SEDIMENTARY RECORD OF PALEOGENE SEQUENCES IN THE PENYU AND MALAY BASINS, OFFSHORE PENINSULAR MALAYSIA

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ABSTRACT

The Eocene to Lower Oligocene deposits of the Penyu and Malay basins are formed by fluvial-lacustrine deposits with marine influence in the latter. The sequence consists mainly of siltstone, with several intercalations of fine-grained sand and volcanic tuff. Based on well data, Mid-Upper Eocene sediments exist in Penyu Basin in the deeper parts of the half-grabens and sub-basins. Hence, this implies the age of basin initiation at Mid-Eocene, rather than Oligocene as traditionally and commonly stated in the literature. By correlation, and as seismic evidences show, Eocene sediments also appear to exist in the deeper, undrilled parts of the Malay Basin, again implying that at the latest, a Mid-Eocene age of basin initiation.

In the Penyu Basin, a prominent near-Base Oligocene Unconformity can potentially be correlated to the Base-Tertiary Unconformity in the adjacent Malay Basin, however the latter term implies all Tertiary sequences, including potential Paleogene deposits above the unconformity. Besides, we also observe intra-Eocene unconformities, called the Top N and Top O. The presence of Eocene strata is likely associated with an early phase of extensional tectonism, and probably related to the onset of rifting of the South China Sea continental crust.

Keywords: Eocene, Oligocene, Penyu Basin, Malay Basin, Stratigraphy, South China Sea

INTRODUCTION

Eocene and Oligocene sediments are the oldest unmetamorphosed sedimentary deposits in the margins of the South China Sea (SCS), often deeply buried under Late Oligocene and Miocene deposits, and show signs of profound diagenetic imprint (Maga et al., 2015; Kessler and Jong, 2018). The Penyu Basin (PB) is located offshore east coast of Peninsular Malaysia and may hold more than 8 km of sediments in the deepest parts (e.g., Madon et al., 2019). The PB is the smallest of the three offshore Tertiary extensional basins of central Sundaland; the others being the Malay Basin (MB) and Natuna Basin (NB) (Figure 1). Undoubtedly, the PB was developed on continental crust and most authors generally considered it as a pull-apart or "rift-wrench" basin (Madon and Anuar, 1999; Haribowo et al., 2013; Md Yazid Mansor et al., 2014; Maga et al., 2015; Jong et al., 2019; Madon et al., 2019). Early Tertiary crustal extension initiated the development of NW-SE and E-W trending grabens, synchronous with the break-up and opening of the SCS marginal basins. This is supported by the presence of major strike-slip and associated normal faults being the main basin-bounding faults. The question remaining is, if the lower rift-related (or "synrift") sequences are indeed the result of rifting, or is actually a pull-apart event precursor of the later Late Oligocene to Neogene basin fills?

The uppermost Oligocene and Neogene succession in the PB is a moderately isopachous stack fluvial to lacustrine strata, often containing coals. It contains fluvial coal-bearing reservoirs, moderate seals and multiple source rock intervals. The stratigraphic schemes of Figure 2 (Iyer et al., 2019), and Figure 3 (modified from Madon et al., 2019), give good summaries of the PB

