Ophiolite obduction on Leti Island, as described by Molengraaff and Brouwer (1915): implications for age and genesis of metamorphic complexes in the Outer Banda Arc, Eastern Indonesia

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Abstract

Geology, rocks and fossils of Leti Island, NE of Timor, were described in great detail by Molengraaff et al. (1915). Folded Early-Middle Permian sediments and basic volcanics in the south of the island gradually become low-grade metamorphics to the North, with further increases in metamorphic grade towards a serpentinite massif in the north of the island. In today's plate tectonic terms this may be characterized as 'ophiolite obduction', i.e. metamorphism of continental crustal material in a subduction zone. The serpentinite massif is overlain by Latest Oligocene shallow marine limestone with reworked clasts and detritus of serpentinite and metamorphic rocks. These observations suggest that the age of the metamorphic-ophiolite complex on Leti island is post-Early Permian (and is therefore not Australian continental crust basement) and younger than latest Oligocene (i.e. too old to represent metamorphism connected with the Late Neogene Banda arc- NW Australian continent collision).

Metamorphic complexes on nearby Timor and on small islands to the East may all have a similar origin, despite the wide range of published radiometric ages and proposed tectonic models (from Precambrian Australian continental basement to 'the world's youngest blueschist belt'). Many complexes are associated with ophiolitic rocks, overlie imbricated Permian-Triassic sediments and are overlain by an Upper Cretaceous- Lower Miocene 'Banda Terrane' succession (not always complete) that includes tropical carbonates, arc volcanics and unconformities, very similar to that of the Sundaland margin. These broad similarities suggest all or most of the metamorphic complexes may be parts of a single 'Timor-Tanimbar' metamorphic belt of Cretaceous age.

If this interpretation of a single, extensive Cretaceous-age collisional/ subduction zone complex is correct, it follows that (1) this could not have taken place along the NW Australia passive margin, where it is today, and (2) if Permian-Triassic sediments and volcanics are indeed the protoliths of all metamorphic complexes, a microplate carrying these 'Gondwana sequence' sediments must already have separated from the Gondwana margin, probably in Jurassic time. This leads us back to the tectonic scenario that was prevalent around 1980 (Barber (1978, 1981, etc.), which

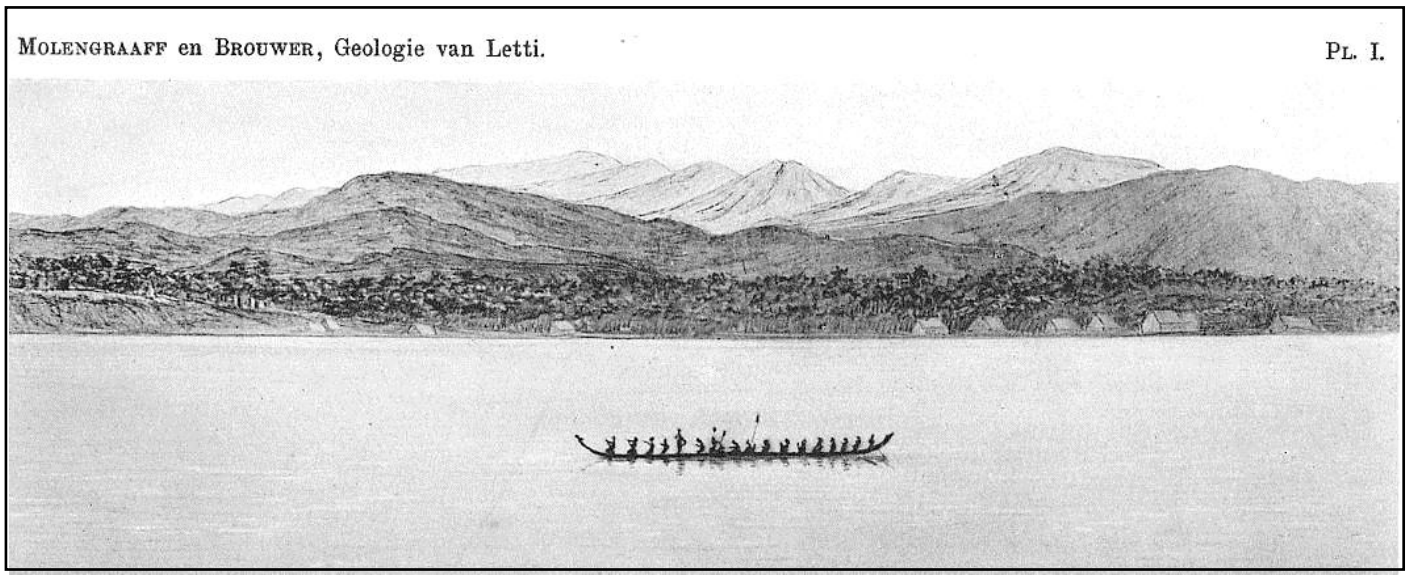


Figure 1. *View of north coast of Leti Island, showing village of Serwaru. Hills in foreground are composed of serpentinite. Larger hills in distance are metamorphic rocks.*

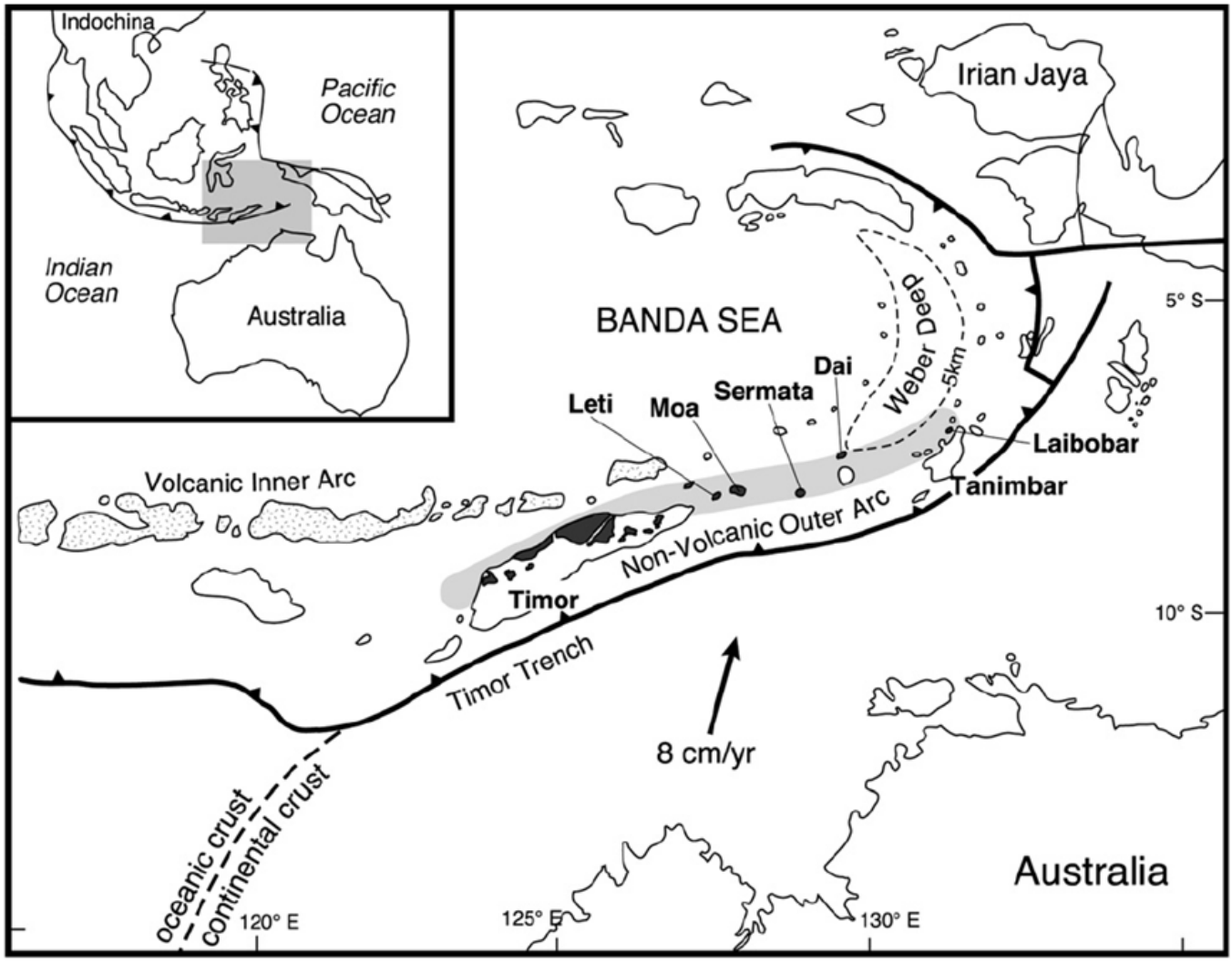


Figure 2. *Location of Leti Island, E of Timor, and the Outer Banda Arc zone with metamorphic-ophiolite complexes (from Kadarusman et al. 2003).*

shows most of Timor as a microcontinental sliver that rifted off the Sundaland margin in the Tertiary (should be ~Late Miocene-Pliocene time) during slab rollback/ arc splitting that opened the South Banda Sea. It returned microcontinental material that had rifted off the Gondwana margin in the Jurassic ('Gondwana sequence'), then collided with the Sundaland margin in the Cretaceous, after which it developed its overprint of Late Cretaceous- Early Miocene arc volcanics, tropical carbonates, etc..

Introduction

As part of the 'Netherlands Timor Expedition 1910-1912' project professor G.A.F. Molengraaff from Delft University and his former Ph.D. student H.A. Brouwer (at that time with the Bandung Netherlands Indies Geological Survey; 'Dienst Mijnwezen'), spent one month in early 1911 surveying and mapping the island of Leti, NE of Timor. Their map and the accompanying 220-page documentation report published in the 'Jaarboek van het Mijnwezen' series are still the most detailed documentation of the surface geology and fossils of Leti Island.

