Protolith origin and plate tectonic setting of metamorphic complexes in the Timor fold and thrust belt, Indonesia

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Geologically, Eastern Indonesia is a 180o orocline created by the dynamic interaction of three opposing tectonic plates. Additional complexity resulted from the sporadic breakup of Gondwana that fragmented the northern margin of New Guinea-Australia (NGA) and caused crustal blocks to collide with SE Asia before the Pliocene arc-continent collision with Australia. One consequence is that protoliths of two distinct metamorphic associations on Timor have mixed Gondwanan and SE Asian affinities. This article presents a reclassification of the metamorphic rocks of Timor that links their formation and radiometric ages to tectonic provenance and key events that occurred as NeoTethys was consumed by subduction. Four periods of metamorphism are recognised, plus radiometric dating evidence of peak and cooling P-T conditions and the tectonic settings that caused metamorphism and deformation of different complexes on the island. Key conclusions are: [1] a basement complex accreted to the Sunda margin from Gondwana in the Cretaceous. [2] Oceanic crust and pelagic sediment of Jurassic to Early Cretaceous age form a tectono-metamorphic complex comprised of volcanic greenstones, greenschists, mn-rich sediments, and radiolarian cherts metamorphosed in the pre-collision Sunda forearc. [3] Eocene back arc spreading led to injection of gabbro and peridotite, and a metamorphic episode that peaked at 45Ma. [4] The metamorphosed Permo-Triassic Aileu Complex originated on Gondwana but includes Sunda upper plate peridotite that became attached during subduction and extrusion at the close of the Miocene.

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Protolith origin and Plate Tectonic Setting of Metamorphic Complexes in the Timor Fold and Thrust Belt, Indonesia

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Key Points:

- Metamorphic complexes with four different origins are found on Timor island.
- Basement schists accreted to SE Asia following Jurassic rifting of Gondwana, and are overlain by metamorphosed Cretaceous forearc deposits.
- Pliocene arc-continent collision exhumed subducted P/Tr Australian sediments, then obducted a forearc ophiolite and its metamorphic sole.

Abstract

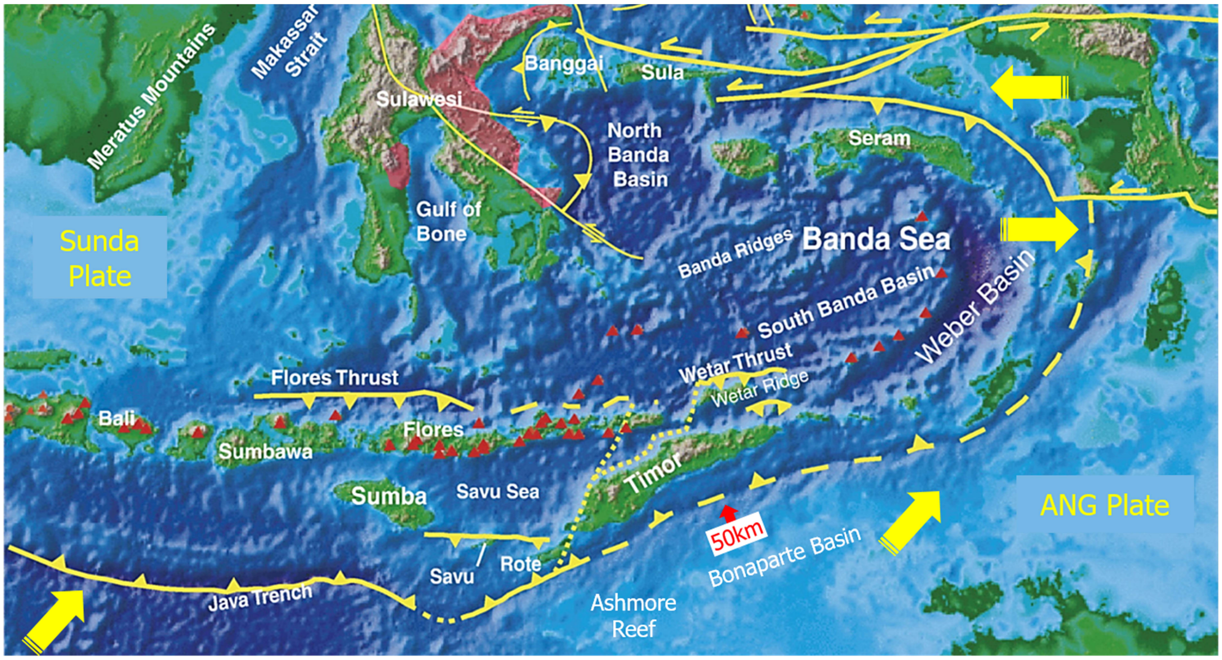
Geologically, Eastern Indonesia is a 180^o orocline created by the dynamic interaction of three opposing tectonic plates. Additional complexity resulted from the sporadic breakup of Gondwana that fragmented the northern margin of New Guinea-Australia (NGA) and caused crustal blocks to collide with SE Asia before the Pliocene arc-continent collision with Australia. One consequence is that protoliths of two distinct metamorphic associations on Timor have mixed Gondwanan and SE Asian affinities. This article presents a reclassification of the metamorphic rocks of Timor that links their formation and radiometric ages to tectonic provenance and key events that occurred as NeoTethys was consumed by subduction. Four periods of metamorphism are recognised, plus radiometric dating evidence of peak and cooing P-T conditions and the tectonic settings that caused metamorphism and deformation of different complexes on the island. Key conclusions are: [1] a basement complex accreted to the Sunda margin from Gondwana in the Cretaceous. [2] Oceanic crust and pelagic sediment of Jurassic to Early Cretaceous age form a tectono-metamorphic complex comprised of volcanic greenstones, greenschists, mn-rich sediments, and radiolarian cherts metamorphosed in the pre-collision Sunda forearc. [3] Eocene back arc spreading led to injection of gabbro and peridotite, and a metamorphic episode that peaked at 45Ma. [4] The metamorphic Permo-Triassic Aileu Complex originated on Gondwana but includes Sunda upper plate peridotite that became attached during subduction and extrusion at the close of the Miocene.

Keywords: Timor, metamorphism, forearc, Gondwana, subduction

1 Introduction

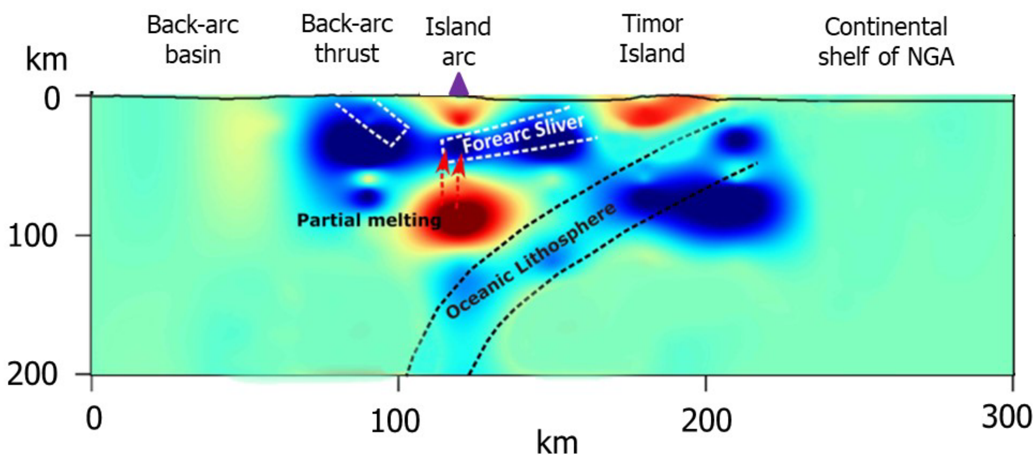
A Cainozoic orogenic belt comprised of Australian continental margin deposits and allochthonous units emplaced from the overriding Sunda plate is exposed on Timor, the largest island of the non-volcanic outer Banda arc, Eastern Indonesia (Fig. 1). The tectonic front is the southern limit of the foreland fold and thrust belt, and is situated in the Timor Trough, whereas the position of the subduction suture lies between Timor and the inner arc (Audley-Charles, 2004).

Figure 1. Map of the Principal Tectonic Elements of Eastern Indonesia. Yellow arrows indicate the direction of plate motion.



Aided by major strike-slip faults, segments of Australian crust encroached on the inner arc and caused volcanism to cease at about 3Ma, for example on Atauro Island (Ely et al., 2011). Magmas in the inactive zone contain a geochemical contribution from subducted continental crust of presumed Australian origin (Elburg et al., 2005), which alternatively could have been derived from the forearc crust supporting the arc (Figure 2). As first recognised from geodetic measurements made nearly 30 years ago (Genrich et al., 1996), continent-arc collision led to plate reorganization by way of strain partitioning and the development of backthrusts north of the now inactive volcanic islands, notably Wetar. This resulted in much-reduced movement along the Timor Trough, the tectonic front (Nugroho et al., 2009; Koulali et al., 2016). Convergence of the plates is oblique and presently causing a degree of dextral strike-slip movement and mantle flow eastwards (Zhang et al., 2022; Harris and Miller, 2022).

Figure 2. 3D Seismic P-Wave model across Timor. After Supendi et al (2020).



Dynamic metamorphism results from subduction or extension at plate margins and therefore such rocks hold vital evidence for understanding regional tectonic histories and orogenesis. On Timor, metamorphic rocks outcrop as numerous isolated and elevated massifs (klippe) strung along the length of the island, including Mt Mutis, at 2,427m one of the highest peaks on the island. But far from being a homogenous group of rocks with similar genesis and development, several complexes with different origins and histories can be identified.

