‘Banda Terrane’ basement and cover in the Noil Meto River section, southern West Timor (Timor Barat, Nusa Tenggara Timur, Indonesia)

Tim R. Charlton[1] and Adept Titu-Eki[2]

[1]Saint Omer Ridge, Guildford, Surrey, U.K.

[2]Dept. of Mining Engineering, Univ. of Nusa Cendana, Jl. Adisucipto, Penfui, Kupang, Indonesia

**Corresponding author: timrcharlton@gmail.com*

ABSTRACT

A previously undocumented body of Mutis metamorphic complex is reported from the Noil Meto River, approximately 7km south of Soe town in southern West Timor. Cover sequences overlying the Mutis Complex include the Cretaceous Haulasi Formation (the upper element of the Palelo Group) which most likely has an unconformable relationship to the metamorphic complex; and (possibly) the Permian Maubisse Formation which may overlie the Mutis Complex with an unresolved stratigraphic or structural contact. This is the first substantial documentation of the Mutis Complex and the Palelo Group to the south of the Central Basin. These elements of the so-called Banda Terrane, widely considered allochthonous ‘Asiatic’ elements, are overthrust by Triassic-Jurassic cover sequences (Aitutu and Wai Luli Formations) of the Australian continental margin succession.

Keywords: Banda Terrane, Mutis Metamorphic Complex, Palelo Group, West Timor

Manuscript received: 30 Nov 2022, revised manuscript received: 18 Jan 2023, final acceptance: 6 Feb 2023.

DOI: 10.51835/bsed.2023.49.1.398

INTRODUCTION

The Banda Terrane (Harris, 1991, 2006) is perhaps the most commonly applied name for the stratigraphic association in West Timor that comprises the Mutis metamorphic complex and its sedimentary cover including the Cretaceous-Paleogene Palelo Group (Figure 1). The Mutis Complex and its cover are found most frequently in the northern mountains of West Timor (Figure 2), in massifs such as Mutis (de Roever, 1940; Rosidi et al., 1979, 1981; Sopaheluwakan, 1989), Miomafo (van West, 1941; Sopaheluwakan, 1989), Molo (Tappenbeck, 1939; Earle, 1980), Boi (Tappenbeck, 1939; Audley-Charles and Carter, 1972; Earle, 1980) and numerous others (e.g. van Voorthuysen, 1940; de Waard, 1954, 1957a, b, 1959; Barber and Audley-Charles, 1976). To

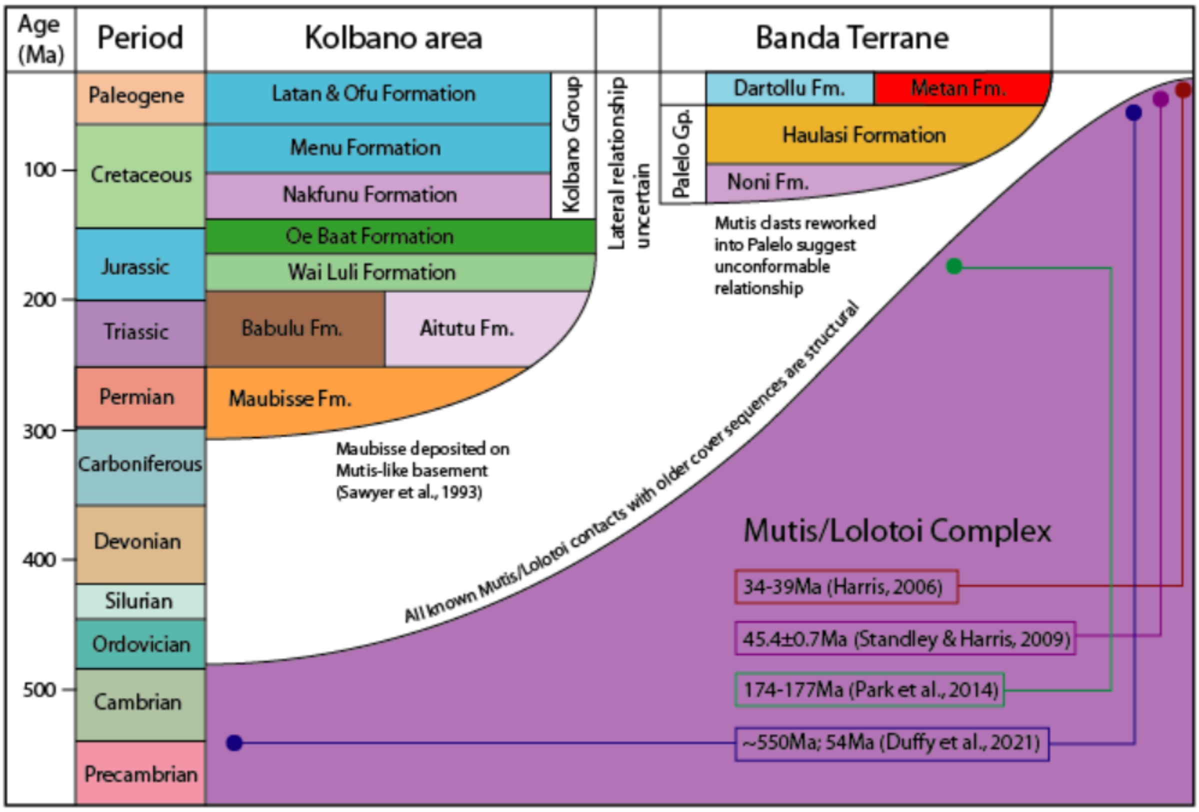

Figure 1: *Pre-Neogene stratigraphic summary for cover sequences in the Banda Terrane and the Kolbano area (location Figure 2), together with metamorphic ages reported for the Mutis metamorphic complex of West Timor and its equivalent the Lolotoi Complex in Timor-Leste.*

