collision fits all" analog for almost any tectonic scenario. Only recently has improved

R. Harris
Brigham Young University, Provo, UT, USA
e mail: ramelau@gmail.com

D. Brown and P.D. Ryan (eds.), *Arc Continent Collision*, Frontiers in Earth Sciences,
DOI 10.1007/978 3 540 88558 0 7, © Springer Verlag Berlin Heidelberg 2011

political stability in the Timor region permitted sustained geological research for the first time in over 30 years. The purpose of this paper is to present some of the new discoveries resulting from these studies and how they help us better understand the role of structural heritage versus plate kinematics in shaping active arc continent collisions and interpreting ancient ones.

7.2 The Banda Orogen

The Banda arc continent collision or Banda Orogen forms a tectonic buffer zone at the triple junction between the huge Indo-Australian, Pacific and Asian plates. It consists of a complex array of island arcs, marginal basins, continental fragments and ophiolites amalgamated by repeated plate boundary reorganizations over the past 200 million years (Hamilton 1979; Pubellier et al. 2004; Harris 2003). Many of the oceanic terranes in the mix were emplaced onto the edges of partially subducted continental margins that began arriving at the triple junction during the mid-Tertiary. The last remains of a series of ocean basins that once separated the Sunda Shelf of Asia from the Sahul Shelf of Australia are closing and setting the stage for a collision between these two continents (Fig. 7.1).

The young deformation in the Banda Orogen is used as a modern analog for the Jurassic amalgamation of Alaska at the mega-triple junction between North America, Kula and Asian Plates (i.e., Silver and Smith 1983; Harris et al. 1987; Audley-Charles and Harris 1990). It has also been used in several papers to support various models for the Jurassic and Cretaceous amalgamation in the Mediterranean mega-triple junction between Africa, Europe and the Tethys (i.e., Searle and Stevens 1984). The 180° bend of the Banda Orogen around the young Banda Sea ocean basin is also similar to several Mediterranean orogenic loops and others such as the Yukon-Koyukuk (Alaska). However, in these orogens ophiolites are nearly all that remains of what once was likely a complex plate boundary system.

The initial closure stage presented by the Banda Orogen offers a unique perspective into how the *nature* of the colliding plates influences the transformation of arcs and passive margins into continents. This transformation includes the poorly understood transitions from subduction to collision, from an accretionary wedge to a fold and thrust belt, from arc volcanism to arc accretion and forearc destruction.

7.2.1 NNE-Directed Subduction Beneath the SE Asian Continent–Ocean Transition

The Banda Arc traces back to the "Great Indonesian Arc" of Early Cretaceous to Oligocene time, which stretched at least from India to the Sunda Shelf (Lytwyn et al. 2001) and most likely eastward beyond the Shelf into oceanic lithosphere all of the way to the Philippines and Halmahera (Hall 2002). This arc collapsed during a Tertiary regional extensional event that opened up several new marginal basins throughout SE Asia (Hall 2002).

The most recent expression of northward subduction of Indo-Australian oceanic lithosphere along the SE Asian Plate is the Late Neogene Sunda arc. The Sunda Arc replaced the Great Indonesian Arc and in many places is mounted on top of its forearc subduction complex. As one of the premier active volcanic arcs, the Sunda Arc stretches for nearly 6,000 km from Myanmar, where it is terminated by continental collision with India, to the Banda Arc where it is transitional with the Banda arc continent collision. The active accretionary wedge of the Sunda arc consists mostly of Late Paleogene to Recent cover sediments and seamounts accreted from the subducting Indian Ocean sea floor (Hamilton 1979). Where these are thick the accretionary wedge rises above sea level to form a series of arc-parallel islands, such as those off of the coast of Sumatra in the NW and in the Lesser Sunda Islands of the Timor region in the SE.

The uplift of the Lesser Sunda Islands is an expression of how the *nature* of both the lower plate of the Sunda subduction system changes from oceanic to continental. The upper plate also changes from the continental Sunda Shelf to a series of composite oceanic basins due to backarc extension. Where the Australian continent enters the Sunda Trench the subduction system is transformed into a collision between the Banda intra-oceanic arc upper plate and

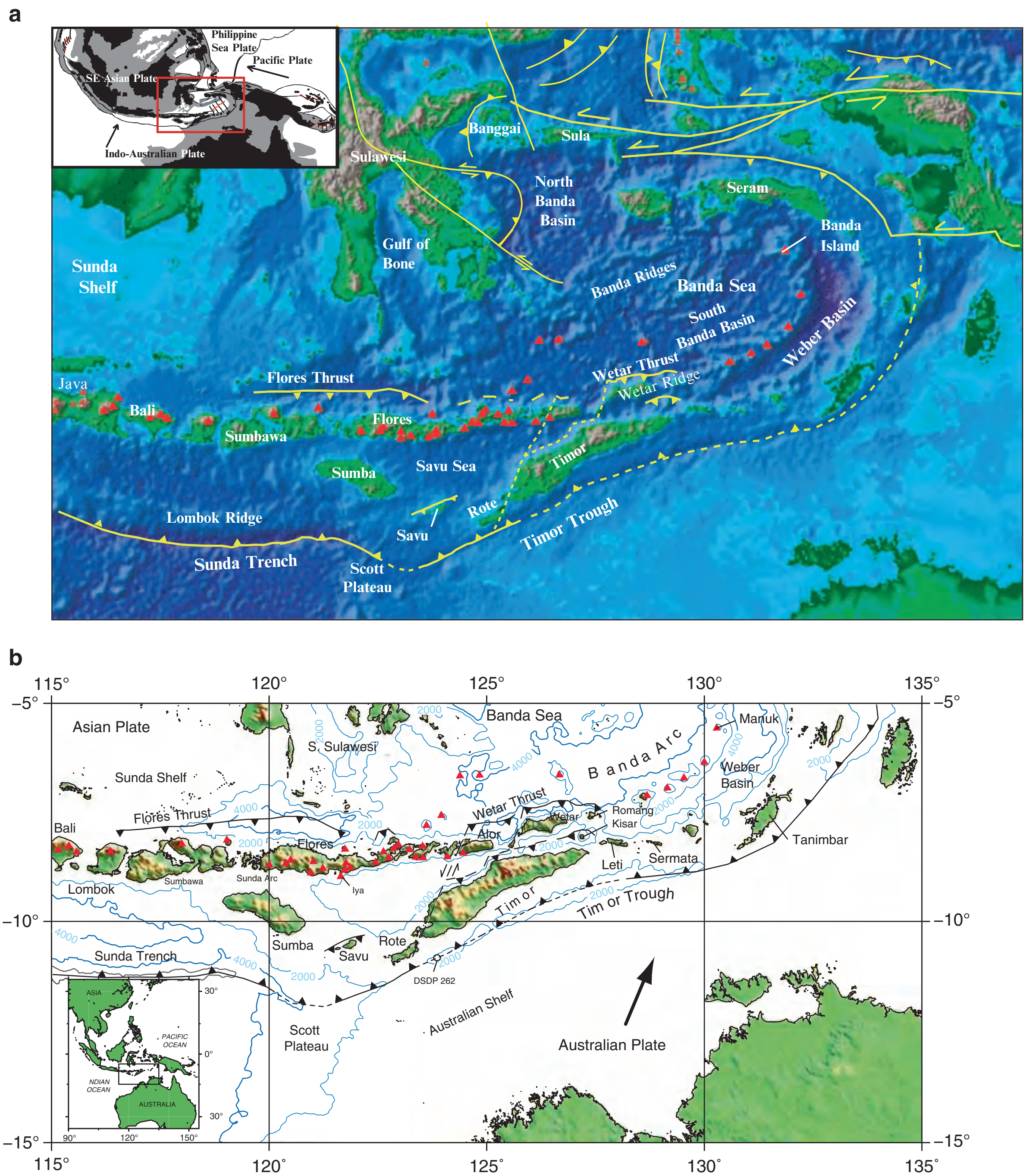


Fig. 7.1 (**a**) DEM of the Banda Arc region showing active faults (*yellow*, *dashed* is poorly defined) and active volcanoes (*red triangles*). *Inset* is plate tectonic map of the SE Asian region with plate vectors. Continental crust is grey and oceanic crust white. *Red box* is area of larger maps. (**b**) Topographic location map of places referred to in text.

long-lived passive continental margin lower plate. The collision actually involves the entire NW part of the Australian continent including the western part of New Guinea. However, the focus of this paper is on the western part of the Banda Orogen, which is the Timor region.

7.2.2 *Seismic Tomography*

Tomographic images to depths of 1,400 km across the Banda arc continent collision show that the entire region is underlain by subducted lithosphere (Widiyantoro and van der Hilst 1997; Hafkenscheid et al. 2001). Up to 5,400 km of convergence is estimated along the Sunda Arc system from a high P-wave velocity anomaly that stretches beneath the Banda Arc region from Java to the southern Philippines. The subducting Indian Ocean plate begins to lose its seismic and tomographic expression below 600 km depth where it merges with a more diffuse zone of high-velocity mantle that underlies the entire region at depths of 600 1,400 km. Tomographic images of the Pacific side of the Banda Arc also connect westward subducting slabs to a high P-wave velocity zone at depth that is interpreted as a slab graveyard.

These results indicate that an entire ocean has been consumed along the Sunda arc-trench system, and that the Australian continent on the other side of this large ocean basin has finally arrived at the subduction zone. What happens when an ocean basins pulls a continent embedded in it into a subduction zone remains a topic of great debate, especially in the Timor region (Audley-Charles 1981; Price and Audley-Charles 1987; McCaffrey et al. 1985; Charlton 1991; Harris and Wu 1991; Sandiford 2008; Fichtner et al. 2010). The debate is about whether the subducting slab stays intact and allows deep continental subduction or the oceanic part breaks off preventing deep subduction and causing isostatic rebound of the continent. Much of the debate is driven by the assumption that deep subduction of continental lithosphere is not possible. However, since the discovery of micro-diamonds and other ultra-high pressure minerals in several collision zones (i.e., Sobolev and Shatsky 1990; Ernst and Liou 2000), there is now direct evidence for deep subduction of continental crust (>350 km).

In the Banda Arc not only are high-pressure assemblages found (Kaneko et al. 2007), but also the youngest arc volcanics are contaminated by deep subduction of cratonic material (van Bergen et al. 1993; Elburg et al. 2004). These features attest to subduction of the passive continental margin to at least 120 km depth. Evidence for deeper subduction without slab break off is provided by tomographic studies that show a 200 km thick zone of high seismic velocities (thickness of Australian continental lithosphere) extending to at least 400 km (Fichtner et al. 2010; Spakman and Hall 2010). The arc above this zone is contaminated by continental crust indicating that the high velocity zone is part of the Australian continent (Fichtner et al. 2010). These results differ significantly from tomograms of the Taiwan arc continent collision (Wu et al. 2007), which show no evidence of deep subduction. These differences are consistent with the low heat flow (40 mWm^{2}) reported for NW Australia (Cull 1982) versus high heat flow (95 mWm^{2}) reported for the southern China continental margin subducting beneath Taiwan (Lee and Cheng 1986).

7.3 Collisional Setting

One of the most significant advantages of studying the Banda arc continent collision is that the pre-collisional characteristics of the arc and continent are both preserved. Both can be progressively tracked into the collision zone along orogenic strike and inspected at various stages of collisional development. Throughout this process it becomes increasingly apparent just how much the *nature* of the lower plate matters in the tectonic evolution of an arc continent collision. The better we understand the structural and stratigraphic heritage of the lower plate, the better we can constrain how much structural inheritance influences mountain building processes.

7.3.1 *Lower Plate: NW Australian Passive Margin and Scott Plateau*

The Australian continental margin has a complex structural heritage that causes many lateral discontinuities that are exploited by arc continent collision. The passive margin formed after Permian to Jurassic intra-cratonic rifting of Gondwana. Middle-Late Jurassic breakup evolved into Early Cretaceous (Berriasian) sea-floor spreading in the adjacent Wharton Basin (Falvey 1972; Larson 1975). The Wharton Basin is one of the oldest remaining ocean basins on the planet, which is a significant inherited feature that adds to the negative buoyancy and strength of the lower plate entering the Banda arc continent collision zone.

7.3.1.1 Structural Evolution

The early stages of Gondwana rifting produced intracratonic basins of similar style and tectonic setting to those found in the North Sea (Spencer et al. 2005). These NW-SE striking basins filled with Permian to Jurassic siliciclastics, carbonates and some volcanic rocks known as the Gondwana Sequence (Fig. 7.2). This early phase of intracratonic rifting is later overprinted by breakup-related extension that produced a nearly perpendicular set of ENE-WSW rift basins that form the Australian continental margin (Fig. 7.3). These rift basins are underlain by a Jurassic breakup unconformity that separates the pre-breakup Gondwana Sequence from the post-breakup Australian Continental Margin Sequence (Fig. 7.2).

During Gondwana breakup some of the earlier NW-SE intra-cratonic rifts were exploited to form a rifted margin with rectangular continental plateaus, such as the NW protruding Scott Plateau (Longley et al. 2002). The Scott Plateau is made up of thinned continental crust 17 18 km thick (Symonds et al. 1998) and rises 2 3 km above the oceanic crust that surrounds it on three sides (Fig. 7.4). Like the Exmouth Plateau to the south it protrudes perhaps as much as 500 km out beyond the ENE-WSW Australian continental shelf (Longely et al. 2002). Magnetic lineations in oceanic crust surrounding the Scott Plateau, and rift basins within the continental plateau, are oriented ENE-WSW. These basins are truncated by transform faults on the NE and SW sides of the plateau.

The transform boundary on the NE side of the Scott Plateau, not the NW facing rifted margin, is colliding with the Sunda-Banda forearc (Fig. 7.4). This collisional geometry brings the ENE-WSW oriented rift basins of the Scott Plateau into the collision zone sub-parallel to their axes. The islands of Sumba, Savu and Rote emerge in the orogenic wedge adjacent to where some of these basins have entered into trench end-on.

The protrusion of the Scott Plateau also causes different parts of the continental margin to collide at different times with the Java Trench. Generally, the continental margin is oriented ENE-WSW from Timor to Rote (Fig. 7.4). The continental margin moves NNE at a rate of 68 km/Ma relative to the Asian Plate (Nugroho et al. 2009). As it collides with the E-W Sunda Trench the arc continent collision propagates WSW at 110 km/Ma (Harris 1991). This plate kinematic solution predicts that the collision initiated in central Timor by at least 6 Ma and has propagated WSW to its current point of initiation south of Sumba Island (Fig. 7.3). However, irregularities in the shape of the continental margin to form the Scott Plateau protrusion (Keep et al. 2002) cause it to collide with the Sunda Trench at around 3.5 Ma (Fortuin et al. 1997), which is much earlier than the immediately surrounding areas.

Structural inheritance in this instance exerts a major control on where collision initiates and how it propagates. For example, collision propagates along the ENE-WSW part of the continental margin from central Timor to Rote as predicted (Roosmawati and Harris 2009). But the protrusion of the Scott Plateau allowed it to arrive at the Sunda Trench much earlier than adjacent parts of the Australian continental margin. The collision of the Scott Plateau propagates southeastward along its NE edge from Sumba to Savu to Rote. Evidence of these irregularities would be difficult to detect in ancient arc continent collisions where mostly orthogonal convergence, straight continental margins, and rifted versus transform boundaries are assumed.

7.3.1.2 Gondwana Sequence

The Permian to Jurassic Gondwana Sequence of the Timor region represents the pre-breakup sedimentary cover of the Australian continental margin. It consists of two groups of rocks: the Kekneno Group (Simons 1940; Audley-Charles 1968), which has a proximal source, and the more distal facies Aileu and Maubisse Formations (Fig. 7.2). Part of this group is also inferred as the protolith of the Aileu metamorphic Complex along the north coast of East Timor (Audley-Charles 1968).

The Kekneno Group is exposed mostly in fensters through structurally overlying nappes of the Banda forearc (Banda Terrane). It consists of Permian to Jurassic siliciclastics with minor interbedded limestone

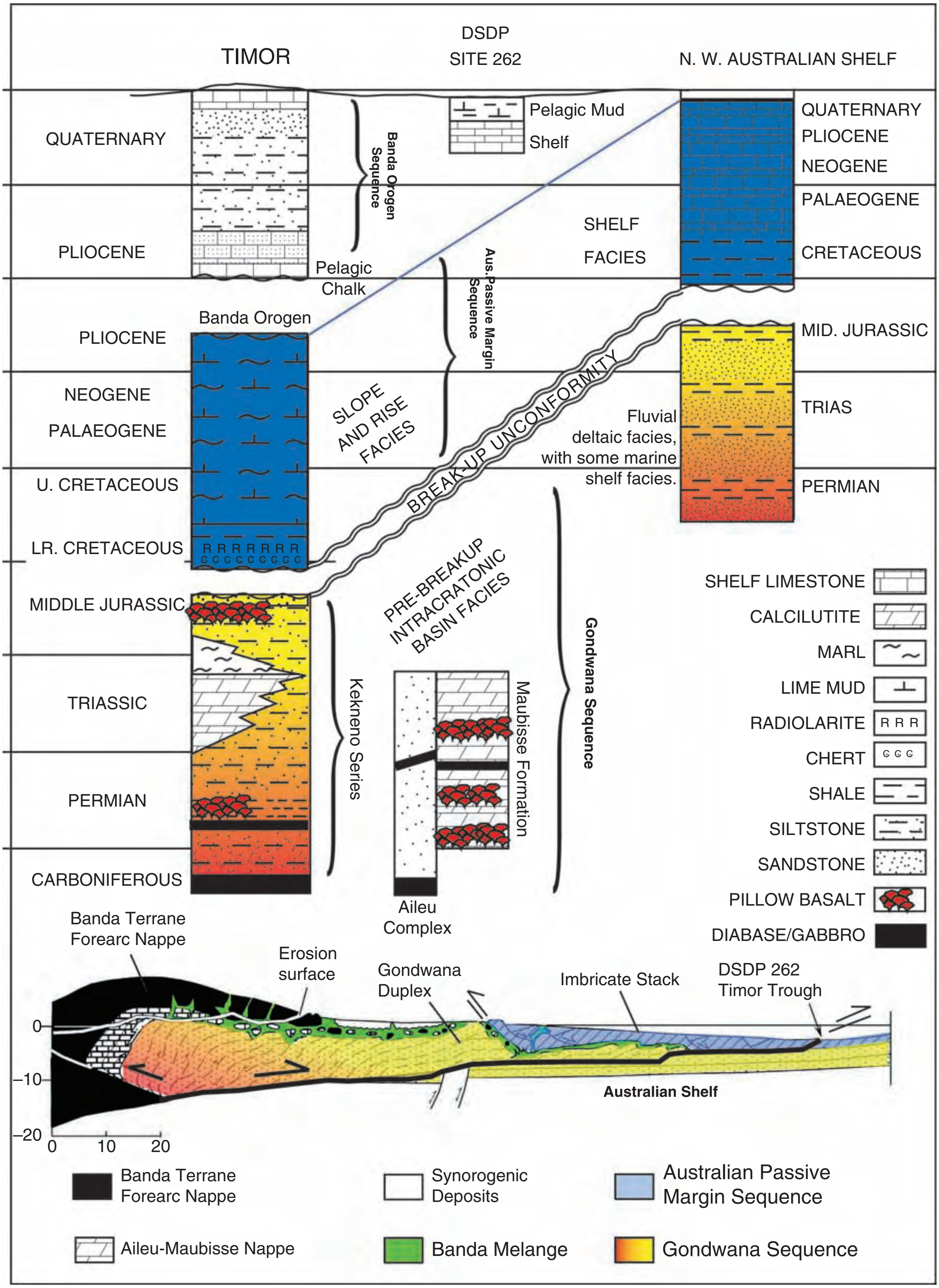


Fig. 7.2 Stratigraphic correlation between in situ and accreted (Timor) lithologies of the Australian continental margin. Cross section is modified from Harris (1991).

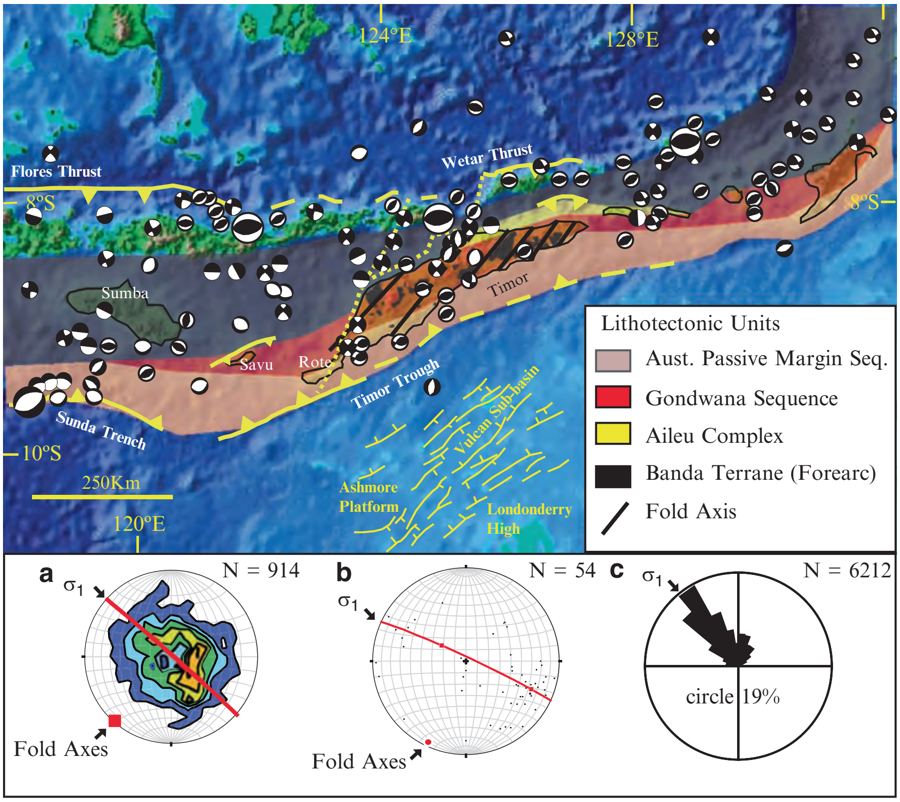
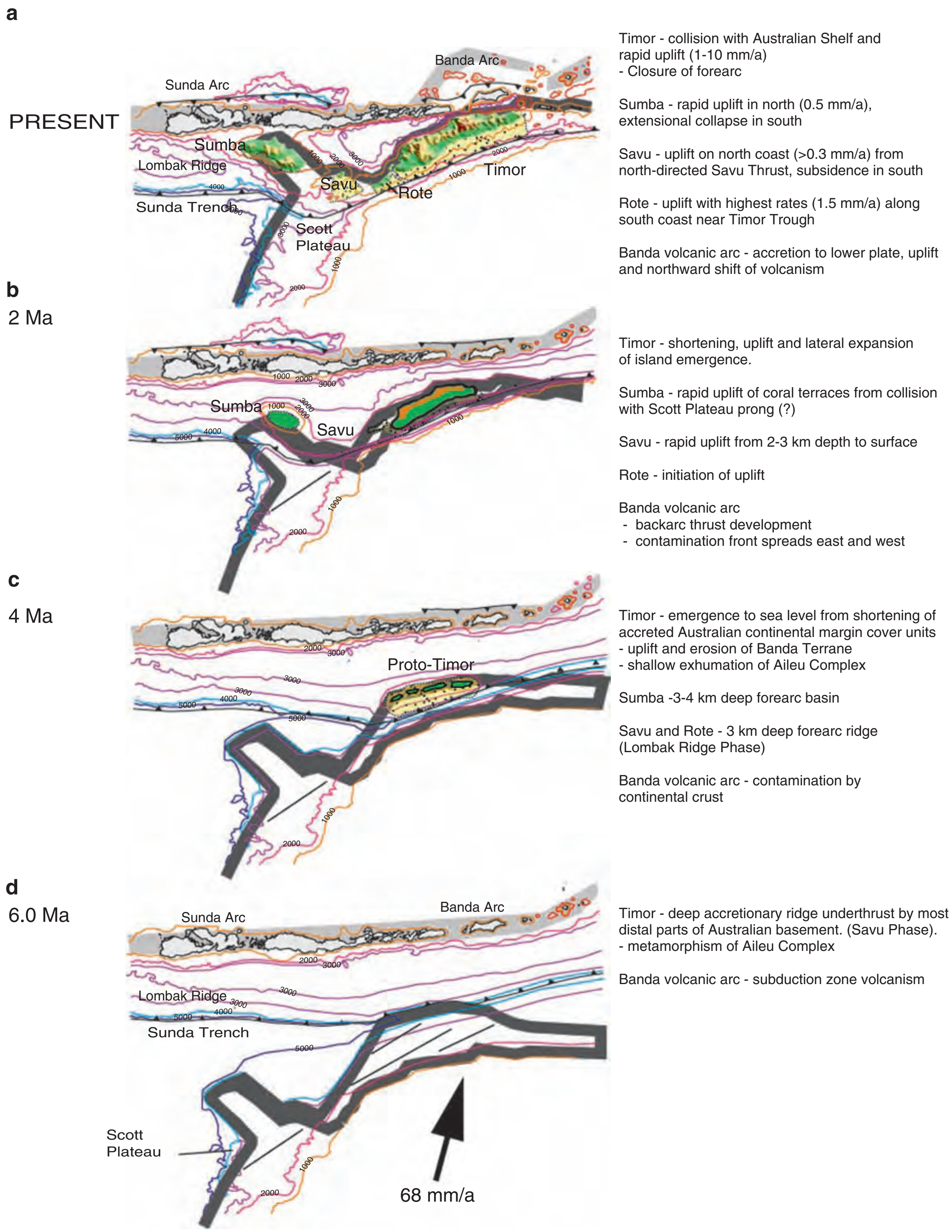


Fig. 7.3 Map showing extent of major lithotectonic units in the Banda Orogen, fault plane solutions, active faults (*thick yellow*) and inherited structure (*thin yellow*). The Banda Terrane (*dark grey*) is forearc crust that forms klippen overlying the Gond wana Sequence in Timor. *Black lines* are hinge lines of anti forms in Timor, which parallel the inherited structure of the northwest Australian continental margin (from Petkovik et al. 2000). Stereographs show (**a**) contour of poles to bedding planes and (**b**) poles to axial planes in folded Gondwana Sequence lithologies. Pi circle (*red*) approximates maximum compressive stress ($\sigma 1$), Pi pole is approximation of fold hinge lines. (**c**) Mode one fracture measurements from synorogenic deposits throughout Timor and Alor (Mikolas and Harris 1986). The large pedal is parallel to $\sigma 1$, which is perpendicular to fold axes and axial surfaces in pre orogenic rocks (above) and to P Axes from shallow earthquakes (Das 2004). The secondary direction is parallel to the plate motion vector measured by GPS (Nugroho et al. 2009).

and volcanics (see review papers by Charlton et al. 2002, 2009). The volcanics are mafic in composition with affinities to rift basin basalt (Berry and Jenner 1982). Similar rocks to the Kekneno Group are well documented in drill cores of the Australian continental margin (Charlton 1989).

