Available online at www.sciencedirect.com

ScienceDirect

Gondwana Research 10 (2006) 207 – 231

www.elsevier.com/locate/gr

GR Focus

Rise and fall of the Eastern Great Indonesian arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor

Ron Harris

Department of Geological Sciences, Brigham Young University, Provo, Utah, 84602-4606 USA

Received 23 February 2006; received in revised form 20 May 2006; accepted 28 May 2006
Available online 28 August 2006

Abstract

New age, petrochemical and structural data indicate that the Banda Terrane is a remnant of a Jurassic to Eocene arc–trench system that formed the eastern part of the Great Indonesian arc. The arc system rifted apart during Eocene to Miocene supra-subduction zone sea floor spreading, which dispersed ridges of Banda Terrane embedded in young oceanic crust as far south as Sumba and Timor. In Timor the Banda Terrane is well exposed as high-level thrust sheets that were detached from the edge of the Banda Sea upper plate and uplifted by collision with the passive margin of NW Australia. The thrust sheets contain a distinctive assemblage of medium grade metamorphic rocks overlain by Cretaceous to Miocene forearc basin deposits. New U/Pb age data presented here indicate igneous zircons are less than 162 Ma with a cluster of ages at 83 Ma and 35 Ma. $^{40}Ar/^{39}Ar$ plateau ages of various mineral phases from metamorphic units all cluster at between 32–38 Ma. These data yield a cooling curve that shows exhumation from around 550 °C to the surface between 36–28 Ma. After this time there is no evidence of metamorphism of the Banda Terrane, including its accretion to the edge of the Australian continental margin during the Pliocene. These data link the Banda Terrane to similar rocks and events documented throughout the eastern edge of the Sunda Shelf and the Banda Sea floor.

Keywords: Banda Terrane; Timor; Banda Arc; Banda Sea; Indonesia; SE Asia; Forearc; Orogenic collapse; Slab rollback; Suprasubduction zone spreading; Arc–continent collision; Terrane accretion; Tectonics; Geochronology; Metamorphism; Structure

Contents

1. Introduction . . . 208
2. Banda Terrane . . . 208
   2.1. Sumba . . . 208
   2.2. Timor . . . 210
      2.2.1. Lolotoi/Mutis Complex of Timor. . . . 212
      2.2.2. Palelo Group and Eocene deposits . . . 218
      2.2.3. Dikes . . . 219
      2.2.4. Palelo Group in East Timor . . . 219
      2.2.5. Cablac Limestone . . . 219
      2.2.6. Ocussi and Manamas volcanics . . . 220
   2.3. Banda Sea . . . 220
      2.3.1. Banda ridges . . . 222
   2.4. Origin of the Banda Terrane. . . . 222
      2.4.1. Geological Associations of Southern Sulawesi . . . 223
      2.4.2. Position of the Banda Terrane in the Great Indonesian Arc . . . 223

E-mail address: rharris@byu.edu.

1342-937X/$ - see front matter © 2006 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.gr.2006.05.010

2.4.3. Demise of the Great Indonesian Arc . . . 224
2.4.4. Dispersal of the Banda Terrane . . . 224
3. Nappe emplacement in Timor . . . 225
3.1. Emplacement processes . . . 225
4. Conclusion. . . . 228
Acknowledgements . . . 228
References . . . 229

1. Introduction

Most volcanic arcs are retreating due to slab rollback of subducting plates (i.e. Dewey, 1980). If the upper plate of the subduction zone cannot keep pace with the retreating trench, it is extended (Elsasser, 1971), and may even form a new supra-subduction zone oceanic basin with embedded fragments of the collapsed arc–forearc system. Extensional collapse of an arc is driven by its high potential energy and thermal weakening (Molnar and Atwater, 1978). The extension direction is commonly normal to the orientation of the trench, which can form trench parallel, highly attenuated ridges of arc and forearc units embedded in newly formed supra-subduction zone oceanic crust (Schellart et al., 2002). Examples of this process are well documented in the Izu–Bonin–Mariana, Mediterranean and Caribbean arc–trench systems. In these regions shortening at the trench was simultaneous with extension in the arc and backarc regions (i.e. Malinverno and Ryan, 1986).

The Banda Arc region of eastern Indonesia (Fig. 1), which is the focus of this paper, also provides a classic example of how arcs evolve by multiple phases of fragmentation and accretion. The unique aspect of the Banda Arc region is that its outer edge is currently colliding with the northern continental margin of Australia. The collision has uplifted and exposed large sections of forearc basement and cover, which provide a rare opportunity to investigate the make-up and complex origin of a forearc slab still attached to an active arc (Fig. 1). These rocks are collectively named the Banda Terrane (Audley-Charles and Harris, 1990).

Discussion in this paper will mainly focus on the age petrology and metamorphic history of basement rocks of the Banda Terrane, and the paleogeographic origins of associated sedimentary and volcanic cover units. These new data from Banda Terrane units in Timor strengthen correlations already made between similar units from different parts of the Banda Sea region (Tappenbeck, 1939; van West, 1941; Haile et al., 1979; Earle, 1983). I will also show how the stratigraphic and age relations of Banda Terrane upper plate units contrast with structurally underlying lower plate units of the Australian continental margin (Fig. 1).

Due to the obliquity of the active Banda arc–continent collision, Banda Terrane thrust sheets in Timor can be traced laterally along orogenic strike to autochthonous units in the present forearc of the western most Banda Arc (Harris, 1991). For example, exposures of autochthonous forearc basement in Sumba are traceable eastward along the submarine Sumba Ridge (Reed et al., 1986) to thin, flat-lying thrust sheets of Banda Terrane up to 2000 km^2 in size and 1–3 km thick in Timor (Fig. 1d). Various stages of roof thrust emplacement and deformation are found along orogenic strike, and provide a rare glimpse of progressive modes of forearc nappe emplacement during an active arc–continent collision (Fig. 1b).

The purpose of this paper is to integrate earlier studies with new data collected throughout the Banda Arc region that focus on the well-exposed Banda Terrane thrust sheets in both West and East Timor. These data include the first U/Pb and $^{40}Ar/^{39}Ar$ age analyses and petrologic and structural studies of Banda Terrane klippen in East Timor, which are critical in addressing various models for the origin of metamorphic rocks in the Timor region.

2. Banda Terrane

The Banda Terrane consists of three distinctive components (Fig. 2): 1) crystalline schist and gneiss, 2) meta-mafic and ultramafic bodies, and 3) arc affinity igneous rocks interlayered with and intruding high-energy forearc basin deposits and volcanogenic and carbonate cover sequences. Various parts of the Banda Terrane are found in Sulawesi, the islands between Sulawesi and Flores, the Banda Ridges, which separate the north and south Banda Sea ocean basins, Sumba and in high-level thrust sheets of the Timor fold and thrust belt (Fig. 1d). The lithotectonic assemblage is interpreted as remnants of a continental arc terrane fringing the southeastern edge of the Sunda Shelf, which has been fragmented and dispersed mostly by opening of the Banda Sea, and is presently partially accreted to the leading edge of the Australian plate (Carter et al., 1976; Haile et al., 1979; Earle, 1983).

Another view of the metamorphic rocks associated with the Banda Terrane of East Timor is that they represent pre-Permian basement from the Australian continental margin exposed as autochthonous horst blocks (Grady, 1975; Chamalaun and Grady, 1978) or basement involved thrusts (Charlton, 2002). The purpose of this section of the paper is to provide a comprehensive overview of the geology and age of various Banda Terrane units in an effort to distinguish between these various models and establish their tectonic affinity.

2.1. Sumba

The westernmost occurrences of the Banda Terrane are exposed on the island of Sumba. Most of the island is covered with Late Neogene chalk and marl, which is characteristic of the oldest forearc basin deposits found throughout the islands of the outer Banda Arc (Audley-Charles, 1986). To the east of Sumba, in Savu, Rote and Timor, the chalk and marl unit is known as the Batu Putih (rock white) Formation (Kenyon, 1974), which

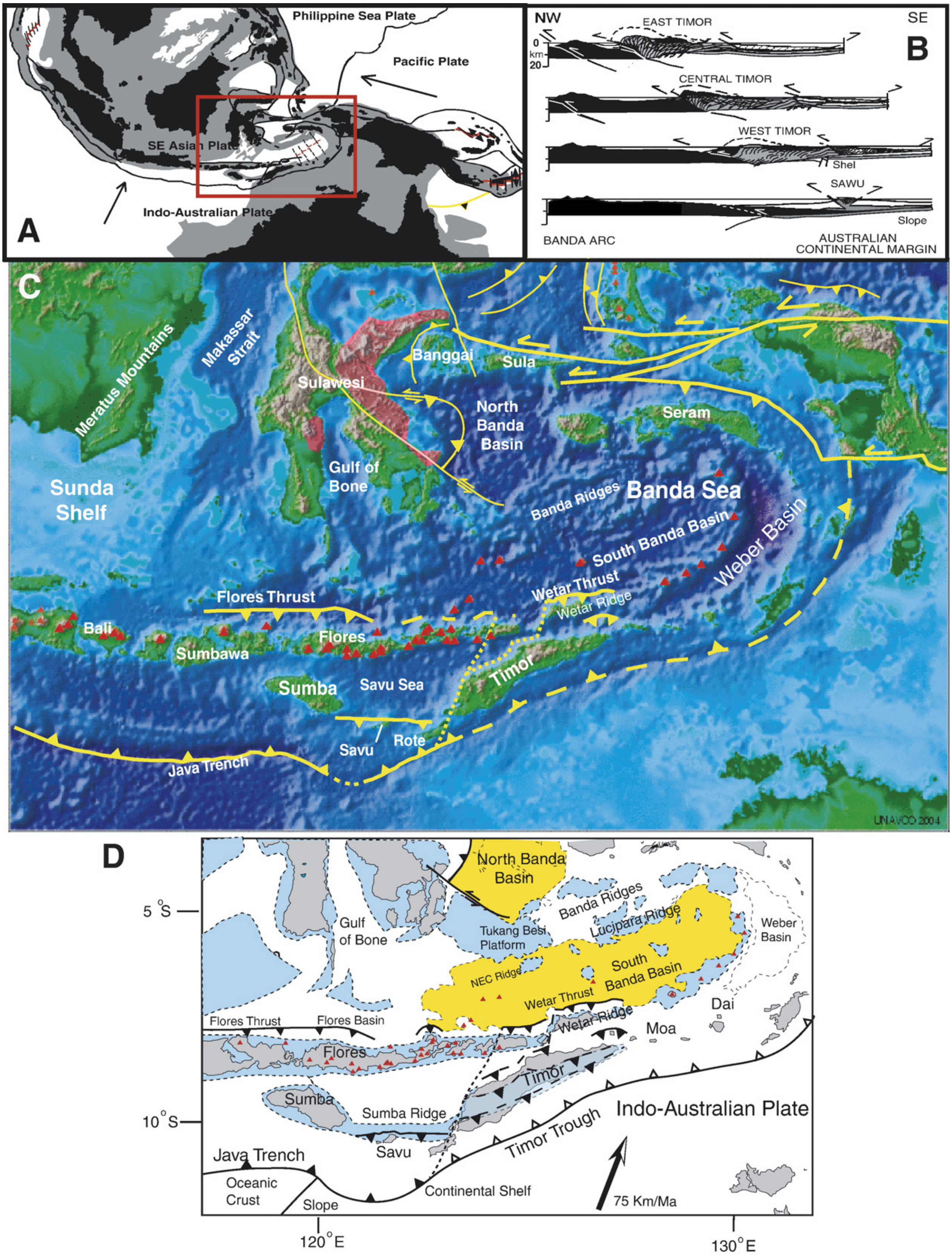

Fig. 1. Maps and serial sections of the Banda Arc region. A) Northern Australasian region. Grey is continental crust and white is oceanic crust. Rectangle is area of map 1C. B) Serial cross-sections through the western Banda Arc from Savu to East Timor. Black is the Banda Terrane of the Asian upper plate. Grey is the pre-break up Gondwana Sequence of the Australian continental margin. White with stripes is the post-breakup Australian passive margin Sequence. White is synorogenic sediment. The sections show how the southern edge of the Banda Terrane is thrust over the Australian continental margin, then becomes detached from its roots as it is incorporated into the retro-wedge thrust system, which thrusts it over the forearc basin as a passive roof thrust of the Timor fold and thrust belt. C) Digital elevation model of the Banda Arc region showing active faults (yellow lines), active volcanoes (red triangles), the Sulawesi ophiolite (pink area), and the many fragments embedded in oceanic crust of the Banda Sea floor. D) Location map of distribution of continental and arc fragments (blue), and Late Miocene Banda oceanic basins (yellow). Compare with (C).

ranges in age from Late Miocene to Pleistocene (Roosmawati, 2005). Erosional windows through the chalk blanket in Sumba expose Cretaceous to Paleocene volcanic and volcaniclastic rocks intruded by gabbroic to granodioritic plutons (Effendi and Apandi, 1981), similar lithologies to those found in the high-level klippen of Timor (Fig. 2). However, the units in Sumba are most likely autocthonous (Fig. 1d) and are presently in the initial stages of tectonic emplacement onto the underthrust Scott Plateau of the distal NW Australian continental margin to the south, and onto forearc basin sediments to the north.

The volcanic arc units of Sumba were initially deformed and eroded to produce a Late Cretaceous angular unconformity with overlying Eocene Carbonate successions (Von der Borch et al., 1983). Overlying the carbonate are successions of Eocene to Early Oligocene volcanic rocks interlayered with turbidites and mudstone (Soeria-Atmadja et al., 1998). A hiatus exists throughout the island from Early Oligocene to Late Miocene (Effendi and Apandi, 1981). No volcanic rocks are found in Sumba after this time.

Geochemical analysis of the igneous and sedimentary rocks throughout Sumba reveal that it evolved as a continent-fringing arc terrane near the edge of the Sunda Shelf, but was most likely mounted on oceanic basement (Lytwyn et al., 2001). The arc terrane formed part of the eastern most 'Great Indonesian Arc' of Cretaceous to Early Oligocene time, which is interpreted to have stretched out from the Sunda Shelf in a similar manner to the Flores to Lembata section of the present Sunda/Banda Arc transition (Lytwyn et al., 2001). The oceanic part of the arc may have continued into the east Philippines and Halmahera (Hall, 2002). Magmatism in the eastern part of the Great Indonesian Arc ceased around the same time as regional extension, which affected the southern part of the Sunda Shelf (Hall, 2002).

2.2. Timor

Some of the best exposures of the Banda Terrane are found in Timor where the Banda Forearc has been uplifted by understacking of the Australian continental margin during the transition from

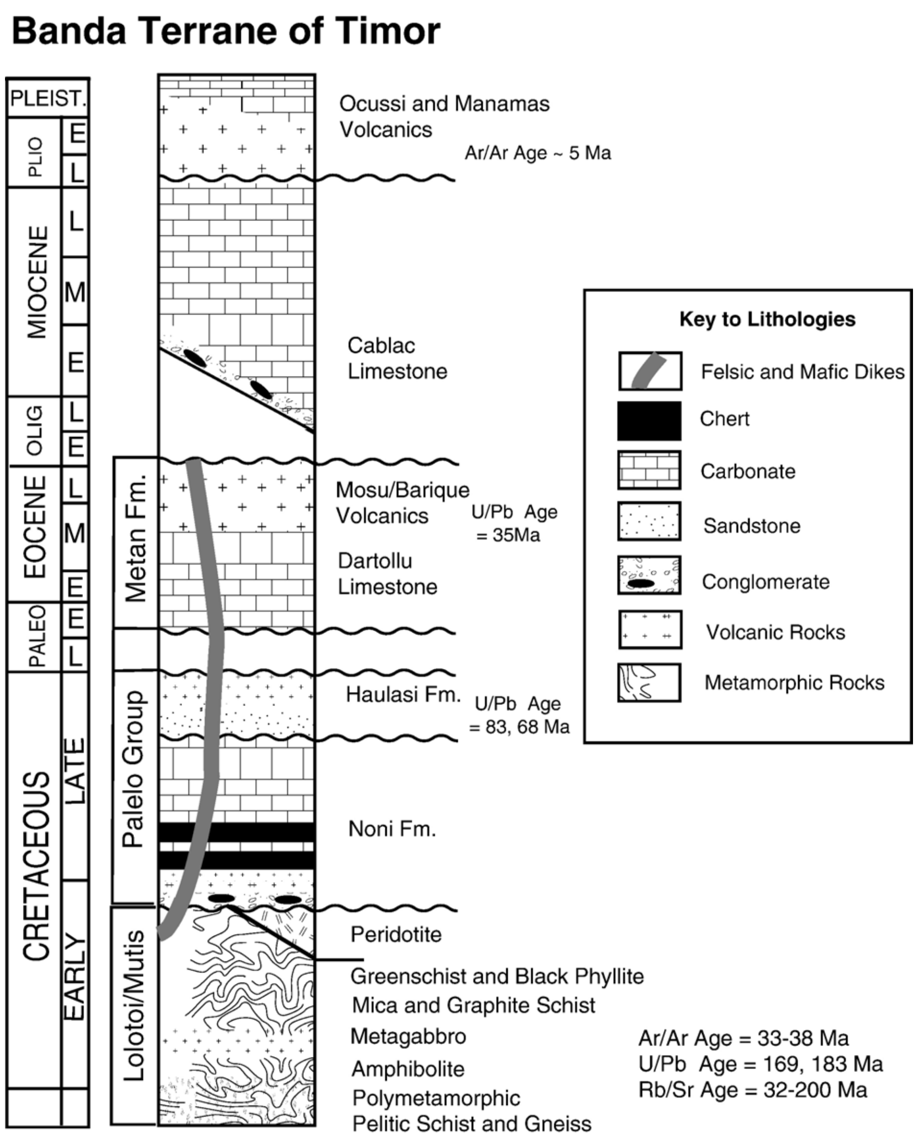

Fig. 2. Lithotectonic units of the Banda Terrane in Timor.