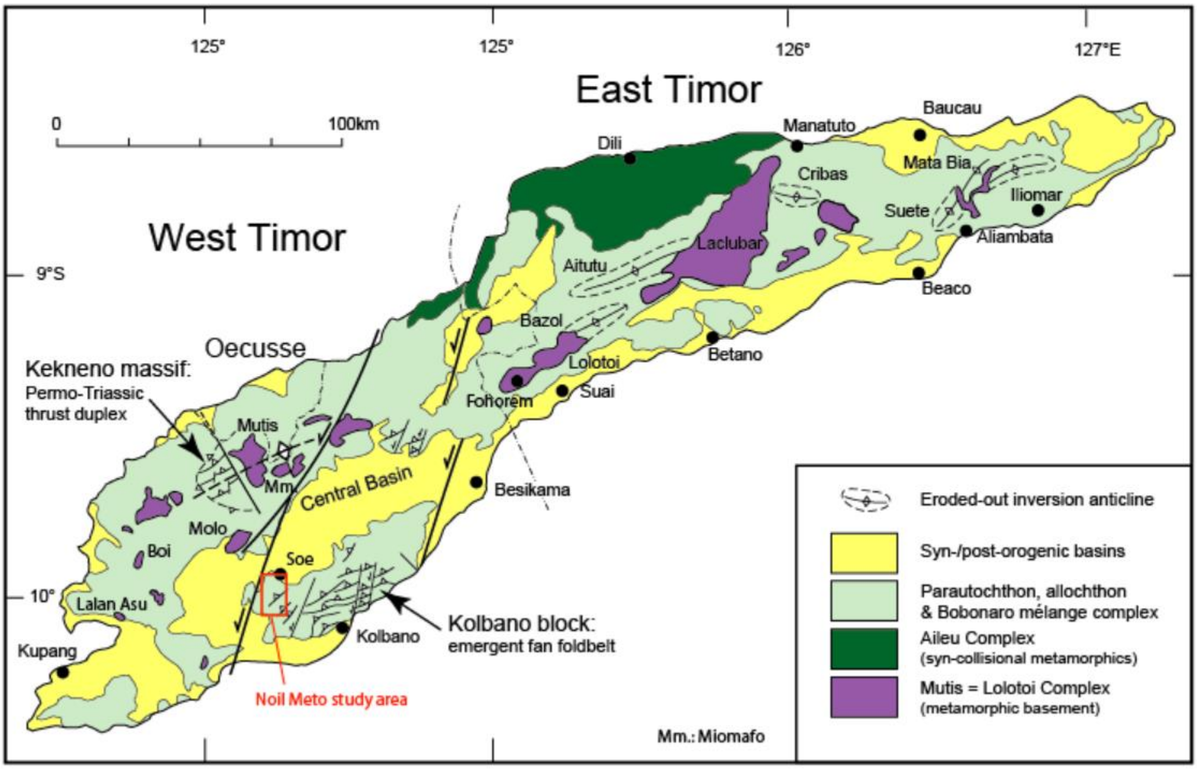

Figure 2: *Location of the Noil Meto study area in south-central West Timor, and the distribution of metamorphic massifs (Mutis Complex in West Timor; Lolotoi Complex in East Timor) across the island.*

date, however, there have been only the briefest indications for the presence of the Mutis Complex to the south of the Central Basin in West Timor (e.g., Sawyer et al., 1993), and as far as the present writers are aware, no reports so far of the Palelo Group in this area. The present short paper documents the occurrence of a substantial body of the Mutis Complex and a cover section including Haulasi Formation (upper Palelo Group) in the Noil Meto River to the south of Soe town in south-central West Timor (Figure 2).

The Noil Meto River originates in Soe town, the administrative centre for Kabupaten (administrative district) Timor Tengah Selatan (South Central Timor). The river arises from the main water springs in Soe town, which develop where porous Quaternary limestones overlie relatively impermeable Triassic Aitutu Formation (Barkham, 1993) at an elevation of

~830m. From this point Noil Meto runs approximately 21km to the southwest, eventually forming a tributary of the larger Noil Mena River. Over a distance of about 8km SW from Soe the river falls to elevations of ~300m, showing a distinctly concave topographic profile with initially very steep and unstable slopes immediately south of Soe, but downstream becoming more gently inclined, with the main river course, as it merges with smaller tributaries, eventually taking the form of a broad, boulder-covered, moderately inclined river plain many tens of metres wide, as is typical of most larger rivers in Timor during the dry season. Downstream from the 300m elevation contour, the river enters a topographically less extreme domain in the valley of the lower Noil Mena River system. Geological exposures on the upstream part of the river are substantial, but downstream outcrops are minimal (Barkham, 1993), largely restricted to syn/post-orogenic successions and the Bobonaro Complex (Rosidi et al., 1979).

PREVIOUS WORK

The GRDC/PPPG 1:250,000 scale reconnaissance geological map of West Timor (Rosidi et al., 1979, 1981) indicates the geology of Noil Meto as consisting of Permian Maubisse Formation and Bobonaro Complex mélange. However, as pointed out by Barkham (1993), neither of these mapping units outcrops to any significant extent in the upper reaches of Noil Meto. Barkham recognised five geological mapping units along the river course (Figure 3). At the source of the river is the Quaternary limestone, assigned on the GRDC map to the Coralline Limestone mapping unit, which is the direct equivalent to the Baucau Formation as defined by Audley-Charles (1968) in East Timor. Locally below this is the Plio-Quaternary Noele Formation, although Barkham only observed this in a single outcrop. The main part of the upper Noil Meto River section exposes fine grained white limestones interbedded on a dm scale with light to dark grey shales of the Aitutu Formation which is of broadly Late Triassic age; and medium to dark grey shales with minor interbeds of limestone and sandstone that is predominantly Jurassic age and is assigned to the Wai Luli Formation. These two formations occur together in a complex series of structural repetitions with an imbricated fold and thrust belt style of deformation, showing a primarily southward vergence of structures, overprinted by a significant degree of left-lateral faulting with a predominant NNE-SSW orientation (Barkham, 1993; Figure 3). The limestones of the Triassic Aitutu Formation apparently correspond in general terms to the Maubisse Formation as indicated in the GRDC mapping, while the rather strongly deformed shale successions of the Wai Luli Formation probably correspond to the Bobonaro Complex as mapped by Rosidi et al. (1979). Additional studies of the Aitutu-Wai Luli succession in Noil Meto were undertaken by Edith Kristan-Tollmann in collaboration with Simon Barkham (Kristan-Tollmann et al., 1987; Kristan-Tollmann, 1988a, b), but while these papers provide important additional stratigraphic-palaeontological details on the Noil Meto succession, they have little relevance to the present study and will not be considered further here.

The fifth geological mapping unit recognised by Barkham (1993; Figure 3) was located at the southern end of the mapped river section, indicated on his map as 'fine sands, stratigraphically undefined'. Barkham described this unit as consisting of lustrous purply-grey to light grey fine sandstones, in all exposures fairly strongly deformed, either intensively calcite-veined or sheared, and forming pencil cleaved rocks. Bedding, where seen, is planar on a scale of 1-15cm, with no additional sedimentary structures observed. In thin section the sandstones were described as sub-lith arenites, angular to subrounded, primarily composed of monocrystalline quartz (>80%), with 5% lithic fragments, and <1% feldspar. Grains are cemented by quartz. No fossils were observed, and no associations with other lithologies were recorded. It proved impossible for Barkham to determine either a palaeontological age or assign this lithology to any recognised stratigraphic formation. Barkham noted that the sands lacked significant mica typical of the Triassic Babulu Formation of the Kekneno area to the north (Cook, 1986; Bird, 1987; Bird & Cook, 1991), and lacked glauconite typical of the Jurassic Oe Baat Formation in the Kolbano area to the east (Charlton, 1987).

Sawyer et al. (1993) reported the results of extensive fieldwork undertaken by oil company Amoseas in their Soe