Petrologic studies of Kekneno Group sandstone in Timor (Audley-Charles 1968; Bird and Cook 1991; Zobell 2007; Haig et al. 2008), Savu (Harris et al. 2009) and Rote (Roosmawati and Harris 2009) indicate it is texturally immature, consists of quartz to lithic wackes with large subangular framework grains of fresh twinned feldspar, mica, and lithic fragments. These relations indicate a proximal source, which according to discriminate diagrams was a recycled orogen.

U/Pb age determinations of detrital zircon grains collected from Timor, Savu and Kisar yield major peaks at 301 Ma and 1882 Ma (Zobell 2007; Harris 2006). The youngest grain analyzed in Triassic sandstone is 234.6 ± 4 Ma and the oldest grains are Archean, with a maximum age of 2725.3 ± 37.6 Ma. The youngest grains in the Aileu Complex are 198 ± 8 Ma (Major et al. 2009). The most likely source region with matching age distributions is Argoland (Zobell 2007), which rifted from the Australian continent during Jurassic breakup of Gondwana and has since accreted to Asia (Stampfli and Borel 2002).


a
PRESENT
Sunda Arc
Banda Arc
Sumba
Lombak Ridge
Savu
Rote
Timor
Sunda Trench
Scott
Plateau
Timor - collision with Australian Shelf and rapid uplift (1-10 mm/a)
- Closure of forearc
Sumba - rapid uplift in north (0.5 mm/a), extensional collapse in south
Savu - uplift on north coast (>0.3 mm/a) from north-directed Savu Thrust, subsidence in south
Rote - uplift with highest rates (1.5 mm/a) along south coast near Timor Trough
Banda volcanic arc - accretion to lower plate, uplift and northward shift of volcanism
b
2 Ma
Sumba
Savu
Timor - shortening, uplift and lateral expansion of island emergence.
Sumba - rapid uplift of coral terraces from collision with Scott Plateau prong (?)
Savu - rapid uplift from 2-3 km depth to surface
Rote - initiation of uplift
Banda volcanic arc
- backarc thrust development
- contamination front spreads east and west
c
4 Ma
Proto-Timor
Timor - emergence to sea level from shortening of accreted Australian continental margin cover units
- uplift and erosion of Banda Terrane
- shallow exhumation of Aileu Complex
Sumba -3-4 km deep forearc basin
Savu and Rote - 3 km deep forearc ridge (Lombak Ridge Phase)
Banda volcanic arc - contamination by continental crust
d
6.0 Ma
Sunda Arc
Banda Arc
Lombak Ridge
Sunda Trench
Scott
Plateau
68 mm/a
Timor - deep accretionary ridge underthrust by most distal parts of Australian basement. (Savu Phase).
- metamorphism of Aileu Complex
Banda volcanic arc - subduction zone volcanism

Aileu Complex

The Aileu Complex consists of late Carboniferous-Jurassic psammite intruded by mafic plutons that grades southward into limestone and basalt associated with the Maubisse Formation (Audley-Charles 1968; Berry and Grady 1981; Prasetyadi and Harris 1996). On the north coast of central East Timor these units are metamorphosed into pelitic schist, marble, phyllite and amphibolite, and are intruded by gabbroic and lherzolitic bodies of unknown age. In some places there are so many intrusions that only screens of metapsammite are found, which is interpreted as a rift event, which may explain the sillimanite grade rocks reported by Berry and Grady (1981). The earliest phase of metamorphism is overprinted by metamorphism associated with latest Miocene onset of collision in central Timor (Berry and McDougall 1986; Harris et al. 2000). Minimum P-T estimates for these rocks along retrograde paths are as high as 9 ± 1.2 kbars and 826 ± 37°C in Timor (Major et al. 2009) and 10 kbars and 600°C on Leti Island to the east of Timor (Kadarusman et al. in press).

Maubisse Formation

The Maubisse Formation consists of volcanic rocks interbedded with a distinctive red, sparitic crinoidal limestone and micritic units interbedded with red shale that were deposited during the Early Permian through Triassic (de Roever 1940; Audley-Charles 1968; Charlton et al. 2002). The volcanic rocks represent a bimodal suite with mostly basalt including common pillow lavas and volcaniclastics, with minor occurrences of rhyolite and some syenitic intrusives (Major et al. 2009). Geochemical studies indicate within-plate and ocean-ridge basalt, which is interpreted as representing the onset of rifting (Berry and Jenner 1982). Clastic sedimentary units found in the Maubisse Formation fine toward the south (Carter et al. 1976). Rocks similar to the Maubisse Formation are documented on the Sahul Shoals of the undeformed Australian continental margin (Archbold 1988).

7.3.1.3 Australian Passive Margin Sequence

The formation of the present NW Australian passive margin is marked in the stratigraphic record by a Middle Jurassic breakup unconformity at the top of the Gondwana Sequence (Fig. 7.2). Overlying the unconformity is a condensed succession of Early Cretaceous pelagic iron- and manganese-rich shale and mudstone interlayered with radiolarian chert and semi-consolidated foraminiferal and nanno-chalk (von Rad and Exon 1983). Exposures of these deposits are found throughout the Banda Orogen and are known as the Nakfunu Formation (Rosidi et al. 1979). They indicate rapid subsidence and development of slope and rise passive margin sedimentary environments. Overlying the Nakfunu Formation is a dense Cretaceous to Tertiary calcilutite interbedded with mudstone and some turbidites in both the present passive margin of Australia and in the Banda Orogen (Charlton 1989). These deposits are known as the Ofu Formation. Most of the accreted slope and rise facies Australian passive margin deposits outcrop in the southern parts of Timor and Rote as part of an imbricate thrust stack (Figs. 7.2 and 7.3). On the present passive margin these slope deposits grade into shelf facies successions of sandstone and shale conformably overlain by thick successions of Cenozoic carbonate up to 3,000 4,000 m thick (Smith and Ross 1986; Balke and Burt 1976). No shelf facies post-breakup successions are recognized in the orogenic wedge. However, upper Pliocene shelf facies limestone was encountered at the bottom of DSDP 262, which drilled into a 2,298 m deep section of the Timor trough

Fig. 7.4 Palinspastic map of the Banda arc continent collision using a plate velocity (68 mm/a) and direction (015°) of conver gence relative to the Asian Plate (Nugroho et al. 2009). Shortening of the Australian continental margin is shown by progressive narrowing. Green represents land near sea level, *brown* mountains, *yellow* turbidite deposition and *light grey* zone of active volcanism. Bathymetry in "B" to "D" is speculative except where constrained by analysis of foraminifera (Roosmawati and Harris 2009). ENE WSW lines in "D" are approximate axes of rift basins on Australian continental margin (see Fig. 7 3). Collision of Australian passive margin initiates in the Timor region and propagates westward toward Rote. Colli sion of the Scott Plateau initiates south of Sumba and propagates SE to Savu and Rote. Modified from Roosmawati and Harris (2009).

near the deformation front (Fig. 7.2). The shelf facies material documents rapid subsidence of the continental margin from sea level to >2,000 m depth in <2.5 Ma (Hamilton 1979).

7.3.1.4 Mechanical Stratigraphy

The major mechanical boundary layers of the Australian continental margin cover are the ~1,000 m thick succession of Late Triassic to Jurassic mudstone known as the Wai Luli Formation and the pelagic mud of the immediately overlying Nakfunu Formation (Harris et al. 1998). Both of these units straddle the breakup unconformity (Fig. 7.2). Most of the clay minerals in the mudstone are smectite-rich, which retain large amounts of water and produce high fluid over-pressures. Wells that penetrate this stratigraphic interval both in the Timor fold and thrust belt (Sani et al. 1995) and on the NW Australian margin (Kingborough et al. 1991) commonly experience borehole blowouts due to very high pore fluid pressures. Triaxial tests of mudstone from the breakout zones show extreme ductility at surface temperatures and differential stress of only 40 70 MPa (Kingborough et al. 1991). The mechanical weakness of this inherited structure and others found near the base of the Permian exert a major control on how the Australian continental margin cover sequences are accreted to the Banda Arc.

7.3.1.5 Shortening of the Australian Continental Margin

As the Australian continental margin arrives at the Sunda Trench its pre- and post-rift sequences are incorporated into the Banda orogenic wedge by both underplating-duplexing and frontal accretion processes, respectively (Fig. 7.5). There are also components of subduction channel flow and diapirism associated with the development and remobilization of thick mélange occurrences. Seismic reflection profiles across the deformation front in the Timor Trough show active décollement propagation into Jurassic and Early Cretaceous mudstone near the breakup unconformity (Breen et al. 1986; Karig et al. 1987; Masson et al. 1991). Large mud diapirs are seen rising from the décollement zone and forming mud ridges (blow-outs) on the seafloor. Some of the diapirs rise seaward of the thrust front and may influence the eventual position of the next forward-stepping thrust fault (Breen et al. 1986). Above the breakup unconformity-level décollement, post-breakup Australian Passive Margin Sequences are frontally accreted to the orogenic wedge as a stack of imbricate thrust sheets (Fig. 7.6) with no lithologies older than Jurassic found in the thrust stack.

The imbricate thrust stack that forms at the front of the orogenic wedge is best exposed in the Kolbano Mountains region of southern west Timor (Fig. 7.5b). The Oetuke River canyon cut through the Kolbano Mountains and exposes at least 25 imbricate thrust sheets in only 13 km of section (Fig. 7.6). The faults repeat a <500 m thick succession of Cretaceous to Pliocene Australian Passive Margin Sequence. The thrust sheets take the shape of truncated fault-propagation folds with mostly overturned forelimbs. The deformed section restores into an originally 27 km long section that is shortened by a minimum of 58%. Axial planar pressure solution cleavage is well developed throughout most of the section and represents a significant amount of volume loss during deformation.

The pre-breakup Gondwana Sequence underthrusts the imbricate stack to deeper levels of the subduction channel where it then stacks up into a thrust duplex zone (Fig. 7.5). The roof of the duplex is near the breakup unconformity-level décollement and the floor is near the base of the Permian. These boundary conditions produce fault-propagation folded thrust sheets 1 3 km thick that repeat various parts of the Permian to Jurassic Gondwana Sequence (Fig. 7.5). The duplex zone first emerges on the Island of Savu at the rear of the orogenic wedge (Harris et al. 2009).

Savu exposes at least four separate thrust sheets of the Triassic to Jurassic Babulu and Wai Luli Formation, which is the upper part of the Gondwana Sequence (Fig. 7.7). Another duplex consisting of lower Gondwana Sequence lithologies is inferred below the one exposed on the surface. The Savu Thrust carries the duplex stack and mélange over the Banda Terrane nappe along the north coast of the island (Fig. 7.7). Seismic reflection profiles across the Savu Thrust show that it consists of a series of northward younging thrust faults that deform the youngest beds on the seafloor. A well drilled on the north coast of Savu penetrated through synorogenic chalk deposits before hitting mélange overlying the top of the Banda Terrane nappe (Harris et al. 2009).

The lower Gondwana Sequence thrust duplex is exposed in several structural windows through the Banda Terrane nappe of Timor (Harris 1991). A structural transect by Zobell (2007) through one of these structural windows in the Cribas region of East Timor reveals several repetitions of mostly Permian to Triassic thrust sheets (Fig. 7.8). The Banda Terrane nappe rests in a synformal region between two

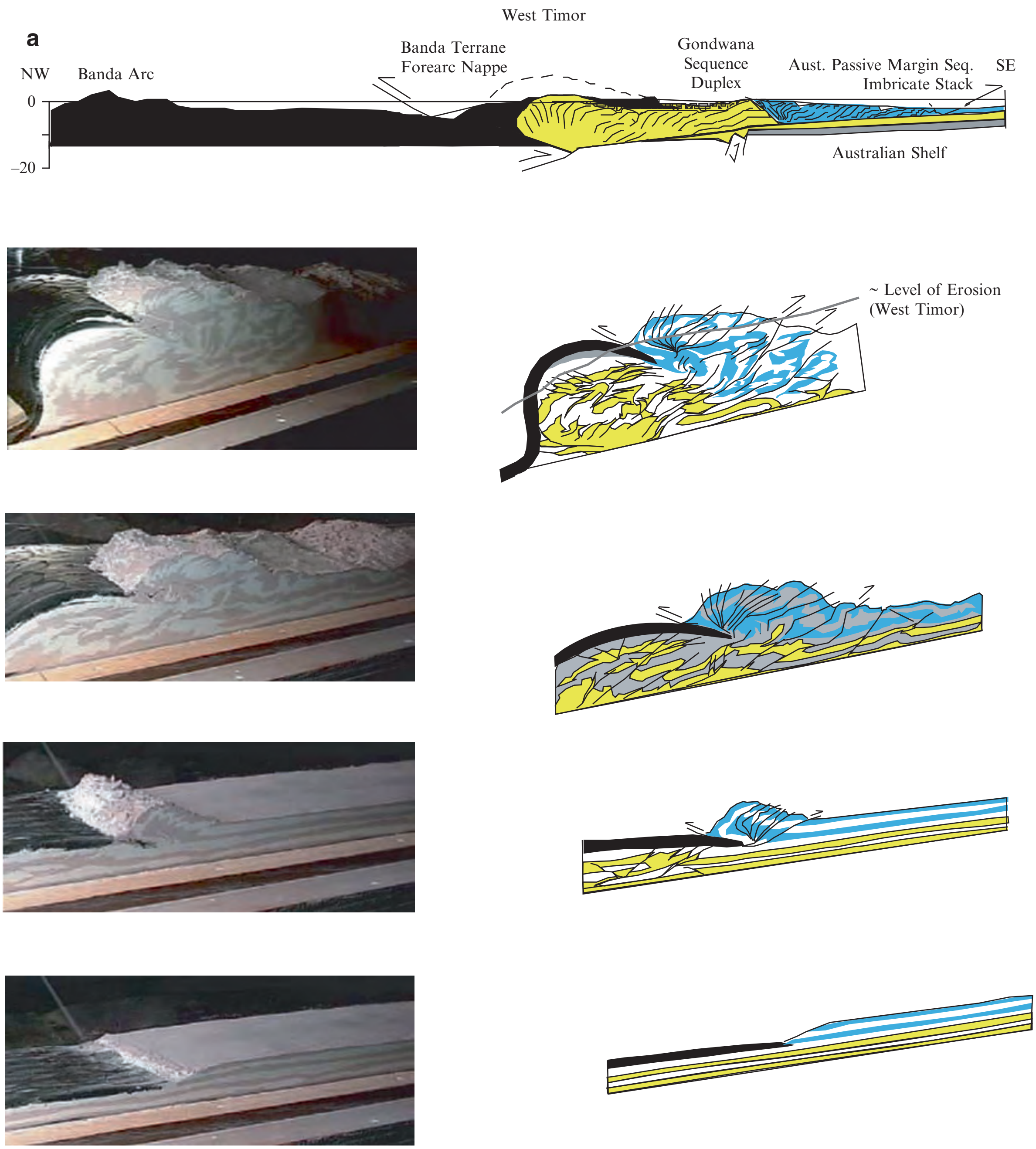


Fig. 7.5 (continued)

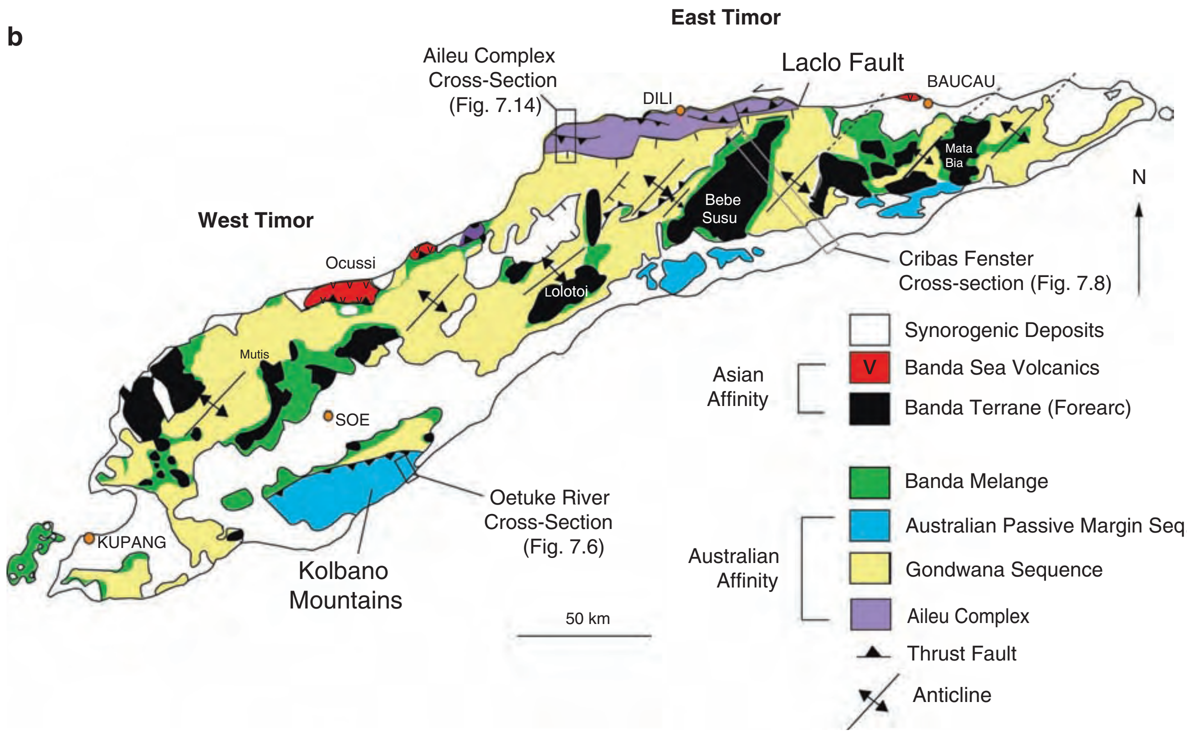


Fig. 7.5 (**a**) Analog sandbox model testing how a strong upper plate structural lid influences orogenic wedge geometry (mod ified from Vorkink 2004). Materials are scaled to the rheology and thickness of the Australian continental margin (*red* and *white*) and Banda Terrane (*black*). In coming continental margin cover successions are detached at two levels. The Australian Passive Margin Sequence is frontally accreted to form an imbri cate thrust stack (*blue*). Gondwana Sequence lithologies (*yellow*) are subduct further before detaching and deform into a fold dominant duplex system. The Banda Terrane is repre sented by black plasticene that is driven back into an asymmet ric retro antiform by under stacking of Gondwana Sequence units. Compare to cross section through West Timor (modified from Harris 1991). The line of section is shown on map. (**b**) Generalized geologic map of Timor taken mostly from Audley Charles (1968), Rosidi et al. (1979) and Harris et al. (2000). Asian affinity Banda Terrane massifs are interpreted as structur ally overlying Australian affinity Gondwana Sequence litholo gies. Banda Mélange (*green*) is found surrounding and beneath the Banda Terrane klippe. The NW SE rectangles are the loca tions of two detailed structural transects and cross sections (see Figs. 7.6 and 7.8).

structural culminations of the duplex. Between the lower Gondwana Sequence duplex and the structurally overlying Banda Terrane nappe is a zone of mélange. Line balanced reconstructions of the duplex estimate at least 48% shortening of an initial 100 km long undeformed section (Zobell 2007).

Gross area balanced cross sections across the orogenic wedge indicate that after only 3 4 m.y. the space available in the wedge would fill with Australian continental margin lithologies (Vorkink 2004; Zobell 2007). This calculation assumes that the wedge extends to at least 30 km depth, which is the depth of metamorphism of the highest-pressure parts of the Aileu Complex. It also assumes 100% accretion of a constant thickness Permian to Pliocene continental margin cover. What the estimate does not take into account are deeper duplexes of Pre-Permian units that may have stacked beneath the lower Gondwana Sequence duplex or even stacks of metamorphic basement or metamorphosed Gondwana Sequence as found in the Aileu Complex. These estimates hint that the hinterland region of the Banda orogen, which is all that is exposed throughout the Banda Arc, formed in less than 3 4 m.y. and is currently being exhumed. Most of the shortening associated with ~70 km/Ma of plate convergence is taken up in other locations such as the back arc region (Wetar and Flores Thrust systems), the rear of the accretionary wedge and at the deformation front in the Timor Trough (Fig. 7.2).

7.3.1.6 Banda Mélange

The Banda Mélange occurs extensively throughout the Banda Orogen and is exposed at the front of, and in erosional windows through the Banda Terrane nappe, and as diapirs (Fig. 7.5). It consists mostly of a pervasively deformed scaly clay-rich matrix with little to no internal continuity that incases a highly mixed assemblage of neighboring blocks of a variety of sizes, rock types, ages and metamorphic grade.

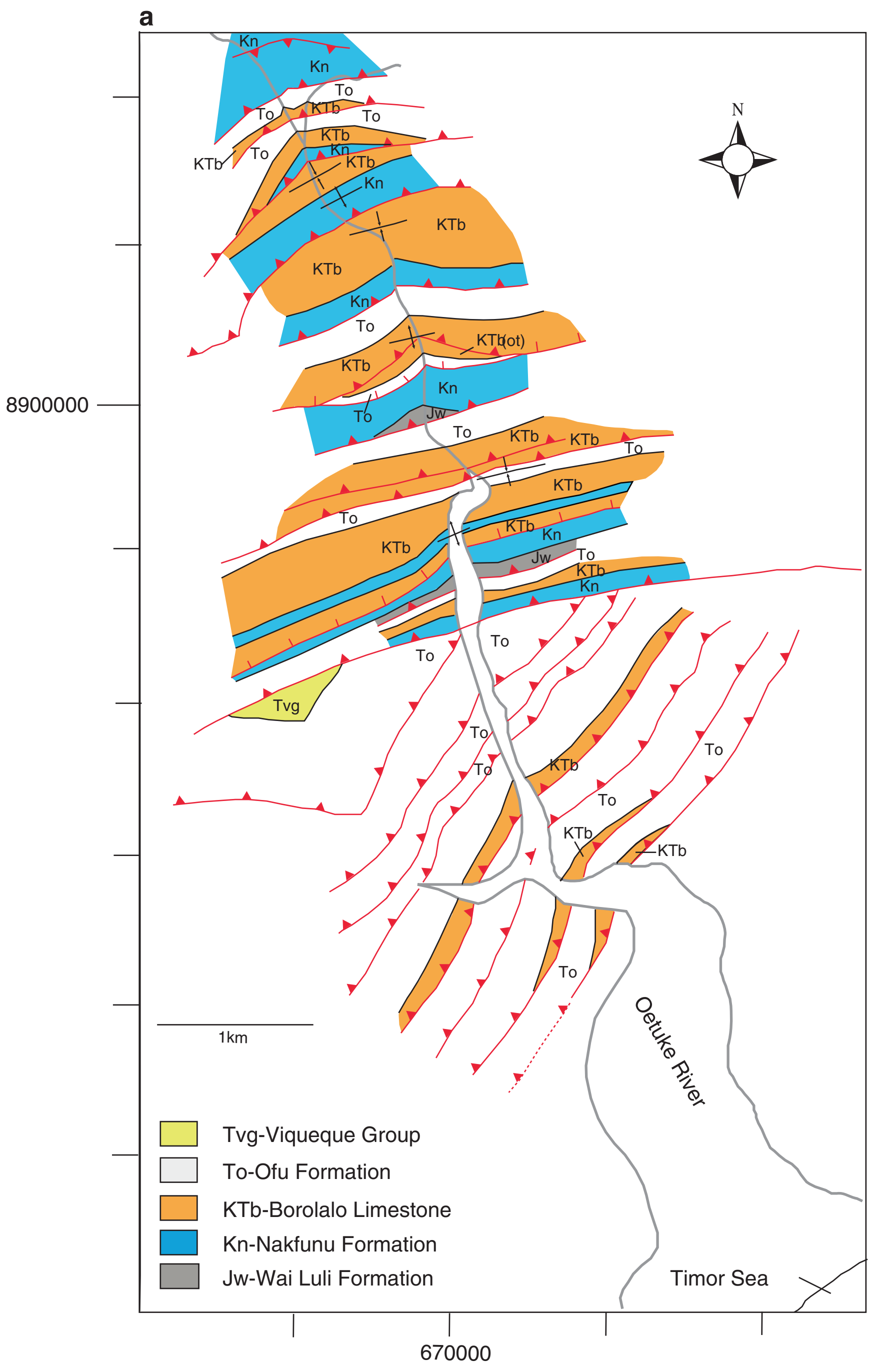


Fig. 7.6 (continued)

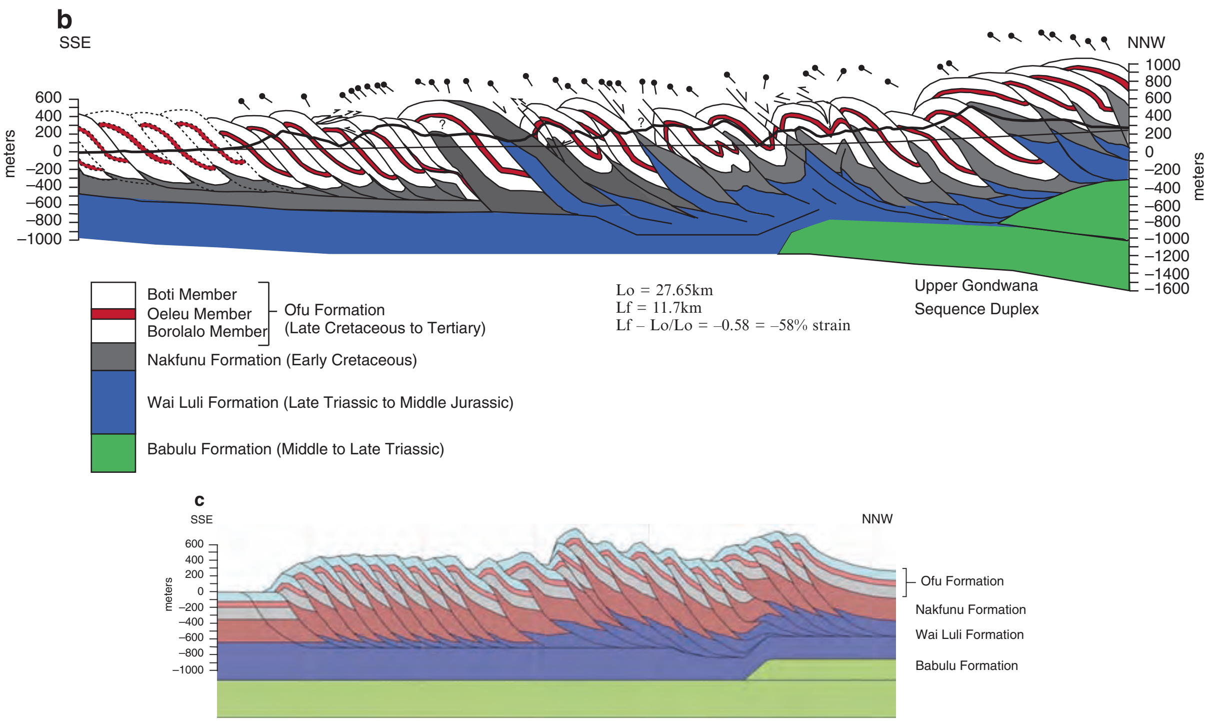


Fig. 7.6 Oetuke River structural transect (see Fig. 7.5 for location). (**a**) Structural map of the lower Oetuke River, which cuts through an imbricate thrust stack of Australian Passive Margin Sequence units. Thrust faults with triangle and normal faults with line on hanging wall. (**b**) Cross section along the Oetuke river with dip symbols and topographic profile (*heavy black line*). (**c**) Pre extensional forward model of cross section using Lithotect software. Imbricate thrust sheets continue off shore where they are imaged by reflection seismic profiles.