Geologists working from about 1910 through the 1950s named the unfossiliferous metamorphic rocks “crystalline schists” and assigned a pre-Permian age on the assumption that the metamorphism was older than the richly fossiliferous Permian rocks that are widespread on Timor. They identified a high-grade series and a low-grade series, a distinction that Barber and Audley-Charles (1976) maintained, but who suggested that the highest-grade rocks could be Precambrian continental basement of SE Asian origin. Conversely, on the north side of Timor Leste lies an extensive area of metamorphosed volcanics, clastics, and limestones termed the Aileu Complex, which is of Carboniferous to Triassic age but which U-Th-Pb dating of monazite indicates a metamorphic peak at ~5Ma (Berry et al., 2016).

Research during the past 50 years has added much new information about regional tectonics and the metamorphic rocks of Timor. Audley-Charles, Barber and fellow researchers in the SEARG team at Royal Holloway in London, and Harris and his students at Brigham Young University have made many insightful and seminal contributions. That said, major uncertainties, different interpretations, and gaps in knowledge remain and are examined herein.

2 Materials and Methods

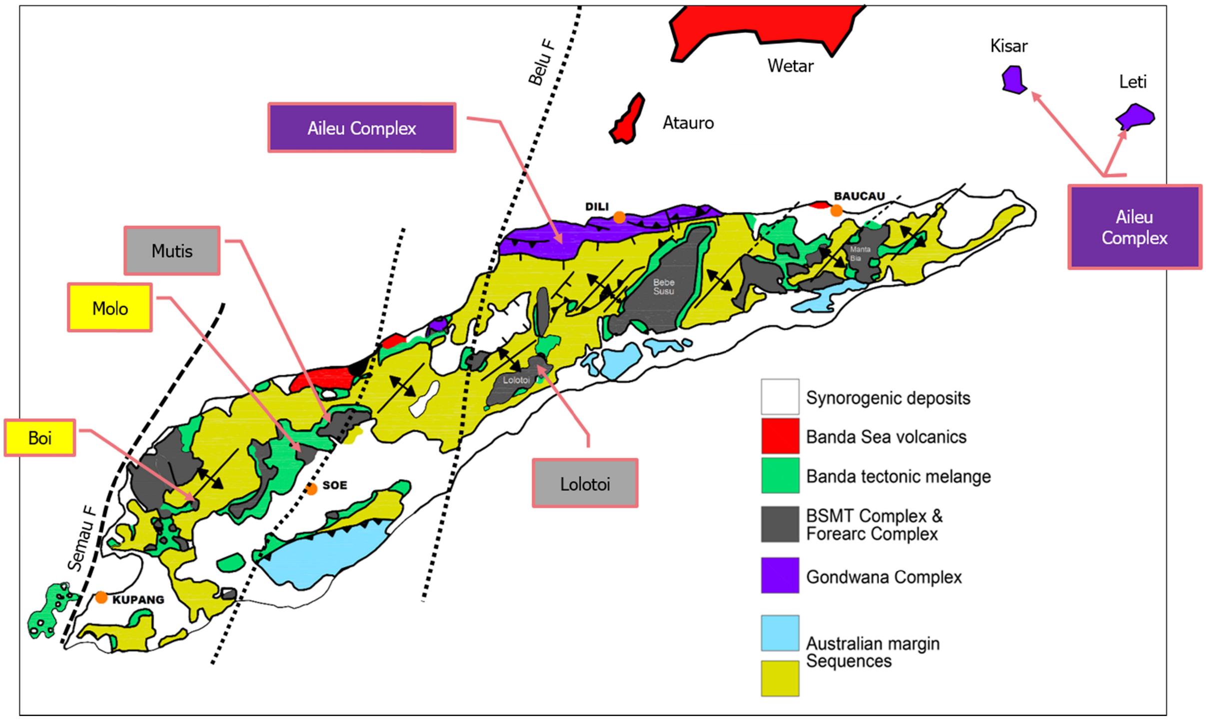
This article arises from the authors' research on Timor, which included fieldwork, mapping, and laboratory analysis, updated and supplemented by a wide-ranging review of more-recent literature on the subject as referenced in sections 3 and 4.

3 Metamorphic Complexes

3.1 Basement Complex (M1)

Thought to have been emplaced as a single thrust sheet, the unfossiliferous "crystalline schists" are named the Mutis Complex in West Timor and the Lolotoi Complex in Timor Leste (Fig. 3). One common feature of the scattered klippe is the field and petrographic evidence of mylonitization and widespread retrogression of amphibolite facies assemblages under greenschist facies conditions. As noted by Earle (1981b), rocks that display higher grade conditions are generally the least deformed and retrogressed, with retrogression particularly prevalent toward the base of some massifs and creating the impression of inverted metamorphic zonation. In the Molo, Mutis, Usu, and Lolotoi massifs, preserved metamorphic conditions peaked in the high amphibolite facies, with rare kyanite as the Al_2SiO_5 polymorph index mineral in metapelites. Perhaps unique to the Boi massif, a pelitic gneiss with relics of an early garnet+/-staurolite+/-kyanite assemblage also occurs as enclaves in a metagabbroic body and feature a lower-pressure sillimanite+cordierite+spinel overprint that crystallized during exhumation from a depth of 30-35km to 20-15km (Brown and Earle, 1983). This paragenesis is transitional to the granulite facies (de Waard, 1966) and therefore the highest grade of metamorphism recorded from Timor.

Figure 3. Distribution of the Metamorphic Complexes of Timor. BSMT Complex and Forearc Complex on Legend are equivalent to the Mutis-Lolotoi Complex and Palelo Group. Boi and Molo are the Authors' research areas.



A distinguishing feature of the crystalline schists is their unique association with the fossiliferous Cretaceous to Paleocene Palelo Group. Many contacts have been observed, including unconformities, and deposits throughout the Upper Palelo formations contain clasts, pebbles, and boulders of crystalline schists. This is unequivocal evidence of an early, pre-Palelo metamorphic event (M1) and a close spatial and temporal association between the two units (Barber and Audley-Charles, 1976; Haile et al., 1979; Earle, 1979). Without inference as to their exact age, the crystalline schists can be regarded as basement to the Cretaceous and younger cover sequence.

Harris (2006) presented a plot of whole rock Rb-Sr versus Sr/Sr data obtained from ten assorted metapelite samples from the Boi, Mosu, and Mutis massifs. Predictably, the data from widely separated areas of Timor show a scatter (R^2 of 0.8) of ages, no doubt due to some combination of open systems, polymetamorphism, lack of equilibrium in the assemblages, deep tropical weathering, and also to partial melting in the case of the Boi samples (Earle, 1981a). Individual samples plot in the range of 200Ma to 30Ma, supporting the concept first advanced by Earle (1979) that the crystalline schists are not Precambrian or even pre-Permian, but Jurassic to Cretaceous in age. Of significance is that the average age of 118Ma +/-40Ma is consistent with metamorphic complexes on the Sunda plate in SW Sulawesi, Central Sulawesi, SW Kalimantan, and Central Java (Parkinson et al., 1998).

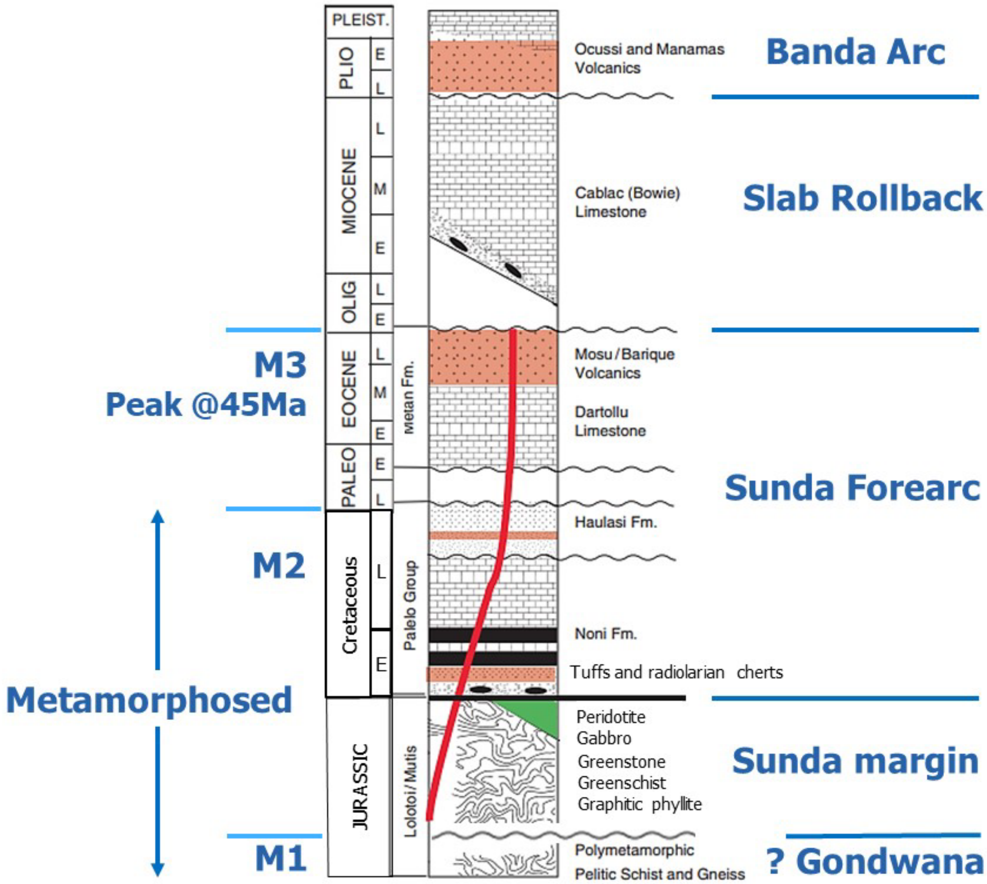
Before it was fragmented in the Cainozoic Era, a volcanic arc resting on continental crust extended west from Sulawesi to Kalimantan and Java. A metamorphic terrane lay to the south along a plate boundary with a north to northwest-dipping subduction zone generating High and Ultra-High P/T complexes including eclogite. As mentioned by many authors, the crystalline schists of Timor likely were part of that forearc-subduction terrane situated near SW Sulawesi. That said, the igneous and sedimentary protoliths could have originated on the northern margin of Gondwana, which in the Jurassic period lay on the opposite side of NeoTethys separated from the SE Asian margin by ~35^{o} of latitude (~4,000km). Between 160Ma and 155Ma, an E-W oriented spreading center rifted fragments of continental crust northwards from Gondwana, fragments that by the Turonian had accreted to the SE Asian margin. Collectively known as Argoland, the crustal blocks have been identified as SW Borneo, East Java, and SW Sulawesi (e.g. Hall, 2012). SW Borneo accreted to Sunda at ~135Ma and became incorporated into the volcanic-plutonic terrane, where Cretaceous forearc sediments experienced Low P/T Buchan-type metamorphism (Breitfeld et al., 2020). Outboard to the southeast, the accreted SW Sulawesi terrane underwent metamorphism in the subduction zone before being exhumed and imbricated with sediments in the forearc basin. A concept proposed by Barber (1979) is that the crystalline schists of Timor also rifted from Gondwana in the Jurassic and accreted to SE Asia in the Cretaceous, a model resurrected by several recent researchers, including Duffy et al. (2021) and van Gorsel (2012). Reported U/Pb ages for zircons, apatites and titanites from the Lolotoi Complex in Timor Leste are consistent with those of Gondwanan continental slivers that accreted to East Java and SW Sulawesi (Duffy et al., 2021). And a compelling proposal backed by U/Pb analysis of more than 6,000 zircon crystals is that West Burma was Argoland, whereas metamorphic complexes in south and central Sulawesi were rifted from the Bird's Head region of New Guinea (Zhang et al., 2020). Though there is no general agreement as to the precise location or locations on Gondwana, the relevant point is that the basement schists were situated on the margin of SE Asia in the Cretaceous and therefore must be an allochthonous, exotic element on Timor.