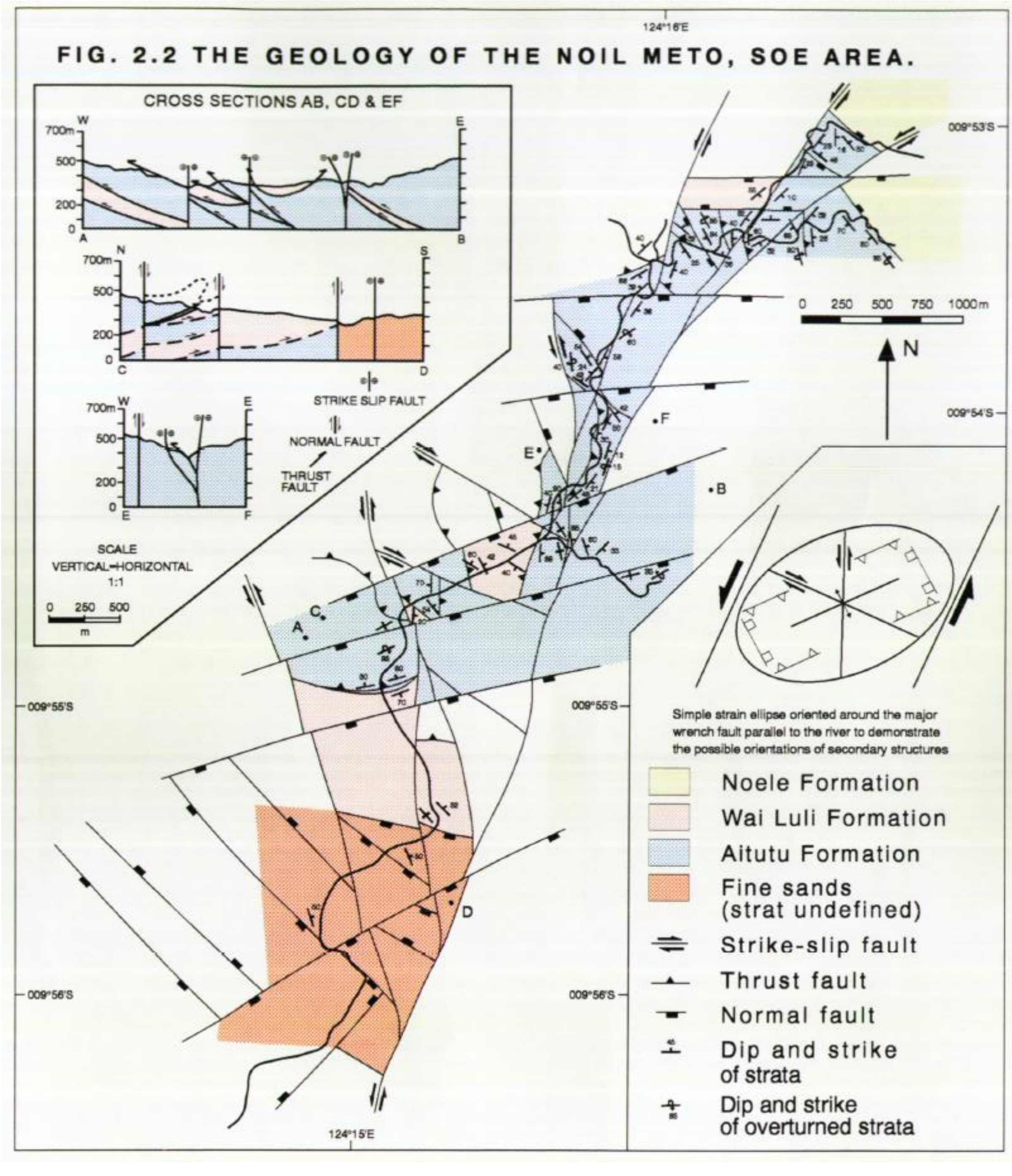

Figure 3: *Geology of Noil Meto as mapped by Barkham (1993).*

Petroleum Production Sharing Contract (PSC) block which covered much of southern West Timor. They mentioned several outcrops from Noil Meto, including reference to samples of a 'klippe of the Banda Terrane (RKS-94)', presumably Mutis metamorphic complex, and 'Maubisse Formation (RKS-161)'. Their accompanying location map places sample RKS-94 some distance to the north of the area mapped in Figure 5 (see below), while sample RKS-161 would locate within the central region of Figure 5. However, poor location accuracy in the Amoseas field survey, which was carried out before the ready availability of GPS location, makes it difficult to tie their sample locations precisely to more recent mapping.

In a PhD study focussed primarily on zircon age dating, Sebastian Zimmerman re-sampled Barkham's (1993) sandstone section in Noil Meto (Zimmermann, 2015; Zimmermann and Hall, 2016, 2019). Three samples were collected from Noil Meto: SZ 44, SZ 46, and SZ 47:

Sample SZ 44 was reportedly collected at latitude/longitude (9.92341°S, 124.24902°E = 9°55.405'S, 124°14.941'E). The rock was described from outcrop as a massive grey siltstone, and from thin section as a sub lithic arenite, poorly to moderately sorted and subangular. The sample yielded 128 zircon grains, from which a youngest age of 148.2±2.1 Ma was obtained by radiometric dating, suggesting a latest Jurassic (Tithonian) or younger age of deposition for the sediment (Zimmermann, 2015; Zimmermann and Hall, 2016). Apparently based on this Late Jurassic age determination, these authors assigned the rock to the Oe Baat Formation, which is an age-equivalent sandstone succession in the Kolbano area to the east of Noil Meto (Figures 1 and 2).

Sample SZ 47 was collected at (9.92198°S, 124.25571°E = 9°55.319'S, 124°15.343'E). This was described from outcrop as a massive sandstone, and in thin section as a lithic sub arenite, moderately to well sorted and subangular. The sample yielded 132 zircon grains, with the youngest dated at 75.50±1.4 Ma, indicating a Campanian (Late Cretaceous) maximum depositional age for the sediment (Zimmermann, 2015; Zimmermann and Hall, 2019). Zimmermann (2015) assigned this rock to the Oe Baat Formation or possibly the Bobonaro Complex, while Zimmermann and Hall (2019) considered it part of a different, so far unnamed formation.

Sample SZ 46 was collected at (9.92273°S, 124.25242°E = 9°55.364'S, 124°15.145'E), and was described as a fine-grained sandstone. No zircons were obtained from the sample (Table 1), and it could not therefore be dated radiometrically. Zimmermann (2015) indicated that the sample was collected from the Triassic Aitutu Formation, although supporting evidence for an origin of this siliciclastic sandstone within the essentially carbonate-clastic Aitutu Formation was not presented.

Two additional samples collected by Zimmermann are relevant to the Noil Meto sampling. SZ 26 and SZ 27 were collected in Noil Haulasi, the type locality for the Haulasi Formation (the upper part of the Palelo Group: Rosidi et al., 1981; Figure 1). This river section is located on the SE flank of the Miomafo metamorphic massif in north-central West Timor (Figure 2). Sample SZ 26 was collected at (9.55642°S, 124.36541°E = 9°33.385'S, 124°21.925'E), and SZ 27 at (9.55424°S, 124.36614°E = 9°33.254'S, 124°21.968'E).

These samples were described by Zimmermann (2015) as arkosic to sub lithic arenites, moderately to well sorted and subangular. Zimmermann (2015) noted petrographic and composition similarity between particularly sample SZ 47 from Noil Meto and sample SZ 27 from Noil Haulasi. The Haulasi Formation in northern West Timor has a probable age range of Late Cretaceous-Paleogene (e.g. Tappenbeck, 1939; van West, 1941; Rosidi et al., 1981), while an equivalent succession in Timor-Leste has been dated to the Late Cretaceous based on palynology (MG Palaeo report to Timor Resources, quoted in Charlton et al., 2018); and late Albian-late Cenomanian and late Coniacian-Maastrichtian based on calcareous nannofossils (Timor Gap field sampling, with age control by P.T. Rafflesia Baru Jakarta, unpublished report to Timor GAP, 2020). These ages are consistent with the zircon-determined age for sample SZ 47 (Campanian, Late Cretaceous or younger).