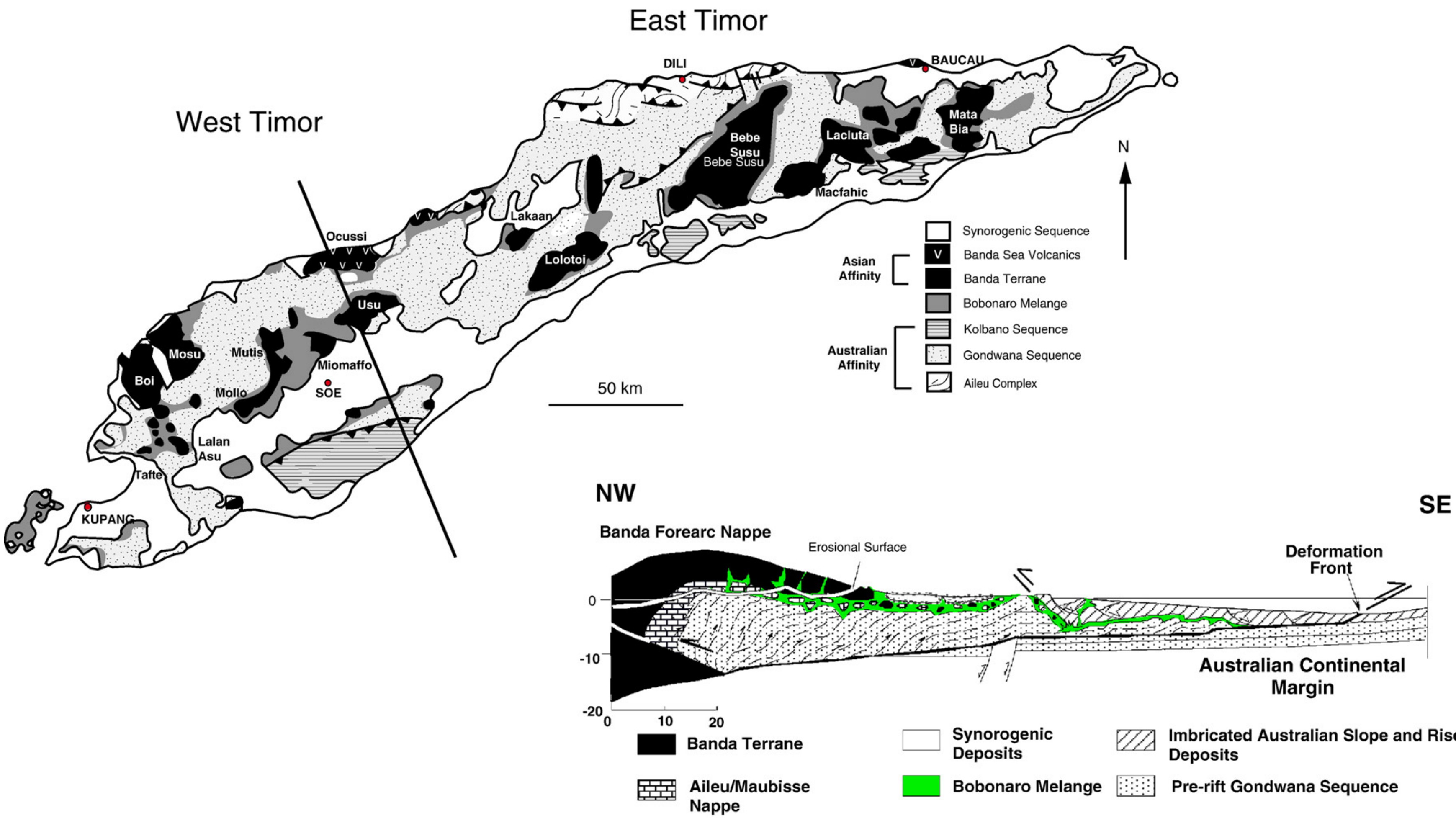

Fig. 3. Generalized geologic map, names of each Banda Terrane klippe, and cross-section of Timor. Metamorphosed part of the Gondwana Sequence is know as the Aileu Complex.

subduction to arc–continent collision (Fig. 3). The westward propagating collision demonstrates the progressive transfer of the leading edge of autochthonous forearc basement found in Sumba to allochthonous klippe found in Timor (Fig. 1b). The result of the collision is tectonic emplacement of Banda Terrane units at the highest levels of the Timor fold and thrust belt (i.e. Carter et al., 1976).

Banda Terrane klippen in Timor form resistant mountainous massifs that stretch in an ENE–WSW belt across the island (Fig. 3). At the NW corner of West Timor the Mosu, Booi, Lalan Asu, and Tafte massifs, which may be partly connected at depth, are the onshore expression of the submarine Sumba Ridge (Harris, 1991). This ridge connects autochthonous Banda Terrane exposures in Sumba with the allochthonous occurrences in Timor. Fragments of the Banda Terrane are also found in mélange and mud volcanoes on the islands of Savu, Rote and Semau (Harris et al., 1998; Vorkink, 2004; Roosmawati, 2005), which are up to 100 km south of the Sumba Ridge crest (Fig. 1d).

In central West Timor, klippe of the Banda Terrane stretch from the north coast (Ocussi Nappe) to the south edge of the Central Basin south of Soe, and include the Ocussi, Mollo, Mutis, Miomoffo and Usu massifs. The Ocussi Massif consists entirely of Late Miocene oceanic crust that is interpreted here as part of the southern Banda Sea, which encases the older parts of the Banda Terrane. The belt of massifs continues into East Timor (now Timor Leste) to form the Lakaan and Lolotoi massifs near the border, the large Bebe Susu massif, and the Macfahic, Lacluta and Mata Bia massifs further to the east (Fig. 2). On the coast of East Timor is the newly discovered Baucau Massif, which is similar in composition and petrochemistry to the Occusi Massif (Stanley and Harris, in press).

Previous studies of Banda Terrane klippen clearly show their allochthonous nature and distinctive tectonostratigraphy (Bucking, 1902; Verbeek, 1908; Molengraaff, 1912; Wanner, 1913; Molengraaff, 1914; Brouwer, 1925; T'Hoen and Van Es, 1926; Rutten, 1927; Tappenbeck, 1939; de Roever, 1940; van West, 1941; van Bemmelen, 1949; Grunau, 1953; de Waard, 1954a,b, c, 1957; Gageonnet and Lemoine, 1958; Audley-Charles, 1968; Audley-Charles and Carter, 1972; Barber and Audley-Charles, 1976; Earle, 1981; Brown and Earle, 1983; Sopaheluwakan et al., 1989; Harris, 1991, 1992; Harris and Long, 2000). Although these klippen have been the focus of over a century of research, their age, origin and tectonic affinity remains in dispute.

Detailed studies and geologic maps are available for the Booi (Tappenbeck, 1939; Earle, 1981), Lalan Asu (de Waard, 1954a), Mollo (Tappenbeck, 1939), Mutis (de Roever, 1940; Sopaheluwakan et al., 1989), Miomoffo (van West, 1941; Marks, 1961; Sopaheluwakan et al., 1989), and Usu (de Waard, 1959) massifs of West Timor, and the Lolotoi and Bebe Susu massifs (Standley and Harris, in press) of East Timor.

2.2.1. Lolotoi/Mutis Complex of Timor

The metamorphic rocks of the Banda Terrane were first investigated in detail during early Dutch expeditions to West Timor led by Molengraaff (1912) and Brouwer (1942). The 'crystalline schists', as they were known, included all the various metamorphic and igneous rocks found in each of the klippen of West Timor, with the exception of the 'ophiolite–spillite' unit. However, in many places it was not possible to differentiate between the two units, which resulted in some regions being mapped as 'heterogeneous complex' (de Roever, 1940).

The 'crystalline schists' and gneiss were named the Mutis unit by Lemoine (1959), and later the Mutis Complex by Rosidi et al. (1979) after the tallest mountain and one of the largest metamorphic klippen in Timor, Gunung Mutis (elevation 2427 m). The allochthonous metamorphic units found in East Timor are known as the Lolotoi Complex (Audley-Charles, 1968). In this paper the names of the two metamorphic complexes are combined to emphasize that both complexes represent parts of the same forearc nappe found at the highest structural levels of the Timor fold and thrust belt.

The Lolotoi/Mutis Complex is mostly composed of low to medium grade chlorite schist and amphibolite, with local occurrences of phyllite, pelitic schist and gneiss, and rare blueschist and granulite. Earle (1981) subdivided the metamorphic rocks in western-most Timor into three major lithotectonic elements: (1) medium to high-grade, polydeformed basic and pelitic schist and gneiss, (2) a commonly inverted low to medium grade, monometamorphic sequence of metabasites, and (3) serpentinite and tectonized peridotite. These units will hereafter be referred to as the (1) polyphase schist and gneiss, (2) metabasite schist, and (3) tectonized peridotite. This classification also applies to rocks found in the Mutis massif (Sopaheluwakan et al., 1989), and other massifs to the east (Grunau, 1953; Lemoine, 1959; Audley-Charles and Carter, 1972; Barber and Audley-Charles, 1976; Harris, 1991; Harris and Long, 2000).

2.2.1.1. Polyphase schist and gneiss. This unit comprises localized parts of both the Mutis Complex in West Timor and Lolotoi Complex of East Timor. It consists mostly of medium to high-grade amphibolitic units (andesine + hornblende ± garnet). Locally pelitic schist and gneiss are found, particularly in the western-most massifs where an early assemblage of garnet + kyanite/sillimanite + biotite + plagioclase + quartz is overprinted by a main assemblage of cordierite + biotite + plagioclase + sillimanite + quartz +/− white mica and hercynite. The late development of cordierite and sillimanite, and low abundances of muscovite and K-feldspar, is consistent with temperatures above the stability of quartz-muscovite and the extraction of a melt phase. It also indicates that pressures were decreasing while high temperatures were maintained (Brown and Earle, 1983). From the Mutis massif to the east, the most common pelitic units are quartz-mica schists, garnet-mica schists and garnet-biotite-staurolite gneiss and schist +/− kyanite and sillimanite (Sopaheluwakan et al., 1989; Standley and Harris, in press). Mylonitic textures are common throughout the gneiss and schist, with top to the SE sense of shear indicators (Standley and Harris, in press). However, many of the last-stage metamorphic minerals, such as staurolite, show little to no deformation.

Isotopic ratios ($^{87}Sr/^{86}Sr = 0.7065$), mineralogy, modal proportions of the pelitic units, and textures indicate a protolith consistent with shale and greywacke (Earle, 1981), while the dominance of meta-mafic units is interpreted as an oceanic crust protolith (Sopaheluwakan et al., 1989). Pelitic units indicate that the protolith was in close proximity to an eroding landmass, which was most likely the mountains that formed along the southern edge of the Sunda Shelf (Earle, 1981).

In East Timor polyphase schist and gneiss were first documented by Grunau (1953), later correlated with the Mutis Complex by Lemoine (1959) and also included in the description of the Lolotoi Complex by Audley-Charles (1968). More recently, Standley and Harris (in press) demonstrated that there is no significant difference in composition, metamorphic conditions or age between the Lolotoi and Mutis Complexes. Studies of metamorphic conditions using phase relations of the major mineral parageneses indicate progressive crystallization as temperatures increased followed by retrograde reactions during cooling. Within the metapelites near the base of the nappes the earliest phase of metamorphism is 'pre-deformational', and associated with the development of $S_1 = S_0$. At the Booi massif, Brown and Earle (1983) document an early high temperature mineral assemblage ($T > 750$ °C, $P = 10$ kbar) that is followed by a decompressional phase ($T = 700$ °C, $P = 5$ kbar) associated with the growth of cordierite. Late-stage mylonitic structures found throughout the Mutis complex are associated with retrograde reactions in polyphase gneiss and prograde reactions in metabasite. Retrograde reactions formed mica and chlorite from garnet, amphibole and plagioclase. de Roever (1940) found that all amphibolite and garnet-bearing rocks show the effects of retrograde metamorphism. However, published age analyses poorly constrain the timing of these events.

2.2.1.2. Metabasite schist. Metabasite schist consists mostly of low-grade greenschists, greenstones, and black and grey phyllite, with only prograde metamorphism. Many relict features are found, including bedding, flow and pillow structures. In the Miomaffo (van West, 1941) and Molo Massifs (Earle, 1980) a complete transition is documented from sub-greenschist facies massive metachert and metabasalt with relict textures, to epidote-amphibolite facies schist. At the Booi, Mutis and Miomoffo massifs these units are structurally overlain by medium-grade amphibolites and metagabbro (Earle, 1981; Sopaheluwakan et al., 1989). At Mutis, Sopaheluwakan et al. (1989) show an increase of metamorphic grade with decreasing distance from peridotite that structurally overlies the metabasite schist. They show an upward increase in temperature from 425 °C at the base of the schist to 840 °C near the contact with peridotite under near isobaric conditions (7 kbar).

Mineral assemblages in the schist range from albite + clinozoisite/epidote + actinolite + calcite in greenschists to plagioclase + hornblende +/− diopsidic augite, and hornblende + plagioclase + quartz + biotite + garnet in amphibolites. Co-existing mineral pairs in medium-grade rocks from the Mutis massif yield *P–T* estimates of peak metamorphism of 6–8 kbars and 540–620 °C for metapelites and temperatures of 525–605 °C for amphibolites (Sopaheluwakan et al., 1989). Thermobarometric studies of samples from the Bebe Susu and Lacluta massifs of East Timor (Standley and Harris, in press) yield *P–T* estimates for most amphibole from 5.0–6.0 kbars and 593–628 °C. Garnet-biotite-muscovite-palgioclase thermobarometry yields temperatures of 526–554 °C at 4.3–5.8 kbars.

Earle (1981) recognized an inverted gradient of metamorphism in Mutis Complex rocks at the Boi and Mollo massifs. Although he infers that the Boi massif was structurally overlain by mantle peridotite, he ruled out that the inverted metamorphic gradient was related to ophiolite emplacement due to the lack of initial increases in pressure (see Searle, 1999) and the structural order of the metamorphic units (high grade polygneisses at the base of the complex). Most of the massifs in West Timor show evidence of steep thermal gradients in the range of 100–200 °C/km (de Waard, 1957; Earle, 1981; Sopaheluwakan et al., 1989). It is not clear whether the step gradients are original or a product of post-metamorphism normal faulting.

2.2.1.3. Age of metamorphism. Age relations of the Lolotoi/Mutis complex involve several questions relating to the ages of the protolith, metamorphism and cooling. Previous attempts to determine a protolith age for the polyphase schist and gneiss involved Rb/Sr analysis of 12 whole rock samples of the Bikmela pelitic schist and gneiss unit found throughout West Timor (Earle, 1981). This age analysis included 7 samples from the Boi massif, 4 samples from the Mosu massif and one from the Mutis massif (Fig. 3). Although these data are reported to define an isochron age of 118 +/− 38 Ma (Brown and Earle, 1983), the scatter of ages is greater than 1 mean standard weighted deviation, and therefore cannot be characterized as an isochron. The degree of scatter may reflect variability in initial Rb/Sr abundance, which is consistent with a sedimentary protolith and later homogenization event (see below). The maximum number of ages that define a line with a mean standard weighted deviation of <1 yields a five point isochron age of 146 +/− 6.5 Ma. However, using this isochron requires elimination of more than half of the other ages without any objective geological criteria.

A more objective way to report the results of the Rb/Sr whole rock age analysis is to use the maximum and minimum ages permissible from the data set, which range from 32 to 200 Ma (Fig. 4). This age range is significant in that it demonstrates that these rocks cannot be Pre-Permian Australian metamorphic basement, as some have suggested (Grady, 1975; Chamalaun and Grady, 1978; Charlton, 2002). The younger age limit is also significant in

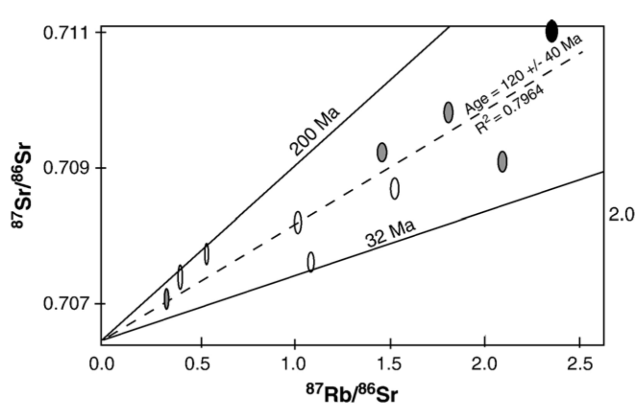

Fig. 4. Rb/Sr whole rock ages from Earle (1981) and Beckinsale (unpublished data). Ellipses are 1σ. Open ellipses are samples from Boi, grey from Mosu, and black from Mutis. The mean age has too much uncertainty for it to represent an isochron. The envelope of age possibilities (maximum and minimum) is shown.

that it argues against models that connect metamorphism in the Banda Terrane with Pliocene arc–continent collision in Timor. The younger age limit for these data is also supported by a two-point Rb/Sr biotite-whole rock isochron from the Mutis massif with an age of 32 Ma (Earle, 1980, uncertainties are not reported).

U/Pb analyses of individual zircon grains in Banda Terrane units of the Bebe Susu massif of East Timor yield maximum ages of 165.8+/−5.1 Ma and 158.5+/−4.4 Ma (Fig. 5a, Table 1), which is consistent with the maximum age limits of the Rb/Sr age analysis (Fig. 4). The oldest zircons were found in an andesite cobble in weakly metamorphosed conglomerates overlying Lolotoi Complex metamorphic rocks. The highest population of Cretaceous igneous zircons cluster around 83+/−1.4 Ma (Fig. 5a).

In order to test maximum age relations between the Lolotoi Complex and Australian affinity metamorphic rocks of East Timor (Berry and McDougall, 1986; Prasetyadi and Harris, 1996), U/Pb age analyses were conducted on detrital zircons from the Aileu metamorphic complex, which is considered part of the distal edge of the Australian continental margin (Fig. 6). The sample analyzed was collected from Kisar Island (off of the north coast of East Timor). It yielded two separate age populations of pre-Permian detrital zircons. The oldest population has $^{207}Pb/^{206}Pb$ ages that range from 1876.1+/−10.9 Ma to 1757+/−10.6 Ma, with an average of 1828.9+/−10.5 Ma (Fig. 6). Similar detrital zircon ages are reported from the Capricorn Orogen on the northern margin of the Yilgarn craton of Western Australia (Bruguier et al., 1999). The younger population has a mean age of 302.4+11.8 and −8.1 Ma (Fig. 6), which is similar to maximum apatite fission track ages found throughout the Gondwana Sequence of Timor (Harris et al., 2000). U/Pb age analyses of metamorphic sections of the Aileu Complex on the north coast of East Timor (Ron Berry, pers. Com.) yield the same detrital zircon age populations to those from Kisar reported here.