For many years the monograph of Molengraaff and Brouwer (1915) was the only documentation of the geology of Leti. The 1:250,000 scale GRDC (1994) map sheet that includes Leti Island did not preserve much of the detail of the 1915 work. Recently a series of papers on the 'Timor-Tanimbar ophiolite' by a Japanese-Indonesian group provided additional detail on the Leti metamorphics and ophiolites and their genesis and exhumation history (Kaneko et al. 2007, etc.).

Remarkably, the Molengraaff et al. (1915) book is rarely mentioned in reviews of the geology of the region. Since their field observations, the accompanying rock and fossil studies and conclusions still have important implications for the geological history of the region it was decided to republish some of their work almost 100 years later and place them in a modern context.

Digital copies of the 1915 book (without the atlas) can be viewed/ downloaded online at: *http://openlibrary.org/books/OL24343736M/Nederlandsche_Timor-expeditie_1910-1912*, or at: *http://archive.org/details/nederlandschetim00mole.* The geologic maps and cross-sections from the accompanying Atlas can be viewed/ downloaded at: *www.vangorselslist.com/gallery.*

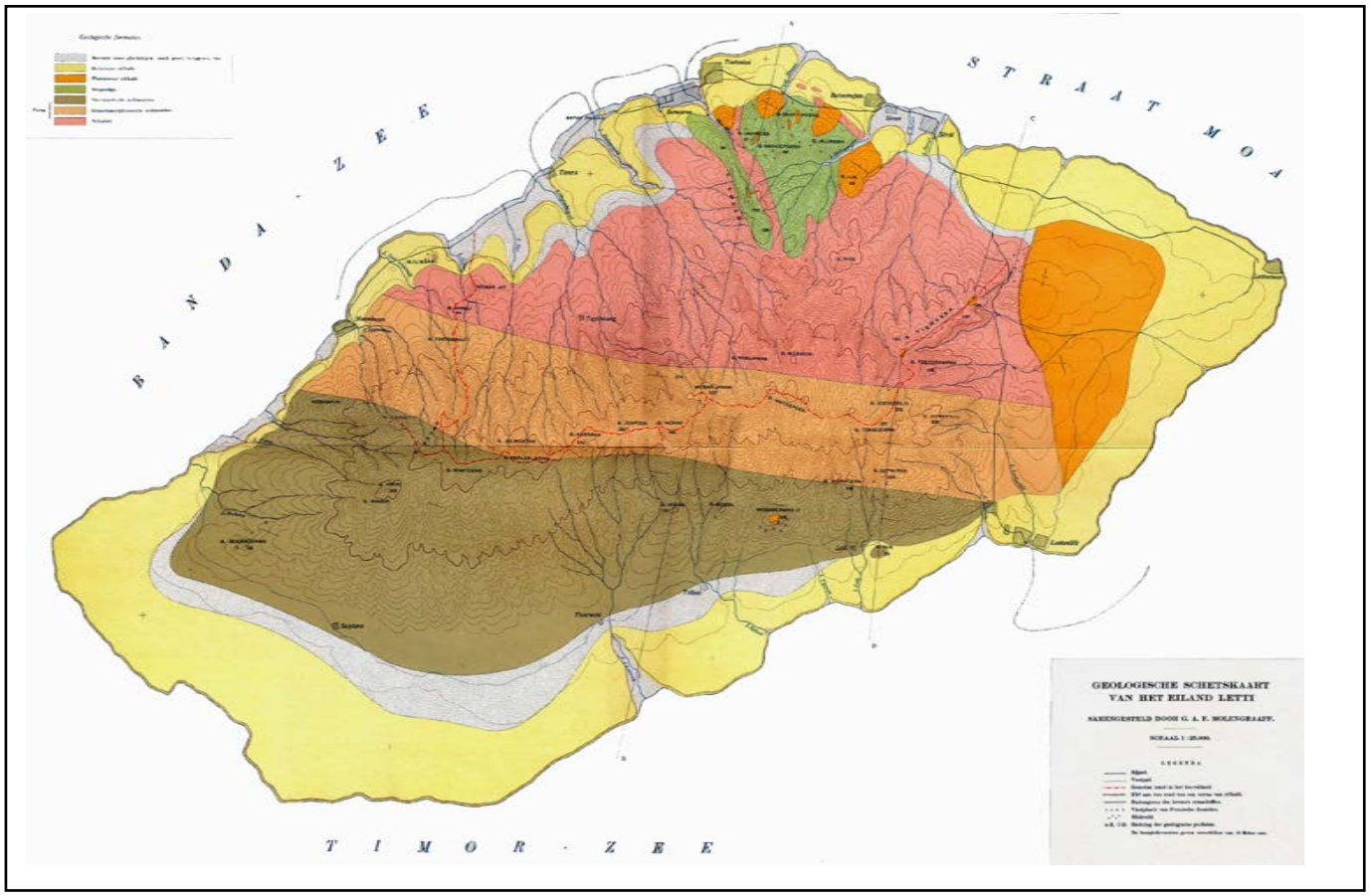


Figure 3. *Geologic map of Leti Island, showing unaltered Permian sediments in South (olive color), grading to high-grade metamorphics in North (pink), overlain by serpentinite (light green). Original map scale is 1:25,000. Length of island ~16 km, width ~7.5 km (Molengraaff and Brouwer, 1915).*

Geology of Leti Island

Leti is a relatively small island (16 x 7.5 km), located about 40 km ENE of Timor Leste (Figure 2). Its geology is clearly an eastern continuation of that of NE Timor. As already noted by Wichmann (1892), it is part of a belt with a rock association of highly deformed Permian- Cretaceous sediments, crystalline schists and ophiolites, which stretches from Roti, Timor and Kisar in the west towards Moa, Sermata, Dai, Babar, Laibobar and Kur in the East, and possibly continuing to Seram and Buru. It is the inner zone of the 'non-volcanic Outer Banda Arc' (Figure 2).

The following rock units were mapped on Leti island by Molengraaff and Brouwer (1915) (Figures 3, 4):

1. Southern zone of unaltered Permian sediments (olive green on map)

This zone is composed of intensely folded, but non-metamorphic Permian clastic sediments (greywacke sandstone, shale) with thin limestones with brachiopods, crinoids, ammonites and fusulinid foraminifera and basic volcanics. Beds invariably dip steeply to the North. It is believed to be a thick section (estimated at possibly 2000m, but hard to measure because of probable repeated sections and instances of isoclinal folding). Molengraaff and Brouwer (1915, p. 24-25) noted that these rocks are very similar to Permian clastics with basic basalts and tuffs between Sufa and Maubisse, in what was then Portuguese Timor.

On nearby Timor Island the sediments described here would be assigned to the Atahoc/Cribas or Kekneno Groups (where clastics-dominated) and the Maubisse or Sonnebait Formations (where dominated by limestones, tuffs and pillow basalts). It is part of what is commonly referred to as 'Para-autochtonous' or 'Gondwana sequence'.

2. Central zone of metasediments (light orange)

The central E-W trending zone of Leti island is composed of low-grade meta-sediments: phyllites, quartzites and schistose limestone. The limestones still have recognizable crinoid stems, demonstrating that these are metamorphosed Permian sediments.

3. Northern zone of high-grade metamorphics (pink)

High-grade metamorphics: amphibolites, schists, gneiss, etc.. Contacts between 1-2 and 2-3 are described as gradual, suggesting a simple, overall gradual increase in metamorphism in Northern direction of original Permian sediments and volcanics. Kadarusman et al. (2010) noted common 'blueschist' metamorphic facies and estimated a maximum burial depth of 30-35 km. This formation is probably equivalent of the 'Aileu Formation' of northern Timor Leste.

4. Serpentinite complex in North (light green)

Two large bodies of serpentinite outcrop in the North of Leti Island in an area of about 2 x 2km, forming the Javanoea and Emderi hills.