Table 1: *Zimmermann's (2015) tabulated rock and heavy mineral compositions for 3 samples from Noil Meto (SZ 44, SZ 47, and SZ 46) together with two from Noil Haulasi (SZ 26 & SZ 27), SE flank of the Miomafo massif and the type locality for the Haulasi Formation (upper Palelo Group).*

	SZ 44	**SZ 47**	**SZ 46**	**SZ 26**	**SZ 27**
Monocrystalline quartz	21.6	10.2		12.0	6.4
Volcanic quartz	13.0	11.4		14.4	4.2
Polycrystalline quartz	9.0	25.4		12.4	30.0
Plagioclase	6.0	4.4		13.6	3.6
K feldspar	11	8.6		7.6	8.2
Lithic fragments	17.4	18.2		18.2	3.8
Glauconite	0.2	-		-	-
Bioclasts	-	-		0.8	0.4
Matrix	4.4	3.8		3.0	2.2
Mica	2.2	4.2		3.2	3.8
Heavy minerals	1.6	2.2		5.0	8.2
Carbonate	-	-		-	9.2
Other	13.6	11.6		9.8	-
Zircon	18.0	27.8	-		
Tourmaline	3.0	0.9	-		
Apatite	34.0	29.5	3.0		
Pyroxene	2.0	-	71.5		
Rutile	0.5	1.3	-		
Garnet	7.0	1.3	0.5		
Epidote	-	0.9	8.5		
Andalusite	13.0	0.9	2.0		
Sillimanite	1.0	2.6	-		
Chrome spinel	-	0.2	-		
Chlorite	21.5	29.8	14.0		
Staurolite	-	1.3	-		
Other minerals	-	3.5	0.5		
Acid igneous	21.0	28.6	0.0		
Basic igneous	2.0	0.0	71.5		
Metamorphic	43.0	38.2	25.0		

NEW FIELD OBSERVATIONS

1. Noil Meto

On a previous visit to the area in 2011, during a field trip organised by Eni and Hess oil companies to investigate their West Timor PSC, TC observed the presence of Mutis Complex in the lower course of Noil Meto River. The intriguing new results from this area reported by Zimmermann (2015) did not mention the presence of Mutis Complex, and the possible significance of 'Australian margin' Late Jurassic Oe Baat Formation in close relationship with 'Banda Terrane' Mutis Complex was therefore not considered in that study. The authors of the present report determined to re-visit Noil Meto to address structural-stratigraphic relationships in the lower course of the river section.

At the start of the traverse, we walked upstream through river gravels, including a final section of strongly dipping (~35°S) river gravels at least 30m thick exposed immediately south of the first GPS locality (site M1: see Table 2 and Figure 5). At locality M1 is a rather poor outcrop of blocky Mutis Complex greenstone. At river level exposure is mainly of fallen blocks, but genuine greenstone outcrop is seen some 10m up the steep slope. Blocks in the slope also include at least two boulders of Maubisse Formation Permian crinoidal limestone (Figure 4b), and it is possible that these have fallen from above, based on subsequent interpretation of Google Earth imagery (see below). The slope also contains hard, reddish shaly material, possibly also Permian in age.

Working upstream along the east bank of the river, further outcrops of pure Mutis Complex with no further Maubisse blocks occur at outcrop localities M2-M9 (Table 2; Figure 5). Lithologies observed along this section consist primarily of meta basic greenstone (Figure 4a), with relatively minor occurrences of schistose metasediments. Both lithologies are very typical of the Mutis Complex regionally.

Immediately upstream from a final Mutis Complex outcrop at M9 are poorly exposed sandstones. One hand specimen of sandstone examined from near locality H1 consisted of a hard, clean, laminated fine to medium quartz sandstone. These sandstones can be traced back southward along a small path, that runs above a gently

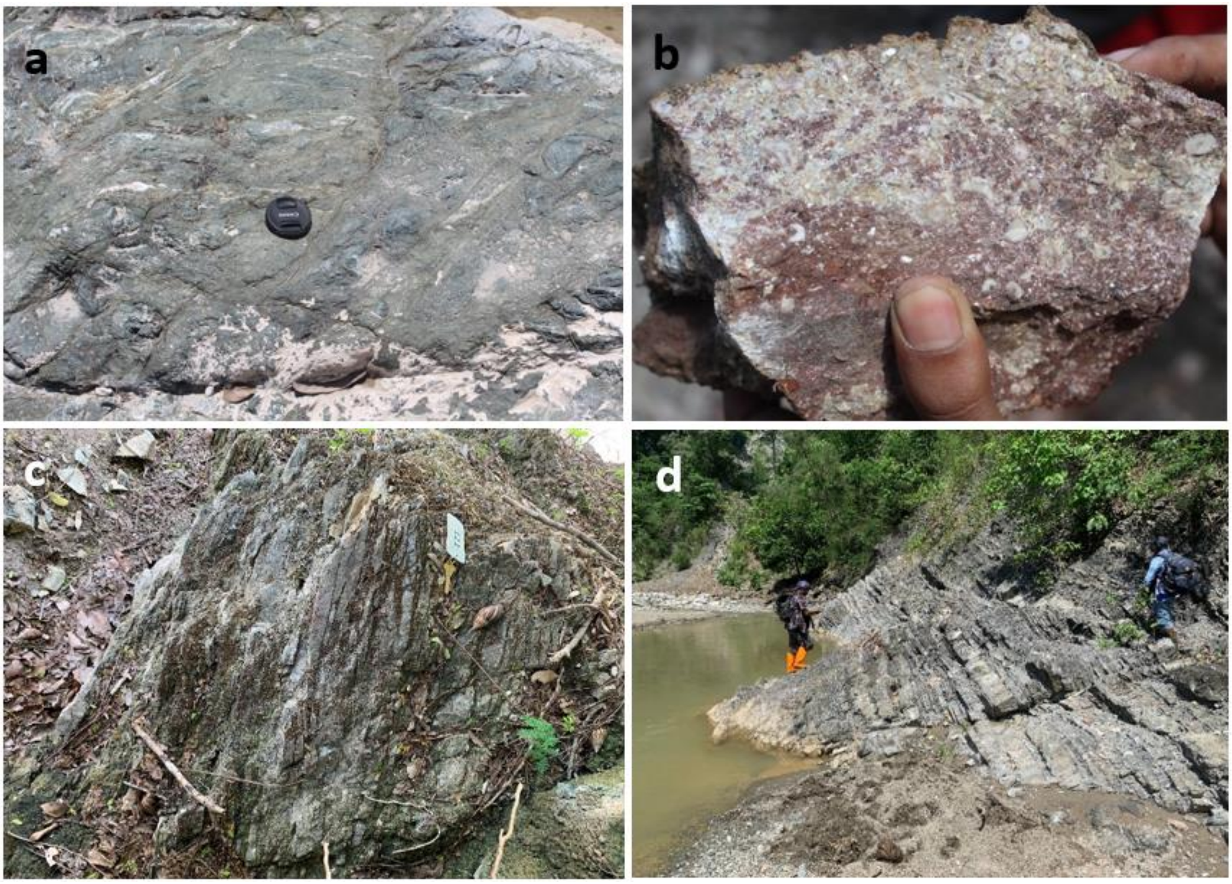

Figure 4: *(a) Mutis Complex greenstone. (b) Maubisse Formation crinoidal limestone clast from outcrop at locality M1. (c) Haulasi Formation in Noil Meto (our locality H3 = Zimmermann's (2015) locality SZ 47). (d) Haulasi Formation in Noil Haulasi, type locality of the Haulasi Formation (Rosidi et al., 1981). This photo was taken midway between Zimmermann's (2015) localities SZ 26 and SZ 27.*

northward- (upstream-) inclined surface on the top of the Mutis Complex, and although exposure is poor, it appears that the sandstones overlie the metamorphic complex above a gently northward-dipping unconformity(?) surface (Figure 6). Thus, outcrop at H1 is in the sandstone unit above the Mutis unit, higher up the hill slope (Figure 5). These sandstones continue upstream in poor outcrop to locality H2 where there is a large but poor outcrop of sandstone, yellowish and fairly hard, fine to medium grained, largely massive but possibly laminated on a multi-dm scale. Then at locality H3, which corresponds to Zimmermann's (Campanian or younger) SZ 47 locality, is a rather larger outcrop

