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Berita Sedimentologi

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A scientific Journal published by Indonesian Sedimentologists Forum (FOSI), a commission of the Indonesian Association of Geologist (IAGI)

Berita Sedimentologi was first published in February 1996 as a newsletter for the members of the Indonesia Sedimentologists Forum (Forum Sedimentologiwan Indonesia or FOSI) only. In its first year, Berita Sedimentologi was published in Indonesian language, then from 1997 onward this publication uses English as the language of communication.

Frequency of publication is 3 issues per year, usually published in April, August and December of each year.

Topics cover sedimentology and stratigraphy of both siliciclastic and carbonate rocks, depositional processes, but also cover biostratigraphy, geochemistry, basin analysis, geodynamics, petroleum geology and structural geology.

From the Editor

Dear Readers,

In the previous issue of Berita Sedimentologi (Vol. 48 No. 1, June 2022), I wrote that our topic for the next publication (which is this issue) would be on Moluccas and Halmahera Islands. Unfortunately, we did not receive any manuscript on the topic therefore we have to sidestep from our pre-planned geographic focus on this publication. As a replacement, we included 3 papers from various region across Indonesia in this **Berita Sedimentologi Vol. 49 No. 1**. The papers consist of previously undocumented 'Banda Terrane' basement and cover found in the Noil Meto river section, West Timor; Paleogene paleogeographic reconstruction of the Upper Kutai Basin; and a discussion on the relationship between major unconformities on the South China Sea shelf margin and the end of seafloor spreading in the South China Sea.

Beyond publishing scientific papers regularly, currently FOSI are organizing a webinar series on "Revisiting Indonesian Stratigraphy". The objectives of this webinar series are to identify inconsistencies and issues related to definition and utilization of stratigraphic nomenclature in various Indonesian basins. The webinar is scheduled to take place bimonthly, starting in mid-January and was then followed by a second webinar in late March. The next webinar is planned to take place in mid May 2023. The webinars are available in FOSI's channel at https://www.youtube.com/@fosiiagi1954. More videos will be added in the future so keep following the updates on our youtube channel!

We have planned to roll out the next issue of Berita Sedimentologi in August and the review process of submitted manuscripts are ongoing right now. More submissions are still welcome, therefore I invite you to get in touch with us to submit your contribution. In the meantime, I hope the papers in this current issue of Berita Sedimentologi will be useful to you all. See you again next time.

Minarwan
Editor-in-Chief

Cover Photograph:

Megaslump structure, Kananggar Formation, East Sumba, Nusa Tenggara Timur Province (photo by courtesy of Hade B. Maulin).

Berita Sedimentologi

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About FOSI

The forum was founded in 1995 as the Indonesian Sedimentologists Forum (FOSI). This organization is a communication and discussion forum for geologists, especially for those dealing with sedimentology and sedimentary geology in Indonesia.

The forum was accepted as the sedimentological commission of the Indonesian Association of Geologists (IAGI) in 1996. About 300 members were registered in 1999, including industrial and academic fellows, as well as students.

FOSI has close international relations with the Society of Sedimentary Geology (SEPM) and the International Association of Sedimentologists (IAS).

Fellowship is open to those holding a recognized degree in geology or a cognate subject and non-graduates who have at least two years relevant experience.

FOSI has organized three international conferences in 1999, 2001 and the most recently in 2018.

Most of FOSI administrative work will be handled by the editorial team. IAGI office in Jakarta will help if necessary.

The official website of FOSI is:
http://www.iagi.or.id/fosi/

FOSI Membership

Any person who has a background in geoscience and/or is engaged in the practising or teaching of geoscience or its related business may apply for general membership. As the organization has just been restarted, we use **LinkedIn** **(www.linkedin.com)** as the main data base platform. We realize that it is not the ideal solution, and we may look for other alternative in the near future. Having said that, for the current situation, LinkedIn is fit for purpose. International members and students are welcome to join the organization.

FOSI - Indonesian Sedimentologists Forum

ABOUT THIS GROUP

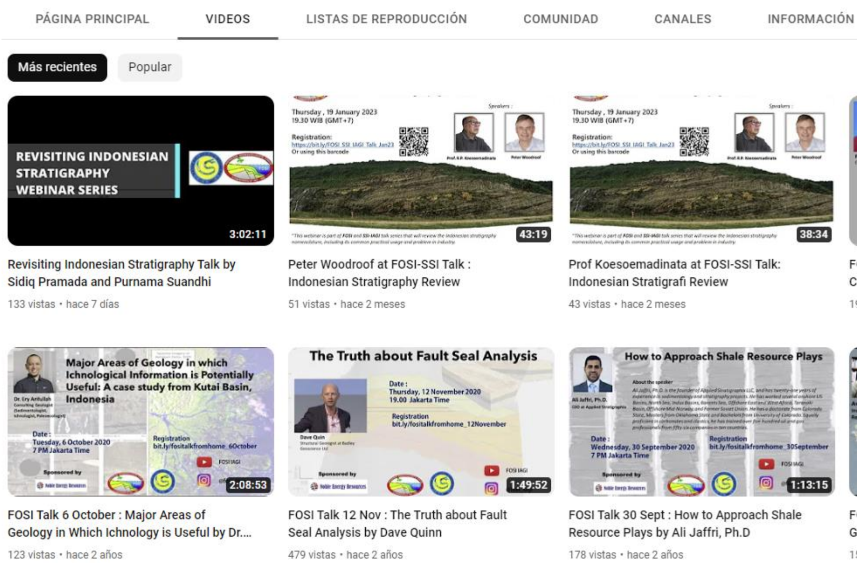
FOSI was established in 1995 and became a commission of IAGI (Ikatan Ahli Geologi Indonesia/Indonesian Geologists Association) few years later. The association is aimed as a discussion forum for Sedimentologists in Indonesia, to share experience and knowledge amongst the members. Through the network with international organizations, such as SEPM and IAS, FOSI tries to put Indonesian sedimentary geology into broader perspective.

FOSI Group Member as of April 2023:

1,021 members

Including Yudistira Effendi and 215 other connections

Visit FOSI's youtube channel at https://www.youtube.com/@fosiiagi1954 to watch recording of recent online webinar!



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‘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

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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

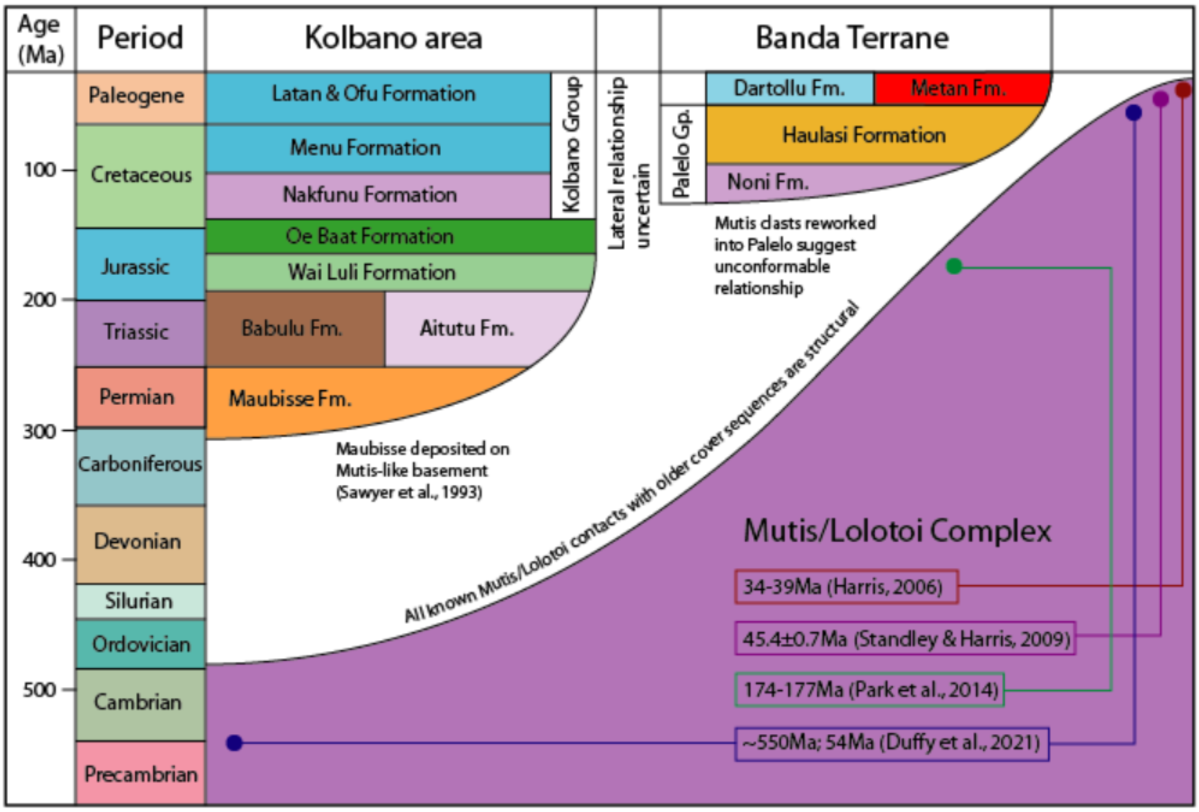

Figure 1: *Pre-Neogene stratigraphic summary for cover sequences in the Banda Terrane and the Kolbano area (location Figure 2), together with metamorphic ages reported for the Mutis metamorphic complex of West Timor and its equivalent the Lolotoi Complex in Timor-Leste.*

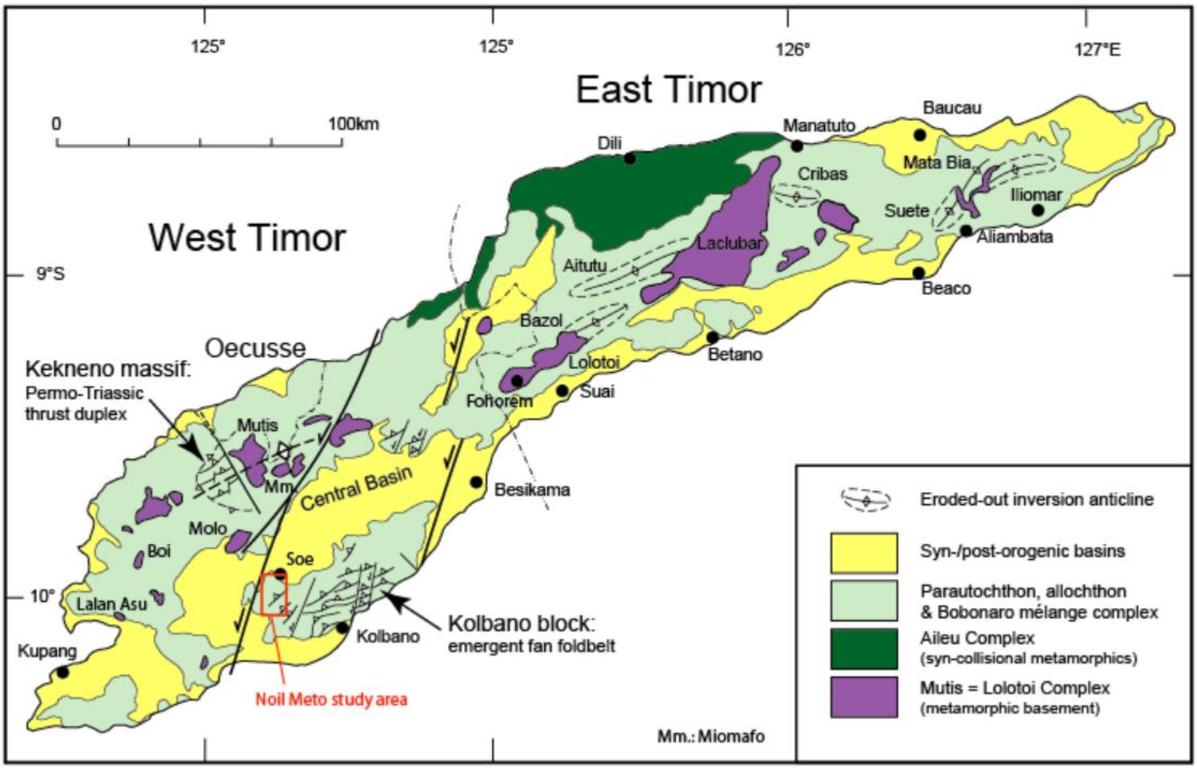

Figure 2: *Location of the Noil Meto study area in south-central West Timor, and the distribution of metamorphic massifs (Mutis Complex in West Timor; Lolotoi Complex in East Timor) across the island.*

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

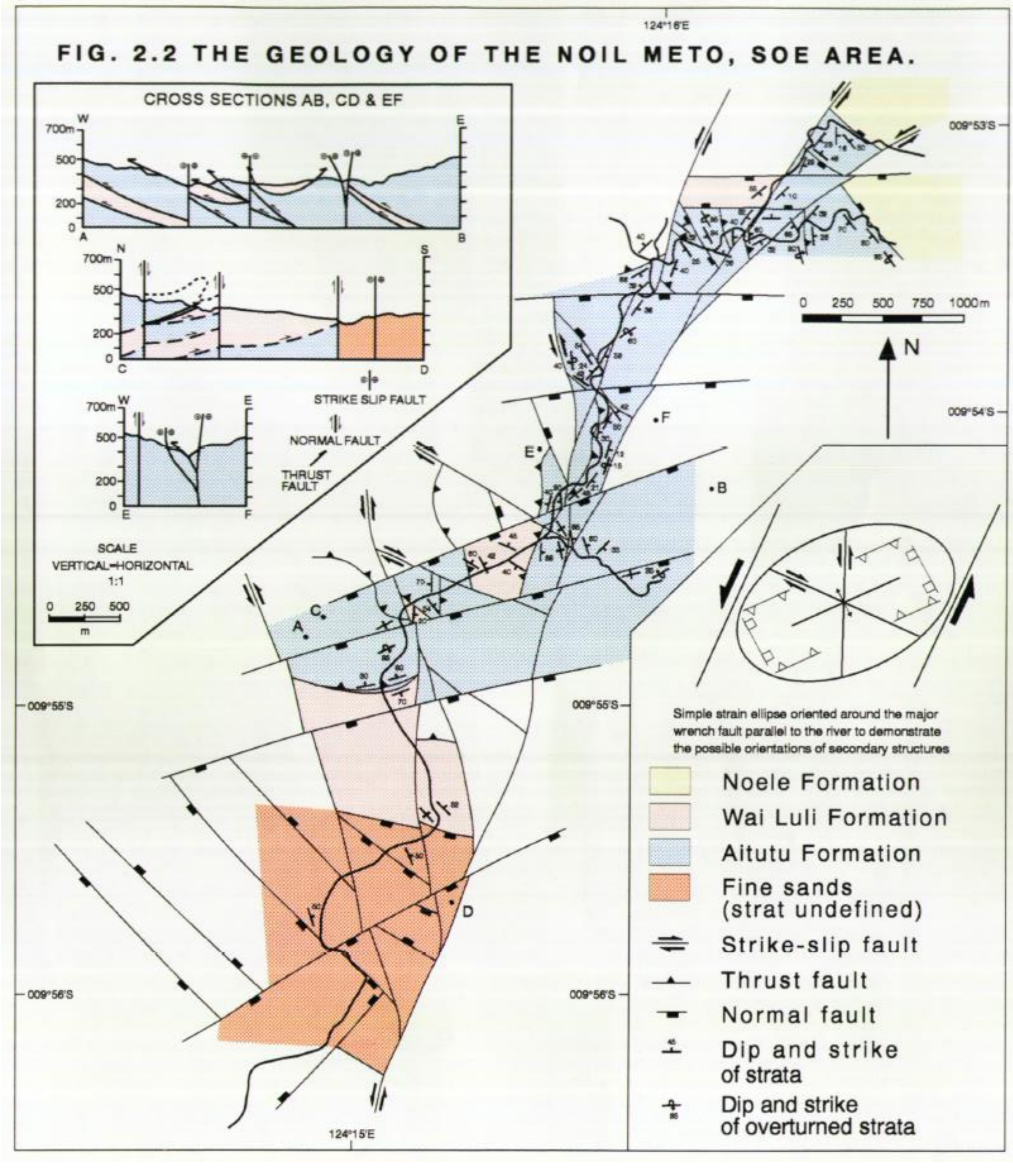

Figure 3: *Geology of Noil Meto as mapped by Barkham (1993).*

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

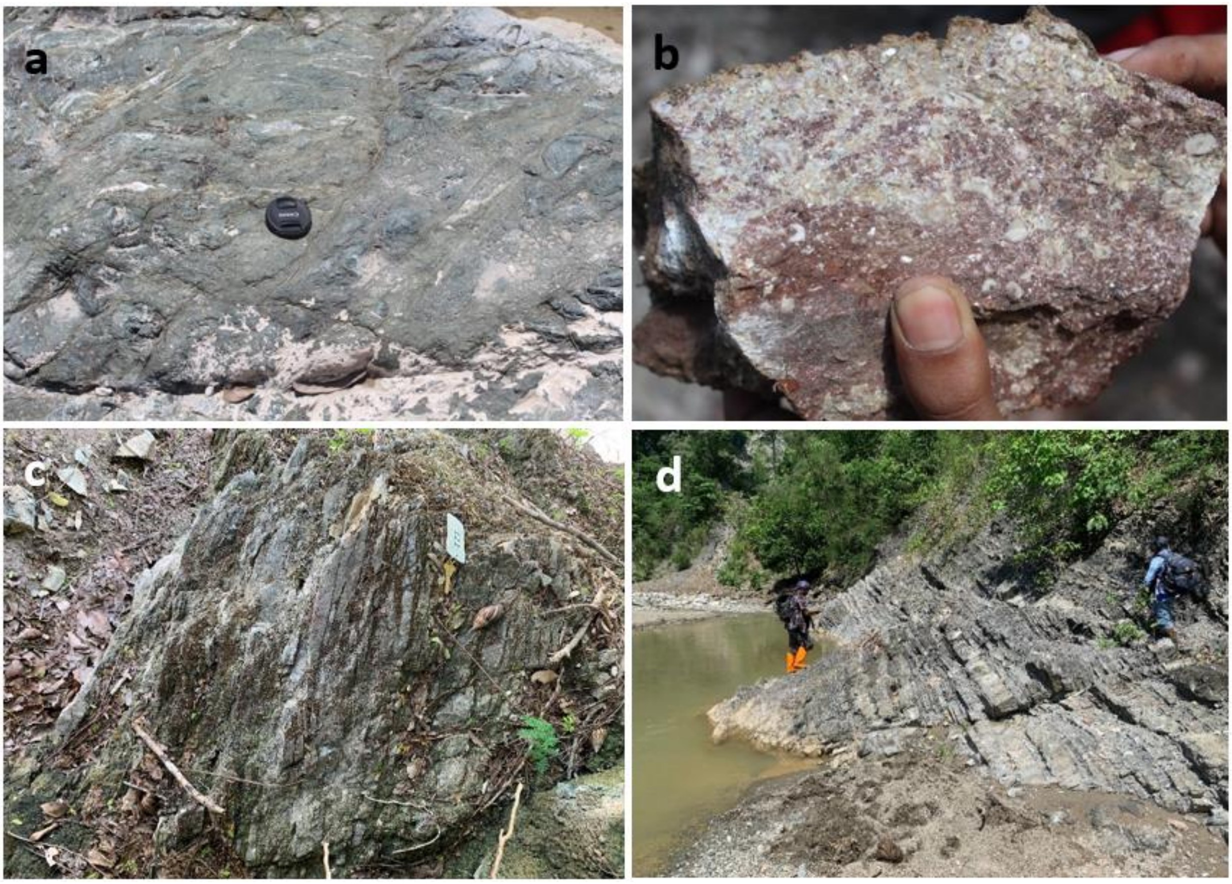

Figure 4: *(a) Mutis Complex greenstone. (b) Maubisse Formation crinoidal limestone clast from outcrop at locality M1. (c) Haulasi Formation in Noil Meto (our locality H3 = Zimmermann's (2015) locality SZ 47). (d) Haulasi Formation in Noil Haulasi, type locality of the Haulasi Formation (Rosidi et al.,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

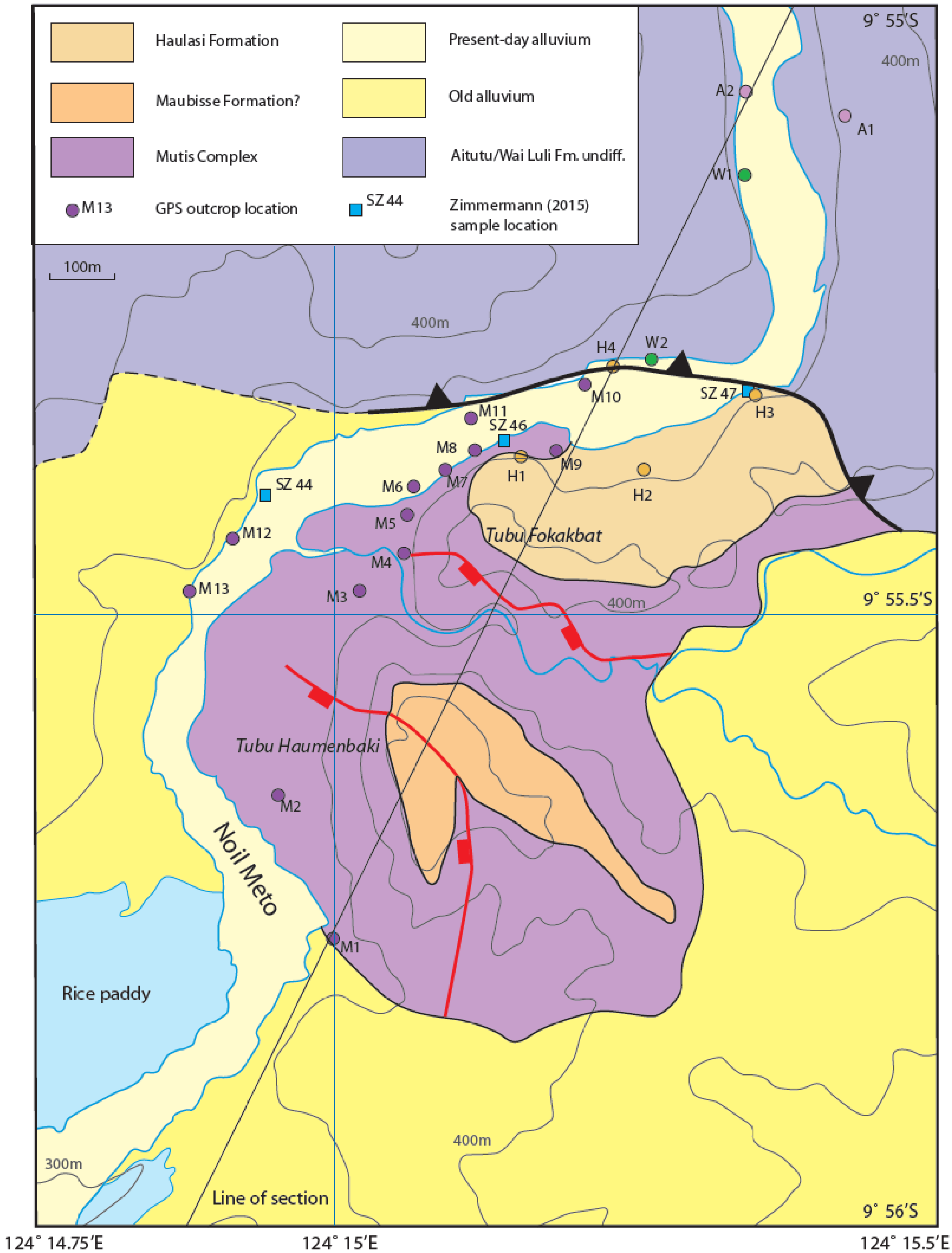

Figure 5: *Geology of the lower section of Noil Meto from GPS-constrained fieldwork and interpretation of Google Earth imagery. Topography at 50m interval contoured from Google Earth.*

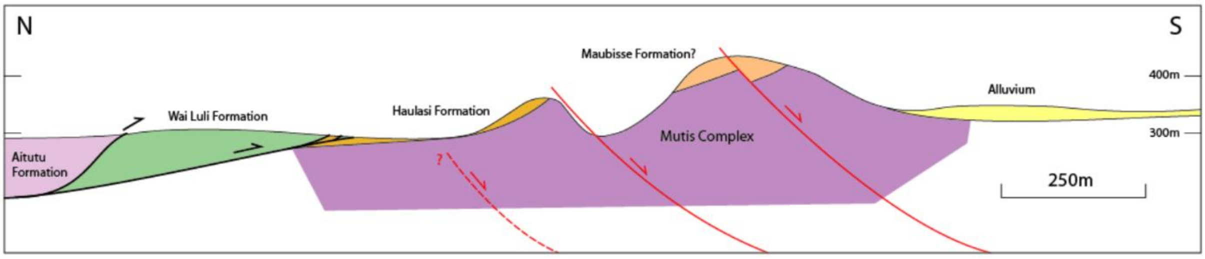

Figure 6: *Cross-section through the Mutis massif in Noil Meto. No vertical exaggeration. Line of the section is in Figure 5.*

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.