Table 1
U/Pb ages of zircon grains

Sample	207/235	1 sigma	206/238	1 sigma	207/206	1 sigma
Name/grain	Age	Abs err	Age	Abs err	Age	Abs err
Andesite from Bebe Susu, East Timor						
70_1a	83.1	2.6	83.5	2.2	46.5	36.1
70_1b	83.5	2.7	81.4	2.2	120.2	36.0
70_2a	90.5	3.3	89.2	2.5	98.2	44.4
70_3a	85.2	3.0	88.8	2.3	0.0	10.2
70_5a	81.4	2.5	80.0	2.1	96.2	31.6
70_6a	86.3	2.6	84.2	2.2	120.3	32.6
70_6b	82.0	2.5	83.0	2.1	26.4	34.0
70_7a	85.8	2.7	80.5	2.1	210.5	36.6
70_8a	85.7	2.6	82.9	2.1	140.0	32.3
70_8b	85.7	2.8	85.0	2.2	81.1	38.5
70_9a	90.6	3.5	82.7	2.3	281.0	53.4
70_9b	85.8	3.1	82.1	2.2	165.3	46.2
70_10a	90.9	3.0	86.9	2.3	171.0	38.1
70_10b	80.8	2.7	81.5	2.2	34.5	42.0
70_10c	83.9	3.0	84.3	2.2	47.4	49.1
70_11a	82.2	2.4	85.0	2.1	0.0	8.2
70_12a	88.5	3.2	86.6	2.5	114.3	42.5
70_13a	169.2	4.8	158.5	4.4	297.7	20.4
70_15a	82.4	3.3	81.1	2.3	96.1	56.3
70_16a	183.4	5.8	165.8	5.1	392.3	25.7
70_17a	85.6	2.7	83.3	2.1	124.3	37.4
70_17b	80.8	2.6	82.5	2.1	6.4	39.6
70_18a	81.5	2.4	81.9	2.1	43.0	30.3

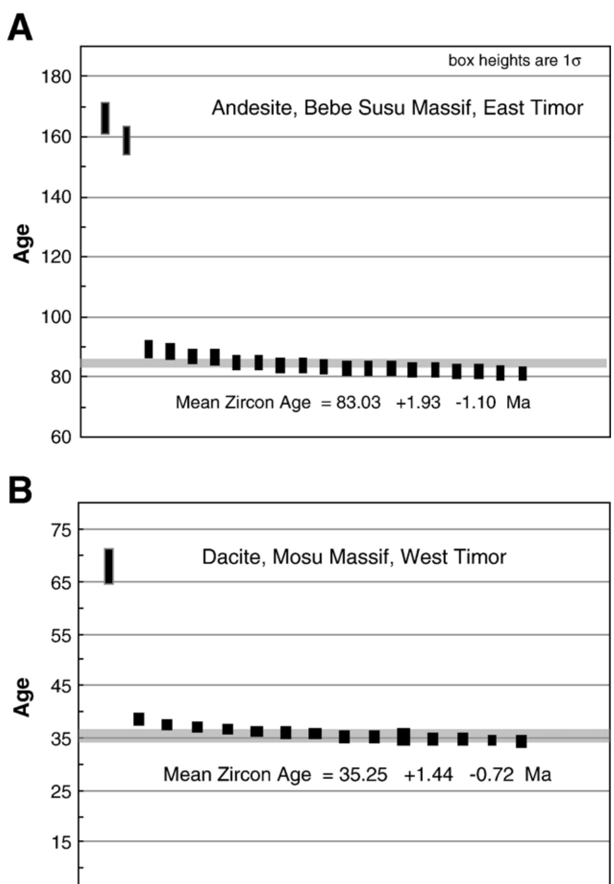

Fig. 5. U/Pb ages of zircon grains from igneous rocks of Banda Terrane klippe in East (A) and West Timor (B). Grey line is mean of dominant populations. The older ages likely represent zircon in xenocrysts incorporated into the melt. Both are recording magmatic events of the Banda Terrane. The youngest event coincides with metamorphic cooling.

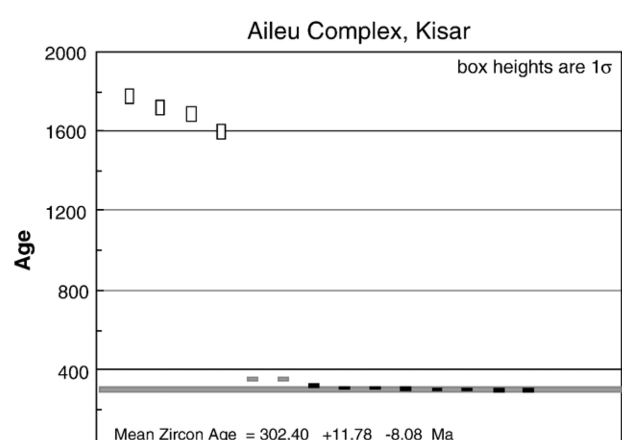

Fig. 6. U/Pb ages of zircon grains in garnet schist from Kisar Island, off the NE coast of East Timor. The metamorphic rocks correlate with the Gondwana Sequence Aileu Complex, which outcrops along the north coast of Timor. These Proterozoic and Paleozoic ages demonstrate the difference between Pre-Permian Australian and Mesozoic and Cenozoic Asian affinity units.

The youngest U/Pb ages from the Banda Terrane were obtained from unmetamorphosed dacite overlying the Mosu massif of West Timor. The mean $^{206}Pb/^{238}U$ age from 14 zircon grains is 35.25 + 1.44, − 0.72 Ma (Fig. 5b, Table 2). A core of one of the grains yielded an age of 67.8 +/− 3.3 Ma. These results constrain the minimum age of Banda Terrane magmatism to around 35 Ma, which may be associated with a thermal overprint of the metamorphic rocks recorded by K/Ar and $^{40}Ar/^{39}Ar$ age analyses. This age is also near the lower limits of the Rb/Sr age envelope (Fig. 4).

K/Ar and $^{40}Ar/^{39}Ar$ ages from various mineral phases found in metamorphic rocks at five different Banda Terrane massifs range from 31–38 Ma. The samples were collected from pelitic schist and amphibolite at the Mosu, Boi, Mollo, Mutis and Usu massifs in West Timor. All of the K/Ar analyses are of hornblende from metagabbroic rocks (Earle, 1980; Sopaheluwakan, 1990; Robert Coleman, unpublished data), which range in age from 31.3 +/− 1.9 to 37.7 +/− 2.2 Ma. The average K/Ar age is 34.2 +/− 1.9 Ma.

$^{40}Ar/^{39}Ar$ age analysis conducted at the Lehigh University Noble Gas Lab produced plateau ages from step heating of various mineral phases (Fig. 7). Analyses of hornblende separates from each of the massifs range in age from 34.0 ± 0.03 to 38.6 ± 2.2 Ma. Muscovite separates from Mutis and Usu range in age from 34.7 to 36.8 ± 0.3 Ma. Biotite separates from Mosu and Mutis range in age from 33.2 ± 0.4 to 33.9 ± 0.03 Ma. These results define a cooling curve (Fig. 8) that shows the rocks moved from depths of around 14 km to the surface in 6 m.y. (assuming an average thermal gradient of extensional regions of 40 °C/km).

Some models have proposed that this Late Eocene to Oligocene metamorphic cooling age is associated with tectonic emplacement of the Banda Terrane onto the edge of the Australian continental margin (i.e. Sopaheluwakan, 1990; Reed et al., 1996). However, there is no evidence of any thermal disturbance of structurally underlying Australian units until the Latest Miocene to Pliocene (Harris et al., 2000). $^{40}Ar/^{39}Ar$ age analysis of the metamorphosed part of the Aileu Complex on the north coast of East Timor yield plateau ages that range from 8–5 Ma (Berry and McDougall, 1986). Thermal models generated from analysis of apatite fission tracks from the Aileu Complex and other Gondwana Sequence units indicate the same results (Harris et al., 2000).

Two major unconformities found in cover units that overlie the Lolotoi/Mutis Complex also provide important constraints on ages of metamorphism and exhumation. The Palelo Group was deposited discontinuously from the Early Cretaceous to Eocene, and the Cablac Limestone was deposited from the end of the Oligocene to Late Miocene (see below). The Palelo group includes massive conglomerate units with boulders and cobbles of multi-deformed metamorphic rocks, which indicates that the main phase of metamorphism pre-dates the conglomerate. These Cretaceous to Eocene units are intensely deformed in places and have a low-grade metamorphic overprint (van West, 1941; Earle, 1980). The Cablac Limestone was deposited immediately after Late Eocene to Oligocene magmatism and metamorphic cooling (Fig. 8). These constraints indicate that there were at least two phases of magmatism and metamorphism from the Jurassic to Early Oligocene. Since the Early Oligocene, there is no evidence of any thermal disturbance in the Banda Terrane, including its Late Miocene to Pliocene accretion to the edge of the NW Australian continental margin.

2.2.1.4. Tectonized peridotite. Perhaps the most enigmatic part of the Lolotoi/Mutis Complex trinity is its close association with peridotite bodies. These masses of mostly lherzolite are interpreted to underlie, intrude into, and overlie the metamorphic rocks of the Lolotoi/Mutis Complex. de Roever (1940) mapped several lherzolite bodies near the structural base of the west flank of Mutis, and inferred that the 'ophiolite–spillite' unit in which they are found structurally underlies, and locally intrudes into the Mutis Complex. A cross-section by Marks (1961) shows peridotite forming the structural base of the Miomoffo massif. Maps of Lalan Asu by de Waard (1954a) show 'ophiolite' on the fringes of, and 'protruding' out from beneath amphibolite units into 'sediments of the overthrust series'. Rosidi et al. (1979) mapped ultramafic bodies surrounding the Mutis massif as structurally underlying the metamorphic units.

The first to interpret the peridotite bodies as structurally overlying other units was Earle (1981) from his studies of the

Table 2
U/Pb ages of zircon grains

Sample	207/235	1 sigma	206/238	1 sigma	207/206	1 sigma
Name/grain	Age	Abs err	Age	Abs err	Age	Abs err
Dacite from Mosu, West Timor						
110d_1b	34.7	1.7	35.2	1.0	0.0	46.6
110d_2a	38.7	1.3	36.2	0.9	172.5	37.6
110d_3a	448.5	19.8	67.8	3.3	3819.1	29.8
110d_4c	36.1	2.1	34.8	1.1	96.4	91.3
110d_5a	40.2	2.2	34.1	1.0	398.2	80.3
110d_5b	36.6	2.0	34.5	1.0	150.6	82.6
110d_6a	38.3	2.2	34.5	1.1	259.5	88.9
110d_6b	37.2	1.5	35.8	1.0	100.6	57.0
110d_7a	38.2	1.5	36.7	1.0	106.8	51.8
110d_8a	36.6	1.6	36.2	1.0	34.7	67.3
110d_9a	46.2	2.8	33.1	1.2	769.2	82.1
110d_10a	39.6	1.7	35.0	1.0	305.5	60.7
110d_11a	36.4	1.4	37.4	1.0	0.0	6.2
110d_12a	35.7	1.8	35.3	1.0	39.8	75.3
110d_13a	43.5	2.7	35.2	1.2	510.0	91.5
110d_14a	39.1	1.3	37.1	1.0	139.6	36.3
110d_15a	39.5	1.5	38.5	1.1	75.1	49.8
Garnet-mica schist, Aileu Complex, Kisar						
48_1a	323.3	8.5	322.7	8.6	302.3	23.2
48_1b	364.5	11.1	294.3	9.1	816.5	29.0
48_2a	1821.7	22.1	1770.6	38.0	1861.0	10.9
48_3a	371.3	8.5	359.0	8.6	424.4	18.9
48_3b	367.6	8.4	357.1	8.5	409.9	19.3
48_4a	1676.8	21.2	1597.7	34.5	1757.5	10.6
48_5a	275.9	6.4	269.9	6.4	303.0	15.8
48_6a	306.4	7.0	302.2	7.2	313.8	15.5
48_6b	311.0	7.1	306.6	7.3	319.6	15.6
48_7a	304.3	7.4	302.4	7.3	294.6	22.9
48_7b	322.9	7.9	311.6	7.6	380.6	22.4
48_8a	297.4	8.3	291.6	7.6	318.6	32.2
48_8b	306.2	7.1	301.3	7.2	319.3	17.3
48_9a	1755.7	21.2	1685.0	35.6	1821.3	10.2
48_9b	1798.4	21.6	1715.8	36.4	1876.1	10.2
48_10a	315.8	7.7	314.2	7.5	303.0	24.2

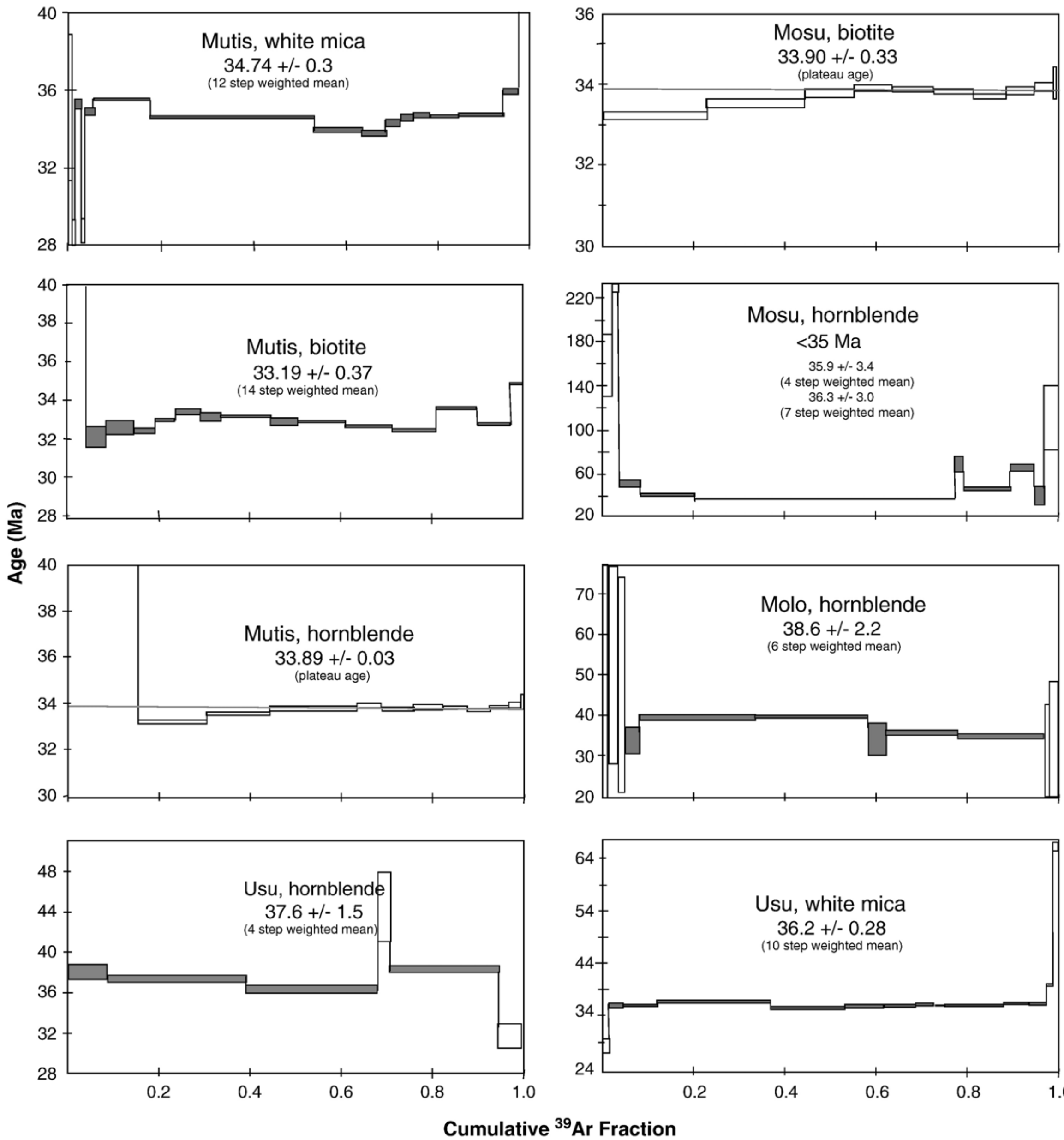

Fig. 7. $^{40}Ar/^{39}Ar$ plateau ages of various mineral phases in amphibolite grade metamorphic units from four different Banda Terrane massifs of West Timor.

Booi massif. Subsequently, Sopaheluwakan et al. (1989) reinterpreted some of the peridotite bodies at Mutis and Miomoffo as structurally overlying an inverted metamorphic complex, a structural relation key to their interpretation of sub-ophiolite metamorphism. In his interpretation, ophiolite emplacement occurred in the Early Oligocene. Earle (1981) documented similar relations at the Boi Massif, but ruled out the possibility of sub-ophiolite metamorphism as the cause in favor of 'inverted' metamorphism as a function of thrust stacking of higher over lower grade rocks.

Mapping of the Nefomasi peridotite body along the eastern fringes of the Mutis massif confirmed the field relations originally presented by Rosidi et al. (1979), and also found localized serpentinite diapirism (Harris et al., 1998; Harris and Long, 2000). It is likely that peridotite structurally underlies, overlies, and is locally injected diapirically into the Lolotoi/Mutis Complex.

Petrologic analysis of several peridotite bodies that structurally underlie the Mutis Complex revealed that they are dominantly composed of clinopyroxene-poor lherzolite (Harris and Long, 2000). The compositional range and characteristics of these bodies are similar to peridotite occurrences not directly associated with the Mutis Complex, such as the Hili Manu lherzolite on the north coast of East Timor (Berry, 1981), the Atapupu peridotite on the north coast of West Timor (Carter et al., 1976), and peridotite blocks in melange of the Bobonaro Complex (Harris and Long, 2000).