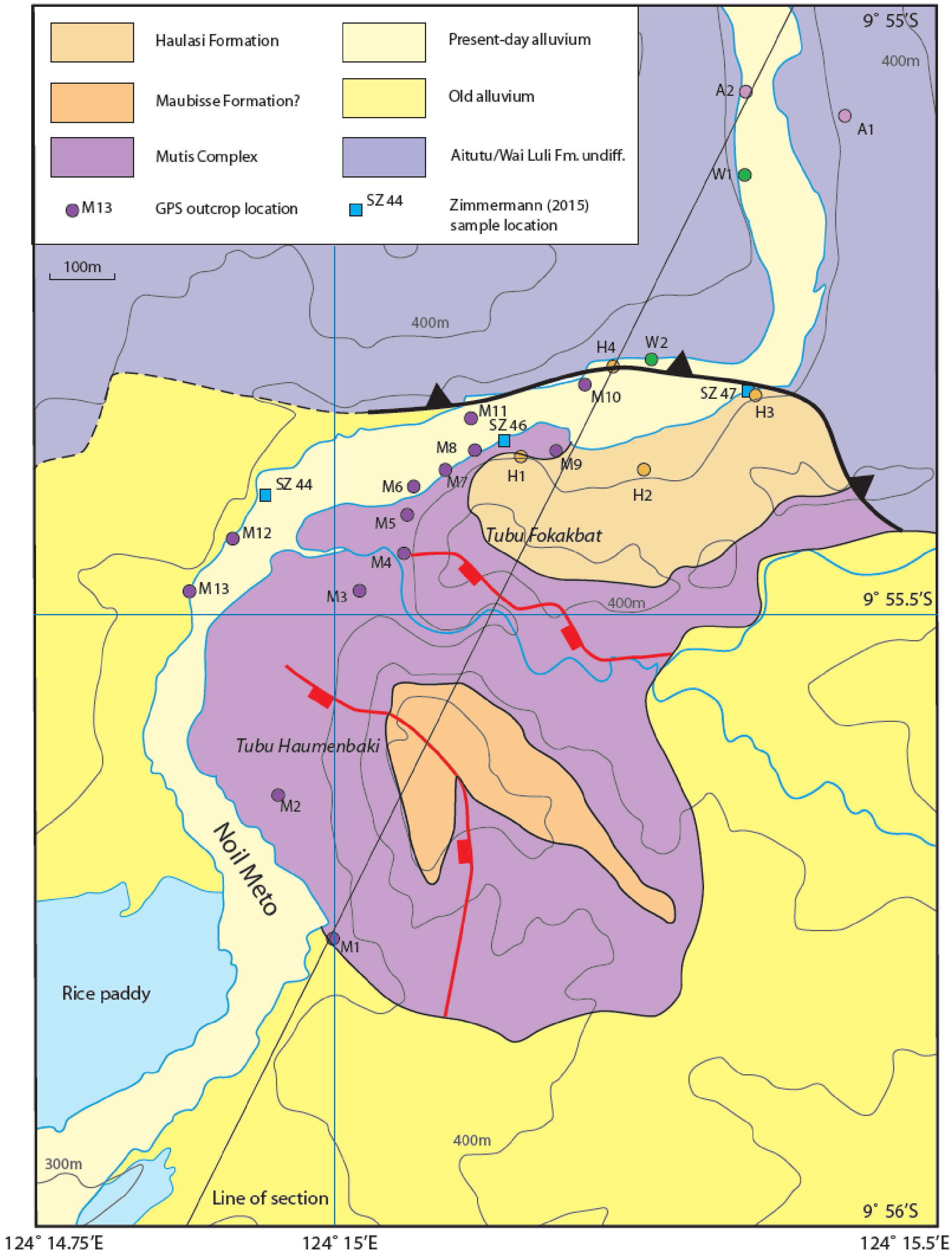

Figure 5: *Geology of the lower section of Noil Meto from GPS-constrained fieldwork and interpretation of Google Earth imagery. Topography at 50m interval contoured from Google Earth.*

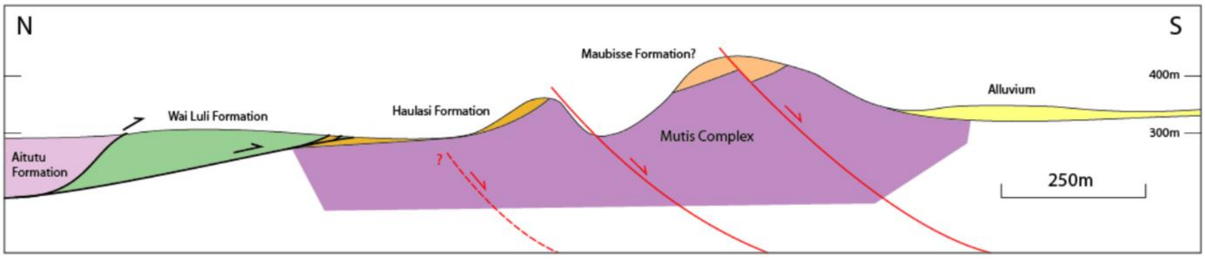

Figure 6: *Cross-section through the Mutis massif in Noil Meto. No vertical exaggeration. Line of the section is in Figure 5.*

of hard and moderately deformed sandstones and siltstones veined by calcite (Figure 4c).

While the H3 locality can be matched precisely with Zimmermann's SZ 47 sample site, Zimmermann's sample locality SZ 44 could not be matched directly to a sandstone outcrop. Zimmermann's reported GPS coordinates (9.92341°S, 124.24902°E = 9°55.405'S, 124°14.941'E) locate within the river plain towards the western bank of the river, and this west bank only exposes older river gravels. Zimmermann's third sample locality, SZ 46 (9.92273°S, 124.25242°E = 9°55.364'S, 124°15.145'E) locates close to our H1 locality, although separated from H1 by an outcrop area of Mutis Complex.

Upstream from the final sandstone outcrop on the east bank (H3) is a gap in exposure, although the river gravels here include numerous soft grey clay balls, probably indicating sub crop of Wai Luli Formation shales below the river gravels (the extreme softness of these clay balls would preclude long distance transport in the river gravels).