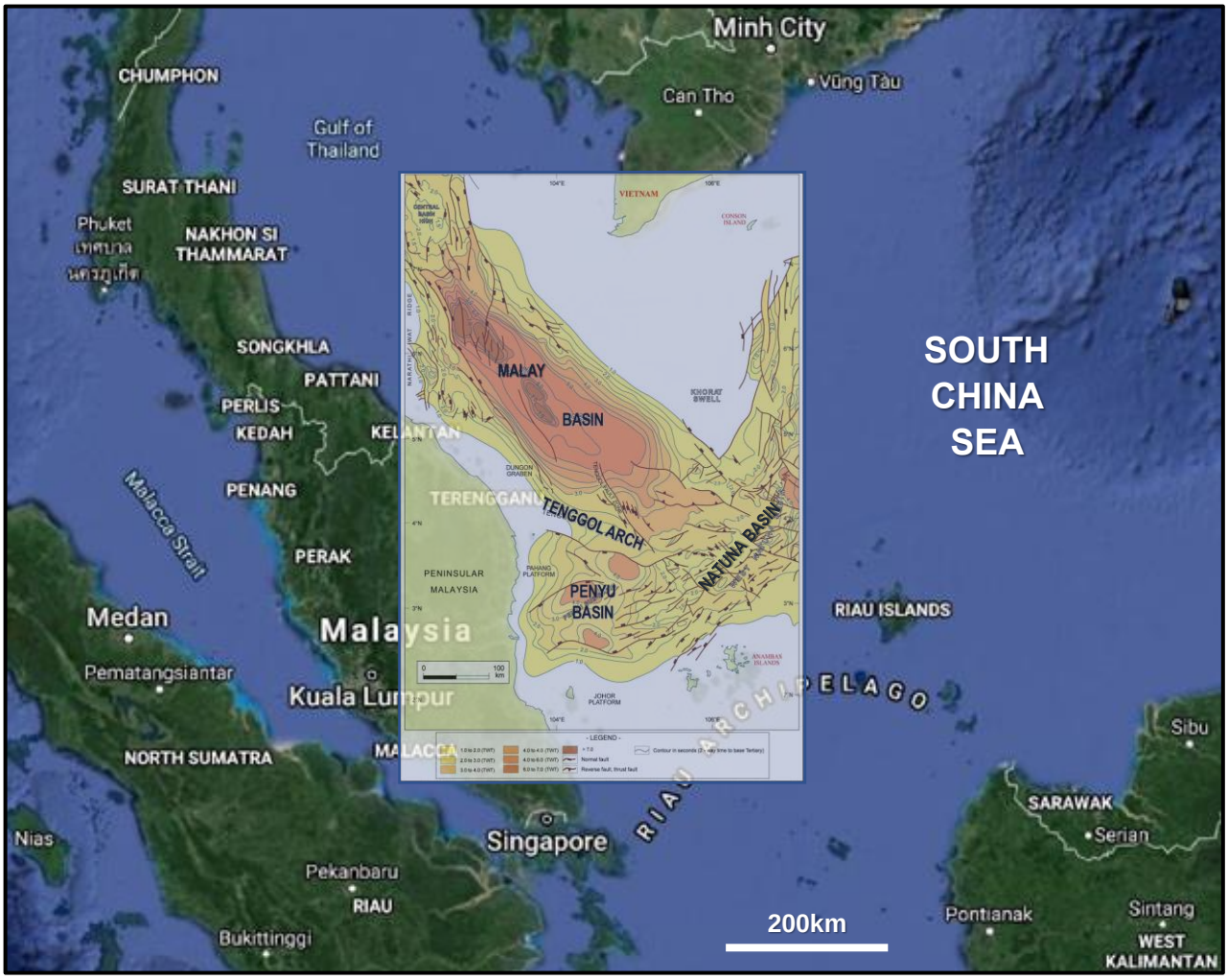


Figure 1: Satellite imagery of the study area in the Penyu and Malay basins, offshore Peninsular Malaysia (source Google Map). Inset map shows structural framework of the Malay, Penyu and Natuna basins with sedimentary thickness in TWT, yellow area = shallow and orange-brown area = depocenters (from IHS Markit, 2010).

stratigraphy, at least down to Base Miocene and show comparisons with neighboring areas. The complex structural elements of the PB is shown in Figure 4, where some of the deep half-grabens appear to contain pre-Oligocene (Late Eocene) sediments. An example is the Rhu-Cherating Graben where Eocene sediments have been penetrated at wells Janglau-1 and Ara-1. A seismic correlation through those wells are shown in Figures 5 and 6. The lithological record of the key well Janglau-1 is shown in Figure 7.

The bigger and more prolific Malay Basin (MB) is separated from the PB by a shallow (<2 km) basement high called the Tenggol Arch (Figure 1 and with more details in Figures 8, 9). The latter is a promontory of pre-rift Mesozoic landmass that is contiguous with onshore Peninsular Malaysia and is underlain by a complex amalgamate of folded and thrusted igneous and metamorphic rock, draped by a Late Oligocene/Miocene-Recent sequence. The Tenggol Fault also marks the south-western edge of the MB (Figure 8). Some exploratory wells have penetrated sediments as old as Eocene (e.g., Janglau-1 in PB, Figure 7). Although Eocene sediments are not proven yet in the MB, seismic data and a regional correlation with PB suggest the likely presence of Eocene sediments (Figure 8).

The stratigraphy in Penyu and Malay basins look similar, yet there are some important differences: In the PB, only a few wells have penetrated the so-far poorly documented sequence of pre-Oligocene strata in the deepest grabens and half-grabens (Figures 3, 5 and 6). Marine incursions which are frequently observed within the MB strata (in particular, the intervals J and K), are hardly seen in the PB. As consequence, the equivalents of Groups I, J and K shales in the PB do not have good sealing quality that is usually attributed to transgressive marine shales.