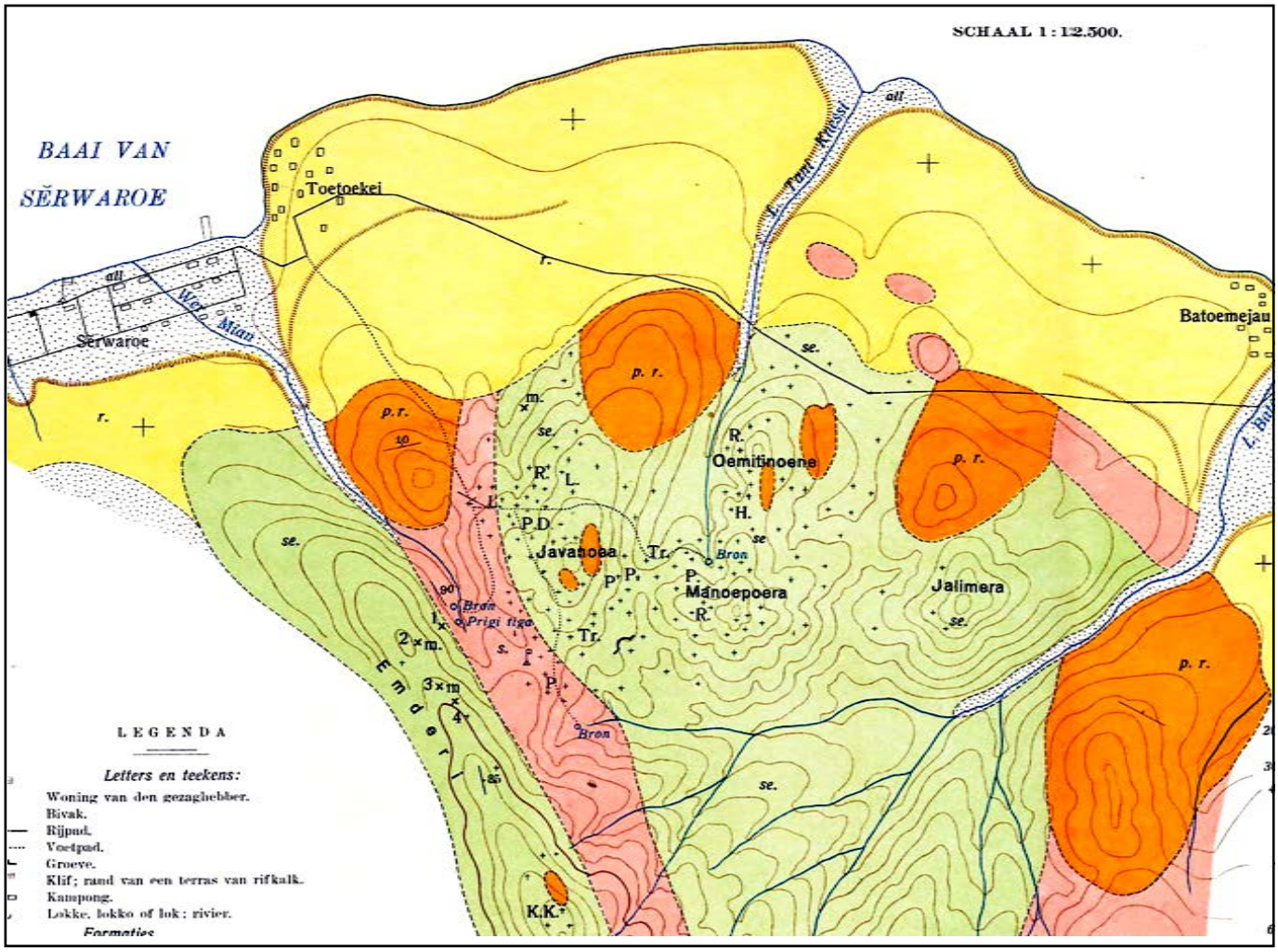


Figure 4. *Detail map of Javanoea and Manoepoera hills, North Leti, showing localities of polymict 'block-cover' (+++) over serpentinite (light green). Other lithologies: amphibolite (pink), Pliocene reef limestone (orange) and Pleistocene fringing terraces (yellow) (Molengraaff and Brouwer 1915).*

These rocks were interpreted by Molengraaff and Brouwer (1915) as serpentinized peridotite/ lherzolite. They struggled with the interpretation of structural relationships and the contact between the ultramafic complex and the metamorphics, whether it is an intrusive body in the Permian section, or, more what it looks like in the field, a relatively flat-lying body that that overlies the metamorphosed Permian (see below).

5. Latest Oligocene 'Cablac' reefal limestone and polymict carbonate breccia

Scattered all over the serpentinites of the Javanoea-Manoepoera hills in Northern Leti are blocks of different rock types, dominated by latest Oligocene shallow marine limestone and breccias (Figure 4). They mostly occur as loose blocks, but in places they look like poorly bedded, slightly North-dipping, in-situ outcrop (Molengraaff 1915, p. 73). The limestone matrix contains the larger foraminifera *Lepidocyclina, Spiroclypeus margaritatus* and *Miogypsinoides complanata*. This assemblage was originally assigned an Early Miocene age by Schubert (1915), but is clearly in larger foram subzone Te4, which in modern calibrations is placed in the Latest Oligocene. The Leti limestone/ limestone breccia contains reworked clasts of older rocks, including serpentinite, schist, radiolarian chert and Upper Cretaceous pelagic limestone.

These limestones on Leti were already compared to a polymict conglomeratic limestone overlying metamorphic rocks of the Lalan Asu metamorphic complex in West Timor by Tappenbeck (1939). It also contains reworked clasts of metamorphics and contains the Te4 index fossil *Miogypsinoides complanata* (Marks 1954). Similar Te reefal-conglomeratic limestones with metamorphic detritus was also found at other metamorphic complexes on West Timor, like Boi (Tappenbeck 1939), Miomaffo (Van West, 1941), Mosu- Nefoneu (Van Voorthuysen, 1940), Usu, etc. (see also Haig et al., 2008). Very similar limestone with basal polymict conglomerates was found across East Timor. It was named 'Cablac Limestone' by Audley Charles (1968) and was also reported by other authors, including Harris (2006; Mata Bia massif). It contains the same latest Oligocene zone Te4 larger foram assemblages, but may range into earliest Miocene. There is some controversy about the use of the name Cablac for this limestone, as Haig et al. (2008) questioned its presence at Mount Cablac, and proposed the informal name Booi Limestone.

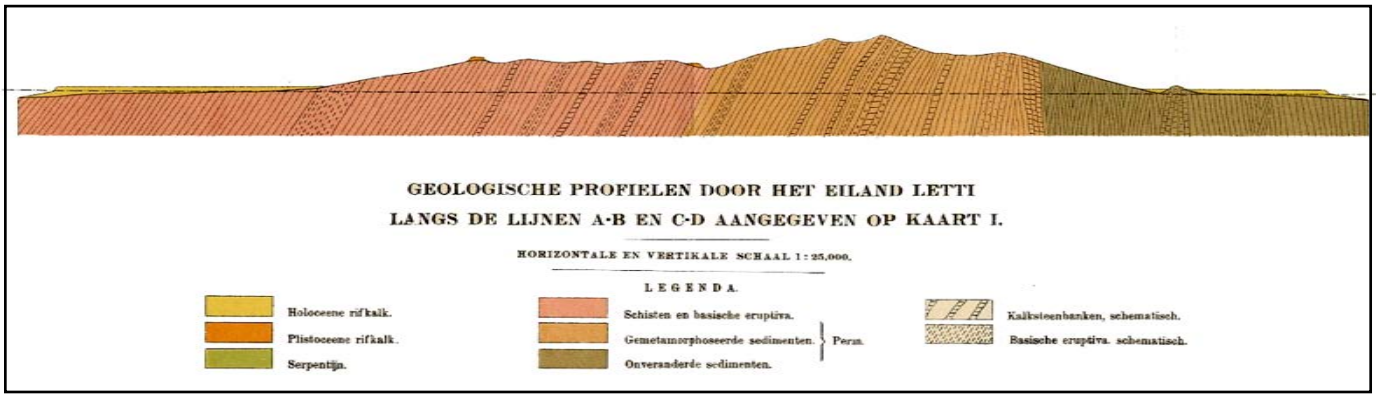


Figure 5. *Diagrammatic NNE-SSW cross section C-D across Leti Island by Molengraaff and Brouwer (1915). Showing mostly North-dipping (but probably imbricated and isoclinally folded) Permian sediments in South (right), grading into metasediments in center of section to high-grade metamorphics in the North (left). Length of section is about 7 km.*

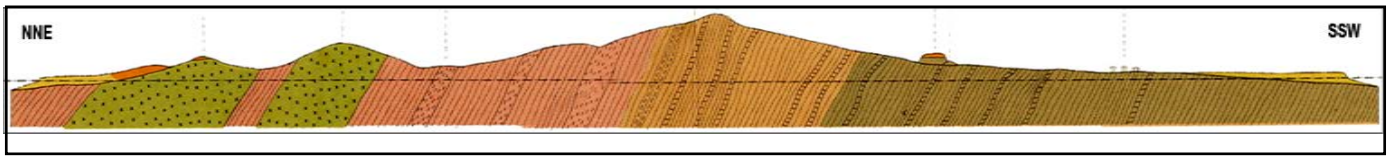


Figure 6. *Diagrammatic NNE-SSW cross section A-B across Leti Island by Molengraaff and Brouwer (1915). Similar to section C-D. Here showing serpentinitites (green; in NNE) as intrusive bodies, a model-driven interpretation not supported by outcrop observations. Length of section is about 10 km.*

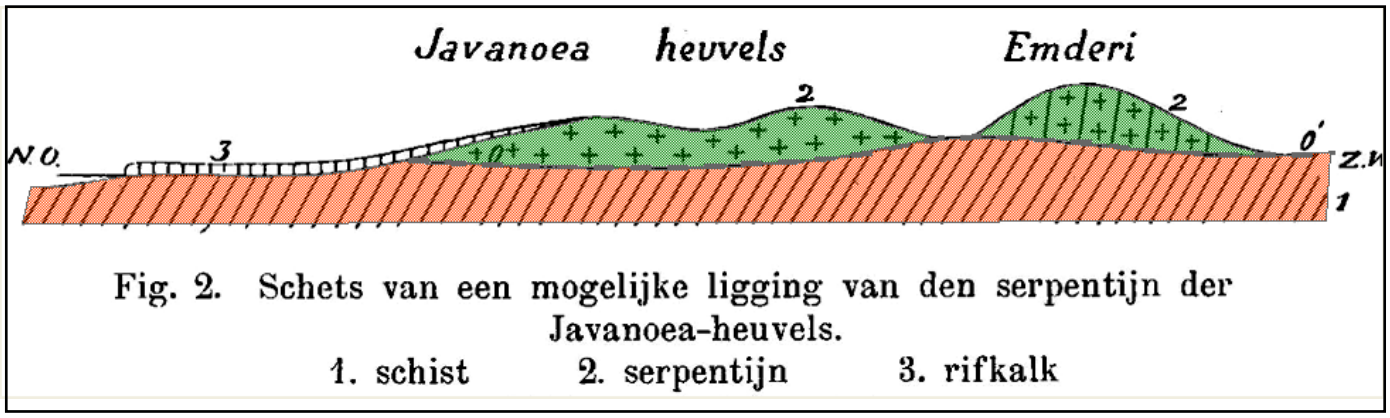


Fig. 2. Schets van een mogelijke ligging van den serpentijn der Javanoea-heuvels.
1. schist 2. serpentijn 3. rifkalk

Figure 7. *Alternative, preferred diagrammatic NE-SW cross-section across North part of Leti island by Molengraaff and Brouwer (1915), showing serpentinites as a flat-lying unit over steeply-dipping metamorphic rocks.*

'Cablac Limestone' is generally regarded as part of the 'allochthonous', 'Banda Terrane' complex. Its main significance is that there is common latest Oligocene conglomeratic limestone on Timor that rests unconformably on multiple older formations and contains reworked Triassic, Cretaceous and Eocene sediments and Oligocene volcanics. On Leti an apparently equivalent conglomeratic limestone suggests that serpentinite, metamorphics and other Late Paleozoic- Mesozoic sedimentary formation were also exposed and eroded here at the end of the Oligocene. If this formation is indeed equivalent of the Timor 'Cablac-Booi', the Leti metamorphic-ophiolite complex may share a common mid-Tertiary history with 'Banda Terrane' of the Mutis complexes and may be more closely related to this group than is generally accepted.