Geochemical analyses of these rocks indicate that they are very similar to average (undepleted) lherzolitic mantle compositions (Harris and Long, 2000). Relative to residual peridotites of most ophiolites, the lherzolite bodies of Timor are anomalous and represent an end-member composition. Bulk abundances of Al_2O_3+CaO are significantly higher than most residual

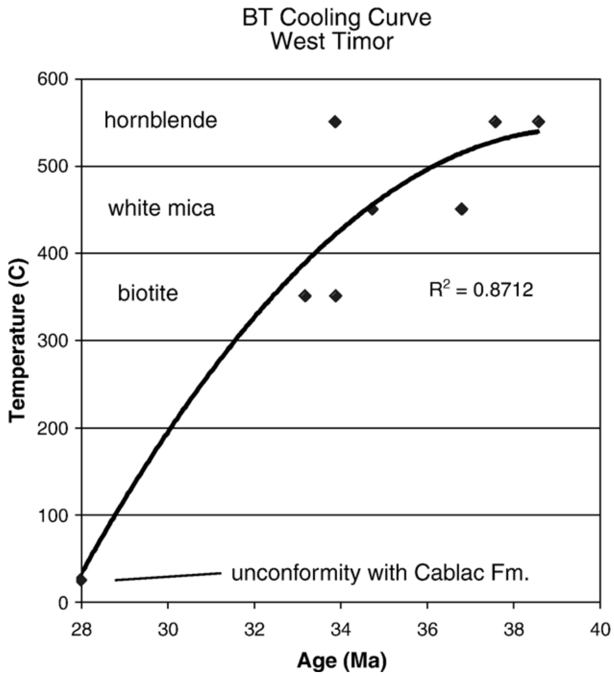

Fig. 8. Metamorphic cooling curve for amphibolite grade metamorphic rocks shown in Fig. 8. These data demonstrate that the metamorphic units rose from around 550 °C to the surface in 6 m.y. The age of arriving at the surface is constrained by deposition of Late Oligocene Cablac Formation conglomerate and limestone unconformably over the metamorphic units.

peridotites associated with ophiolites. For example, rare lherzolite bodies at the base of the Semail nappe in Oman have an average bulk $Al_2O_3 + CaO$ of 2.3 wt.% compared to 5.0 wt.% of Mutis Complex lherzolites. Al_2O_3 abundance in orthopyroxene is also anomalously high.

The only known ophiolite sequences similar in composition to the Banda Terrane lherzolite are the Ligurian massifs of the Alps (Ernst and Piccardo, 1979), and the Tinaquillo lherzolite found in the arc–continent collision zone of Venezuela (Green, 1963). Both of these occurrences are now considered exposures of sub-continental rather than sub-oceanic mantle. Similar mantle peridotite occurrences are also reported from autochthonous extensionally exhumed mantle near the ocean–continent transition at the SW Australian, Iberian, and Spitsbergen passive continental margins (Bonatti and Michael, 1989).

If these lherzolite bodies indeed represent sub-continental mantle exhumed during passive continental margin extension, then they would likely be the first parts of the lower plate continental margin incorporated into the Banda arc–continent collision zone. This would place the lherzolite bodies immediately beneath the upper plate Banda Terrane, and would provide a likely scenario for local serpentinite diapirism.

A different interpretation for the lherzolite bodies of Timor is presented by Ishikawa et al. (in press-a). They point out that Timor lherzolites have low Na values, which is not consistent with sub-continental mantle. This distinction leads Ishikawa et al. (in press-a) to interpret lherzolite bodies as fertile asthenosphere that is replenishing the mantle wedge of the Late Miocene Banda Arc, and that the ultramafic rocks are part of a dismembered ophiolite suite. It is important to note that Ishikawa et al. (in press-a) made no distinction between any of the ultramafic bodies in terms of field relations. For example, ultramafic rocks on the north coast of Timor and from islands to the east that structurally overlie the Aileu Complex (Late Miocene metamorphic cooling age) may have a Banda Arc association. However, ultramafic rocks associated with the Banda Terrane, which has a mean metamorphic cooling age of 35 Ma (Fig. 7), must be older. Although Ishikawa et al. (in press-a) lump all of the ultramafic and mafic bodies into one group without any age constraints, it is possible due to differences in ages of metamorphism that these bodies are from different sources and emplaced during different events.

What about the peridotite bodies inferred to overthrust metabasite schist of the Mutis Complex? The only samples analyzed from these bodies show mostly harzburgite compositions (Sopaheluwakan, 1990; Ishikawa et al., in press-a), with trace element abundances consistent with highly depleted, supra-subduction zone-type origins. Based on these data, it is possible that the harzburgite bodies are associated with an arc–trench system, such as the Great Indonesian Arc described above. However, the emplacement of these bodies would have to significantly pre-date the Miocene emplacement of the Banda Terrane onto the edge of the Australian margin due to the Late Eocene to Oligocene metamorphic cooling ages in the immediately underlying gneiss and schist (see Section 2.2.1.3).

2.2.1.5. Structure of metamorphism. Structural studies of the Mutis Complex conducted throughout West Timor recognize a dominant S2 foliation that is locally overprinted by up to three later deformational phases including brittle deformational features (de Waard, 1954b; Earle, 1980; Sopaheluwakan et al., 1989). Not all of the deformation phases are recorded in each of the metamorphic units. Earle (1981) suggested that the pelitic gneisses at the structural base of the Mutis Complex may have been metamorphosed earlier than other structurally overlying units, which only have S2 and later structures. Both Earle (1980) and Sopaheluwakan et al. (1989) show that later deformational phases are more prevalent in the structurally overlying metabasite units.

The earliest recognizable fabric (S1) is pre-to syn-peak metamorphism foliation that is transposed by the development of S2. The S2 fabric consists mostly of flat-lying, axial-planar foliation associated with asymmetric, tight to isoclinal folds, and mylonitic fabrics. The development of S2 represents the deformational main phase, which outlasted peak metamorphism and overprints many mineral assemblages. The orientation of S2 generally strikes ENE–WSW throughout the metamorphic klippen of Timor, with fold hinges plunging only slightly. The sense of shear of these folds is mostly top-to-the-SE, with some NW-directed structures in structurally overlying peridotite (Earle, 1981). Later broad folds cause a steepening in dip angle and scatter in dip direction of the S2 foliation. A similar pattern is also found in Lolotoi Complex massifs of East Timor (Standley and Harris, in press).

The consistent pattern of metamorphic structures over such a broad distance indicates a mostly vertical maximum stress direction associated with flattening or horizontal stretching, with a component of top-to-the-SSE directed simple shear

(Standley and Harris, in press). It also indicates that the klippen have not rotated much relative to one another, and were most likely emplaced as part of more extensive sheet that has been stripped away in places by erosion.

Later phases of deformation are recorded at varying degrees throughout the Lolotoi/Mutis Complex. S2 is modified by open folds, crenulation cleavage and a strong linear fabric (Earle, 1981; Standley and Harris, in press). Post-S2 mylonitic fabrics may be associated with the extensional exhumation of the metamorphic complex. Other indications of structural thinning are the sharp boundaries and discontinuities between narrow subfacies (de Waard, 1957) with significant amounts of missing section.

The timing of these events is poorly constrained except for the final brittle phases most likely associated with Pliocene nappe emplacement. Peak metamorphism must pre-date the deposition of weakly metamorphosed overlying Cretaceous sedimentary units including conglomerates with large blocks of polymetamorphic schist and gneiss.

2.2.2. Palelo Group and Eocene deposits

Juxtaposed with the metamorphic rocks of the Banda Terrane are Early Cretaceous to Eocene sedimentary and volcanic units known as the Palelo Group (Fig. 2). The Palelo Group was named by Brouwer (1925) for excellent exposures along the Palelo River (SE side of the Mollo massif). Tappenbeck (1939) later subdivided the Palelo Series into a lower deep-water section and upper shallow water section. These cover units of the Lolotoi/Mutis metamorphic rocks are among the most stratigraphically distinct and tectonically significant deposits in the Banda orogenic zone, providing indisputable evidence for an origin associated with subduction zone and magmatic arc development along the eastern margin of Asia. Equivalent age units deposited on the passive continental margin of Australia, and now tectonically juxtaposed with Palelo Group units, distinctly differ in composition, depositional environments and fossil assemblages.

Rosidi et al. (1979) subdivided the Palelo Group into two formations that correspond generally to the lower and upper Palelo Series of Tappenbeck (1939). Each of these units is found in places to directly overlie mostly amphibolite and greenschist of the Lolotoi/Mutis Complex along a shear zone. The lower Palelo Group corresponds to the Noni Formation, and consists of a distinctive Aptian–Turonian radiolarian chert (Earle, 1983) with interbedded tuffaceous clastics, volcanic units and carbonate. Most chert layers (5 to 15 cm thick) are tightly folded and broken by faults. A conglomerate with metamorphic and felsic igneous clasts is locally found at the base of the Noni Formation (Haile et al., 1979).

The upper Palelo Group is known as the Haulasi Formation. It consists of a massive basal conglomerate, Late Cretaceous tubiditic successions and Paleogene tuffs and lavas. The conglomerate has clasts of Lolotoi/Mutis polyphase metamorphic rocks, felsic igneous material, quartzite and chert. One of the andesitic cobbles in the conglomerate overlying the Bebe Susu metamorphic rocks yielded an U/Pb age of 83 Ma with Jurassic xenocrysts (Fig. 5). Crossite-bearing greenschists are also found in some of the cobbles (Earle, 1980), which imply that high-pressure metamorphism occurred before deposition of the Haulasi Formation. Also important is a notable lack of any clast types of Australian affinity units.

Field descriptions of lavas throughout the Banda Terrane are sparse, but indicate mostly andesitic compositions with trends of silica enrichment upward through the succession (Earle, 1981). Geochemical analyses of 21 different volcanic units throughout the Palelo Group of West Timor yield a range of compositions from basalt to rhyolite, with andesite and dacite most common (Tjokrosajoetro, unpublished data, Univ. of London). Similar rocks collected from the Barique Formation (Audley-Charles, 1968) in East Timor near Mata Bia and Same are mostly pyroxene-bearing andesite and basalt with trace element abundances indicative of subduction-related genesis (Standley and Harris, in press).

Well-exposed sections of the Palelo Group are found at the Mollo, Miomoffo, and Lalan Asu massifs of West Timor (Tappenbeck, 1939; van West, 1941; de Waard, 1954a) and the Bebe Susu, and Mata Bia massifs of East Timor (Carter et al., 1976; Standley and Harris, in press). Where the Paleo Group is found, it manifests a distinctive low-grade metamorphism, folding and faulting, and well-developed pressure-solution cleavage in sedimentary units. The overall sedimentary facies represents a shallowing and coarsening upward sequence from deep marine chert, turbidites and pelagic shale near the base to shallow water Eocene carbonate, which is followed by a major hiatus in deposition throughout the Oligocene (Carter et al., 1976). This hiatus is also found in wells drilled throughout the Sunda Shelf region (Curray, 1989) and is coincident with metamorphic cooling ages of the Lolotoi/Mutis Complex (Table 2).

Overlying the Palelo Group is a series of Eocene deposits known as the Metan Formation (Rosidi et al., 1979), which consists of the Mosu and Dartollu facies (Audley-Charles and Carter, 1972). The Mosu facies is named after abundant volcanic units that form a major part of the Mosu massif in westernmost Timor. The volcanic units consist of agglomerates with a tuffaceous matrix, pyroxene basalt and andesite lavas, and andesitic and dacitic tuffs (some associated with ignimbritic eruptions). These volcanic units are intercalated with fossiliferous marl, limestone and shale. A dacitic volcanic unit overlying the Mosu metamorphic massif yielded a mean U/Pb age of 35 Ma, with one zircon core of 67.8 Ma (Fig. 5, Table 2).

The Dartollu facies consists of calcarenites, calcilutites and calcirudites with volcanic clasts. In these rocks is found a pure microfaunal assemblage with characteristic large foraminifera that are only found in Sundaland and on low latitude Pacific islands. These fauna are characterized by three genera: *Assilina, Pellatispira,* and *Biplanispira*, know as the "APB" assemblage, which indicate a low latitude, shallow marine environment (Lunt, 2003). This distinctive faunal assemblage, and shallow water facies contrast significantly with age equivalent Australian affinity units incorporated into the Timor fold and thrust belt, which consist of deep-water marls deposited at high latitudes, thousands of km to the south of the Banda Terrane (Audley-Charles and Carter, 1972; Carter et al., 1976).

The deep marine to shallow water carbonate sedimentary units and inter-layered arc-related volcanic units of the Palelo Group is a characteristic succession found throughout the eastern edge of the Asian Plate and the Western Pacific (Haile et al., 1979; Hawkins et al., 1984). The margins of these plates consist of many Cretaceous to Tertiary metamorphic and igneous basement complexes overlain by Cretaceous to Eocene arc-related volcanic and sedimentary units. The succession is then interrupted by major phases of Early Oligocene extension and intra-arc basin development.

2.2.2.1. Structure and metamorphism. Another distinctive feature of the Palelo Group is its low-grade metamorphic overprint and structural relations. Upper zeolite to lower prehnite-pumpellyite, and locally greenschist facies mineral assemblages are found (190–300 °C at 1–2 kbar) that are injected with veins and dikes. Primary mineral phases in many veins are deformed and have undulatory extinction (Earle, 1980). Most volcanic rocks are altered to albite, chlorite and epidote, which may be associated with dike intrusion. Dioritic dikes are both altered and unaltered, and intrude the complete succession of units (Earle, 1980).

Structural studies of the Palelo Group reveal multiple phases of shortening and extension. Most of the older units are intensely folded about an NE–SW axis (de Waard, 1957; Earle, 1980), with shorter wavelength folds in less rigid Eocene units (de Waard, 1954b). Fold asymmetries and thrusts mostly indicate top-to-the-SSE vergence (de Waard, 1954c; Standley and Harris, in press). However, the most striking aspect of the deformational history are intense phases of pre-and post-shortening extension that attenuate the entire Palelo Group to less than half its measured thickness in many places (van West, 1941; Earle, 1981). Although parts of the Palelo Group are folded and thrust, no major repetitions are reported.

Earle (1980) claims that low-grade metamorphism pre-dates much of the brittle deformation in the Palelo Group. This interpretation is consistent with Oligocene extensional deformation and some thrusting during Late Miocene to Pliocene emplacement as suggested by de Waard (1954b) from similar amounts of strain in both Eocene and Miocene cover successions.

2.2.2.2. Contact relations. The basal contact of the Palelo Group is described throughout Timor as a crush zone indicating, “a displacement of the Palelo–Tertiary complex with respect to the underlying schists” (de Waard, 1957). Detailed descriptions of this contact are provided by van West (1941) from observations he made along the Noni River at Miomoffo. The contact there comprises a breccia zone around 20 m thick with ‘crushed’ chlorite schist at its base, which becomes progressively more brecciated upwards toward a sheared contact overlain by brecciated chert of the Palelo Group. Most of these faults are interpreted as extensional in nature due to the fact that they juxtapose younger over older units (van West, 1941). The hangingwall of these fault contacts is commonly a basal conglomerate or volcanic breccia, with abundant clasts of igneous and metamorphic units.

Locally, Eocene and Miocene limestone lies directly on the Lolotoi/Mutis Complex (Tappenbeck, 1939; Audley-Charles and Carter, 1972; Carter et al., 1976). At Usu and Miomoffo (van West, 1941; Marks, 1961) basal Palelo units show a low-grade metamorphism that is transitional with greenstones and greenschists of the Mutis Complex. Earle (1981) reports that all of the Eocene units studied at Booi have an incipient recrystallization. This event is documented by secondary chlorite, calcite, albite, calcic amphibole, clinozoisite-epidote, white mica, ± sphene, opaques, quartz, zeolites, pumpellyite, and prehnite.

The paleogeographic association of the Palelo Group with a nearby volcanic arc may indicate that metamorphism was caused by an arc-related thermal overprint. However, a large gap in *P*–*T* conditions remains between the metamorphic rocks that cooled to at least 300 °C in the Early Oligocene and the overlying cover units. To account for this gap the contact between the metamorphic units and overlying cover units is interpreted as an extensional fault system with rapidly exhumed metamorphic rocks in the footwall and structurally thinned cover units in the hangingwall.

2.2.3. Dikes

Dioritic dikes intrude both the Lolotoi/Mutis Complex and overlying Cretaceous to Eocene sedimentary and volcanic units (van West, 1941; Rosidi et al., 1979). Most of these consist of augite and hornblende ± quartz with multiple generations of secondary albite. Some dark dikes have olivine psuedomorphs. Dike mineralogy is consistent with intermediate compositions. Geochemical analyses of dikes intruding through the Lolotoi complex near the town of Same and Laclubar indicate mixed arc affinities (Standley and Harris, in press).

2.2.4. Palelo Group in East Timor

Interpretations of the Lolotoi Complex of East Timor as Pre-Permian Australian continental basement (i.e. Charlton, 2002) have overlooked the many occurrences of the Palelo Group and Metan Formation in East Timor. These units were first recognized by Gageonnet and Lemoine (1958) near Same. Later, Carter et al. (1976) correlated these units with the Palelo Group based on the distinctive successions of high-energy, shallow water siliciclastic units, Nummulites-bearing carbonate and associated volcanic rocks of the extensive Barique Formation. This unit includes a massive boulder agglomerate at its base with clasts of volcanic rocks and Eocene limestone encased in a tuffaceous matrix. Overlying the agglomerate are layers of dacitic tuff, with occasional andesitic lavas, dikes and volcanic-rich sandstone. Locally developed pillow structures and interbedded sedimentary rocks indicate a mostly submarine depositional setting. Geochemical analyses of these units indicate they are arc-related (Standley and Harris, in press). U/Pb age analyses of boulders in the basal conglomerate yield Late Cretaceous ages (Table 1). These units could not have been deposited on the passive continental margin of Australia, which was over a thousand kilometers from any plate boundary at the time, and in a starved slope to rise depositional environment.

2.2.5. Cablac Limestone

The Oligocene to mid-Miocene Cablac Limestone consists entirely of hard, commonly massive units of calcilutite, oolitic limestone, calcarenite, and intraformational breccia, agglomerate and tuffaceous units that are well exposed on or around Banda Terrane klippen, particularly at Mata Bia and Cablac Mountains on the SW edge of the Bebe Susu nappe (Audley-Charles, 1968). At the base of the Cablac Limestone is a distinctive conglomerate, first reported by T'Hoen and Van Es (1926) in the Boi region, which consists of clasts from older Banda Terrane units embedded in a carbonate matrix. A photomicrograph of this conglomerate found at the base of Mata Bia is shown in Fig. 9. It is composed of clasts of polymetamorphic pelitic schist and a range of volcanic and some plutonic clasts, Eocene *Nummulites* fragments and large Oligocene foraminifera. The conglomerate is overlain by massive calcilutite with Late Oligocene foraminifera (Audley-Charles and Carter, 1972). A shallow water depositional environment is indicated by coralline and melobesioid fragments of calcareous algae, and by the presence of intraclasts, grapestones, oolites, pellets, and conglomerate (Audley-Charles, 1968).

Near the top of the Cablac Limestone 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, which yields Middle Miocene K/Ar ages from nearby arc volcanics in Wetar and Alor (Abbott and Chamalaun, 1981).