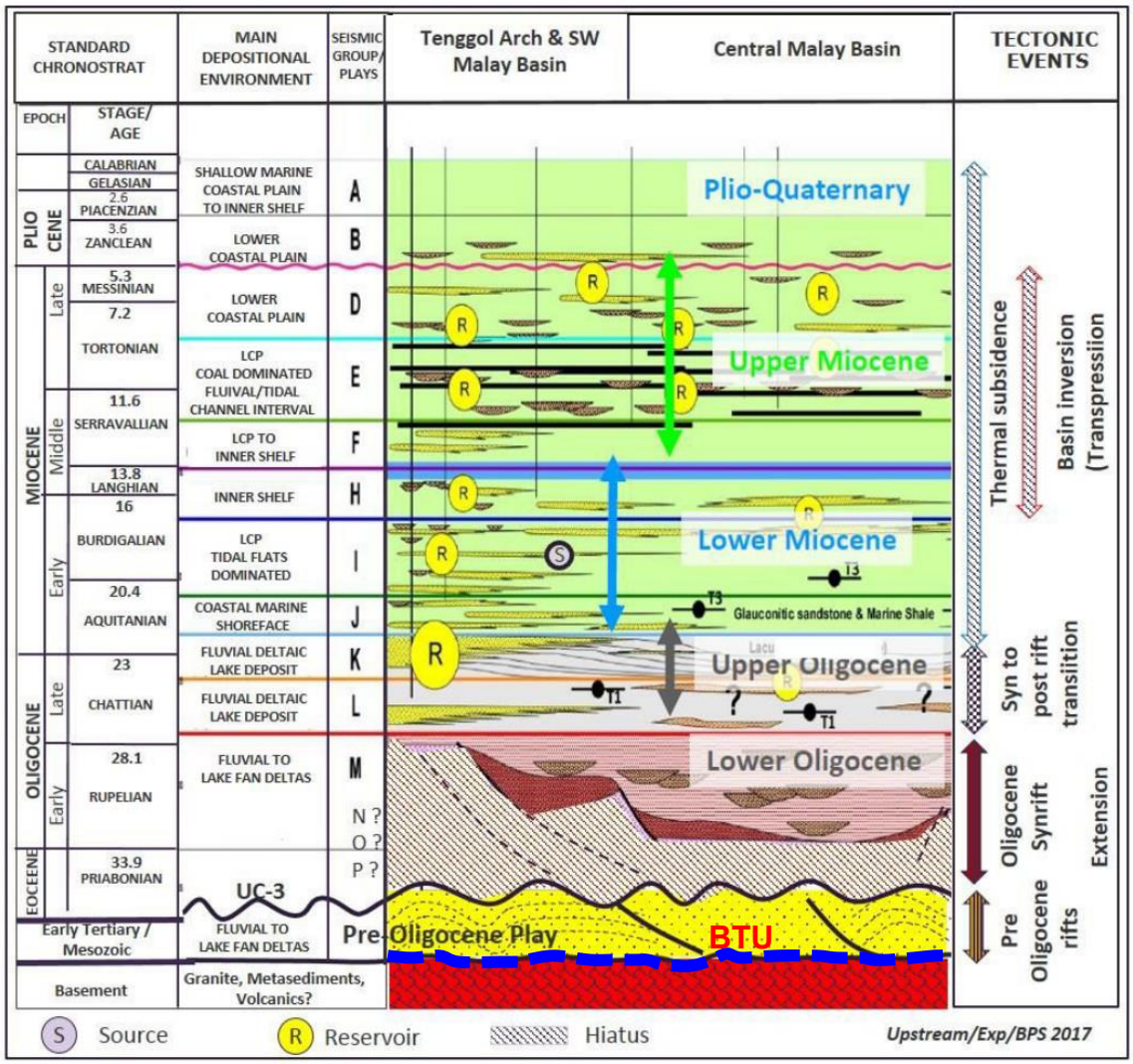


Figure 2: Stratigraphy of the Tenggol Arch and Malay Basin by Iyer at al. (2019). A word of caution - the signature of the lowermost pre-Oligocene sequence (yellow shading with dots) is suggestive for a sand-prone rock. The equivalent penetrated intervals in Janglau-1 and Ara-1 in the Penyu Basin, however, are indicative for a clay-dominated rock sequence, and seem to hold very little porous sandstone intervals. Interestingly though, the entire Group K and older sequences, even including the Mesozoic, has produced oil shows. Also, in the follow-up study by Madon et al. (2020), the authors have interpreted that the Lower Oligocene and pre-Oligocene (i.e., Eocene section) is a continuous sedimentary succession and the main hiatus as highlighted by Iyer et al. (2019) is redefined at the base of the Eocene as the Base Tertiary Unconformity (BTU – dashed blue line).

REGIONAL GEOLOGICAL SETTING

The SCS, in geological terms, is an area of thinned continental crust overlain by Oligocene to Recent clastic and carbonate sequences, overlying areas of uplifted basement, and whereas its margin is characterized by a complex interaction of basin subsidence, erosion and uplift of mountain ranges (e.g., Kessler and Jong, 2016). Data points on the deeper Eocene-Oligocene sedimentary section of SCS are rare and derived from only a few oil and gas exploration wells located predominantly near-shore. However, to which degree pre-Oligocene rocks are present beneath the explored sequences in the PB remains a conundrum to-date with limited well penetrations, even in the well-explored MB.

The SCS is also dissected by a few major lineaments (e.g., Red River Fault and Three Pagoda Fault systems; see Morley and Racey, 2011), along which transgressive movements occurred and subsidence was enhanced. Structural movements took place during Oligocene and Miocene times, and the direction of movement may have flipped as intra-plate stress patterns changed over time. Both the Malay and Penyu basins at the south-western flank of SCS are examples of strike-slip induced subsidence (Madon et al., 2019, 2020).

STUDY OBJECTIVE AND DATABASE

This paper summarizes selected pre- and Early Oligocene data and interpretations from the Penyu