3.2 Forearc Complex (M2)

As mentioned by van West (1941), without detailed analysis, the Palelo Group in the Miomaffo massif is weakly metamorphosed and closely related to a series of low-grade rocks. Van West grouped the greenstones and greenschists with the crystalline schists because their metamorphic state can be observed in outcrop, whereas metamorphism of the Palelo Group is weak and evident only under the microscope. A similar low-grade succession outcrops on the Molo massif, where greenstones and greenschists carry mineral assemblages reminiscent of those in Chlorite Zones 2-4 of the Otago Schist belt (Earle, 1981a), a Jurassic-Cretaceous age accretionary prism metamorphosed in a forearc basin on the eastern margin of Gondwanaland (Craw and MacKenzie, 2016). A similar genesis on the margin of Sunda is thought likely for the Timor succession (Earle, 1981a).

Originally basalt, dolerite, chert, organic-rich siliceous ooze now graphitic phyllite, and manganese-rich deposits now with piemontite and spessartine garnet, this monometamorphic series ("MM Series") is a succession of non-calcareous pelagic sediments and a suite of igneous rocks with oceanic crust petrogenesis, which at the lowest grade display igneous textures and pillow structures. As if in geological continuity, if not conformity, the MM Series is succeeded by weakly metamorphosed volcanics and radiolarian cherts of the Lower Palelo (Fig 4), evidently also deposited in deep water below the carbonate compensation depth. As first recognized on Molo, the MM Series and Lower Palelo succession are metamorphosed, collectively, from Zeolite to Prehnite-Pumpellyite to Pumpellyite-Actinolite to Greenschist Facies (Earle, 1981a). Clearly, they form a single tectono-metamorphic complex, though much disturbed by imbrication and folding, and likely with gaps in the stratigraphic succession.

Figure 4. Simplified Tectono-Stratigraphic Column of the Banda Allochthon.



Field and laboratory research led Earle (1979) to propose that the Lower Palelo and MM Series are related units of Middle Jurassic to Cretaceous age. This was speculative in 1979, but abundant confirmation has since emerged from several metamorphic klippe in Timor. U/Pb zircon ages with a combined range of 177Ma to 159Ma have been obtained from basaltic greenstones and greenschists of the Bebe Susu massif (Harris, 2006) and volcanics sampled in the Fohorem area of the Lolotoi massif (Park et al., 2014). Villeneuve et al. (2013) report a K/Ar age of 157Ma from a basaltic lava flow in the Bijeli massif south of Mt Mutis, and a K/Ar age of 150Ma from a basaltic greenstone of the Lower Palelo (MM Series?).

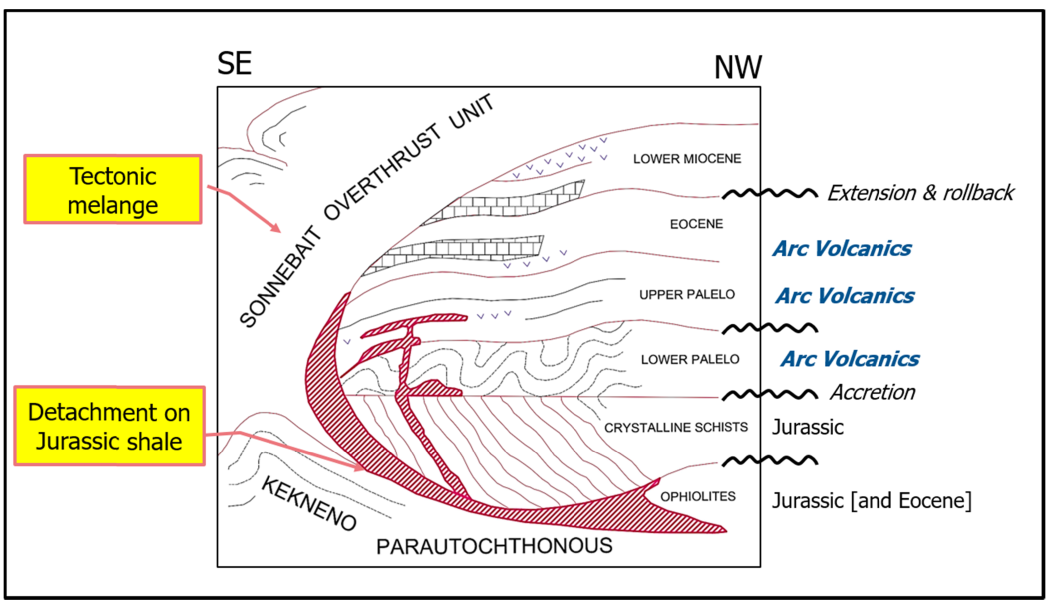
Obtaining Early to Middle Jurassic ages of the meta-igneous rocks confirms an origin as NeoTethyan oceanic crust that predated the Late Jurassic breakup of northern Gondwanaland. The frequent association of serpentinized peridotite, greenstones (spilite), and radiolarian cherts in the klippe is reminiscent of the Steinmann Trinity, an association now understood to mark emplacement during the early stages of subduction, probably as transitional crust present on a highly extended passive margin (Desmurs et al., 2001). Regarding Timor, the MM Series would have been outboard of the continental crust of Sunda before subduction started, and perhaps comprised of transitional crust with a mixture of crystalline basement blocks, oceanic crust, and mantle elements, which became entrained in the forearc after the start of subduction in the Late Jurassic.

Purple, emerald green and chocolate-colored cherts in the Lower Palelo contain a variable mixture of tuffaceous material from the Sunda volcanic arc, and poorly preserved radiolaria which until recently were only sufficient to hint at an Early to Middle Cretaceous age. Munasri and Harsolumakso (2020), however, recovered a distinctive assemblage of Albian-Cenomanian radiolaria from cherts that outcrop in the River Noni in West Timor, dating to about 100Ma. Their work confirmed that the Lower Palelo fauna resembles that of SW Sulawesi, but contrasts with Early Cretaceous radiolaria recovered a few kilometers distant in the Kolbano area from the Nakfunu Formation of Timor, a formation associated with the Australian plate and originally situated on the Gondwana side of NeoTethys. This is further evidence that the Lower Palelo, MM Series, and basement schists of Timor were part of SE Asia in the Cretaceous period. Lower Palelo cherts and the overlying Aptian to Turonian limestones of the Paleo Group Noni Formation are faulted and in places intensely folded, and succeeded by a sequence of less disturbed flysch deposits with interbedded arc volcanics of the Late Cretaceous to Paleocene Upper Palelo. Its deposition confirms the presence of a continental hinterland to the north. As in New Zealand, rapid burial, tectonic thickening of the pile, and depressed isotherms in the forearc wedge more likely explain the low grade metamorphism (M2) of the cover sequence, rather than deep subduction.

Dutch expeditions noted the similarity between their Crystalline Schists-Palelo Series association of Timor and the Bantimala Complex of SW Sulawesi, a correlation more recently described by Haile et al. (1979) and by Earle (1983), who included the Meratus Complex of SE Kalimantan in the comparison. The Bantimala Complex contains blueschists and amphibolites, as well as serpentinized peridotites and “unmetamorphosed” pelagic sediments such as radiolarian chert and turbidites (Wakita et al., 1994). Dating of muscovite in the metasediments gives K-Ar cooling ages of between 130Ma and 120Ma (Bohnke et al., 2019), with the younger ages close to overlapping with the faunal range of the cherts, probably an indication of rapid recycling in the forearc. A distinctive fauna of radiolaria recovered from the cherts confirms the Late Aptian to Early Cenomanian age of the strata to be approximately 100Ma, as on Timor. Matthews et al. (2012) document a global plate reorganization between 105Ma and 100Ma, and therefore it is possible that the Lower Palelo cherts were the initial deposits in a restructured Sunda forearc.

The striking similarity between the two areas now 700km apart is a clear indication that they formed a continuous terrane on the southern edge of the Sunda plate (Haile et al., 1979, Earle, 1981a). On SW Sulawesi as on Timor, the forearc succession is completed by Eocene limestones and interbedded arc volcanics. On Timor, the entire succession from crystalline schists to the Eocene deposits was named the Mutis Overthrust Unit by de Waard (1957), see Figure 5, but is now referred to as the Banda Terrane (Audley-Charles and Harris, 1990).