One of the most unique and characteristic features of the Cablac Limestone is its elevated and isolated occurrence, forming steep walled peaks called 'Fatus' by the Timorese. The 'Fatu Limestone' as it was known in early Dutch reports is interpreted by Carter et al. (1976) as reefal buildups on locally elevated parts of a seafloor composed of foundered fragments of the Banda Terrane. Carter et al. (1976) also speculated that the Cablac Limestone was 'carried on the back of the Lolotoi thrust sheets' during Pliocene tectonic emplacement. Some of the largest klippen of Cablac Limestone are found in the western-

Fig. 9. Photomicrograph of the basal conglomerate deposited unconformably over the Banda Terrane metamorphic rocks (photo is 0.5 in width). Large shell in the center is a *Nummulities* fragment found in Eocene limestone. The rectangular fragment in the lower left is *Discocylina* (or *Asterocyclina*) of the Eocene. Below this is a small Cenozoic planktic foram (David Haig, pers. com.). Surrounding these fossils are rectangular fragments of multi-deformed quartz–mica–garnet and graphitic schist. The semi-rounded dark fragments are intermediate to felsic volcanic rocks. Fragments of granodiorite are also found. The lack of any rock fragments of Australian affinity is notable.

and eastern-most parts of Timor, which are the youngest parts of the collision complex to emerge from the sea (Harris, 1991).

2.2.6. Ocussi and Manamas volcanics

Brouwer (1942) was the first to recognize similarities between upper Tertiary volcanic rocks exposed in the Banda volcanic arc and those found on the north coast of Timor. From his observations during the expedition of 1937 he concluded, "remains near the north coast of Timor of...volcanic rocks resemble part of the volcanic rocks of the northern row (Banda Arc), and it is very possible that similar rocks extend along the bottom of the present Savu Sea between the two..."

Subsequent studies of a thick (1–2 km) volcanic pile exposed in the former Portuguese enclave of Ocussi by Leme and Coelho (1962) revealed that they consist mostly of interbedded basaltic volcanic agglomerate, pillow lavas, tuff and sheet flows. Petrochemical analysis of the volcanic units (Harris, 1992) reveal that they are both clinopyroxene-phyric basalts and basaltic-andesites of the low-K tholeiite series. Trace element abundances show strong affinities with island-arc tholeiites. Radiometric age analyses yield u-shaped $^{40}Ar/^{39}Ar$ release spectra with a maximum age of 5 Ma (Harris, 1992). Unconformably overlying the volcanics are tuff and marl deposits containing Late Miocene (early N.18) microfauna (Carter et al., 1976; Harris, 1992). The age of the Ocussi volcanic units demonstrate that they are most likely part of the Late Miocene South Banda Basin, as initially interpreted by Brouwer (1942).

Much of the volcanic pile and overlying sedimentary deposits are steeply dipping. Harris and Long (2000) associate the steep dips with north-directed folding of the Banda Terrane after it was emplaced over Australian continental margin units. Duplexing of the structurally underlying units most likely caused uplift and northward translation of the Banda Terrane nappe. The steeply dipping units form the forelimb of a large, north-verging asymmetrical fold. The structural unit comprising the Ocussi volcanics, the Ocussi nappe, dips northward into the forearc basin of the Banda volcanic arc. Dredge samples collected by the HMS Darwin from the forearc basin near the north coast of Timor are very similar in age and petrochemistry to the Ocussi Volcanics (Harris, 1992).

Pillow basalt similar in to the Ocussi volcanics is also found in a narrow band along north coast of East Timor (Standley and Harris, in press). The geochemistry of these rocks are similar to those reported from modern intra-arc basins, such as the Mariana Trough (Hawkins and Melchoir, 1985) and East Scotia Sea (Saunders and Tarney, 1979). Based on these results, Harris (1992) concluded that the Ocussi volcanics represent a period of broad and voluminous supra-subduction zone volcanism associated with tectonic development of the South Banda Sea intra-arc basin. These results support the hypothesis developed here that arc-parallel fragments of Banda Terrane are embedded in supra-subduction zone oceanic crust.

2.3. Banda Sea

Unlike the long-lived Sunda arc–trench system along the western margin of Sundaland, the eastern margin of the SE

Asian Plate is modified by subduction of the oldest part of the Pacific Plate (Hamilton, 1979). Arc terranes along the eastern margin of the Asian continent have experienced multiple phases of intra-arc spreading driven by westward trench retreat. These phases of extension resulted in the opening of several marginal basins since the Paleocene (Harris, 2004). The Banda Sea ocean basin represents one of these marginal basins that developed along the southeastern edge of Asia.

The Banda Sea occupies a series of anomalously deep (4–5 km) oceanic basins separated by stretched and foundered continental and arc material (Fig. 1). The Middle-Late Miocene to Present Banda volcanic arc forms along its outer edge due to subduction of Indian Ocean lithosphere from the south and Pacific microplates from the north. The subducting slab from the south has a torn, spoon-shaped geometry that approximates the irregular shape of the northern Australian passive margin (Hamilton, 1979). The northern part of the Banda Sea is strongly influenced by the western motion of the Pacific Plate, which translates fragments of northern Australia westward along transcurrent faults (Fig. 1).

Most models for the origin of the Banda Sea consider the deep sub-basins as trapped fragments of oceanic lithosphere older than the Banda Arc (Bowin et al., 1980; Silver et al., 1985; Lapouille et al., 1986; McCabe et al., 1993) or *in situ* oceanic lithosphere produced by back arc (Carter et al., 1976; Hamilton, 1979) or intra-arc spreading (Honthaas et al., 1998). These different ways of viewing the Banda Sea are referred to here as the 'Bering Sea' and 'Philippine Sea' models, respectively. Pre-arc oceanic lithosphere of the Bering Sea was trapped in a back arc position by re-positioning of the Aleutian Arc (e.g. Cooper et al., 1992). Whereas in the Philippine Sea region, new arc-affinity oceanic lithosphere was constructed during arc infancy (Stern and Bloomer, 1992), then later by inter-arc spreading as the arc retreated oceanward away from the continental margin due to subduction zone roll-back (e.g. Hawkins et al., 1984).

Another important feature of the Banda Sea ocean basin is that it occupies the center of an orogenic loop, where the Banda volcanic arc and arc–continent collision zone makes a 180° bend. Extension on the interior, and shortening on the exterior of the loop is simultaneous. The geometry and contrasting deformation regimes of the orogenic loop has been interpreted in various ways. Some models for the origin of the bend emphasize the combined plate kinematic effects of northward convergence of Australia and westward convergence of the Pacific plate (e.g. Silver et al., 1985). Other studies of similar types of orogenic loops found in collision zones throughout the world call on buoyancy forces (Dewey, 1988) or asthenospheric escape (Flower et al., 2001). Schellart and Lister (2004) address each of these models and show that they may contribute, but that the dominant mechanism for the progressive out-bowing of most arcs is slab rollback, which is most consistent with data from the Banda Arc.

Examples of other orogenic systems that have been compared 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 in a similar manner to trench retreat associated with subduction zone rollback (Malinverno and Ryan, 1986; Doglioni et al., 1999a,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 like what is found on the Banda Sea floor. This type of behavior is most like a Philippine Sea model for marginal basin development.

The ridges of arc–forearc and attenuated continental fragments that are embedded in the Banda Sea floor form an array of E–W trending ridges separated by anomalously deep oceanic basins (Fig. 1). Dredge samples (Silver et al., 1985; Honthaas et al., 1998) and mapping of magnetic anomalies (Hinschberger et al., 2001) support the original interpretation by Hamilton (1979) that the ocean basins opened during Late Miocene to Pliocene arc magmatism, within the stretched eastern edge of the Asian continental margin.

Separating the sub-basins are the Banda and Nieuwerkerk–Emperor of China (NEC)–Lucipara Ridges (Fig. 1d). These ridges along with the Wetar and Sumba ridges to the south, consist mostly of Neogene arc-volcanic deposits mounted on much older volcanic and metamorphic basement that formed the structurally attenuated edge of the southern Sunda continental margin and possibly collided slivers of the New Guinea part of the northern Australian continent (Silver et al., 1985; Honthaas et al., 1998).

Age analysis of samples and magnetic anomalies of the sub-basins of the Banda Sea are interpreted to indicate that the basins opened sequentially toward the SE behind the incipient Banda volcanic arc (Honthaas et al., 1998; Hinschberger et al., 2001). According to these data the South Banda Basin is the youngest feature. However, the magnetic surveys only cover a small area, and while the proposed magnetic section used by Hinschberger et al. (2001) fits the Late Miocene to Pliocene section well, they do not show how many other parts of the time scale the section may also fit. Another problem is that the area around the Banda Ridges has a high heat flow, is bathymetrically high and associated with E–W trending transform structures (Silver et al., 1985). In contrast, the South Banda Basin is deep, cold and buried by 1–2 km of Pliocene-Quaternary sediment. These data may indicate a difference in both age and tectonic evolution between the North and South Banda Basins.

Geochronological studies of the North Banda Basin show that it opened first at around 9.4–7.3 Ma, and separated the Banda Ridges from the SE part of Sulawesi (Honthaas et al., 1998). Dredge samples from horst blocks within the basin and along its margins are basalt and trachyandesite in composition with negative Nb and Ta anomalies in the range of Back Arc Basin Basalt (Honthaas et al., 1998).

The South Banda Basin opened within the stretched continental borderlands of the southern Sunda Shelf, and is transitional with the Bali and Flores Basins. The NEC–Lucipara Ridges form the northern boundary of the South Banda Basin and the Wetar Ridge forms the southern boundary (Fig. 1d). However, in this paper the southern boundary is extended to south of the Savu Basin and Wetar Strait oceanic lithosphere.

Geochronology and magnetic anomaly studies are interpreted to indicate a spreading event at around 6–3 Ma (Honthaas et al., 1998; Hinschberger et al., 2001). Spreading rates of 3 cm/yr. are estimated along what are interpreted as several arc-parallel ridge segments (Hinschberger et al., 2001).

Although no samples have been dredged from the floor of the South Banda Sea Basin, geochemical and geochronological analysis of samples dredged from the Wetar and NEC–Lucipara Ridge have strong affinities, suggesting that each of these ridges represent fragments of a single magmatic arc that was split by the opening of the South Banda Basin (Honthaas et al., 1998). Calc-alkaline andesites with high LILE/HFSE ratios, negative Nb anomalies, and some cordierite, are a dominant feature of both ridges.

The southern portion of the South Banda Basin has been overthrust by the Wetar Ridge (southern Banda Arc) along the Wetar Thrust, which now takes up the bulk of the convergence between the Australia and Asia plates (Silver et al., 1983; Harris, 1991; Genrich et al., 1996; Nugroho, 2005). Loading associated with the Wetar thrust may explain the anomalous depth versus young age of the South Banda Basin.

The origin of the Banda Sea, in so far as it is discernable in the absence of drill samples, is a Philippine Sea-type suprasubduction zone basin that formed within the transition from oceanic to continental crust at the eastern edge of the Sunda Shelf. It is composed of an array of E–W trending continental/oceanic and volcanic ridges separated by anomalously deep oceanic basins (Fig. 1). These ocean basins accommodated the eastern expansion of the Sunda arc to form the Banda Arc, and isolated many fragments of the collapsed arc as aseismic submarine ridges.

2.3.1. Banda ridges

A group of high-standing submarine ridges separate the 4–5 km deep North and South Banda Basins of the Banda Sea (Fig. 1). The ridges are interpreted as an extended and translated continental borderland region that is around 400–500 km long and 150 km wide (Silver et al., 1985). Dredge samples from the ridges brought up Triassic limestone, pelitic schist and gneiss, amphibolite, phyllite, quartzite, marble, lithic-breccia, conglomerate, greywacke, argillite, chert, limestone and calc-alkalic andesite (Silver et al., 1985; Honthaas et al., 1998; Villeneuve et al., 2000). Metamorphic samples have K–Ar whole-rock ages of 10.8 and 22.5 Ma. Volcanic samples have whole-rock K–Ar and $^{40}Ar/^{39}Ar$ ages that range from 6.2 to 9.5 Ma, and are associated with pelagic clays with late Miocene microfauna. From these data collected by Silver et al. (1985) the ‘bacon-slicer’ model was proposed, which interprets the Banda Ridges as continental fragments progressively ‘sliced’ from the Bird’s Head region of western New Guinea by left-lateral strike-slip faults, and translated into an old (Cretaceous to Eocene) Banda Sea marginal basin. Other models show the ridges as rifted from the SE edge of Sulawesi (i.e. Honthaas et al., 1998). Both of these regions consist of Australian affinity units that have collided with Asian-Pacific arc terranes as early as the Oligocene. These occurrences indicate that some currently autochthonous Banda Terrane blocks include rocks of Australian origin.

The ‘old’ Banda Sea floor hypothesis was challenged by Honthaas et al. (1998) who recovered 9.4–7.3 Ma backarc basalt (BAB) from fault scarp exposures of the basement of the North Banda Basin. They also recovered pelitic metamorphic rocks from the Sinta and Tukang Besi Ridges, and Lower Miocene limestone from the Rama Ridge further to the south (Fig. 1). Other dredge samples from the Lucipira and NEC ridges, and volcanic islands within the South Banda Basin, include Late Miocene to Early Pliocene backarc basalt, and cordierite-and sillimanite-bearing andesite. The occurrence of cordierite and sillimanite xenocrysts, and high Sr and low Nd ratios of samples throughout the region require that volcanic units are mounted on, and erupted up through continental crust (Honthaas et al., 1998) with similar mineral assemblages to the Banda Terrane metamorphic basement.

These results led Honthaas et al. (1998) to also interpret the Banda Ridges as foundered continental crust pulled from the edge of Sulawesi by intra-arc spreading. The arc complex is mounted on the southern edge of the detached continental fragment, which was repeatedly pulled apart by diffuse spreading and the opening of intra-arc basins. According to this model, the eastern Sunda and western Banda Arc islands from Pantar to Damar are volcanic constructs mounted on a continental fragment that was rifted from the Tukang–Besi platform and Banda Ridges during the Late Miocene to Early Pliocene opening of the South Banda Basin (Fig. 1d). However, these studies of the interior of the Banda Sea are mute about compositional and age similarities between rocks of the southern Banda Sea Basin, Banda and Wetar Ridges, and the Ocussi Volcanics and Banda Terrane klippe south of the Savu Sea basin.

These similarities, as first noted by Brouwer (1942), have since been confirmed by $^{40}Ar/^{39}Ar$ age and petrochemical analyses of these rocks (Harris, 1992). Similar connections may also exist between boninites exposed on the islands of Dai and Moa (Fig. 1d) and the composition of forearc basement of the adjacent Weber Deep (Richardson, 1994).

2.4. Origin of the Banda Terrane

From the earliest geologic studies of eastern Indonesia by the Dutch it was apparent that a series of similar units with distinctive geologic associations were scattered throughout the Banda Sea region. Tappenbeck (1939) compared the schist, ultramafic rock, Palelo Group trinity he found throughout the klippen of western-most Timor with similar occurrences in SW Sulawesi. van West (1941) made a similar comparison between units found at Miomoffo and those from the Meratus region of southern Kalimantan. Later detailed studies in both regions strengthened the correlations (Haile et al., 1979; Earle, 1983).

Most Banda Terrane occurrences in Sulawesi, Kalimantan and the Banda Arc are linked temporally and spatially with the Cretaceous to Early Tertiary Great Indonesian arc–trench system that formed along the southeastern edge of the Sunda Shelf. The arc is bounded to the west by a belt of Cretaceous tonalite, granodiorite and granites (Haile et al., 1979), and to the east by an extensive Franciscan-like subduction complex (Hamilton, 1979). The arc–trench system stretches from central Java to the

Meratus Mountains of SE Kalimantan, and into southern and central Sulawesi (Fig. 1). The southern Sulawesi part of the system was fragmented by rifting during opening of the Kuti, Bali, and Flores Basins, the Gulf of Bone, and the Banda Sea ocean basins. Some of the fragments were incorporated into the Late Miocene eastern Sunda Arc. The Bantimala Complex of SW Sulawesi has the closest affinities to the Banda Terrane of Timor (Carter et al., 1976; Haile et al., 1979).

2.4.1. Geological Associations of Southern Sulawesi

SW Sulawesi consists of a basement of Early Cretaceous mica and glaucophane-bearing schists, cordierite-sillimanite-bearing gneiss, and ultramafic rocks, overlain by sedimentary breccia, chert and sandstone with intercalated rhyolitic tuff all comprising the Bantimala Complex (van Leeuwen, 1981). The schist yields K/Ar ages ranging from 132–114 Ma (Wakita et al., 1994).

The sedimentary and volcanic cover units immediately overlying the Batimala complex are correlative to the Palelo Group of Timor (Fig. 2). A schist breccia that grades into sandstone forms the base of cover units, which is overlain by chert with Albian–Cenomanian radiolaria (Haile et al., 1979; Wakita et al., 1994). Overlying the chert are marine clastics of Albian to Coniacian age (Balangbaru Formation). These are overlain by the Paleocene to Eocene Langi Volcanics, which consist mostly of very altered andesitic lavas and tuffs with continental arc affinities that are interlayered with marginal marine limestone and shale (van Leeuwen, 1981). The upper part of the Eocene Malawa Formation inter-digitates with shallow marine, *Nummulites*-bearing carbonate similar to Eocene limestone found in the Metan Formation of Timor. The volcanic rocks found throughout the succession cease at the end of the Eocene (Polve et al., 1997) like those in Timor. The end of magmatism associated with the eastern Great Indonesian Arc is most likely due to collision of the Sulawesi subduction zone with the Buton continental fragment. The collision resulted in emplacement of the East Sulawesi Ophiolite, which was the oceanic forearc of the eastern Great Indonesian Arc, and blueschist metamorphism that yields $^{40}Ar/^{39}Ar$ ages from phengite of around 35 Ma (Wijbrans et al., 1994).

At the end of the Eocene the Sulawesi orogen collapsed to the south (Milsom et al., 2001) to form a broad area of highly attenuated arc and forearc fragments embedded in new suprasubduction zone oceanic crust. This phase of extension affected the entire eastern Indonesian region (Bolliger and de Ruiter, 1975), and is responsible for the opening of the Bali, Flores, and Savu Sea Basins (Harris, 2004). The collapse was accommodated by trench migration to the south and east, which pulled several fragments of the Great Indonesian Arc system and Sulawesi collision zone to the south and left them foundering in a backarc position. This event is well-documented by major Early Oligocene unconformities in southern Sulawesi, the Sunda Shelf, Sumba, and the Banda Terrane of Timor overlain in places by basal carbonate breccia.