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Paleogene paleogeographic reconstructions of the Kutai Basin: Refinement based on outcrop and subsurface data

Herman Darman (INDOGEO Social Enterprise, Jakarta)

Corresponding author: herman_darman@yahoo.com

ABSTRACT

The Kutai Basin is a Cenozoic sedimentary basin located in the eastern part of Borneo Island. Many studies were done on the eastern part of the basin, which is dominated by Neogene sediments. The west margin of the basin is outcropped onshore and to the east, the basin opens up to the Makassar Strait. Paleogene and older rocks outcrop in the west margin of Kutai Basin. The terrain and the access to the area are difficult and no significant hydrocarbon discovery was made in Paleogene sediments up to now.

This study revisited the field works completed in the 1970s by a Shell team, which focused on the Paleogene section of the Kutai Basin. The result was integrated with later studies, and altogether were synthesized into a series of paleogeographic maps. A new set of paleogeographic maps is proposed in this paper, for Middle Eocene, Late Eocene, Early Oligocene, and Late Oligocene levels. The works included in this study comprised outcrop observations, biostratigraphy analysis of the samples and limited seismic in parts of the area. The results were integrated with other more recent work to build the new set of Paleogene paleogeographic maps.

Outcrops data and well information show the distribution of shallow marine sediment in the Middle Eocene time with some fluvial input from the north and southwest of the basin. In the Late Eocene, some carbonates developed in the north of the basin. During Early Oligocene, the carbonate complex developed both in the south and in the north of the basin. In the Late Oligocene, the carbonate in the south became more stable. Through Paleogene time the center of Kutai Basin was dominated by the bathyal section.

Keywords: Upper Kutai, Paleogene, Eocene, Oligocene, paleogeography

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INTRODUCTION

The Kutai Basin is located in the eastern part of Borneo Island (Figure 1). The basin is tilted to the east. The west margin is located in onshore Borneo, with exposed Paleogene age rocks and the east side opens into the Makassar Strait. The basin is sub-divided into Upper and Lower Kutai Basin. The Lower Kutai Basin is dominated by Neogene sediments with significant petroleum discoveries such as the Mutiara, Tunu, and Tambora Fields. The Upper Kutai Basin covers the western margin of the basin. It has more

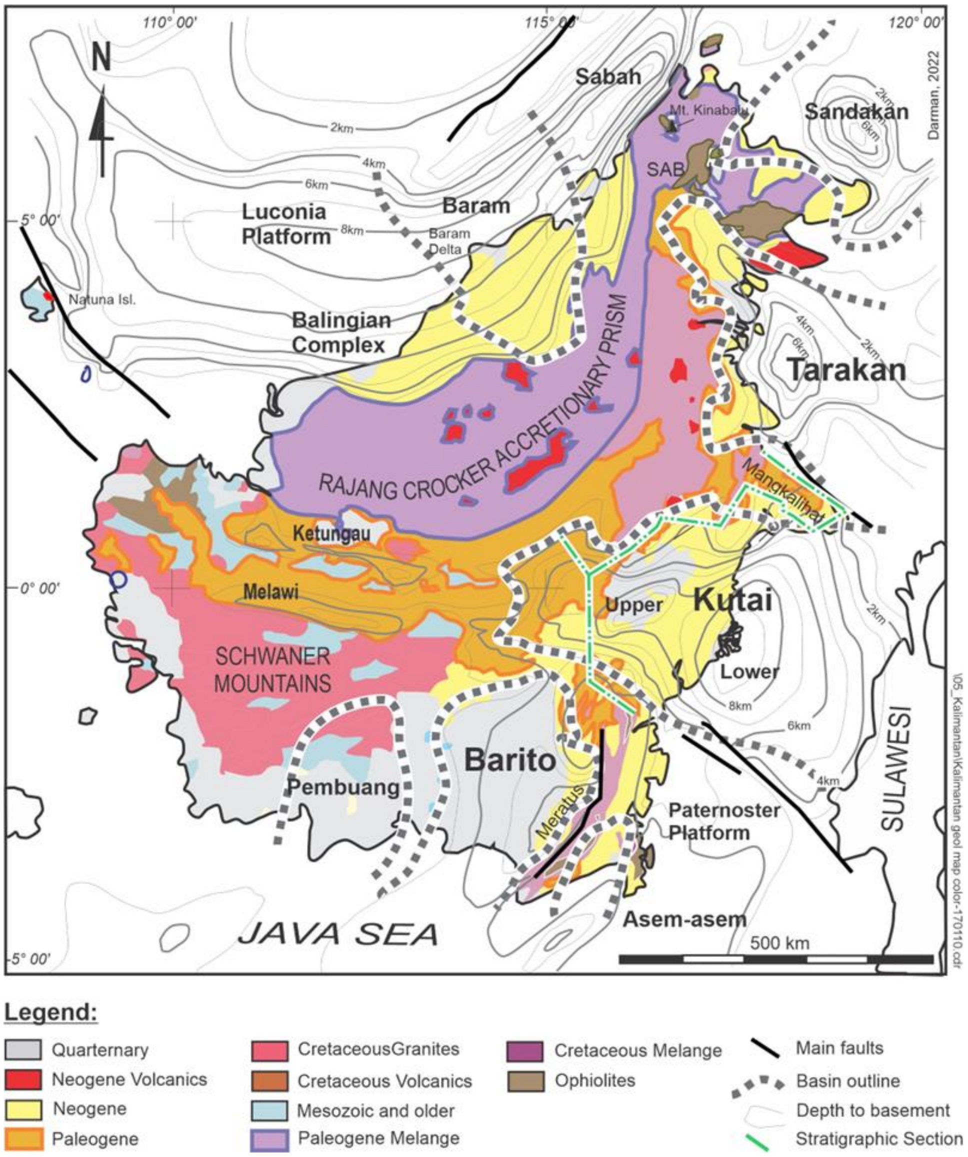

Figure 1: *Simplified geological map of Borneo. Kutai Basin is located in the east of the Island. This basin has two depocenters so-called the Upper and Lower Kutai, shown by the depth to basement contours. The Paleogene outcrops are observed in the basin margin. In Lower Kutai the Paleogene is too deep to observe.*

Paleogene outcrops, and except for the small Kerendan gas field (Unocal, 1982), there is no significant petroleum discovery in this region until now. The Paleogene outcrops are located in remote areas, at more than 200 m altitudes above sea level (Figure 2).

Most of the ‘modern’ work on the Upper Kutai basin is from the 1970s and later. However, there is a significant, but poorly-known body of work from the Dutch colonial era, including reports of geological expeditions, the Central Borneo Expedition by G. Molengraaff in 1894 (Molengraaff, 1900), the Midden-Oost Borneo Expeditie of 1925 by H. Witkamp (Witkamp, 1927; M.G. Rutten, 1948; Albrecht, 1946), work by the Geological Survey (Harting, 1925, 1930; Ubaghs, 1937), the Koetai Expedition of M. Hartmann in 1937 and unpublished BPM and NKPM oil company work (for references see www.vangorselslist.com). All these old geologists reported widespread intensely folded Jurassic-Cretaceous oceanic sediments with radiolarian cherts (“Danau Formation” of Molengraaff, 1902), intruded by granitoids, unconformably overlain by relatively little-deformed Middle and Late Eocene non-marine and shallow marine sediments (incl. limestones with Letter Stages Ta and Tb foraminifera).

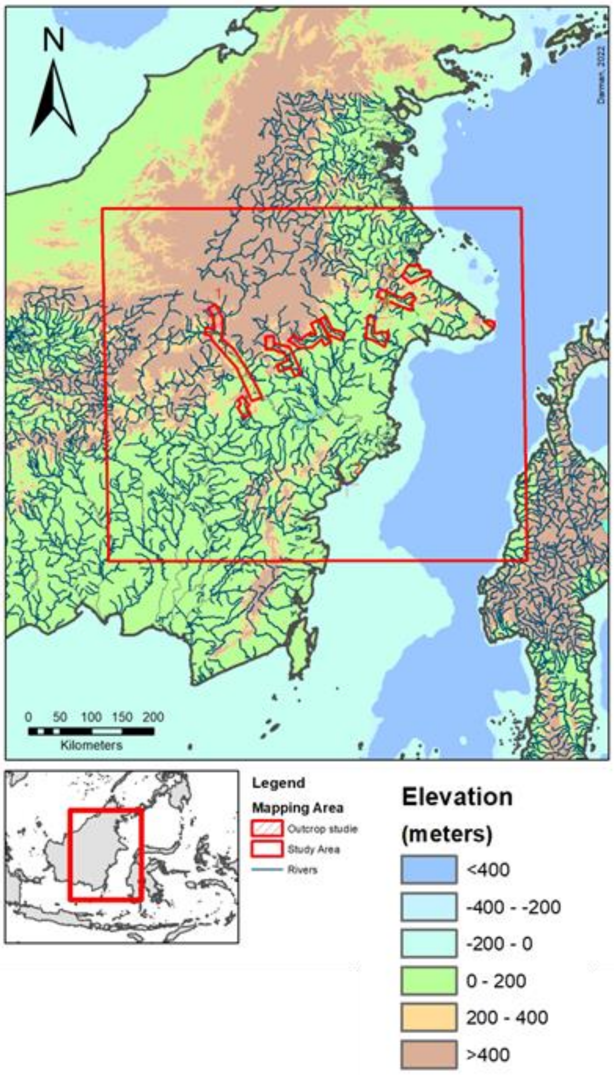

Figure 2: *Terrain of the study area which covers>200 m elevation above sea level. The field mapping area is located in the interior part of Borneo Island with difficult road access. The red box is the area of interest in this study and the red polygons are Cartier and Yeats (1973) working area which is revisited in this study.*

As the more prolific part of the basin, there are many seismic and well data in the Lower Kutai Basin. Hence there are many publications in this area. The Upper Kutai Basin, however, has much-limited subsurface data. There are several outcrop studies in different parts of the basin margin such as Van de Weerd and Armin (1992), Saller and Vijaya (2002), Bachtiar et al. (2013) in the southwest, Wilson et al. (1999, 2002), Guritno et al. (1999, 2012), and Moss et al. (1997, 1999) in the northwest of the basin (Figure 3). Generally, the outcrops in this area are relatively weathered and many parts are covered by vegetation and the logistic to reach this area is very challenging.

Several basin-wide regional paleogeographic maps were completed by previous authors e.g., van de Weerd and Armin (1992), Laya et al. (2013), Bachtiar et al. (2013a, b), Darmawan et al. (2013), and Darman (2017). Other authors published detailed paleogeographic maps for certain parts of the basin, e.g., Saller and Vijaya (2002) for the southern margin and Wilson and Evans (2002) for the Mangkalihat area in the north.

The aim of this paper is to gather and revisit earlier Paleogene outcrop sections, mainly using the work by Cartier and Yeats (1973), with additional data analysis by Moss and Chambers (1999) and other subsurface data. These data were then utilized to refine Paleogene paleogeographic maps. The integration of published maps, controlled by outcrop and subsurface data, resulted in several updated paleogeographic maps for the Middle Eocene, Late Eocene, Early Oligocene, and Late Oligocene.

REGIONAL GEOLOGY

Topographically, Borneo Island is cored by a curving mountainous terrain called the Rajang-Crocker Range (Figure 1), which is a mid-Cenozoic paleo-accretionary prism, mainly consisting of hemipelagic and turbidite deposits (Stauffer, 1966). These deep-water deposits are now partly metamorphic and of Cretaceous to Late Eocene age. Some ophiolite fragments were found within this unit.

In the southwest of Borneo Island, there is another mountainous terrain, which is called the Schwaner Mountains (Figure 1). It consists of Cretaceous granites, which are the main provenance of quartz minerals of the clastic sediments in the surrounding basins, including the Melawi, Ketungau, Kutai and Barito Basins. The lithology and age of Schwaner Block indicate that it is part of the continental crust of Sundaland.

The Melawi and Ketungau basins are the sedimentary basins located between Rajang-Crocker Range and the Schwaner Block, containing very thick Eocene non-marine clastics and probably representing Eocene-Oligocene rift basins (Williams et al., 1989). These Paleogene sediments were also transported to the east and are exposed in the western margin of Kutai Basin. Investigation of these outcrops shows that most of the Eocene is composed of marine shale deposits, which are believed to be the distal parts of Melawi and Ketungau Basins. Shallow to deep water sandstone occurs in Late Eocene (Figure 4).

The oldest sediments in the Kutai Basin are of Middle Eocene age; they unconformably overlie more deformed Cretaceous and possibly older rocks. The Middle Eocene onset of the Paleogene depositional cycle of the greater Kutai Basin is supposed to be controlled by the Middle Eocene and younger rifting episode that affected much of Western Indonesia, and created the adjacent Barito and Tarakan Basins.

During the Oligocene, carbonates developed both in the northern and southern margins of Kutai Basin. The carbonate in the north of the Kutai Basin occurs on basin highs from Oligocene up to Pliocene (Figure 4). In the south, Oligocene carbonate developed on a relatively stable area called the Barito Platform, which extends offshore to the Paternoster Platform in the Makassar Strait.

DATA DISTRIBUTION

Cartier and Yeats (1973) conducted field surveys of the northwest and northeast margins of the Kutai Basin for the Kaltim Shell oil company. Data were collected from 14 locations in the Upper Kutai Basin (Figure 3), namely:

1) Muruh;
2) Konyatan;
3) Lower Mahakam / S. Nyawatan;
4) Upper Mahakam / S. Boh;
5) S. Belayan, S. Ritan, S. Len;
6) S. Atan / S Menyok;
7) S. Klinjau;
8) S. Marah;
9) S. Bungalun / S Mangkupa;
10) Saka-1 well, NW Kariorang, Sambang-1 well cluster;
11) Birah-1 well;
12) Tg. Mangkalihat / Gn. Antu;
13) Tabalar A&B; and
14) Karangan

(See Figure 3 caption for abbreviation information).

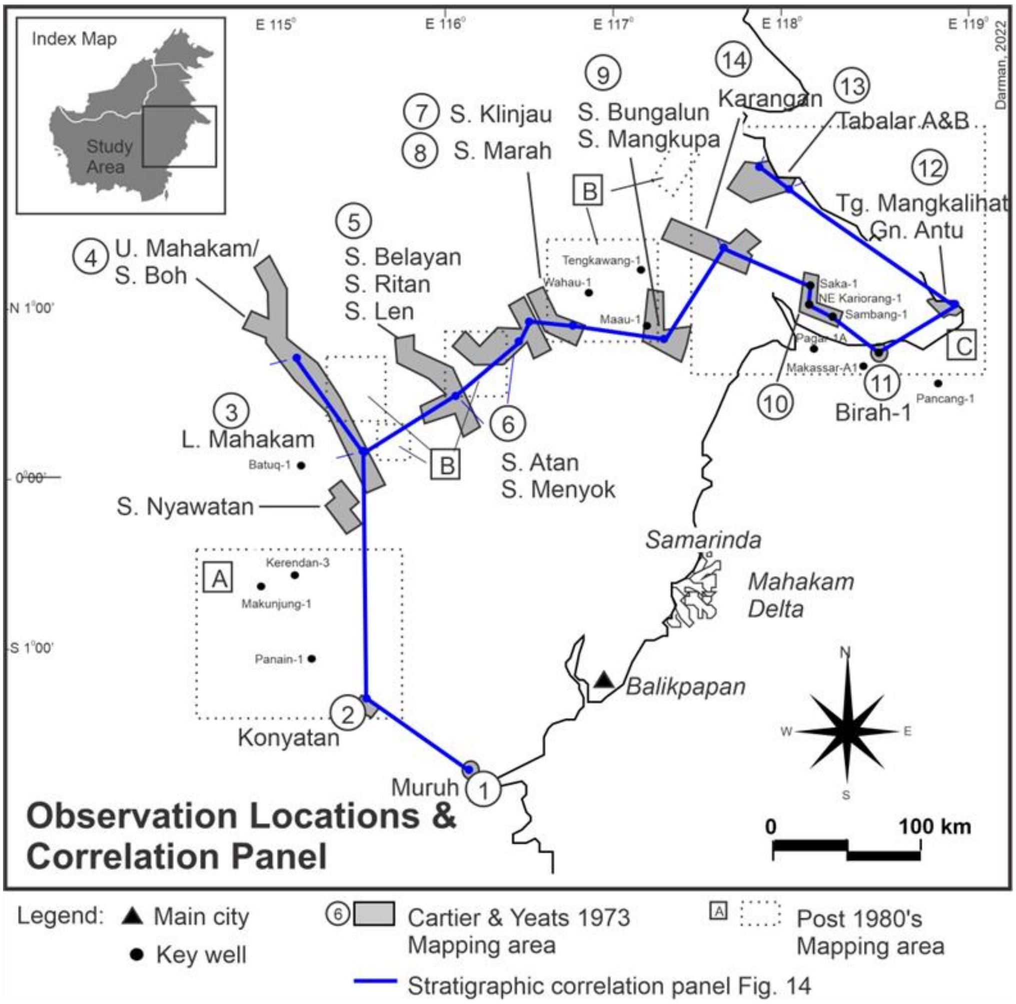

Figure 3: *Location map of outcrop mapping with circled numbers 1 to 14. A, B, and C are areas of other papers referred to in this paper. A = Kerendan Area, B = areas studies by Moss & Finch (1997); B = Mangkalihat Peninsula Area. "S" is an abbreviation of Sungai, which means river; "Tg" is for Tanjung which means peninsula and "Gn" is Gunung which means mount.*

Their report includes stratigraphic sections of each area with foraminiferal studies for age dating and depositional environment identification. Additional biostratigraphic data were provided by Moss and Finch (1997), including nannofossils, which provided additional age control of the outcrops (Figure 3).

The southwest margin of the basin was studied by Unocal geoscientists, who were focused on the Kerendan area (Figure 3), e.g., van de Weerd et al. (1987), van de Weerd and Armin (1992), and Saller and Vijaya (2002).