6. Miscellaneous blocks in 'Block fields'

The Javanoea and Manoepoera hills in the North of Leti Island are composed of serpentinite and are overlain by numerous large and small blocks of a different rock types (Figure 4). These may be reworked from formerly nearby outcrops during a time of major erosion, or they may be equivalent of the widespread 'Bobanaro' olistostrome/ mélange' of Timor.

Rock types include (1) metamorphic rocks (amphibolite, schist, etc.), (2) igneous rocks, including andesitic volcanics (not observed elsewhere else on Leti island), (3) rare Permian crinoidal limestone and limestone with fusulinid larger foraminifera, (4) radiolarian limestone (believed to be of Triassic and Jurassic age by Molengraaff et al. (1915), but ages were not confirmed biostratigraphically (radiolarites also occur in Upper Cretaceous of the Banda Terrane of Timor), (5) Triassic *Halobia* (pelagic bivalve) limestone and (6) Upper Cretaceous pelagic limestone with *Globotruncana cf. linneana*, as clasts in Late Oligocene limestone and as isolated blocks.

7. Fringe of Plio-Pleistocene uplifted reefal limestones (orange and yellow)

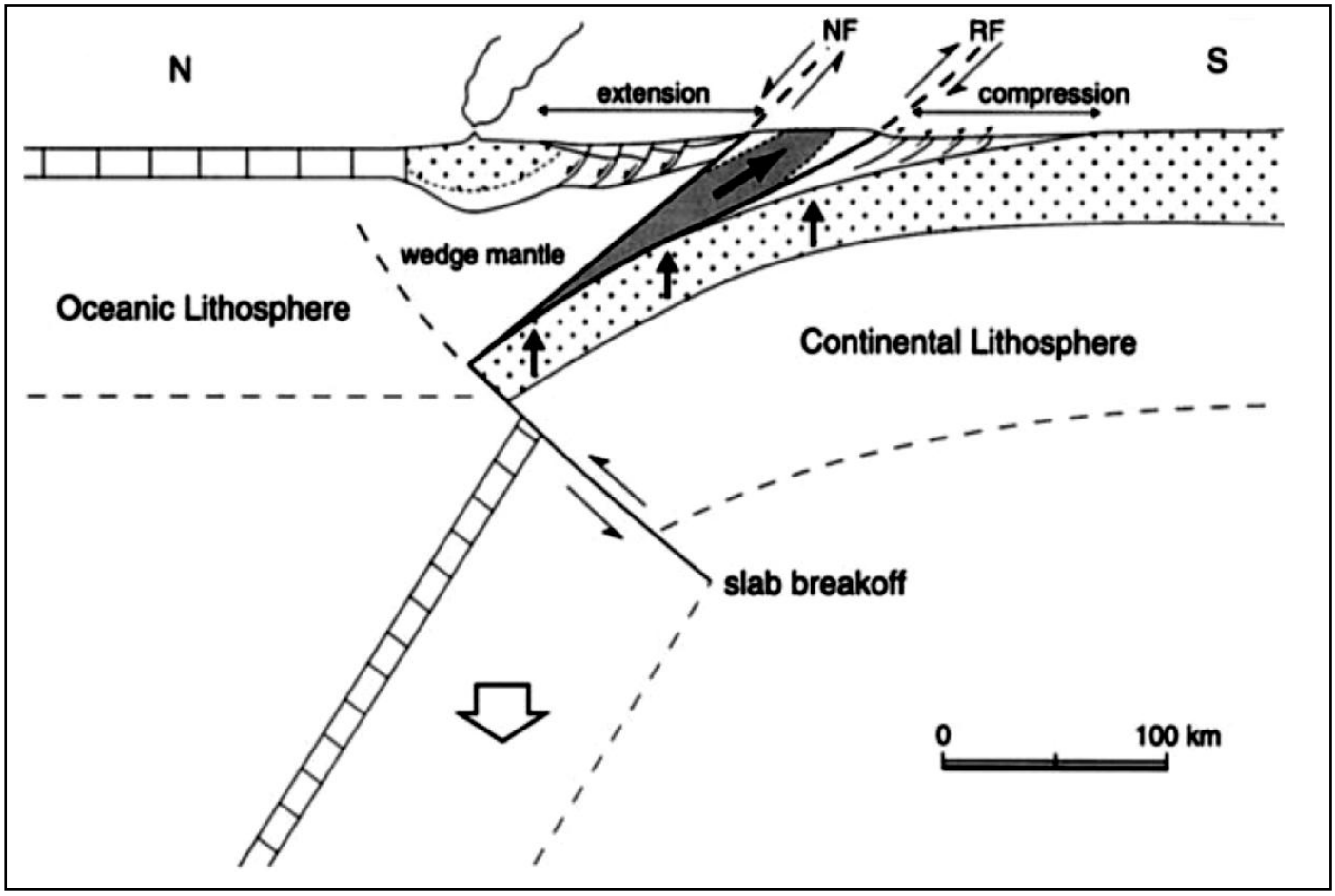


Figure 8. *N-S diagrammatic cross-section across Outer Banda Arc zone, showing uplift and exhumation of metamorphic-ophiolite complex after slab break-off (from Ernst et al. 1997). This Figureure illustrates the process, not necessarily the location at which subduction-exhumation of Leti- Timor complexes took place (more likely at Sundaland margin; see text).*

The entire island of Leti is surrounded by two or more terraces of Pleistocene reefal limestone, at about 10 and 20m above sea level (yellow on map of Figure 3). Remnants of older terraces (orange on Figure 3), believed to be of Pliocene age by Molengraaff et al. (1915), were observed up to 134m above sea level. Leti has fewer reef terraces than Timor island, which were also not uplifted as high (Timor Pleistocene terraces present until ~1200m above sea level).

Outcrop Relations between Metamorphic Rocks and Serpentinite

Molengraaff and Brouwer (1915) struggled with the nature of the contact between the serpentinite and metamorphics.
Clear contacts between the two units were not seen in outcrop. There was little doubt in their minds that the metamorphism was the result of contact with younger hot ultrabasic igneous rocks, so in their 'official' interpretive cross-section they show the serpentinites as intrusive bodies (Figure 6).

However, in their discussion Molengraaff and Brouwer (1915, p. 24-26) emphasize that on Leti the serpentinites are restricted to the hills, with amphibolite/ schist in intervening saddles, making it look like a relatively flat-lying unit over the metamorphics (as depicted in their alternative, preferred model; Figure 7).

Geology of Leti Island: Example of 'Ophiolite Obduction'?

The mapping and outcrop observations of Molengraaff and Brouwer (1915) clearly support a genetic relationship between the Leti metamorphic complex and the overlying serpentinite/ophiolite complex. In plate tectonic terms this pairing is often interpreted as 'ophiolite obduction'. This does not really mean overthrusting of mantle-type rock over other units. It is the result of sinking of continental crustal material into a subduction zone, dragged down by an attached downgoing oceanic plate to depths of ~35 km and more, until the relative buoyancy of the volume of continental slab material prevents further sinking. The downgoing oceanic slab will continue to sink, breaks off, and the buoyant continental material is released/ exhumed back towards to surface. The now metamorphosed exhumed continental material often comes back with parts of the overlying ultramafic mantle wedge, with which it has been in contact (see e.g. Figure 8). Such ultramafic material is often serpentinized, carries evidence of hyperextension, but is not always preserved after exhumation of the metamorphic rocks.