Further north up the east bank, the hill slope at locality A1 consists of Aitutu Formation limestone blocks, but there is no outcrop. Directly opposite on the west bank of Noil Meto at locality A2 is good outcrop of a simply dipping (40°NW/053°) succession of Aitutu Formation consisting of dm-bedded limestones with only thin intervening shales. Downstream along the western riverbank, at locality W1 are deformed grey shales, presumably Wai Luli Formation near to a thrust plane. The shales also contain entrained blocks of Aitutu limestone. Broadly similar deformed shales continue along the west

Table 2: *Outcrop field data*

Code	Latitude	Longitude	Notes
M1	9°55.768’ S	124°12.998’ E	Greenstone metabasites; also, Maubisse crinoidal limestone and indeterminate red shale blocks.
M2	9°55.649’ S	124°14.952’ E	Greenstone metabasite, minor schist.
M3	9°55.484’ S	124°15.052’ E	Greenstone.
M4	9°55.453’ S	124°15.057’ E	Greenstone.
M5	9°55.418’ S	124°15.060’ E	Greenstone.
M6	9°55.395’ S	124°15.065’ E	Large hill to E appears to be composed of Mutis Complex.
M7	9°55.386’ S	124°15.091’ E	Large hill to E appears to be composed of Mutis Complex.
M8	9°55.365’ S	124°15.115’E	Greenstone.
M9	9°55.366’ S	124°15.183’E	Greenstone.
M10	9°55.314’ S	124°15.208’E	Metamorphic in shear zone?
M11	9°55.347’ S	124°15.112’E	Small blocky outcrop of Mutis greenstone.
M12	9°55.445’ S	124°14.915’E	Blocky Mutis outcrop continuing.
M13	9°55.485’ S	124°14.879’E	And continuing.
H1	9°55.372’ S	124°15.154’E	On sandstone above Mutis. Contact dips ~10°N.
H2	9°55.382’ S	124°15.256’E	Large but poor sandstone outcrop, massive to multi dm-laminated. Yellowish, fairly hard, fine to medium grained.
H3	9°55.320’ S	124°15.348’E	Hard and moderately deformed sandstone-siltstone succession, calcite veined. Poor outcrop. Dip 50°E/165°.
H4	9°55.300’ S	124°15.235’E	Wai Luli shales upstream and downstream of this sandstone body.
A1	9°55.093’ S	124°15.424’E	No outcrop: slope of Aitutu limestone blocks.
A2	9°55.070’ S	124°15.342’E	Dm bedded Aitutu limestone with only thin shales. Dip 40°NW/053°.
W1	9°55.140’S	124°15.341’E	Deformed grey shale with entrained Aitutu limestone blocks.
W2	9°55.294’S	124°15.267’E	Coherent outcrop of Wai Luli shales.

bank for a further ~100m, followed by a gap in exposure.

At locality W2 is a coherent outcrop of bedded Wai Luli Formation, and similar section continues downstream sporadically for ~80m before what appears to be an outcrop of the sandstone unit at locality H4. But then 20m further downstream from this are more highly sheared Wai Luli shales crosscut by calcite veins. Sheared outcrop continues to locality M10 which is a further outcrop of Mutis Complex, after which there is a gap in exposure until another outcrop of Mutis greenstone at locality M11; and another at M12 which is semi-continuous to the final recorded GPS locality at M13, after which outcrop of Mutis Complex continues for a further 20m downstream before only older river gravels are exposed in the western riverbank.

2. Noil Haulasi

In our fieldwork we also visited the location of Zimmermann's (2015) sample sites SZ 26 and SZ 27. These samples were taken from exposures in a well-bedded sandstone-siltstone-shale succession along the river Noil Haulasi, which is the type locality for the Haulasi Formation (upper Palelo Group: Rosidi et al., 1981; Figure 1). As has already been mentioned, Zimmermann (2015) highlighted the petrographic and composition similarity between particularly sample SZ 27 from Noil Haulasi and sample SZ 47 from Noil Meto. The general similarity of outcrop lithologies in the two river sections is illustrated in Figures 4c & d.

INTERPRETATION

Figure 5 shows a reconnaissance geological map of the Noil Meto field area based on our GPS-constrained field data and interpretation of Google Earth imagery, while Figure 6 shows a north-south cross-section through the mapped area. The map locates a body of Mutis metamorphic complex approximately 1km in diameter in the hills Tubu Haumenbaki and Tubu Fokakbat (names as shown on the local Bakosurtanal 1:25,000 topographic map sheet). The Mutis Complex is mapped as overlain by two distinct bodies of cover sequence. In the more southerly hill Tubu Haumenbaki the Mutis Complex is interpreted to be overlain by a gently NE-dipping body of sedimentary rocks, provisionally interpreted as Permian Maubisse Formation based on fallen blocks observed at field locality M1 (Figure 4b); we did not climb to the top of this hill during our preliminary fieldwork. The Maubisse(?) outcrop body appears to be cut by a southeastwardly-throwing normal fault (shown on the map by the red line with square teeth in the fault hanging wall). The Mutis Complex exposed on the more northerly hill Tubu Fokakbat is interpreted to be overlain by a body of Haulasi Formation (discussed further below), the basal contact of which dips gently northward (perhaps ~10°N based on our field observations). The two Mutis hills are separated by a second normal fault down throwing to the SW. The sinuosity of the two fault traces relative to topography suggests that the southern fault dips to the SW at about 50°, while the more northerly fault is less-well constrained, but may dip about 60°SW.

The cover succession on the northern hill Tubu Fokakbat is interpreted as Haulasi Formation. This interpretation is based on the observation of petrographic and composition similarity between sample SZ 47 from Noil Meto and sample SZ 27 from the type section of the Haulasi Formation (Zimmermann, 2015); on the Late Cretaceous or younger zircon radiometric age for sample SZ 47; and on our own observations of the similarity in lithology between the Noil Meto sediments and sandstone successions in the Haulasi Formation type section (Figures 4c and d).

There remains, however, the problem of the Late Jurassic (or younger) zircon radiometric age obtained for sample SZ 44 (Zimmermann, 2015; Zimmermann and Hall, 2016). Three plausible scenarios may explain this age:

1. The Haulasi Formation ranges in age back to the Late Jurassic in the Noil Meto area.

2. The Haulasi Formation in Noil Meto is Late Cretaceous in age as elsewhere in Timor, but sample SZ 44 happens not to have yielded any Cretaceous zircons.

3. Sample SZ 44 should be assigned to the Late Jurassic Oe Baat Formation of the Kolbano area (cf. Zimmermann, 2015).

Unfortunately, we could not verify the character of the SZ 44 sample locality because the given GPS coordinates for this sample site did not match with any outcrop found during our fieldwork. Certainly, the outcrop photograph of the SZ 44 locality in Zimmermann's (2015) thesis appears broadly comparable in lithology to the Haulasi Formation, and therefore an assignment to this formation seems appropriate on lithological grounds. However, it seems unlikely that very similar depositional environments would have persisted in the Noil Meto area throughout the entire period from the latest Jurassic to the Late Cretaceous, Campanian (a time span of some 70 million years), and so the local extension of the age range of the Haulasi Formation from the Late Cretaceous back to the Late Jurassic seems to us an unlikely possibility.

Perhaps more likely is that the rock at locality SZ 44 is Late Cretaceous in age (as for sample SZ 47 and the Haulasi Formation in its type locality) but that the original SZ 44 sediment happened to receive no reworked Cretaceous zircons. It is noteworthy that samples SZ 44 and SZ 47 contain zircons with strikingly different age profiles. The Late Cretaceous or younger sample SZ 47 contains zircon grains of Cretaceous age (12.1%); no grains of Jurassic age; and Permo-Triassic (12.9%), Cambrian to Carboniferous (15.9%), Proterozoic (55.3%) and Archaean (3.8%) ages. The Late Jurassic or younger sample SZ 44, in contrast, contains primarily Phanerozoic zircon grains, with only a single Proterozoic and no Archaean zircons, and with nearly all the Phanerozoic grains (85.9%) yielding Jurassic ages, and the remainder (13.3%) dating to the Permo-Triassic interval. It may be significant that the peak age for the Jurassic zircons in sample SZ 44 (160-180 Ma: Zimmermann, 2015) coincides closely to the age of zircons from the Lolotoi Complex (East Timor equivalent of the Mutis Complex) in the Fohorem area of SW Timor-Leste (174-177 Ma: Park et al., 2014; location of Fohorem in Figure 2). If the Mutis Complex in Noil Meto has a similar protolithic age to the Lolotoi Complex in the Fohorem area, then perhaps the SZ 44 sediment was only receiving zircons through erosion of its local (Early to Middle Jurassic) basement during unroofing in the Late Cretaceous. In contrast, the SZ 47 sediment was presumably receiving clastic input from a distinct source, perhaps the northwest Australian continental margin given the high proportion of Proterozoic and early

Phanerozoic (Triassic and older) zircons in that sample – although an Australian margin sedimentary source is not compatible with the usually interpreted allochthonous 'Banda Terrane' origin for the Haulasi Formation.