Biostratigraphic analysis of the scaly clay matrix yields a less mixed assemblage of palynoflora, nannoflora, and microfauna mostly derived from Jurassic and Cretaceous clay-rich units near the breakup unconformity. However, the large range of taxa (Lower Triassic to Pliocene) indicates a high level of mixing that is not consistent with sedimentary processes.

The mélange was mapped in Timor as the Bobonaro scaly clay (Audley-Charles 1968), and like many mélanges was initially interpreted as an olistostrome, but later recognized as primarily a tectonic feature (Barber et al. 1986; Harris et al. 1998). It is referred to here as the Banda Mélange due to its ubiquitous occurrence throughout the Banda Orogen and most common structural position at the base, and immediately in front of Banda Terrane nappes (Fig. 7.2). Other occurrences are also documented that may relate to secondary sedimentary and diapiric processes (Audley-Charles 1968; Barber et al. 1986; Masson et al. 1991).

Stratal disruption within the Banda mélange involves mostly viscous flow at low temperatures due to the *nature* of the expandable clay that feeds into the mélange from the Wai Luli Formation. There are at least two phases of deformation: a pervasive mostly coaxial layer-parallel extension and more localized non-coaxial shear. Layer-parallel extension is characterized by boudinage with viscous flow of clay-rich layers out from between competent layers. Calcite fibers in bed normal fractures throughout mélange blocks indicate coaxial strain about an axis normal to bedding during hydro-fracturing, which attests to fluid pressures at least 95% of lithostatic. Non-coaxial shear is localized throughout the mélange, particularly in broken formation of the Gondwana Sequence near the base of the mélange and along the base of the Banda Terrane roof thrust near the top of the mélange, which is consistent with flow in a subduction channel (Shreve and Cloos 1986).

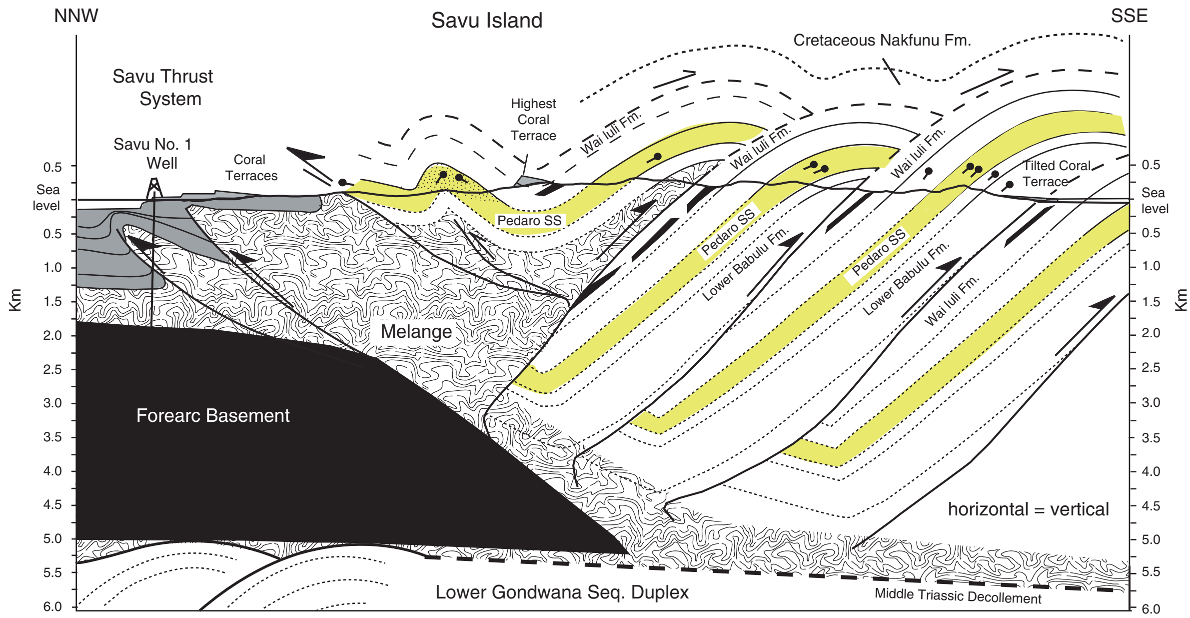


Fig. 7.7 Composite cross section across Savu (modified from Harris et al. 2009). *Upper* Gondwana Sequence duplex of Tri assic Babulu Formation and Jurassic Wai Luli Formation as seen at base of Oetuke River section (Fig. 7.6). *Black lines* within the Wai Luli Formation are pillow basalt layers. Grey is latest Miocene to Pleistocene pelagic chalk (Batu Putih For mation) synorogenic cover. Savu No. 1 well drilled through synorogenic cover into top of Banda Terrane forearc basement. Active Savu Thrust carries rear of orogenic wedge and mélange over forarc basin deposits. The structure of northern section is according to seismic profiles off the north coast and from drilling data. Folds and thrust faults are determined from field mapping (Harris et al. 2009). Dip measurements are given by *black dots* with line pointing in direction of dip. Black bodies in Wai Luli Formation are basalt. Detachment depth is estimated from the projected depth of the Sumba Ridge and stratigraphic thickness of units incorporated into thrust sheets. Cretaceous units are interpreted as a roof thrust for the Upper Triassic Jur assic duplex. Assuming no subduction erosion, the southern edge of the forearc was the initial position of the pre collisional Sunda Trench. Southward tilted coral terraces are shown at both coast lines and above the syncline.

Block types are highly mixed but vary in abundance from top to bottom and north to south throughout the mélange. Serpentinized mantle and deep crustal lithologies from the Banda Terrane (Fig. 7.9) are more abundant near the top and to the north while upper crustal oceanic material and Gondwana Sequence lithologies are most abundant in the lower and southern sections. The middle of the mélange is a chaotic mixture of both types, with ubiquitous Gondwana Sequence lithologies such as the sandstone and siltstone from the Kekneno Group, and pink crinoidal limestone and associated pillow basalt of the Maubisse Formation.

Mantle material incorporated into the mélange is mixed with early-accreted lithologies sourced from the upper most oceanic crust (pillow basalt, chert, manganese nodules). Sandstone blocks and matrix is also sourced from the upper part of the Gondwana Sequence and the distal most Australian Passive Margin Sequence. These lithologies dominate in mélange exposed near the south coast along with predominately crustal versus mantle material from the forearc upper plate. Dense blocks supplied from the forearc upper plate sink through the low-density mud and mix with lower plate lithologies. Mud extrusion around the edges of many of these blocks is still active and observed in several places throughout Timor forming fresh mud lumps on the surface.

7.3.1.7 Mud Diapirism

Diapirs of matrix-rich mélange locally rise from overpressured horizons up through the Banda Orogenic wedge. The most common sites are at the deformation front in the Timor Trough, at the front of the Banda

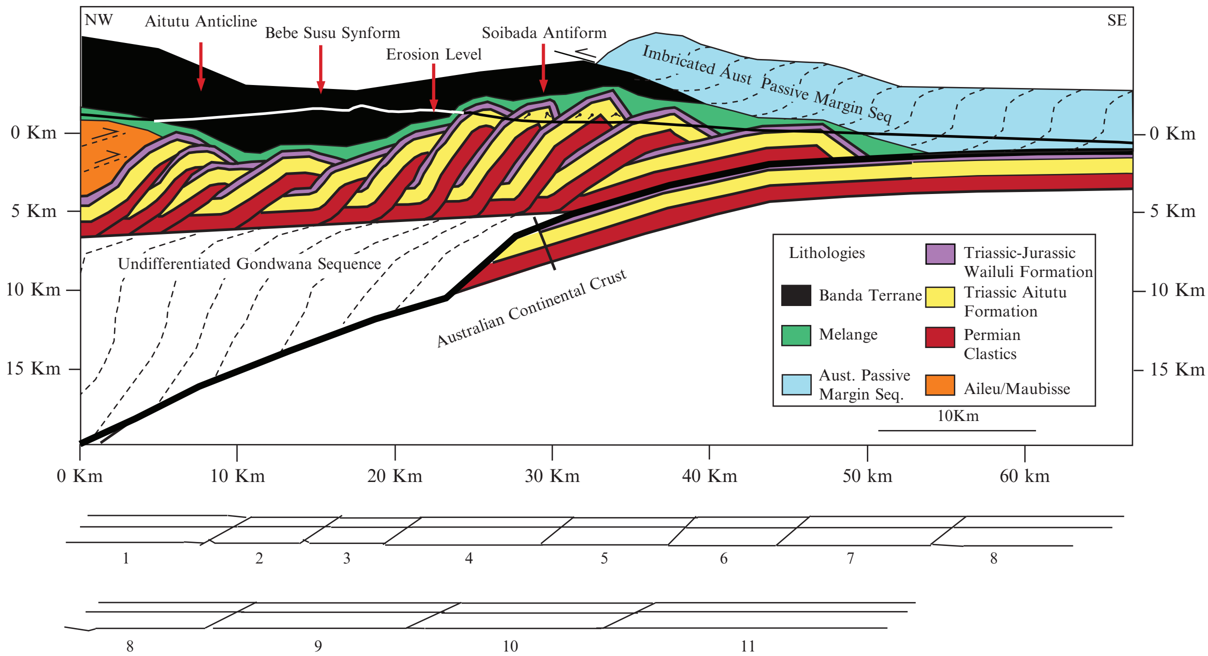


Fig. 7.8 Cribas fenster cross section (modified from Zobell 2007). See Fig. 7.5b for line of section. Duplex of mostly Permian to Triassic *lower* Gondwana Sequence lithologies beneath the Banda Terrane as seen at base of Savu cross section (Fig. 7.7). Balanced reconstruction (below). Thrust sheets on restored section are numbered in order of deformation (1 is accreted first). Green zone is mixed block and clay mélange that represents the original subduction channel. Current ero sional level is shown.

Terrane nappe, along the retrowedge thrust front (Savu Thrust) and faults cross-cutting the orogen (Barber et al. 1986; Harris et al. 1998). Many active diapir fields are imaged offshore (Breen et al. 1986; Masson et al. 1991). Onshore diapirs are found intruding into basal synorogenic chalk and turbidites and along fault zones (Harris et al. 1998).

Seismic profiles and side-scan sonar images across the deformation front show disturbed areas in the subsurface that connect with mud diapirs on the surface. The disrupted horizons rise from near the breakup unconformity where drilling on the NW Australian continental margin has documented over-pressured mudstone. The diapirs form a series of mud ridges 20 km long and up to 300 m high that parallel the thrust front within the Timor Trough (Breen et al. 1986). The mud ridges define the deformation front, which deforms the bedded continental margin units by diapirism before they are accreted to the thrust front.

Large diapirs are also imaged along the Savu Thrust at the rear of the accretionary prism (Reed et al. 1986). Some of these diapirs are exposed on the island of Savu and consist of block in clay mélange with blocks derived from both the Gondwana Sequence and Banda Terrane.

Another large occurrence of mélange diapirs is found at the 123° East discontinuity (Barber et al. 1986), which forms the western edge of Timor and intersects the islands of Semau and Rote (Fig. 7.1). A line of several diapir islands rise along this NNE-SSW zone that is sub-parallel to the direction of plate convergence. Each island consists of active mud volcano fields extruding block in clay mélange through eroded lag deposits of a variety of block types. Systematic block counts on these islands and in exposures of mélange throughout the Timor region document a high degree of mixing under conditions of hydrofracturing (Harris et al. 1998).

The characteristics associated with the Banda mélange are most consistent with subduction channel versus sedimentary processes (Harris et al. 1998). These characteristics include the extensive occurrence of the mélange, its structural position at the base of forearc nappes and at active thrust fronts,

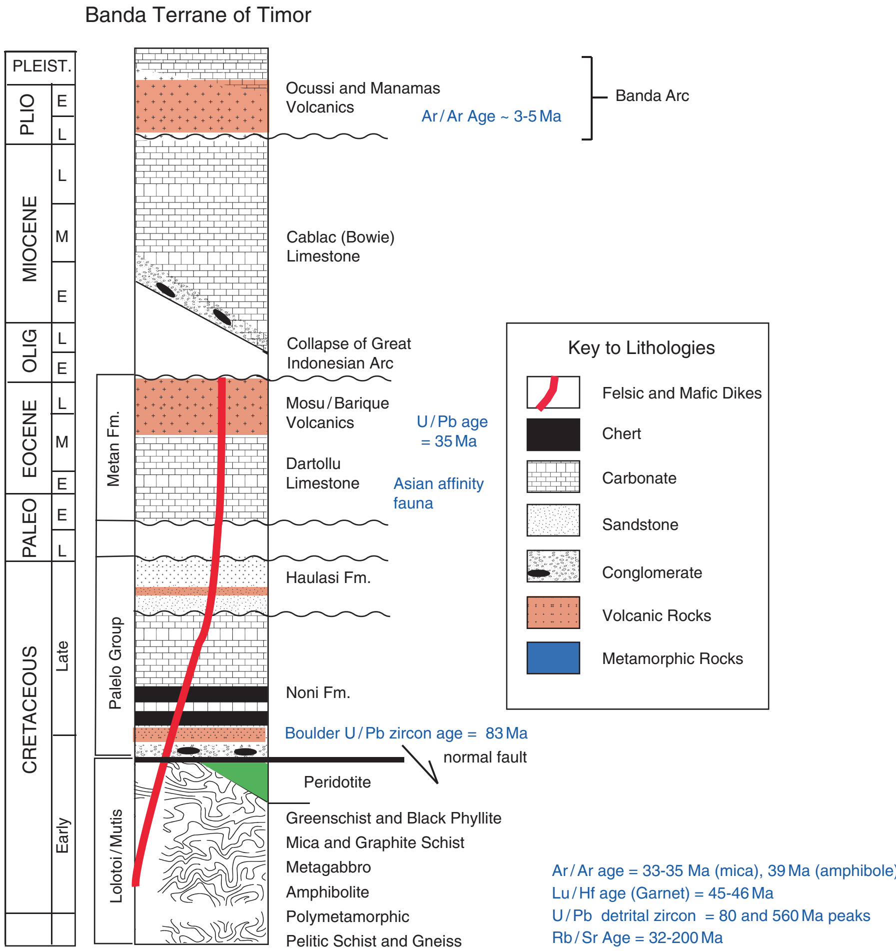


Fig. 7.9 Lithologies and ages of the Banda Terrane (Banda forearc). Modified from Harris (2006).

the high degree of block dispersal and mixing, intense viscous strain, hydro-fracturing, mix of fossil assemblages and perhaps most significant, its lack of any synorogenic sedimentary features. A thick layer of deep marine chalk (see Batu Putih Formation below) overlies the Banda Mélange in many places. The chalk uniformly yields planktic foraminifera of stage N18 (5.6 5.2 Ma) and indicates water depths near the lysocline (>3 km) (Roosmawati and Harris 2009). These data indicate that the mélange was being covered with chalk near the trench and during the earliest stages of arc continent collision. The common occurrence of mélange beneath the Banda Terrane also extends it from near the surface at the trench into the subduction channel where it can mix with mantle material and blocks of much higher temperature and pressure conditions moving up the channel (e.g. Shreve and Cloos 1986). Even in the northern most exposures of the mélange, where it would have been in deeper parts of the channel, the clay matrix is not metamorphosed indicating a very flat trajectory into the subduction zone.

The part of the Banda Mélange that is overlain by the Batu Putih Formation can be traced from exposures onshore to the accretionary ridge offshore that forms in front of the Banda Terrane upper plate (Harris et al. 1998). Offshore seismic reflection profiles across the ridge show chaotic reflectors immediately beneath well-bedded sediments (Harris et al. 2009). Wells drilled through this contact confirm that it consists of pelagic chalk deposits overlying mélange with a variety of block types encountered in the wells (Audley-Charles

1968; Harris et al. 1998, 2009). The accretionary ridge collapses to the south where it is underthrust by the Australian continental margin south of Savu. Where this occurs the surface slope of the ridge decreases dramatically from 6° to 2° causing the deformation front to bulge southward by more than 100 km (Harris 1991). The collapse opened several slope basins (Fig. 7.7) in this part of the accretionary wedge, which are well documented by marine geophysical studies by van der Werff (1995).

Extensional collapse of the orogenic wedge early in its collisional history explains the ubiquitous layer-parallel extension in the mélange, its close association with diapirism and the overlying pelagic chalk (Harris et al. 1998). The contact between the mélange and overlying chalk is ubiquitously irregular due to diapirism and remobilization of the scaly clay. It is difficult to interpret this contact as sedimentary in origin. Also, massive submarine landslides, such as olistostomes, are notably lacking in seismic reflection profiles or sonar images of the seafloor throughout the Banda Arc (Breen et al. 1986; Masson et al. 1991). In some ways the collapse of the orogenic wedge mimics a mega-landslide, but the fundamental processes are associated with weakening of the décollement at the base of the accretionary wedge by overpressured mudstones of the underthrust Australian continental margin. The relationships are much more consistent with highly overpressured mud "blowing out" of the subduction channel as seen in seismic reflection profiles across the deformation front (Breen et al. 1986).

7.3.2 Upper Plate: Banda Arc–Forearc Complex

The Banda Arc formed due to subduction of Cretaceous to Jurassic age oceanic lithosphere attached to an irregular-shaped continental margin. The combination of these factors resulted in a strongly arcuate pattern of trench retreat that opened supra-subduction zone ocean basins. In the case of the Banda Arc, and many other subduction zones like it, if the upper plate cannot move or keep pace with a retreating trench, it must stretch by internal extension and magmatism (Elsasser 1971; Schellart et al. 2002). The young north and south Banda Sea ocean basins in the upper plate separate highly attenuated ridges of continental and arc material pulled away from the pre-existing continental arc (Harris 2006). The ocean basins opened from NW to SE (Honthaas et al. 1998; Hinschberger et al. 2001) as the Banda Trench retreated into the large continental embayment west of New Guinea (Fig. 7.10). The direction of trench retreat is recorded by the SE migration of active volcanism in individual volcanoes of the Banda Arc producing linear hot-spot tracks with the active volcanoes at the eastern edges of the tracks (Fig. 7.1). Additional bending of the northern part of the Banda Arc may have involved oroclinal bending associated with left lateral shear with the Pacific Plate (Silver et al. 1985). These variable directions of trench retreat produced a spoon-shaped subducting slab (Hamilton 1979).

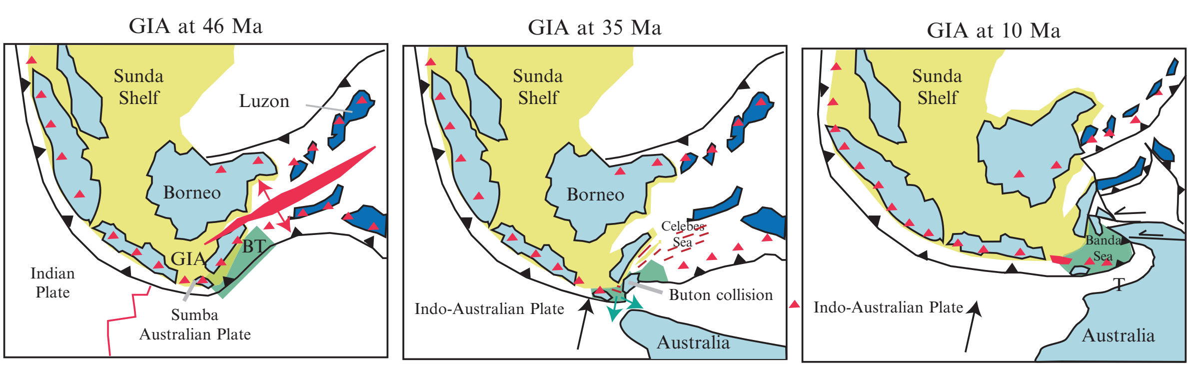


Fig. 7.10 Reconstruction of the collapse of the Great Indonesian Arc (GIA), opening of the Banda Sea, dispersal of the Banda Terrane (BT green) and development of the Banda Arc (from Harris 2006). Red lines active rifting, Red triangles active volcanism, T Timor.

The orogenic loop of the Banda Arc and other orogens is interpreted in various ways that emphasize buoyancy forces (Dewey 1988), asthenospheric escape (Flower et al. 2001) and plate kinematics (Dilek and Harris 2004), such as the combination of northward convergence of Australia and westward convergence of the Pacific plate to produce the bend in the eastern Banda Arc (e.g. Silver et al. 1985). However, Schellart and Lister (2004) show that although each of these geodynamic processes may contribute, the dominant mechanism for the progressive out-bowing of most arcs is slab rollback, which is also most consistent with data from the Banda Arc.

Examples of other orogenic systems comparable to the Banda Arc are the Yukon Koyukuk Arc of northern Alaska (Harris et al. 1987), the Carpathian, Betic Rif, Tyrrhenian, and Aegean arcs of the Mediterranean region (Harris 1992; Royden 1993; Milsom et al. 2001), and the Scotia and Caribbean arcs of the western Atlantic (Schellart and Lister 2004). Each of these orogens has collapsed toward an unconstrained margin associated with subduction zone rollback (Malinverno and Ryan 1986; Doglioni et al. 1999a and b). Space created in the wake of the collision zone is filled with highly attenuated continental and arc crustal fragments embedded in new oceanic lithosphere, which produces a composite marginal basin.

Several continental and arc fragments are scattered throughout the Banda Sea, such as the NEC-Lucipara Ridges, which form the northern boundary of the South Banda Basin, and the Wetar Ridge, which forms its southern boundary. Geochemical and geochronological analysis of samples dredged from both of these ridges on either side of the South Banda Basin show strong affinities suggesting that they once formed a single magmatic arc that was split by the opening of the South Banda Basin (Honthaas et al. 1998). The southern part of the South Banda Basin is now being overthrust by the Wetar Ridge along the Wetar Thrust, which takes up some of the convergence between the Australia and Asia plates (Silver et al. 1983; Genrich et al. 1996; Nugroho et al. 2009). Loading associated with the Wetar Thrust may explain the anomalous depth versus young age of the South Banda Basin.

Fragments of the Wetar Ridge and southern Banda Sea ocean floor that are incorporated into the Banda Orogen are known as the Banda Terrane (Harris 1992). The Banda Terrane is exposed in situ in Sumba and on Timor as nappes thrust over partially subducted Australian continental margin lithologies (Harris 1991). The nappes are part of the Banda forearc that was uplifted by duplexing of the Gondwana Sequence beneath it. The uplift and exposure of sections of a forearc due to continental underthrusting provides a rare opportunity to observe the composition of forearc basement still attached to an active arc, and reveal how forearc nappes are emplaced onto continents or destroyed in suture zones.

7.3.2.1 Banda Terrane

Oceanic lithosphere is commonly inferred to occupy the forearc of intra-oceanic arc systems. However, the Banda forearc includes large fragments of arc-derived meta-sediment that were intruded by arc-related plutons and metamorphosed during another life as part of the Great Indonesian Arc. The lack of oceanic lithosphere in the forearc and occurrence of arc rocks at its southern edge attests to a significant amount of subduction erosion (e.g. Scholl et al. 2008). The forearc fragments are known as the Banda Terrane (Audley-Charles and Harris 1992). The Banda Terrane consists mostly of a mix of pelitic and mafic metamorphic rocks consisting of gneiss, schist and greenstone (Lolotoi Complex of East Timor and Mutis Complex of West Timor) that is structurally overlain by Cretaceous to Miocene sedimentary and volcanic cover units (Fig. 7.9). The cover units are remnants of a Cretaceous-Early Tertiary forearc succession (Palelo Group and Metan Formation), which is depositionally overlain by Oligocene-Miocene massive limestone (Bowie Limestone).

Petrologic analysis of the Lolotoi/Mutis metamorphic complex indicates a mostly Cretaceous sedimentary origin with deposition of inter-layered volcanogenic and pelitic sedimentary successions (shale-greywacke) and arc-related volcanic deposits (basalt to basaltic andesite compositions). Provenance interpretations obtained from various geochemical discriminant diagrams from these rocks indicate mixed MORB and volcanic arc affinities for the igneous units and intermediate to mafic continental and oceanic arc sources for the sedimentary successions (Harris 2006; Standley and Harris 2009). The protolith studies point to a proximal forearc basin setting on the southern edge of the eastern Great Indonesian Arc before it collapsed to form the Banda Sea floor and current Banda Arc.

Protolith age estimates are obtained from Rb/Sr and U/Pb age analyses. The Rb/Sr ages from 12 whole rock samples of pelitic schist and gneiss found throughout the Mutis Complex of West Timor (Earle 1981) yield a poorly defined isochron with maximum and minimum ages of 200 to 32 Ma (Harris 2006). Detrital zircons from para-amphibolite of the Lolotoi Complex in East Timor yield U/Pb ages as young as 82 Ma, which provides a maximum deposition age for the metamorphic protolith (Harris 2006). The age distribution has spikes at 663, 120 and 87 Ma, which is typical for the Great Indonesian Arc of Asia, but very different from Australian affinity lithologies (see above).