Their studies include some sections based on 2D seismic interpretation, which clearly defined the Kutai basin margin. Bachtiar et al. (2013) also did intensive fieldwork in this area and their

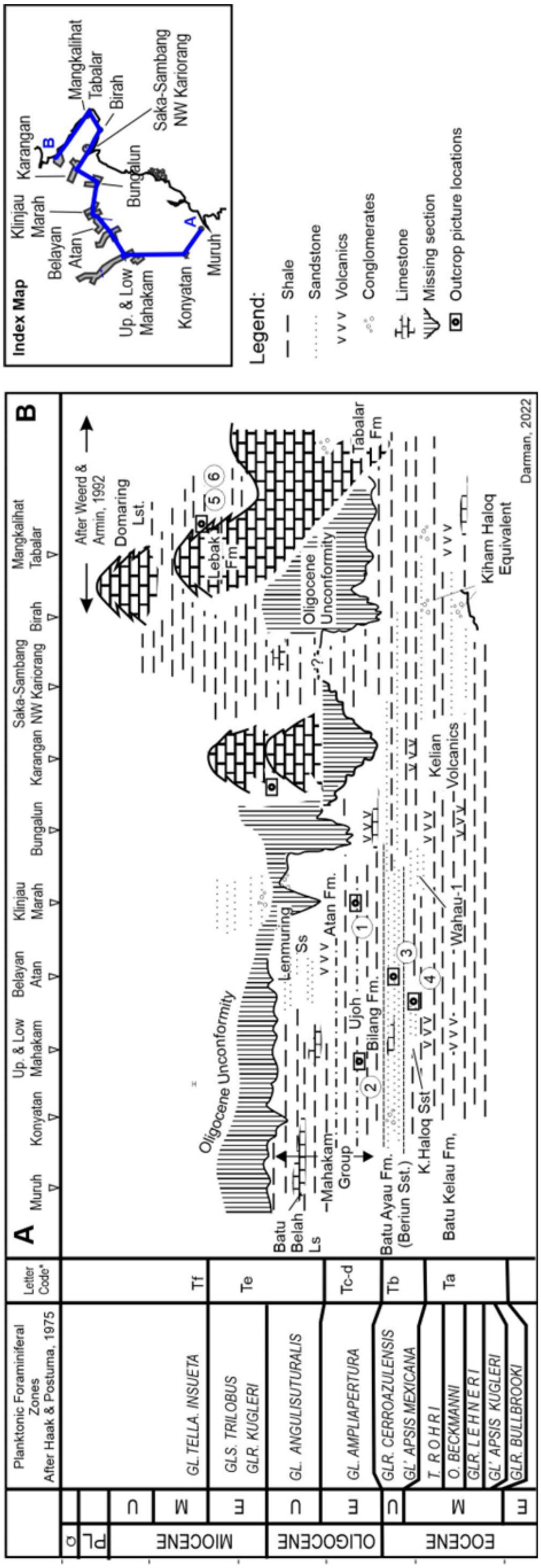

*Figure 4: Stratigraphy of the study areas. Beriun sandstone gets shalier to the east. Oligocene unconformity erodes deeper sections in the east. The unconformity didn't develop in the Saka-Sambang-NW Kariorang area. The camera symbols indicated the location of the outcrop photos. 1) Fig. 5; 2) Fig. 6; 3) Fig. 8a; 4) Fig. 8b; 5) Fig. 12-8a; 5) Fig. 12-8b. *Letter code after van der Vlerk & Umbgrove (1927).*

data points were integrated into this study.

In the northwest margin of the basin is the Mangkalihat Peninsula area (Figure 3), where Wilson et al. (1999) and Wilson and Evans (2002) studied the carbonate outcrops in great detail. Satyana and Biantoro (1995), Guritno and Chambers (1999) and Guritno et al. (2012) included subsurface data in this area and provide additional perspectives on the Paleogene section of the northern area of Kutai Basin.

OUTCROP ANALYSIS

Outcrop observations reported by Yeats and Cartier (1973) are revisited here by integrating them with newer data and analysis.

Their outcrop sections have been correlated with each other and displayed in five correlation panels to provide a better stratigraphic understanding (Figures 4, 7, 9, 10, 11).

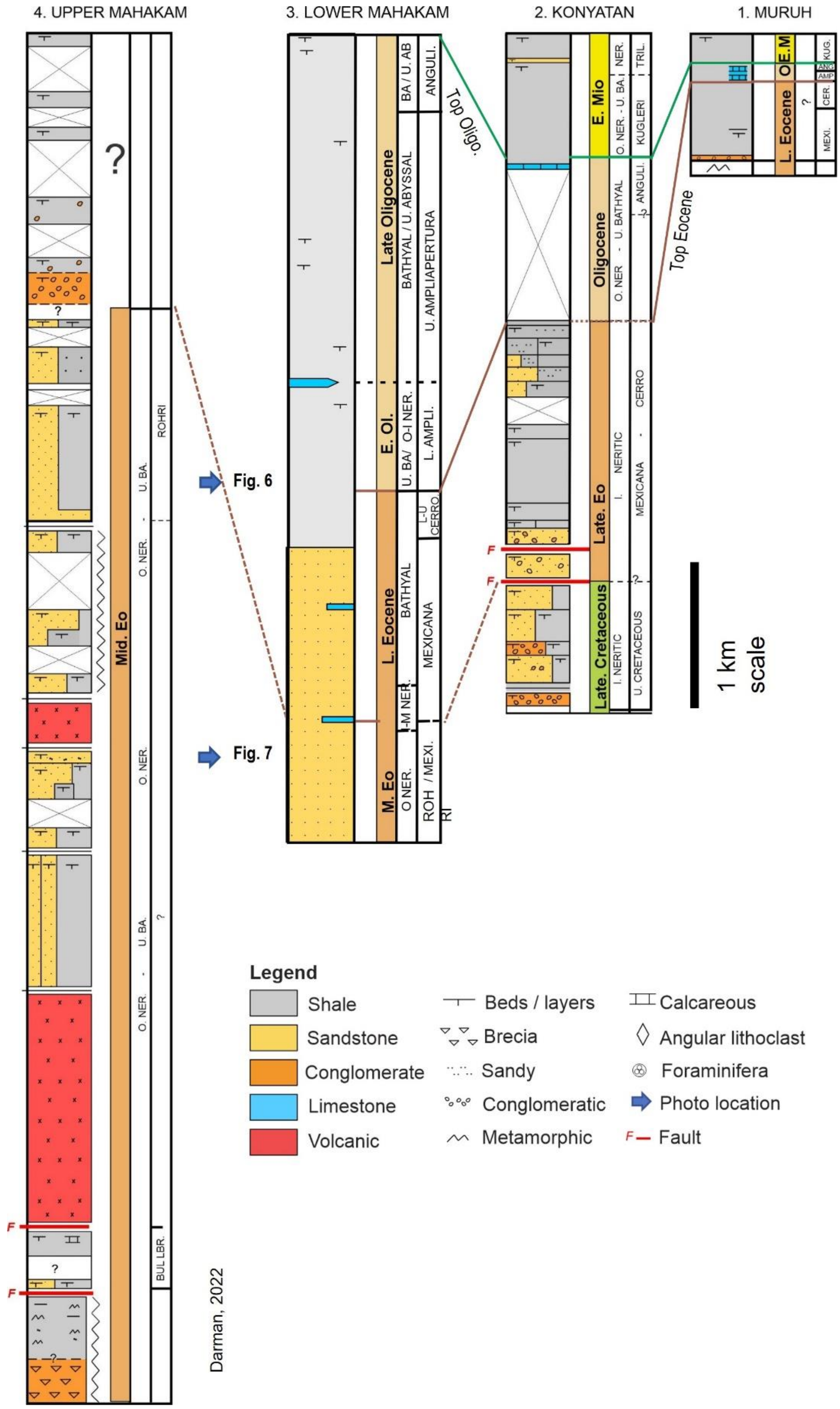

Figure 5: *Panel-1. Stratigraphic sections of 1) Muruh, 2) Konyatan, 3) Lower Mahakam and 4) Upper Mahakam after Cartier and Yeats (1973), roughly Northwest to Southeast orientation (see Fig. 3 for location). Both the Oligocene and Eocene units are thinning to the east. The blue arrow is the position of the outcrop photos.*

Figure 6: *Oligocene Atan Fm. which is dominated by bathyal shale deposit. Photo courtesy Rusniati S. Mehang. The clift on the left is about 5 meters high.*

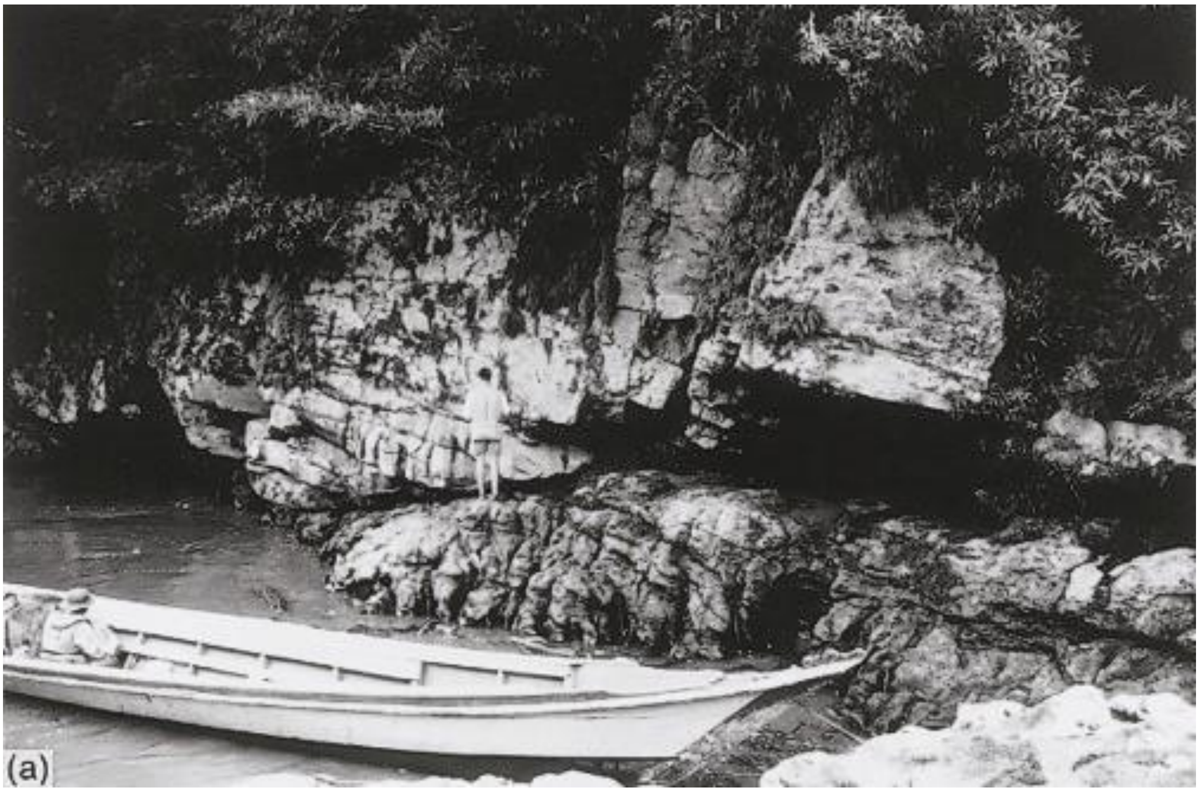

Figure 7: *A field photo of a sandstone channel incised into an earlier channel within the early syn-rift facies of the Middle Eocene Kiham Haloq Sandstone Formation. Upstream from Long Bangun. After Moss & Chambers (1999).*

Panel 1 (Figure 5): This panel went through the eastern part of the Kerendan Area (Figure 3), from Muruh to Upper Mahakam, which is the distal part of the SW margin of the Kutai Basin. Pre-Tertiary rocks were observed at the bottom of the Konyatan section (Cretaceous) and the meta-sediment section at the bottom of Muruh section with an inconclusive age. Middle Eocene section was observed in the Lower and Upper Mahakam sections, and they are identified based on the occurrence of *Acarinina bullbrooki* in Upper Mahakam and *Acarinina rohri* in both Upper and Lower Mahakam (Figure 4). Both forams identified Middle Eocene age (equivalent of Letter Stage Ta of van der Vlerk and Umbgrove, 1927), deposited in upper bathyal to outer neritic environment. Volcanic deposits were observed in the Middle Eocene of the Upper Mahakam section.

Late Eocene sections were encountered in Lower Mahakam, Konyatan, and Muruh. They were deposited in bathyal to inner neritic environments. Middle Eocene sandstone was observed by Moss and Chambers (1999) at Kiham Haloq (Figure 7). Although they reported the outcrop as a fluvial channel deposit, Cartier and Yeats (1973) and Moss and Finch (1997) reported foraminifera and identified the sandstone as a shallow marine / neritic deposit. In Lower Mahakam, the section is dominated by sandstone, whilst in Konyatan it becomes much shalier. In Upper Mahakam, the outcrops are not well exposed and the biostratigraphic analysis was inconclusive.

From Lower Mahakam to Muruh, the Oligocene section becomes thinner, and it is a shale-dominated section with some limestone lenses, called the Atan Formation (Figure 6). Benthonic foraminifera analysis indicated an abyssal to an outer neritic environment of deposition. The analysis of the Konyatan Oligocene section is only from the top part of the section as the majority is unobservable in the field. This stratigraphic unit is overlain by Early Miocene sections which are observed in the eastern part of the area, in Konyatan and Muruh.

Panel 2: (Figure 8) is a correlation panel with several outcrop sections described by Yeats and Cartier (1973) in the north-western margin of Upper Kutai Basin. It starts with the Belayan section in the west and ends with the Bungalun section in the east. The oldest section encountered is a metasediment in the Klinjau area. Middle Eocene sections were only found in Atan and Bungalun, indicating a bathyal environment in the

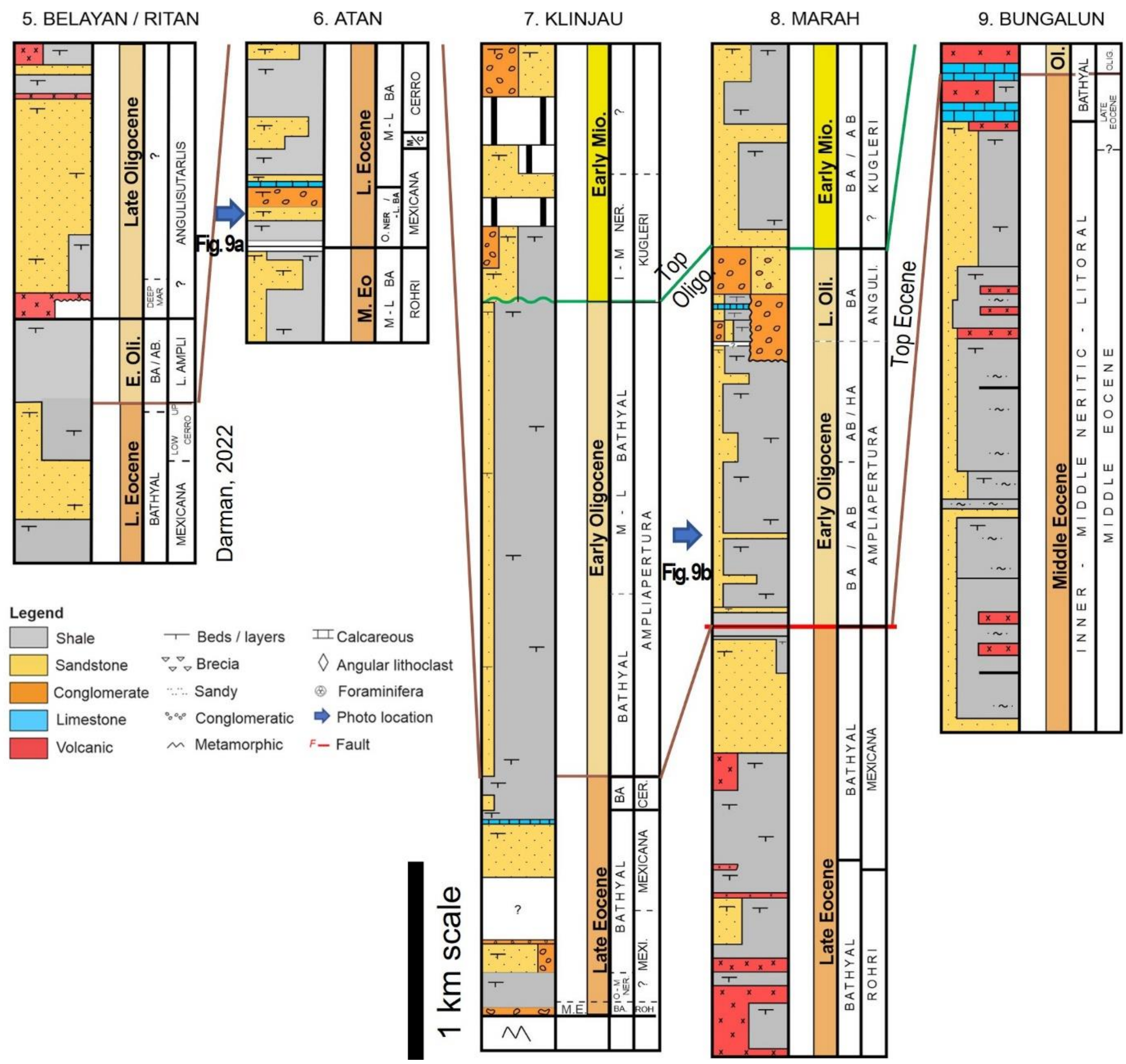

Figure 8: *Panel 2. Stratigraphic sections of 1) Muruh, 2) Konyatan, 3) Lower Mahakam and 4) Upper Mahakam, approximately West to East orientation (see Fig. 3 for location). The Oligocene unit is thinning to the east. Blue arrow indicates the outcrop photo location.*

west to a littoral environment in the east. The Bungalun section in the east contains Middle Eocene clastics with higher shale composition. Some thin layers of volcanic rocks were observed in the area.

Late Eocene sections were found in all 5 locations, and they are dominated by clastic sediments deposited in bathyal environment. *Globorotalia mexicana* and *Turborotalia cerroazulensis* are common index planktonic foraminifera in these sections (Figures 4 and 8). The bottom of the Late Eocene section in Bungalun is not well-identified biostratigraphically. In Atan, the section contains cross-bedded sandstone with minor conglomerates (Figure 9a) and thin limestone beds. In Bungalun, some

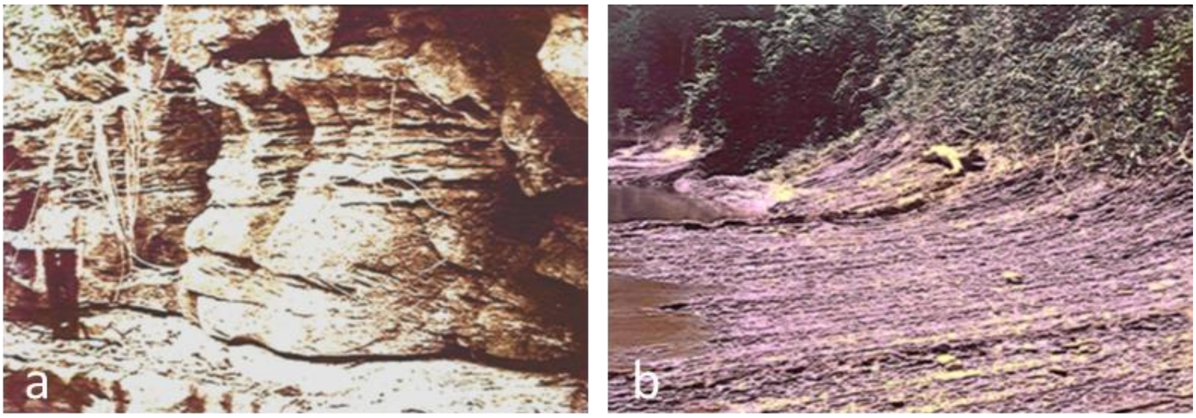

Figure 9: *a) Crossbedded sands and conglomerates from the Kiham Haloq clastics, Late Eocene (Mexicana Zone) of Sei Atan. Crossbedded units such as this are not found further north; b) Typical Atan Clastics, Early Oligocene ("Ampliapertura Zone") in Sei Marah. 10 cm turbidite sands from up to 20% of the section in a dominantly bathyal clay lithology. The river is at a low stage and so outcrop conditions are very good.*

volcanic and limestone beds occur in the outcrops.

A shale-dominated unit of Early Oligocene overlies the Late Eocene unit. This stratigraphic unit is indicated by the presence of *Turborotalia ampliapertura*. The benthonic forams of this section indicated a dominantly bathyal setting. In parts, there are indications of abyssal setting. This section is missing in Atan and only a short section remains in Bungalun.

Late Oligocene sections, which overlie the Early Oligocene unit, are found in Belayan/Ritan and Marah (Figure 9b). In Klinjau there is an unconformity above the Early Oligocene section, below the Miocene succession, which indicates that the Late Oligocene has been eroded. The Belayan/Ritan section is dominated by sandstones which are calcareous in parts and contain some volcanic layers. The Marah section has some conglomerate units and minor limestone. Potentially it is a slope deposit in deeper water.

The Late Oligocene section is overlain by Early Miocene deposits indicated by the presence of *Paragloborotalia kugleri*. Early Miocene sections were observed in the Klinjau and Marah areas. The section in Klinjau is conglomeratic, deposited in the inner to the middle neritic environment with relatively high energy. In Marah, the section contains more shale units with thin turbidite sands (Yeats and Cartier, 1973), deposited in a more distal environment.