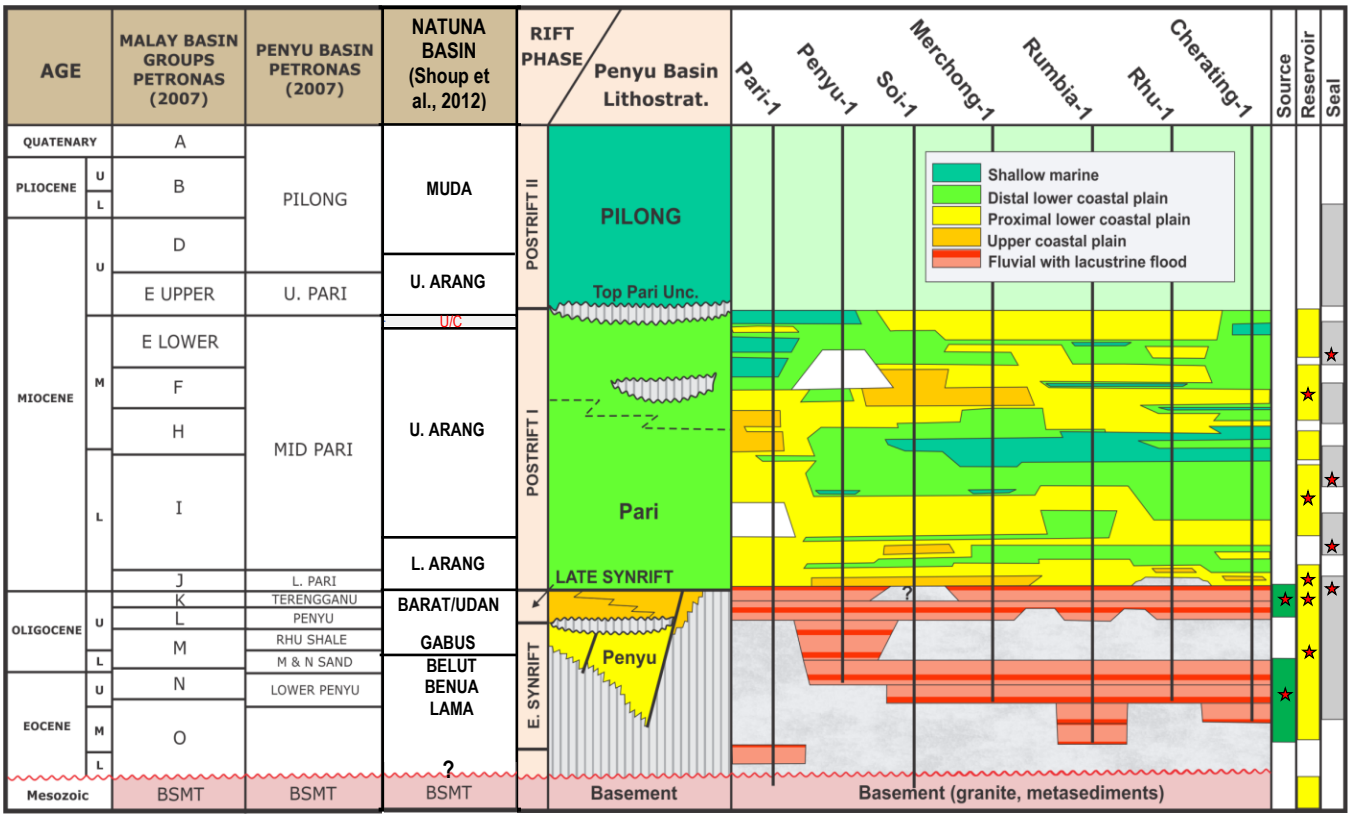


Figure 3: Stratigraphic summary and paleoenvironments of the Penyu Basin showing a comparison with the neighboring Malay and Natuna nomenclatures (based on Morley, 2009 and Barber, 2013). Paleoenvironments based on palynological and paleontological analyses of selected wells are shown, some of which penetrate the basement composed by granite and metasediments. Besides Pari-1 and Soi-1, the other wells that penetrated pre-Tertiary basement are Merawan Batu-1, Batu Hitam-1, Janglau-1, Rhu-2, Rhu-3 and Selada-1. Potential source, reservoir and seal rocks are indicated on the panel to the right with the best source, reservoir and seal sections (annotated by stars). The "Top-Pari" Unconformity marks the end of basin inversion and truncates the "Sunda folds". Modified from Madon et al. (2019).

well Janglau-1 (Lundin Malaysia, 2012; Maga et al., 2015; Madon et al., 2019; Madon et al., 2020), as well as some seismic data of the MB. The wells Janglau-1, Ara-1 and Merawan Batu-1 (which, according to PETRONAS, also TD in Eocene) are particularly important given they provide critical insights into the stratigraphic evolution in the SCS during the Paleogene. The well record is compared with Anding Utara-1, at the southern edge of the MB.

The data from PB used in this paper were extracted from expanded studies previously conducted by the authors (e.g., Maga et al., 2015; Jong et al., 2019; Madon et al., 2019, 2020), the final well reports, operator study reports and cited literature, as well as own unpublished study materials. Given there are different stratigraphic schemes, an effort was made to align stratigraphic terminology and to review unit boundaries and unconformities on seismic and well records, starting from the lowest Miocene units down to TD. In many instances, it was difficult to reconcile between the different data sources and practical decisions had to be made on which source to honor.

STRATIGRAPHIC FRAMEWORK AND NOMENCLATURE OF THE PENYU AND MALAY BASINS

Stratigraphically, the PB appears to be a "condensed" version of the MB; with less than half the total thickness of sediment deposited over the same period of geologic time (Madon et al., 2019). Figure 3 shows the paleoenvironments and stratigraphic subdivision of the PB in comparison with the neighboring Malay and Natuna nomenclatures. Similar to the MB, the sediments in the PB are entirely siliciclastic, consisting of interbedded shale, siltstone, sandstone and, in the middle, coaly sequences.

Sedimentation was initially characterized by non-marine fluvial-lacustrine facies in the synrift half grabens, passing into upper coastal plain deposits (Penyu Formation; Groups L, M and N) (Figure 3). The synrift sequences are overlain, in places with