In Sulawesi these deposits are part of the Tonasa Limestone, which formed a carbonate platform over dispersed Banda Terrane fragments in southern Sulawesi (Wilson and Bosence, 1996). The Tonasa Limestone is a 500–1000 m thick deposit of Late Eocene to Middle Miocene carbonate that consists of a basal succession of well-bedded, shallow water limestone with *Nummulites* and coralline algae. These grade into thick-bedded, pinkish-grey massive limestone that is truncated by a major Lower Oligocene hiatus. The hiatus is coincident with metamorphic cooling ages of the Mutis Complex in Timor. Above the hiatus is a basal carbonate breccia overlain by massive calilutites with large benthonic foraminifera. Characteristic interlayers of redeposited carbonate facies with lithic-rich breccias form the upper part of the section. Lithic fragments are mostly angular and include clasts of schist, serpentine, ultramafic material, shale, and quartzose sandstone (Wilson and Bosence, 1996). Similar types of redeposited carbonate, with the same range of clast types, are found at the base of the Late Oligocene to Middle Miocene Cablac Limestone of Timor (Fig. 9).

The range and immaturity of clast types in the Tonasa Limestone indicate that they were most likely derived from an extensional margin that exposed basement lithologies of the Bantimala Complex (Wilson and Bosence, 1996). Some of the coarsest redeposited units are found juxtaposed with metamorphic rocks in the footwalls of normal faults. In places the Tonasa Limestone unconformably overlies metamorphic rocks and Eocene limestone and tuff along a basal conglomerate. Similar types of contact relations are found at the base of the Cablac Limestone of Timor. These deposits clearly document the extensional collapse of the southern part of Sulawesi orogen to form the Tonasa Platform during the end of the Eocene and Early Oligocene.

2.4.2. Position of the Banda Terrane in the Great Indonesian Arc

Important differences exist between parts of the Banda Terrane found in South Sulawesi, Sumba and Timor. Large plutons of the Great Indonesian Arc are found both in Sulawesi and Sumba, but are not found in the Banda Terrane of Timor. The lack of large plutons, but existence of dikes, hydrothermal activity (veins), and abundant, but altered volcanic material in Banda Terrane klippen of Timor indicate a position near, but off-axis of the magmatic belt. A forearc basin position is consistent with these and other geologic associations, such as the abundant deep marine sedimentary units intercalated with the volcanic units, and the protolith and P–T conditions of the Lolotoi/Mutis metamorphic complexes. The abundance of metabasite and local occurrence of metapelites in these complexes, and the intermediate P–T conditions of metamorphism are also consistent with a forearc basement origin. High-pressure blueschist metamorphism found in the Bantimala Complex of Sulawesi is rare in Banda Terrane klippen of Timor, and only documented in some of the metabasites of the Mutis massif and in conglomerate clasts (Earle, 1980; Sopaheluwakan et al., 1989; Kaneko et al., in press; Ishikawa et al., in press-a,b). Blueschist metamorphism is also found on the neighboring island of Leti (Kadarusman et al., in press). However, the ages of these rocks remain unknown.

The occurrence of turbidites found throughout the Palelo Group, shallow water carbonates and finally ignimbrite deposits indicate that the arc terrane was most likely partly mounted on continental basement (Earle, 1981). The increase of volcanic units to the west throughout the cover sequences of Banda Terrane klippen in Timor are consistent with an arc source to the

NW of the present position of the klippen. The western most klippe, the Mosu massif, hosts abundant ignimbrite deposits (van Voorthuysen, 1940; Earle, 1980). Differences in the composition of the Banda Terrane klippen may also be reflected in lower abundances of metapelites and volcanic cover from the Mutis massif to the east, and the lack of Banda Terrane units reported on islands east of Timor (Richardson, 1994). For these reasons it is proposed here that the arc–foreac terrane was facing SE, and that different parts of it are expressed in Banda Terrane klippen of Timor.

2.4.3. Demise of the Great Indonesian Arc

Banda Terrane bodies found in the western Banda Arc represent fragments of the southern-most section of the Great Indonesian Arc system that was split apart and extinguished near the end of the Eocene. During this time the Great Indonesian Arc was colliding with the Indian continent to the west and New Guinea to the east, collisions that may have precipitated changes in plate boundaries. For example, near the end of the Eocene, India and Australian became a single plate, which significantly increased the northward motion of Australia (Hall, 2002). Also around this time, the motion of the Pacific plate changed by 55° (Duncan and Clague, 1985). It is changes in upper plate motion, most likely due to nearby collision events, that results in rapid pulses of suprasubduction zone spreading and the formation of intra-arc ocean basins. During these extensional phases the ocean basins are the manifestation of the volcanic arc, and have oceanic crust structure and arc-type compositions (Harris, 2004).

Tectonic events in the SE Asian region that may be associated with plate motion changes include:

- Splitting of the Izu–Bonin–Marianas Arc (Okino et al., 1998).
- Propagation of spreading in the Celebes Sea into the Sunda Shelf to open the Makassar Strait and detach the Great Indonesian Arc of the western arm of Sulawesi from SE Kalimantan (Hamilton, 1979; Cloke et al., 1999).
- Cessation of volcanism documented in Java (Hamilton, 1979), Sulawesi (Polve et al., 1997), Sumba (Lytwyn et al., 2001), and Banda Terrane klippen in Timor.
- A regional Late Oligocene unconformity that separates tilted Eocene units from mostly horizontal overlying strata found in wells throughout the Sunda Shelf (Bolliger and de Ruiter, 1975).
- Basal conglomerate of the Cablac (Timor) and Tonasa (SE Sulawesi) Limestones with clasts of schist, Palelo Group, and redeposited carbonate.
- Basin development throughout the Sunda Shelf, with thick sections of Late Oligocene to Miocene marine deposits (Curray, 1989).
- Intra-arc seafloor spreading in the Bali and Flores basins (Prasetyo, 1994), and the oldest volcanic units found in the Banda Sea Basin (Honthaas et al., 1998).
- Eruption of BAB in western Sulawesi (Polve et al., 1997).
- Metamorphic cooling ages of Banda Terrane klippen in Timor.

After Oligocene extensional unroofing of metamorphic rocks and structural thinning of the Banda Terrane, fragments of the Great Indonesian Arc were dispersed again further away from the Sunda Shelf by Late Miocene opening of the Banda Sea basins. Recognizing that Banda Terrane klippen are of Asian affinity, Carter et al. (1976) stated that,

> The Banda Sea, between the Banda Arc and the nearest Asian continental margin of Sundaland, separates the allochthonous facies (*Banda Terrane*) from their place of origin. The origin of the Banda Sea must therefore be closely associated with the mechanism for the detachment of the Asian allochthonous rocks from the Asian margin, *and* their subsequent emplacement on the Australian margin. (*words in italics added*)

2.4.4. Dispersal of the Banda Terrane

The demise of the eastern Great Indonesian Arc is closely associated with dispersal of the Banda Terrane away from the edge of the Sunda craton. The first episode of dispersion initiated during the Late Eocene and Early Oligocene, which coincides with the formation and obduction of the East Sulawesi ophiolite (Parkinson, 1998). This collision resulted from the arrival of the Buton continental fragment, which was displaced westward from the northern most Australian margin, and collided with the Great Indonesian Arc during the Late Eocene to Early Oligocene. Early Oligocene cooling ages of the metamorphic sole of the ophiolite (Parkinson, 1998) and blueschist in the underlying rocks (Wijbrans et al., 1994) overlap with those of Banda Terrane klippen in Timor reported here. These ages most likely record the timing of orogenic collapse of the Sulawesi collision. Milsom et al. (2001) use this interpretation to explain the distribution of ultramafic rocks, which are presumably parts of the ophiolite, around the Banda Sea and associated gravity anomalies. According to their model, buoyancy-driven collapse of the Sulawesi orogen displaced much of the crust that once occupied the Gulf of Bone to the south and east (Fig. 1).

It is possible that potential energy and E–W convergence of the Sulawesi collision contributed to the orogenic collapse, but the collapse was most likely directed and driven by rollback of the Banda Arc subduction zone. The difference being that rollback acts to ‘pull’ rather than ‘push’ thickened crust to the SE by creating space (Schellart and Lister, 2004).

The orogenic lobe that pulled away from the Gulf of Bone is defined by the distribution of Banda Terrane fragments. Thickened crust that forms the islands between the SW arm of Sulawesi, Flores and Sumba form the western part of the lobe (Fig. 1). The Sumba Ridge and fragments of Banda Terrane found in Savu, Rote and Timor form the southern-most, frontal part of the collisional collapse. The southward bulge of the Savu segment of the Java Trench may have inherited its shape from this event. The eastern boundaries of the collapse are poorly constrained. However, the curvature of the Banda Arc may be inherited to some extent from the original 90° bend in the Great Indonesian Arc around the southern edge of the Sunda Shelf combined with the original curved shaped of the NW Australian continental margin.

The Late Miocene southward opening of the Northern and Southern Banda Basins coincides with the collision of the Banggai–Sula continental fragment with Sulawesi in a similar manner to earlier collision of Buton. Again, the opening of the Banda Sea basins was accommodated by rollback of old Indian Ocean lithosphere to the south and east. This resulted in the rifting of arc and forearc crustal fragments, such as the Banda Ridges, away from eastern Sulawesi. Paleomagnetic studies indicate that the Banda Terrane of Timor arrived at a latitude of at least 10° south before the Late Miocene to Pliocene arrival of the NW Australian continental slope (Wensink and van Bergen, 1995, 1997). Some of these fragments may have dispersed far enough to the east to account for similar rocks to the Banda Terrane incorporated into the Seram fold and thrust belt.

In summary, the Banda Sea floor owes its origin to episodes of subduction rollback of old Indian Ocean lithosphere, which is coincident in time with two different collisions in eastern Sulawesi. The first involved the Late Eocene to Oligocene collision with the Buton continental fragment and the emplacement of the Eastern Sulawesi ophiolite. The second involved the Late Miocene collision of the Banggai–Sula continental fragment. On both occasions the orogens collapsed to the south and east dispersing fragments of the Great Indonesian Arc that once straddled the edge of the Sunda Shelf. As one part of the eastern Asian plate boundary experienced crustal thickening by terrane accretion, adjacent regions experienced lateral spreading and terrane dispersion (Fig. 1).

3. Nappe emplacement in Timor

The allochthonous nature of the Banda Terrane units in Timor has been recognized from the earliest geologic investigations of the island (Wanner, 1913). Melange and broken formation of sheared and chaotic clay-rich rocks derived mostly from structurally underlying Australian affinity units are well documented along the structural base of the Lolotoi/Mutis Complex (Harris et al., 1998). These disrupted rocks were called the 'Sonnebaite Series' by early Dutch investigators (e.g. Brouwer, 1942), and described as a highly strained chaos of Permian to Mesozoic units between massifs of the Mutis Complex and the structurally underlying 'Kekneno Series' (pre-breakup Australian continental margin units, or Gondwana Sequence). The structurally disrupted nature of this contact was described during one of the first expeditions to the island by Wanner (1913), who called it the 'klippenzone'.

During the expedition led by Brouwer, de Roever (1940) documented in detail several places along the western side of the Mutis massif where Permian to Triassic units of the Gondwana Sequence structurally underlie and grade into the 'Sonnebaite Series', which was structurally overlain by the Mutis Complex. Carter et al. (1976) demonstrated from field studies in East Timor that the basal decollement for the nappes was within the Jurassic Wai Luli Formation. Harris et al. (1998) renamed the 'Sonnebaite Series' the Sonnebaite Disruption Zone, and attributed it to a zone of decollement propagation and strain localization along the structural base of the Banda Terrane thrust sheet. Remobilization of mudstones into the decollement zone from mostly underthrust Jurassic and Cretaceous units, and the mixing of the mud with a variety of blocks from competent units (Barber et al., 1986), produces a classic Tethyan-type collisional mélange called the Bobonaro scaly clay by Audley-Charles (1968) and Bobonaro mélange by Harris et al. (1998).

Exposures of the low-angle contact at the structural base of the Banda Terrane in deeply incised streams reveal it is mostly flat lying and broadly folded by the development of duplex structures in underlying Gondwana Sequence units (Harris and Long, 2000). These observations are corroborated by gravity models that demonstrate Banda Terrane klippe must be less than 3 km thick and lie along a nearly flat thrust above low-density units (Standley and Harris, in press). If any Australian metamorphic basement is involved in the fold and thrust deformation of Timor, the gravity profile would be characterized by positive anomalies associated with exposures of the metamorphic klippen, which are not observed (Milsom et al., 2001).

Diapirs of mélange and serpentine are also found locally piercing the base of Banda Terrane klippen. For example, at the edge of the Lolotoi and Bebe Susu massifs diapirs of matrix-rich mélange and serpentinite are found protruding through fractures (Standley and Harris, in press). Serpentinite diapirs are also found along the edges of Banda Terrane nappes in West Timor, such as along the western edge of the Lalan Asu massif (de Waard, 1957), and at Mutis (de Roever, 1940; Harris and Long, 2000). These features are consistent with rock–fluid interactions along the structural base of the nappe.

3.1. Emplacement processes

Serial sections through the oblique arc–continent collision (Harris, 1991) reveal the progressive nature of collisional emplacement and deformation of Banda Terrane forearc nappe in the Timor region (Fig. 1b). Structural studies of various klippen throughout the oblique collision zone of the western Banda Arc (Harris, 1991, 1998; Harris and Long, 2000; Vorkink, 2004; Standley and Harris, in press) demonstrate that initially, the Banda Terrane forearc basement acted as an accretionary splitting-maul that collides with and delaminates units of the Australian continental margin. Post-rift Australian passive margin units stack up against and over the Banda Terrane backstop, while pre-rift Gondwana Sequence units mostly slide beneath the Banda Terrane before accretion; the former is accreted as an imbricate stack, the later as a duplex stack (Figs. 3 and 11).

The Sonnebaite Disruption Zone and associated Bobonaro melange forms in the zones of high strain at the base of the imbricate stack and along the roof thrust of the duplex zone. Continued stacking of Gondwana Sequence thrust sheets beneath the Banda Terrane roof thrust in northern Timor caused it to uplift to elevations of at least 2500 m in Central Timor (Fig. 10). In the southern part of Timor the Banda Terrane is still mostly below sea level and buried in synorogenic sediment. Drill holes have penetrated around 245 m of quartz-veined gneiss with dark grey to black schist at depths of −2585 m, which is overlain immediately by Dartollu Limestone and melange (Timor Oil, unpublished data). A similar relationship is found along the south coast of West Timor (Fig. 3) where Banda Terrane units protrude

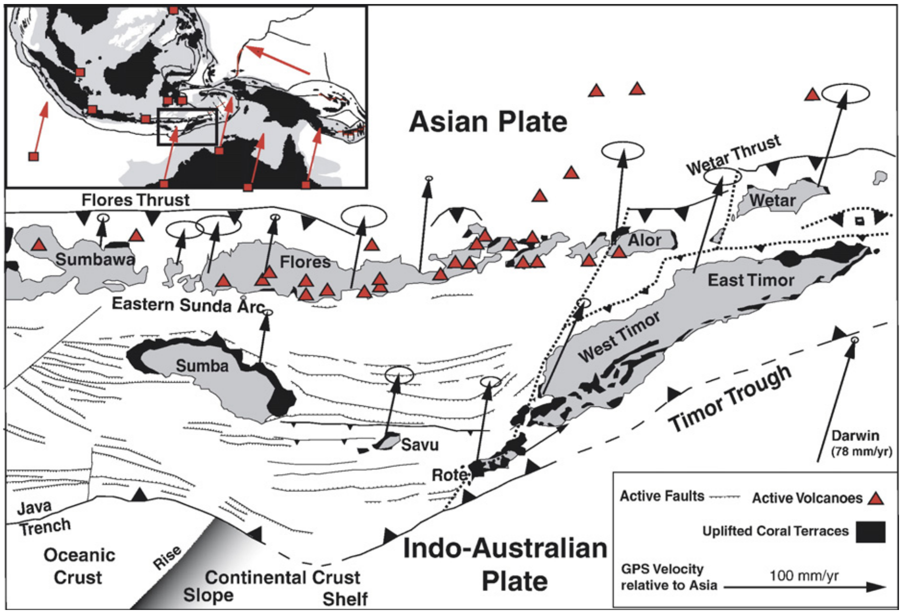

Fig. 10. GPS velocities relative to the SE Asian Plate of the eastern Sunda and Banda Arc (modified from Nugroho, 2005). Inset is map of regional velocity field with most reference station velocities plotted relative to SE Asia Plate stations (red boxes with not motion). Velocities increase in groups eastward, which reveals increased amounts of movement along the Flores and Wetar backarc thrust systems, and an increase in coupling towards Timor of the Banda Arc to the Australian plate. The displacement of active volcanism northward coincides with the highest zone of coupling. The velocities of Timor, Alor and Wetar are 70% of the velocity of Australia relative to SE Asia. The remaining 30% may account for much of the active uplift of Timor. The prominence of uplifted coral terraces on the north coast of many islands may relate to northward-verging thrusts that are part of the retrowedge fold and thrust system.

up through mélange deposits and most likely extend to some depth (Harris et al., 1998).

Although the predominate vergence direction of thrusting was southward, the orogenic wedge and its Banda Terrane structural lid were successively pushed northward (Fig. 1b and 11) with the accretion of additional thrust sheets of underthrust Australian continental margin units (Harris, 1991). This northward, retrowedge motion folded the Banda Terrane nappe into an orogen-scale asymmetric anticline with a near vertical northern forelimb and mostly flat-lying southern backlimb. The steeply dipping forelimb is well represented in the vertical beds of Ocussi Volcanics on the north coast of West Timor (Harris and Long, 2000). The flat lying backlimb of the roof thrust is represented by the majority of Banda Terrane klippen in Timor, which overlie mostly flat-lying thrusts (Fig. 3).

The arrival of the Australian continental margin at the Java trench initiates a series of changes to the arc–trench system. West along orogenic strike from the Timor collision zone, oceanic lithosphere subducts along the Java Trench. Most deformation (earthquakes and active faults) in this pre-collisional setting is localized within 30 km of the trench, and very little material is accreted. South of Sumba, where the distal continental slope of Australia first arrives at the Java Trench, the entire arc–trench system is shortened. This deformation gives rise to forearc basin inversion (Sumba) and backarc thrusting (Flores Thrust). South of Savu underthrusting of the Scott Plateau and accretion of its 3–4 km thick section of volcanic and sedimentary units overwhelm the subduction channel. The Savu thrust accommodates the northward translation of this widened accretionary wedge over the Banda Terrane (Vorkink, 2004). In the back arc, the Wetar Thrust moves the volcanic arc over the Banda Sea floor (Fig. 1). These retrowedge thrust systems are well imaged by the BIRPS deep seismic profile off the east coast of Timor (Snyder et al., 1996).