It seems unlikely to us, despite its apparent Late Jurassic zircon age, that sample SZ 44 could be assigned to the Oe Baat Formation (cf. Zimmermann, 2015). Although this sample contains very minor glauconite (0.2%: Table 1), this is considerably less than the richly glauconitic sandstone and siltstone successions of the Oe Baat Formation of the Kolbano area, where point counts from four thin sections yielded glauconite percentages ranging from 12-49% (mean 25%: Charlton, 1987, Figure 6.5).

Considering all the evidence, it seems to the present writers that the most likely explanation for the Late Jurassic zircon age for sample SZ 44 (Zimmermann, 2015) is that the original sediment was deposited during the Late Cretaceous as part of the Haulasi Formation, but that its zircons, which are dominantly of Early-Middle Jurassic age, derive from erosion of a geographically restricted basement terrane – presumably the locally sub cropping Mutis Complex that may have a Jurassic protolithic age comparable to the Fohorem Lolotoi Complex in East Timor (Park et al., 2014). Sample SZ 47, which yielded a Late Cretaceous zircon age and is petrographically and compositionally comparable to the Haulasi Formation in its type locality in northern West Timor, may have been deposited broadly contemporaneously in the Late Cretaceous, but with a distinct clastic sedimentary provenance. We also suspect that sample SZ 46, which yielded no zircons, is also assignable to the Haulasi Formation rather than to the Triassic Aitutu Formation as was suggested by Zimmermann (2015).

In Noil Meto the body of Mutis Complex and its two cover successions are probably overthrust on their northern boundary by the combined Aitutu-Wai Luli cover succession exposed in the upper course of the river (Figure 6; cf. Barkham, 1993). Evidence for this over thrusting is seen along the E-W section of Noil Meto River in Figure 5, including strong shearing of Wai Luli Formation with entrained blocks of Aitutu Formation (locality W1), the occurrence of Haulasi-type sandstones at locality

H4 sandwiched between outcrops of Wai Luli Formation shales, and the sheared nature of the most northerly outcrop of Mutis Complex on the western riverbank (locality M10). The curvature of the inferred thrust trace (black line with triangular tooth symbols in the fault hanging wall: Figure 5) suggests late domal uplift of the sub thrust Mutis block. Late-stage doming is also suggested at the southern margin of the Mutis block where older river gravels are tilted to dips of ~35°S immediately south of outcrop locality M1.

CONCLUSIONS, WIDER TECTONOSTRATIGRAPHIC IMPLICATIONS AND FURTHER WORK

The occurrence of a substantial body of Mutis Complex in southern West Timor, immediately west of the Kolbano fold and thrust belt (emergent fan duplex: Charlton et al., 1991; Figure 2) is highly significant for the gross structure of the Timor orogenic belt. The Mutis Complex and the Haulasi Formation together comprise typical elements of the so-called Banda Terrane of Timor (e.g., Harris, 1991, 2006), and are widely interpreted as allochthonous elements, derived from the northern side of the pre-collisional Banda Arc – Australia plate boundary, and fundamentally distinct from the Australian continental margin succession represented in this area by the Aitutu and Wai Luli Formations (Figure 1). As an allochthonous body, the Banda Terrane should occupy a very high structural position, thrust over the par autochthonous elements of the Australian continental margin succession. But, as in many other massifs of the Mutis/Lolotoi Complex across Timor, this is not the case for the Mutis-Haulasi structural element in Noil Meto, which is apparently overthrust by the Australian margin Aitutu-Wai Luli succession. A simpler explanation for the structural relationships in the Noil Meto section is that the Mutis Complex represents differentiated Australian continental margin basement that formed a relatively high-standing horst block on the pre-collisional Australian continental margin, capped by a relatively restricted horst-top succession represented by the Haulasi Formation (and perhaps the Maubisse Formation: see below). Meanwhile the standard Australian margin succession including the Aitutu and Wai Luli Formations accumulated in graben basins adjacent to the Mutis horst block. Then, during collision, the graben successions were simply thrust over the adjacent Mutis-Haulasi horst block.

It also appears that the Mutis Complex in Noil Meto may be overlain by the Permian Maubisse Formation as well as the Cretaceous Haulasi Formation. The relationship between the Mutis/Lolotoi Complex and the Maubisse Formation has long been controversial, with many authors assigning the Maubisse Formation to the allochthon together with the metamorphic complexes (e.g., Audley-Charles, 1968; Rosidi et al., 1981), but there is clear palaeontological, stratigraphic and palaeomagnetic evidence linking the Maubisse Formation to the Australian continental margin succession (summarised in Charlton et al., 2002). An unconformable relationship between the Maubisse Formation and the Lolotoi Complex has been reported locally in East Timor (e.g., Chamalaun and Grady, 1978), but this has been disputed by others (e.g., Standley and Harris, 2009). In West Timor the mapping of de Roever (1940) on the western margin of the Mutis metamorphic massif might suggest another possible unconformable relationship, although de Roever preferred an interpretation of a Sonnebait Nappe including material that we would now assign to the Maubisse Formation thrust over the Mutis metamorphic successions (apparently another example of reversed tectonic stacking, with 'par autochthon' thrust over 'allochthon'). It should, however, also be noted that the Jurassic ages for at least the greenstone portion of the Mutis/Lolotoi Complex is incompatible with a simple Mutis-Maubisse unconformable relationship. This is an unresolved issue that is a problem for both the Asiatic and Australian interpretations of the Banda Terrane: the Maubisse Formation must have been deposited on top of something, and, as noted by Sawyer et al. (1993), "We suspect that pre-Permian basement in Timor is compositionally similar to the Mutis/Lolotoi, on the basis that Mutis/Lolotoi lithologies were associated in the field with Permian age Maubisse Formation and Kekneno Sequence, and both contained accessory minerals similar to the Mutis/Lolotoi Complex". Most of the known Mutis-Maubisse contacts across Timor tend to be in rather inaccessible locations such as high on the flanks of Gunung Mutis, but the Noil Meto locality is readily accessible, and Google Earth imagery suggests a good chance that the inferred Mutis-Maubisse boundary on Tubu Haumenbaki should be relatively well exposed. This should be a target for future fieldwork in the Noil Meto area.

ACKNOWLEDGEMENTS

Our thanks to Nusa Cendana students Deni Manikita and Rizky Boki who assisted us in the field, and geologist Permenas Manilapai (Barka) and student Jefrianus Tmaisan who joined us for some of the fieldwork. Thanks also for useful comments by an anonymous reviewer.

REFERENCES

Audley-Charles, M.G. 1968. The geology of Portuguese Timor. Memoir of the Geological Society of London 4.