Because the downgoing slab is relatively cold, metamorphism in this subduction scenario is mainly 'High

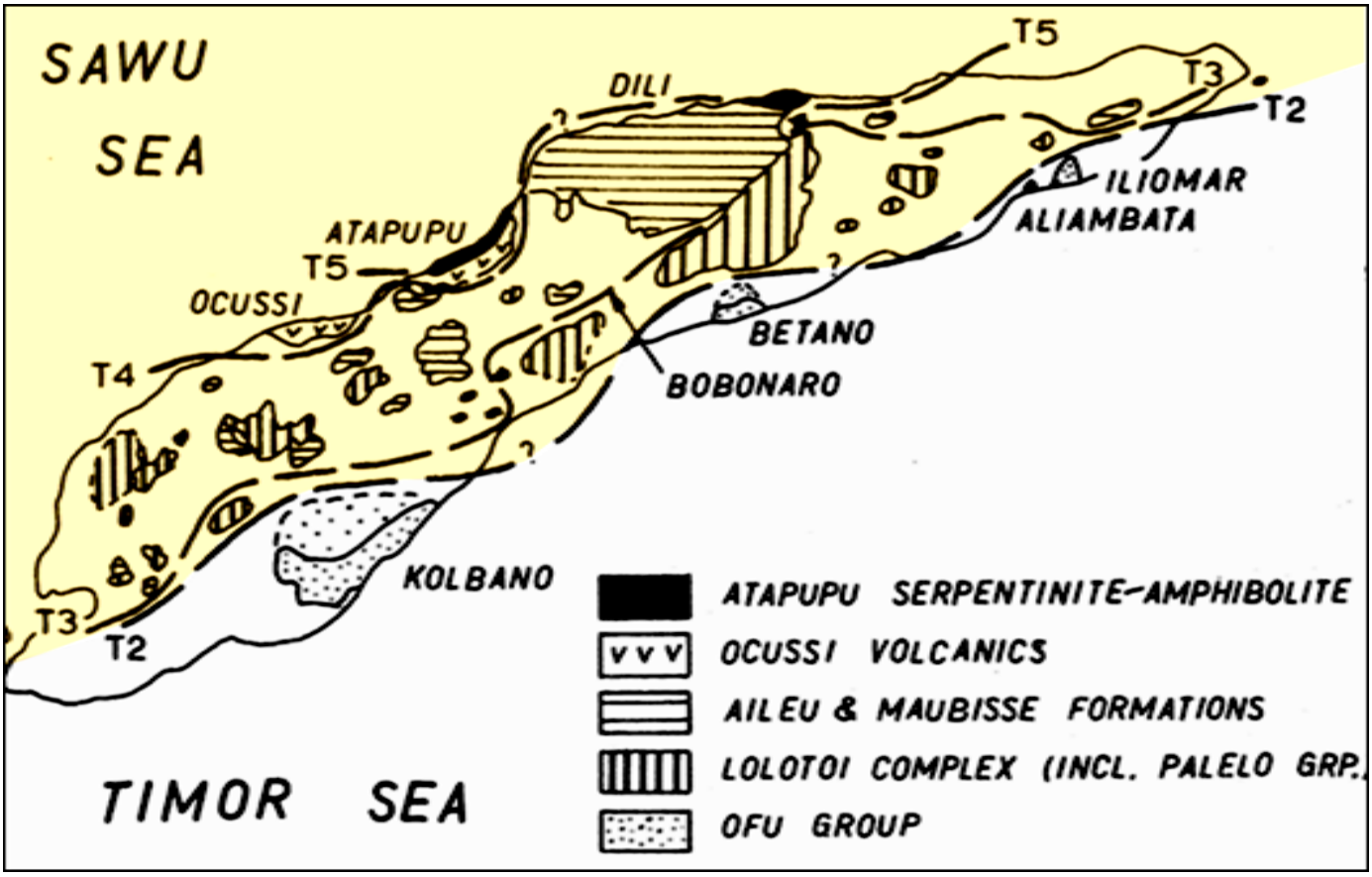


Figure 9. Outline geological map of Timor, showing Lolotoi (includes Mutis) and Aileu metamorphic complexes (Barber, Audley Charles and Carter, 1977). Blue color is undisputed NW Australian margin cover, now in accretionary complex; yellow is overriding fore-arc plate, most recently from Sundaland.

Pressure - Low Temperature' metamorphism ('blueschist facies'). During exhumation this is commonly overprinted by lower pressure-temperature ('greenschist facies') metamorphism. This presence of 'blueschist' metamorphic facies was confirmed recently for the Leti metamorphics by Kaneko et al. (2007) and Kadarusman et al. (2010).

The close relationship between ophiolite complexes and metamorphic rocks has been noted at many other localities on Timor and other islands along the Outer Banda Arc, with ophiolites generally observed to be overlying the metamorphics (e.g. Kadarusman et al., 2003, Ernst et al. 2007). Kadarusman et al. (2003) characterized the Timor-Tanimbar metamorphic/ophiolite belt as up to 2 km thick, 50 km wide and extending laterally for more than 1000 km.

The first author to interpret the formation of metamorphic complexes on Timor as a result of hot ophiolite emplacement was Sopaheluwakan (1989, 1990, 1991; Mutis and Miomaffo complexes, W Timor), observing a systematic decrease in metamorphic grades away from the peridotite from amphibolite to greenschist facies. Ophiolite obduction was also invoked for Aileu complex metamorphism below the Atapupu peridotite of northern Timor and for the Kaibobo complex of Seram (Helmers et al., 1989). Earle (1981) observed an inverted metamorphic gradient in the Boi and Mollo massifs of West Timor and noted that the Boi massif was overlain by altered mantle peridotite. However, Harris and Long (2000) argued against obduction of ophiolite as a cause of metamorphism on Timor.

Kaneko et al. (2007) and Kadarusman et al. (2010) also interpreted the geology of Leti as metamorphism related to subduction, followed by exhumation and uplift. However, instead of the gradual, transitional contacts between metamorphic grades described by Molengraaff and Brouwer (1915), they observed normal fault contacts between the metamorphics and overlying ultramafic rocks and a reverse fault zone between the metamorphics and underlying unmetamorphosed Permian sediments. These are probably complexities related to the exhumation process, but do not change the overall 'obduction' concept.

Age of Leti Island Metamorphics

The field observations of Molengraaff and Brouwer (1915) provide stratigraphic constraints on the age of metamorphic rocks of northern Leti Island, which suggest that this complex is too young to be a fragment of (Precambrian) NW Australian continental margin crust, and too old to be part of the ongoing Banda Arc- NW Australian continental margin collision:

(1) Metamorphism is of post- Early Permian age, because Early Permian rocks are altered by metamorphism;
(2) The metamorphic-ophiolite complex of Leti was exhumed before the end of the Oligocene (~24 Ma), as

demonstrated by reworked serpentinite and schist fragments in overlying conglomeratic reefal limestone with latest Oligocene larger foraminifera (see above).

An 11.0 Ma K-Ar radiometric age was reported for pelitic schist from Leti Island (Kaneko et al. 2007, Kadarusman et al. 2010). This is much younger than the minimum age of ~24 Ma suggested by the eroded serpentinite and metamorphic detritus. It is one of many radiometric ages in the Timor region that appear to be too young when compared to observed stratigraphic constraints and may reflect younger exhumation ages or thermal resets during later volcanic episodes (see below). Their conclusion that the Leti metamorphics are part of the 'world's youngest blueschist belt' may therefore need to be confirmed. Below we argue that the age of metamorphism on Leti and in similar complexes on Timor is probably Cretaceous.

Relation to Metamorphic Complexes of Timor

As noted above, a series of similar metamorphic complexes associated with mafic/ultramafic bodies are exposed from Timor and Kisar to Leti and smaller islands to the East, and form parts of the 'Timor-Tanimbar ophiolite' belt of Ishikawa et al. (2007). About 15 metamorphic rock complexes have been identified on Timor (Figure 9). There continues to be considerable debate on whether these are all of similar age and origin, or whether there are multiple types. The main hypothesis in this paper is that they are all related.
Charlton (2002) distinguished three categories of metamorphic complexes on Timor:

(1) Aileu Complex of NE Timor: believed to be a young metamorphic series with an inverted metamorphic gradient developed beneath overthrust allochthonous peridotite;
(2) Mutis Complex of West Timor: allochthonous metamorphic basement from the Banda forearc;
(3) Lolotoi- Laclubar and other complexes of Timor Leste: Australian continental basement crust.

1. Aileu Complex, NE Timor
The 'Aileu Complex' of northern Timor Leste around Dili appears to be very similar to the metamorphic-ophiolite complex of Leti Island. It also features a gradual SW to NE increase in metamorphism of Permian shales, sandstones, limestones and basalts towards a metamorphic- ophiolite complex. The metamorphic complex is mainly slate in the south and higher grade mica schists, marbles and hornblende schists/ amphibolite near the north coast. Metamorphics are overlain by the Hili Manu ophiolite complex (Barber and Audley Charles 1976, Barber et al. 1977, Berry and Grady 1981, Berry and McDougall 1986, Harris and Long 1990, Charlton 2002, Bachri 2004, etc.). Brunnschweiler (1978) and Bachri (2004) observed that Triassic-Late Jurassic sediments were probably also involved in metamorphism of the Aileu complex, suggesting a post-Jurassic age of metamorphism.

Most radiometric ages from the 'Aileu Complex' are relatively young, mainly between about 10 and 6 Ma, Late Miocene (Berry and McDougall 1986, Utoyo and Permanadewi 1994, Ely 2009, etc.). This is why it is commonly viewed as metamorphism tied to the Banda Arc-NW Australia collision. However, if the Aileu and Leti metamorphic complexes are genetically related, as the basal parts of both complexes would suggest, these radiometric ages are 'too young' relative to ~24 Ma age of the limestones that overlie the Leti serpentinite.

Berry and McDougall (1986) actually noticed a wide range in radiometric ages for the Aileu Complex, and concluded from hornblende Ar isotopes that the age of prograde metamorphism was at least 70 Ma (Cretaceous), with a reheating event at ~8- 5 Ma. We therefore speculate that the generally quoted young ages may all be caused by a younger volcanic heating event (in this case the Ocussi Volcanics, dated at ~5 Ma). If (1) the proposed Cretaceous radiometric minimum age of principal metamorphism of the Aileu Complex is correct, and (2) the Aileu complex is indeed closely related to the Leti complex, and (3) the Leti complex can be tied to the 'Banda Terrane' via its Late Oligocene "Cablac' limestone/ unconformity, then the Aileu complex may be more closely related to the Mutis, Mollo and other Timor massifs than is generally accepted (see below).