Metamorphism of the Mutis and Lolotoi Complexes is attributed to subduction zone processes occurring beneath the arcward part of the forearc basin. Various mineral assemblages yield pressure-temperature estimates of 5 10 kbar and 530 680°C, which resulted in upper greenschist and amphibolite facies metamorphism (Brown and Earle 1983; Sopaheluwakan et al. 1989; Standley and Harris 2009). The age of peak metamorphism is well constrained at 45 46 Ma by Lu Hf age analysis of garnet (Standley and Harris 2009), which was followed by rapid uplift based on $^{40}Ar/^{39}Ar$ cooling ages for hornblende of 39 Ma and biotite of 34 Ma (Harris 2006).

The sedimentary and volcanic units faulted down against the Mutis and Lolotoi Complexes consist of a distinctive basal unit of Aptian Turonian radiolarian chert with interbedded tuffaceous clastics, volcanic units and carbonate (Haile et al. 1979; Earle 1983). This succession is unconformably overlain by a conglomerate with metamorphic and felsic igneous clasts, quartzite and chert. One of the andesitic cobbles in the conglomerate overlying the Lolotoi metamorphic rocks yields an U/Pb age of 83 Ma with Jurassic xenocrysts.

Late Cretaceous turbiditic successions and Paleogene tuffs and lavas overlie the conglomerate. The volcanic rocks consist of agglomerates with a tuffaceous matrix, pyroxene basalt and andesite lavas, and andesitic and dacitic tuffs (some associated with ignimbritic eruptions). Geochemical analysis of these volcanic rocks and those with volcanic protoliths in the metamorphic complexes uniformly indicate subduction-related affinities with overlap of the two different groups on most discriminate diagrams (Standley and Harris 2009). Samples of the same age from Sumba (Lytwyn et al. 2001) along with dredge samples collected from the Wetar Strait north of Timor (Harris 1992) and the South Banda Basin (Honthaas et al. 1998) also show overlap (Standley and Harris 2009). An age determination from a dacitic volcanic unit yields a mean U/Pb age of 35 Ma, with one zircon core of 67.8 Ma (Harris 2006).

Closely related to the volcanic rocks is a distinctive Eocene carbonate that includes calcirudites with volcanic clasts and a pure microfaunal assemblage with characteristic large foraminifera. These fauna are only found in low latitude, shallow marine environments of Sundaland and some Pacific islands (Lunt 2003).

A major hiatus in deposition occurs throughout the Oligocene (Carter et al. 1976), which is also found in wells drilled throughout the Sunda Shelf region (Curray 1989). The hiatus is also coincident with exhumation of the Lolotoi and Mutis metamorphic complexes. By Oligocene time the metamorphic rocks had reached the surface and were unconformably overlain by basal conglomerates and limestone of the Oligocene to mid-Miocene Bowie Limestone.

The Bowie Limestone (formerly the Cablac Limestone) of West Timor consists of hard, commonly massive units of calcilutite, oolitic limestone, calcarenite, and intra-formational breccia, agglomerate and tuffaceous units that are well exposed on or around Banda Terrane klippen in West Timor. Identical units are also found associated with the Mata Bia and Cablac massifs of East Timor, (Fig. 7.5) which is why the limestone was initially named the Cablac Limestone by Audley-Charles (1968). However, rocks of Triassic age also make up some of the Cablac Massif (Haig and McCartain 2007), so the name of the unit has been changed to the Bowie Limestone (Haig et al. 2007). At the base of the Bowie Limestone is a distinctive conglomerate, first reported by T'Hoen and Van Es (1926) in West Timor and is also reported from the Mata Bia massif in East Timor (Harris 2006), which consists of clasts from older Banda Terrane units, such as polymetamorphic pelitic schist and a range of volcanic and some plutonic clasts, Eocene *nummulites* fragments and large Oligocene foraminifera embedded in a carbonate matrix. Near the top of the Bowie Limestone in West Timor are an increasing abundance of ash layers interbedded with Middle Miocene marl (Carter et al. 1976). These deposits may document the birth of the subaerial Banda Arc (see below), which yields Late Miocene ages from nearby arc volcanics in Wetar and Alor (Abbott and Chamalaun 1981; Elburg et al. 2005).

Exhumation of the metamorphic basement of the Banda Terrane was assisted by normal faults that juxtapose various Cretaceous to Eocene cover units with the Eocene metamorphic rocks. This tectonic scenario is consistent with apatite fission track model ages that indicate cooling below 120°C during the Oligocene, then renewed burial into the partial annealing zone until rapid Pliocene Pleistocene uplift (Standley and Harris 2009).

Late Miocene to Pliocene opening of the Banda Sea further fragmented the Great Indonesian Arc and transported the Banda Terrane southward and eastward until it became captured in the forearc of the Banda Arc. Collision from Early Pliocene to the present has uplifted much of the Banda Terrane, which is one of the few places on the planet where large sections of the forearc of an active arc are exposed. The uplift of the metamorphic rocks from the partial annealing zone of apatite was so recent that no new fission-tracks are found.

Structural analyses and observations of contact relationships (Standley and Harris 2009) show that during tectonic emplacement, the Banda Terrane was thrust over Gondwana Sequence units of the Australian continental margin as indicated by extensive outcrops of mélange and broken formation at the structural base of the Banda Terrane (see mélange above). This phase of deformation is recorded in the Banda Terrane by parallelism between the orientations and transport directions of structurally underlying Gondwana Sequence and the latest phases of deformation of the Banda Terrane (Standley and Harris 2009). Duplex stacking of Gondwana Sequence units beneath the Banda Terrane uplifted it from a forearc basement position to higher than 2,500 m elevation in places. Erosion has removed much of the likely continuous metamorphic terrane leaving only isolated klippen with similar orientations of structural features (Harris 2006).

Due to the obliquity between the Australian continental margin and the Banda Trench, allochthonous thrust sheets of the Banda Terrane in Timor can be traced laterally along orogenic strike to autochthonous units in the present forearc of the westernmost Banda Arc island of Sumba (Harris 1991). Forearc basement exposed in Sumba is traceable eastward along the submarine Sumba Ridge (Reed et al. 1986) to the mostly flat-lying thrust sheets of Banda Terrane in Timor (Fig. 7.5). Various structural expressions of the Banda Terrane are found along orogenic strike and provide a rare glimpse of progressive modes of forearc nappe emplacement during an active arc continent collision.

7.3.2.2 Ophiolite?

Mafic and ultramafic bodies associated with the Banda Terrane are commonly reported as a dismembered ophiolite, but no characteristic ophiolite sequence is found, neither is an age or compositional relationship demonstrated for the assortment of fragments that are documented (Harris and Long 2000). It is not clear which of the mafic and ultramafic bodies are part of the upper plate Banda Terrane or the most distal edge of the lower plate Australian continental margin. Lherzolitic and gabbroic bodies identical in composition to those found intruding the Aileu Complex (see above) are dredged from the distal Australian continental margin (Nicholls et al. 1981). These bodies were emplaced and exhumed during continental breakup and in Timor are now thrust back over the continental margin during Latest Miocene to Pliocene arc continent collision.

The best candidate for a supra-subduction zone ophiolite is the 3 5 Ma Ocussi volcanic pile on the north coast of West Timor, which structurally overlies the Gondwana Sequence (Harris 1992). However, nothing more than pillow basalt and sheet flows overlain by Pliocene forearc sedimentary successions are found. These steeply dipping volcanic units have $^{40}Ar/^{39}Ar$ ages (3 5 Ma) and supra-subduction zone (SSZ) geochemical characteristics similar to dredge samples from other parts of the southern Banda Sea Basin (Harris 1992). A similar body of pillow basalt with SSZ characteristics also occurs near Baucau in East Timor (Standley and Harris 2009). Ultramafic blocks in mélange at the base of both of these nappes are geochemically depleted with an estimated 20 25% partial melting (Harris and Long 2000). Based on these relations, the Ocussi and Baucau volcanics are interpreted as the emergent tip of part of the SSZ ocean basin that formed within the eastern Sunda Arc in a similar way to the southern Banda Basin.

Another possible subduction-related ultramafic body is the fault-bounded Hili Manu lherzolite of central East Timor. Nd and Sr isotopes, REE and associated harzburgite of this ultramafic body show similar patterns to other ultramafic bodies with known supra-subduction zone crustal affinities (Falloon et al. 2006). Based on these new data it is possible that the gabbro and lherzolitic bodies along the north coast of Timor and even those found within the Banda Terrane may be associated with rifting of south Banda Basin immediately before or during collision initiation.

Several lines of evidence indicate that the most recent phase of extension of the Banda Basins was synchronous with the arrival of the Australian continental margin at the Java Trench and the onset of arc continent collision. For example, the first part of the Australian continental margin to accrete to the edge of the southern Banda Basin, the Aileu Complex, yields reliable $^{40}Ar/^{39}Ar$ metamorphic cooling ages of around 5 Ma (Berry and McDougall 1986), which overlap those of the South Banda Basin. These concordant ages indicate that the distal part of the Australian continental margin had already accreted to the edge of the Asian plate, and cooled from 600 to 350°C, around the same time as the Banda Basins were opening and forming new oceanic lithosphere. The synorogenic sedimentary record of Timor (see below) also dates the initial emergence and erosion of the Banda arc continent collision at around this time (Audley-Charles 1986; Fortuin and de Smet 1991). These relations are consistent with those documented for other arc continent collisions like in Oman where supra-subduction zone ophiolites have ages that overlap those of its tectonic emplacement over continental margins (Harris 1992).

Although the Banda Terrane was probably emplaced over the continental margin of Australia in a similar way to Oman-type ophiolite nappes its composition is more akin to a composite forearc terrane. It inherits its metamorphism and early deformational history from its previous life as part of a proximal forearc basin of a continental arc. The composition and age relations of the Banda Terrane do not fit the conventional model for oceanic lithosphere constituting the basement of intra-oceanic forearcs. Age and compositional relations are mixed. Most of the forearc formed and was metamorphosed during an event distant in time and space from the Banda Orogen, while the Ocussi Volcanics show a direct relationship with the arc continent collision it is incorporated into. Other places where similar relations to the Ocussi body may occur is in the Weber Basin, which is a forearc region along orogenic strike to the east that consists of oceanic lithopshere >7,000 m deep (Bowin et al. 1980). Parts of the Weber Basin are uplifted in the hinterland of the Banda Orogen near Tanimbar and represents a large ophiolite in the initial stages of emplacement onto the Australian continental margin, an ophiolite as large as any known (Harris 1992).

7.3.2.3 Banda Volcanic Arc

The Banda volcanic arc is an extension of the eastern Sunda Arc, both of which are considered intra-oceanic volcanic arcs mounted on mostly oceanic crust (Fig. 7.1a). Both arcs formed by subduction of Indian Ocean floor. However, the Banda volcanic arc is younger (0 8 Ma, Honthaas et al. 1998; Elburg et al. 2005), due to its association with opening of the Banda Sea, and is contaminated by subduction of continental material. The contamination causes some of the most extreme compositional variation known from island arcs, including everything from tholeiitic through calcalkaline and shoshonitic to leucititic compositions. It also manifests the widest range of K_2O values and lowest He^3/He^4 ratios known (Wheller et al. 1987). These variations result from mixing of peridotitic and contaminated mantle with continental material in the source region. Both spatial and temporal geochemical variations are observed that relate directly to lateral variations in composition and structure or the "nature" of the lower plate subducting beneath the arc (Whitford et al. 1977, 1981; Whitford and Jezek 1979; Hilton and Craig 1989; Hilton et al. 1992; Vroon et al. 1993; van Bergen et al. 1993).

The spatial transition from parts of the arc that are not contaminated by continental crust and those that are, happens around Iya Volcano in central Flores (Fig. 7.1b). Although there are exceptions to this, such as non-contaminated volcanoes to the east and some that are contaminated to the west, central Flores marks the current position of the main westward propagating continental contamination front.

A notable exception to this pattern is found in Sumbawa (Fig. 7.1b) where recent shoshonitic to high-K volcanoes yield higher Pb and He isotopic values than the low-K volcanoes surrounding them or lavas from earlier eruptions (Elburg et al. 2004). The Sumbawa segment of the volcanic arc is adjacent to the Sumba segment of the collision, which has evolved in a different manner than the Timor region (see Sumba below). Contamination of the Sumbawa volcanoes is predicted by models for the evolution of the Sumba segment of the Banda Orogen resulting from subduction of the Scott Plateau continental prong ahead of the arrival of continental crust into immediately adjacent parts of the arc (Harris 1991; Keep et al. 2003; Fleury et al. 2009).

Tracking continental contamination of the arc through time is possible in the parts of the volcanic arc that are deeply eroded due to shifts in the position of active magmatism, such as in Wetar Island (Fig. 7.1) north of central Timor and Ambon Island near Seram. The earliest signs of contamination are found in cordierite- and garnet-bearing rhyolite and dacite lavas in Ambom (ambonites) and Wetar. These volcanics yield reliable $^{40}Ar/^{39}Ar$ ages of around 5 Ma (Elburg et al. 2005). This age is consistent with a 4.9 Ma $^{40}Ar/^{39}$ age for volcanic rocks with clear evidence of continental contamination reported by Scotney et al. (2005). The most contaminated volcanics on Wetar yield a $^{40}Ar/^{39}$ age of 2.4 Ma (Herrington et al. 2011) indicating increased contamination through time.

These age and geochemical data indicate that continental contamination started at least by around 5 Ma near Wetar and has swept westward to its present position in central Flores. The contamination front also spread eastward from Wetar (e.g. Whitford et al. 1977; Elburg et al. 2005) where volcanoes become progressively less contaminated toward Banda Island (Fig. 7.1b). In a similar pattern to that of continental contamination, cessation of volcanism along the axis of the Banda Arc started at Wetar (<2.4 Ma) then progressed to Romang (<1.7 Ma) and Alor (<1.3 Ma) to the east and west, respectively (Fig. 7.1b).

Since the cessation of volcanism in the Wetar segment of the arc new volcanic centers have risen out of the Banda Sea north of Wetar, Alor and eastern Flores (Fig. 7.1). Active volcanism in this region is enigmatic because it happens above a deep part of the Benioff zone. However, compositionally the samples collected from these 0 0.4 Ma volcanoes are very similar to slightly contaminated volcanic rocks of Wetar, with the exception of high Mg values (Schwartz et al. 1984). The fact that continental contamination is detected in these new volcanoes is difficult to explain unless the continent is taking a very shallow trajectory into the subduction zone and has shifted or re-established the asthenospheric wedge 90 km to the north of the Benioff zone (Harris 2003). The Wetar volcanic ridge is shifted 45 km to the north of the main axis of volcanism along strike slip faults imaged on the sea floor off the west coast of Wetar (Breen et al. 1989a, b).

The location of the abandoned segment of the arc and its high levels of continental contamination is consistent with many other lines of evidence that demonstrate collision initiated in the Central Timor/ Wetar region and therefore more continental crust is subducted there than any other part of the Banda Orogen (Harris 1991). The youngest volcanic rocks in Wetar present an end-member of extreme continental contamination among studied volcanic arcs worldwide with $^{87}Sr/^{86}Sr$ ratios as high as 0.7223, $^{206}Pb/^{204}Pb$ ratios as high as 19.6, $^{143}Nd/^{144}Nd$ ratios as low as 0.5195 and He^3/He^4 ratios much lower than normal (2.0 average). These anomalous compositions require the incorporation of large amounts of subducted continental sediment into the magma source regions of these volcanoes (Vroon et al. 1993; Elburg et al. 2005; Scotney et al. 2005).

Much of the compositional variation in the volcanic rocks can be traced directly to the composition of sediment entering the subduction zone. Lead isotope variations, and trace element abundances in the volcanic rocks parallel variations found in the sediment dredged from the seafloor entering the trench (Vroon et al. 2001). Incompatible trace-element ratios in these volcanics, such as K/Rb and La/Th, are unique among island arcs (Vroon et al. 2001). Common trace elements used to detect a subduction component, such as the Nb and Ta anomalies, can be traced directly to similar anomalies found in the sediment entering the subduction zone (Vroon et al. 1993).

Bulk mixing calculations by Vroon et al. (1993) indicate that the amount of the subducted continental material increases along the Banda Arc from 0.1% near the northward bend in the arc (Island of Manuk, Fig. 7.1b) to as much as 5.0% toward the central Timor/Wetar region. The composition, age and thickness of sediment entering the subduction zone also vary depending on the structure of the continental margin. For example, greater amounts of contamination by Proterozoic and Paleozoic sedimentary rocks is detected where the Bonaparte Gulf Basin is subducting (Vroon et al. 1993), which is one of the only basins containing thick sections of these sediments on the NW continental margin of Australia (Harrowfield and Keep 2005). The large of amount of subducted sediment in the Banda Orogen provides a modern analog for how subducted sediment can produce mantle heterogeneities, such as the EMII anomaly found in ocean-island basalts (e.g. Ben Othman et al. 1989).

Continental contamination of arcs may also play a previously unrecognized role in mineralization. The economic Au Ag Hg-bearing barite units mined on the island of Wetar are related to Pliocene (4.7 2.4 Ma) pumping of marine hydrothermal fluids through fracture networks that vented onto the seafloor as smoker systems (Scotney et al. 2005). The timing of this event is coincident with the first evidence of contamination of the subduction system by continental crust.

7.3.3 Banda Orogen Sequence

The subduction of the Australian continental margin beneath the Banda Arc produced a submarine orogenic wedge that is overlain by synorogenic sedimentary successions known as the Banda Orogen Sequence (Fig. 7.11). The sediments most likely unconformably overlie the Banda Mélange, but the contact is irregular due to remobilization of the scaly clay. Unconformities are found with most other units from both the

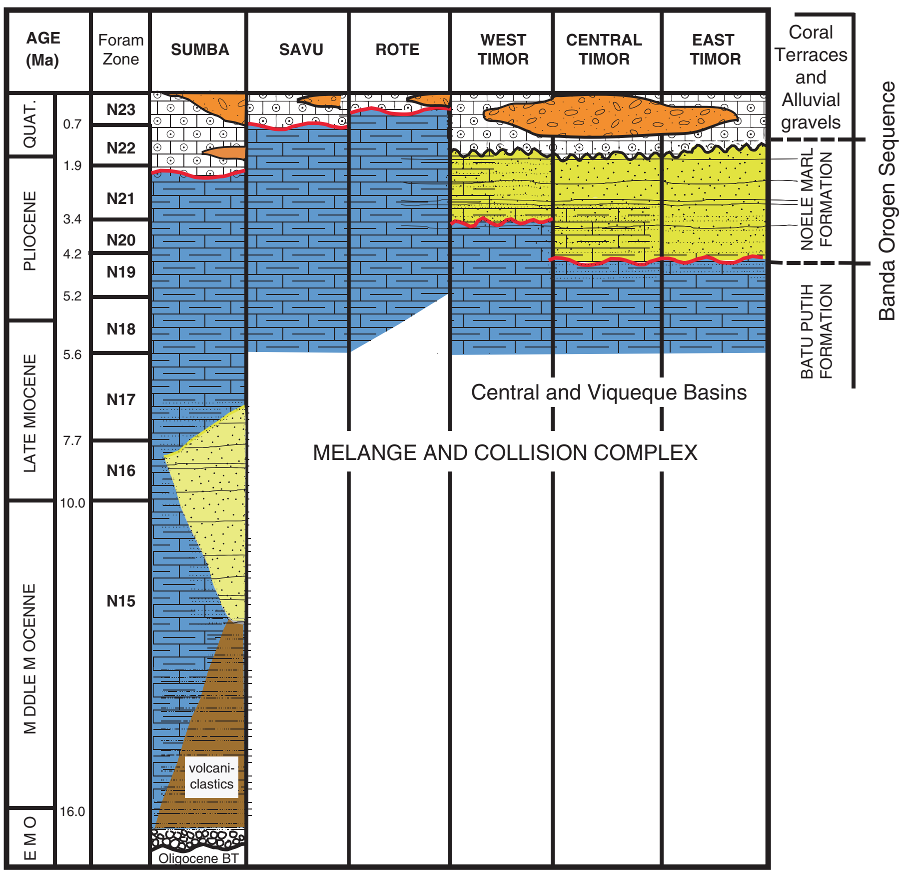


Fig. 7.11 Spatial and temporal distribution of Banda Orogen Sequence synorogenic sedimentary rocks from East Timor to Sumba. Changes in lithofacies and depth of deposition through time indicate the arc continent collision propagated westward along the Australian passive margin from East and Central Timor to Rote, and along the eastern edge of the Scott Plateau from Sumba to Rote. The Noele Marl Formation is most likely currently being deposited in offshore basins of Rote and Savu. Modified from Roosmawati and Harris (2009).

Australian continental margin and the Banda Arc, which form the Banda orogenic wedge. The basal unit of the Banda Orogen Sequence is a distinctive pelagic chalk succession, which documents the birth of the accretionary prism and much of its uplift history. These are overlain in places by turbidites shed from the first land created by the rise of the orogenic wedge above sea level. As the orogen emerged close to sea level it was encrusted in coral reefs and locally buried by fluvial gravels that form the uppermost units of the sequence.

The basal unit of the Banda Orogen Sequence is known as the Batu Putih Formation (Audley-Charles 1968), which consists of a few hundreds of meter thick massive, foraminifera-rich calcareous pelagite and chalk deposits with some calcilutite and vitric tuff horizons. The depositional environment is consistent with deep, low energy, open sea conditions of the Banda forearc with no terrigenous input in the basal section and some mica and metamorphic rocks fragments in the upper section (Haig and McCartain 2007). The basal contact between the Batu Putih Formation and underlying accretionary wedge is poorly defined. In the type location it is interpreted by Haig and McCartain (2007) as unconfomable. However, it is very irregular in places. In many places the contact is highly disturbed by remobilization of mélange.

Detailed biostratigraphic age analyses by Haig and McCartain (2007) of the type location of the Viqueque Group in East Timor yield ages of Neogene foraminifera zone N18 for the basal Batu Putih Formation. This age corroborates those obtained by Kenyon (1974) from the type locality of the Batu Putih Formation in the Central Basin of West Timor. The earliest sign of turbidite deposition within the Batu Putih Formation is during N20 (4.2 3.35 Ma). The youngest age of the Batu Putih Formation varies westward from N19 (5.2 4.2 Ma) in East Timor (Haig and McCartain 2007) to N20 (4.2 3.4 Ma) in western-most Timor (Kenyon 1974) to N22-N23 (1.9 0.7 Ma) in Rote and Savu (Roosmawati and Harris 2009), and is latest Pliocene in Sumba (Fig. 7.11).

Overlying the Batu Putih Formation in Timor is the Noele Marl Formation, which consists of calcilutite and marl interbedded with turbiditic sandstone, and tuffaceous material (Fig. 7.11). These deposits become more clastic-rich up section, and the clasts also coarsen upwards. The clasts are dominated by metamorphic rock fragments. The oldest turbidites of the Noele Marl Formation ranges in age from N21 (3.35 Ma) in East Timor (Haig and McCartain 2007), to N22 (4.2 0.7 Ma) in West Timor. The absence of the Noele Marl in Rote, Savu and Sumba (Fig. 7.11) indicates that these islands are at different stages of collisional evolution than Timor. During the time of Noele Marl Formation deposition in Timor, Batu Putih Formation pelagic deposits were deposited on the accretionary ridge (Savu and Rote) and in the forearc basin (Sumba) to the west. The lack of turbidite deposition in the synorogenic rocks exposed on these islands indicates that they are the first parts of the orogenic wedge in these regions to emerge above sea level and experience erosional exhumation, which happened much earlier in Timor (Roosmawati and Harris 2009).

The upper part of the Banda Orogen Sequence consists of the Quaternary Baucau (coral limestone) Formation and the Ainaro (gravel) Formation (Audley-Charles 1968). These two units are commonly interbedded along the coast and represent the emergence to sea level of the Banda orogenic wedge (coral) and uplift and erosion (gravels) of the islands mostly during the Quaternary (Fig. 7.11). Both of these units are uplifted and form marine and fluvial terraces throughout Timor and other islands that are locally warped by ongoing deformation (see Uplift History below).

7.3.3.1 Synorogenic Basins and Foredeep

The Banda Orogen Sequence accumulates to thicknesses of >3,000 m in slope basins that formed during the collapse of the accretionary wedge shortly after initial underthrusting of the Australian Continental Margin (Figs. 7.12 and 7.13). Sonar mapping of the seafloor and seismic reflection profiles show that most of these basins are half-grabens with top-down-to-the-south basin bounding faults (van der Werff 1995). Some strike-slip faults are also found that may link many of these basins to pull-apart structures (Mark Quigley, Brendan Duffy and Myra Keep, personal communication). Some of the basins also manifest structures that suggest some tectonic inversion during collision, but generally most basins show few contractional structures (Fig. 7.13). Much of the deformation within the basins originally interpreted as shortening (Kenyon 1974) is disturbed mostly by local diapiric movement of the underlying Banda Mélange.