Figure 5. The Banda Terrane as Imagined by de Waard (1957), with gravity sliding as an emplacement mechanism. Annotations by this Author.



3.3 Subduction Complex (M4)

3.3.1 Aileu Complex

A large area of predominantly greenschist facies rocks outcrops in the northwest part of Timor Leste up to the north coast. It is a series of quartz-rich mica schists with slates, marbles, amphibolites and bodies of intrusive gabbro collectively named the Aileu Complex. Long assigned to the Permo-Triassic on field and fossil evidence (see Charlton et al., 2002), Permian and even Carboniferous ages have been obtained recently from U-Pb dating of detrital zircons (Costa et al., 2020; Ely et al., 2013; Standley, 2007; Spencer et al., 2015). The clastic rocks that dominate the series are distal, perhaps inter-reef facies to the richly fossiliferous Permian Maubisse Formation, and the two are mapped as transitional series (Prasetyadi and Harris, 1996). Tholeiitic volcanics in the Maubisse Formation testify to a continental rift setting on the margin of Gondwana. Notably, the dominance of clastic lithologies contrasts with the predominantly mafic igneous and pelagic sediment protoliths of the MM Series and crystalline schists.

Inversion on reactivated faults embedded in the extended and formerly passive margin of Australia is the simplest explanation for the presence of the Aileu Complex on the northern limit of the Australian crust, an unfashionable interpretation first proposed by Berry and Grady (1981) and more recently by Charlton (2001). Its structural position relative to the Banda Terrane and its place of origin is much debated, however, and discussed in Section 7.

Metamorphic grade in the Aileu Complex follows a typical Barrovian succession over a distance of about 30km, from greenschist facies in the WSW to high amphibolite facies with rare fibrous sillimanite in the ENE, where two bodies of peridotite are in contact with amphibolites on the eastern edge of the complex. Whole-rock and chromite pod geochemistry of the Hili Manu Peridotite attest to an upper mantle genesis in a supra-subduction zone setting on the Sunda plate (Lay et al., 2017; Falloon et al., 2006). Consequently, the peridotite and probably the metagabbroic bodies are much younger components of the Aileu Complex, likely dating to the Miocene and related to subduction. Detailed mapping by Berry (1979) showed that the isograds and outcrops of lithological units are curved, an indication that the Dili massif might be an elongate dome with an axial plunge to the WSW. I infer from this that the main direction of higher metamorphic grade is not ENE but north, toward the leading edge of the Australian crust. Metamorphism likely was caused by subduction that was short-lived because of the buoyancy of the downgoing crust and sediment. Given that the Australian plate was moving at 7cm/yr, subduction down to about 30km would have taken only 0.5 million years.

P-T analysis of amphiboles analysed by Beery (1979) produced Tmax estimates of 650-700^{o}C at a pressure of up to 7kbar, equivalent to a depth of ~24km and an average geothermal gradient of ~27^{0}C/km. Estimates of up to 9kbar (32km) and 850^{O}C were obtained from the Aileu Complex further north, on Kisar Island (Major et al. 2011). Both estimates of temperature are much higher for the corresponding depth than expected in an active subduction zone (see Penniston-Dorland et al., 2015). Nevertheless, subduction is the only mechanism that could take a package of surficial sediments to such depths in a collision zone. That said, a source of heat is required to explain the elevated temperatures, perhaps as some have speculated emanating from the adjacent Banda volcanic arc, though heat alone does not explain the localized folding and intense deformation. Intrusion by gabbro and serpentinized peridotite and likely hydration during extension are more probable causes (see Harris 2011). The sequence of events therefore seems to have been subduction, extension with igneous intrusion, and peak metamorphism during intense deformation and exhumation. K-Ar ages obtained from muscovite crystals indicate that cooling was occurring at ~5Ma (Berry and McDougall, 1986; Major, 2011; Ely et al., 2014), a young age confirmed by more recent U-Th-Pb dating of Monazite by Berry et al. (2016), who posit that peak metamorphism occurred at ~5Ma, an event that definitely preceded the arc-continent collision, but not the initial contact between Sunda and continental sediments on the Australian plate.

Kisar is a small island north of the eastern tip of Timor and is uniquely situated between the outer and inner arcs (Fig 3), perilously close to the fossil subduction suture. The island is largely composed of metasedimentary rocks, principally psammitic but also amphibolites and metapelites such as phyllite, graphitic phyllite, graphite schist and quartzite metamorphosed up to high amphibolite facies (Major, 2011). The suite of rocks on Kisar is almost entirely mylonitized, likely caused by shear stress during extension and extrusion from the subduction zone.

3.3.2 Metamorphic Sole Complex

Outcrops of peridotite on the outer arc islands of Leti, Moa and Sermata east of Timor provide key evidence of the origin of the associated metamorphic rocks. Though casually termed "ophiolite" by some authors, the peridotite slabs occur on top of the metamorphic pile without any other component of oceanic lithosphere being present, such as gabbro, sheeted dyke complex, basalt flows or pelagic sediment. This means that the peridotites are thin slices of mantle from the overriding Sunda plate, hot mantle that welded to it subducted sediments and oceanic crust during the subduction and emergence of the NGA plate and caused a metamorphic sole only a few hundred meters thick.

As mapped during the Netherlands Timor Expedition in 1910-12, intensely folded Permian clastic sediments with thin limestone beds and basic volcanics in the south of Leti Island are metamorphosed at low grade in the center of the island and succeeded further north by high-grade amphibolites and schists (Molengraaf and Brouwer, 1915). A body of serpentinized peridotite caps the steeply-dipping metamorphic rocks near the north coast and therefore adjacent to the plate suture in the Banda Sea. This gross metamorphic zonation across Leti is reminiscent of that in the Aileu-Maubisse Series on Timor (van Gorsel, 2012) except that blueschist facies minerals crossite and glaucophane occur in the amphibolites of Leti. Evidently, there was lateral variation in the tectonic conditions of the leading edge of Australia, likely due to the oblique collision, the irregular margin and thickness of the continental crust, and to variation in subduction depth and duration. Pressure estimates of up to 10kbar (Ota and Kaneko, 2010) suggest up to 35km of overburden, which far exceeds the pressure that could be generated by even a complete ophiolite, again indicating that subduction not obduction is the tectonic environment that generated the metamorphic sole. Ota and Kaneko (2010) estimated that the peridotite is 300m thick, and this might be close to its original exhumed thickness.

Van Gorsel (2012) pointed out that the serpentinized peridotite on Leti is overlain by the unmetamorphosed Booi Limestone, which is a post-tectonic, shallow marine limestone of Oligo-Miocene age that contains reworked clasts of peridotite and metamorphic rocks. Clearly, the subduction metamorphism evident in the metamorphic complex predates the Pliocene arc-continent collision and deposition of the Miocene limestone. A single K-Ar cooling age of 11Ma obtained from phengitic mica in a pelitic schist (Kaneko et al., 2007) indicates a late Miocene timing of post-subduction uplift. At 10km wide, Leti island is too narrow to host a complete stratigraphic succession from unmetamorphosed rocks to blueschists subducted to 35km. However, and notwithstanding a major omission of section, it is possible that the “unmetamorphosed” but deformed succession in the south of the island was also subducted, but experienced ultra-low temperatures in the forbidden zone where reactions do not occur.

NGA had a passive northern margin throughout the Mesozoic, and the key to metamorphism of the Aileu Complex, M4, seems to be that sediments along sections of the margin became entrained in tectonic events earlier than the Pliocene collision between Australia and the inner Banda arc, as discussed in Section 4.

One well documented metamorphic sole is present on Timor. It outcrops along a short section of the north coast, west of the Aileu Complex. Whereas on Leti and elsewhere in the outer arc the metamorphic rocks are not associated with an ophiolite, on Timor the sole lies beneath the Ocussi Ophiolite Nappe that consists of peridotite, serpentinite and a 3km to 4km-thick section of island arc tholeiitic basalts that were part of the Banda Sea oceanic crust (Audley-Charles and Harris, 1990). Helmers et al (1989) studied the pelitic and mafic rocks beneath the peridotite at Atapupu, concluding that prograde conditions were “nearly obliterated” by subsequent mylonitisation and re-equilibration of assemblages, from initial conditions of ~7kbar and 800^{o}C down to 500^{o}C and ~4.5kbar. Evidently, as observed along the outer arc, the sole includes sea-floor sediment or crust that was subducted then welded to upper plate and exhumed during obduction. $^{40}Ar/^{39}Ar$ plateau ages of basalt in the ophiolite are 3-5Ma (Harris, 1992), dating them to the time immediately before jamming of the subduction zone.

4 Discussion

4.1 Eocene Metamorphism (M3)

Mid-Eocene to earliest Oligocene metamorphic ages on Timor were first reported by Earle (1981a). K-Ar dating of hornblende crystals analyzed on five samples of amphibolite gneiss from different localities on the Boi massif gave a tight grouping of calculated cooling ages between 37Ma and 32Ma. Hornblendes have a closing temperature of $500^{O}C$ +/-$50^{O}C$, which is higher than the pervasive greenschist facies conditions that last affected the Basement Complex. In thin section, however, the crystals of hastingsite to pargasitic hastingsite amphibole show core-to-rim differences indicative of changes due to cooling, notably the loss of a pleochroic brown tinge on beta and gamma, and a color change from brown-green to green. Additionally, greenschist facies minerals epidote, chlorite and sphene are observed caught in the process of replacing the amphibolite facies assemblage, evidence that the meta-igneous intrusions became co-metamorphic with the retrogressed schists while the entire complex was being exhumed. A further indication of M3 conditions is that in Eocene cover rocks and small intrusive dykes sampled around the Boi massif there is evidence of incipient recrystallization and the development of metamorphic minerals including chlorite, albite, white mica, clinozoisite-epidote, calcite sphene and quartz (Earle, 1981a).