2. Mutis Complex and Banda Terrane
Scattered across Timor are a group of metamorphic complexes that are commonly viewed as part of the 'allochthonous/ SE Asia' 'Banda Terrane' (Barber et al. 1977, Earle 1979, Brown and Earle 1983, Audley-Charles and Harris 1990, Harris,1992) also called 'Schist-Palelo Complex' by Brouwer (1942) and his students. They are commonly viewed as remnants of a recently obducted terrane of Asian (Sundaland) origin. In addition to the large Mutis complex, smaller complexes in West Timor include Mollo, Miomaffo, Usu, Lalan Asu, Boi, Mosu, etc. The Lolotoi, Bebe Susu, Lachluta and Mata Bia complexes of Timor Leste may or may not be part of this same group (see below).

Typical Banda Terrane consists of Early-Middle Cretaceous metamorphics (some associated with ophiolites), overlain by Late Cretaceous radiolarian chert, turbiditic sediments and arc volcanics, Middle Late Eocene reefal limestones (Dartollu Fm) and Late Eocene arc volcanics (Metan/Mosu/ Barique volcanics; ~35 Ma) and latest Oligocene- earliest Miocene reefal limestones (Cablac Fm). As noticed by numerous workers before, these rocks do not belong on the NW Australian passive margin, but are remarkably similar to the Cretaceous- Tertiary succession of West Sulawesi and Sumba, and should be viewed as part of Sundaland during Cretaceous- Miocene time and became part of the overriding Banda forearc plate during its collision with the Australian continental margin.

A good indicator of a Cretaceous minimum age of metamorphism is shown by overlying sediments. The oldest rocks are Middle-Late Cretaceous clastics, locally with fragments of metamorphic rocks (Mollo Massif, Tappenbeck (1939), Miomaffo, Van West (1941) and Lalan Asu, De Waard (1954)). These are overlain by open marine Upper Cretaceous calcareous shales with volcanoclastic turbidites, much like West Sulawesi and Sumba. Other metamorphic massifs in both West and East Timor have less complete overlying 'Banda Terrane' sections, with Middle-Late Eocene

shallow marine with *Nummulites-Alveolina-Pellatispira* limestones or latest Oligocene- Early Miocene Cablac Limestone as oldest rocks.

Radiometric ages of metamorphic rocks are highly variable. Some confirm the likely Mid- Cretaceous for peak metamorphism (Brown and Earle 1983, Booi massif, Sopaheluwakan 1990). Many others obtained Late Eocene radiometric ages. Sopaheluwakan (1990) suggested the 37 Ma radiometric age for the Mutis massif reflects a Late Eocene reheating event. There is indeed widespread Middle-Late Eocene arc volcanism associated with these terranes (Mosu, Barique, etc. volcanics). It is tempting to consider all other Eocene and younger radiometric ages as thermal resets as well (31-38 Ma for Mosu, Boi, Mollo, Mutis, Usu massifs (Harris, 2006); 45 Ma for Lolotoi massif (Standley and Harris, 2009), etc.)

3. Lolotoi - Lachlubar Complexes, Timor Leste
Charlton (2002, 2012) interpreted the Lolotoi- Lachlubar and other complexes of Timor Leste as old, Australian continental basement crust, mainly based on interpretation of 'thick-skinned' steep faults bordering these massifs. Most other workers viewed the 'Lolotoi' metamorphic complexes as equivalents of the West Timor 'Mutis' complexes (among the latest Standley and Harris 2009, Audley Charles 2011). There are indeed many similarities between the Lolotoi massifs and 'true' Banda Terrane metamorphic massifs, including the presence of Eocene *Alveolina-Nummulites-Pellatispira* limestones on the Laclubar, Lolotoi and Bebe Susu massifs, Eocene and Miocene arc volcanics, etc.. As noted above, these rocks do not belong in a distal Australian NW shelf passive margin setting.

Metamorphic Complexes did fot form at NW Australian Margin?

As explained above, 'ophiolite obduction' takes place in a collisional (subduction zone) setting. If ages of metamorphism and exhumation of Leti-Timor metamorphic complexes are indeed Cretaceous, this cannot have formed at the NW Australian margin, because this was a pre-collisional passive margin, far away from a subduction zone, from the Paleozoic until the onset of Banda Arc collision in Late Miocene or Pliocene time.

The more likely setting would be the margin of Sundaland, probably a southern extension of SW and SE Sulawesi. The Sundaland margin was dismembered in Late Miocene time during a process of arc splitting during slab rollback, which eventually led to the creation of the South Banda Sea oceanic basin. The dismembered pieces are now found from Sumba through Timor, Leti, W Tanimbar, possibly all the way to Seram and Buru (zone depicted in Figure 2). Elements of this history have already been incorporated in many of the proposed tectonic scenarios, including Barber (1978, 1981), Milsom (2000, 2001), Harris (2006), Villeneuve et al. (2010) and more recently also Spakman and Hall (2011).

Conclusions and Speculations

1. Old geological field surveys contain valuable information on Leti island geology
The well-documented geological survey work on Leti Island by Molengraaff and Brouwer in 1911 provides: (1) significant observations on the relationships between metamorphic rocks and their underlying sediments and overlying ophiolite complexes, and (2) ages of sediments underlying and overlying the metamorphic-ophiolite complex, which demonstrate that the age of metamorphism was between Permian and latest Oligocene. This means that the metamorphic complex on Leti neither represents (Precambrian) Australian continental margin continental crust, nor is it related to the ongoing collision between the Banda Arc and the Australian NW Shelf margin, which probably did not start before ~3-4 Ma.

2. Documentation of relationship between metamorphism and ophiolites on Leti Island
On Timor Island the close association between ophiolites and crystalline schists had been noticed by many authors (e.g. Brouwer 1942). The rock assemblages described on Leti, where ophiolites overlie high-grade metamorphics which grade downward into unaltered sediments, can be interpreted as an example of 'ophiolite obduction', or, better, partial subduction of originally Gondwanan or Australian continental crust, followed by buoyancy-driven slab breakoff and exhumation. This model also appears to be suitable for most or all of the metamorphic complexes in the 'Timor-Tanimbar' metamorphics and ophiolite belt (e.g. Kaneko et al. 2007).

3. Similarities between metamorphic complexes of Timor and Leti
Despite widely varying radiometric ages and differences in interpretations of metamorphic complexes between 'schools', there are remarkable similarities in underlying ('Gondwana Sequence' Permian-Triassic at Aileu, Leti, Mutis, Miomaffo, Mollo, etc.) and overlying formations (complete or partial Upper Cretaceous- Miocene 'Banda Terrane' succession). A possibly simplistic, but tempting conclusion from this is that perhaps all metamorphic complexes of the Timor-Leti-Tanimbar belt are parts of the same collisional event, with mid-Cretaceous as the most likely age of peak metamorphism.

4. Age of Banda Arc- NW Australian margin collision
Latest Miocene- Early Pliocene 'Batu Putih-Viqueque Formations' pelagic marls and chalks are widespread across Timor. The rich foraminiferal assemblages show that probably all of Timor was under 500-2500m of water at that time (De Smet et al. 1990, Van Marle 1991, Roosmawati and Harris 2009, Haig 2012). It also means that the Timor area had subsided significantly since Early-Middle Miocene and was tectonically very quiet between ~6 Ma and 3.5 Ma. One obvious explanation is that this regional subsidence is associated with the rifting at the Sundaland margin and opening/spreading of the oceanic South Banda Sea, which that led to the transfer of the Sumba-Timor, etc. sliver from the Sundaland margin to the NW Australia collision zone.

Significant uplift, with evidence of emergence of parts of Timor above sea level is shown by the appearance of turbiditic, volcanoclastic sands and conglomerates above the Batu Putih marls, starting only about 3-4 million years ago (3.3 Ma; Haig 2012). The uplift process still continues today. One could therefore argue that all compressional tectonic events older than ~3-4 Ma must predate the Banda Arc- NW Australia collision and therefore probably took someplace away from the NW Australian continental margin.

5. 'Gondwana sequence': how Australian is it really?
Folded Permian-Triassic 'flysch-type' clastic sediments, often associated with Permian crinoidal and fusulinid limestones and pillow basalts, are widespread in the topographically and structurally lower parts of Timor and also on southern Leti Island (see above). This sequence has been referred to as 'Gondwana (Mega-) sequence' or 'Kekneno series' or '(para-) autochthonous unit'. Many authors today take it for granted that these deposits formed more or less in their present-day position off NW Australia, in an intra-continental rift setting, prior to the Jurassic separation of 'Argoland' (e.g. Charlton op. div., Keep and Haig 2010). However, there are significant differences between the Permian-Triassic sediments of Timor and equivalent sediments of the NW Shelf. Whilst paleogeographic scenarios can be drawn to explain these differences (e.g. Charlton 2002, 2012), it is equally conceivable that the Timor 'Gondwana Sequence' is part of a microplate that rifted off some other part of the Gondwana margin, possibly closer to Papua New Guinea, which collided with the Sundaland margin in the Cretaceous and is now part of the Banda forearc complex (see tectonic history below).

Provenance studies of Permian- Triassic sandstones do not support a link between the Timor immature, proximal sandstones (derived from metamorphic- volcanic sources to N or NE) and the Australian NW margin (more mature, quartz-rich sediments) (Bird and Cook, 1991). Detrital zircon age peaks are also dissimilar. Age peaks from the Timor Aileu Complex are similar to those from the 'Gondwana sequence' of Savu, but neither of them matches populations from NW Australia; they show closer ties to populations from the East Australia New England foldbelt or even East Malaya (Ely, 2009).

Finally, as observed by paleontologists for over 100 years, Permian-Triassic macro- and microfaunal assemblages of Timor 'Gondwana sequence' tend to be of higher diversity and reflect lower paleolatitude positions than their nearby NW Australia counterparts. These have therefore been viewed as 'exotic' or 'Asian' for a long time and authors have prefered to place them farther away from Australia.