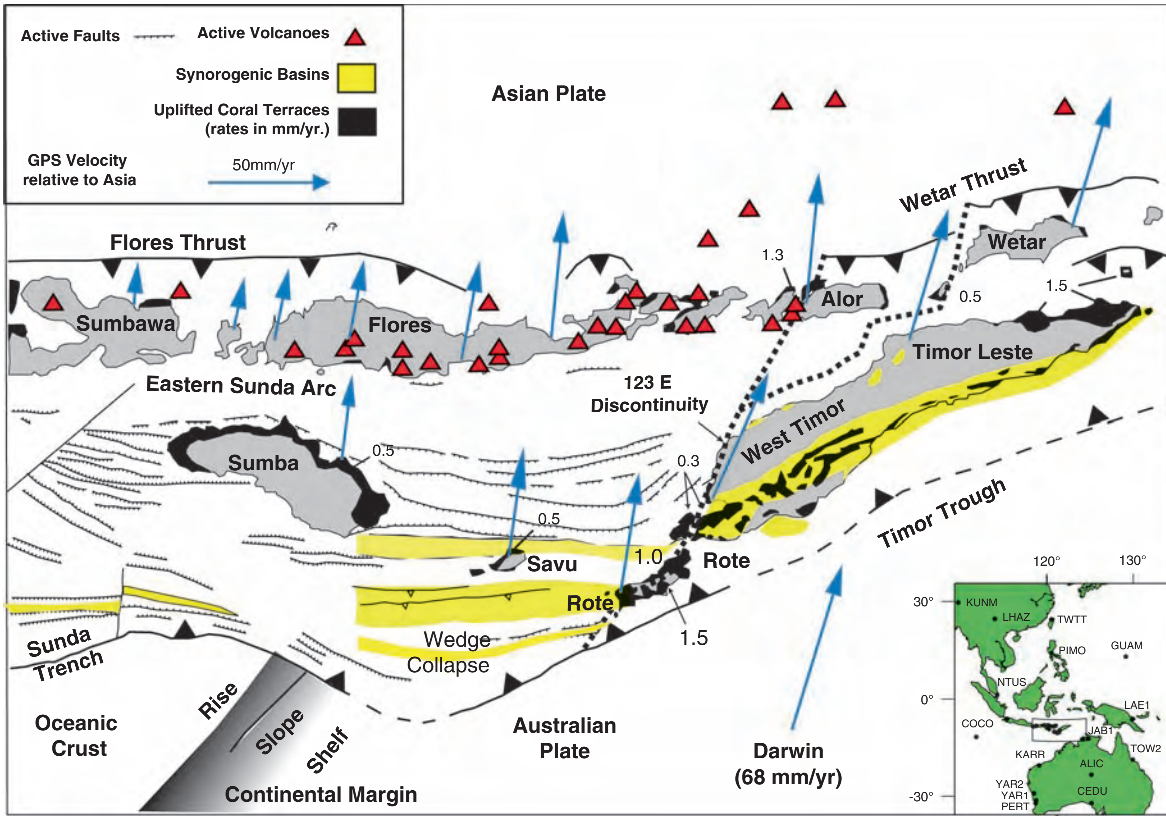


Fig. 7.12 Neotectonic map of the Timor Region showing active faults, active volcanism, surface uplift rates and GPS velocities. Velocities are plotted relative to Asian reference frame (see stations on *inset* map). Synorogenic basins open during collapse of the accretionary wedge east of Sumba and are uplifted due to subduction of the Australian continental margin. Uplift rates vary throughout the region and correlate best with proximity to active faults. Sea floor structure from van der Werff (1995). Uplift rates from Cox et al. (2006). GPS velocities from Nugroho et al. (2009).

The Banda Orogen Sequence progrades into the 3 km deep Timor Trough, which is a classic example of an under-filled collisional foredeep. Drilling data from DSDP 262, which was drilled 400 m into sediments in the Timor Trough, indicates a yield of mostly pelagic ooze, containing nannofossils, foraminifers, and radiolaria overlying Pleistocene age shallow water shelf strata (Veevers et al. 1974). The pelagic sediment documents the rapid subsidence of the Australian Shelf as it flexes downward from near sea level to enter into the Timor Trough. Modeling of the flexure indicates an effective elastic thickness of 25 km (Lorenzo et al. 1998) and only 200 m of forebulge uplift. This contrasts with an effective elastic thickness of 11 km for the China continental margin as it bends beneath the Taiwan arc continent collision (Ma and Song 2004). However, unlike Taiwan, a foreland basin has not yet developed in the Banda Orogen. The difference may be related to the greater rigidity of the Australian continental margin, which is more than 100 Ma older than the China margin, and the lack of source sediment coming from the Australian continent.

7.4 Initiation of Collision

When collision initiated in the Banda Orogen depends upon how "collision" is defined. Most commonly the time of collision initiation is interpreted as the age of: (1) the youngest material accreted from the subducted continental margin, (2) the oldest synorogenic deposits, (3) metamorphism of continental margin lithologies, and (4) continental contamination and extinction of the volcanic arc.

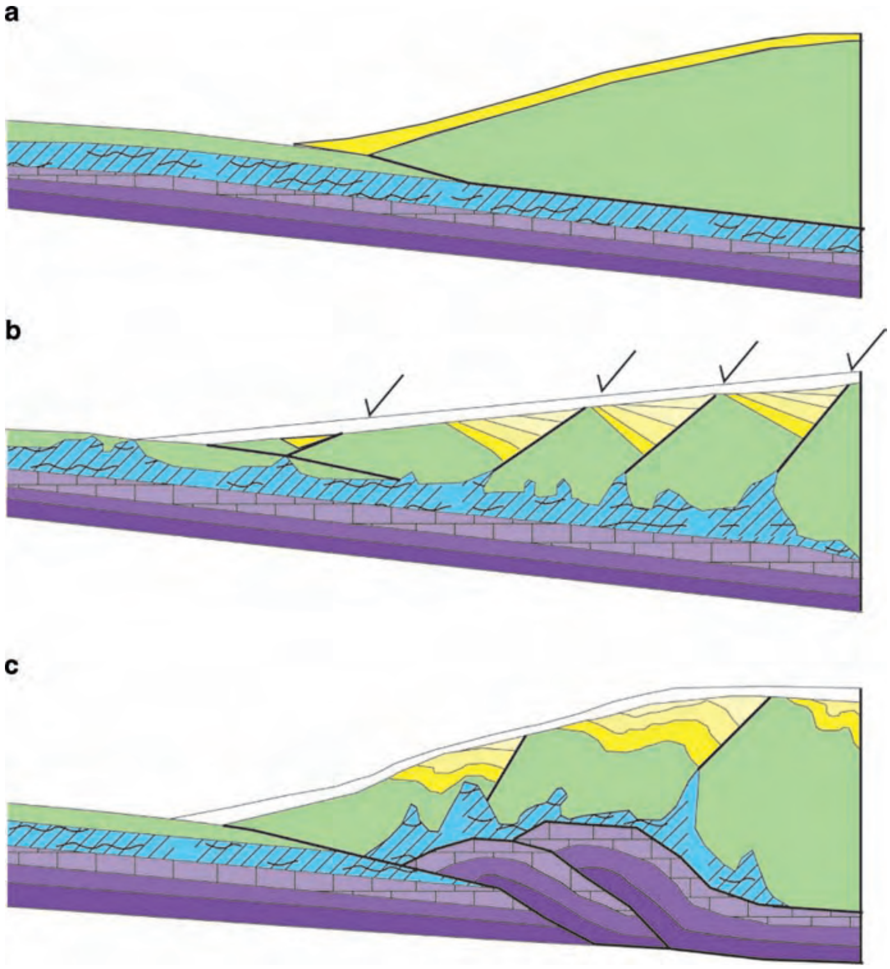


Fig. 7.13 Idealized structural evolution of accretionary wedge collapse south of Savu. (**a**) pre collisional geometry with slope angle of 5 6°. Green is accretionary wedge and mélange over lain by Batu Putih formation pelagic chalk (*yellow*). (**b**) Under thrusting of continental margin with highly over pressured Cretaceous and Jurassic mudstone (*blue*) weakens décollement causing collapse of the accretionary wedge to the south, opening of synorogenic slope basins, diapirism and collisional mélange development. Surface slope decreases to 2 3°. (**c**) Development of Gondwana Sequence duplex (*purple*) uplifts the orogenic wedge and may cause mild inversion of slope basins.

7.4.1 Youngest Passive Margin Lithologies

If collision is distinguished from subduction by under-thrusting of continental versus oceanic lithosphere, then where collision is initiating in the Banda Arc is easy to pin point by where the distal most edge of the Scott Plateau is entering the Java Trench south of Sumba (Fig. 7.1). However, due to the obliquity between the Australian continental margin and the trench the age of collision, and the irregular shape of the continental margin, collision initiation varies along orogenic strike. In older parts of the Banda Orogen evidence for collision initiation, according to this definition, may be constrained by identifying the youngest continental margin lithologies that were accreted to the deformation front. However, identifying these lithologies can be difficult because as the continental margin approaches the accretionary wedge both are overlain by the same sedimentary units. Ideally the age of collision initiation could be bracketed across an angular unconformity where the youngest known continental margin rocks of the accretionary wedge are unconformably overlain by undeformed synorogenic deposits close to the same age. However, these types of relations are difficult to constrain.

The youngest distinguishable continental margin units incorporated into the Banda Arc accretionary wedge form an imbricate stack that is partially exposed along the south coast of Timor (Audley-Charles 1968; Rosidi et al. 1979) and in Savu and Rote (Harris et al. 2009; Roosmawati and Harris 2009). The best exposures are in the Kolbano Mountains along the cross-strike Oetuke River in West Timor (Fig. 7.6). This drainage exposes a southward-verging imbricate stack of at least 21 separate thrust sheets consisting mostly of slope and rise facies pelagic lithologies that range from Upper Jurassic Tithonian to Lower Pliocene Zanclian stage (Sawyer et al. 1993). Unconformably overlying the imbricate stack are successions of Pliocene chalk and calcilutite of foraminifera stage N18-19 (5.6 4.2 Ma). The youngest units of the Australian Passive Margin Sequence found to date in East Timor yield ages of 8 Ma (Keep and Haig 2010).

7.4.2 Oldest Synorogenic Deposits

The oldest synorogenic deposit is calcareous pelagite at the base of the Batu Putih Formation (Kenyon 1974; Audley-Charles 1986; Haig and McCartain 2007), which yields ages of (N18, 5.6 5.2 Ma). Locally, Late Miocene calcilutite and tuffaceous lithologies are found at the base of the chalk (Kenyon 1974; Haig and McCartain 2007) that may represent the earliest pre-collisional synorogenic deposits. The first turbidite in the Batu Putih Formation (N20, 4.2 3.35 Ma) and those that define the Noele Marl Formation (N21, 3.35 1.9 Ma) document the emergence of the Timor Island above sea level and the initiation of erosional exhumation. As mentioned earlier, the age of this transition decreases to the west where in Rote and Savu there is no record of it at all, but is likely happening offshore of these islands (Roosmawati and Harris 2009). These ages document the rise of the orogenic wedge from pelagic depths of >3,000 m to the surface between 5.6 and 4.2 Ma in East Timor and later to the west.

7.4.3 Metamorphic Cooling Ages

There are two distinct metamorphic complexes exposed throughout the Banda Orogen: the Asian affinity complexes of the Banda Terrane, which were metamorphosed ~40 m.y. prior to the Banda Orogen (see 7.3.2.1 above), and the Australian affinity Aileu Complex. The age of metamorphic cooling of the Aileu Complex was investigated initially by Berry and Grady (1981) who report K/Ar ages for biotite and white mica of 5.4 5.7 $\pm$ 0.2 Ma and amphibole ages of 7.7 16.5 Ma. Nearly identical ages were produced by Berry and McDougall (1986) using $^{40}Ar/^{39}Ar$ methods. However, only one white mica age yields an acceptable plateau age (5.36 $\pm$ 0.05 Ma). Reanalysis of these data using ISOPLOT yields unacceptable MSWD values (>60) for inverse isochron plots for every age determination except the one white mica age (Major et al. 2009). Therefore, there is only one reliable age of metamorphism for the Aileu Complex, which indicates that it experienced metamorphic cooling to around 420°C (closure temperature of white mica, Kirshner et al. 1996) at 5.4 Ma.

The age of exhumation of the Aileu Complex is further constrained by fission-track analyses of apatite grains (Harris et al. 2000). Nearly all of the fission-tracks are highly to completely annealed, which indicates a low-temperature exhumation age of <4 Ma. These ages are also consistent with plate reconstructions (Hall 2002; Roosmawati and Harris 2009) of when the NW Australian continental margin arrived at the collision zone (Fig. 7.4).

7.4.4 Arc Contamination and Extinction

The age of arc extinction is commonly used as an indicator of collision initiation, but in the Banda Arc it is obvious that volcanism continued after collision initiation and still may not have ceased completely. The deeply eroded Wetar to Alor section of the arc is not active currently and the youngest volcanic rocks are 2.5 and 1.3 Ma, respectively (see Banda Arc above). However, there are lavas on these islands that show ^{238}U-^{230}Th disequilibrium that limits their age to <350,000 years (Vroon et al. 1993). There is also a line of active volcanoes north of the Wetar-Alor segment that are similar in composition to the Banda Arc (Schwartz et al. 1984). Dredge samples from a submerged seamount in this region yield ages of 0.4 Ma (Morris et al. 1984). There is abundant evidence from multiple sources that arc continent collision initiated in the Wetar to Alor segment of the arc significantly earlier than volcanism ceased (see above). It is also important to note that there are well-documented inactive segments of the Sunda Arc to the west that are not related to collision. For example, there is a 200 km long extinct segment of Sunda Arc in central Java. For these reasons it is advisable to reconsider how arc volcanism is modified by collision (Vroon et al. 1993).

The age of continental contamination of the Banda Arc provides a minimum age of collision initiation that would be at least 2 m.y. too young due to the time it takes for the edge of the continent to reach the depths of arc magma generation. Evidence for contamination shows up in volcanic rocks of Wetar as early as 5 Ma (Scotney et al. 2005), which is consistent with other minimum ages of collision initiation mentioned earlier. The Wetar segment of the Banda volcanic arc is also offset northward from the rest of the arc by 40 km. Instead of ramming into the accretionary wedge as in Taiwan, the Banda volcanic arc is accreting to the lower plate and moving mostly with it along the Wetar Thrust to the north of the arc (see Fig. 7.12). These geochemical and structural modifications to the volcanic arc are adjacent to the oldest part of the collision based on other indicators, such as the position of the Aileu Complex, highest topographic relief and oldest synorogenic sedimentary rocks.

Unlike Taiwan, volcanism is still active in most parts of the collision zone in the Banda Orogen. The West Timor to Sumba section of the collision, which is at least 3 m.y. old, is adjacent to the active, but contaminated volcanoes of Flores Island and those between Flores and Alor. A similar situation is found in the Wetar to Alor arc segment where continental contamination of arc volcanics is found as early as 5 Ma, but arc volcanism persisted on Wetar until at least 2.5 Ma (Scotney et al. 2005) and may be still active. East of Romang the active volcanism is part of the collision zone that stretches nearly all of the way to Seram (Fig. 7.1).

7.4.5 Summary

The above indicators of collision initiation in Timor converge at a Latest Miocene age ($<$ 8 Ma). Taking into account the lag times between collision initiation and (1) emergence and erosion of the orogen at 4.2 Ma, (2) metamorphism and later metamorphic cooling to 420°C at 5.3 Ma, and (3) continental margin underthrusting ($<$ 8 Ma) and eventual contamination of the volcanic arc at Wetar by at least 5 Ma, the collision initiated south of Wetar at around 8 Ma. The age of collision initiation young's to the west towards Rote Island, but initiated earlier in Sumba due to the Scott Plateau protrusion.

7.5 Tectonic Features of the Banda Orogen

Due to the Scott Plateau protrusion the Banda Orogen is shaped by two arc continent collisions. The first is the arrival of the NW Australian continental margin to Banda Trench at around 8 Ma in the central Timor/Wetar region. This collision propagated to the west in a time-space equivalent manner to just beyond Rote Island. Its propagation to the east is only constrained by the eastern propagation of the contamination front. The second collision is the arrival of the Scott Plateau at the Sunda Trench at around 3 Ma to form the Sumba Ridge. This collision propagated from Sumba to the SE through Savu to Rote Island (Harris et al. 2009; Roosmawati and Harris 2009). Both of the collisions merge in the Rote region to form the western Banda Orogen.

Serial sections through the collision reveal various orogenic phases of collision propagation (Fig. 7.15). These include, (1) the birth of Savu Island above the Savu Thrust and collapse of the accretionary wedge south of the Island, (2) deformation along a lateral ramp in Rote, (3) development of the Gondwana Sequence duplex beneath the Banda Terrane in West Timor, (4) folding, uplift and detachment (?) of the Banda Terrane tectonic lid, (5) forearc closure and cessation of volcanism in central Timor, (6) forearc sinking, arc accretion and northward translation adjacent to

Wetar, (7) strong coupling of the lower plate creating an oblique-slip extensional system (East Timor), and exhumation of metamorphic rocks (East Timor).

7.5.1 Sumba Ridge: Collision with a Continental Plateau

The most vivid expression of the initiation of collision in the Banda Orogen is the abrupt uplift of the Sunda forearc basin from 5 km below sea level to the surface to form the island of Sumba. Sumba Island is the emergent part of the Sumba Ridge (Fig. 7.4), which stretches in a NW-SE direction from the distal continental margin of Australia under the Sunda trench and forearc all of the way to the volcanic arc. The Sumba Ridge uplifts the Sunda Trench and forearc by at least the same amount as the 2 3 km difference in bathymetry between the Scott Plateau and the Jurassic oceanic crust that surrounds it. The Sunda Trench becomes the Timor Trough at this point. However, an additional 20 30 km of shortening in the region or a thicker crust is needed to lift Sumba up from its forearc basin origins to the surface and expose its basement rocks. Gravity data from Sumba (Chamalaun et al. 1981) indicate that whatever the uplift mechanism is, it must involve continental-type crust, which underlies the forearc basement exposed at the surface.

The Sumba Ridge also indents the Sunda Arc and shifts it around 30 km northward near the island of Sumbawa (Fig. 7.1). The indentation is accommodated by slip along the Flores Thrust, which has propagated over 300 km to the west near Lombak Island and nearly the same distance to the east. The volcanoes in the region of the indentation are contaminated with continental crust and include the explosive giant of Tambora.

The Sumba Ridge is likely the expression of the subducted NE edge of the Scott Plateau (Harris 1991; Keep et al. 2003), which arrived at the Sunda Trench at around 3 Ma (Fig. 7.4). Subduction of the Scott Plateau presents an end member of arc continent collision of semi-buoyant thinned continental lithosphere with only a thin veneer of cover sediment. The initial stages of collision in the Sumba region are even characterized as that of a seamount asperity forcing wedge taper adjustments of shortening followed by extension (Fleury et al. 2009).

The collision of the Scott Plateau is also manifest in the volcanic arc and backarc region. Volcanoes above where the Scott Plateau is subducted show evidence of recent continental contamination (see Volcanic Arc above) to the west of the main contamination front, which is in central Flores. Adjacent to this region in western Flores arc volcanism has ceased.

7.5.2 Transition from Subduction to Collision: Uplift and Shortening of the Forearc

Where the Scott Plateau intersects the deformation front the Sunda Trench becomes the Timor Trough and manifests many structural features not seen in the accretionary prism to the west. Differences in the way incoming material is accreted is described by Breen et al. (1986). In the Sunda Trench the thin sedimentary cover blanketing the Indian Ocean seafloor is picked up by horizontal propagation of short décollements into small, accreted slices that shorten along closely spaced thrusts and conjugate strike-slip faults. Seismic images of the accretion zone show chaotic reflections interpreted as mélange. Where the Scott Plateau enters the Timor Trough (between 120°40′ E and 121°, Fig. 7.1b) Breen et al. (1986) report décollements propagating up to 15 km south of the thrust front into significantly thicker sections of incoming layered successions allowing for the accretion of long slabs of lower plate material (Fig. 7.6). The length/thickness ratio of these thrust sheets is more like what is found in fold-thrust zones. The thrust front is well defined by a vertical separation along faults and folds 2 4 km long that occur throughout the lower slope. Mud diapirism is also seen for the first time and produces ridges of mud volcanoes south of the thrust front in the lower plate that are sourced from the décollement. The décollement is traced as a strong to moderate reflector into what is interpreted as Cretaceous shale (Reed 1985; Karig et al. 1987). Exposures of this unit in Timor show that it is actually a mudstone composed of expandable clays (see Banda Mélange above) that overlie pre-rift Gondwana Sequence cover sediment of the Australian continental margin.

Another difference in the deformation pattern between subduction in the Sunda Trench and collision in the Timor Trough is the partitioning of strain away from the deformation front in the later. In the Sunda Trench a sharp boundary is found between the lower and upper slope of the accretionary wedge (Karig et al. 1987; Breen et al. 1986). Seismic reflection and sonar data show that this boundary marks the northern limit of the deformation front where recently accreted sediments are disturbed. In most places along the Sunda Trench this boundary is 20 30 km from the deformation front, with no evidence of any deformation in parts of the arc-trench system beyond this narrow zone. This observation implies that in the Sunda Trench most of the convergence between Indo-Australia and SE Asian Plates occurs at very high strain rates within only the lower slope region of the accretionary wedge, which is consistent with the abundance of mélange generated in this zone. The only other site of convergence in the zone of subduction is the Flores Thrust to the north of the Sunda volcanic arc. However, it is most likely a product of subduction of the Scott Plateau and its impingement on the Sunda volcanic arc.

Distribution of strain away from the deformation front due to underthrusting of the Scott Plateau south of Sumba involves: (1) initiation of northward-verging thrust systems (Flores and Savu thrusts), (2) shift of shallow seismicity away from the trench into the forearc and backarc, (3) uplift of the forearc basin (Sumba) and ridge (Savu), (4) abrupt widening of the accretionary wedge by >100 km, (5) formation of top-down-to-the-south half graben slope basins, and (6) extensive mud diapirism. Features 1 3 may relate to increased coupling due to positive buoyancy of the underthrust continental plate. Features 4 7 are most likely caused by adjustments of the accretionary wedge to basal décollement weakening as over-pressured Australian continental slope units enter the trench (Harris et al. 1998).

7.5.3 Savu: Initiation of the Retro-Wedge Thrust System and Fore-Wedge Collapse

Savu Island emerged from the sea at around 0.8 Ma where it was encrusted with coral terraces (Harris et al. 2009). The coral terraces are tilted to the south away from active thrust fault near the north shore (Fig. 7.7). Erosional windows through the coral terraces reveal that Savu is composed mostly of Triassic to Jurassic Gondwana Sequence with some Cretaceous Australian Passive Margin Sequence that are stacked by thrust faults (Harris et al. 2009). The thrust sheets are up to 2 km thick and verge to the south in the southern part of the island and to the north near the north shore (Fig. 7.7). Along the north coast and immediately offshore are splays of the active Savu Thrust, which offset uplifted coral terraces on shore and rupture all of the way to the surface in several places offshore (Harris et al. 2009). The island is part of the ENE-WSW Savu-Rai Jua Ridge that corresponds to a rift basin of the same orientation within the Scott Plateau lower plate and the position of the Lombak forearc accretionary ridge on the upper plate. Analysis of foraminifera within synorogenic deposits reveal that the accretionary ridge at Savu was uplifted from depths of 2.5 km below sea level to the surface between ~1.5 and 0.7 Ma, which is also when the NE edge of the subducted Scott Plateau arrived beneath Savu (Fig. 7.4).

The SSE dipping Savu Thrust forms where the rear of the accretionary wedge ramps up over the uplifted edge of the Banda forearc basement. Its orientation and that of most other thrusts and fold axes on the island parallels the ENE-WSW structural grain of NW Australian continental margin rift basins (Fig. 7.3). Even before the Australian continental margin arrives at the Timor Trough some of its rift basins are inverted to form anticlines with fold axes oriented parallel to east-northeast west-southwest rift basins (Dore and Stewart 2002). In many ways, the Savu Rai Jua ridge can also be considered an inverted rift basin of the Scott Plateau. Bedding attitude measurements throughout Savu show a dominantly ENE-WSW strike, which is also the orientation of fold hinge lines and thrust faults (Fig. 7.3). These observations show that the pattern of deformation in Savu during the earliest phases of arc continent is more strongly influenced by structural inheritance than NNE plate convergence, which would produce fold axes and thrust faults that strike WNW. This same pattern persists into more advanced stages of collision. South of Timor, the thrust front also rotates to parallelism with the structural grain of the northwest Australian continental margin (Fig. 7.1).

One of the most unique features of the transition from subduction to collision is the abrupt change in surface slope angle of the accretionary wedge from 6° to the west at the Lombak Ridge to around 2° south of Savu. The collapse of the accretionary wedge to the south is like a massive submarine slump that opens rift basins in the upper slope and causes mud-cored folds and thrusts at its toe (Figs. 7.12 and 7.13). The mega-slump is most likely caused by décollement weakening associated with underthrusting of highly over-pressured Jurassic to Cretaceous mudstone (see Banda Mélange above). In many ways the structure of the accretionary wedge south of Savu is similar to the structure of the slumping sedimentary wedge of the northern Gulf of Mexico.

7.5.4 West Timor: Anatomy of the Collision Revealed

Traveling from west to east on the only paved road through the island of Timor is like climbing up through an enormous plunging antiform. On the west coast all that is exposed are coral terraces encrusting the most recently uplifted part of the WSW propagating Banda Orogen. Below the coral veneer is a thick section of synorogenic deposits of the Central Basin (Fig. 7.5) that document rapid uplift of the accretionary wedge from depths of >3 km to the surface during the past 3 Ma (Kenyon 1974; De Smet et al. 1990). Further to the east and deeper into the antiform is a landscape that is a chaotic mix of two very different worlds (Fig. 7.5). To the north are the steep spires of deeply eroded Asian affinity rocks of the Banda Terrane. To the south are piles of dismembered thrust sheets of Gondwana Sequence. Between the two is a block and scaly clay mélange, which is a chaotic mixture of the rocks on either side.

Erosional windows through the Banda Terrane reveal that it structurally overlies the mélange and Gondwana Sequence. The mélange formed as part of the original subduction channel at the base of the Banda Terrane that was eventually clogged by and included parts of the Gondwana Sequence. The Gondwana Sequence is folded and thrust, but not enough structural relief is available to make out the pattern of deformation. However, the repetition of Permian to Jurassic successions indicate that it is detaching near the base of the Permian and is overlain by a roof thrust above which the rest of the Cretaceous to Tertiary section (Australian Passive Margin Sequence) is found.

To find the Australian Passive Margin Sequence requires braving the tortuous dirt roads to the Kolbano Mountains along the south coast of West Timor. The lower part of the Oetuke River exposes an astonishing section of at least 24 imbricate thrust repetitions each around 200 300 m thick of Early Cretaceous to Late Tertiary slope and rise deposits (Figs. 7.6 and 7.7). The thrust sheets are deformed mostly by fault-propagation folding with the thrust faults truncating the overturned forelimb. The structural relief increases upstream until at its headwaters the river breaches the basal décollement in the Wai Luli Formation. North of this point mostly only Gondwana Sequence lithologies are exposed in what is interpreted as a thrust duplex (Harris 1991).

In the northern part of West Timor uplift and erosion exposes several large massifs of the Banda Terrane along strike of the submerged Sumba ridge to the west that is exposed in Sumba. These nappes cover much of the Gondwana Sequence duplex that varies in structural relief beneath them making it difficult to establish any lateral continuity of the underlying structure. The erosional level is such that the subduction channel beneath the Banda Terrane nappes is well exposed in several key places. It shows evidence of high fluid pressures associated with hydrofracturing of both lower and upper plate blocks along a basal and roof décollement that may have been active simultaneously. Traction along the basal shear zone of the channel pulls continental material deeper into the channel while at the same time material is plucked from the structurally overlying Banda Terrane roof thrust, which may explain the strongly attenuated nature of these nappes.