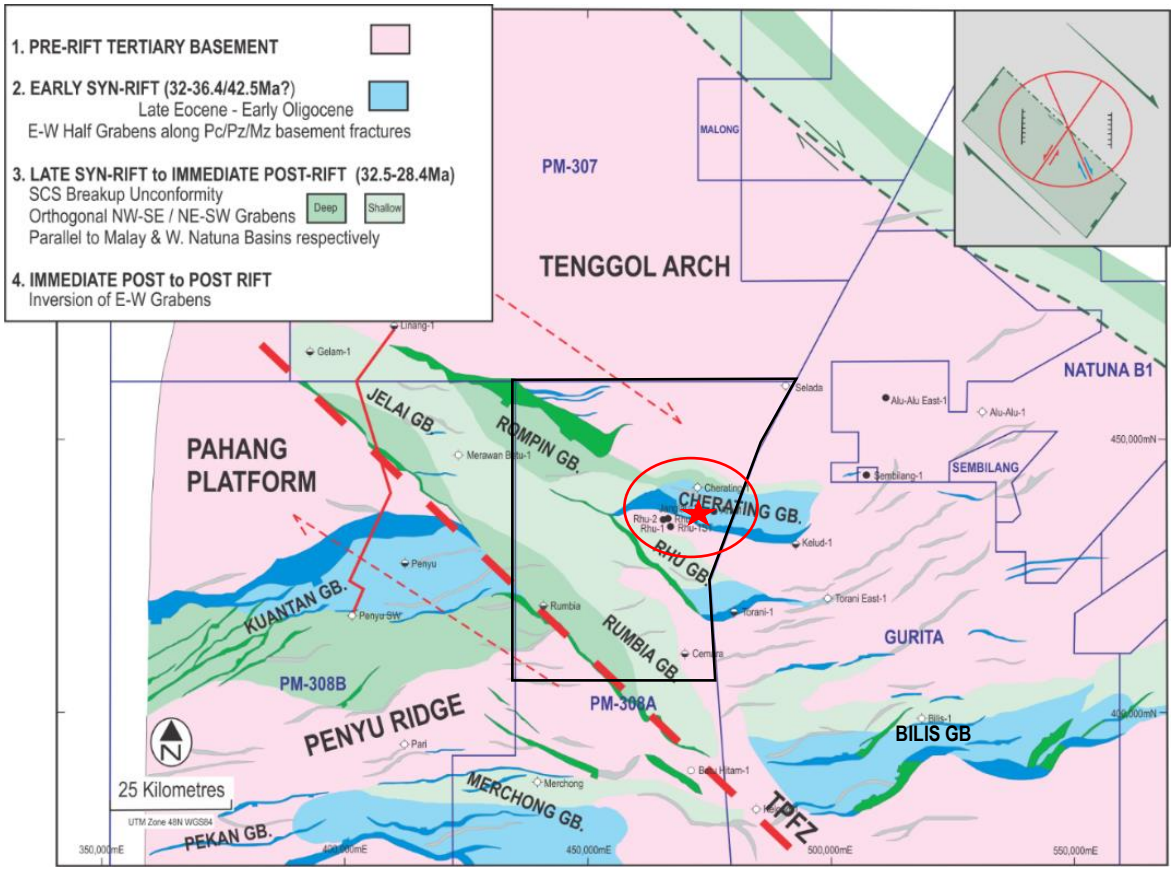


Figure 4: Structural elements of the Penyu Basin. The history of the basin is complex, only a few graben segments appear to contain pre-Oligocene sediments. Possibly, the Eocene graben strike was E-W, with the Cherating segment joining the Kuantan Graben, and the Merchong Graben linked to the Bilis Graben. The Red circle shows the study area with Janglau-1 highlighted by the red star. TPFZ – Trans-Penyu Fault Zone. Adapted from Madon et al. (2019).

unconformity ("Base-Pari Unconformity"; Madon and Anuar, 1999), by coal-bearing lower coastal plain sediments indicating increasing marine influence during the post-rift phase of sedimentation (Pari Formation; Groups E, F, H, I and J). This overall transgressive marine sedimentation started in the Late Oligocene, generally concomitant with the regional transgression in the MB associated with the "K" shale (Figure 3).

The post-rift phase is accompanied by a basin inversion phase during the Late Miocene which resulted in unconformities, the most significant one being the Late Miocene "Top-Pari Unconformity", which is a regional unconformity that is correlated with the major erosional unconformity at the base of seismic Group B in the MB (Madon et al., 2006). The post-unconformity sequence in the PB is referred to as the Pilong Formation (combined Groups A and B; Figure 3). The post-rift sequence represents Miocene to Quaternary sedimentation in a much wider thermal sag basin, which by that time was probably intermittently connected to and influenced by the ancestral SCS, *via* the West Natuna Basin. Whereas the thickness of synrift sequences in the half-graben fills is determined by the amount of extension along the bounding faults, the post-rift sequence has a relatively uniform thickness across the entire basin as a result of gentle sagging due to non-fault-related thermal subsidence. In this paper, for regional correlation purpose, we have adopted the MB seismic "Group" nomenclature of the Oligocene and Eocene sedimentary sequences.

OLIGOCENE-EOCENE SEDIMENTS IN PENYU BASIN: JANGLAU-1

Janglau-1 was drilled by a consortium operated by Lundin Malaysia in 2011. The well was positioned in a fault sliver down-dip from the Rhu High, where sub-economic oil was found (Figures 5 and 6).

Janglau-1 is the most complete data set currently available in the PB (Lundin Malaysia, 2012). The well reached the bottom of the Oligocene section at 3151 m measured depth below rotary table (MDRT) and TD at 3820 m MDRT in very tight, possibly Mesozoic rock. The sequence of 669 m