The basement complex of the Boi klippe lies beneath bodies of metagabbro and serpentinized peridotite, and all lithologies were deformed together, as testified by common foliar and linear orientations. Near its base, the metagabbro is deformed into banded amphibolites, but a large volume above the base is massive and little deformed. Relic igneous textures are observed in the gabbro and peridotite, which were converted from their higher-temperature igneous assemblages directly into the high amphibolite facies at an estimated temperature of $650^{O}C$-$700^{O}C$ (Earle, 1981a). This simple, unidirectional metamorphic history and preserved relic textures contrasts with the progressive-regressive history of the poly-deformed and mylonitized basement schists, confirming the younger age of the meta-igneous units.

In the absence of blueschist facies minerals and or an inverted metamorphic zonation, the evidence on Boi points to extension, intrusion, deformation and exhumation, not subduction as the agent of the metamorphic overprint. Detachment faulting brought hot gabbro and mantle peridotite into contact with the schists, and the entire complex was stretched and flattened before variable retrogression during exhumation.

To date, Eocene ages have been reported from six other Mutis-Lolotoi complex klippe across Timor, in various rock types and minerals, using five different dating techniques (Harris, 2006; Standley, 2007; Standley and Harris, 2009; Ota and Kaneko, 2010; Costa et al., 2020; Berry et al., 2020). The oldest dates of 47Ma to 45Ma were obtained from Lu-Hf analysis of garnets in garnet mica schists sampled from the Bebe Susu and Lacluta massifs in Timor Leste, and are believed to be the age of peak metamorphism (Standley, 2007). Younger ages of 40Ma to 32Ma obtained by various methods from hornblendes and micas record cooling ages. Metamorphism was accompanied by igneous activity, as testified by a detrital zircon Lu-Hf age of 37Ma reported from volcanics of the Eocene Barique Formation (Costa et al., 2020), and a U-Pb zircon age of 35Ma obtained from a Dacite in the Mosu massif in West Timor (Harris, 2006).

This metamorphic episode was coincident with a global plate reorganization (Rona and Richardson, 1978) and the ~45Ma onset of accelerated subduction on the margin of the Sunda plate consequent on the separation of Antarctica and NGA. At this time, rifting in the Sunda forearc led to intrusive and extrusive activity that is particularly evident in the Mosu massif on Timor, an indication that the NW area of the (exposed) Banda Terrane lay closest to the Sunda arc before separation of the terrane by rifting.

Harris (2011) describes the breakup of the Great Indonesian Arc of Sundaland. It followed the collision on the margin by continental fragments that were sliced from the Birds Head region of New Guinea by the westward motion of the Pacific plate against the northward motion of the NGA continent (Milsom et al., 1999; Harris, 2006; Maulana et al., 2013; Zhang et al., 2020). Of direct significance to Timor was the formation of the Makassar Strait by back-arc rifting and sea-floor spreading between Kalimantan and West Sulawesi, which likely separated the Banda Terrane from the Sunda forearc. The separation ensured that the Banda Terrane moved away from the active volcanic arc, in contrast to the western arm of Sulawesi where granitic plutons of Cretaceous age caused arc metamorphism of the Palu Complex in the northwest of the island (van

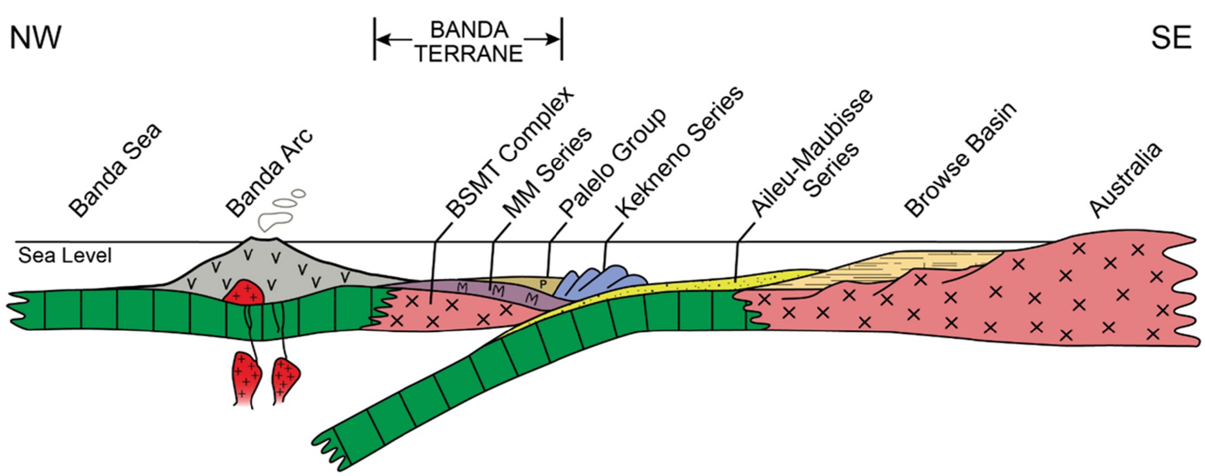
Leeuwen et al., 2016). And in North Sulawesi, Zhang et al. (2022) have linked Late Eocene to Oligocene magmatism, metamorphism beneath mantle peridotite, and initiation of subduction with the onset of accelerated northward motion of Australia that commenced at ~37Ma.

Extension, metamorphism and vulcanism in the Banda Terrane occurred before a major hiatus in the geological record that lasted until the latest Oligocene. The youngest deposits below the hiatus are shallow-water limestones and interbedded arc volcanics of the Eocene Barique Formation.

4.2 Slab Rollback

After the Oligocene depositional hiatus, slab rollback and the accompanying back-arc spreading led to further fragmentation of the continental arc and opened the Banda Sea basins, driving the Banda Terrane passively toward Australia (Fig 6). The chain of volcanic islands of the Banda arc became established in the Miocene, in part located on oceanic crust, in part on the crustal fragment carrying the mobile Banda Terrane. Several authors and groups have modelled reconstructions of the Mio-Pliocene tectonic evolution of the Banda arc and arc-continent collision, including Spakman and Hall (2010), who posited that slab rollback led to delamination of the Banda oceanic slab and separation of the crust from the denser mantle.

Figure 6. A Schematic Cross-Section of the Banda Orogen in Miocene Times.



Emplacement of the Banda Terrane thrust sheet onto the continental margin of Australia occurred along an overpressured detachment surface in Lower Jurassic shales of the autochthon, facilitated by the creation of a muddy tectonic melange named the Bobonaro Complex (Figure 5). Using the deformation as observed through the succession as an indicator, the timing of emplacement has been interpreted as Late Miocene (Wanner, 1913) or Oligocene (Tappenbeck, 1939; Villeneuve et al., 1999). Later studies across Timor using forams and apatite fission track analysis have mostly proposed a Pliocene age of the collision (see Harris, 2006), but emplacement and arc-continent collision are not the same tectonic events. Specifically, it seems that jamming or locking of the subduction system in the Pliocene was the definitive event that caused uplift of Timor island (Audley-Charles, 2011), emplacement of the Aileu Complex and Ocussi Nappe, but it was preceded by unnnderthrusting of the Banda Terrane by the incoming distal wedge of continental margin sediments. Keep and Haig (2010) correlate the locking event with deposition of lower to middle bathyal carbonates under quiescent tectonic conditions around 5Ma, which coincides with exhumation of the Aileu Complex.

A related collision occurred when the Sula Spur on the Birds Head of New Guinea encountered the Sunda margin at about 25Ma (late Oligocene). At this time, NeoTethyan oceanic crust in the Banda Embayment on the NGA plate entered the subduction zone between Sulawesi and Sumba (Hall, 2012). This could have been the trigger that initiated back-arc spreading and the separation of the Banda Terrane from the margin of Sundaland, and also have entrained old oceanic crust in the collision zone. Ely et al. (2013) are confident that the Sula Spur collision caused brief subduction and metamorphism of the Aileu Complex before it drifted across the Banda Sea to be emplaced on Timor. In Section 4.3 below I propose an alternative explanation.

4.3 Tectono-Stratigraphy

There is no consensus regarding the relative structural position of the Aileu-Maubisse Series and the Banda Terrane. Some interpretations place the Banda Terrane below a thrust sheet comprised of the Aileu-Maubisse Series (e.g. Barber, 1979), other authors reverse the order (e.g. Harris, 2006). As is often the case with polarized arguments, however, the answer could be that both interpretations are partially correct at a regional scale. Owing to back-arc spreading in the Banda Sea, the Banda Terrane was emplaced over unmetamorphosed autochthonous Australian deposits that included the Aileu-Maubisse Series. But with continued convergence and compressive stress, the distal and subducted margin of the continent was thrust back over the crystalline schists as the continent plowed onward and foreshortened the arc-trench gap. The Aileu-Maubisse Series is therefore probably both beneath and above the Banda Terrane, which explains how the Gondwana Aileu Complex became the most northerly complex of metamorphic rocks with the youngest cooling ages.

On smaller islands to the east of Timor, notably Kai, Kisar, Leti and Moa, the metamorphic rocks clearly belong to the Aileu Complex and were subducted, extruded and cooled before the Pliocene arc-continent collision. Notably. this Complex has a substantial regional extent, with a SW-NE breadth greater than 500km between Timor and Tanimbar-Lailobar, whereas it is only about 50km wide (NW-SE). An object with such dimensions is more likely to be the inverted margin of the continent to which it is parallel, and not a string-like sliver of crust that rifted from Sunda or the Sulu Spur and drifted for hundreds of kilometers across the Banda Sea to be a veneer on the margin of Australia.