South of the Gondwana Sequence duplex zone the Banda Terrane is tilted southward and even extends to the south coast of the island in East Timor where it was penetrated by wells (Audley-Charles 1968). North of the duplex the Banda Terrane nappe is tilted steeply northward and is likely detached from its roots and carried by backthrusts over itself (Fig. 7.5). The best example of northward back tilting is the steepening to vertical dips of alternating pillow basalt and sheet flow layers of the Occusi nappe on the north coast of West Timor (Fig. 7.5).

7.5.5 East Timor: Fall of the Forearc and Rise of the Hinterland

The one paved road through Timor enters East Timor (Timor Leste) along the north coast of the central part of the island where two new features appear on the eastern horizon. The closest is a large mountain range (Aileu Range) of metamorphic rocks of the Australian affinity Aileu Complex. The other feature is the deeply eroded Banda volcanic arc island of Alor. Only 30 km separates the coast of Alor from the western-most north coast of East Timor. Between the two is the nearly 3 km deep Wetar Strait. The Wetar Strait is the site of the Wetar Suture proposed by Price and Audley-Charles (1983) to explain the narrow gap between the Banda volcanic arc and Australian continental margin material. They inferred a large fault that ruptured through the entire Australian Plate and moved it over the forearc. The location of the thrust at the base of the north-facing slope of the accretionary wedge (Fig. 7.14) is confirmed by seismic reflection profiles across the Wetar Strait (Breen et al. 1989a, b; Snyder et al. 1996). However, it is not known whether the fault ruptures through the entire lithosphere or connects with the basal décollement like a more advanced stage of the Savu Thrust (Fig. 7.7).

Additional confirmation of the northward motion of the orogenic wedge is provided by structural field mapping of the Aileu Complex (Prasetyadi and Harris 1996). These studies locate several top-to-the north thrust faults near the north coast of East Timor and a switch to top-to-the-south motion near the crest of the Aileu Range (Fig. 7.14).

The metamorphic fabric of the Aileu is characterized by an initial flattening (S0 = S1), which is overprinted by an axial planar foliation (S2) associated with isoclinal and nearly recumbent folds with generally top-to-the-south vergence. Berry and McDougall (1986) suggest that mica in the Aileu Complex records the age of S2 (~6 Ma). Rf-ϕ analysis of quartz grains yield a nearly horizontal prolate ellipsoid with the long (x) axis oriented N-S (Fig. 7.14). These features are overprinted by low-angle generally top-to-the-north thrust faults in the northern part of the range and top-to-the-south thrust faults in the central and southern parts of the range (Fig. 7.14). The last phase of deformation is the development of high-angle normal faults with an array of orientations, but predominately top-down-to-the-north sense of shear along the north coast.

The structure of the Aileu metamorphic complex documents an initial layer-parallel extensional phase most likely associated with compaction and perhaps even a rift-related thermal event associated with passive margin development. A close association with rifting is indicated by a series of enigmatic intrusions of lherzolite and gabbro bodies (Fig. 7.14) into mica schist mostly in the western part of the Aileu Complex (Prasetyadi and Harris 1996). The later layer-parallel shortening phase is most likely associated with arc continent collision. Subsequent brittle deformational phases document uplift by retro-wedge motion to the north and extensional exhumation.

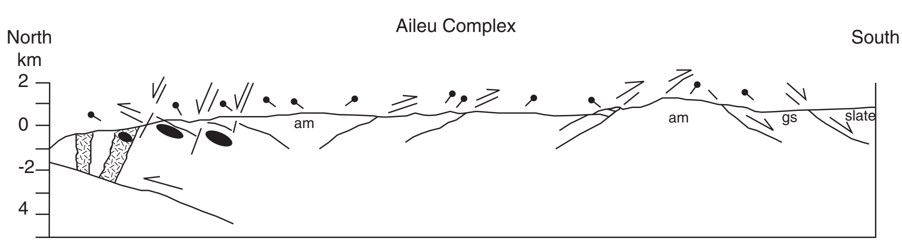


Fig. 7.14 Cross section across the Aileu Complex near the border of West and East Timor (modified from Prasetyadi and Harris 1996). See Fig. 7.5 for location. Stippled areas are mafic and ultramafic intrusions. Abbreviations for metamorphic grade: am amphibolite facies, gs green schist facies. Ellipses are in the x z plane and show relative amounts of strain and direction of stretching from Rf ϕ analysis of quartz grains. Normal faults are the youngest features and cross cut northward verging faults near the intrusions and accommodate exhumation on the southern part of the complex. The Laclo Fault is similar to these top down to the south normal faults, but with some left lateral strike slip motion.

7.5.5.1 Where is the Banda Forearc?

Retro-wedge motion along the Wetar Suture is used to explain the progressive closure of the Banda forearc north of Timor (Price and Audley-Charles 1983; Harris 1991). What happens to the forearc, and in many cases the arc complex as well, during arc continent collision is poorly understood. If the thrust in the Wetar Strait completely over-rides the northern Banda forearc basin then the forearc basement should be beneath Timor. If this is the case then it would produce a gradually decreasing gravity high from the north coast toward the center of the island (Zobell 2007). However, what is observed is perhaps the steepest gravity gradient known that increases sharply from the north coast but does not extend south beneath Timor (Zobell 2007). Modeling this pattern from a combination of detailed gravity measurements across central Timor (Chamalaun et al. 1981) and regional data (Kaye 1990) predicts a geometry very different from those proposed by Price and Audley-Charles (1983) and Harris (1991, 2003). The most viable way to reasonably reconcile the predicted and observed gravity values is to subduct the majority of the forearc with the Australian lower plate. A similar solution to is also presented by Richardson and Blundell (1996) for gravity data collected east of Timor.

7.5.5.2 Structure of the Gondwana Duplex

At the same time as the forearc is sinking into the subduction zone the adjacent hinterland of the orogenic wedge is rising. Enough uplift and erosion has occurred in Central Timor to expose the lower Gondwana Sequence duplex that structurally underlies the Banda Terrane roof thrust. Although structural studies of this package of rocks are hampered by lack of good biostratigraphic data, there are a few key marker units for identifying various stratigraphic intervals, such as the distinctive Triassic limestone of the Aitutu Formation. The Aitutu Formation is repeated several times in N-S transects along drainages through the Ramelau Range (Fig. 7.8). Most of the repetition is associated with abrupt breaks in stratigraphy that both dip and face upward to the NNW indicating thrust versus fold repetition. Fault-propagation folds are observed at wavelengths of up to 1 2 km (Fig. 7.8). The overall pattern of deformation is one of ENE-WSW striking folds and thrusts.

Space considerations require that there are likely multiple levels of detachment within the Gondwana Sequence that produce multiple duplex zones. For example, in Savu a duplex of upper Gondwana Sequence forms in front of the Banda Terrane nappe while the lower section of the Gondwana Sequence that is exposed in northern Timor is inferred to stack up beneath it (Fig. 7.8).

7.5.5.3 Late-Stage Oblique-Slip Normal Faulting

The general pattern of ENE-WSW folds and thrusts is disturbed by normal faults with significant amounts of oblique slip that crosscut the Gondwana Sequence duplex . These faults are only now being recognized on shore in places where they down-drop thick sections of the Banda Orogen Sequence (synorogenic deposits) and juxtapose them against much deeper structural levels. Perhaps the largest of these structures is the Laclo Fault, which was first recognized by Berry and Grady (1981). This fault dips at a moderate angle to the south and juxtaposes the upper parts of the Gondwana Sequence duplex against amphibolite to granulite facies sections of the Aileu Complex. More recent studies of the fault recognize kinematic indicators that vary from top-down-to-the-south to left-lateral strike-slip motion along the fault. The Laclo River separates the Laclo Fault zone and its thin hangingwall of Gondwana Sequence to the north from the largest Banda Terrane massif on the island (Fig. 7.5), which is most likely preserved due to top-down-to-the-south faulting on the Laclo Fault. The oblique-slip nature of these faults may reflect the increased coupling between the Banda Orogenic wedge and the Australian continental margin. A series of NE-SW left-lateral wrench faults formed at around 3 Ma in parts of the Australian continental margin near the Timor Trough (Clough et al. 2000).

7.5.5.4 Eastern East Timor Plateau

East of the Aileu Complex the north coast of Timor displays two very important features that help interpret the evolution of arc continent collision. The first is large section of ultramafic rocks associated with mélange that structurally overlies the Gondwana Sequence duplex and exposes the subduction channel that these rocks entered (Harris and Huang 2010). The

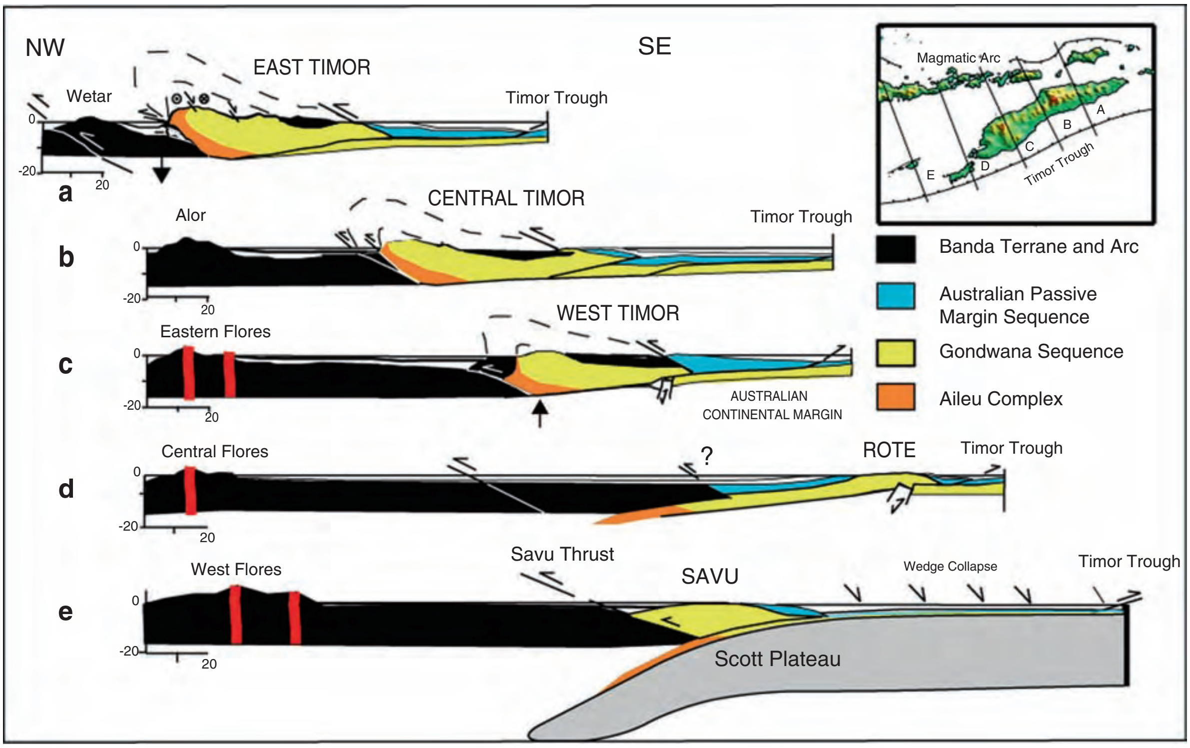


Fig. 7.15 Serial sections through the Banda arc continent col lision from East Timor (**a**) to Savu (**e**). Initiation of retrowedge thrust (Savu Thrust) and collapse of overcritical wedge south of Savu. Shortening of subcritical wedge in Rote begins progres sive northward translation of the Timor Trough as coupling increases with the Australian lower plate. In Wetar the arc is also translated northward as it couples with the lower plate. Active volcanism (*red lines*) ceases in Alor and Wetar, but is still active during collision in C E. In the Timor region the southern edge of the forearc is folded and uplifted as a passive roof thrust by accretion of Australian continental margin cover units beneath it. North of Timor progressive closure of the forearc requires it to sink into the subduction zone (downward arrow). Maximum coupling with the lower plate in East Timor results in mostly left lateral oblique extension.

second feature is an unprecedented series of uplifted coral terraces that rise to a high plateau over 600 m above sea level. At least 25 individual terraces are found in some places, and most of them are warped into what may be ENE-WSW trending anticlines and synclines that intersect the north coast of Timor at oblique angles (Cox et al. 2006). The warping of the terraces demonstrates active deformation in the region over the past 0.1 Ma.

7.5.6 Uplift History

Investigating the pattern of uplift throughout the Banda Orogen provides a way to test a fundamental unresolved question about the geodynamics of collisions generally. The question is about how much uplift is due to crustal shortening versus lithospheric scale processes, such as buoyancy of subducted continental lithosphere, and delamination or tearing off of the oceanic slab. Crustal shortening is documented throughout the Banda Orogen, and enough material has been brought into the orogenic wedge over the past 8 Ma to fill all of the space needed to account for its size and topography. However, much of the incoming sediment may have subducted and not accreted. One test of crustal shortening versus slab-tear is the longevity of uplift. If most of the uplift is from shortening during collision propagation then there should also be a pattern of *sustained* uplift that young's in the direction of collision propagation to the west and east, which is what is observed. In contrast, a pulse of rapid, simultaneous uplift throughout variously shortened parts of the orogen followed by no uplift would be more consistent with a whole lithosphere process. The rate of uplift through time is also a key to distinguishing between these two mechanisms or the relative contributions of each.

The emergence of several islands throughout the Banda Orogen over the past few million years provides a rare glimpse of the temporal distribution of vertical strain in an active arc continent collision over time scales of 10^3 to 10^6 years. Multiple proxies for measuring both *surface* and *rock* uplift rates are available including the rates of sediment discharge, thermochronology of metamorphic rocks, depth versus age relations from benthic and planktic foraminifers in synorogenic deposits, rates of patterns of uplift from flights of coral terraces and other geomorphic features such as stream asymmetry.

7.5.6.1 Erosion Exhumation and Sediment Discharge

The Banda Arc provides the rare opportunity to measure both *rock* and *surface* uplift rates throughout the same orogen. This comparison provides a way to test the significance of erosional or tectonic exhumation in young mountain systems. It is commonly assumed that erosional exhumation positively correlates with total annual precipitation or rates of uplift, which is manifest by high amounts of sediment discharge in streams. However, measurements of sediment discharge in Seram and Timor are markedly different even though these islands of similar size and shape have nearly identical uplift patterns, topography, geomorphology, rock types, and basin catchment size (Cecil et al. 2003). The only other major factor controlling sediment discharge that may account for differences in sediment discharge on these islands is climate.

The Banda Arc straddles two different climate zones and provides a natural laboratory for testing the extent that climate may control rates of erosional exhumation (Harris et al. 2008). The southern part of the Banda Arc (Timor) is seasonal and has a lengthy, 8-month dry season with around 1,300 mm/a of rainfall during its short rainy season. The northern Banda Arc (Seram) is perhumid with little to no dry season. During some months Seram receives up to 600 mm of precipitation, with a total of 3,250 mm/a. However, even though the total amount of rainfall in Seram is nearly three times that of Timor, sediment discharge in Timor during its short rainy season is more than 27 times that of the annual sediment discharge in Seram. Timor annualized sediment concentration is 0.7×10^6 metric tons/km^3 of water discharged. This value is 60% of that of the Ganges/Bramaputra River system (Cecil et al. 2003).

These data are consistent with other indicators of sediment discharge rates found in Seram and Timor. The rivers of Seram are characterized by meandering, acidic blackwater with exceedingly low solute and suspended-sediment concentrations, but with significant amounts of terrestrial organic matter. They also have limited fluvial bed loads, primarily as point bars, which diminish downstream into estuaries without sediment fill derived from fluvial systems. The coastal regions where the rivers discharge are mud-dominated, sediment-starved, host large stands of mangrove and have few, if any coral reefs. In contrast, the rivers of Timor are braided from the mountains to the coast where sedimentation keeps pace with rising sea level to produce deltas. Riverbed sediment is dominated by cobbles and pebbles with lesser amounts of sand-size material, which also characterizes the beaches. The coastlines are mostly estuary and mangrove free and have thick encrustations and large build-ups of coral.

With most other factors nearly equal, it is evident that seasonality of climate, not total amounts of precipitation is the major controlling factor of erosional exhumation in the Banda Arc (Cecil et al. 2003). The protracted dry season in the Timor region results in less vegetative cover and higher rates of sediment run off into streams. Higher rates of erosional exhumation in Timor may explain why deeper structural levels are exposed there compared to Seram.

7.5.6.2 Thermochronology

Rock uplift rates for the metamorphic core of the Banda Orogen are inferred from a combination of pressure and temperature estimates, ^{40}Ar/^{39}Ar cooling ages, and apatite fission track analyses. Using the only reliable ^{40}Ar/^{39}Ar age determination from white mica in the Aileu Complex discussed above (5.3 Ma) along with the pressure and temperature estimates for these rocks (600 700°C and 8 10 kbars, Major et al. 2009) yields a geothermal gradient of around 20 25°C/km and long-term rock uplift rates of around 3 mm/yr over the past 5 m.y. Fission track analyses of apatite grains in the same rocks show uplift from the partial annealing zone (80 120°C) to the surface in <4 m.y. (Harris et al. 2000). This requires a rock uplift rate of 1-2 mm/yr over the past 4 m.y. The exposure of these metamorphic rocks in the part of the orogen with the most shortening is consistent with uplift caused by crustal shortening associated with extensional and erosional exhumation versus regional lithospheric processes.

7.5.6.3 Foraminifers in Synorogenic Deposits

Synorogenic foraminifera-rich chalk and turbidites provide depth and age constraints for tracking when various parts of the Banda Orogen emerged from an accretionary wedge at pelagic depths to where they are exposed at the surface. Although there is some erosion of these deposits after they reached the surface, the majority of their ascent was in a submarine environment, with little to no erosion. Therefore, the record of vertical movements is interpreted as mostly *surface* versus *rock* uplift.

The Batu Putih Formation chalk at the base of the Banda Orogen Sequence has scarce benthonic foraminifera, but those that are found are characteristic of very deep water (>3 km). Abundant planktonic foraminifer's of biozone Neogene (N) 18 (5.6 5.2 Ma) are partially dissolved indicating water depths near the lysocline (~ 3 km). In early emerging parts of the Banda Orogen the Batu Putih Formation is overlain by turbidites of the Noele Marl Formation, which varies in age along strike from N20 (4.2 3.4 Ma) in East Timor and N21 (3.4 1.9 Ma) in West Timor (Audley-Charles 1986) and Sumba (Fortuin et al. 1997). However, in between the large islands of Timor and Sumba the deep water conditions of the Batu Putih Formation continued until N21 as in Savu (1.9 07 Ma) and N23 (<0.7 Ma) as in Rote (Fig. 7.11).

These data indicate that collision of the Australian continental margin with the Banda Arc initiated much earlier in Timor and Sumba than in Savu and Rote where it has just begun. A rough pattern of westward propagation of uplift exists between East Timor and Rote, and eastward propagation of uplift from Sumba to Savu. The pattern of westward propagation is consistent with underthrusting and shortening of the NE-SW trending part of the Australian continental margin beneath the E-W Sunda Trench. Underthrusting of the Scott Plateau beneath the western-most part of the Banda Orogen explains SE propagation of uplift from Sumba (2 3 Ma) to Savu (1.0 0.5 Ma) and then to Rote (0.2 Ma). Average rates of *surface* uplift of the Batu Putih Formation pelagic deposits during the past 2 m.y. in Rote and Savu are ~1.5 and 2.3 mm/a, respectively (Roosmawati and Harris 2009).

7.5.6.4 Uplifted Coral Terraces

Uplifted coral terraces throughout the Banda orogen reveal how strain is distributed over the past of 10^3 to 10^5 years. U-series age analysis of the lowest coral terraces yields surface uplift rates that vary by almost an order of magnitude from 0.2 to 1.5 mm/a (Fig. 7.12). The pattern of uplift correlates best with proximity to active faults. Merritts et al. (1998) calculated coral uplift rates on the south coast of Rote, which is near the deformation front, of 1 1.5 mm/a. Coral terraces on the north coast of Savu, which are associated with the north-directed Savu thrust system, yield uplift rates at least 0.3 mm/a (Harris et al. 2009). A series of islands along the western edge of West Timor yield uplift rates of 0.2 0.3 mm/a on Semau Island and the adjacent coast of West Timor (Merritts et al. 1998; Jouannic et al. 1988). Both of these sites are part of a linear zone of uplift along the 123° East structural discontinuity. Eastern Sumba has uplifted coral terraces just on its north and east coast at rates as high as 0.5 mm/a (Pirazzoli et al. 1991). A south dipping thrust fault has been mapped offshore of this region (van der Werff 1995). The previously mentioned uplifted coral terraces along the north coast of East Timor may correlate with the retrowedge thrust system imaged by seismic offshore to the north and rates of uplift vary from 0.3 to 1.5 mm/a (Cox et al. 2006). Uplifted terraces on the north coasts of Alor and Wetar (Fig. 7.12) may be associated with uplift along the Wetar Thrust. On Atuaro Island, which is much further from the Wetar Thrust, Chappell and Veeh (1978) measured uplift rates of 0.5 mm/yr. These uplifted terraces are used as evidence for slab tear by Sandiford (2008).

However, most of these flights of coral terraces are warped at short wavelengths. For example, coral terraces are tilted north in Sumba, SSE in Savu, NNW in Rote and generally south along the north coast of Timor. In all of these cases the tilt is away from zones of active thrusting and folding. In Sumba the forearc is ramping up and over the northern edge of the Scott Plateau along what is most likely a north dipping thrust (Fleury et al. 2009). In Savu the coral terraces form on the back of the accretionary wedge, which is ramping up over the forearc basin on the south dipping Savu Thrust (Harris et al. 2009). In Rote coral terraces form on the front of the accretionary wedge where it is ramping up over the Australian continental margin (Merritts et al. 1996; Roosmawati and Harris 2009). The north coast of East Timor may be uplifted by ramping of the rear of the accretionary wedge over the base of the volcanic arc (Cox et al. 2006). Localized uplift of circular islands surrounded by others with no uplift is also common and may be associated with diapirism (Major 2010). Generally, the pattern of uplift is consistent with short wavelength deformational processes with highly variable rates that correlate with loading rates measured along active faults by GPS.

7.5.7 Active Faults

Active faults in the Banda Orogen are found near where islands emerge and flights of coral terraces are uplifted (Fig. 7.12). The Wetar and Flores Thrusts along the backside of the volcanic arc are well defined on the seafloor and by sonar, seismic reflection studies and shallow seismicity. The amount of slip along the Wetar Thrust is estimated at around 50 km from the size of the fold and thrust belt it has produced (Silver et al. 1986). The fold and thrust belt associate with the Flores Thrust (Silver et al. 1983) decreases in size in both directions away from Western Flores, which implies that it has propagated away from where the arc-trench system was first impacted by the Scott Plateau.

The Savu Thrust within the forearc is recognized as a site of active shortening from several lines of evidence (Harris et al. 2009). Reflection seismic profiles show several active splays of the thrust system breaking the surface of the sea floor. Some of the thrust strands offset uplifted Pleistocene coral terraces along the north coast of Savu. Also, GPS measurements show up to 7 mm/a of strain accumulation across the fault (Fig. 7.12).

Similar relations are found along the Timor Trough where thrust splays cut the seafloor and GPS measurements across the structure document a strain accumulation rate of 21 mm/a. The lack of seismicity at the deformation front has led some to interpret it as inactive. However, thrust mechanism earthquakes throughout the island of Timor document that the basal décollement linked to the Timor Trough is still active and the deformation front has seismic potential (Harris et al. 1997).

The characteristics of the Timor Trough are similar in many ways to the northern part of the Sunda arc-trench system in the Sumatra region where subduction is oblique and the trench is overstuffed with sediment, which is typical of arc-trench systems that produce mega-thrust earthquakes (Scholl et al. 2008). Historical accounts from Dutch outposts in the Banda Islands document earthquakes of this magnitude with tsunami run-ups of 20 m that trace back to the Timor Trough (Major et al. 2008). The bad news is that it has been nearly 200 years since the last recorded event.

Active thrust faults are also imaged breaking through to the sea floor from reflection seismic profiles across the southern edge of the Wetar Strait north of East Timor (Breen et al. 1986; Snyder et al. 1996). These faults extend east at least as far as Kisar Island. Kisar rises up in the middle of the Wetar Strait and exposes the Aileu Complex overlain by several flights of coral terraces with uplift rates of 1.5 mm/a (Major et al. 2010).

The 123° East discontinuity, which stretches from the island of Rote along the western edge of West Timor and into a linear volcanic field west of Alor, has several shallow earthquakes with left-lateral strike-slip fault plane solutions. The fault zone is also imaged in seismic lines off the NW coast of West Timor (Karig et al. 1987). This linear structure most likely represents a transcurrent fault or lateral ramp that separates two segments of the Banda Orogen with differing amounts of shortening and coupling to the Australian plate. Across the discontinuity the forearc rises from around 1,000 m below sea level to >2,000 m above sea level in the mountains of West Timor. Differences in GPS velocities are also observed across the structure (Nugroho et al. 2009).

7.5.8 GPS Measurements

Another way to define where collision initiates and how strain is partitioned in the Banda arc continent collision is with geodetic measurements. Although these measurements only record movement over a very short temporal range (decade or less), they correspond very closely with predictions over geological time scales using plate kinematic models, such as NUVEL-1.

The obliquity of collision allows documentation of different strain regimes at various stages of collision development. A series of campaign-style GPS measurements throughout the Banda Orogen over the past two decades (Fig. 7.12) reveal that large sections of the SE Asian Plate are progressively accreting to the edge of the Australian continent by distribution of strain away from the deformation front to newly forming forearc and backarc plate boundary segments (Genrich et al. 1996; Nugroho et al. 2009). These segments or crustal blocks have a nearly uniform GPS velocity field, indicating little if any internal deformation. Each crustal segment of the arc continent collision is 400 500 km in strike length and moves parallel to the subducting Australian Plate, but at different rates.

West of the collision in the Sunda continental arc nearly all of the 68 mm/a of convergence between the Australian oceanic plate and the Asian continental margin (Tregoning et al. 1994) is taken up within a narrow 30 km wide zone near the Sunda Trench (Stockmal 1983; Sieh et al. 1999). No component of the NNE subducting lower plate is detected on the islands of Java or Bali, which indicates a decoupled subduction system in this region (Nugroho et al. 2009).