Audley-Charles, M.G. and Carter, D.J. 1972. Palaeogeographical significance of some aspects of Palaeogene and early Neogene stratigraphy and tectonics of the Timor Sea region. Palaeogeography, Palaeoclimatology and Palaeoecology, 11, 247-264.

Barkham, S.T., 1993. The Structure and Stratigraphy of the Permo-Triassic Carbonate Formations of West Timor, Indonesia. Ph.D. thesis, London University.

Bird, P.R., 1987. The Geology of the Permo-Triassic Rocks of Kekneno, West Timor. Unpublished Ph.D. thesis, London University.

Bird, P.R. and Cook, S.E., 1991. Permo-Triassic successions of the Kekneno area, West Timor: implications for palaeogeography and basin evolution. Journal of SE Asian Earth Sciences, 6(3/4), 359-371.

Chamalaun, F.H. and Grady, A.E., 1978. The tectonic development of Timor: a new model and its implications for petroleum geology. Journal of the Australian Petroleum Exploration Association, 18, 102-108.

Charlton, T.R., 1987. The Tectonic Evolution of the Kolbano-Timor Trough Accretionary Complex, Timor, Indonesia. Unpublished Ph.D. thesis, London University.

Charlton, T.R., Barber, A.J. and Barkham, S.T., 1991. The structural evolution of the Timor collision complex, eastern Indonesia. Journal of Structural Geology, 13(5), 489-500.

Charlton, T.R., Barber, A.J., Harris, R.A., Barkham, S.T., Bird, P.R., Archbold, N.A., Morris, N.J., Nicoll, R.S., Owen, H.G., Owens, R.M., Sorauf, J.E., Taylor, P.D., Webster, G.D. and Whittaker, J.E., 2002. The Permian of Timor: its stratigraphy, palaeontology, and palaeogeography. Journal of Asian Earth Sciences, 20, 719-774.

Charlton, T., Gandara, D., Freitas, D., Guterres, M. and da Costa, N., 2018. TIMOR GAP's Onshore Block: a preliminary assessment of prospectivity in onshore Timor-Leste. PESGB-SEAPEX Asia-Pacific E&P Conference, 27-28 June 2018, conference proceedings, 8pp.

Cook, S.E., 1986. Triassic Sediments of east Kekneno, West Timor. Unpublished Ph.D. thesis, London University.

Duffy, B., Lew, B., Boland, K., Kohn, B., Matchan, E., Maas, R., Dixon, D., Pedro, L., de Carvalho, P. and Sandiford, M., 2021. Cenozoic affinity of the Gondwanan rocks of eastern Timor: evidence from geothermochronology. Australian Earth Science Convention presentation (mp4 file).

Earle, M.M., 1981. A study of Boi and Molo, two metamorphic massifs in Timor, eastern Indonesia. Unpublished Ph.D. thesis, London University.

Harris, R.A., 1991. Temporal distribution of strain in the active Banda Orogen: a reconciliation of rival hypotheses. Journal of SE Asian Earth Sciences, 6, 373-386.

Harris, R., 2006. Rise and fall of the Eastern Great Indonesian arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor. Gondwana Research, 10, 207-231.

Kristan-Tollman, E., Barkham, S. and Gruber, B., 1987. Pötschenschichten, Zlambachmergel (Hallstätter, Obertrias) und Liasfleckenmergel in Zentraltimor, nebst ihren Faunenelementen. Mitt. Osterreich. Geol. Ges., 80, 229-285.

Kristan-Tollman, E., 1988a. I. Coccolithen aus den Älteren Allgauschichten (Alpiner Lias, Sinemur) von Timor, Indonesien. Geol. Palaont. Mitt. Innsbruck, 15, 71-83.

Kristan-Tollman, E., 1988b. II. Coccolithen aus den Pliensbach (Ältere Allgauschichten, Alpiner Lias) von Timor. Geol. Palaont. Mitt. Innsbruck, 15, 109-133.

Park S.I., Kwon S.H. and Kim S.W., 2014. Evidence for the Jurassic arc volcanism of the Lolotoi complex, Timor: Tectonic implications. Journal of Asian Earth Sciences, 95, 254-265.

Roever, W.P. de, 1940. Geological investigations in the south-western Moetis region (Netherlands Timor). PhD thesis, Amsterdam University. 244pp, also in: Geological Expedition to the Lesser Sunda Islands under the Leadership of H.A. Brouwer, 2, 97-344.

Rosidi, H.M.D., Suwitodirdjo, K. and Tjokrosapoetro, S., 1979 (map) and 1981 (accompanying brochure). Geologic map of the Kupang-Atambua Quadrangles, Timor. 1:250,000. GRDC/PPPG.

Sawyer, R.K., Kartono Sani and Brown, S., 1993. Stratigraphy and sedimentology of West Timor, Indonesia. Proceedings of the Indonesian Petroleum Association Annual Convention 22, 1-20.

Sopaheluwakan, J., 1989. Ophiolite obduction in the Mutis Complex, Timor, Eastern Indonesia: An example of inverted, isobaric, medium-pressure metamorphism. Ph.D. thesis, Free University, Amsterdam.

Standley, C.E. and Harris, R.E., 2009. Tectonic evolution of forearc nappes of the active Banda arc-continent collision: Origin, age, metamorphic history and structure of the Lolotoi Complex, East Timor. Tectonophysics, 479(1-2), 66-94.

Tappenbeck, D., 1939. Geologie des Mollogebirges und einiger benachbarter Gebiete (Niederlandsch Timor). PhD thesis, Amsterdam University. 105pp. Also in: Geological Expedition to the Lesser Sunda Islands (edited H. Brouwer), 1, 1-105, 1940.

Voorthuysen, J.H. van, 1940. Geologische Untersuchungen im Distrikt Amfoan (NW Timor). PhD thesis, Amsterdam University, also in: Geological Expedition to the Lesser Sunda Islands under the Leadership of H.A. Brouwer, 2, 345-368.

Waard, D. de, 1954. Contributions to the geology of Timor, V. Structural development of the crystalline schists in

Timor, tectonics of the Lalan Asu massif. Indonesian Journal of Natural Sciences, 110, 143-153.

Waard, D. de, 1957a. Contributions to the geology of Timor, XII. The third geological expedition, preliminary results. Indonesian Journal of Natural Sciences, 113, 7-42.

Waard, D. de, 1957b. Zones of regional metamorphism in the Lalan Asu massif, Timor. Proc. K. Ned. Akad. Wetens., 60, 383-392.

Waard, D. de, 1959. Anorthite content of plagioclase in basic and pelitic crystalline schists as related to metamorphic zoning in the Usu Massif, Timor. American Journal of Science, 257, 553-562.

West, F.P. van, 1941. Geological investigations in the Miomaffo region (Netherlands Timor). PhD thesis, Amsterdam University, 131pp, also in: Geological Expedition to the Lesser Sunda Islands (edited Brouwer, H.), 3, 1-131.

Zimmermann, S., 2015. Provenance of Mesozoic sandstones in the Banda Arc, Indonesia. Ph.D. thesis, London University. 418pp.

Zimmermann, S. and Hall, R., 2016. Provenance of Triassic and Jurassic sandstones in the Banda Arc: petrography, heavy minerals, and zircon geochronology. Gondwana Research, 37, 1-19.

Zimmermann, S. and Hall, R., 2019. Provenance of Cretaceous sandstones in the Banda Arc and their tectonic significance. Gondwana Research, 67, 1–20.