A further relevant observation is that the stratigraphy of the Aileu-Maubisse Series could extend into the Jurassic (Brunnschweiler, 1978), not coincidentally also the youngest age of the Australian autochthon and the stratigraphic position of the regional detachment. Younger deposits of the Australian shelf are stacked in the Kolbano imbricate wedge behind the tectonic front (trench), but where is the equivalent succession above the P/Tr Aileu-Maubisse Series? Could it be that the “missing” section is also within the present-day imbricate wedge (see Charlton et al., 1991), and that the decapitated succession continued to underthrust the Banda Terrane and became subducted until being exhumed by inversion in the Late Miocene-Pliocene?

5 Conclusions

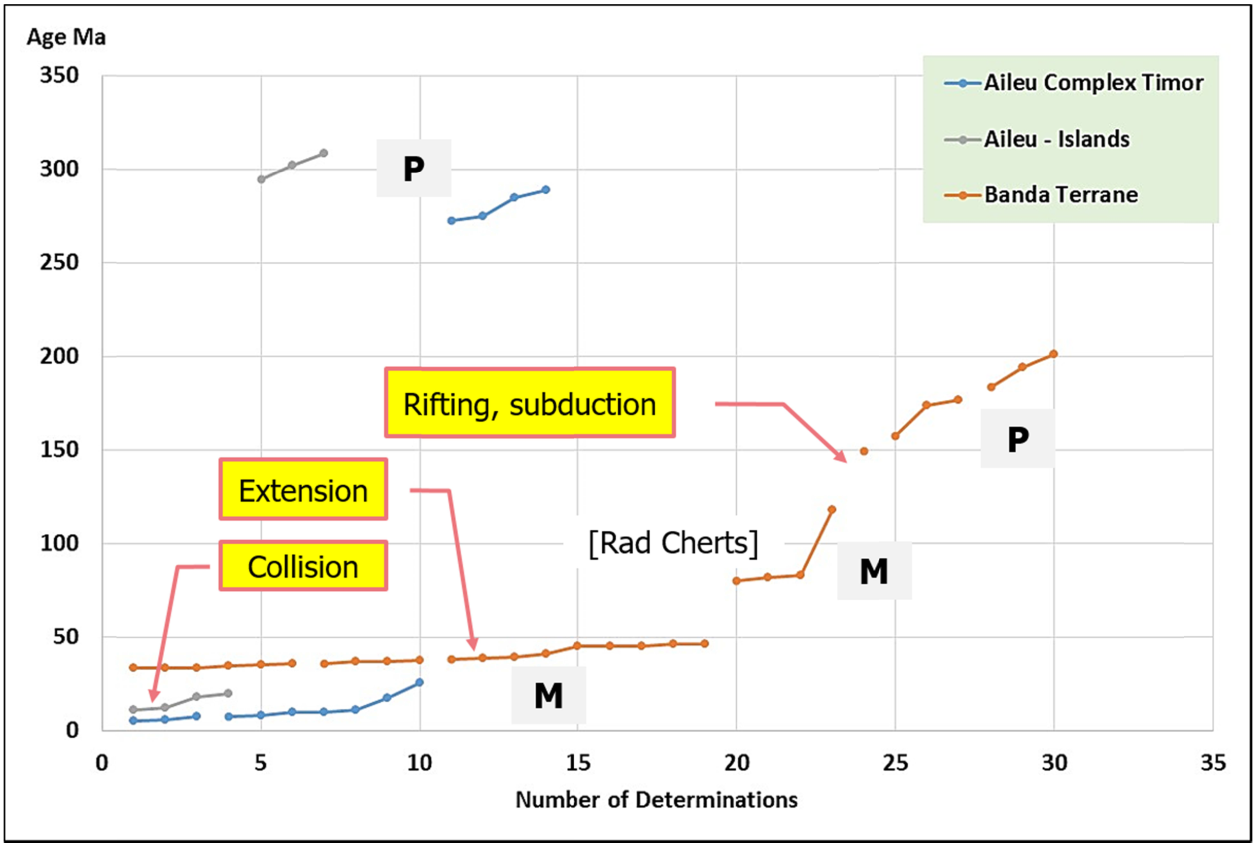
Following several earlier extensional events on the northwest Australian margin (Gartrell et al., 2022), between 160Ma and 155Ma at a peak of global extension (Muller et al., 2019), Argoland and probably other fragments of continental crust separated from the northern margin of NGA. The formation of new oceanic crust was preceded by a rift phase with attendant igneous activity and exhumation of the basement and perhaps subcontinental mantle peridotite. Extension and rifting were accommodated on the margin of Sundaland by subduction and capture of the NeoTethyan oceanic lithosphere and pelagic sediment behind the subduction trench, protoliths of the MM Series. Albian radiolarian cherts were among the earliest sediments of a shallowing upward succession of forearc deposits laid down on the MM Series and basement.

The Late Cretaceous to Paleocene Upper Palelo contains abundant andesitic volcanics interbedded with coarse flysch deposits derived from an emergent hinterland, probably near Kalimantan. Sedimentation supplemented by imbrication and folding filled the forearc basin, seemingly sufficient to give rise to burial metamorphism, M2. At 45Ma, the onset of rapid subduction seems to have triggered rifting between Kalimantan and West Sulawesi, attended by the intrusion of peridotite and gabbro. Eocene rifting of the Sunda forearc was the likely cause of peak (M3) metamorphism in the Banda Terrane.

Subduction occurred on a wide front of the continental margin of NGA, including the Aileu-Maubisse Series now outcropping on the north coast of Timor and on islands to the east, principally as metamorphic soles to the Sunda mantle. The Banda Terrane on the upper plate was driven toward and underthrust by the continental margin of Australia, but the process subsequently jammed, ejecting the Aileu Complex from the subduction zone, and it was emplaced over the Banda Terrane along the northern margin of Timor Leste.

A compilation of radiometric dates from the Outer Banda Arc shown in Figure 7 reveals a clear difference between the Aileu Complex and the Banda Terrane succession, and confirms the Jurassic-Cretaceous age of the metamorphic complexes and their Palelo Group cover.

Figure 7. A Plot of Radiometric Ages from the Outer Banda Arc. P is protolith. M is metamorphism. Data compiled from referenced sources.



Metamorphic rocks on Timor group into four distinct complexes. [1] Polymetamorphic crystalline basement schists and gneisses of Jurassic protolith age and possible Gondwana origin. [2] A low-grade monometamorphic series of Jurassic to Cretaceous or Paleocene age formed in the forearc of the Sunda margin. [3] Permo-Carboniferous sediments of NGA that were subducted on the distal margin of Australia in the Miocene, and thrust back over the continent with peridotite from the upper plate. [4] A metamorphic sole beneath an ophiolite of young oceanic crust from the Sunda margin. This classification solves some of the problematic issues of Timor, but requires more research to test, validate, modify or reject the concepts.

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Figure 1.

Figure 1. Map of the Principal Tectonic Elements of Eastern Indonesia. Yellow arrows indicate the direction of plate motion.

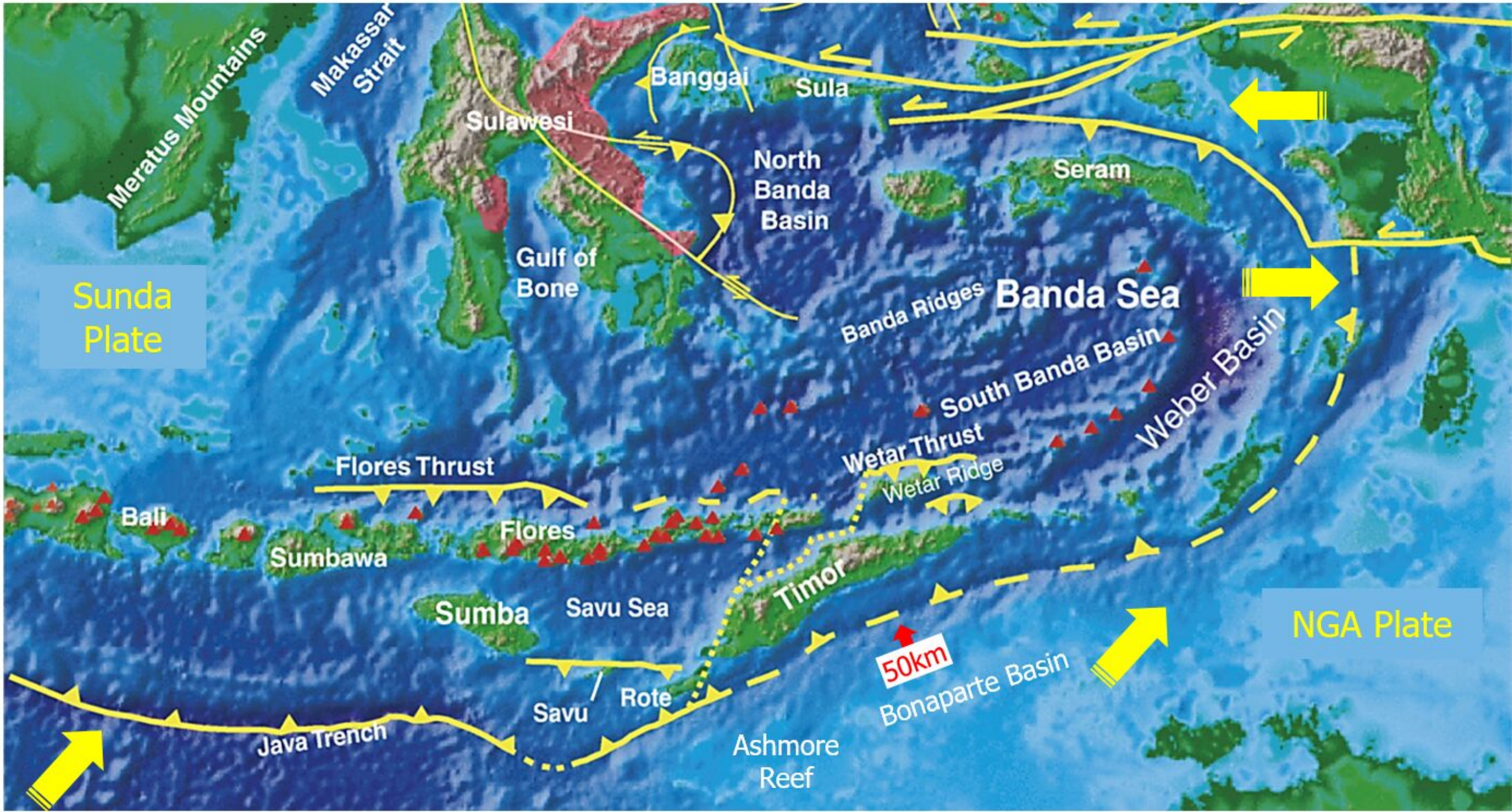


Figure 2.