<u>Panel 3 (Figure 10):</u> Four wells were drilled in the southern part of

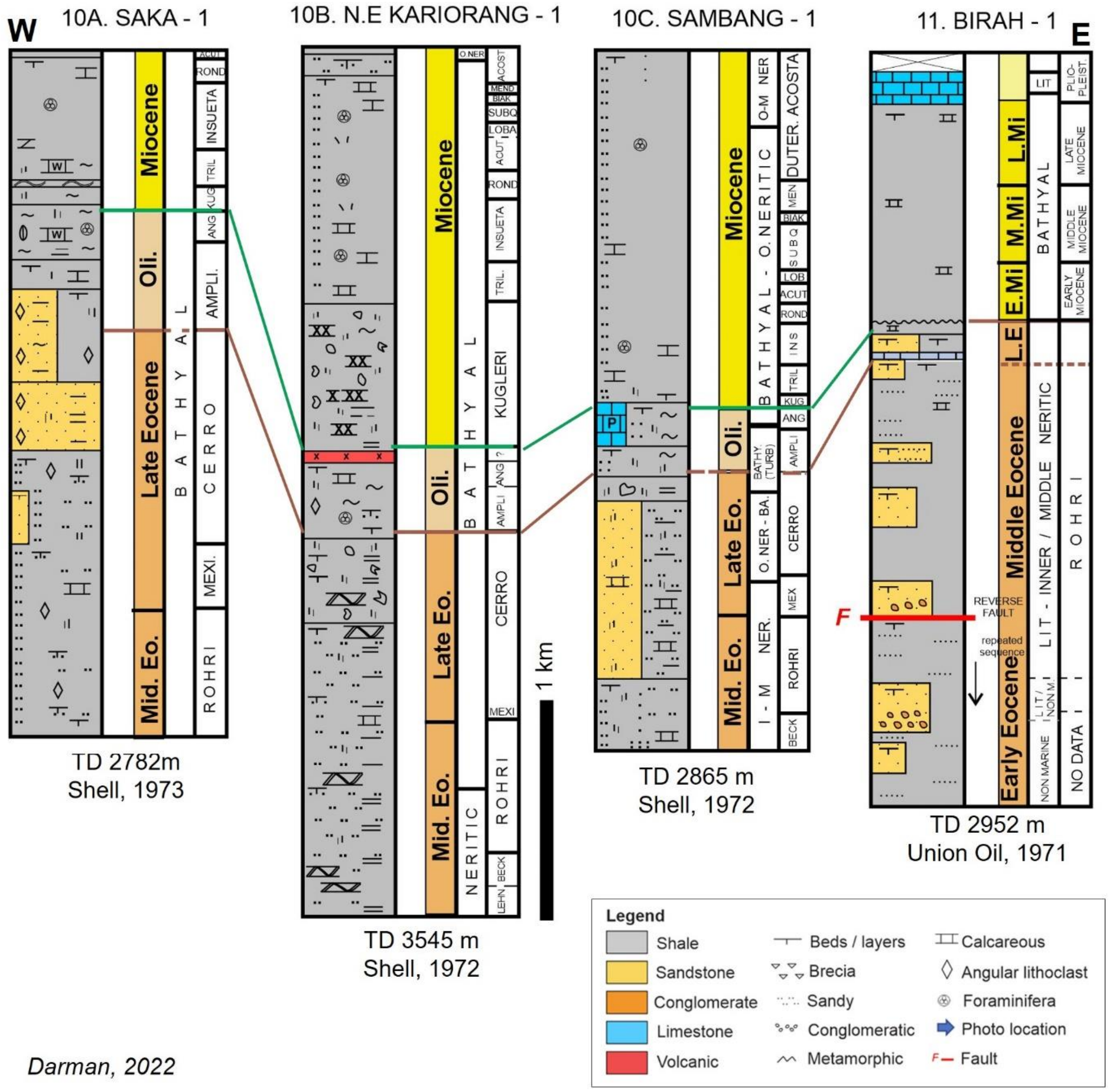

Figure 10: *Panel 3. Correlation panels of 4 wells in the south of Mangkalihat peninsula showing a complete Mid-Eocene to Miocene section. The Oligocene section was missed only in Birah-1. Modified after Cartier and Yeats (1973).*

Mangkalihat Peninsula, namely Saka-1 (Shell, 1973), NE Kariorang-1 (Shell, 1972), Sambang-1 (Shell, 1972), and Birah-1 (Union Oil, 1971), which is displayed in Panel 3 (Figure 10). The correlation panel's orientation is west-east and the first 3 wells in the west are located onshore. Yeats and Cartier (1973) identified an Early Eocene non-marine deposit at the bottom part of Birah-1 well.

Overall, Panel 3 shows that these wells penetrated shale dominated Middle Eocene sections. Saka-1 section indicated a bathyal deposit and NE-Kariorang have neritic deposits in the lower section and a bathyal deposit in the upper section. Both Sambang-1 and Birah-1 are dominated by neritic deposits. The lower section of Birah-1 is interpreted as non-marine to littoral as the interval is barren. The conglomeratic sandstone in the unit indicates a high-energy environment.

A Late Eocene section is encountered in all four wells in this panel. They are bathyal deposits in Saka-1 and NE-Kariorang-1 in the west and change to a neritic-bathyal setting in Sambang-1. To the east, Birah-1 shows most of the Late Eocene section has been eroded. The Pagar-1A and Makassar-1A wells in the area also penetrated this stratigraphic unit (Guritno et al., 2015; See Figure 3 for well location map) and they are useful as additional control points to understand Late Eocene paleogeographic setting.

The Oligocene section in the southern part of Mangkalihat thins to the east as shown in Panel 3. This stratigraphic unit overlies the Late Eocene section, but in Birah-1, the easternmost well in Panel 3, the Oligocene section has been eroded. An Oligocene volcanic bed was encountered in NE-Kariorang-1 and an Oligocene limestone bed was penetrated in Sambang-1. The Oligocene section is overlain by Miocene bathyal shale.

<u>Panel 4 (Figure 11):</u> A metamorphic unit at the bottom of Gunung (Mount) Antu is the oldest unit in Panel 4 (Figure 11), but the age is undetermined, and it has a fault contact with the Eocene unit.

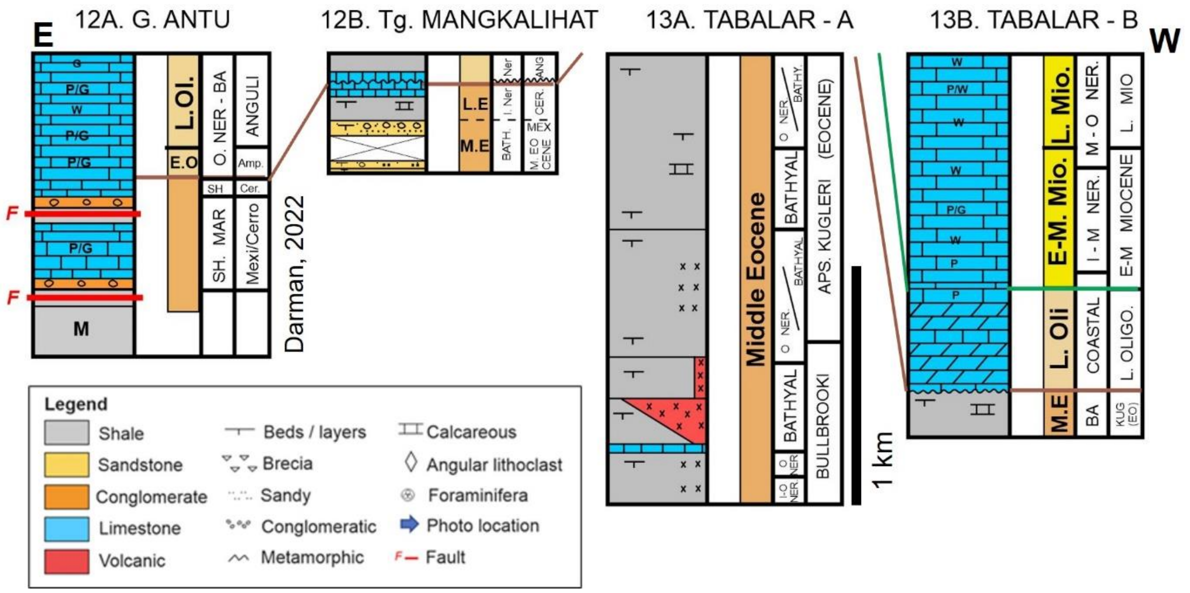

Figure 11: *Panel 4. Stratigraphic sections of outcrops in the north of Mangkalihat Peninsula, modified after Cartier and Yeats (1973). P=packstone, G=grainstone, W=wackestone, M=mudstone.*

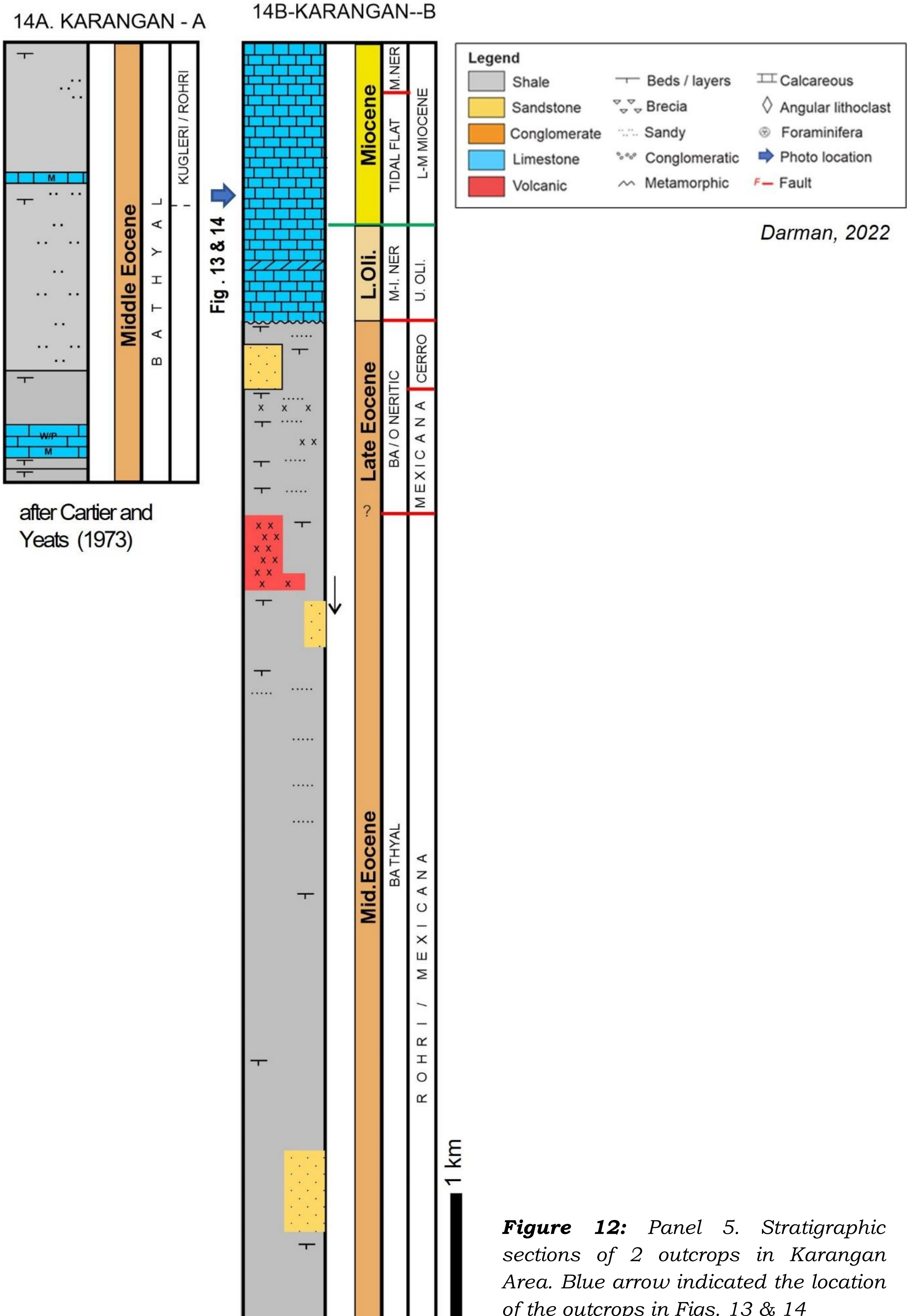

Figure 12: *Panel 5. Stratigraphic sections of 2 outcrops in Karangan Area. Blue arrow indicated the location of the outcrops in Figs. 13 & 14*

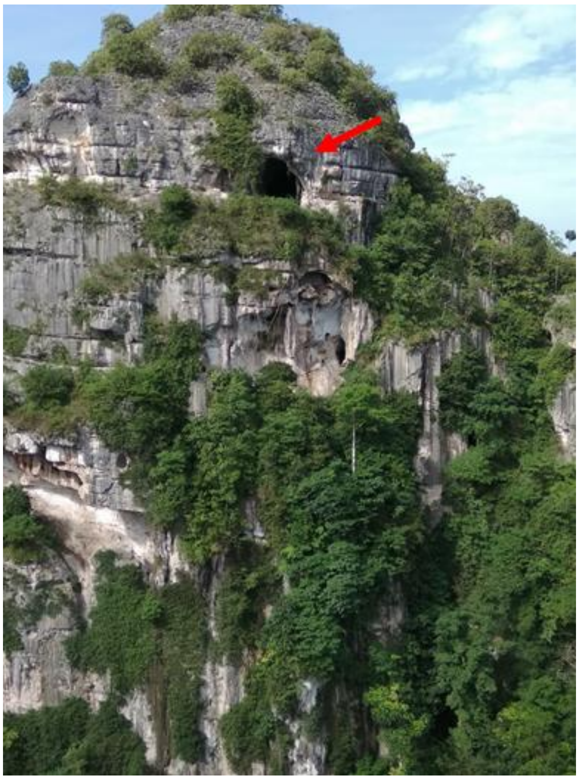

Figure 13: *Gua Mengkuris in Karangan Area. The geology consists of Upper Oligocene to Miocene carbonate outcrop, part of Lebak Fm. Photo courtesy: Thyo Theviking. The cave (red arrow) is about 4 m high.*

Middle Eocene unit is encountered in Tg Mangkalihat, Tabalar-A and Tabalar-B section and they are dominated by bathyal deposits (Cartier and Yeats, 1973). Only the section in Tabalar-A has some outer neritic deposits. *Globigerinatheka kugleri* is the index fossil for this Middle Eocene section.

A short section of Late Eocene was observed in G. Antu and Tg. Mangkalihat, both containing limestone beds. The Late Eocene section in Gunung Antu has a fault contact with the metamorphic unit below it. The Middle Eocene interval that overlays this section contains mudstone, packstone and wackestone carbonate layers, but overall, this section is very shaly. A couple of sandstone interbeds were observed in places. Volcanic units occur in the latest part of the Middle Eocene.

A thin Early Oligocene deposit overlays the Late Eocene unit in G. Antu and Tg Mangkalihat, but it is missing in Tabalar-A and Tabalar-B. Late Oligocene carbonate beds occur in G. Antu and Tabalar-B. The biostratigraphic analysis indicated a distal environment in the east and a proximal environment in the west. The section in Tabalar-B also has dolomitic units. Thick Miocene carbonates were deposited above the Late Oligocene section as observed in Tabalar-B.

Panel 5: In the west of Mangkalihat Peninsula, there are 2 outcrop observations in Karangan (Figure 12). The sections are called Karangan-A and Karangan-B. In the Karangan area, the Middle Eocene is an extremely thick bathyal deposit. There are carbonate interbeds with reworked material and there are also minor volcanic interbeds. The Upper Eocene is observed in Karangan-B, and it is a transition from

Figure 14: *Mt. Kulat carbonate outcrop, Upper Oligocene to Miocene carbonate outcrop, Lebak Formation (GRDC) Photo courtesy: Dasep Gunawan.*

bathyal to an outer neritic environment, dominated by shale.

The Lower Oligocene is missing in Karangan-B, but the Upper Oligocene carbonate occurs above the Upper Eocene unit with an unconformity contact. The carbonate is deposited in the middle to inner neritic, followed by Miocene carbonate (Figures 13 and 14) which is deposited in a tidal flat to the middle neritic environment. The age of the carbonate is not fully determined by biostratigraphic analysis.

PALEOGEOGRAPHIC SETTING

Observation and data for Early Eocene interval are limited, therefore paleogeographic reconstruction for this level is too difficult to construct. Middle Eocene to Late Oligocene paleogeographic maps for the studied area were prepared, based on outcrop analyses, wells and seismic interpretation, which were completed previously.

1. Middle Eocene

Middle Eocene fluvial deposits were identified in the west of Kutai Basin e.g., in the Ketungau and Melawi Basins (Figure 1) and in the south in the Barito Basin (Figures 1 and 15). Guritno and Chambers (1999) reported a Middle Eocene fluvial deposit in Wahau-1 well (Figures 3 and 15). Bachtiar et al. (2013) identified some non-marine deposits in the southwest margin of the Kutai Basin.

Littoral to sublittoral deposits occur in the southwest of the Kutai Basin. Cartier and Yeats (1973) found Middle Eocene shallow marine deposits in most of their sampling locations. In places like Atan, Klinjau, Karanga and Tabalar-B, there are bathyal shale-dominated deposits with some sandstone units. There are limited data available around the border of the facies belt, therefore the extent of the depositional units is approximate.

2. Late Eocene

Late Eocene shallow marine outcrops were identified in the southwest margin of Kutai Basin (e.g., Bachtiar et al., 2013) and in the northeast margin around Klinjau and Marah area (Figure 16). There are changes from neritic to bathyal at a later stage of Late Eocene as observed in Bungalun, Atan, Lower Mahakam, and also in Sambang-1 well.

Late Eocene biostratigraphic analysis of samples from Belayan, Klinjau, and Marah outcrops identified the bathyal environment of deposition. Saka-1 and NE Kariorang-1 well in the north of the basin encountered deep marine shale sections. Many believed that towards the center part of the basin there are more deep marine deposits, but these are now buried at great depths, beyond the reach of conventional oil wells.

3. Early Oligocene

In the Early Oligocene, there were fewer littoral deposits in the west of the studied area (Figure 17). Shallow water carbonates developed in the SW and NE margins of the Kutai Basin. The Barito and Paternoster Platform are large carbonate complexes developed in the south. The northern edge of both platforms followed a trend which was probably caused by WNW-ESE trend Adang Fault. The Maratua Carbonate Complex developed in the north of the Mangkalihat Peninsula. The facies distribution and facies changes in the SW are relatively well-constrained as there are more data points. The Upper Mahakam section NW of the area indicates a transition from a deep-water to a shallow-water environment (Figures 4 and 17).

Panel 2 which shows a correlation panel from Belayan to Bungalun (Figure 7) goes along strike at the northern margin of Kutai Basin. All Early Oligocene sections in this area show a bathyal environment of deposition. There are limited observation points in this area and the transition from neritic to bathyal is poorly constrained.