East of Bali the consistent pattern of decoupled subduction changes to one of increasing amounts of coupling with the lower plate eastward (Fig. 7.12). This is expressed as movement of arc and forearc islands relative to the rest of the Asian Plate and in the same direction as the lower plate. The first hint of coupling with the lower plate is found on the island of Lombok, which is across the famous "Wallace Line" from Bali. The deep water between these islands that limited faunal migration into the eastern Sunda Arc marks the edge of the Sunda Shelf. At this boundary the *nature* of the crust the Sunda Arc is mounted on changes from continental to transitional or oceanic.

GPS measurements on Lombak and Sumbawa Islands show slight amounts of movement relative to Asia in nearly the same direction as the lower plate and at around 20% of its velocity. Most, if not all, of this movement is taken up along the Flores Thrust, which is shoving the Sunda Arc over transitional backarc crust. The Flores thrust has propagated into this area from the collision with the Scott Plateau 500 km to the east. At face value, these GPS measurements document that collision is initiating in the Lombak region due to its partial movement with the lower plate and the propagation of the Flores Thrust into its backarc. Yet, the Sunda Arc is still a subduction zone in every other way.

The uniform velocity and direction of movement of the Lombak-Sumbawa segment changes at the Komodo Islands, between the Islands of Sumbawa and Flores (Fig. 7.12). Across this 125 km distance the direction and velocity of the upper plate changes so that Komodo Island moves in the same direction as the lower plate, like the rest of the crust to the east, but at a velocity slightly higher than the 400 km long arc segment to the west, but much less than the 400 km long arc segment to the east. In the 30 km of distance between the stations we measured on Komodo and Flores Islands the percentage of movement with the lower plate jumps from 25% to 40% (Nugroho et al. 2009). The fact that the upper plate is moving more with the lower plate is not surprising since there is other compelling evidence of collision in this region, such as the uplift of the forearc basin and ridge to form the island of Sumba. What is surprising, however, is that the velocity is nearly constant over 400 km of arc crust to the west and another 400 km of arc crust to the east, but changes abruptly in this narrow straight. There is no evidence of a major fault zone in the region, although the data available is sparse.

The GPS measurements reveal two important processes associated with the mechanical behavior of arc accretion that is not very well understood. First, the arc is not adhering to the lower plate in a progressive manner, but rather in large jumps where a 400 km long segment of the arc becomes partially attached with uniform velocities throughout the segment, then more attached uniformly. The second process is diffusive versus localized shear as no fault zone is observed across the boundary between the two crustal blocks although there is seismicity.

The next accreting crustal segment of the arc to the east of the Komodo Islands is the Flores-Savu-Sumba block. It also shows nearly uniform directions and velocities of movement among its stations, with some notable exceptions. One of these is the 7 ± 1 mm/a difference in velocity between the Island of Savu and western Flores, which crosses the Savu Thrust. This result is consistent with other evidence that the Savu Thrust is active (see Active Faults below).

The northern boundary of this arc segment is the Flores Thrust, which is well imaged by sonar and seismic reflection data (Silver et al. 1983) and according to GPS measurements accumulates around 22 mm/a of strain. Earthquakes along this thrust of magnitudes >7.5 are consistent with fault segments and rupture lengths of similar size to the strike length of crustal blocks based on our GPS measurements.

The eastern boundary of the Flores-Savu-Sumba block lies near the 123°E structural discontinuity (Fig. 7.1). The Timor Alor-Wetar crustal block to the east of the discontinuity moves at 63% of the motion of the Australian Plate, which is close to the 70% predicted from total shortening based on structural studies throughout Timor (Harris 1991).

Although the Timor Alor-Wetar segment is interpreted as accreted to the Australian continent (Genrich et al. 1996), there remains around 21 mm/a of Australian Plate motion unaccounted for between Timor and Darwin, Australia (Nugroho et al. 2010). This motion is most likely taken up along the basal décollement of the Banda Orogen that surfaces at the Timor Trough.

7.5.9 Seismic Gaps

The pattern of seismicity in the Banda Orogen mimics in many ways the distribution of strain documented by GPS measurements and along active faults. Shallow earthquakes around Timor Island have mostly thrust fault plane solutions and depths consistent with slip along a basal décollement attached to the deformation front in the Timor Trough (Fig. 7.3). Although many researchers invoke major amounts of strike-slip motion along lineaments cross-cutting the Banda Orogen, there is little evidence of strike-slip geomorphic features in the region and few strike-slip fault plane solutions.

In terms of deeper earthquakes associated with the Benioff zone beneath the Sunda and Banda Arcs there is a nearly continuous zone of seismicity from the shallow depths all of the way to around 600 km. However, a notable lack of seismicity is observed at intermediate depths (71 300 km) in places where arc volcanism has mostly ceased. Although lack of seismicity at these depths is common in many subduction zones it is distinct throughout the 500 km strike-length of the Alor-Wetar segment of the Banda Arc (Cardwell and Isacks 1978). Similar low levels of seismic activity at this depth also occur along two other abandoned volcanic arc segments in central Java and western Flores.

A combination of factors in the Alor-Wetar arc segment, such as the intermediate level seismic gap, lack of volcanism, the high relief of the inactive arc segment and the regionally extensive uplift of coastlines has led to a slab rupture hypothesis (McCaffrey et al. 1985; McCaffrey 1989; Sandiford 2008). Several characteristics of the earthquakes in the region are used to support this hypothesis. However, tomographic images of the area do not support slab tear (Spakman and Hall 2010; Fichtner et al. 2010). After relocating more than 800 earthquakes in the Banda Arc region, Das (2004) warned that existing models often explain some observations but ignore others, such as the fact that the only parts of the Indonesian arc-trench systems with continuous seismicity from the surface to below 600 km are those under the highest stress in regions of greatest arc curvature. In other words, adjacent slabs may be separated by a structural discontinuity that allows for different amounts of slab stress and produce a "seismic gap" that does not relate to tearing at all.

Another consideration is the effect of distributed heterogeneities within the slab, such as preexisting faults (Silver et al. 1995; Kirby et al. 1996). The intermediate depth seismic gap in the Alor-Wetar region may be a function of the multi-deformed and extremely heterogeneous *nature* of the subducting plate in this region, which involves the irregular northern rifted continental margin of Australia.

A gap in shallow seismicity also exits throughout the eastern part of East Timor. However, in this same region there are also many other indicators of active deformation, such as the warped coral terraces and seismic reflection images of thrust faults rupturing the seafloor. Due to the small temporal range of the earthquake record it is possible that the shallow seismic gap may be a locked fault segment, and that uplift is co-seismic. Numerical models (Yang et al. 2006) show that uplift of inactive segments of the volcanic arc can be explained by increased coupling with the lower plate and does not require a slab tear.

7.5.10 Numerical Modeling

Quantifying horizontal and vertical strain through GPS and surface uplift rate measurements, and shear stress data from fault plane solutions, provides a way to numerically model deformation patterns in the Banda Arc. One of the key questions these models address is whether the observed pattern of vertical and horizontal movements (Fig. 7.12) can be replicated by simply a progressive eastward increase in plate coupling or does

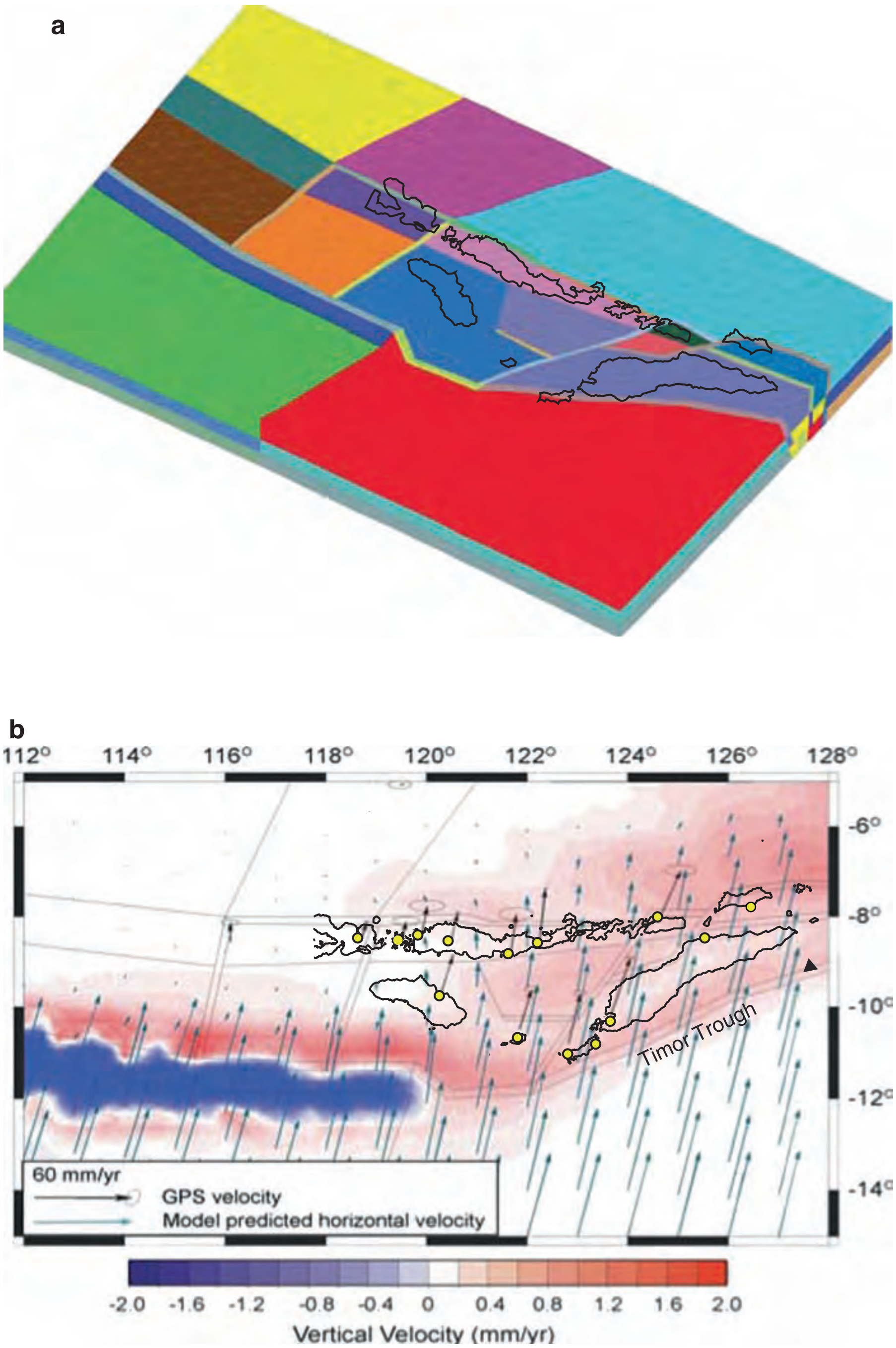


Fig. 7.16 (continued)

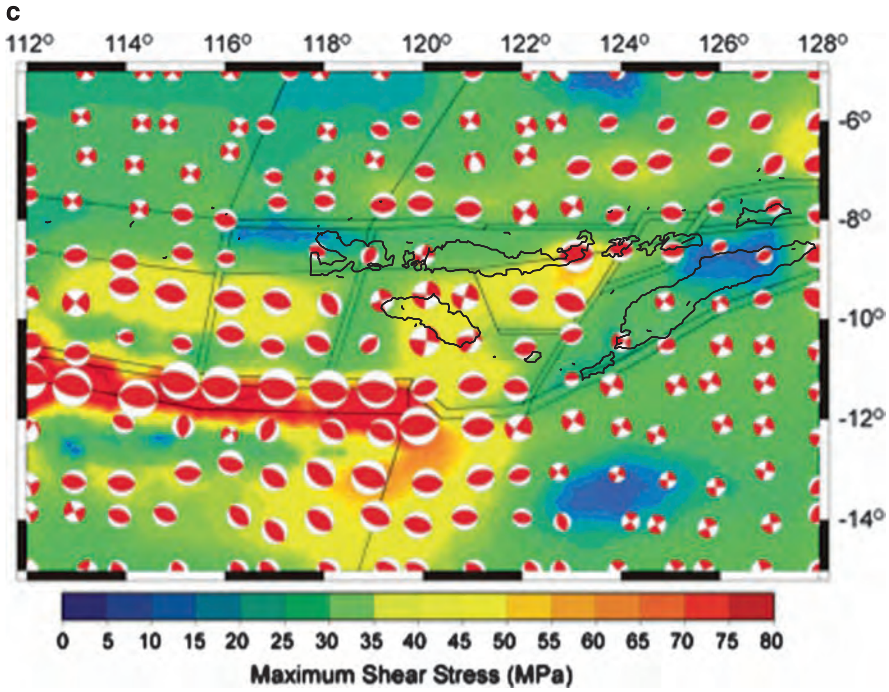


Fig. 7.16 Three dimensional finite element model of the Banda Arc (modified from Yang et al. 2006). (**a**) vertically exaggerated reference model with vertical variation in rheology and segmented crustal domains. For assumptions and model conditions see Yang et al. (2003). (**b**) Best fit model to GPS velocities (*blue arrows*). Viscosity along faults increases east ward simulating increased plate coupling. Predicted uplift rates are shown in color gradient. The model predicts uplift rates of 0.5 mm/a and greater for the inactive Alor to Wetar arc segment without slab tear or any other lithospheric process. (**c**) Shear stress prediction using model B. Shear stress in MPa is shown as color gradient. Fault plane solutions predict types and size of earthquakes associated with stress field.

it require other processes, such as slab tear or large amounts of strike-slip movement?

This question was investigated by Yang et al. (2006) using a 3-D power-law viscous flow model (Fig. 7.16a). The model includes vertical variations of rheology with major active fault zones simulated as weak zones using a special fault element (Goodman et al. 1968). The model includes only the crust (30 km thick). The velocity boundary conditions are constrained by GPS velocities that are applied to the edges of the model domain. Topographic loading is calculated from Etopo 5 data. Spring elements are applied on the surface and bottom of the model to simulate isostatic restoring forces. The evolution of the finite strain is calculated using the finite element method (Yang et al. 2003).

A series of forward models were used to explore the effects of major factors on vertical and horizontal strain partitioning, such as variation in coupling and plate boundary reorganization. The model that fits the GPS velocity field (Fig. 7.16b) also predicts a similar surface uplift rate pattern to what is observed (Fig. 7.12). What is especially telling are surface uplift rates of >0.5 mm/a predicted by the model for the Alor to Wetar segment of the Banda Arc, which is close to rates measured from uplifted coral terraces in the region. The model demonstrates that increased coupling alone according to the pattern provided by the GPS velocity field can account for uplift of the abandoned arc segment without having to invoke an additional slab tear component. The result is also consistent with several other indicators that the collision is mostly progressive versus episodic.

Model C shows the shear stress field predicted by model B, which is very similar to observed shallow earthquake fault plane solutions for the region (compare with Fig. 7.3). The model also shows the importance of strain partitioning with most of the convergence distributed away from the deformation front, but not all. This result is consistent with only partial accretion of the volcanic arc and at least 21 mm/a of strain accumulation across the deformation front in the Timor Trough. Fitting the strain partitioning also puts constraints on the crustal rheology (effective viscosity) in the range of 10^{22} to 10^{23} Pa s.

7.6 Conclusion

The Australian Plate pulls into the Sunda and Banda Trenches a passive margin with many inherited features that strongly influence the way arc continent collision is expressed in the Timor region. Some of its characteristics provide modern analogs for other arc continent collisions. However, in older orogens where the collision process is complete it may be difficult to detect these features. For example, in most collisions lower plate heterogeneities that influenced the collision are completely buried by a thick fold and thrust belt or overprinted by metamorphism. Perhaps even more critical is the loss to subduction of the forearc and arc, which contain a crucial record of pre- and syn-collisional events.

One of the most profound inherited controlling factors of the Banda arc continent collision is the thermo-mechanical influence of an old and cold lower plate. This single attribute may account for most of the tectonic differences the arc continent collisions of Taiwan and Timor. Some of these features unique to the Banda arc continent collision:

- Pre-collisional trench retreat, extensional collapse and subduction erosion of the upper plate to form a forearc consisting of highly attenuated arc crust separated by young supra-subduction zone ocean basins. The last phase of opening of the southern Banda Basin happened during collision initiation.
- Collision of an irregularly shaped continental margin.
- Initial collapse of the accretionary wedge as overpressured mudstones of the continental margin are subducted and weaken the basal décollement.
- Massive mud diapirism by remobilization of overpressured mudstone.
- Mélange development due to diapirism coupled with subduction channel processes where material from the upper part of the lower plate mixes with blocks plucked from the lower part of the upper plate.
- Extrusion of mélange along the subduction channel and out onto the sea floor at the deformation front.
- Opening followed by inversion of accretionary wedge slope basins.
- Partitioning of strain away from the deformation front into the forearc and backarc, and the development of new plate boundary segments as plate coupling increases.
- Emplacement of nappes of the upper plate onto the shortened continental margin.
- Increased coupling of the arc to the continent one ~400 km long arc segment at a time.
- Uplift primarily from crustal shortening through the development of multiple detachments and duplex systems.
- Closure and eventual burial or sinking of the forearc.
- Deep subduction of the continental lower plate to depths where it experiences a high-pressure metamorphism and contaminates the volcanic arc. The contamination front initiates at Wetar Island at ~5 Ma and spreads laterally in space and time.
- Continued subduction of the continent to depths of at least 400 km with no slab break off.
- Active arc volcanism several millions of years after collision initiation and even after initiation of arc accretion.
- Movement of the arc partially with the lower plate and development of a backarc fold and thrust belt without subduction polarity reversal.

Acknowledgements I would like to thank the National Science Foundation for support of much of my research in the Banda Arc region. Major grants were also provided by Chevron/Texaco and Union Texas Petroleum. Logistical support in Indonesia is provided primarily by the GRDC and Universitas Pengbangu nan Nasional (UPN) Yogyakarta. Field research relied heavily on the invaluable assistance of several faculty and students from UPN, especially the assistance of Carolus Prasetyadi. In East Timor I appreciate the assistance of SERN directors and staff, and several East Timorese field assistants who have accompanied me over the past 20 years. I have also enjoyed rich collabora tions with colleagues in the field including Mike Audley Charles, Carolus Prasetyadi, Sahat Tobing, Rob Sawyer, Dor othy Merritts, Nova Roosmawati, Hendro Nugroho and many others including several graduate students whose names appear as authors and co authors in this manuscript. The manuscript benefited from reviews by Mike Sandiford, Sebastien Meffre, Carl Hoiland and Tim Charlton.

References

Abbott MJ, Chamalaun FH (1981) Geochronology of some Banda Arc volcanics. In: Barber AJ, Wiryosujono S (eds) The geology and tectonics of Eastern Indonesia, vol 2. Geological Research and Development Centre, Special Publications, Bandung, Indonesia, pp 253 268

Archbold NW (1988) Permian brachiopoda and bivalvia from Sahul Shoals No. 1, Ashmore Block, northwestern Australia. Proc R Soc Victoria 100:33 38

Audley Charles MG (1968) The geology of Portuguese Timor. Geological Society of London Memoir, vol 4. 76 pp

Audley Charles MG (1986) Rates of Neogene and Quaternary tectonic movements in the southern Banda Arc based on micropaleontology. Geol Soc London 143:161 175

Audley Charles MG (1983) Reconstruction of western Gondwanaland. Nature 306(5938):48 50

Audley Charles MG (1981) Geometrical problems and implications of large scale over thrusting in the Banda Arc Australian margin collision zone, vol 9. Geological Society of London, Special Publication, London, pp 407 416

Audley Charles MG, Harris RA (1990) Allochthonous terranes of the Southwest Pacific and Indonesia. Phil Trans R Soc London 331:571 587

Balke B, Burt D (1976) Arafura Sea area, Economic geology of Australia and Papua New Guinea 3. Australas Inst Min Metall Monogr 7:209 214

Barber AJ, Audley Charles MG (1976) The significance of the metamorphic rocks of Timor in the development of the Banda Arc, eastern Indonesia. Tectonophysics 30: 119 128

Barber AJ, Tjokrosapoetro S, Charlton TR (1986) Mud volcanoes, shale diapirs, wrench faults and mélanges in accretionary complexes, Eastern Indonesia. AAPG Bulletin 70:1729 1741

Ben Othman D, White WM, Patchett J (1989) The geochemistry of marine sediments, island arc magma genesis, and crust mantle recycling. Earth Planet Sci Lett 94:1 21

Berry RF, Grady AE (1981) Deformation and metamorphism of the Aileu Formation, north coast, East Timor and its tectonic significance. J Struct Geol 3(2):143 167

Berry RF, Jenner GA (1982) Basalt geochemistry as a test of the tectonic models of Timor. J Geol Soc London 139:593 604

Berry RF, McDougall I (1986) Interpretation of (super 40) Ar/(super 39) Ar and K/Ar dating evidence from the Aileu Formation, East Timor, Indonesia. Chem Geol Isot Geosci 59(1):43 58

Bird PR, Cook SE (1991) Permo Triassic successions of the Kekneno area. West Timor: Implications for paleogeography and basin evolution. J Southeast Asian Earth Sci 6:359 371. doi:10.1016/0743 9547(91)90081 8

Bowin C, Purdy GM, Johnston C, Shor G, Lawver L, Hartono HMS, Jezek P (1980) Arc continent collision in Banda Sea region. Bull AAPG 64:868 915

Breen NA, Silver EA, Roof S (1989a) The Wetar backthrust belt, eastern Indonesia: the effects of accretion against an irregularly shaped arc. Tectonics 8:85 98

Breen NA, Silver EA, Hussong DM (1986) Structural styles of an accretionary wedge south of the island of Sumba. Indonesia, revealed by Sea Marc II side scan sonar. Geol Soc Am Bull 97:1250 1261. doi:10.1130/0016 7606

Breen NA, Silver EA, Roof S (1989b) The Wetar backthrust belt, eastern Indonesia: the effects of accretion against an irregularly shaped arc. Tectonics 8:85 98

Brown M, Earle MM (1983) Cordierite bearing schists and gneisses from Timor, eastern Indonesia. P T implications of metamorphism and tectonic implications. J Metamorph Geol 1:183 203

Cardwell RK, Isacks BL (1978) Geometry of subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions. J Geophys Res 83:2825 2838

Carter DJ, Audley Charles MG, Barber AJ (1976) Stratigraphical analysis of island arc continental margin collision in eastern Indonesia. Geol Soc London 132:179 198

Cecil CB, Dulong FT, Harris RA, Cobb JC, Gluskoter HG, Nuroho H, (2003) Observations on climate and sediment discharge in selected tropical rivers, Indonesia. In: Cecil CB, Edgar T (eds) Climate Controls on Stratigraphy, vol 77. Soc. Sedimentary Geology Special Publication, pp 29 50

Chamalaun FH, Grady AE, von der Borch CC, Hartono HMS (1981) The tectonic significance of Sumba. Bull Geol Res Develop Centre Bandung 5:1 20

Chappell J, Veeh HH (1978) Late Quaternary tectonic movements and sea level changes at Timor and Atauro Island. Geol Soc Am Bull 89:356 368

Charlton TR (1989) Stratigraphic correlation across an arc continent collision zone: Timor and the Australian Northwest Shelf. Aust J Earth Sci 36:263 274

Charlton TR (1991) Post collisional extension in arc continent collision zones, eastern Indonesia. Geology 19:28 31

Charlton TR, Barber AJ, Harris RA, Barkham ST, Bird PR, Archbold NW, Morris NJ, Nicoll RS, Owen HG, Owen RM, Sorauf JE, Taylor PD, Webster GD, Whittaker JE (2002) the Permian of Timor; stratigraphy, palaeontology and palaeogeography. J Asian Earth Sci 20(6):719 774

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. J Asian Earth Sci 36(4 5):341 363

Clough M, Keep M, Longley I (2000) Neogene structural modifications of petroleum systems of the Timor Sea. AAPG Bull 84(9):1412 1413

Cox NL, Harris RA, Merritts D (2006) Quaternary uplift of coral terraces from active folding and thrusting along the northern coast of Timor Leste. Eos Trans AGU 87(52): T51D 1564

Cull JP (1982) An appraisal of Australian heat flow data. BMR J Aust Geol Geophys 7(1):11 21

Curray JR (1989) The Sunda Arc: a model for oblique plate convergence. Neth J Sea Res 24:131 140

Das S (2004) Seismicity gaps and the shape of the seismic zone in the Banda Sea Region from relocated hypocenters. J geophys Res 109. doi:10.1029/2004JB003192

de Roever WP (1940) Geological investigation in the South western Moetis region (Netherlands Timor), Ph.D. Thesis, University of Amsterdam, 244 pp.