Figure 2. 3D Seismic P-Wave model across Timor. After Supendi et al (2020).

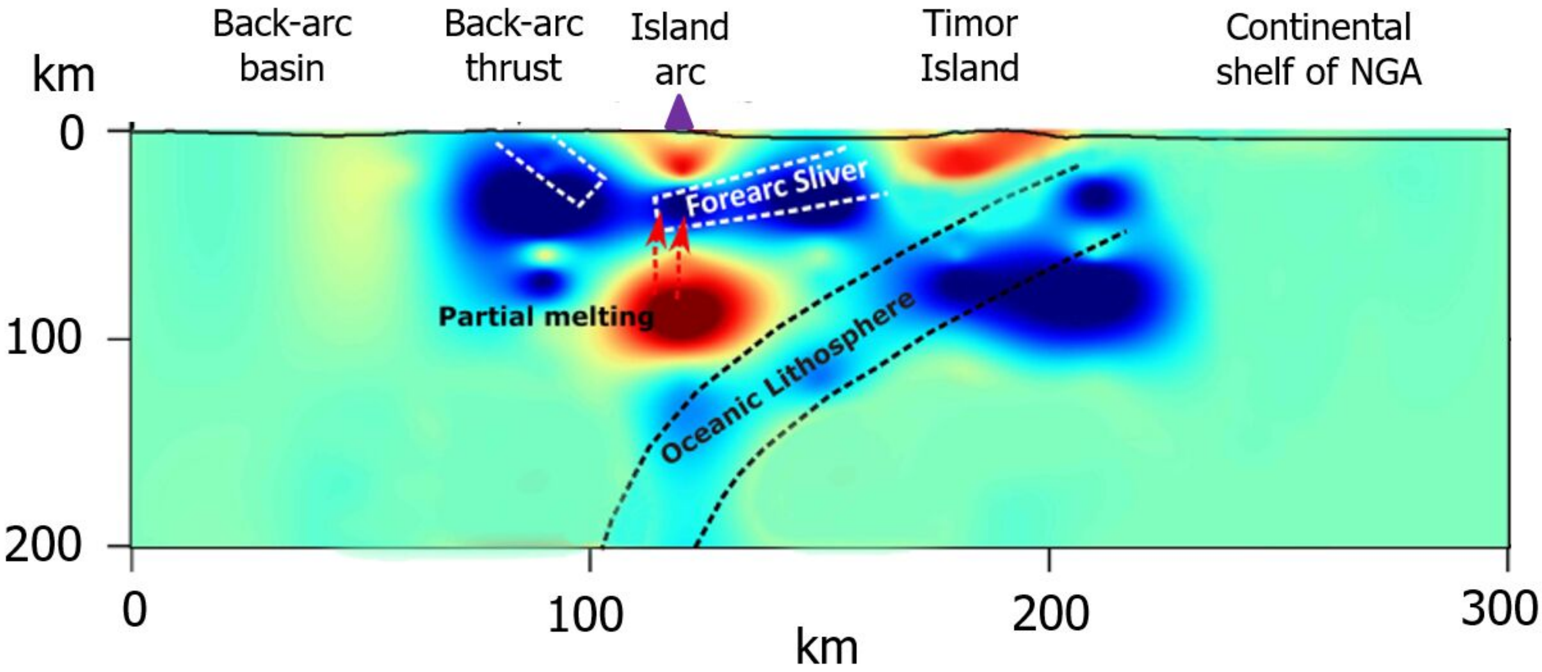


Figure 7.

Figure 7. A Plot of Radiometric Ages from the Outer Banda Arc. P is protolith. M is metamorphism. Data compiled from referenced sources.

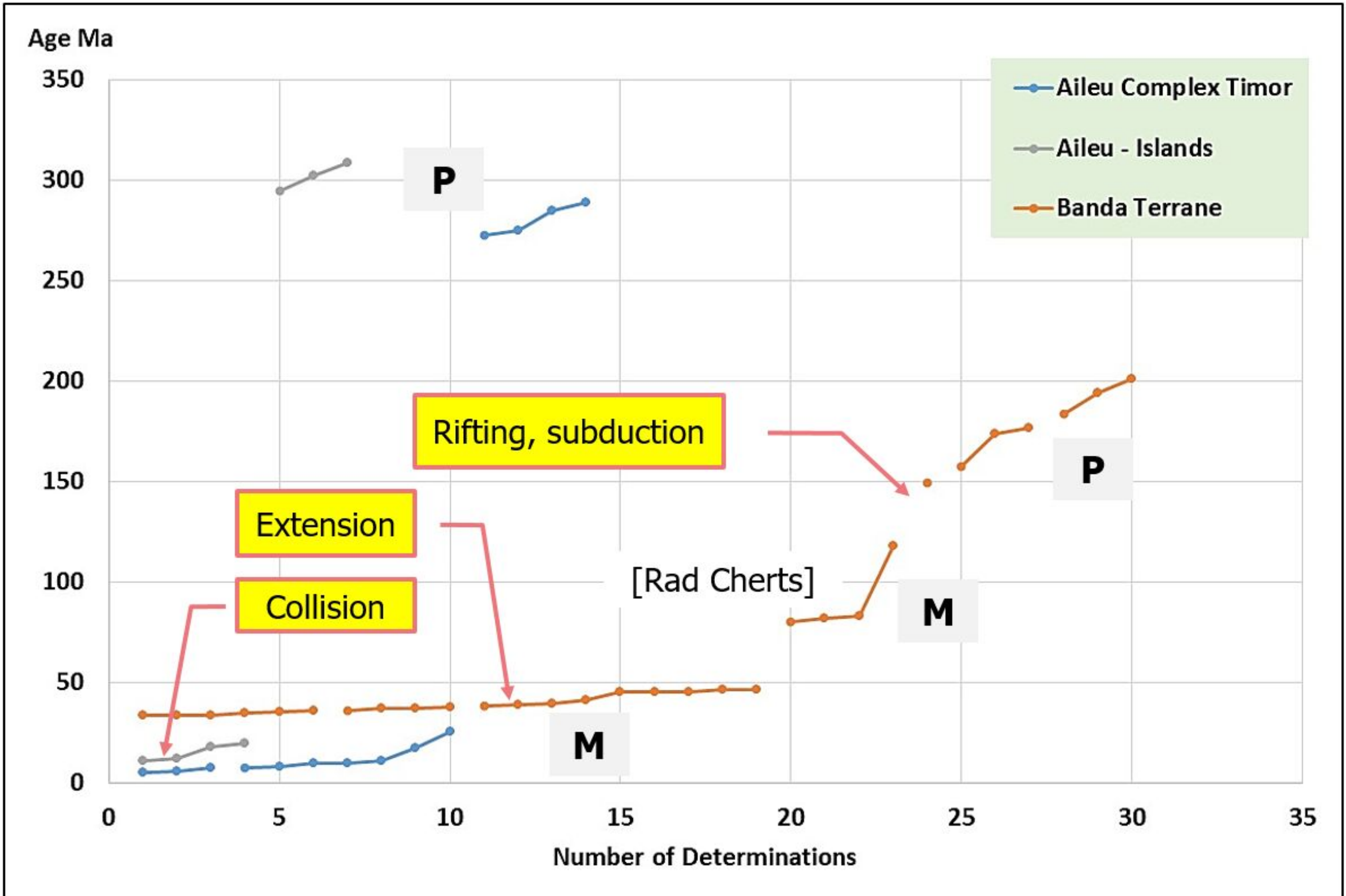
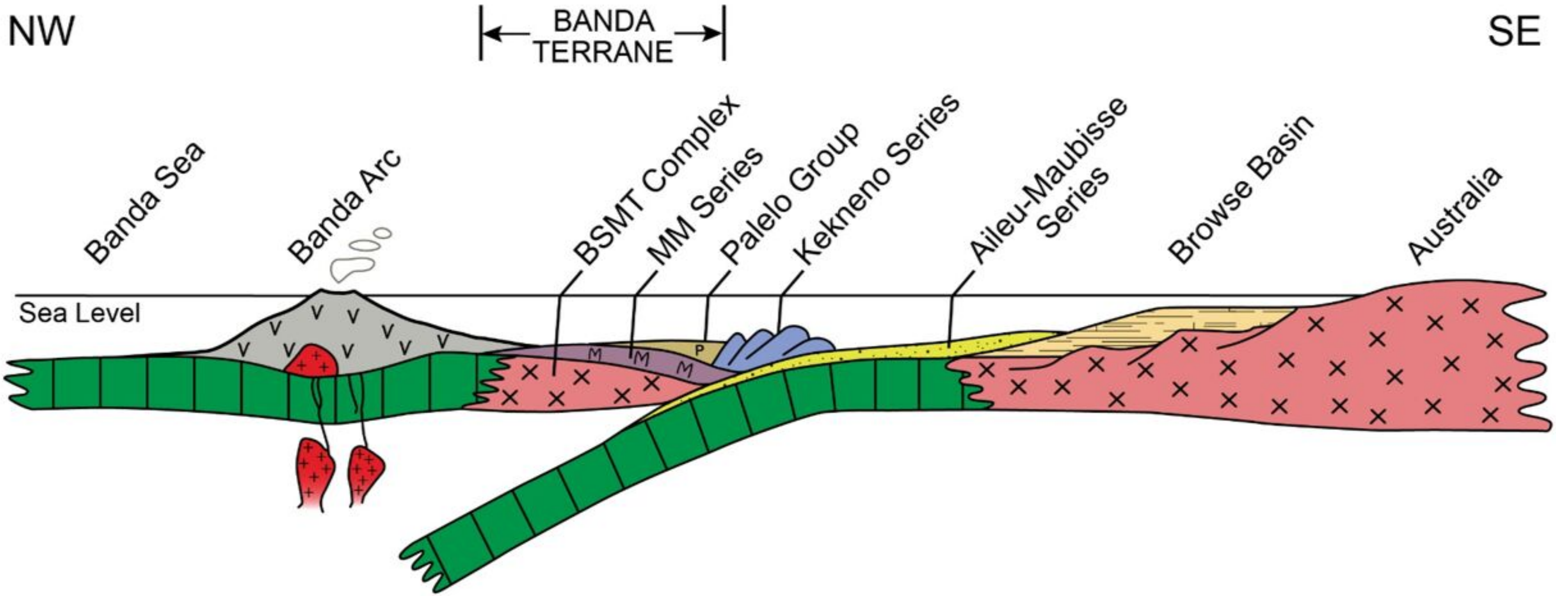


Figure 6.