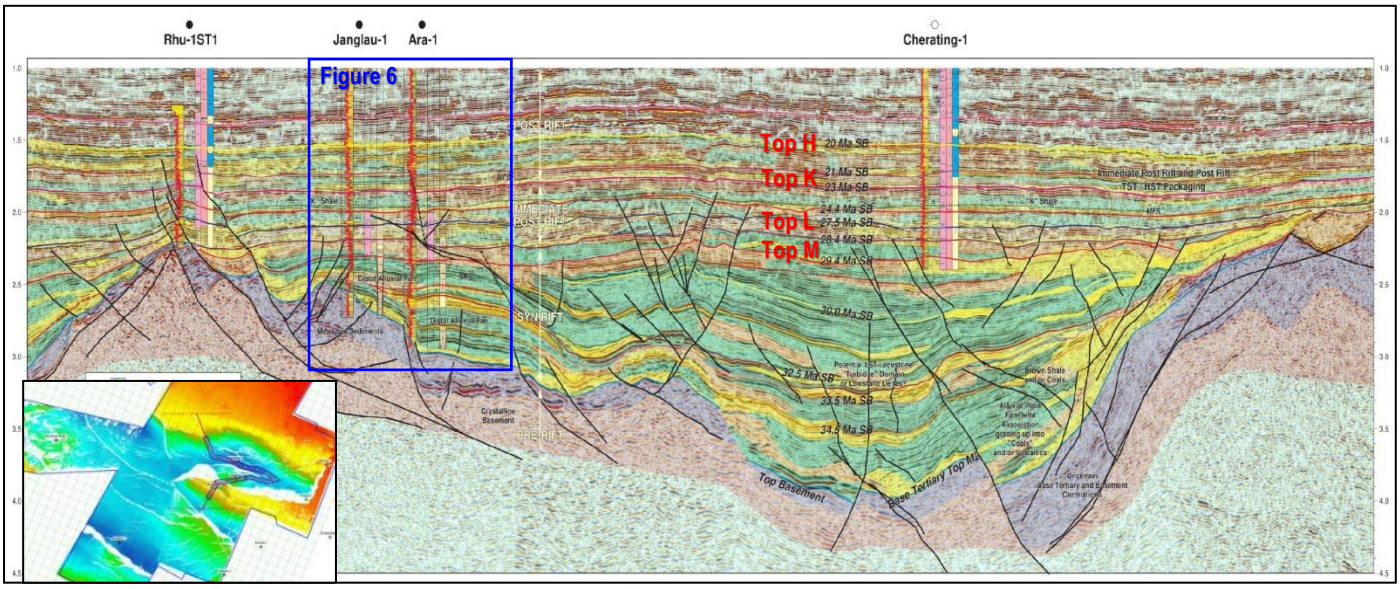


Figure 5: Penyu Basin regional seismic section illustrating mapped sequence boundaries (SB) and related depositional facies; yellow = sandy facies, green = lacustrine shales, purple = meta-sediments. The depositional system of the Penyu is mainly restricted lacustrine facies up to Base Miocene, near Top L event and was isolated from the fluvial sedimentary pulses of the Malay Basin until this time. The pre-Oligocene sequence is only present in the older Graben segments, and the facies interpretation should be contemplated with caution – the available well data indicate that the entire pre-Oligocene setting may only contain a few sands with more than 5 m in thickness. Adapted from Maga et al. (2015) from Barber (2013).

between Base Oligocene and TD is composed of clastic, deposited in fluviatile, marginal marine and even pelagic environments. Given that the drilled sequence is mostly, if not entirely, non-marine, the current zonation and age determination is derived from palynomorphs (see Table 1). In the absence of marine fauna, there is uncertainty in the stratigraphy.

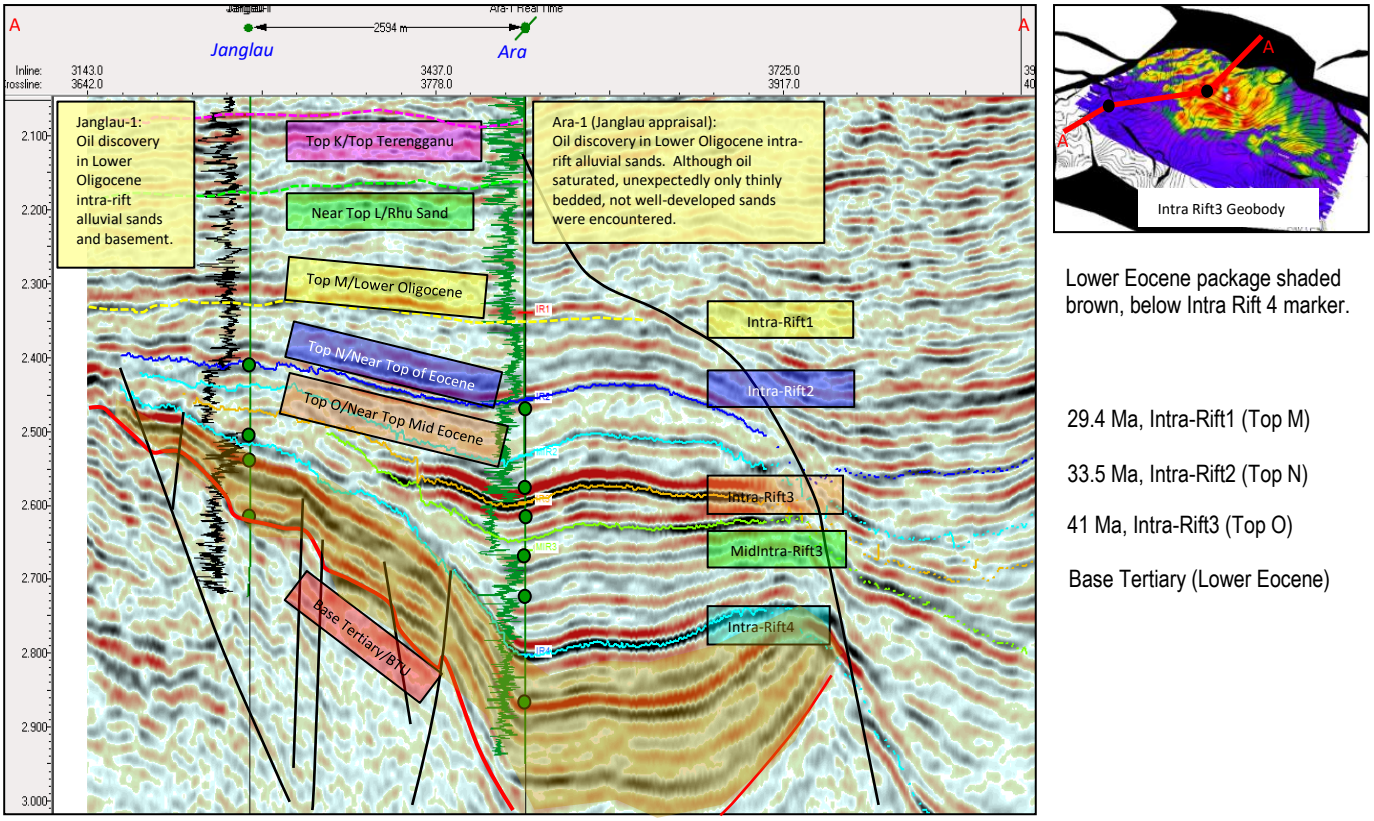


Figure 6: Seismic correlation between Janglau-1 and Ara-1. Modified after Madon et al. (2019). Seismic Markers are based on the Final Well Report, Janglau-1 (modified from Lundin Malaysia, 2011). Note the assigned ages of the mapped seismic markers remain tentative.