The arrival of the Australian Shelf at the deformation front increases the accretionary influx by an order of magnitude and introduces thick shelf-facies carbonate units. It is this event that is most responsible for retroarc folding and detachment of the Banda Terrane from its forearc roots. As the southern 50–70 km of the forearc detaches, it becomes a passive roof thrust (Fig. 1b) at the highest structural levels of the developing Timor fold and thrust belt (Harris, 1992). Most deformation at this stage is partitioned away from the deformation front into the interior and rear of the orogenic wedge (Harris, 1991).

As the collision evolves, the forearc basin closes due to partioning of strain away from the deformation front to retrowedge thrust systems, such as the Savu thrust (Vorkink, 2004), Wetar Suture (Audley-Charles, 1981; Breen et al., 1986) and Wetar Thrust (Silver et al., 1983; Breen et al., 1989; Snyder et al., 1996). The southern 50–70 km of the Banda forearc basement is incorporated into this northward-verging thrust system (Harris, 1992). Retrowedge movement along the Wetar Suture eventually causes complete closure of the forearc basin, such as in the Wetar Strait where the orogenic wedge abuts up against the volcanic arc and both move northward at the same rate (Fig. 11).

At this stage of the collision the orogenic wedge is squeezed between two major crustal obstructions, the volcanic arc to the north and the Australian shelf to the south. The result is a major phase of uplift resulting mostly from internal shortening and ramping of the orogenic wedge over the forearc basement. This phase of uplift is well documented by analysis

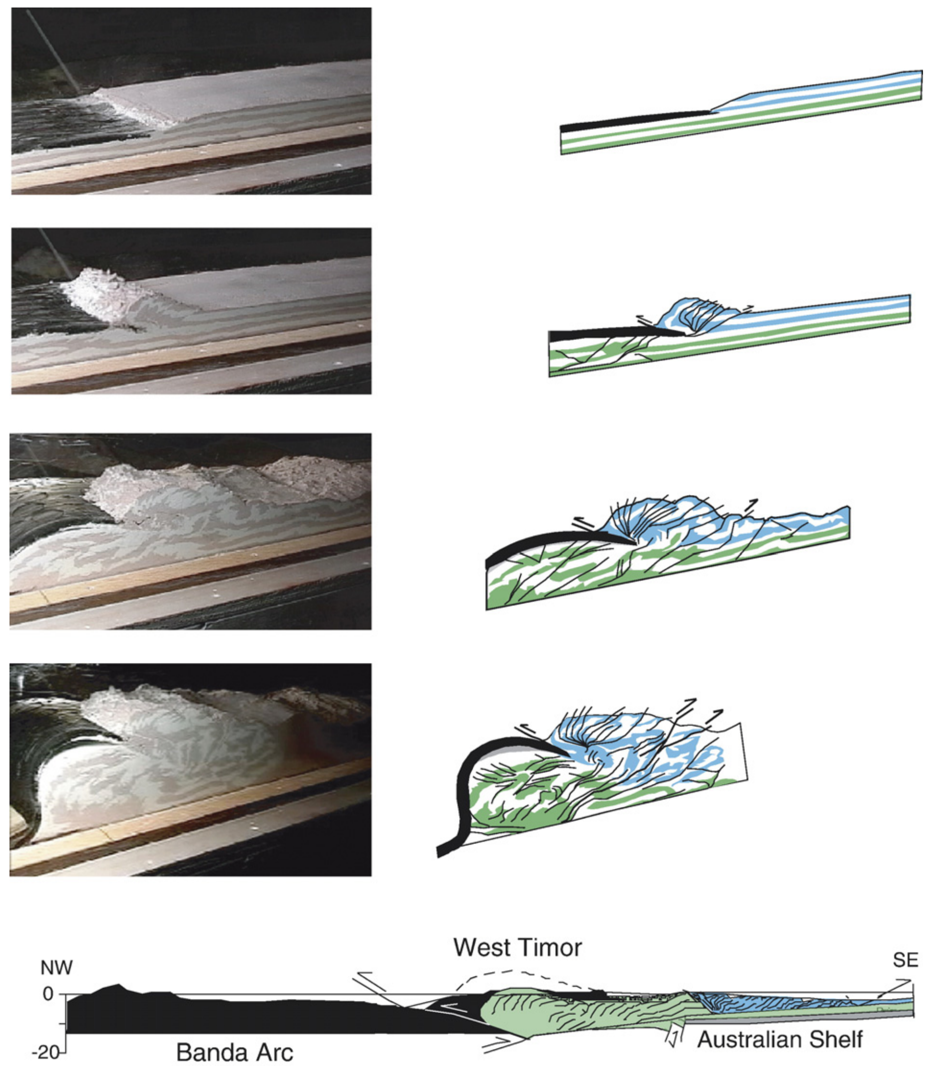

Fig. 11. Analog sandbox model of the sequential influence of a strong upper plate structural lid on orogenic wedge geometry (modified from Vorkink, 2004). Materials are scaled to rheologies and thicknesses of the Australian continental margin (red and white) and Banda Terrane (black). In coming passive margin units are detached at two levels. Blue units represent the post-rift passive margin sequence that deforms into an imbricate thrust stack. Green units represent the pre-rift Gondwana sequence that deforms into a fold-dominant duplex system. The Banda Terrane is represented by black plasticene that is driven back into an asymmetric retro antiform by overthrusting of the imbricate stack on to its edge, and understacking of Gondwana Sequence units. A cross-section through West Timor (modified from Harris, 1991) is shown for comparison.

of foraminifera (de Smet et al., 1990; Roosmawati, 2005) and flights of uplifted coral terraces (Fig. 10) throughout the Timor region (Brouwer, 1921; Gageonnet and Lemoine, 1958; Merritts et al., 1998). The complete erosional removal of the Banda Terrane from the northern part of Timor in the past 3–4 m.y. since the orogenic wedge has emerged above sea level (Audley-Charles, 1986; Roosmawati, 2005) indicates erosion rates of at least 1 km/m.y.

Scaled analog sandbox models of emplacement of the Banda Terrane thrust sheet by Vorkink (2004) provide a kinematic context for understanding how the forearc nappe deforms during accretion and its influence on the geometry of the orogenic wedge (Fig. 11). Folding of the Banda Terrane nappe into an arcward-verging asymmetrical antiform causes neutral-surface extension as the orogen expands. This syn-emplacement extensional phase may account for some of the structural features observed throughout the Banda Terrane thrust sheets, such as hanging-wall drop faults and gravity sliding of cover units (Standley and Harris, in press). The model also demonstrates how multiple detachments allow for thrust stacking both in front of, and beneath the Banda Terrane Nappe (Vorkink, 2004), which is consistent with structural models of the Timor orogen (Carter et al., 1976; Audley-Charles, 1981; Charlton et al., 1991; Harris, 1991; Audley-Charles, 2004).

Geodetic measurements in the Timor region (Fig. 10) show how at decadal time scales the Banda Arc and the abutting orogenic wedge of Timor move as one block northward relative to the Asian plate (Genrich et al., 1996) at 70% the rate of the Australian plate. The remaining 30% (25 mm/yr. of convergence) may account for the dramatic effects of ongoing uplift by internal shortening, which is manifest by uplifted flights of coral terraces (Fig. 10). The GPS velocity field progressively changes to the west of Timor where the Sumba–

Savu block shows less coupling with the Australian Plate and parts of the Sunda Arc further to west show little to no coupling. These results document the progressive accretion of the Banda Arc and forearc to the edge of the Australian continental margin (Nugroho, 2005).

The timing of nappe emplacement was initially interpreted by Wanner (1913) as Late Miocene based on deformation of Miocene sediments. Later recognition of other events in the Banda Terrane led Tappenbeck (1939) to propose an earlier Oligocene age, which was corroborated later in East Timor through studies of the Lolotoi Complex by Grunau (1953). However, de Waard (1954b) documented similar amounts of deformation in both the Eocene and Miocene deposits overlying the Mutis Complex, and Pliocene deposits that overlapped the nappes. These age constraints demonstrate that Wanner (1913) had it mostly right, and that the Oligocene age deformational events documented by the others were pre-collisional upper-plate events associated with subduction along the eastern edge of the Asian Plate.

Detailed investigations throughout Timor of foraminifera in synorogenic deposits (Kenyon, 1974; Carter et al., 1976; Audley-Charles, 1986; de Smet et al., 1990; Roosmawati, 2005), and apatite fission track analysis (Harris et al., 2000) demonstrate a mostly Pliocene age for Banda Terrane thrust sheet emplacement in Timor. However, thrust emplacement of the Banda Terrane to the west of Timor near Savu and Sumba is currently in progress.

4. Conclusion

The ongoing oblique collision of the Banda Arc with the continental margin of Australia lifts up the southern edge of the Banda forearc basement, providing a rare glimpse of a complex forearc basement slab. Although these rocks in Timor are commonly characterized as an 'ophiolite', this is an oversimplification that masks the heterogeneous makeup of the Banda Sea floor. The term Banda Terrane is used here instead to emphasize that the allochthonous, high-level thrust sheets of Timor represent a part of a much larger group of rocks that are found dispersed throughout the Banda Sea region, and preserve a partial record of their travels. Banda Terrane klippen that form the structural lid of the Timor fold and thrust belt consists of crystalline rocks with multiple phases of igneous activity and metamorphism. These units are overlain by distinctive successions of Cretaceous to Miocene sedimentary and volcanic cover sequences. The same lithotectonic succession is also found in autochthonous settings such as Sumba, the Banda Ridges, Sulawesi, Kalimantan and perhaps central Java. For these reasons the Banda Terrane is interpreted as Asian affinity. These rock assemblages, and the subduction-related events they record, contrast greatly with equivalent age rocks of the Australian passive continental margin in which they are now tectonically interleaved.

Studies of the composition and age of the Banda Terrane indicate that it originated as a Jurassic to Eocene arc–forearc terrane fringing the SE edge of the Sunda Shelf, which correlates with the eastern-most Great Indonesian Arc. Eocene collision of this arc with India to the west and Australia to the east initiated a series of plate motion changes that affected the regional stress regime of the eastern Indonesian region. It was at this time that dispersion of the Banda Terrane began.

First, Sulawesi was separated from the subduction complex in Kalimantan by opening of the Makassar Strait in the Paleogene. Then it collided with continental fragments sheared from northern Australia during the Early Oligocene. These events were most likely responsible for extensional exhumation of Banda Terrane metamorphic units at rates of around 2–3 mm/yr. during 38 to 33 Ma, and structural attenuation of their cover units. By the Late Oligocene the dispersed fragments of the Banda Terrane were foundering in a shallow marine environment that allowed for deposition of thick carbonate build-ups of the Cablac Limestone. This depositional phase continued throughout the dispersion of the Banda Terrane.

Trench rollback continued to the south as the old oceanic lithosphere of the Australian/Indian Plate subducted. The upper plate was forced to extend, which resulted in suprasubduction zone seafloor spreading to form the Banda Sea basin. Trench retreat eventually brought the southern-most rifted ridge of Banda Terrane into collision with the Australian continental margin. As the cover sequences of the Australian slope and rise stacked up in the collision zone the Banda Terrane was folded, detached, and uplifted, during accretion to the edge of Australia. Now the southern most part of the Banda Terrane forms an allochthonous thrust sheet that acts as the structural lid of the Timor fold and thrust belt. As the collision progressed it widened and the plate boundary localized in the thermally weakened backarc where the southern Banda Sea Basin underthrusts the Banda Arc. Closing of the Banda Sea basins puts the allochthonous part of the Banda Terrane on a collision course with autochthonous Banda Terrane fragments imbedded in the Banda Sea floor, and eventually with Sulawesi, where most of these fragments started their journey over 50 m.y. ago.

Acknowledgements

Many have assisted with this investigation of the Banda Terrane. Mike Audley-Charles first introduced me to the problem and brought me to many of the key localities of various units throughout Timor. Carolus Prasetyadi provided invaluable support as a field companion and colleague. Peter Zeitler assisted Mike Dropkin with $^{40}Ar/^{39}Ar$ analyses at Lehigh University. Garret Hart conducted the ICP-MS U/Pb age analyses at Washington State University. David Haig assisted with fossil identification. Myra Keep and Steve Nelson provided valuable support. I also appreciate the contributions made by many students, especially those of Carl Standley, Elizabeth Zobell, Johnny Reis, Jamie Robinson and Sahat Tobing. Field studies in the Timor region were sponsored by GRDC, LIPI and Universitas Pembangunan Nasional (UPN) of Indonesia, and the Ministry of Mines in East Timor. Funding was provided by the National Science Foundation (EAR 9118151) and the petroleum industry (Union Texas, Chevron and Texaco).

References

Abbott, M.J., Chamalaun, F.H., 1981. Geochronology of some Banda Arc volcanics. In: Barber, A.J., Wiryosujono, S. (Eds.), The Geology and Tectonics of Eastern Indonesia. GRDC Spec. Pub., vol. 2, pp. 253–268.

Audley-Charles, M.G., 1968. The Geology of Portuguese Timor. Geol. Soc. Lond., Mem. 4, 76.

Audley-Charles, M.G., 1981. Geometrical problems and implications of large-scale overthrusting in the Banda Arc–Australian Margin Collision Zone. Geol. Soc. London, Spec. Publ. 9, 407–416.

Audley-Charles, M.G., 1986. Rates of Neogene and Quaternary tectonic movements in the southern Banda Arc based on micropaleontology. J. Geol. Soc. (Lond.) 143, 161–175.

Audley-Charles, M.G., 2004. Ocean trench blocked and obliterated by Banda forearc collision with Australian proximal continental slope. Tectonophysics 389, 65–79.

Audley-Charles, M.G., Carter, D.J., 1972. Palaeogeographical significance of some aspects of Paleogene and Early Neogene stratigraphy and tectonics of the Timor Sea region. Palaeogeogr. Palaeoclimatol. Palaeoecol. 11, 247–264.

Audley-Charles, M.G., Harris, R.A., 1990. Allochthonous terranes of the Southwest Pacific and Indonesia. Philos. Trans. R. Soc. Lond. 331, 571–587.

Barber, A.J., Audley-Charles, M.G., 1976. The significance of the metamorphic rocks of Timor in the development of the Banda Arc. Tectonophysics 30, 119–128.

Barber, A.J., Tjokrosapoetro, S., Charlton, T.R., 1986. Mud volcanoes, shale diapirs, wrench faults and melanges in accretionary complexes, eastern Indonesia. Am. Assoc. Pet. Geol Bull. 70 (11), 1729–1741.

Berry, R.F., 1981. Petrology of the Hili Manu lherzolite, East Timor. J. Geol. Soc. Aust. 28, 453–469.

Berry, R.F., McDougall, I., 1986. Interpretations of $^{40}Ar/^{39}Ar$ dating evidence from the Aileu Formation, East Timor, Indonesia. Chem. Geol. 59, 43–58.

Bolliger, W., de Ruiter, P.A.C., 1975. Geology of the south central Java offshore area. Proc. 4th Ann. Conv. Indon. Petrol. Assoc., 75–81.

Bonatti, E., Michael, P.J., 1989. Mantle peridotites from continental rifts to ocean basins to subduction zones. Earth Planet. Sci. Lett. 91, 297–311.

Bowin, C., Purdy, G.M., Johnston, C., Shor, G., Lawyer, L., Hartono, H.M.S., Jezek, P., 1980. Arc–continent collision in the Banda Sea region. Am. Assoc. Pet. Geol. Bull. 64 (6), 868–918.

Breen, N.A., Silver, E.A., Hussong, D.M., 1986. Structural styles of an accretionary wedge south of the Island of Sumba, Indonesia, revealed by SeaMARC II side scan sonar. Geol. Soc. Amer. Bull. 97 (10), 1250–1261.

Breen, N.A., Silver, E.A., Roof, S., 1989. The Wetar back arc thrust belt, eastern Indonesia: the effect of accretion against an irregularly shaped arc. Tectonics 8 (1), 85–98.

Brouwer, H.A., 1921. The horizontal movement of geanticlines and the fractures near their surface. J. Geol. 29, 560–577.

Brouwer, H.A., 1925. The Geology of The Netherlands East Indies. Macmillan, New York.

Brouwer, H.A., 1942. Summary of the geological results of the expedition. Geol. Exp. Lesser Sunda Islands, vol. 4, pp. 345–402.

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

Bruguier, O., Bosch, D., Pidgeon, R.T., Byrne, D.I., Harris, L.B., 1999. U–Pb chronology of the Northampton Complex, Western Australia— evidence for Grenvillian sedimentation, metamorphism and deformation and geodynamic implications. Contrib. Mineral. Petrol. 136, 258–272.

Bucking, H., 1902. Beitrage zur Geologie vonCelebes. Samml. Geol. Reichsmus. Leiden 7, 29–207.

Carter, D.J., Audley-Charles, M.G., Barber, A.J., 1976. Stratigraphical analysis of island arc-continental margin collision in eastern Indonesia. J. Geol. Soc. (Lond.) 132, 179–198.

Chamalaun, F.H., Grady, A.E., 1978. The tectonic evolution of Timor: a new model and its implications for petroleum exploration. J. Aust. Pet. Exp. Assoc. 18, 102–108.

Charlton, T.R., 2002. The structural setting and tectonic significance of the Lolotoi, Laclubar and Aileu metamorphic massifs, East Timor. J. Asian Earth Sci. 20, 851–865.

Charlton, T.R., Barber, A.J., Barkham, S.T., 1991. The structural evolution of the Timor collision complex, eastern Indonesia. J. Struct. Geol. 13, 489–500.

Cloke, I.R., Milsom, J., Blundell, D.J.B., 1999. Implications of gravity data from east Kalimantan and the Makassar Straits: a solution to the origin of the Makassar Straits? J. Asian Earth Sci. 17, 61–78.

Cooper, A.K., Marlow, M.S., Scholl, D.W., Stevenson, A.J., 1992. Evidence for Cenozoic crustal extension in the Bering Sea region. Tectonics 11, 719–731.