Figure 6. A Schematic Cross-Section of the Banda Orogen in Miocene Times.



- M1. Late J to Early K. Basement Complex
- M2. Cretaceous to Palaeocene forearc 'burial'
- M3. Eocene. Makassar Strait rifting & slab rollback
- M4. Eocene or Miocene subduction. Aileu Complex/Aileu-Maubisse Series

Figure 5.

Figure 5. The Banda Terrane as Imagined by de Waard (1957), with gravity sliding as an emplacement mechanism. Annotations by this Author.

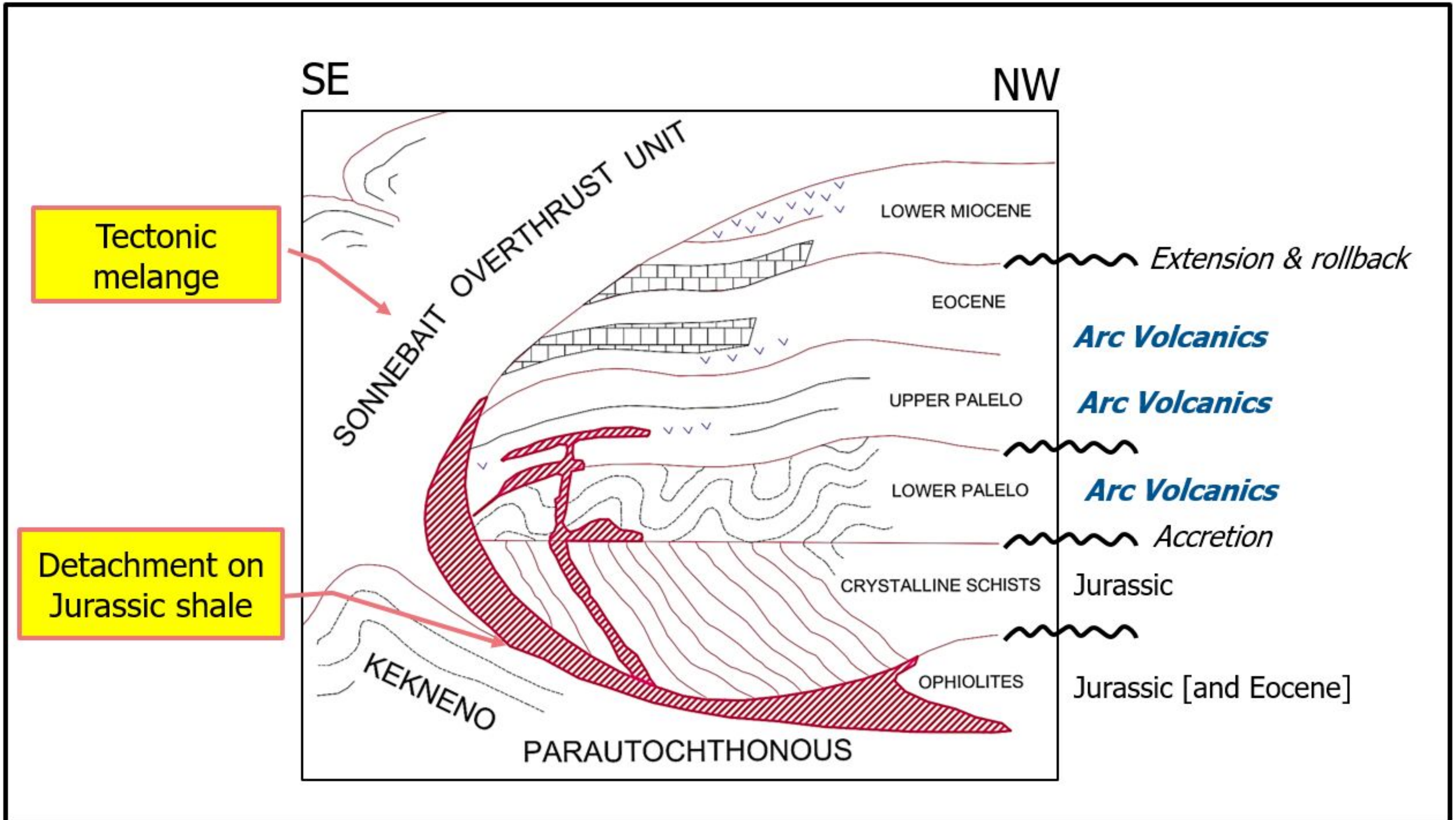


Figure 4.

Figure 4. Simplified Tectono-Stratigraphic Column of the Banda Allochthon.

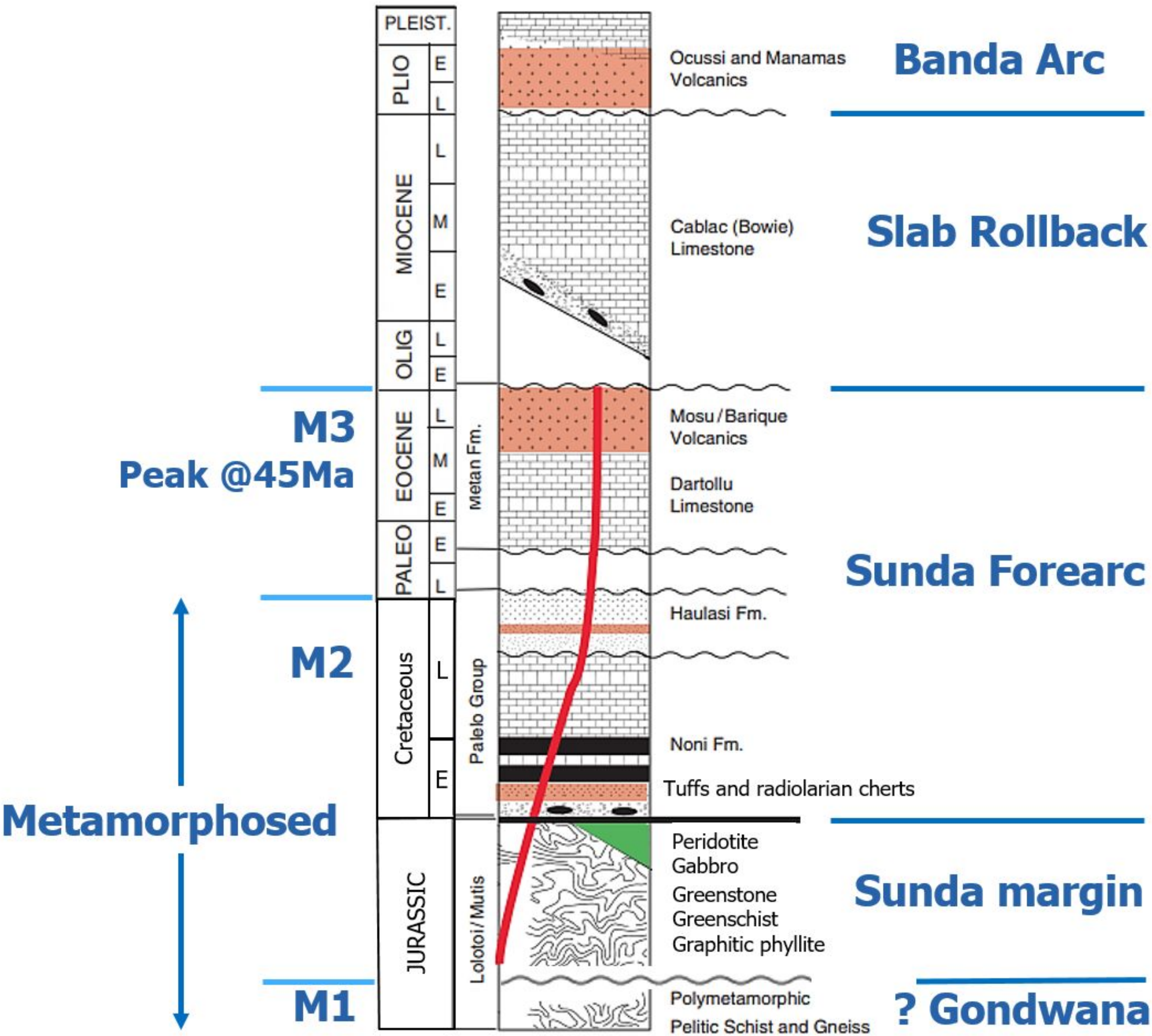


Figure 3.

Figure 3. Distribution of the Metamorphic Complexes of Timor. BSMT Complex and Forearc Complex on Legend are equivalent to the Mutis-Lolotoi Complex and Palelo Group. Boi and Molo are the Authors' research areas.