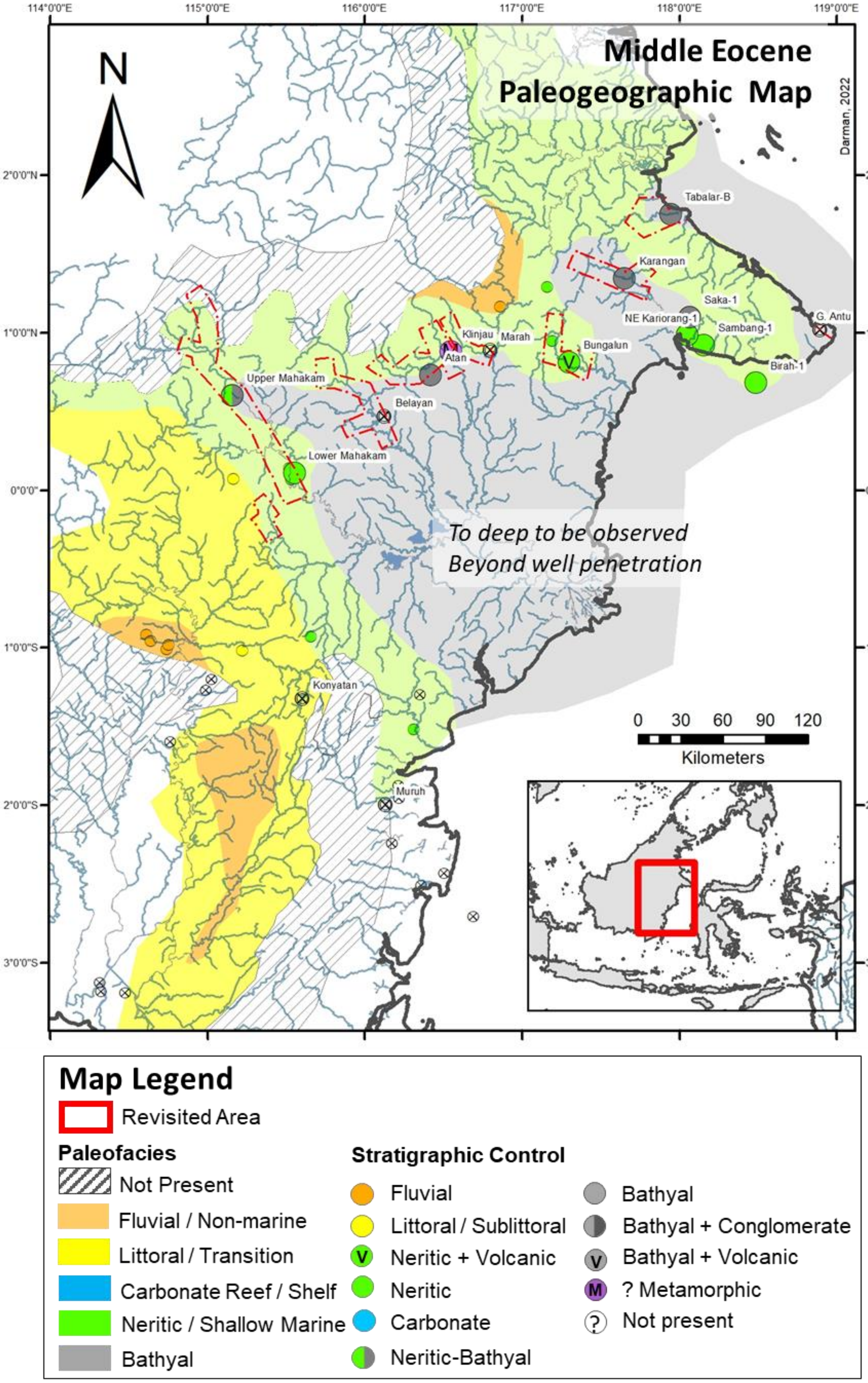

Figure 15: *Middle Eocene paleogeographic map.*

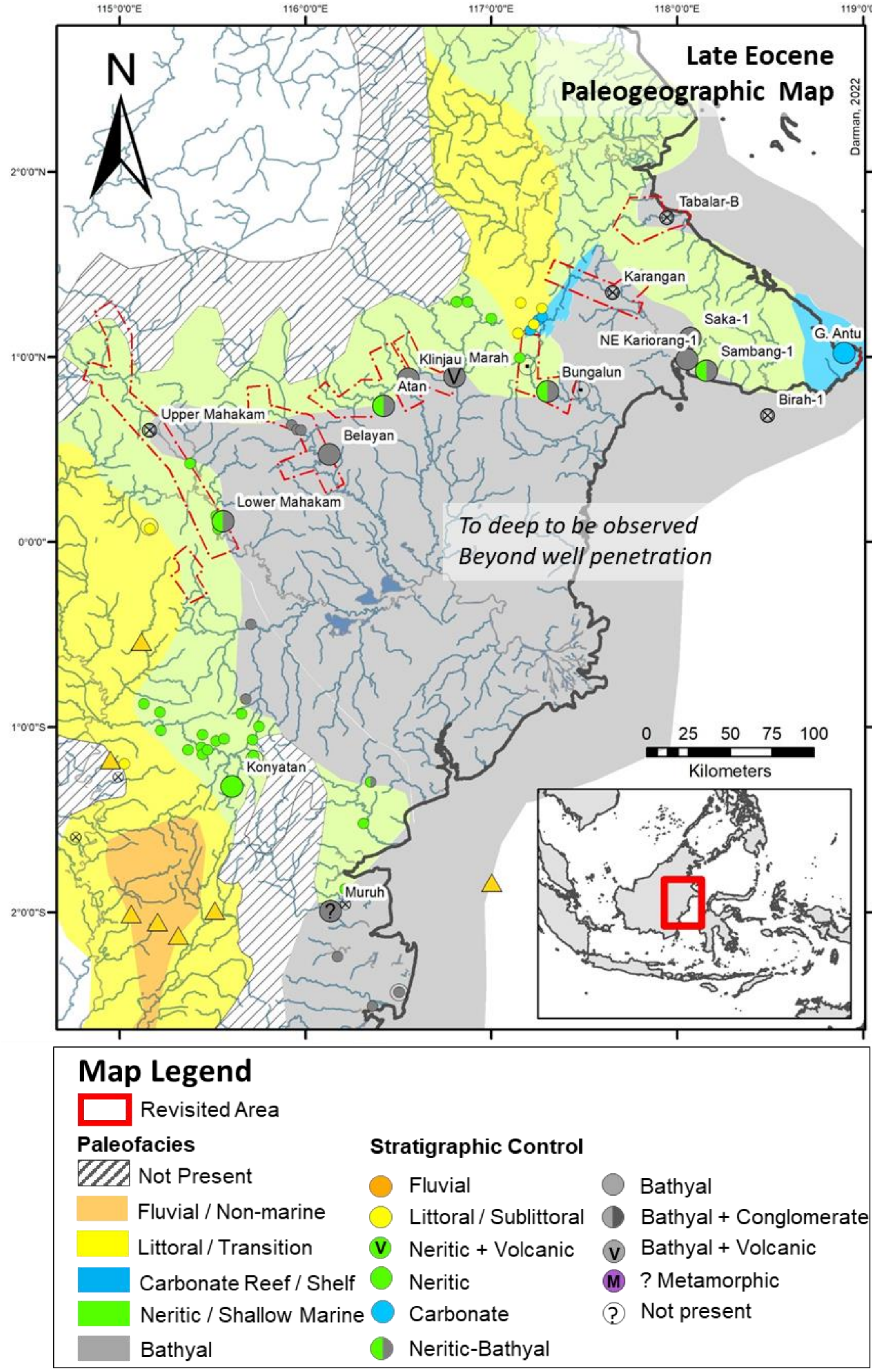

Figure 16: *Late Eocene paleogeographic map.*

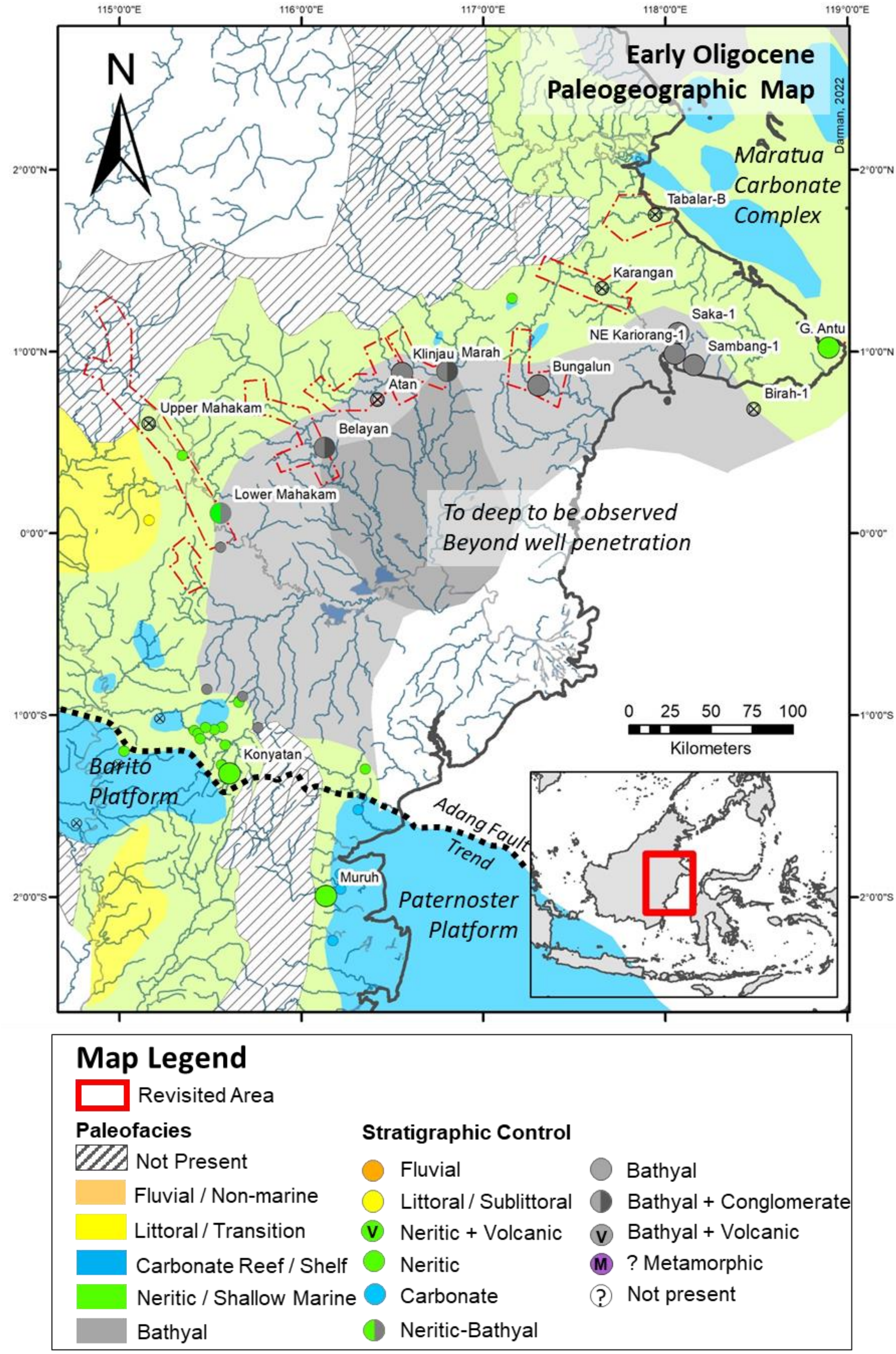

Figure 17: *Early Oligocene paleogeographic map.*

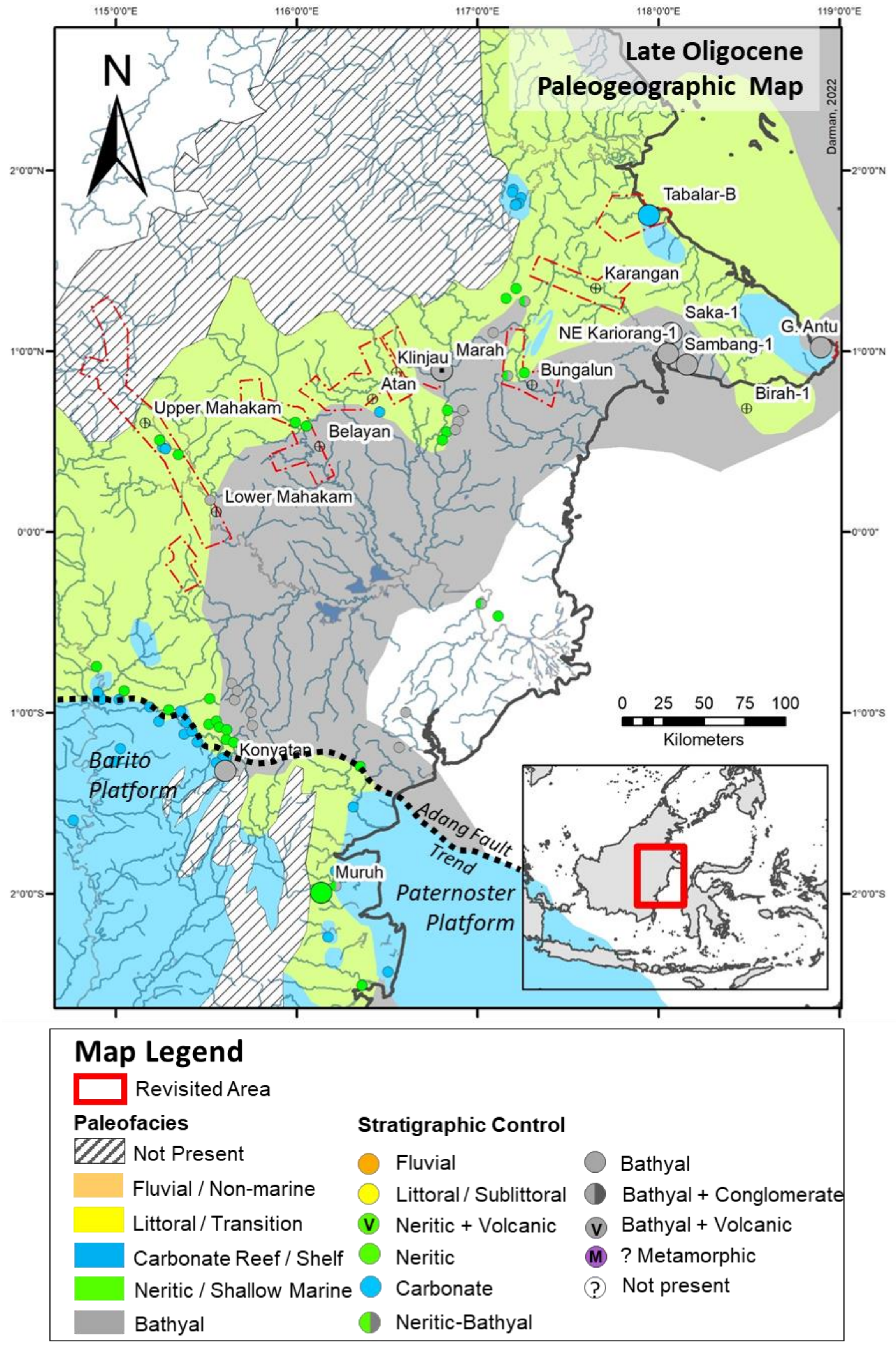

Figure 18: *Late Oligocene paleogeographic map.*

The Early Oligocene section is missing in a large part of the Mangkalihat Peninsula. Probably many of them have been eroded as indicated in Birah-1 well, Karangan, and Tabalar-B section (Figures 14 and 17). This area is part of the Mangkalihat High which separates the Kutai Basin from the Muara Sub-Basin in the north. Oligocene carbonates developed and are well preserved in the north of this high.

4. Late Oligocene

The carbonate platforms in the southwest of Kutai Basin developed intensively in the Late Oligocene (Figure 18). The facies transition from the carbonate system to the littoral, and to the bathyal clastic environment are well constrained as there are many field-observation points in the area. The facies changes are also observed in seismic sections as reported by Saller and Vijaya (2002). Similar to Early Oligocene, the northern edge of Barito and Paternoster Platform follows the WNW-ESE Adang Fault trend.

The facies distribution in the northwest of the studied area has fewer control points. In the south of Marah, Moss et al (1997) collected some outcrop data. These observations are useful to observe the changes of the depositional environment of the sediments from the neritic to the bathyal setting.

In the Bungalun area there are also several locations to observe the changes. The limestone outcrop provides some detail of the basin margin. To the north, around the Mangkalihat Peninsula, there was a significant uplift and erosion, and parts of the Late Oligocene section are missing, e.g. in Bungalun, Karangan, and Birah-1. The carbonates here only develop locally.

DISCUSSION

The SW margin of Kutai Basin is best observed as there are seismic, well and outcrop data. Similarly, the NE margin part the basin is covered by some data points. Their data quantity and quality, however, are not as good as the SW. The NW margin of the basin is an area with much fewer data. There are not enough wells to observe the Paleogene section and no seismic data to cover this area. The paleogeographic reconstruction in this area is based on limited outcrop observation. More data is required to refine the facies boundary.

Eocene sandstone is the primary petroleum exploration target in the margin of the Kutai Basin. The southern area has better sandstone development compared to the north (Figure 14). They are located in a more proximal area as they are closer to the provenance.

Several authors observed that many of the Paleogene sandstones in outcrops around the Kutai Basin tend to be tight (e.g., Bachtiar et al., 2013a) and thermally overmature (e.g. Guritno and Chambers, 1999). The reason for this may be deep burial of Paleogene before the extensive ~mid-Miocene regional uplift of much of Borneo Island, including the Upper Kutai Basin, where 1000s of meters of sediments may have been eroded since the Middle Miocene, as well as uplifts in local inversion structures. In addition, reservoir quality of Middle and Late Eocene sandstones in the northern part of the Kutai Basin may be adversely affected by unstable volcanoclastic and chert grains, derived from the Late Mesozoic oceanic accretionary complex ('Danau Formation') in the likely source area (e.g., Guritno and Chambers, 1999).

Potential carbonate reservoirs developed in the Oligocene time and were covered by a younger seal in the south. The Kerendan gas field proved this play potential in the area. In the north, many carbonates were exposed to the surface with minimum seal.

CONCLUSION

The Eocene sediments along the present-day margin of the Kutai Basin, including the sand packages known as the Eocene Beriun Sandstone or the Kiham Haloq clastics, were for the most part deposited in neritic to deep marine environments. The source of these sediments mainly came from the west and southwest. The northwestern high source areas, formed as the NE-SW axis of Central and North -Borneo, only appeared after Late Oligocene.

There was less tectonic activity during Early Oligocene. The basin was generally subsided and filled with shale. There was more carbonates development in the NE and SW margins. In mid-Oligocene an uplift occurred in the north which generated an unconformity. The unconformity developed in the southwest in Late Oligocene. In Late Oligocene the southern part of Kutai Basin was very stable and a large carbonate system developed well. The carbonate in the north only developed around local tectonic high in the Mangkalihat area.

Paleogene potential traps for petroleum exploration developed well in the southern margin of the basin. Eocene clastics and Oligocene carbonates in this area are better preserved here compared to other parts of the Kutai Basin. The center part of the basin is very distal with a smaller chance for both clastic and carbonate reservoirs to develop. At present, it is also too deep to be explored.

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A Discussion on the relationship between prominent unconformities on the SCS shelf margins and the end of seafloor spreading in the South China Sea

Franz L. Kessler[1, #], John Jong[2]

[1]Geologist and Geophysicist, Trainer, Glattbach Germany

[2]JX Nippon and Gas Exploration (Malaysia) Limited, KL, Malaysia

[#]*Corresponding author: franzlkessler32@gmail.com*

ABSTRACT

In an effort to reconcile different data sources (seafloor spreading, seismic and gravity images, well calibrations, outcrop studies) in the South China Sea (SCS), we reviewed the unconformity records, in particular in the context with the shut-off of seafloor spreading in the SCS. With respect to the start of spreading, there is a consensus: ca. 34-41 Ma. Recent data infer an end of spreading, near to the magnetic Anomaly 5 = ca. 15.5 Ma (Langhian age). In Northwest Borneo, it is suggested that this event is coeval with the Deep Regional Unconformity (DRU) in Sabah and Brunei, and the Mid-Miocene Unconformity (MMU) in Sarawak. The MMU is also recognized in offshore Vietnam and Palawan, on the Western and Southeastern margins of the SCS, respectively. The MMU/DRU may constitute the border between active margin and passive margin deposits within the marine SCS sub-basins. The progradation of clastic shelves post-MMU/DRU may have hampered growth of bioherms whilst creating prolific sandstone reservoir sequences offshore Northwest Borneo and Vietnam.

Keywords: *DRU, MMU, SCS, spreading, unconformities, Middle Miocene, polarity reversal, paleomagnetism, Northwest Borneo*

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INTRODUCTION: SCS UNCONFORMITIES, ONSET AND TERMINATION OF SEAFLOOR SPREADING

The objective of this paper is to compare different data sources: well data, seismic imaging, gravity, magnetic polarity reversal results, outcrop data, etc., in the context of major shelfal unconformities as well as the observed spreading records in the South China Sea (SCS). We attempted to find evidence for a coeval timing of the Mid-Miocene Unconformity (MMU) and the end of spreading in the center of the SCS.

On the Northwest Borneo shelf, several unconformities appear to indicate dramatic shifts in the tectonic and sedimentary setting of the SCS. It is an area of apparent high geological complexity, and there are still different opinions what caused the rifting in the first place – a subject which lies beyond the scope of this paper, with authors such as C.S Hutchison (2004) interpreting the SCS being formed as a result of the rifting of the continental Sundaland lithosphere. At the end of seafloor spreading, no more oceanic crust was formed at the seafloor spreading center of the SCS. The end of spreading also prompted changes of sedimentary deposition and tectonic patterns on the shelves including faults and lineaments. Noted in most regions, shelf areas prograded seaward towards the center of the basin.

Older publications often cite an earlier onset of rifting and a later shut-off. According to Hutchison (2004), "rifting began in the Eocene (~46 Ma) and ceased at 19–21 Ma (Anomaly 6), where seafloor spreading began much later than along the shelf of China". The break-up hiatus lasted ~3–5 Myr marked by the MMU and is also preserved onshore Sarawak. The post-rift strata date from ~16 Ma and drape over the rifted topography. To the east is a convergent margin that became a collision zone in the Middle Miocene. Interestingly, there is no reasoning given for the long duration of the "break-up" hiatus.

The term "MMU" was thought to be first coined by Shell geologists and seismic interpreters in the Baram Delta of Sarawak, and neighboring Brunei. However, there was no noted mention of the MMU in the 1970's and 1980's, which at the time discussions were still centered around the "Cycle" transgressions and regressions (Ho, 1978; Doust, 1981), rather than tectonic causes. Doust (1981) mentioned the early Middle Miocene as the start of rapid subsidence, albeit there was no reference to an unconformity. The first publication with the mentioning of MMU was believed to be by Mohd Idrus et al. (1995), in which the unconformity and structure of deepwater Sarawak were described, and later summarized by Madon et al. (2013). "DRU" on the other hand, was well defined and described by Levell (1987), based on Sabah Inboard seismic data.

An unconformity, being related to the end of seafloor spreading, would be a dividing line within the passive margin setting, and describe a trend leading from deeper marine to increasingly shallow marine sediments (e.g. Kessler and Jong, 2015, 2016). The end-of-spreading unconformity may define the boundary between bathyal and neritic in the central SCS, and between neritic and shelf deposits on the flanks. One would expect a marked and erosive unconformity at the basin flanks, and a

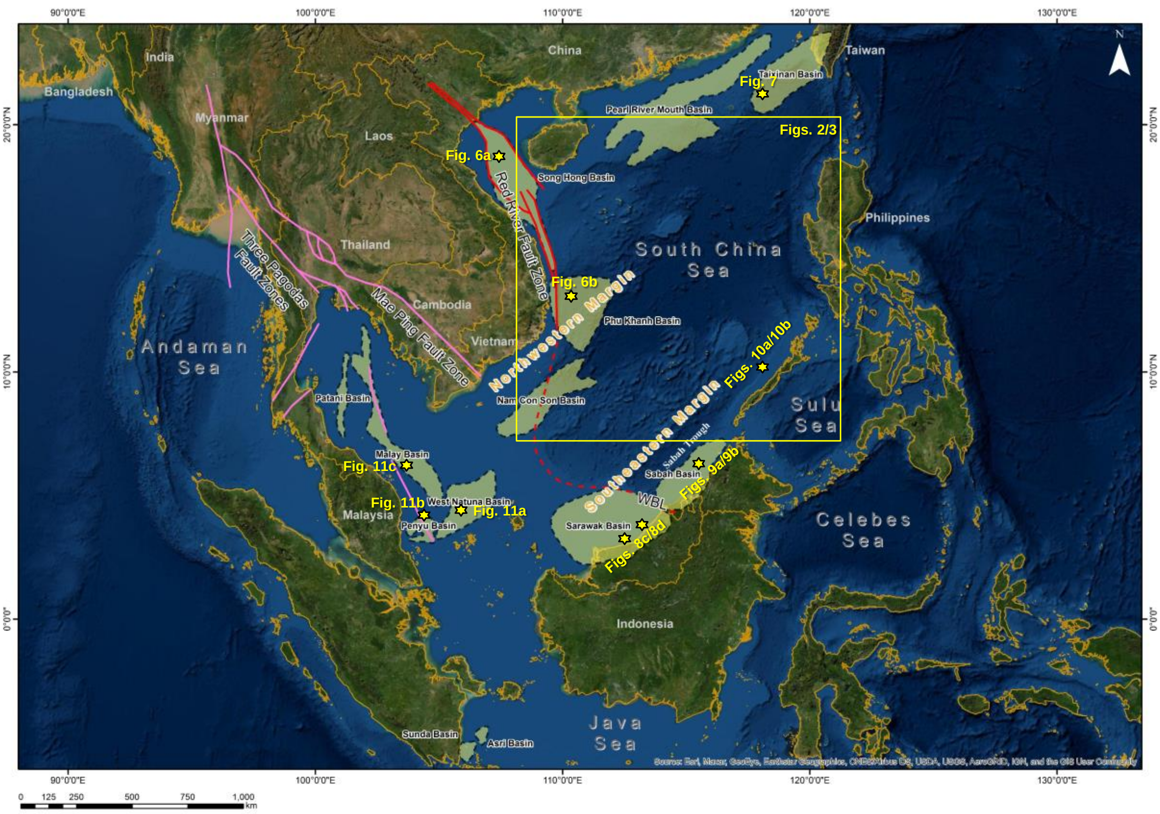

__Figure 1__: Area index map – satellite imagery of SE Asia. Key SCS Sub-basins that originated during the Paleogene are shown in black dashed line with light green fill (from Kessler et al., 2021b). The areas of oceanic crust and strongly thinned continental crust flanks are potentially bounded by the red line Red River Fault System, and the West Baram Line (WBL) (Jong et al., 2014; Kessler and Jong, 2016). Note Figures 2 and 3 are outlined in the yellow box area, while the approximate locations of key seismic lines are indicated by the yellow stars with the relevant figure numbers annotated.

disconformity in the basial setting. Supposedly such an unconformity might be an event of a diachronous nature but by only little.

In a previous publication (Kessler and Jong, 2016), we gave examples of the observed unconformities, which are seismically defined features and often poorly calibrated by well and outcrop data. However, unconformities are coined in individual sub-basins, and correlations between the SCS sub-basins are spurious. Therefore, this and the many data gaps have prevented establishing a clear context between SCS unconformities and seafloor spreading. Nevertheless, despite the mentioned correlation and data gap problems, we discuss which regional unconformities observed on the shelves might be coeval with the end of seafloor spreading.