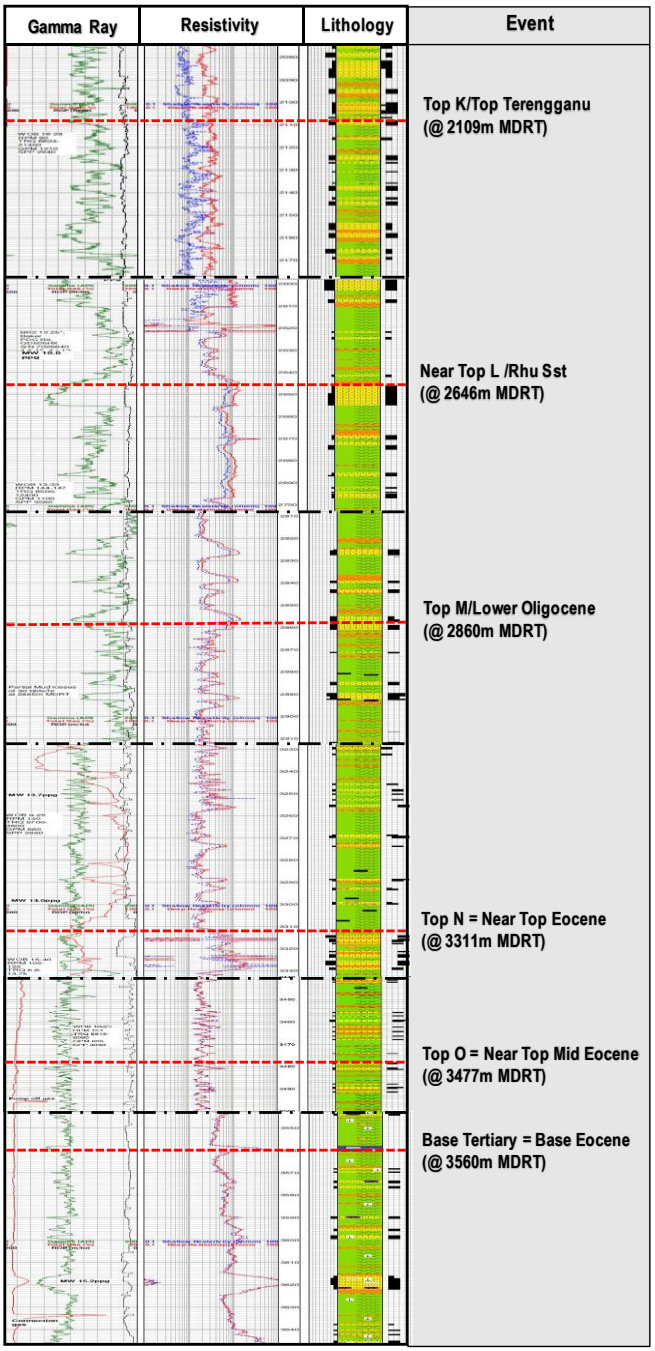


Figure 7: Modified composite log of Janglau-1 (from Lundin Malaysia, 2011), illustrating the key events identified by palynomorphs that were tied to seismic (see Figure 6). Resistivity log: shallow = blue, deep = red. Lithology: yellow = sandstones, orange = sand/siltstone, green = claystone, blue = carbonate. Red dashed lines = key mapped events. Black dashed lines = depth breaks (i.e., non continuous depth).

There are multiple occurrences of tuff in the Lower M sequence, and another tuff level is seen in the O sequence (see Table 2). These tuffaceous sediments imply repeated volcanic eruptions in the neighborhood and suggest tectonic and magmatic activity during this time interval. The drilled strata contain a number of source rock and oil-bearing reservoir intervals, some of which contain non-moveable oil.