De Smet MEM, Fortuin AR, Troelstra SR, Van Marle LJ, Karmini M, Tjokrosapoetro S, Hadiwasastra S (1990)

Detection of collision related vertical movements in the Outer Banda Arc (Timor, Indonesia), using micropaleontology data. J Southeast Asian Earth Sci 4(4):337 356

Dewey JF (1988) Extensional collapse of orogens. Tectonics 7:1123 1139

Dilek Y, Harris RA (2004) Continental margins of the Pacific Rim: Tectonophysics Special Issue, V. 392, 348 p

Doglioni C, Guegen E, Harabaglia P, Mongelli F (1999a) On the origin of west directed subduction zones and applications to the western Mediterranean, vol 156. Geological Society of London, Special Publication. pp 541 561

Doglioni C, Harabaglia P, Merlini S, Mongelli F, Peccerillo A, Piromallo C (1999b) Orogens and slabs vs. their direction of subduction. Earth Sci Resour 45:167 208

Dore AG, Stewart IC (2002) Similarities and differences in the tectonics of two passive margins; the Northeast Atlantic margin and the Australian North West Shelf. In: Keep M, Moss SJ (eds) Sedimentary basins of Western Australia. Petroleum Exploration Society of Australia Symposium Proceedings, vol 3. pp 89 117

Ernst WG, Liou JG (2000) Ultra high pressure metamorphism and geodynamics in collision type orogenic belts. In: Ultra high pressure metamorphism and geodynamics in collision type orogenic belts, vol 4, International Book Series. Bellwether, Geological Society of America, Columbia, MD, 293 p

Earle MM (1981) The metamorphic rocks of Boi, Timor, eastern Indonesia. In: Barber AJ, Wiryosujono S (eds) The geology and tectonics of Eastern Indonesia, vol 2. Geological Research and Development Centre, Special Publications, Bandung, Indonesia, pp 239 251

Earle MM (1983) Continental margin origin for cretaceous radiolarian chert in western Timor. Nature 305:129 130

Elburg MA, Foden JD, van Bergen MJ, Zulkarnain I (2005) Australia and Indonesia in collision: geochemical sources of magmatism. J Volcanol Geotherm Res 140: 25 47

Elburg MA, van Bergen MJ, Foden JD (2004) Subducted upper and lower continental crust contributes to magmatism in the collision sector of the Sunda Banda arc, Indonesia. Geology 32:41 44

Elsasser WM (1971) Sea floor spreading as thermal convection. J Geophys Res 76:1101 1112

Falloon TJ, Berry RF, Robinson P, Stolz AJ (2006) Whole rock geochemistry of the Hili Manu peridotite, East Timor; implications for the origin of Timor ophiolites. Aust J Earth Sci 53(4):637 649

Falvey DA (1972) Sea floor spreading in the Wharton Basin (north east Indian Ocean) and the break up of eastern Gondwanaland. Aust Petrol Explor Assoc J 12:86 88

Fichtner A, De Wit M, van Bergen M (2010) Subduction of continental lithosphere in the Banda Sea region: combining evidence from full waveform tomography and isotope ratios. Earth Planet Sci Lett 297(3 4):405 412

Fleury JM, Pubellier M, de Urreiztieta M (2009) Structural expression of fore arc crust uplift due to subducting asperity. Lithos 113(1 2):318 330

Flower MFJ, Russo RM, Tamaki K, Hoang N (2001) Mantle contamination and the Izu Bonin Mariana (IBM) 'high tide mark': evidence for mantle extrusion caused by Tethyan closure. Tectonophysics 333:9 34

Fortuin AR, De Smet MEM (1991) Rates and magnitudes of late Cenozoic vertical movements in the Indonesian Banda Arc and the distinction of eustatic effects, vol 12. International Association of Sedimentologist, Special Publication, pp 79 89

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. J Asian Earth Sci 15:61 88

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 15:288 295. doi:10.1029/95TC03850

Goodman RE, Taylor RL, Brekke TL (1968) A model for the mechanics of jointed rock. American Society of Civil Engineers, New York, pp 637 659

Grady AE, Berry RF (1977) Some Paleozoic Mesozoic stratigraphic structural relationships in Timor Leste and their significance to the tectonics of Timor. J Geol Soc Aust 24:203 214

Guilou H, Arnaud N, Honthaas C, Rehault J, Maury RC, Bellon H, Hemond C, Malod J, Cornee J, Villeneuve M, Cotten J, Burhanuddin S, Guillou H, Arnaud N (1998) Neogene back arc origin for the Banda Sea basins: geochemical and geochronological constraints from the Banda ridges (East Indonesia). Tectonophysics 298:297 317

Hafkenscheid SH, Buiter MR, Wortel W, Spakman HB (2001) Modeling the seismic velocity structure beneath Indonesia: a comparison with tomography. Tectonophysics 333:35 46

Haig DW, McCartain E (2007) Carbonate pelagites in the post Gondwana succession (Cretaceous Neogene) of East Timor. Aust J Earth Sci 54(6):875 889

Haig DW, McCartain E, Barber L, Backhouse J (2007) Triassic Lower Jurassic foraminiferal indices for Bahaman type carbonate bank limestones, Cablac Mountain, East Timor. J Foraminiferal Res 37:248 264

Haig DW, McCartain EW, Keep M, Barber L (2008) Re evaluation of the Cablac Limestone at its type area, East Timor; revision of the Miocene stratigraphy of Timor. J Asian Earth Sci 33(5 6):366 378

Haile NS, Barber AJ, Carter DJ (1979) Mesozoic cherts on crystalline schists in Sulawesi and Timor. Geol Soc London 136:65 70

Hall R (2002) Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer based reconstructions, model and animations. J Asian Earth Sci 20: 353 431

Hamilton W (1979) Tectonics of the Indonesian region. U.S. Geology Survey Professional Paper 1078, pp 1 345

Harris RA (1991) Temporal distribution of strain in the active Banda Orogen. A reconciliation of rival hypotheses. J Southeast Asian Earth Sci 6:373 386

Harris RA (1992) Peri collisional extension and the formation of Oman type ophiolites in the Banda Arc and Brooks Range. In: Parson LM, Murton BJ, Browning P (eds) Ophiolites and their modern oceanic analogues, vol 60. Geological Society of London, Special Publication, London, pp 301 325

Harris RA (2003) Geodynamic patterns of ophiolites and marginal basins of the Indonesian and New Guinea regions.

In: Dilek Y, Robinson PT (eds) Ophiolite in Earth history, vol 218. Geological Society of London, Special Publication, London, pp 481 505

Harris R (2006) Rise and fall of the eastern Great Indonesian Arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor. Gondwana Res 10:207 231

Harris RA, Audley Charles MG (1987) Taiwan and Timor Neo tectonics: a comparative review. Memoir Geological Society of China, vol 9. pp 45 61

Harris RA, Wu S (1991) Postcollisional extension in arc continent collision zones, eastern Indonesia. Geology 20(1):92 93

Harris RA, Long T (2000) The Timor ophiolite, Indonesia. Model or myth? In: Dilek Y, Moores EM, Elthon D, Nicolas A (eds) Ophiolites and oceanic crust. New insights from field studies and the Ocean Drilling Program. Geologic Society of America Special Paper vol 349, pp 321 330

Harris RA, Huang CY (2010) Linking mélange types and occur rences with active mélange forming processes in Timor and Taiwan. Geological Society of America, Tectonic Cross roads Mtg., abstract 49 1, pp 84 85

Harris RA, Stone DB, Turner DL (1987) Tectonic implications of paleomagnetic and geochronologic data from the Yukon Koyukuk basin, Alaska. Geol Soc Am Bull 99:362 375

Harris RA, Donaldson K, Prasetyadi C (1997) Geophysical disaster mitigation in Indonesia using GIS, vol 5. Buletin Teknologi Mineral pp 2 10

Harris RA, Sawyer RK, Audley Charles MG (1998) Collisional mélange development: geologic associations of active mél ange forming processes with exhumed mélange facies in the western Banda orogen: Indonesia. Tectonics 17:458 480

Harris RA, Kaiser J, Hurford A, Carter A (2000) Thermal history of Australian passive margin cover sequences accreted to Timor during Late Neogene arc continent colli sion, Indonesia. J Asian Earth Sci 18:47 69

Harris RA, Cecil CB, Dulong FT, Nugroho H (2008) Is sediment discharge controlled more by climate or tectonics? Studies of suspended and dissolved loads from rivers in active orogens of Indonesia. Himalayan Geol 29(3):32 33

Harris RA, Vorkink MW, Prasetyadi C, Zobell E, Roosmawati N (2009) Transition from subduction to arc continent colli sion: geological and neotectonic evolution of Savu, Indone sia. Geosphere 5:1 20. doi:10.1130/GES00209.1

Harrowfield M, Keep M (2005) Tectonic modification of the Australian North West Shelf: episodic rejuvenation of long lived basin divisions. Basin Res 17(2):225 239

Herrington RJ, Philip A, Scotneybe M, Roberts S, Adrian B, Boyce C, Harrison D (2011) Temporal association of arrested subduction, progressive magma contamination in arc volcanism and formation of gold rich massive sulphide deposits on Wetar Island (Banda arc). Gondwana Res

Hilton DR, Craig H (1989) A helium isotope transect along the Indonesian archipelago. Nature 342(6252):906 908

Hilton DR, Hoogewerff JA, van Bergen MJ, Hammerschmidt K (1992) Mapping magma sources in the East Sunda Banda arcs, Indonesia; constraints from helium isotopes. Geochi mica et Cosmochimica Acta 56(2):851 859

Hinschberger F, Malod J A, Dyment J, Honthaas C, Rehault J, Burhanuddin S (2001) Magnetic lineations constraints for the back arc opening of the Late Neogene south Banda Basin (eastern Indonesia). Tectonophysics 333:47 59

Hinschberger F, Malod JA, Rehault JP, Villeneuve M, Royer JY, Burhanuddin S (2005) Late Cenozoic geodynamic evolution of eastern Indonesia. Tectonophysics 404(1 2):91 118

Honthaas C, Rehault J, Maury R, Bellon H, Hemond C, Malod JA, Cornee JJ, Villeneuve M, Cotten J, Burhanuddin S, Guillou H, Arnaud N (1998) A Neogene back arc origin for the Banda Sea basins: geochemical and geochronological constraints from the Banda ridges (East Indonesia). Tecto nophysics 298:297 317

Jouannic C, Hoang CT, Hantoro WS, Delinom RM (1988) Uplift rate of coral reef terraces in the areas of Kupang, West Timor: preliminary results. Palaeogeogr Palaeoclima tol Palaeoecol 68:259 272

Kadarusman A, Maruyama S, Kaneko Y, Ohta T, Ishikawa A, Sopaheluwakan J, Omori S in press. World's youngest blues chist belt from Leti Island in the non volcanic Banda outer arc of eastern Indonesia. Gondwana Res 18(1):189 204

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 11:218 233

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. Geol Soc Am Bull 98:18 32

Kaye SJ (1990) The structure of Eastern Indonesia: an approach via gravity and other geophysical methods. Unpublished Ph. D. thesis, University of London, 290 pp

Keep M, Haig DW (2010) Deformation and exhumation in Timor: Distinct stages of a young orogeny. Tectonophysics [Tectonophysics]. Vol. 483, no. 1 2, pp. 93 111

Keep M, Longley I, Jones R (2003) Sumba and its effect on Australia's northwestern margin. In: Hills RR, Mueller RD (eds) Special Paper Geological Society of America, vol 372. pp 309 318

Keep M, Clough M, Langhi L, Moss SJ (2002) Neogene tectonic and structural evolution of the Timor Sea region, NW Aus tralia. In: Keep M, Moss SJ (eds) Sedimentary Basins of Western Australia. Proceedings of the Petroleum Explora tion Society of Australia Symposium, vol 3, pp 341 353

Kenyon CS (1974) Stratigraphy and sedimentology of the Late Miocene to Quaternary deposits in Timor. Ph.D. Disserta tion, University of London

Kirby SH, Engdahl ER, Denlinger R, Roger P (1996) Interme diate depth intra slab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle meta morphism in subducting slabs. Geophys Monogr 96: 195 214

Kirschner DL, Cosca MA, Masson H, Hunziker JC (1996) Staircase 40Ar/39Ar spectra of fine grained white mica: timing and duration of deformation and empirical constraints on argon diffusion. Geology 24:747 750

Kingborough RH, Williams AF, Hillis RR (1991) Borehole stability on the Northwest Shelf of Australia. SPE 23015, Soc. Petrol. Engin., Perth, Australia, pp 653 662

Larson RL (1975) Late Jurassic sea 11oar spreading in the eastern Indian Ocean. Geology 3:69 71

Lee C R, Cheng W T (1986) Preliminary heat flow mea surements in Taiwan. In: Proceedings of the Fourth Cir cum Pacific Energy and Mineral Resources Conference, Singapore

Longley IM, Buessenschuett C, Clydsdale L (2002) The North West Shelf of Australia A Woodside perspective. In: Keep M, Moss S (eds) Sedimentary basins of Western Australia. Petroleum Exploration Society of Australia Symposium pro ceedings, vol 3. pp 27 88

Lorenzo JM, O'Brien GW, Stewart J, Tandon K (1998) Inelastic yielding and forebulge shape across a modern foreland basin; northwest shelf of Australia, Timor Sea. Geophys Res Lett 25(9):1455 1458

Lunt P (2003) Biogeography of some Eocene larger foraminif era, and their application in distinguishing geological plates. Palaeontologia Electronica 6:1 22

Lytwyn J, Rutherford E, Burke K, Xia C (2001) The geochem istry of volcanic, plutonic, and turbiditic rocks from Sumba, Indonesia. J Asian Earth Sci 19:481 500

Ma K F, Song Teh Ru Alex (2004) Thermo mechanical struc ture beneath the young orogenic belt of Taiwan. Tectono physics 388(1 4):21 31

Major J (2010) The tectonic significance and origin of Kisar, Indonesia, AAPG Bulletin, vol. 94, no. 1, pp.132

Major JR (2010) Metamorphism, thermochronology and uplift of the Aileu Complex on Kisar Island, Banda arc continent collision, unpublished MSc. Thesis, Brigham Young Univer sity, 150 p

Major JR, Harris RA, Robinson JS (2008) Earthquake and tsunami history and hazards of eastern Indonesia. Eos Trans AGU 89(53), Fall Meet. Suppl., Abstract T53E 2009

Major JR, Harris RA, Chiang H, Prasetyadi C, Shen C (2009) Variation in deformational mechanisms in the Banda Arc: uplift and tectonic implications of Kisar, Indonesia. Eos Trans AGU 90(52), Fall Meet. Suppl., Abstract T33B T1915

Malinverno A, Ryan WBF (1986) Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migra tion driven by sinking of the lithosphere. Tectonics 5:227 245

Masson DG, Milsan J, Barber AJ, Simumbang N, Dwiyanto B (1991) Recent tectonics around the island of Timor, eastern Indonesia. Mar Pet Geol 8:35 49

McCaffrey R, Molnar P, Roecker SW, Joyodirwiryo YS (1985) Microearthquake seismicity and fault plane solutions related to arc continent collision in the eastern Sunda Arc, Indone sia. J geophys Res 90:4511 4545

McCaffrey R (1989) Seismological constraints and speculations on Banda Arc tectonics. Neth J Sea Res 24:141 152

Merritts, Dorothy, Eby, Rebecca, Harris, Ron, Edwards, R. Lawrence, and Cheng, Hai (1998) Variable Rates of Late Quaternary Surface Uplift Along the Banda Arc Australian Plate Collision Zone, Eastern Indonesia, In: Stewart IS, Vita Finzi C (eds) Coastal Tectonics, Geological Society of Lon don Special Publications No. 146, p. 213 224

Mikolas M, Harris RA (1986) Variations of stress in time and space of an oblique arc continent collision; analysis of frac tures in synorogenic deposits of Timor, Abstracts with Pro grams. Geol Soc Am 28(5) p 91

Milsom J, Sardjono R, Susilo A (2001) Short wavelength, high amplitude gravity anomalies around the Banda Sea, and the collapse of the Sulawesi orogen. Tectonophysics 333:61 74

Morris JD, Gill JB, Schwartz D, Silver EA (1984) Late Miocene to recent Banda Sea volcanism, III, Isotopic compositions. EOS Trans AGU 65:1135, V22A 04

Myra K, David HW (2010) Deformation and exhumation in Timor: distinct stages of a young orogeny. Tectonophysics 483(1 2):93 111

Nicholls LA, Ferguson J, Jones H, Marks GP, Mutter JC (1981) Ultramafic blocks from the ocean floor southwest of Austra lia. Earth Planet Sci Lett 56:362 374

Nugroho H, Harris RA, Amin WL, Bilal M (2009) Active plate boundary reorganization in the Banda arc continent colli sion: insights from new GPS measurements. Tectonophysics 479:52 65. doi:10.1016/j.tecto.2009.01.026

Peter Petkovic, Clive DN Collins, Doug M Finlayson (2000) Crustal structure across the Vulcan Sub basin from seismic refraction and gravity data, Exploration Geophysics 31:287 294

Pirazzoli PA, Radtke U, Hantoro WS, Jouannic C, Hoang DT, Causse C, Borel Best M (1991) Quaternary raised coral reef terraces on Sumba Island, Indonesia. Science 252: 1834 1836

Prasetyadi C, Harris RA (1996) Hinterland structure of the active Banda arc continent collision, Indonesia: constraints from the Aileu Complex of East Timor. In: Proceedings of the 25th Convention of the Indonesian Association of Geol ogy pp 144 173

Price NJ, Audley Charles MG (1983) Plate rupture by hydraulic fracture resulting in overthrusting. Nature (London) 306 (5943):572 575

Price NJ, Audley Charles MG (1987) Tectonic collision pro cesses after plate rupture. Tectonophysics 140 (2 4):121 129

Pubellier M, Monnier C, Maury RC, Tamayo R (2004) Plate kinematics, origin and tectonic emplacement of supra sub duction ophiolites in SE Asia. Tectonophysics 392(1 4): 9 36

Reed DL, Silver EA, Prasetyo H, Meyer AW (1986) Deforma tion and sedimentation along a developing terrane suture: Sunda forearc, Indonesia. Geology 14:1000 1003. doi: 10.1130/0091 7613

Reed DL (1985) Structure and stratigraphy of eastern Sunda forearc, Indonesia: geologic consequences of arc continent collision. Unpublished Ph.D. thesis, Scripps Institute of Oceanography, La Jolla, California

Richardson AN, Blundell DJ (1996) Continental collision in the Banda Arc. In: Hall R, Blundell D (eds) Tectonic evolution of Southeast Asia, vol 106. Geological Society of London, Special Publication, London, pp 47 60

Roosmawati N, Harris RA (2009) Surface uplift history of the incipient Banda arc continent collision: geology and synoro genic foraminifera of Rote and Savu Islands, Indonesia. Tec tonophysics 479:95 110. doi:10.1016/j.tecto.2009.04.009

Rosidi HMO, Suwitopiroyo K, Tjokrosapoetro S (1979) Geo logical map Kupang Atambua Quadrangle, Timor 1:250, 000. Geological Research Centre, Bandung, Indonesia

Royden LH (1993) The tectonic expression of slab pull at con tinental convergent boundaries. Tectonics 12:303 325

Sani K, Jacobson ML, Sigit R (1995) The thin skinned thrust structures of Timor. In: Indonesian Petroleum Association 24th Annual Convention, Jakarta, pp 277 293

Sandiford M (2008) Seismic moment release during slab rupture beneath the Banda Sea. Geophys J Int 174(2):659 671

Sawyer, RK, Sani K, Brown S (1993) The stratigraphy and sedimentology of west Timor, Indonesia. Paper presented

at 22nd Convention of the Indonesian Petroleum Association, Jakarta, pp 1 20
Schellart WP, Lister GS (2004) Tectonic models for the formation of arc shaped convergent zones and back arc basins. Geol Soc Am Spec Pap 283:237 258
Schellart WP, Lister GS, Jessell MW (2002) Analogue modeling of back arc extension. J Virtual Explor 7:25 42 (on line)
Scholl DW, Keranen K, Kirby SH, Blakely RJ, Wells RE, Ryan HF, von Huene R, Fisher MA (2008) Abstracts with Programs. Geol Soc Am 40(6) pp 160
Schwartz O, Gill JB, Duncan RA (1984) Late Miocene to recent Banda Sea Volcanism: II petrology. EOS Trans AGU 65(45) p 1135, abstract V22A 03
Scotney PM, Roberts S, Herrington RJ, Boyce AJ, Burgess R (2005) The development of volcanic hosted massive sulfide and Barite Gold ore bodies on Wetar Island, Indonesia. Mineralium Deposita 40:76 99
Searle MP, Stevens RK (1984) Obduction processes in ancient, modern and future ophiolites. In: Gass LG, Lippard SL, Shelton AW (eds) Ophiolites and oceanic lithosphere, vol 13. Geological Society of London, Special Publication, London, pp 303 320
Shreve RL, Cloos M (1986) Dynamics of sediment subduction, mélange formation, and prism accretion. J Geophys Res 91 (B10):10229 10245
Sieh K, Ward SN, Natawidjaja D, Suwargadi BW (1999) Crustal deformation at the Sumatran subduction zone revealed by coral rings. Geophys Res Lett 26:3141 3144
Silver PG, Beck SL, Wallace TC, Meade C, Myers SC, James DE, Kuehnel R (1995) Rupture characteristics of the deep Bolivian earthquake of 9 June 1994 and the mechanism of deep focus earthquakes. Science 268:69 73
Silver EA, Smith RB (1983) Comparison of terrane accretion in modern Southeast Asia and the Mesozoic North American Cordillera. Geology 11(4):198 202
Silver EA, Reed R, McCaffrey R, Joyodiwiryo Y (1983) Back arc thrusting in the eastern Sunda arc, Indonesia: a consequence of arc continent collision. J Geophys Res 88:7429 7448. doi:10.1029/JB088iB09p07429
Silver EA, Gill JB, Schwartz D, Prasetyo H, Duncan RA (1985) Evidence of submerged and displaced borderland, north Banda Sea, Indonesia. Geology 13:687 691
Silver EA, Breen NA, Prasetyo H, Hussong DM (1986) Multibeam study of the Flores backarc thrust belt, Indonesia. J Geophys Res 91:3489 3500. doi:10.1029/ JB091iB03p03489
Simons AL (1940) Geological investigations in northeast Netherlands Timor. Geol Exped Lesser Sunda Islands 1:107 213
Smith MR, Ross JG (1986) Petroleum potential of northern Australian continental shelf. Am Assoc Petrol Geol Bull 20:1700 1712
Snyder DB, Prasetyo H, Blundell DJ, Pigram CJ, Barber AJ, Richardson A, Tjokrosapoetro S (1996) A dual doubly vergent orogen in the Banda arc continent collision zone as observed on deep seismic reflection profiles. Tectonics 15:34 53
Sobolev NV, Shatsky VS (1990) Diamond inclusions in garnets from metamorphic rocks; a new environment for diamond formation. Nature 343(6260):742 746
Sopaheluwakan I, Helmers H, Tjokrosapetro S, Surya Nila E (1989) Medium pressure metamorphism with inverted gradient. Associated with ophiolite nappe emplacement in Timor, Netherlands. J Sea Res 24:333 343
Spakman W, Hall R (2010) Surface deformation and slab mantle interaction during Banda arc subduction rollback. Nat Geosci 3:562 566. doi:10.1038/ngeo917
Spencer A, Chew K, Leckie G (2005) The discovery patterns of the resources of the rift and gas provinces of the North Sea compared with some analogous provinces worldwide. In: Dore AG, Vining BA (eds) Petroleum geology; north west Europe and global perspectives. proceedings of the 6th petroleum geology conference, vol 6. Pp 25 33
Stampfli GM, Borel GD (2002) A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. Earth Planet Sci Lett 196(1 2):17 33
Standley C, Harris RA (2009) Banda forearc basement accreted to the NW Australian continental margin: a geochemical, age and structural analysis of the Lolotoi metamorphic complex of East Timor. Tectonophysics 479:66 94. doi:10.1016/ j.tecto.2009.01.034
Stockmal GS (1983) Modeling of large scale accretionary wedge deformation. J Geophys Res 88:8271 8287
Symonds PA, Planke S, Frey O, Skogseid J (1998) Volcanic evolution of the western Australian continental margin and its implications for basin development. Petroleum Exploration Society of Australia Proceedings, vol 2. pp 33 54
T'Hoen CWAP, Van Es LJC (1926) The exploration for minerals in the island of Timor. Jaarb Mijn Ned Indie 2:1 80
Tregoning P, Brunner FK, Bock Y, Puntodewo SSO, McCaffrey R, Genrich JF, Calais E, Rais J, Subarya C (1994) First geodetic measurement of convergence across the Java Trench. Geophys Res Lett 21:2135 2138
Van Bergen MJ, Vroon PZ, Hoogewerff JA (1993) Geochemical and tectonic relationships in the East Indonesian arc continent collision region: Implications for the subduction of the Australian passive margin. Tectonophysics 223:97 116
van der Werff W (1995) Cenozoic evolution of the Savu Basin, Indonesia: forearc basin response to arc continent collision. Mar Petrol Geol 12:247 262
Veevers JJ, Falvey DA, Hawkins LV, Ludwig WJ (1974) Seismic Reflection Measurements of Northwest Australian Margin and Adjacent Deeps. AAPG Bull 58(9):1731 1750
von Rad U, Exon NF (1983) Mesozoic Cenozoic sedimentary and volcanic evolution of the starved passive continental margin off NW Australia. In: Watkins JS, Drake CL (eds) Studies in continental margin geology. American Association of Petroleum Geologists Memoir, vol 34. pp 253 281
Vorkink (2004) Incipient tectonic development of the active Banda arc continent collision : geologic and kinematic evolution of Savu Island, Indonesia. MSc. Thesis, Brigham Young University, 87 p
Vroon PZ, Van Bergen MJ, White WM, Varekamp JC (1993) Sr Nd Pb Isotope systematics of the Banda Arc, Indonesia: Combined subduction and assimilation of continental material. J Geophys Res 98:22349 22366
Vroon PZ, Lowry D, van Bergen MJ, Boyce AJ, Mattey DP (2001) Oxygen isotope systematics of the Banda Arc: Low δ18O despite involvement of subducted continental material in magma genesis. Geochimica et Cosmochimica Acta 65:589 609

Wang Z, Zhao D, Wang J, Kao H (2006) Tomographic evidence for the Eurasian lithosphere subducting beneath south Tai wan. Geophys Res Lett 33(18):L1830

Wheller GE, Varne R, Foden JD, Abbott MJ (1987) Geochem istry of Quaternary volcanism in the Sunda Banda are, Indo nesia, and three component genesis of island arc basaltic magmas. J Geotherm Volcanol Res 32:137 160

Whitford DJ, Jezek PA (1979) Origin of late Cenozoic lavas from the Banda arc, Indonesia; Trace element and Sr Isotope evidence: Contributions to Mineralogy and Petrology. Pages 68:141 150

Whitford DJ, Compston W, Nicholls IA, Abbott MJ (1977) Geo chemistry of late Cenezoic lavas from eastern Indonesia: Role of subducted sediments in petrogenesis. Geology 5:571 575

Whitford DJ, White WM, Jezek PA (1981) Neodymium isotopic composition of Quaternary island arc lavas from Indonesia. Geochimica et Cosmochimica Acta 45:989 995

Widiyantoro S, van der Hilst R (1997) Mantle structure beneath Indonesia inferred from high resolution tomographic imag ing. Geophys J Int 130:167 182

Wortel MJR, Spakman W (2000) Subduction and slab detach ment in the Mediterranean Carpathian region. Science 290:1910 1917

Yang Y, Liu M, Stein S (2003) A 3 D geodynamic model of lateral crustal flow during Andean mountain building. Geophys Res Lett 30(21):2093. doi:10.1029/2003GL018308

Yang Y, Liu M, Harris RA (2006) From subduction to arc continent collision: geodynamic modeling of strain partition ing and mountain building in the Indonesia Archipelago. Eos Trans AGU 87(52) T41C 1589

Yih Min Wu, Chien Hsin Chang, Li Zhao, J Bruce H Shyu, Yue Gau Chen, Kerry Sieh, and Jean Philippe Avouac (2007) Seismic tomography of Taiwan: Improved con straints from a dense network of strong motion stations, Journal of Geophysical research, vol. 112, B08312, doi:10.1029/2007JB004983

Zobell E (2007) Origin and tectonic evolution of Gondwana sequence units accreted to the Banda Arc: a structural tran sect through central East Timor. M.S. thesis, Provo, Utah, Brigham Young University, 75 p