The correlation of shelfal sequences with the center of the SCS could be important in the context of regional basin evolution and modeling. In the discussions below, we briefly review areas of the Central SCS, the Northwestern SCS shelf margin (Southern China, Vietnam, Gulf of Thailand, Malay and Penyu basins), and the Southeastern shelf margin (NW Borneo - Sarawak, Sabah and Palawan, Figure 1).

It is noted that a recent paper by Deng et al. (2020) has provided an excellent documentation on the transition from wide continental rift to continental breakup of the SCS.

METHODOLOGY, DATA SOURCES, AND DATA LIMITATIONS

In our investigation, timing of unconformity events such as the MMU and DRU are put in context with well and outcrop records and compared with magnetic polarity reversal ages of deep-sea drilling results recorded in the center of the SCS. In respect of the data collection, we considered the following sources in our synopsis:

(i) *Well data*. These can be categorized as shelfal wells, drilled in the context of oil and gas exploration, and several vintages of research wells, located in the center of the SCS. However, only data fragments of O&G wells have been released to the public. On the contrary, deep-sea drilling results are in the public domain, but given their position in the center of the SCS, the penetrated sedimentary record is limited and a direct link with unconformities on the shelf cannot be achieved.

(ii) *Seismic data*. Like the well records, we see ample and excellent industry data (often 3D) acquired on the shelves, and 3D reconnaissance seismic (mostly 2D) in the center of the SCS. Nonetheless, seismic lines, which both image shelfal and deepwater areas, are rare.

(iii) *Gravity* (Figure 2). Gravity data in the public are Free Air Gravity and Bouguer Gravity data. Free Air Gravity can be used to map the outlines of SCS topography, as it reflects mainly the impact of water depth. Bouguer data are very useful in highlighting variations in the crustal architecture (Figure 2b) and in the sedimentary overburden but contain elements of digital filters which may be based on assumptions only.

(iv) *Magnetic polarity reversal data.* These can be recorded only over magmatic crust with little or no sedimentary overburden, and interpretation of the reversal has often led to ambiguous results.

(v) *Geological outcrops.* Outcrop interpretations can provide excellent data in respect of stratigraphy and describing the character of unconformities and their stratigraphic ties. This said, outcrops can give only one-dimensional answers to three-dimensional problems and should preferably be evaluated together with well and seismic controls.

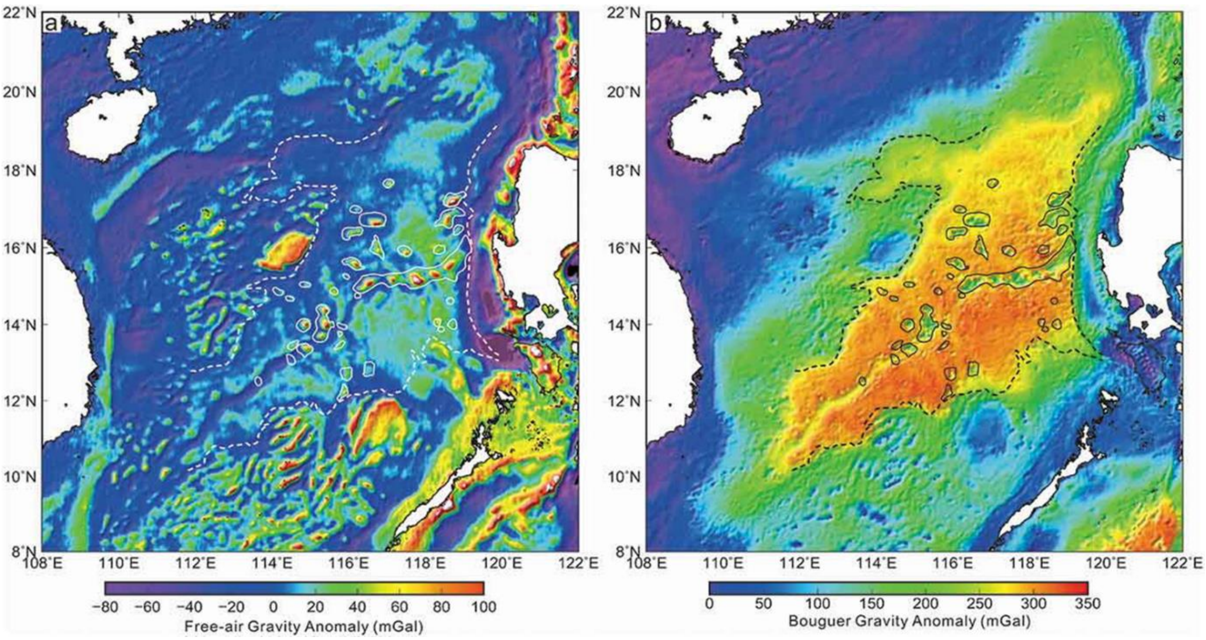

Figure 2: *(a) Free-air gravity anomaly map of the SCS basin (Sandwell et al., 2014) and (b) complete Bouguer gravity anomaly computed from (a) with the distribution of the post-spreading seamounts. Potential post-spreading seamounts in the SCS show free-air gravity anomalies of > 30 mGal and Bouguer anomalies of < 300 mGal, which is consistent with the observation by Zhao et al. (2018). Figures after Zhou et al. (2020). See map outline in Figure 1.*

A COMPARISON OF SCS SUB-BASIN AREAS

For discussion purpose, we subdivide areas surrounding the SCS as follows (Kessler and Jong, 2016; Kessler et al., 2021a, 2021b) (Figure 1):

- The **Central SCS** covers by far the largest part of the discussed topic. Seismic coverage is sparse and irregular, and only a few research wells (ODP, IODP) provide rudimentary calibration points. The area is mostly constituted by deep marine settings, oceanic crust plus several remnants of rafted continental crust.
- The **Northwestern shelf margin** is formed by a string of sub-basins starting from Peninsula Malaysia to Vietnam margin to Hainan Island, and southern China. The well is well covered by seismic and numerous exploration wells.
- In the **Southeastern shelf margin**, we see several sub-basins located in the Borneo margin to Palawan Trough. As in the Northwestern margin, there is mostly good seismic coverage, and relatively good calibration by wells and outcrops fringing the tectonic border with the Rajang/Crocker Basin. Eocene deposits in the area were described and discussed in Kessler et al. (2021a).

Central SCS area

The central SCS, a deep basin, has become the subject of scientific drilling research since 1999. Over the last 20 plus years, around 17 sites were drilled and nearly 10,000 m of cores recovered, including 320 m of basement basalt (Wang et al., 2019). The area is characterized by bathyal deepwater setting, with thin sequences of fine clastic deposits from Eocene to recent.

The published data comprehend gravity and magnetic data, regional 2D seismic grids, and several deep-sea drilling holes. Systematic geological exploration dates to the 1970's when geophysical data – seismic, gravity and magnetic were acquired in the context of the deep-sea drilling campaigns and when the first extensional models were developed (Taylor and Hayes, 1980). These showed that there is a triangular-shaped area being underlain by oceanic crust, surrounded by the continental shelves and slopes of Hainan, Vietnam, the Philippines, and Borneo.

Figure 2 shows a broad Bouguer gravity anomaly coinciding with the center of the SCS and the area of seafloor spreading. The gravity data also allow distinction of the central SCS spreading area (in orange color), thinned continental crust (green color) and

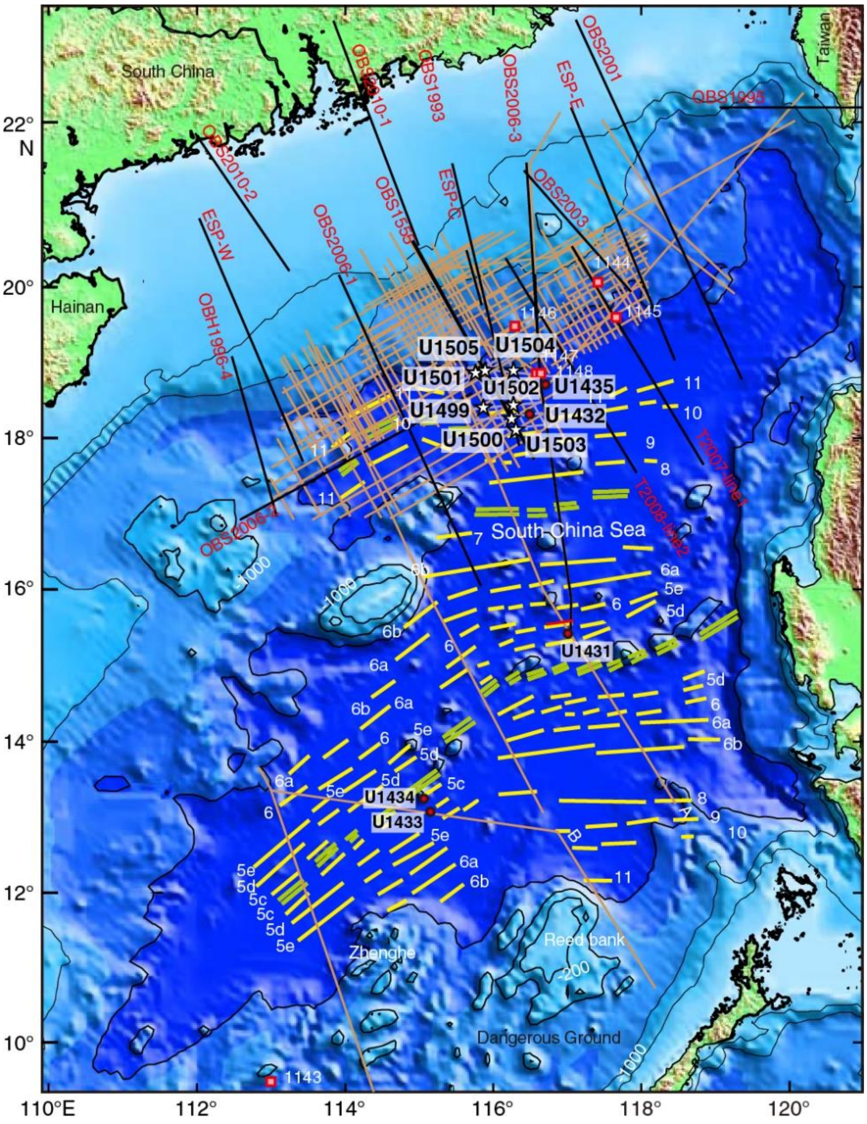

***Figure 3**: Magnetic polar reversal patterns shown by Childless et al. (2020) in Sun et al. (2020), as result of the IODP drilling program, leg 367/368. Note that the oldest reversal lines shown in the immediate vicinity of the mid-ocean ridge is the Anomaly 5c (on either side of the spreading centre). Black lines = ocean-bottom seismometer refraction data. Other seismic lines (orange) are mostly multichannel seismic reflection data. Yellow lines = magnetic isochrons from Briais et al. (1993). White stars = Expeditions 367, 368, and 368X drill sites. Red squares = ODP Leg 184 sites. Red circles = IODP Expedition 349 sites. See map outline in Figure 1.*

mildly or unstretched crust elements with passive margin sedimentary cover (blue color).

A tabulation of magnetic data was compiled in Cande & Kent (1995) (Table 1). They showed a symmetrical pattern of seafloor spreading, in the eastern part of the basin, indicating a spreading activity from Mid-Oligocene to Early Miocene (Hutchison, 1996). Although the mere fact of oceanic crust formation by seafloor spreading was never disputed, there is an ongoing discussion about when seafloor spreading started and when it ended.

Key concepts regarding the seafloor spreading in the SCS, discussed by various authors have been summarized by Kessler and Jong (2016); these include intrusion-based models (e.g., Tapponier et al., 1982; Replumaz and Tapponier, 2003), as well as subduction-based models (e.g., Taylor and Hayes, 1980; Briais et al., 1993; Hall, 2002; Hall et al., 2008) and hybrid models (e.g., Cullen, 2010; Cullen et al., 2010). However, when considered in detail, the data regarding the onset and termination of seafloor spreading appear less coherent, as shown in the summary by Morley (2016). One of the primary goals the deep-sea drilling projects in the SCS was to establish a "testing hypotheses for lithosphere thinning during continental breakup", rather than establishing stratigraphic control in the basement rocks and in sediments overlying the magmatic oceanic crust. A great effort was made in recognizing and differentiating the hypothesis models for the formation of the SCS by using data from deep-sea drilling projects.

In the SCS, there is a pattern of several normal-to-reverse polarity switches that are relatively well aligned. The critical challenge is to identify the polarity reversal pattern and to assign correct ages to both measured individual reversal points and the interpreted polarity reversal pattern. The magnetic polarity reversals happened at highly irregular intervals during seafloor spreading. However, polarity reversals have been mapped, catalogued, and correlated on a world-wide scale, and can offer fairly reliable time markers, if a good local calibration is achieved.

Start (Ma)	End (Ma)	Reversal Event
14.800	14.888	5Bn.1n
15.034	15.155	5Bn.2n
16.014	16.293	5Cn.1n
16.327	16.488	5Cn.2n
16.556	16.726	5Cn.3n
17.277	17.615	5Dn
18.281	18.781	5En
19.048	20.131	6n
20.518	20.725	6An.1n
20.996	21.320	6An.2n
21.768	21.859	6AAn
22.151	22.248	6AAr.1n
22.459	22.493	6AAr.2n
22.588	22.750	6Bn.1n

Table 1: *Polarity reversal events and tertiary ages. The SCS spreading shut-off uncertainty range is indicated by the red bar (from Cande and Kent, 1995). Recent data suggest that the shutoff may have occurred close to Anomaly 5.*

Nevertheless, the well results have delivered a few good absolute ages, as well as biostratigraphy data points in respect to the age of sediments overlying the magmatic oceanic crustal rock. International Ocean Discovery Program

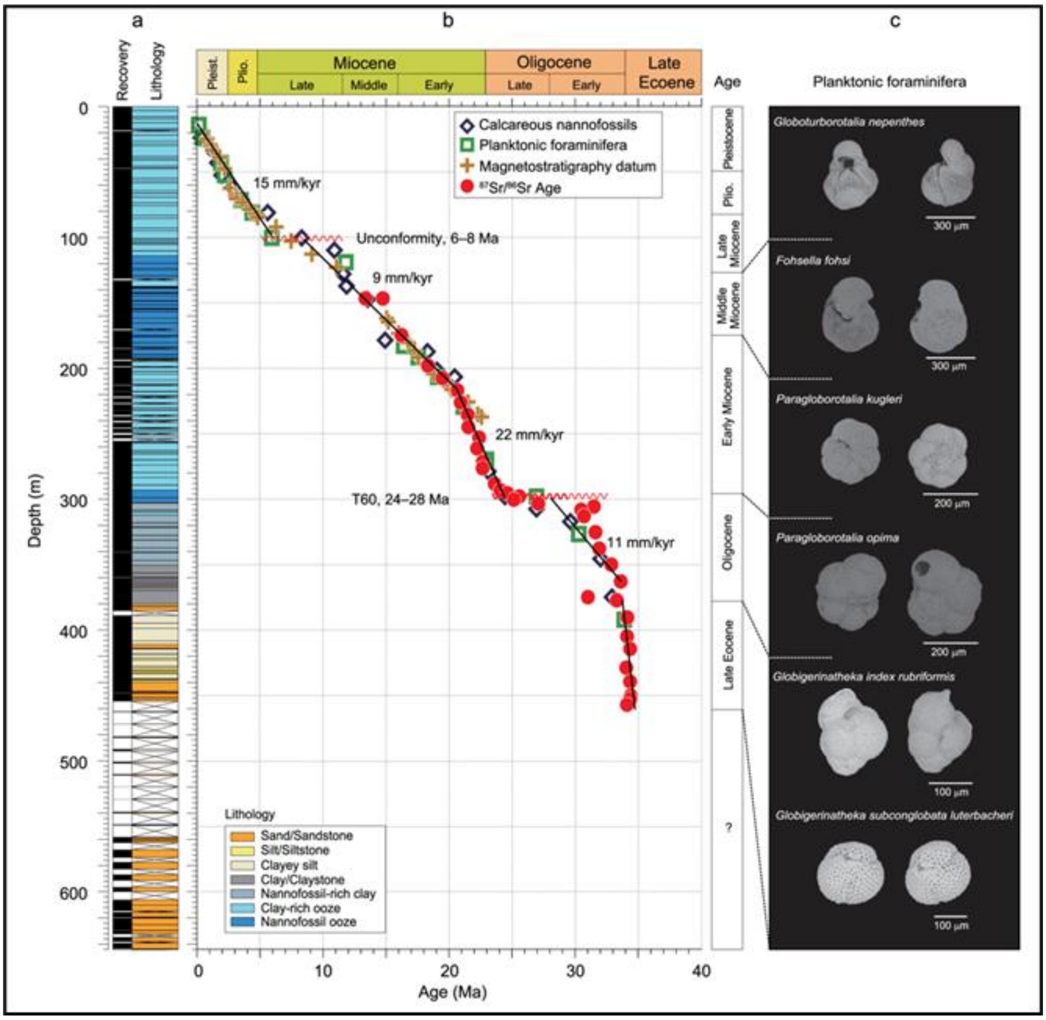

Figure 4: *Litho-, bio- and magneto-stratigraphic and strontium isotope stratigraphic correlations at Site U1501. (a) Lithology; (b) depth-age plot of Site U150 based on the shipboard biostratigraphic data of calcareous nannofossils and planktonic foraminifera, magnetostratigraphic data and the Sr isotopic ages with numbers beside the lines indicate the average sedimentation rates. Red zigzag lines represent the unconformities, while T60 indicates the seismic reflector; (c) SEM photographs of index planktonic foraminifera including typical Late Eocene species. These data overall point to the Late Eocene start of seafloor spreading in Central SCS (from Jian et al., 2019).*

(IODP) Expedition 367 successfully recovered at Site U1500 the mid-ocean ridge basalt (MORB) representing the magma activity of the initial spreading of the SCS during the earliest Oligocene (Yu and Liu, 2020). From the other sites (U1431, U1433, U1146, U1147, U1148), only U1435 logged Paleogene sediments at locations in proximity to the continental-to-oceanic crustal boundary (C.-F. Li et al., 2014; Figure 3). Most of the wells, however, were drilled in the central area of the SCS, where there is no continental crust that could host a Paleogene sediment cover, given that the oldest sediments found are (with one exception) of Early to Mid-Miocene age. Another IODP well, U1501 (Figure 3), penetrated Late Eocene rock on the northeastern shoulder of the central SCS rift (see Jian et al., 2019) (Figure 4). Arguably one can pinpoint the onset of oceanic crust formation in the Late Eocene (?Priabonian, 34 – 41 Ma) or slightly older.

There seems to be less uncertainty in respect of the start of spreading, but significantly more for the termination of spreading. This may be related to varying interpretations with respect to the measured and interpreted polarity reversals. Barckhausen et al. (2014) interpreted the most recent polarity reversal located near the axis of spreading as Anomaly 6, whilst more recent interpretations by Childless et al. (2020) and summarized in Sun et al. (2020) proposed a younger polarity reversal Anomaly 5 (Figure 3). Regarding the end of spreading, central SCS wells provide only some tangible information. Chang et al. (2014), in a reply to

__Figure 5:__ Simplified stratigraphic scheme of NW Borneo shelf margin showing correlation of the Sabah, Sarawak and Brunei cycles and stages with SB and TB nomenclatures, Shell deepwater terminology and lithostratigraphy. Note the Mid-Miocene Unconformity and Deep Regional Unconformity (MMU, DRU) are annotated at the base of TB2.4 at around 15.5 Ma (from Morrison and Wong, 2002).

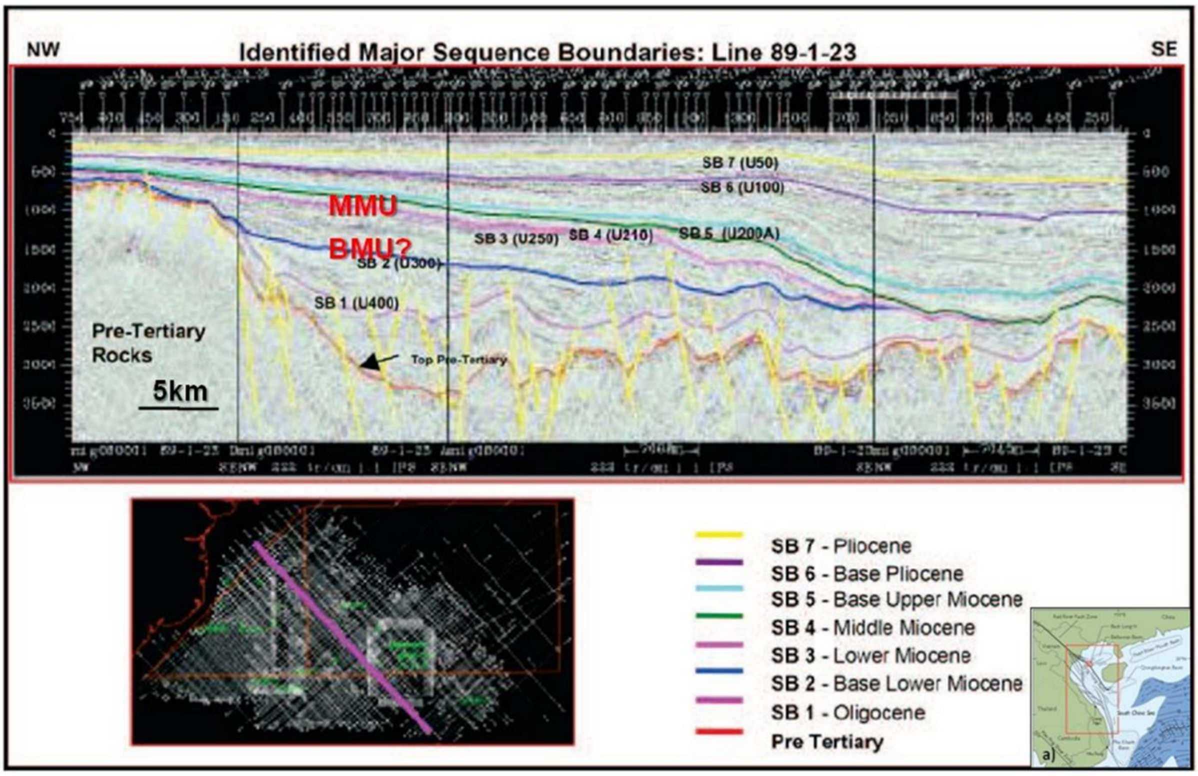

Figure 6a: *Seismic section of Song Hong depocentre with SB4 equivalent to MMU and SB2 is likely Late Oligocene unconformity/BMU. There is a clear division in a pre-MMU section (=active shelf margin) and a post-MMU section which is formed by passive margin deposits. From Unir and Mahmud (2006) with location map from Fyhn et al. (2012). See approximate line location in Figure 1.*

Barckhausen et al. (2014) argued that a bio-stratigraphically determined age of 16.7 to 17.5 Ma, was obtained from a borehole close to the spreading center of the SCS and appeared to point to a Mid-Miocene age for the end of spreading, instead of Early Miocene (20.5 Ma), as proposed by Barckhausen et al. (2014). This way they could extrapolate the results to the ridge and conclude, that the spreading was still ongoing at least until 17.5 Ma but probably later, and hence pointed to a Burdigalian-Langhian age as the end of spreading (Figure 5).