6. The Late Oligocene unconformity/uplift event on Timor and Leti
Limestones with zone Te4 latest Oligocene larger foram assemblages overlie the serpentinites on Leti and contain polymict conglomeratic interbeds with reworked metamorphics, serpentinite and Paleozoic- Mesozoic sediments (Molengraaff et al. 1915; see above). This occurrence on Leti is not well known, but is significant as it appears to be identical to 'Cablac/ Booi' Limestones, generally viewed as part of the allochthonous 'Banda Terrane'.

The 'Cablac/Booi limestone' represents a latest Oligocene transgressive surface above an angular unconformity, usually above an Early-Middle Oligocene hiatus (Carter et al. 1976). This Oligocene-age uplift event apparently exposed and eroded all older formations, and overlying rocks are less deformed. For this reason the 'Base Cablac unconformity' was viewed as the principal deformation event on Timor by several authors (Tappenbeck 1939, Brouwer 1942, Gageonnet and Lemoine 1958, Reed et al. 1996, etc.). This Late Oligocene 'Cablac' event obviously pre-dates the Late Pliocene-Recent collision of the Banda Arc- Australian continental margin. It cannot be tied to events on the NW Australian passive margin, but a similar Oligocene angular unconformity/ hiatus was observed on Sumba, West Sulawesi, etc., which suggests it would fit well in a Sundaland margin setting.

7. Reliability of radiometric ages
As discussed above, many of the radiometric ages of Timor-Leti metamorphics and ophiolites are in conflict with other age data, like ages of overlying or underlying biostratigraphically dated rocks. Radiometric ages are frequently 'too young' and may reflect thermal reactivation during younger volcanic events (mainly Late Eocene, Late Miocene- Early Pliocene), not age of main metamorphism. Interestingly, even if one has confidence in the 'young' radiometric ages, most of them probably are still too old to represent metamorphism or cooling associated with the ongoing Banda Arc- Australian NW margin collision, which started less than 3-4 million years ago.

8. Tectonic history of the Timor region: are the 'Gondwana Sequence', metamorphic-ophiolite complex and 'Banda Terrane' generations of one family?
The complex geology around Timor Island has been subject of numerous interpretations and debates for over 100 years. Debates continue on how much of Timor is 'NW Australian' versus 'SE Asian', whether the dominant structural style is thrusting or block faulting, the timing of various tectonic events, etc. For listings of the numerous papers written on the subject see the Timor and East Indonesia chapters in the 'Bibliography of Indonesia Geology' (*www.vangorselslist.com*). A selection of recent papers will give a sense of continuing diverging opinions among different 'schools': Harris (2006, 2011), Charlton (2002, 2002b, 2009 and 2012, this journal), Audley Charles (2004, 2011), Keep and Haig (2009) and Villeneuve et al. (2004, 2005, 2010).

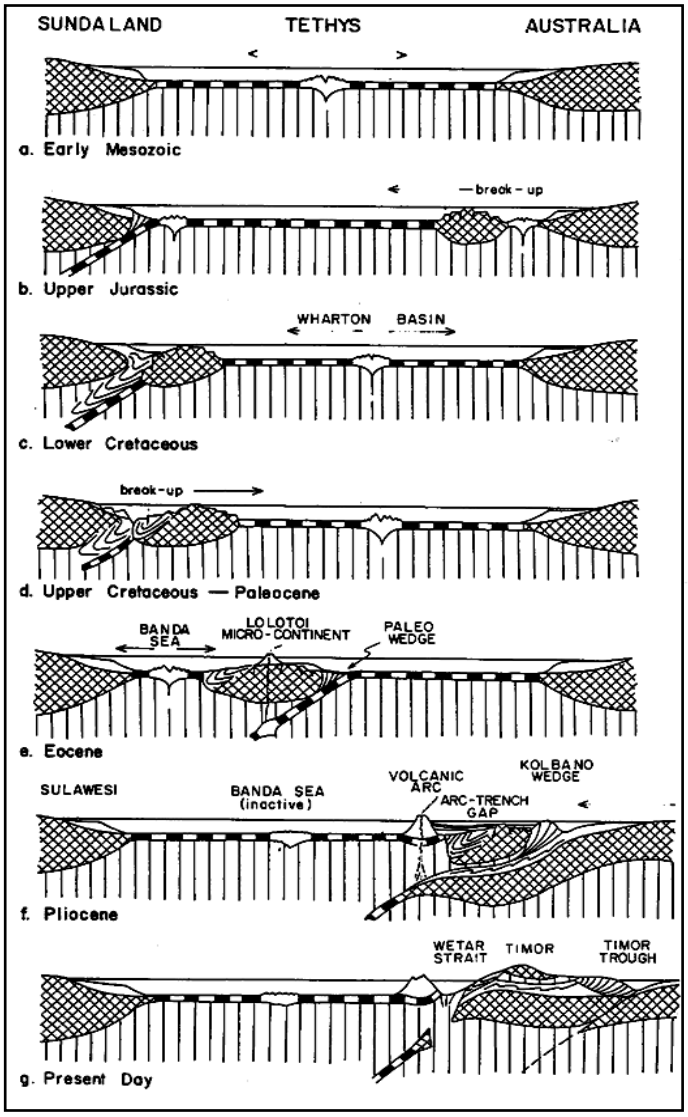


Figure 10. *Diagrammatic tectonic history of Timor, showing break-up of continental fragment from Australian margin in Late Jurassic, collision with Sundaland margin in Cretaceous, separation in Tertiary and collision with Australia in Pliocene (Barber 1978). This is an elegant way to 'marry' Permian-Jurassic 'Gondwana Sequence', mid-Cretaceous Metamorphic-Ophiolite Complexes' and Upper Cretaceous-Miocene 'Banda Terrane' stratigraphy.*

Most authors (1) recognize the 'Asian' nature of the 'Banda Terrane', (2) believe Banda Terrane to be thrust onto the NW Australian continental margin during the Late Miocene-present Banda Arc- NW Australian continent collision, and (3) assume that the low-lying, 'para-autochtonous'/ 'Gondwana mega-sequence' represents part of the Australian margin (Audley Charles, Charlton, Harris, Keep and Haig 2009, 2010, etc.). Inspired a.o. by the Molengraaff et al. (1915) observations from Leti, we like to argue that the tie between Timor- Leti metamorphics and the underlying 'Australia/Gondwana sequence' was cemented long before the Banda Arc collision, probably in early or middle Cretaceous, and probably along the Sundaland margin. Most metamorphic complexes are overlain by 'Sundaland' 'Banda Terrane' stratigraphy. If they are not separated by major thrusts (which are often inferred by authors, but can rarely be observed due to inadequate outcrops), the Permian-Jurassic Gondwana sequence, Early Cretaceous metamorphic-ophiolite complex and Late Cretaceous-Miocene Banda Terrane all look like parts of one continuous genetic succession.

This succession represents a tectonic history that is very similar to the scenario that was popular around 1980 (Figure 10) (Barber 1978, re-published in 1981, Earle 1979, 1981, Johnston 1981, Bowin et al. 1981), which shows separation of a sliver from the Gondwana margin in Late Jurassic time, collision of this block with Sundaland in Early Cretaceous, separation of this block (now called 'Lolotoi microcontinent') from the Sundaland margin in the Tertiary (should be Late Miocene-Pliocene; creating the South Banda Sea), and finally collision of this microplate with the Australian NW continental margin in the Latest Tertiary. Remnants of this Sundaland sliver are not only present on Timor and Leti, but also Sumba, Savu and numerous small islands in the inner part of the Outer Banda Arc (Figure 1). This 'Barber model' appears to have lost some popularity, but appears to be a good fit for many of the stratigraphic and paleobiogeographic relationships observed on Timor and Leti. Some of the 'French School' reconstructions are also close to this model (Villeneuve et al., 2010).

This model resurrected here implies that most of the rocks exposed on Timor and Leti are part of the overriding Banda forearc plate, not recently thrusted slivers of Australian continental margin. The only true Australian continental margin sediments would be in the Kolbano- Ofu Complex of Jurassic-Tertiary sediments along the south coast of Timor and the adjacent offshore down to the Timor Trench (blue on Figure 9). These imbricated deep water sediments, scraped off the now-closed Indian Ocean floor and the most distal parts of the NW Australian continental margin, represent the Late Neogene accretionary complex. This structural model makes the drawing of a cross-section of the Banda Arc- NW Australia collision zone a lot simpler, as it does not require huge stacks of imbricated material to fill the space between the downgoing Australian plate and the mountains of Timor.

Finally, the geology of Timor with its multiple compressional and extensional phases is very complex, and is hard to unravel as it is partly obscured by mud volcanoes, olistostromes, inadequate outcrops, etc. The model advocated here is strongly biased towards honoring stratigraphic relationships and unconformities that signify tectonic events. It is in conflict with some radiometric ages, and probably also with certain observed or inferred local structural relationships. However, for those viable alternative explanations can probably be found more easily. Interpretations will undoubtedly continue to evolve for many more years.

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APPENDIX: Leti Island Fossils

The fossils from Leti collected Molengraaff and Brouwer in 1912 were studied by paleontological specialists in Germany (two of whom tragically died in the war in 1914-1915, before publication of their work).