Curray, J.R., 1989. The Sunda Arc: a model for oblique plate convergence, Netherlands. J. Sea Res. 24, 131–140.

de Roever, W.P., 1940. Geological Investigation in the Southwestern Moetis Region (Netherlands Timor) [PhD Thesis]: Amsterdam.

de Smet, M.E.M., Fortuin, A.R., Troelstra, S.R., Van Marle, L.J., Karmini, M., Tjokrosapoetro, S., Hadiwasastra, S., 1990. Detection of collision-related vertical movements in the outer Banda Arc (Timor, Indonesia), using micropaleontological data. J.S.E. Asian Earth Sci. 4, 337–356.

de Waard, D., 1954a. Geological research in Timor, an introduction. Contributions to the Geology of Timor Island. Indones. J. Nat. Sci. 110, 1–8.

de Waard, D., 1954b. The orogenic main phase in Timor. Contributions to the Geology of Timor 2. Indones. J. Nat. Sci. 110, 9–20.

de Waard, D., 1954c. Structural development of the crystalline schists in Timor Tectonics of the Lalan Asu Massif. Contributions to the Geology of Timor 5. Indones. J. Nat. Sci. 110, 143–153.

de Waard, D., 1957. The third Timor geological expedition: preliminary results. Contributions to the Geology of Timor 12. Indones. J. Nat. Sci. 113, 7–42.

Dewey, J.F., 1980. Episodicity, sequence and style at convergent margins. Geol. Assoc. Can. Spec. Pap. 20, 553–573.

Dewey, J.F., 1988. Extensional collapse of orogens. Tectonics 7, 1123–1139.

Doglioni, C., Guegen, E., Harabaglia, P., Mongelli, F., 1999a. On the origin of west directed subduction zones and applications to the western Mediterranean. Geol. Soc. London, Spec. Publ. 156, 541–561.

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

Duncan, R.A., Clague, D.A., 1985. Pacific Plate motion recorded by linear volcanic chains. In: Nairn, A.E., Stehli, F.G., Uyeda, S. (Eds.), The Ocean Basins and Margins. The Pacific Ocean. Plenum Press, New York, pp. 89–121.

Earle, M.M., 1980. A Study of Boi and Molo, Two Metamorphic Massifs on Timor, Eastern Indonesia. [PhD Thesis] University of London.

Earle, M.M., 1981. The metamorphic rocks of Boi, Timor, eastern Indonesia. In: Barber, A.J., Wiryosujono, S. (Eds.), The Geology and Tectonics of Eastern Indonesia. GRDC Spec. Pub., vol. 2, pp. 239–251.

Earle, M.M., 1983. Continental margin origin for cretaceous radiolarian chert in western Timor. Nature 305, 129–130.

Effendi, A.C., Apandi, T., 1981. Geological Map of Sumba Quadrangle. GRDC, Indonesia.

Elsasser, W.M., 1971. Sea-floor spreading as thermal convection. J. Geophys. Res. 76, 1101–1112.

Ernst, W.G., Piccardo, G.B., 1979. Petrogenesis of some Ligurian peridotites– I. Mineral and bulk rock chemistry. Geochim. Cosmochim. Acta 43, 219–237.

Flower, M.F.J., Russo, R.M., 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.

Gageonnet, R., Lemoine, M., 1958. Contribution a la connaissance de la geologie de la province porugaise de Timor. Monograph, Portugal, Ministerio Ultramar, Est. 48.

Genrich, J.F., Bock, Y., McCaffrey, R., Calais, E., Stevens, S.W., Subarya, C., 1996. Accretion of the southern Banda Arc to the Australian plate margin determined by Global Positioning System measurements. Tectonics 15, 288–295.

Grady, A.E., 1975. A reinvestigation of thrusting in Portuguese Timor. J. Geol. Soc. Aust. 22, 223–227.

Green, D.H., 1963. Alumina content of enstatite in a Venezuelan high-temperature peridotite. Geol. Soc. Amer. Bull. 74, 1397–1402.

Grunau, H.R., 1953. Geologie von Portugiesisch Ost-Timor. Eine Kurze Ubersicht. Eclogae Geol. Helv. 46, 29–37.

Haile, N.S., Barber, A.J., Carter, D.J., 1979. Mesozoic cherts on crystalline schists in Sulawesi and Timor. Geol. Soc. Lond. 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. Geol. Surv. Prof. Pap. 1078.

Harris, R.A., 1991. Temporal distribution of strain in the active Banda orogen: a reconciliation of rival hypotheses. J.S.E. Asian Earth Sci. 6, 373–386.

Harris, R.A., 1992. Peri-collisional extension and the formation of Oman-type ophiolites in the Banda Arc and Brooks Range. In: Parson, L.M., Murton, B.J., Browning (Eds.), Ophiolites and their Modern Oceanic Analogues. Geol. Soc. London, Spec. Publ., vol. 60, pp. 301–325.

Harris, R.A., 2004. Geodynamic patterns of ophiolites and marginal basins of the Indonesian and New Guinea regions. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolite in Earth History. Geol. Soc. London, Spec. Publ., vol. 218, pp. 481–505.

Harris, R.A., Long, T., 2000. The Timor ophiolite, Indonesia: model or myth? In: Dilek, Y., Moores, E.M., Elthon, D., Nicolas, A. (Eds.), Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program. Geol. Soc. Am., Spec. Pap., vol. 349, pp. 321–330.

Harris, R.A., Stone, D.B., Turner, D.L., 1987. Tectonic implications of paleomagnetic and geochronologic data from the Yukon–Koyukuk basin, Alaska. Geol. Soc. Amer. Bull. 99, 362–375.

Harris, R.A., Sawyer, R.K., Audley-Charles, M.G., 1998. Collisional melange development: geologic associations of active melange-forming processes with exhumed melange facies in the western Banda orogen: Indonesia. Tectonics 17, 458–480.

Harris, R.A., Kaiser, J., Hurford, A.J., Carter, A., 2000. Thermal history of Australian passive margin sequences accreted to Timor during Late Neogene arc–continent collision, Indonesia. J. Asian Earth Sci. 18, 47–69.

Hawkins, J.W., Melchoir, J.T., 1985. Petrology of Mariana Trough and Lau Basin basalts. J. Geophys. Res. 90, 11431–11468.

Hawkins, J.W., Bloomer, S.H., Evans, C.A., Melchoir, J.T., 1984. Evolution of intra-oceanic arc–trench systems. Tectonophysics 102, 175–205.

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.

Honthaas, C., Rehault, J., Maury, R., Bellon, H., Hemond, C., Malod, J.A., Cornee, J.J., 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). Tectonophysics 298, 297–317.

Ishikawa, A., Kaneko, Y., Kadarusman, A., Ohta, T., in press-a. Fore-arc origin of Late Miocene ophiolite in Timor–Tanimbar region, Eastern Indonesia, In: Santosh M., and Maruyama S. (editors), Island Arcs Past and Present. Gondwana Res.

Ishikawa, M., Kaneko, Y., Kadarusman, A., in press-b. Structural constrains on the exhumation of metamorphic rocks in Timor, Eastern Indonesia, In: Santosh M., and Maruyama S. (editors), Island Arcs Past and Present. Gondwana Res.

Kadarusman, A., Kaneko, Y., Ohta, T., Parkinson, C.D., in press. Petrology and *P–T* conditions of the world's youngest high-pressure schists from Leti, eastern Indonesia. In: Santosh M., and Maruyama S. (editors), Island Arcs Past and Present. Gondwana Res.

Kaneko, Y., Maruyama, S., Kadarusman, A., Ota, T., Ishikawa, M., Tsujimori, T., Ishikawa, A. and Okamoto, K., in press. On-going orogeny in the outer arc of Timor–Tanimbar region, eastern Indonesia, In: Santosh M., and Maruyama S. (editors), Island Arcs Past and Present. Gondwana Res.

Kenyon, C.S., 1974. Stratigraphy and sedimentology of the late Miocene to Quaternary deposits of Timor. PhD. Dissertation, Univ. London.

Lapouille, A., Haryono, H., Larue, M., Pramumijoyo, S., Lardy, M., 1986. Age and origin of the seafloor of the Banda Sea (Eastern Indonesia). Oceanol. Acta 8, 379–389.

Lemoine, M., 1959. Un example de tectonique chaotique — Timor. Rev. Geogr. Phys. Geol. Dyn. 2, 205–230.

Leme, J.C. De Azerado, Coelho, A.V.P., 1962. Geologia do Enclave de Oecusse (Provincia de Timor). Garcia de Orta 10, 553–566.

Lunt, P., 2003. Biogeography of some Eocene larger Foraminifera, and their application in distinguishing geological plates. Palaeontol. Electronica 6, 2.

Lytwyn, J., Rutherford, E., Burke, K., Xia, C., 2001. The Geochemistry of volcanic, plutonic, and turbiditic rocks from Sumba, Indonesia. J. Asian Earth Sci. 19, 481–500.

Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. Tectonics 5, 227–245.

Marks, P., 1961. The succession of nappes in the western Miomoffo area of the island of Timor: a possible key to the structure of Timor. Proc. Of Pac. Sci. Cong., vol. 12, pp. 306–310.

McCabe, R., Harder, S., Cole, J.T., Lumadyo, 1993. The use of palaeomagnetic studies in understanding the complex tertiary tectonic history of east and southeast Asia. J.S.E. Asian Earth Sci. 8, 257–268.

Merritts, D., Eby, R., Harris, R.A., Edwards, R.L., Cheng, H., 1998. Variable rates of Late Quaternary surface uplift along the Banda Arc–Australian Plate collision zone, eastern Indonesia. In: Stewart, I.S., et al. (Ed.), Coastal Tectonics. Geol. Soc. London, vol. 146, pp. 213–224.

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

Molengraaff, G.A.F., 1912. On recent crustal movements in the Island of Timor and.their bearing on the geological history of the East Indian Archipelago. Proc. Koninkijke Nederlandse Akademie van Wetenschappen: Amsterdam Special Sci., vol. 15, pp. 224–235.

Molengraff, G.A.F., 1914. De Fatoes can Timor. Versl. Geol. Sectie Geol. Mijnb. Genootschap 1.

Molnar, P., Atwater, T., 1978. Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere. Earth Planet. Sci. Lett. 41, 330–340.

Nugroho, H., 2005, GPS Velocity Field in the transition from subduction to collision of the Eastern Sunda and Banda Arcs, Indonesia. Unpub. MSc. Thesis, Brigham Young Univ.

Okino, K., Kasuga, S., Ohara, Y., 1998. A new scenario of the Parece Vela Basin genesis. Mar. Geophys. Res. 20, 21–40.

Parkinson, C., 1998. Emplacement of the East Sulawesi Ophiolite: evidence from subophiolite metamorphic rocks. J. Asian Earth Sci. 16, 13–28.

Polve, M., Maury, R.C., Bellon, H., Rangin, C., Priadi, B., Yuwono, S., Juron, J.L., Soeria-Atmadja, R., 1997. Magmatic evolution of Sulawesi (Indonesia): constraints on the Cenozoic geodynamic history of the Sundland active margin. Tectonophysics 272, 69–72.

Prasetyadi, C., Harris, R.A., 1996. Hinterland structure of the active Banda arc–continent collison, Indonesia: constraints from the Aileu Complex of East Timor. Proc. 25th Conv. Indonesian Assoc. Geol. , pp. 144–173.

Prasetyo, H., 1994. The tectonics of the "Sunda–Banda" forearc transition zone, eastern Indonesia. Bull. Mar. Geol. Inst. Indones. 1, 23–47.

Reed, D.L., Silver, E.A., Prasetyo, H., Meyer, A.W., 1986. Deformation and sedimentation along a developing terrane suture: Eastern Sunda forearc, Indonesia. Geology 14, 977–1092.

Reed, T.A., de Smet, M.E.M., Harahap, B.H., Sjapawi, A., 1996. Structural and depositional history of East Timor. Proc. Indonesian Petrol. Assoc. Ann. Conv., vol. 25, pp. 297–312.

Richardson, A. N., 1994. Lithospheric structure and dynamics of the Banda Arc, eastern Indonesia [PhD thesis] Univ. of London.

Roosmawati, N., 2005. Long-Term Surface Uplift History of the Active Banda Arc–Continent Collision. Depth and Age Analysis of Foraminifera from Rote and Savu Islands, Indonesia. Unpub. MSc. Thesis, Brigham Young Univ.

Rosidi, H.M.O., Suwitopiroyo, K., Tjokrosapoetro, S., 1979. Geological map Kupang–Atambua Quadrangle, Timor 1:250,000: Geological Research Centre, Bandung, Indonesia.

Royden, L.H., 1993. The tectonic expression of slab-pull at continental convergent boundaries. Tectonics 12, 303–325.

Rutten, L.M.R., 1927. Voordrachten over de Geologie van Nederlandsch Oost-Indie. J.B. Wolters, The Hague.

Saunders, A.D., Tarney, J., 1979. The geochemistry of basalts from a back-arc spreading centre in the East Scotia Sea. Geochim. Cosmochim. Acta 43, 555–572.

Schellart, W.P., Lister, G.S., 2004. Tectonic models for the formation of arc-shaped convergent zones and back arc basins. Geol. Soc. Am., Spec. Pap. 283, 237–258.

Schellart, W.P., Lister, G.S., Jessell, M.W., 2002. Analogue modeling of back-arc extension. J. Virtual Explor. 7, 25–42 (on line).

Searle, M.P., 1999. Tectonic setting, origin, and obduction of the Oman Ophiolite. Geol. Soc. Amer. Bull. 111, 104–122.

Silver, E.A., Reed, D., 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.

Silver, E.A., Gill, J.B., Schwartz, D., Prasetyo, H., Duncan, R.A., 1985. Evidence of submerged and displaced borderland, north Banda Sea, Indonesia. Geology 13, 687–691.

Snyder, D.B., Prasetyo, H., Blundell, D.J., Pigram, C.J., Barber, A.J., Richardson, A., Tjokosaproetro, S., 1996. A dual doubly-vergent orogen in the Banda Arc continent–arc collision zone as observed on deep seismic reflection profiles. Tectonics 15, 34–53.

Soeria-Atmadja, R., Suparka, S., Abdullah, C., Noeradi, D., Sutano, 1998. Magmatism in western Indonesia. J. Asian Earth Sci. 16, 1–12.

Sopaheluwakan, J., 1990. Ophiolite Obduction in the Mutis Complex, Timor, Eastern Indonesia: An Example of Inverted, Isobaric, Medium-High Pressure metamorphism. [PhD Thesis]: Amsterdam, Free University.

Sopaheluwakan, J., Helmers, H., Tjokrosapoetro, S., Surya Nila, E., 1989. Medium pressure metamorphism with inverted thermal gradient associated with ophiolite nappe emplacement in Timor. Neth. J. Sea Res. 24, 333–343.

Standley, C.E., Harris, R.A., in press. Tectonic evolution of the Lolotoi Complex of East Timor: Active accretion of an Asian forearc terrane to the NW Australian continental margin. Gondwana Res.

Stern, R.J., Bloomer, S.H., 1992. Subduction zone infancy: examples from the Eocene Izu–Bonin–Mariana and Jurassic California arcs. Geol. Soc. Amer. Bull. 104, 1621–1636.

T'Hoen, C.W.A.P., Van Es, L.J.C., 1926. The exploration for minerals in the island of Timor. Jaarb. Mijn. Ned. Indie. 2, 1–80.

Tappenbeck, D., 1939. Geologiedes Mollogebirges und Einiger Benachbanen Gebiete (Niederlandisch Timor). [PhD Thesis], Amsterdam.

van Bemmelen, R.W., 1949. The Geology of Indonesia. General Geology of Indonesia and Adjacent Archipelgoes. Spec. Ed. Indonesia Bur. Mines, Batavia.

van Leeuwen, T.M., 1981. The geology of Southwest Sulawesi with special reference to the Biru area. Geol. Res. Centre, Indonesia Spec. Publ., vol. 2, pp. 277–304.

van Voorthuysen, J.H., 1940. Geologische Untersuchungen im distikt Amfoan (Nordwest Timor). Geol. Exped. Lesser Sunda Islands, vol. 3, pp. 1–131.

van West, F.P., 1941, Geological investigations in the Miomaffo region: [PhD Thesis], Amsterdam.

Verbeek, R.D.M., 1908. Molluken Verslag. Jaarb. Mijn. Ned. Indie. 37, 826.

Villeneuve, M., Cornee, J.J., Rhault, J.P., Honthaas, C., Gunawan, W., 2000. Tectonostratigraphy of the east Indonesian blocks. Am. Assoc. Pet. Geol. Bull. 84, 1511.

Von der Borch, C.C., Grady, A.E., Hardjoprawiro, S., Prasetyo, H., Hadiwisastra, S., 1983. Mesozoic and late Tertiary submarine fan sequences and their tectonic significance, Sumba, Indonesia. Sediment. Geol. 37, 113–132.

Vorkink, M., 2004. Incipient Tectonic Development of the Active Banda Arc–Continent Collision: Geologic and Kinematic Evolution of Savu Island. Unpub. MSc. Thesis, Brigham Young Univ.

Wanner, J., 1913. Geologie von West Timor. Geol. Rundsch. 4, 136–150.

Wakita, K., Munsari, Sopaheluwaken, J., Iskandar, Z., Miyazaki, K., 1994. Early Cretaceous tectonic events implied in the time-lag between the age of radiolarian chert and its metamorphic basement in the Banimala Complex area, South Sulawesi, Indonesia. Isl. Arc 3, 90–102.

Wensink, H., van Bergen, M.J., 1995. The tectonic emplacement of Sumba in the Sunda–Banda Arc: paleomagnetic and geochemical evidence from the Early Miocene Jawila volcanics. Tectonophysics 250, 15–30.

Wijbrans, J.R., Helmers, H., Sopaheluwakan, J., 1994. The age and thermal evolution of blueschists from South-East Sulawesi, Indonesia: the case of slowly cooled phengites. Mineral. Mag. 58A, 975–976.

Wilson, M.E.J., Bosence, D.W.J., 1996. The Tertiary evolution of South Sulawesi: a record in redeposited carbonates of the Tonasa Limestone Formation. Tectonic Evolution of Southeast Asia. Geol. Soc. London, Spec. Publ., vol. 106, pp. 365–389.

Ron Harris is a Professor of Tectonic Processes in the Department of Geological Sciences at Brigham Young University, Utah, USA. He is an Associate Editor of the Bulletin of the Geological Society of America. He has also worked for Oil and Mining companies, and the USGS. After graduating with a BSc from the University of Oregon, he completed a MSc from the Geophysical Institute of Alaska, and a PhD from University College London (1989), where he joined the SE Asian Research Group. He became an Associate Professor of Structural Geology at West Virginia Univeristy (1989–1998). He was awarded a Fulbright Research Fellowship to investigate seismic hazards in Indonesia, which led to the publication in 1997 of warnings about the countries vulnerability to large earthquakes and tsunami. He has conducted research in Indonesia for 20 years. The focus of his research is mostly on active mountain building processes and geological hazards. Harris has also investigated the geological evolution of mountain building processes in Alaska, Oman, Cyprus, East Timor and many parts of the North American Cordillera.