Northwestern shelf margin

This area corresponds to the Gulf of Thailand and offshore peninsular Malaysia, as well as contemporaneous shelf areas of Thailand, Vietnam and southern China.

The Vietnam to Southern China shelf margin is characterized by predominantly shelfal settings with several isolated and deeper sub-basins. The Vietnam continental shelf area lies above a system of Cenozoic sub-basins within a transition zone leading from the

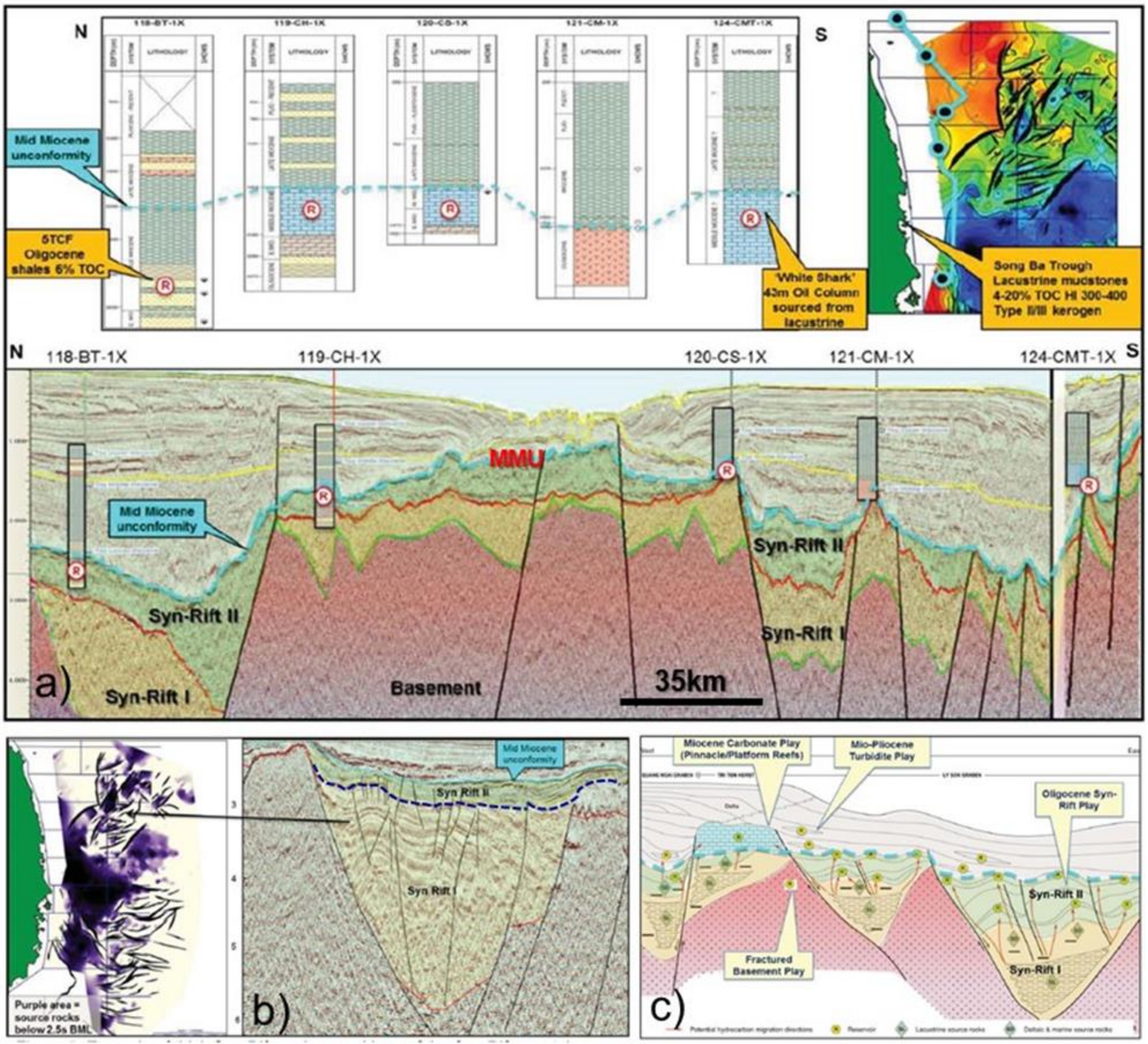

__Figure 6b:__ a) Geo-seismic sections offshore Vietnam going through several wells and highlighting the major stratigraphic units with mapped MMU (light blue horizon) illustrated across the Phu Khanh Basin, dashed dark-blue line = Late Oligocene Unconformity/BMU. b) Syn-rift depocentre. c) Schematic summary of the play types of the Phu Khanh Basin. Modified after Choi and McArdle, 2015. See approximate line location in Figure 1.

continental crust of the Indochina Block to the sub-oceanic crust of the eastern deepwater basins.

These basins developed here are rift basins with multiphase history as summarized by Fyhn et al. (2009b, 2012) (Figures 6a and 6b). As summarized in Clift et al. (2002) and Morley (2016), the strong extension and structural inversion largely pre-date the 16 Ma unconformity. The authors called this event MMU, following Hutchison (2004) (Figures 6a and 6b), and the post-rift strata were dated from ~16 Ma and draped over the older rifted topography. To the east is a convergent margin that became a collision zone in the Middle Miocene. An extensional phase was initiated around 28 Ma, moderate extension is noted at 22–23 Ma. Normal faulting ceased after an inversion event at ca. 16 Ma, although, representing the end of basin extension, and indicating compressive stress. C.-F. Li et al. (2014) and L. Li et al. (2014) infer that faulting stopped at the unconformity (see Figures 6a and 6b), whilst the underlying Early Miocene section is faulted. 1D subsidence models indicate rapid “syn-rift” subsidence, possibly lasting until 10 Ma, despite the lack of observed extensional faulting (L. Li et al. 2014).

In contrast, Fyhn et al. (2009a, b) see the main termination of extension of the Vietnam Margin at the Lower Miocene – Oligocene boundary (i.e. 23-21Ma). Note the MMU features very clearly in the Nam Con Son and the southern Phu Khanh Basins (Fyhn et al., 2009a) (Figure 6b).

In the Late Miocene, the basin was again tectonically restructured by a mild inversion, followed by thermal subsidence, resulting in large carbonate reefal buildups, and infilled by sandy turbidites on the basin floor. The process was interrupted in the Early Pliocene due to a major transgression.

Further south in the Gulf of Thailand, Malay and Penyu basins, the margin is characterized by an embayment formed by thick non-marine and marginal marine sequences, where intertidal marine clastics and coals were deposited since the Early Miocene. Despite a continuous subsidence during the Neogene, the area remained covered by shallow marine water. There is no prominent unconformity signature noted at the Mid-Miocene time, nor is there any important facies change recognized (Madon et al., 1999, 2019; see later Figure 11).

Admittedly not a focus area of our investigation, it is interesting to note that an additional complexity of the Northeastern SCS margin is the presence of a Necking Domain, as described by Mi et al. (2023). The most striking characteristic of the bended or flexed necking domain in the area is the densely spaced, landward-dipping faults and fractures that are organized in a domino configuration in the homogeneous basement. Seismic stratigraphy in the necking domain can be divided into pre-, syn- and post-rift sequences based on the nature of sequence-bounding unconformities and their relation with faults. Seismic expression of continental crust exhibits two types of reflection characteristics –

homogeneous upper crust and layered lower crust. In some shelfal areas, the necking has led to a tilting of both the syn-rift and post-rift sequence. A clear boundary between syn-rift and post-rift sequences can be interpreted (Figure 7), but whether this boundary is coeval with the MMU in other parts of the SCS, remains speculative at this point in time.

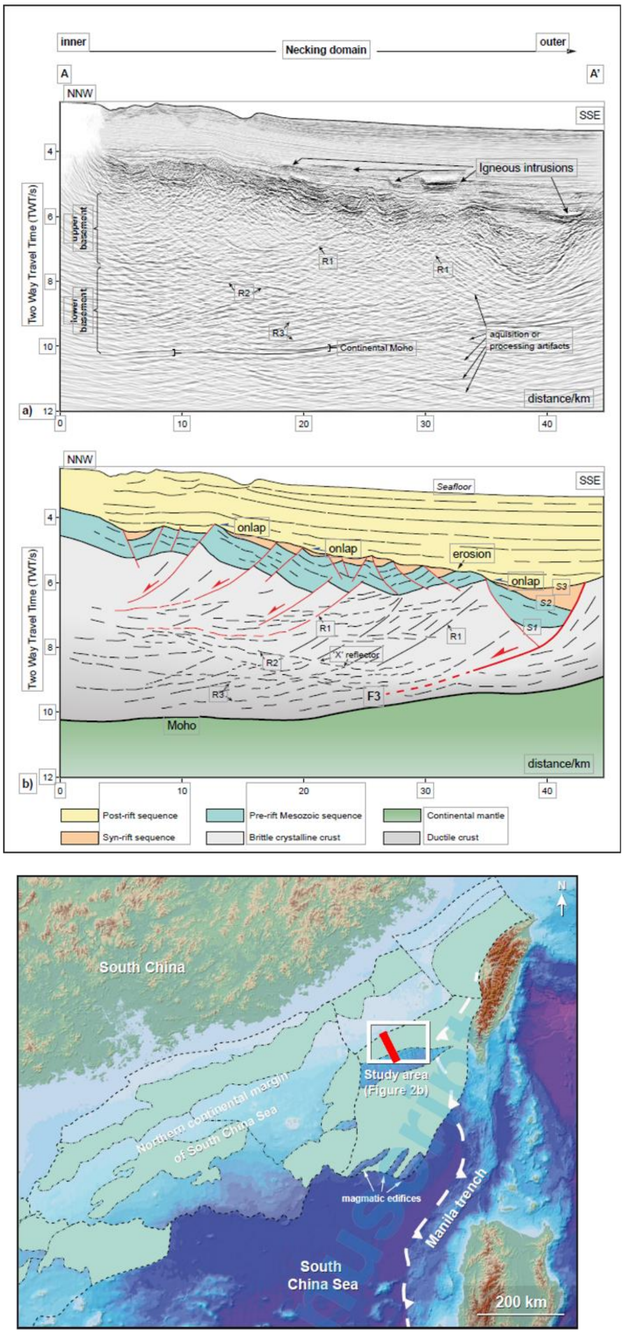

Figure 7: Uninterpreted seismic section A-A' (a) and its interpretation (b) showing detailed deformation of the necking domain (section location see bold red line in index map). F3 is the outer breakaway complex. S1, S2, and S3 are three unconformities that separate the top-basement, pre-rift, syn-rift, and post-rift sequences. However, whether S3 is coeval with the MMU in other parts of the SCS, remains speculative at this point in time (S3=MMU?). R1, R2, and R3 are three types of reflectors in the basement. Note that the homogenous basement in the upper part of the necking domain is dominated by land-ward dipping reflections (R1) that are interpreted as fractures. R2 is sub-parallel to the top basement. R3 is sub-parallel to the seismic Moho. In the post-rift sequence, the high-amplitude, saucer-shaped and step-like reflections are interpreted as igneous intrusions (from Mi et al., 2023). See also the approximate line location in Figure 1.

Southeastern shelf margin

This area covers the Sarawak-Sabah-Palawan margin, with Sarawak characterized by shallow shelf with many bioherms; shallow-marine clastic deposits in Baram Delta.

As suggested in Jong et al. (2014) and Kessler et al. (2021a, 2021b), the so-called Mid-Miocene Unconformity (MMU; Figures 8a-8d) might be a good candidate for an event for a correlation with the end of the SCS spreading. The Sarawak shelf is divided into the stable

Figure 8a*: View of the Mid-Miocene Unconformity (MMU) with a mid-size SUV for scale, located in Bukit Lambir (red mark in the inset map of northern Borneo), a large pop-up between two branches belonging to the West Baram Line system. The above outcrop is situated next to a highway construction site and is showing a rare example of a large-scale unconformity exposure. Cross-bedded Late Miocene Lambir sandstones are seen above scoured clay and siltstone of the Early-Mid Miocene Setap Formation (from Kessler et al., 2019).*

Central Luconia Platform and the less rigid Baram Delta area.

The unconformity is relatively well dated in the onshore Baram Delta deposits of Sarawak, and its age was identified as ca. 15.5 Ma in an outcrop of Bukit Lambir (Entulang section, Wannier et al., 2011), where it is seen to scour clay-dominated rocks of the Setap Shale (Kessler et al., 2019, Figures 8a and 8b); the sediments underlying the unconformity are Burdigalian and contain further up a NN4-5 planktonic assemblage (assumed Langhian). The hiatus at the unconformity was estimated as 0.5 Myr but may vary in other areas depending on scouring.

Future work may focus on reviewing the location of the MMU in SCS exploration wells and analyzing facies changes in the stratigraphic sequences located below and above the unconformity. In the adjacent Luconia Platform, the appearance of the MMU appears to be different, and may not be an unconformity in the traditional sense (van Vliet and Krebs, 2009).

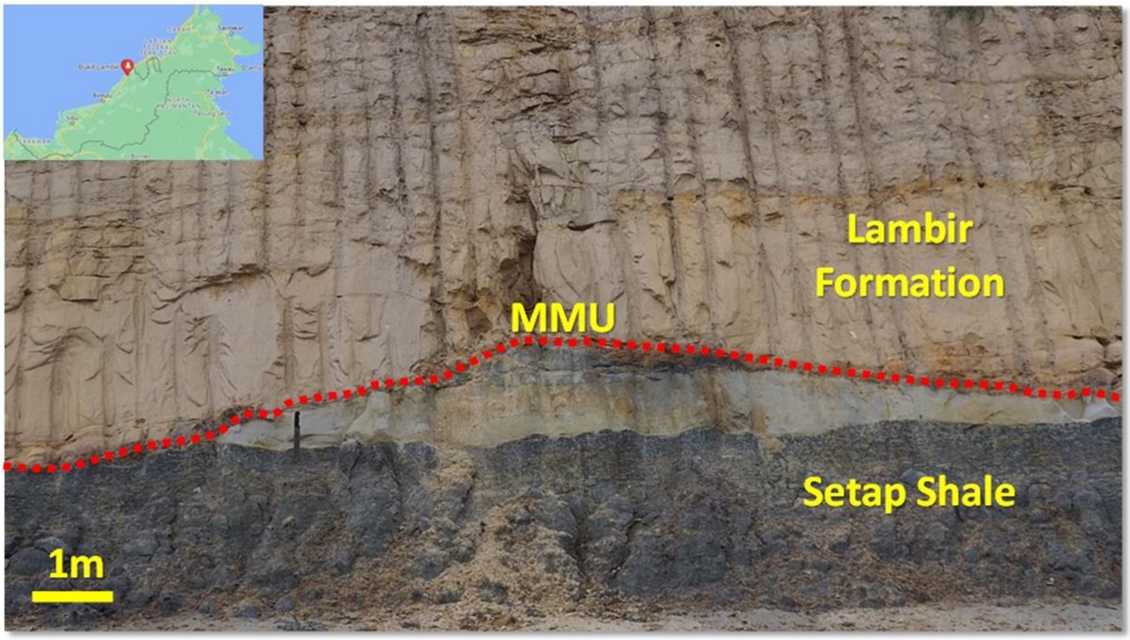

Figure 8b: *View of the Mid-Miocene Unconformity (MMU, red dashed line), road cut in Bukit Lambir, NW Sarawak. The unconformity is seen scouring Setap Shale, here formed by black shale and grey siltstone. Above the unconformity lies the sands of the Lambir Formation (from Kessler et al., 2019). The unconformity has been age-dated by Wannier et al. (2011), in an outcrop nearby assigning a tentative age of 15.5 Ma to the scoured clastics beneath the unconformity.*

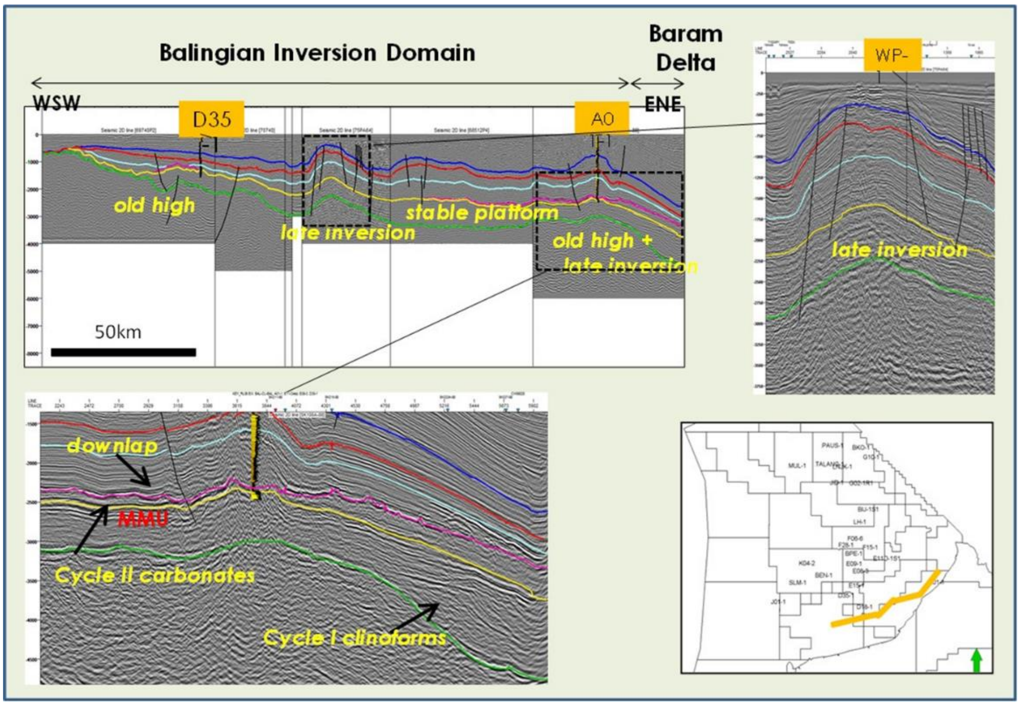

Figure 8c: *Balingian Province to Baram Delta with inversion created broad anticlines that continued into the Pliocene with ggeneral thickening and deepening to the east. The MMU is approximately at Top Cycle II represented by a yellow horizon (from Kessler and Jong, 2016). See approximate line location in Figure 1.*

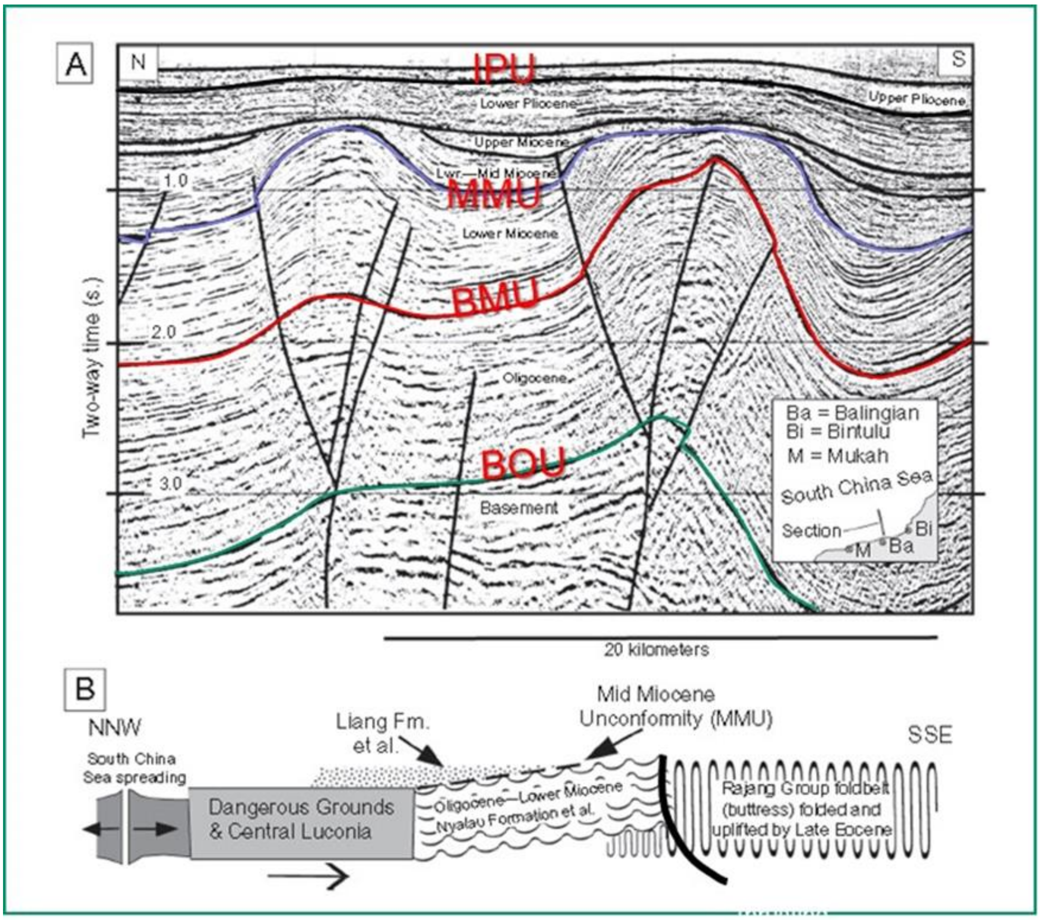

Figure 8d: *Seismic section immediately south of Central Luconia, showing the tightly compressed and eroded anticlines as a product of the Mid-Miocene Unconformity, MMU (Mat Zin and Tucker, 1999). The thrust-up and eroded anticlines have been commonly mistaken for horsts (Hutchison, 2005). (B) The cartoon suggests the cause of folding within the Balingian, Central Luconia and Miri zones, and could point to the location of the Sundaland Plate Margin located beneath the Rajang thrust belt. Modified after Hutchison and Vijayan (2010). Following the cessation of sea-floor-spreading (MMU/DRU), the progradation of shelfal clastics led to an environment less suitable for bioherm growth in large parts of Central Luconia. See approximate line location in Figure 1.*

The Sabah margin is characterized by a relatively narrow shelf-to-slope zone, with basinal sediments comprised of turbiditic deposits and pelagic shales. The margin exhibits a complex relationship which the Rajang/Crocker hinterland. Unlike Sarawak shelf, there is no extension of SCS deposits in the onshore area, the outcropping sediments of the hinterland occupying the onshore and a narrow band offshore belong to the anchi-metamorphic Rajang/Crocker system and are of Eocene or older age.