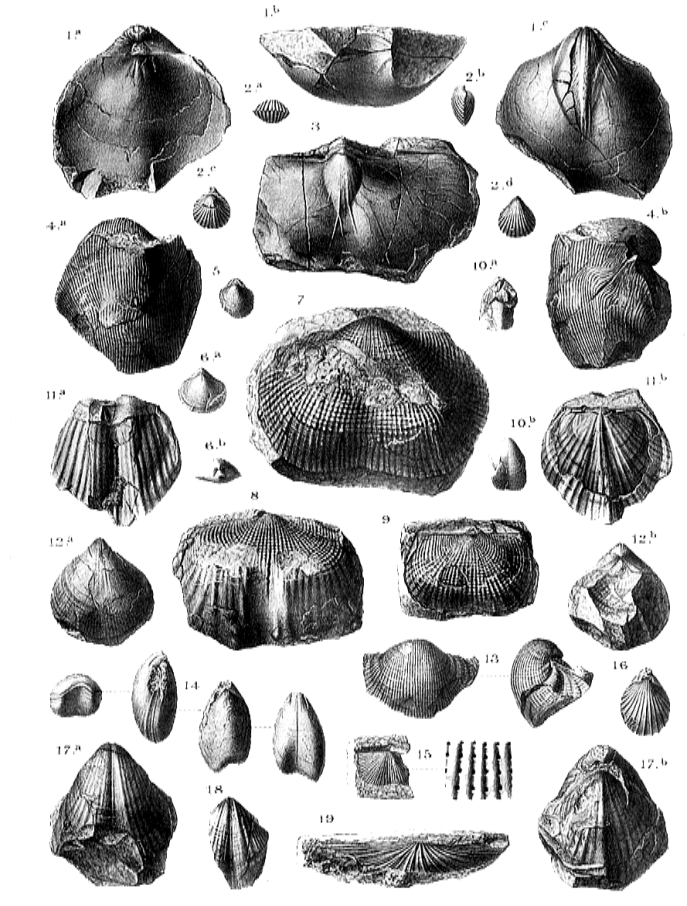


Figure 11. *Permian brachiopods from Letti (Broili 1915)*

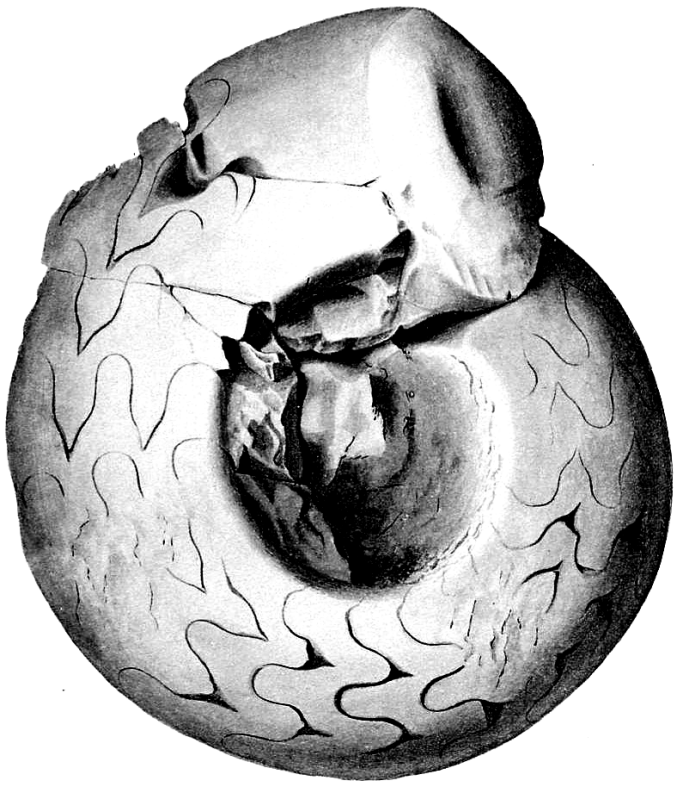


Figure 12. *Ammonoid Paralegoceras sundaicum from Permian greywacke-shale, Leti (Haniel 1915)*

Broili (1915) described a small, but relatively diverse Permian brachiopod assemblage with species of *Spirifer, Productus* and others from shales and sandy shales at the 'small Warlawan' and Boernoewan hills (Figure 11). Many are from concretions and are deformed by 'mountain formation pressure'. Many of the species described are also known from other parts of the world and are apparently not particularly diagnostic for age (other than probable Permian) or biogeography.

Permian ammonoids are relatively rare on Leti and not well preserved. A small collection of molds from greywacke shale at the south slope of Woerlawan II hill contains species identified as *Paralegoceras sundaicum*, *Agathiceras sundaicum* and *Propinacoceras* sp. (Haniel 1915; Figure 12). These species are also common in the Lower Permian of Timor (Bitauni, etc.)

Foraminifera studied by Schubert (1915) include Permian fusulinids, described as *Doliolina lepida* var. *lettensis* (Figure 13). This species from the 'block field' appears to be more complex and probably younger than the fusulinids found in outcrop in the clastics-dominated section in the South of Letti island, which may be more comparable to the relatively simple *Monodiexodina wanneri*, which is locally abundant on Timor.

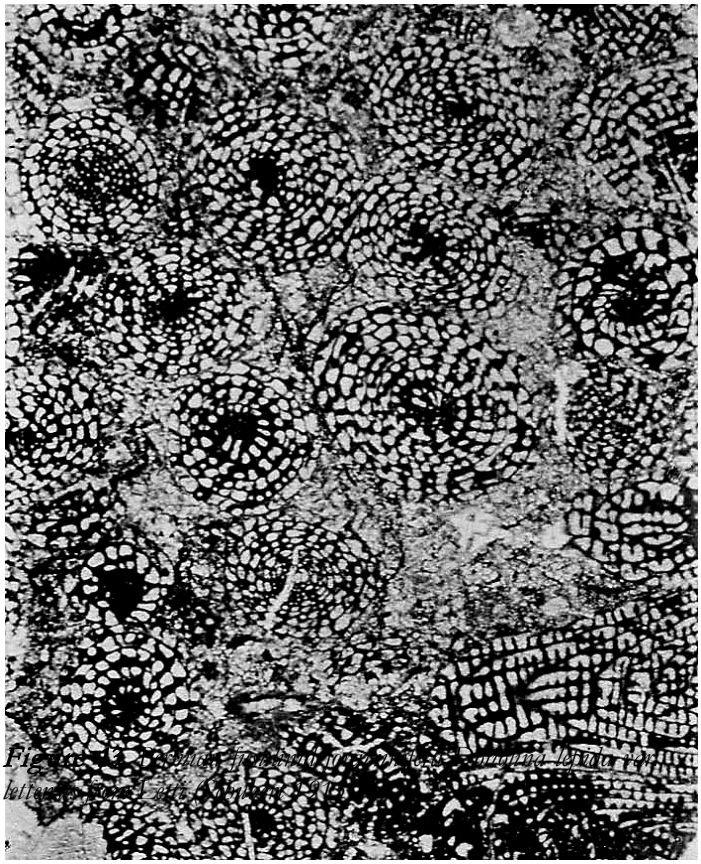


Figure 13. *Permian fusulinid foraminifera Doliolina lepida var. lettensis from Letti (Schubert 1915)*

This species from the 'block field' appears to be more complex and probably younger than the fusulinids found in outcrop in the clastics-dominated section in the South of Letti island, which may be more comparable to the relatively simple *Monodiexodina wanneri*, which is locally abundant on Timor.

Reworked fragments of Upper Cretaceous limestone with *Globotruncana linneana* are present in the Late Oligocene limestone. They are pictured on Plates XIX and XX of Schubert (1915).

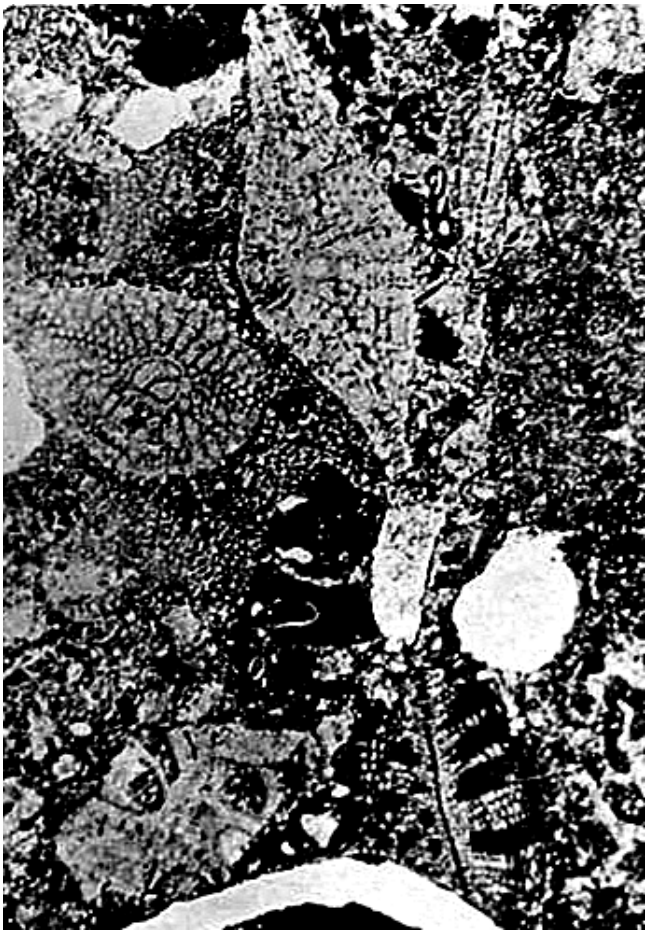


Figure 14. *Latest Oligocene larger foraminifera from Letti, including Lepidocyclina spp and Spiroclypeus (Schubert 1915)*

As described above, 'block fields' and probable in-situ outcrop on the serpentine hills of North Leti contain common shallow marine limestone with *Lepidocyclina* spp. (both *Eulepidina* and *Nephrolepidina* types), *Heterostegina margaritata* (=*Spiroclypeus*), *Miogypsina* cf. *complanata* (= *Miogypsinoides*) and *Rotalia schroeteriana* (more likely *Neorotalia mecatepecensis*). This association clearly represents zone Te4, of latest Oligocene age (Figure 14).