In the offshore Sabah Basin, we recognize “Deep Regional Unconformity” the DRU (Levell, 1987, Figures 9a and 9b). This in seismic terms a widespread unconformity event has been calibrated in a number of offshore Sabah wells and has been age-dated as TB 2.4 (Mid-Miocene, Langhian; Figure 5). The angular unconformity has been dated by some 19 exploration or appraisal wells and is closely constrained to occur within the *Globorotalia peripheroacuta* zone, i.e., “early Middle Miocene”. The *G. peripheroacuta* zone was established by Blow (1969) and later became renamed N10 in his 1979 scheme (citation in Lunt and Madon, 2017).

The DRU separates a deeper, slope or basin setting, lean in sand from a younger and shallower, often deltaic sequence. Accordingly, this Sabah unconformity might be time-equivalent to the MMU in Sarawak (Figures 5 and 9a). However, Lunt and Madon (2017) claimed that the DRU was, by the nature of its outstanding magnitude, not only the unconformity associated with the end of seafloor spreading in the SCS but

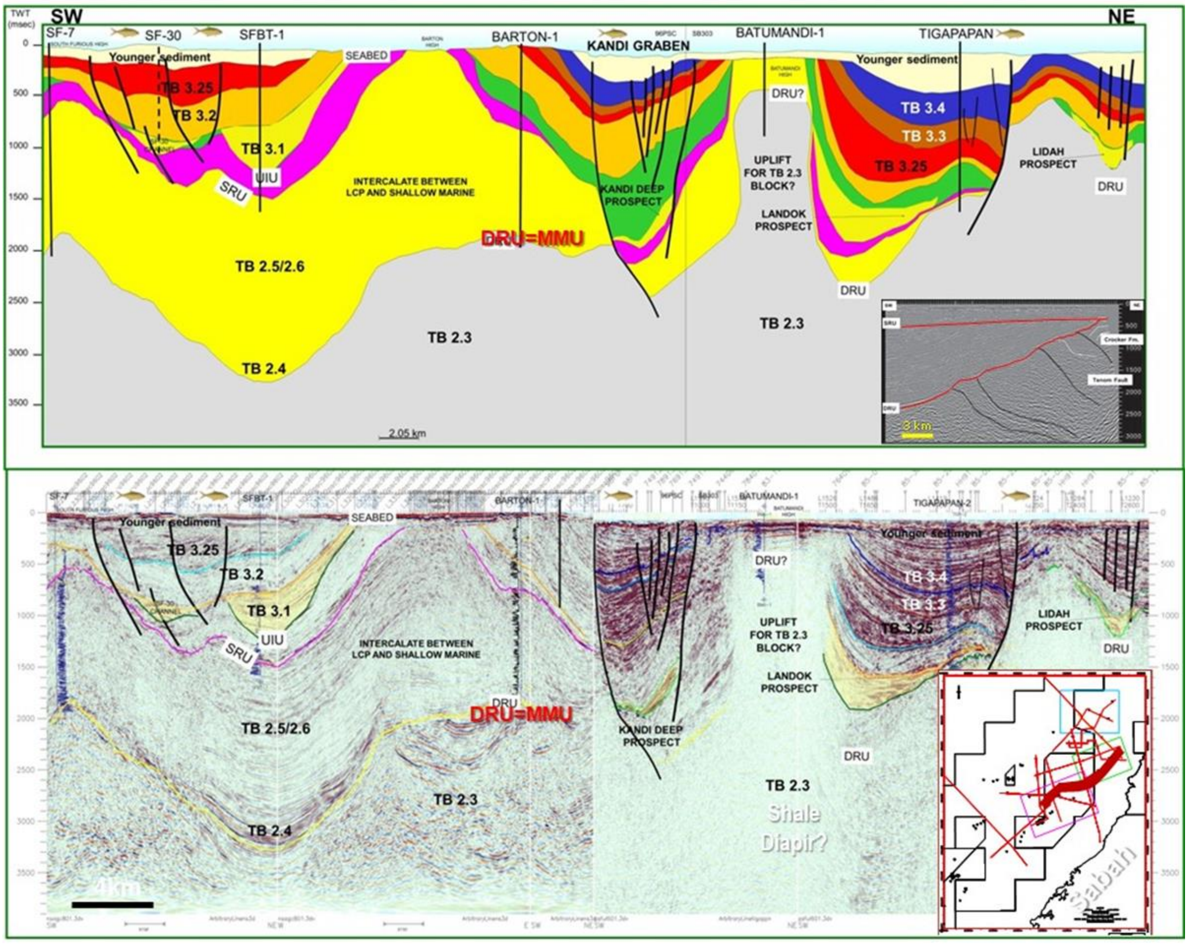

__Figure 9a__: Regional composite 2D seismic line with mapped TB sequences from Sabah Inboard area showing areas of tremendous uplift, exhumation and amalgamated unconformities with development of mini basins between ridges. The inset seismic shown an example of DRU, which might correspond to the MMU (from Kessler and Jong, 2016). See approximate line location in Figure 1.

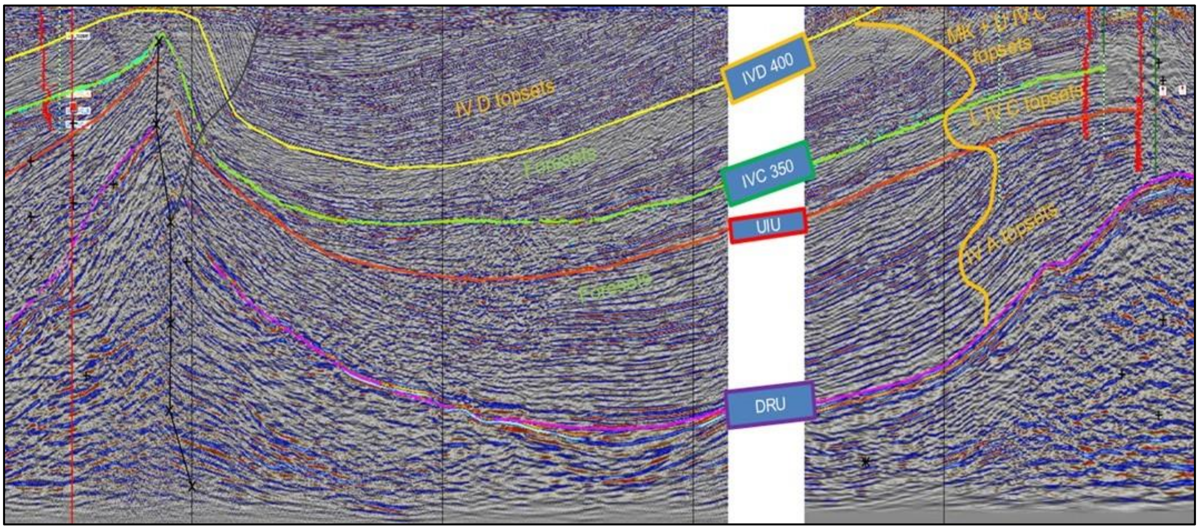

__Figure 9b:__ Seismic section in offshore Sabah near the St. Joseph Field. The DRU (purple marker) is the oldest mapped unconformity in this area. It separates a younger (post Mid-Miocene) shelf to slope setting from a deeper slop to basin setting lean in sand. The post-DRU/MMU setting is characterized by massive clastic deposits, at least partly caused by a significant uplift of the Rajang hinterland. See approximate line location in Figure 1.

has seen an overprint of other tectonic factors.

Summarizing the above, we recognize an important unconformity, the MMU in Sarawak, of Mid-Miocene, Langhian age, which is equally prominent along the Vietnam margin. Another unconformity in the neighboring Sabah waters, the DRU, appears to be roughly of the same age. This is based on O&G exploration wells in Sabah which penetrated the clay-dominated Stage III sequence, the latter underlying the post-DRU Stage IV sands. The coeval timing of the events is proposed as the end of spreading in the center of the SCS, which is about 15.5 Ma. Therefore, the MMU/DRU is seen as a major stratigraphic boundary in Sarawak and Brunei, separating Cycle IV from Cycle III, and also separating Stage IV from Stage III in Sabah (Figure 9c). Ages aside, there is also discussion about the geological meaning of prominent unconformities, the MMU and the DRU. Although both events appear to be related to the SCS seafloor spreading, at least the DRU may also be

__Figure 9c:__ Outcrop in Limbang (with a geological hammer for scale), Limbang River Valley (red star in inset map) showing Stage III equivalent deposits in a sand-lean (slope?) distal turbidite facies. This section is located immediately beneath the inferred DRU location.

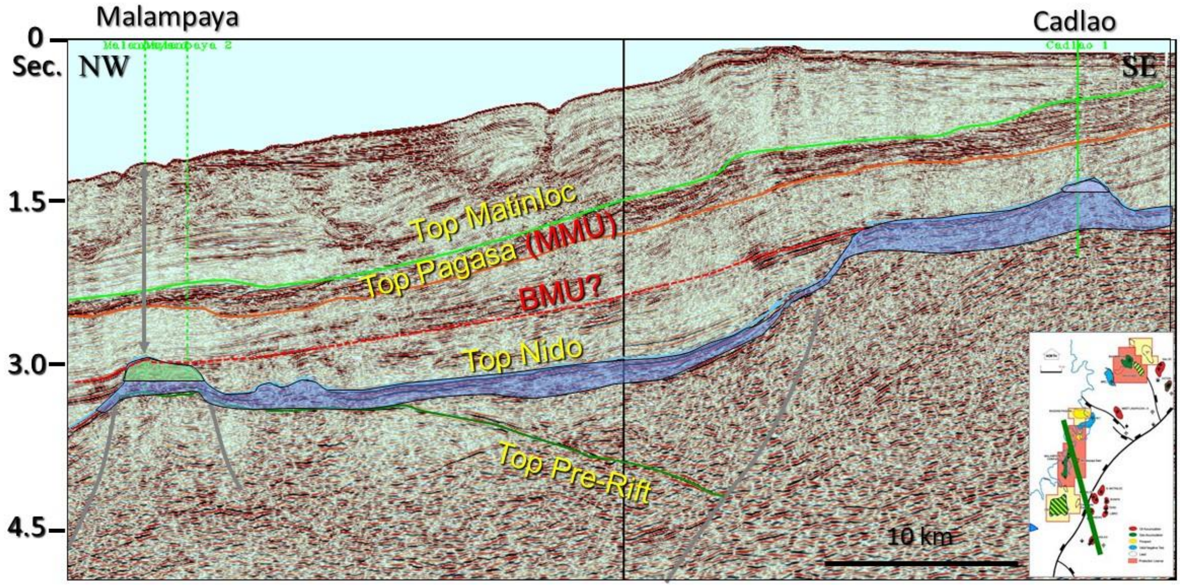

Figure 10a: *Cross-section through the Palawan margin (after Steuer et al., 2014 and Kessler and Jong, 2016). Similar to Sabah, the Palawan hinterland saw uplift and tilting. The post-MMU/DRU sequence points to a scoured and canyonized shelf/slope setting. See approximate line location in Figure 1.*

affected by compression and mountain-building processes in NW Borneo and probably also Palawan.

North of the Sabah margin, the Palawan margin is characterized carbonate-clastic shelf with block-faulting above carbonate buildups (see Figure 10a). The Palawan margin indicates a development of a rifted sequence and carbonate growth on high areas, such as Malampaya (Steuer et al., 2014). There is a southeastward tilt indicating the uplift of Palawan Island. The main Mid-

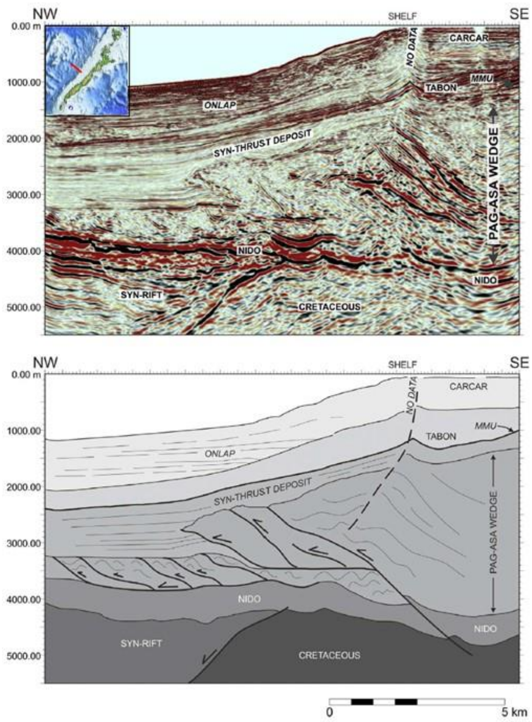

Figure 10b: *NW-SE oriented 3D seismic line (in meter depth) in offshore SW Palawan (top) and its structural interpretation (bottom). Other structural features include: a 600 m-thick deformed sequence of lower Pagasa Formation, marking the onset of under thrusting of the Nido Limestone; a northwestward progressing front of the thrust-fold in the Pagasa Wedge; syn-thrust deposition above the top folds of the fold-thrust; MMU truncating the wedge, overlain by Tabon (Matinloc Formation) and Carcar Limestone (Quezon Formation) (from Aurelio et al., 2014). See approximate line location in Figure 1.*

Neogene seismic unconformity is called the Red Unconformity dated at about 12–13 Ma (equivalent to the DRU of Sabah; Luan and Lunt, 2022). The MMU/DRU (or the Red Unconformity?) is draped over the older (Pre-Neogene) horst-and-graben setting and has led to some erosion on the high areas. This occurred when the uplift of a foreland overthrust system paused, and a locally erosional surface was rapidly transgressing.

Note according to Aurelio et al. (2014), the Pangsa Wedge, the thrust-fold belt built within the Mid-Miocene due to deformation of the Early-Middle Miocene Pangsa Formation is truncated by the regionally observed MMU (Figure 10b).

MMU AND INVERSION TECTONISM

Inversion tectonics are seen in many areas of the Northwestern SCS. Inversion tectonics occur at Cretaceous levels (Huang et al., 2017), such as at the Dongsha-Penghu Uplift of the Northwestern SCS continental margin. Inversion tectonism is also prominently during the Cenozoic. There are inversion examples in Brunei's Baram Delta (Morley et al., 2003) and the onshore greater Miri area (Kessler and

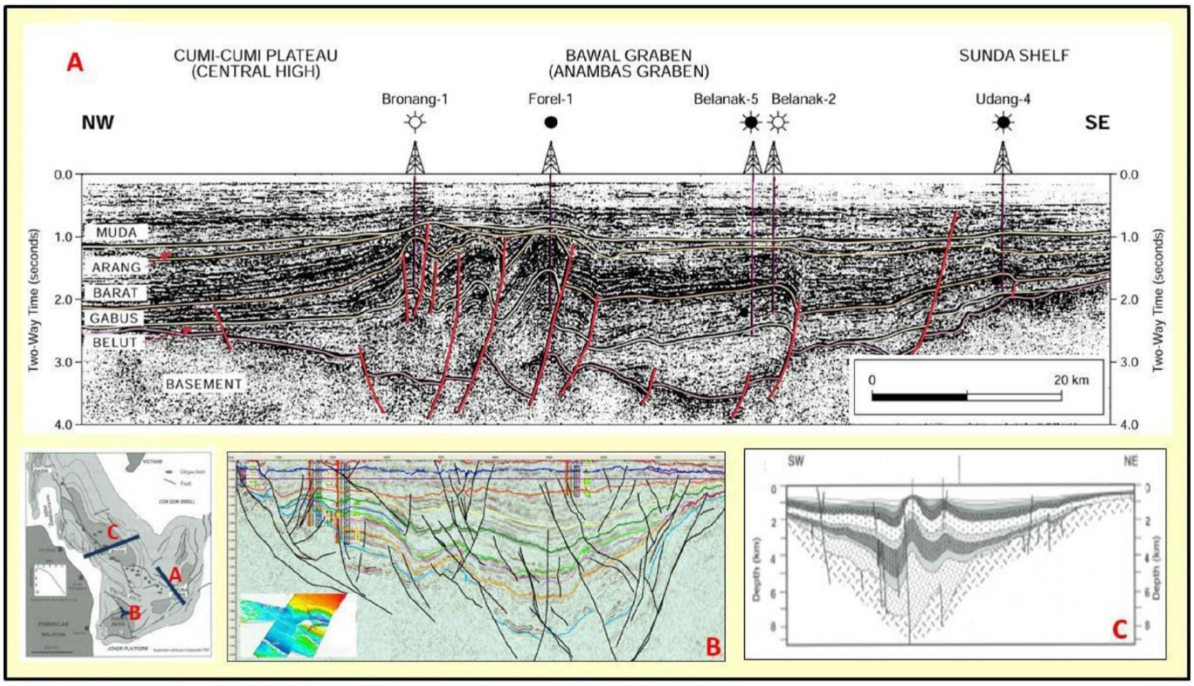

__Figure 11:__ West Natuna-Malay-Penyu basins examples of inversion structures, (a) Seismic from HIS Markit of inverted basin in the West Natuna (Sunda Fold), (b) Seismic example of flower structures in the Penyu Basin driven by strike-slip faulting, and (c) Structure cross section of the Malay Basin with inverted anticlinal features from Mazlan et al. (1999). Figures compiled by Jong et al. (2014). See approximate line locations in Figure 1.

Jong, 2013, 2014). Madon et al. (1999, 2019) showed seismic examples of inversion tectonics from the Malay and Penyu basins. Miocene inversion is also cited by Jong et al. (2014, 2017) in the SCS with an inverted deep low called the Bunguran Trough, and well-noted in the adjacent Natuna Basin (Burton and Wood, 2010). Figure 11 compiled by Jong et al. (2014) shows some examples of inversion structures in the West Natuna-Malay-Penyu basins.

Inversion tectonics can be related to compression and perhaps a relatively mobile underlying basement, and inversion is in some areas (Malay and Penyu basins) related to strike/slip tectonism.

At this point, the authors do not see any obvious causal connection between inversion processes and the MMU. The apparent coincidence of inversion tectonism examples and the MMU might be coincidental, if not proven otherwise, and an attempt to describe the processes encompassed by inversion would be beyond the scope of this paper.

DISCUSSION AND RECOMMENDATIONS

The magnitude of tectonism and facies change at the DRU/MMU is seen to vary considerably in the respective areas, which may be explained by differences in the amount of crustal stretch and subsidence, as well as accommodation space.

In the center of the SCS, the MMU is difficult to spot, given it is poorly expressed in very thin bathyal deposits. In Sabah, an area relatively adjacent to the central part of the SCS, the change at the MMU is incredibly significant, marking a change from sand-lean deepwater deposits to sandy turbidite deposits and later shelfal sediments. The stratigraphic and tectonic setup of Sabah-Palawan margin appears to be more complex, given the early onset of compressional tectonics.

On the Northwestern margin (Vietnam, South China), the MMU is equally prominent, albeit not mapped extensively, and appears to divide the stratigraphic sequence from an older strongly extended and faulted sequence to a younger passive margin fill sequence.

The imprint of the MMU is less visible in areas located more distant to the SCS spreading center, such as in the stratigraphic record of the Luconia Platform (Sarawak), partly due to a lack of well penetration to depth below the carbonate build-ups, albeit clearly interpretable on more recent seismic data. The extension of the continental crust was far lower compared to central SCS areas. Consequently, shelfs were already established ahead of the Mid-Miocene time, and accordingly there is no sharp stratigraphic division between the Lower and Upper Miocene sequences. This appears equally to be the case in areas, where the Tertiary basin fill is predominantly of non-marine sediments (Gulf of Thailand, Malay and Penyu basins), and the DRU/MMU equivalent doesn't offer any obvious signature.

In the context of future research, the following aspects appear to be noteworthy:

- Improve the calibrations of the MMU/DRU in wells and outcrop sections;
- Attempt to better define and map the MMU/DRU on the Southeastern shelf margin and to tie it to deep-sea wells, likewise on the Palawan shelf.

Such research could confirm the proposed picture, namely that the SCS rift sequence on the shelfs is corresponding to the period of seafloor spreading in the basin center; that the MMU/DRU is a basin-wide unconformity which separates rift and post-rift sequences and also is time-coeval with the end of rifting in the center of the SCS.

CONCLUSION

Recent calibration and correlation work appears to suggest that the SCS spreading ended at ca. 15.5 Ma. The latter number of 15.5 Ma, derived from polar reversal interpretation appears to be consistent with other regional data. We believe the widespread seismic events/unconformities mapped as MMU and DRU by various authors tie with the end of SCS spreading and form a basin-wide event describing the transition from active rifting to a passive margin setting. On the Southeastern margin however, compressive tectonics may have overprinted the DRU signature in areas of Sabah and Palawan. Accordingly, in simple terms, the SCS sediments can be divided into a rift stage (from age Mid-to-Late Eocene to the MMU) and a passive margin stage (MMU/DRU to? recent) modified by local compressive tectonics, such as inversion observed in various sub-basins. Future work should focus on reviewing the location of the MMU in SCS wells and provide better calibration. One might also focus on further extending seismic interpretations on regional lines from shelf to deepwater, as well as examining facies changes in the stratigraphic sequences located below, and above the MMU unconformity.

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