Depth (m)	Age	Zone		Events/Remarks	
2550 - 2875	Early Oligocene	WN11	PR1	This zone assigned based on: • Presence of *Florschuetzia trilobata* (robust type) at 2550m. • Presence of *Cribroperidinium tenuitabulatum* at 2665m. • The base of this interval is located at the FDO of *Laevigatosporites catajenensis* at 2875m.	Top L/Rhu SST (2646m MDRT)
2925 - 3245	Late Eocene	WN12a	No Zone	This zone assigned based on: • FDO of *Pediastrum* spp., *Bosedinia* taxa, and *Selenopemphix nephroides* at 2925m, increasing markedly downhole throughout this interval. • This interval is capped by an acme of superabundant *Magnastriatites howardi* at 2955m and LDO of *Magnastriatites howardi* at 3245m (more frequent). Local or regional marine pulses, within this strongly freshwater driven interval (hence the lack of foraminifera), may be expressed at various depths: • Presence of dinoflagellate cysts indet. at 3060m. • Presence of *Leiosphaeridia* spp. at 3085m. • Local influxes of ?marine algae respectively at 3120m. Within this interval other palynomorph events indicating facies shifting are observed an acme of superabundant *Pediastrum* spp. and the LDO of consistent *Botryococcus braunii* at 3180m.	Top M (2860m MDRT)
3265 - 3395	Late - Middle Eocene	WN12b		Assigned on stratigraphic position below LDO of *Magnastriatites howardi* at 3245m. This zone also assigned based on: • FDO of *Diporites* spp. at 3265m. • FDO of *Cupaniedites* spp. at 3350m. Local or regional marine pulses, within this strongly freshwater driven interval may be expressed of ?marine algae (local influxes) respectively at 3265m and 3335m.	Top N (3331m MDRT)
3435 - 3520	Middle Eocene	WN13a		This zone assigned based on: • FDO consistent of *Monoporites homeopunctata* at 3435m. • LDO of *Florschuetzia trilobata* at 3450m. • LDO of *Magnastriatites howardi* at 3505m (rare). • FDO of *Monoporites homeopunctata* at 3520m. Within this interval other palynomorph events indicating facies shifting are observed an acme of superabundant *Bosedinia* taxa at 3450m. The base of this interval is close to the LDO of consistent *Bosedinia* taxa and abundant *Pediastrum* spp. at 3520m. This base seems to be the closest to a stratal surface observed on logs between 3520m and 3540m.	Top O (3477m MDRT)
3540 - 3750	Mesozoic			This Mesozoic Zone that may correspond to basement in this well, is based on the FDO of low palynomorph (miospores and algae) recovery at 3540m and FDO of very sparse assemblages at 3580m. The base of this Zone is defined on FDO of *Corollina* spp. (?reworked) at 3655m ; the LDO of *Monoporites homeopunctata* ; *Discoidites borneensis*(caved) ; *Corollina* spp. (?reworked) at 3750m . Based on the above palynoflora, the age of this horizon is Mesozoic, with probable Early Jurassic/Late Triassic reworking or *in situ* Early Jurassic/Late Triassic with rare Oligocene to Middle Eocene caving evidence.	Base Tertiary /Base Eocene
3770 - 3805	Indeterminate			The bottom two samples at 3770m and 3805m are barren of palynomorphs.	

Table 1: Janglau-1 palynomorph fossil contents, and depths of key events mapped with seismic data (see Figure 7).

Given the very high temperatures, particularly in the lowermost part (171 ^{0}C, after Horner correction, at 3700 m MDRT, see Figure 10), all reservoirs have undergone severe diagenetic alteration that resulted in the deterioration of reservoir properties (Maga, et al, 2015; Kessler and Jong, 2018). The following key events can be identified:

- *Top K = Top Terengganu (MB nomenclature) = Base Pari Unconformity (PB nomenclature; Madon and Anuar, 1999), ca. 23 Ma, lowermost Miocene.* Top K is picked in Janglau-1 at 2109 mMDRT (Figures 6 and 7). It is a regional marker which can be

DEPTH (m)	HEIGHT (m)	CYCLE	GDS	LITHOLOGIES (dominant type first)
3150-3160	10+	20	Transitional marine or lacustrine	Mudstone, sandstone, chert
3160-3165	5	19	Transgressive lag or proximal fan	Conglomerate
3165-3255	90	18	Lacustrine-floodplain	Mudstone, siltstone, sandstone, limestone (mud additive), coal
3255-3300	45	17	Middle fan	Conglomerate, sandstone, tuff
3300-3310	5	16	Distal fan-floodplain	Redbeds, siltstone, mudstone, sandstone
3310-3320	10	15	Mid fan	Conglomerate, sandstone, mudstone, tuff
3320-3325	5	14	Proximal fan	Conglomerate, tuff
3325-3355	30	13	Indeterminate	Indeterminate
3355-3405	50	7-12	Littoral-lacustrine	Redbeds, dolomitic siltstone-mudstone, limestone (mud additive), sandstone, palaeosol, tuff
3405-3535	130	2-6	Lacustrine	Mudstone, dolomitic mudstone, marl, rare sandstone/conglomerate
3535-3540	5+	1	?	Mudstone, sandstone

Table 2: Logged rock lithologic summary based on cuttings evaluation in Janglau-1. Noted are multiple occurrences of tuff in the investigated section. These tuffaceous sediments imply repeated volcanic eruptions in the neighborhood, and may point to active tectonic activity during the investigated time interval.

mapped in the PB, the Tenggol Arch and in the MB. In the latter, it forms the base of an overall increasing marine influence, and the Group K interval also contains both source rock and reservoir levels. In the PB, however, there is no evidence of marine environments. In Janglau-1, the Top K corresponds to facies change from a clay-dominated sequence to a sand-prone unit above, at 2109 mMDRT, with no evidence of an erosive contact.

- The interval between Top K and Top M is often referred to as late synrift sequence, a transition between the deeper and strongly faulted synrift basin fill and the transgressive Oligo-Miocene sequence above (see Figure 3). Arguably, a first pulse of strike-slip faulting and inversion has originated during that time in the Tenggol Arch border areas.
- *Near Top L, a clean 10-15 m sandstone unit of good porosity, with producible oil in Rhu-1 (Madon and Anuar, 1990; Madon et al., 2019),* is called the Rhu sand and was penetrated in Janglau-1 at 2646 mMDRT (Figures 6 and 7).
- *Top M = Lower Oligocene marker near Top Rupelian = Top Gabus (NB nomenclature), ca. 29.4 Ma, also referred to as top synrift (Figure 3).* The unconformity was picked in Janglau-1 at 2860 mMDRT (Figures 6 and 7). It is perhaps the most prominent (regional) unconformity in the basin (e.g., Kessler and Jong, 2016; Morley, 2016), and appears to mark the shift from a predominantly clay-prone section (M sequence) to the younger sand-prone interval (L sequence). The section from M down to basement appears to be unusually hot, with elevated temperatures seen in Janglau-1 (182 ^{0}C calculated at TD).
- *Top N = Near Top Eocene, ca. 33.5 Ma, = near Top Lower Penyu = Intra-Rift2 (Figures 6 and 7).* The unconformity was picked in Janglau-1 at 3311 mMDRT (Figure 7).

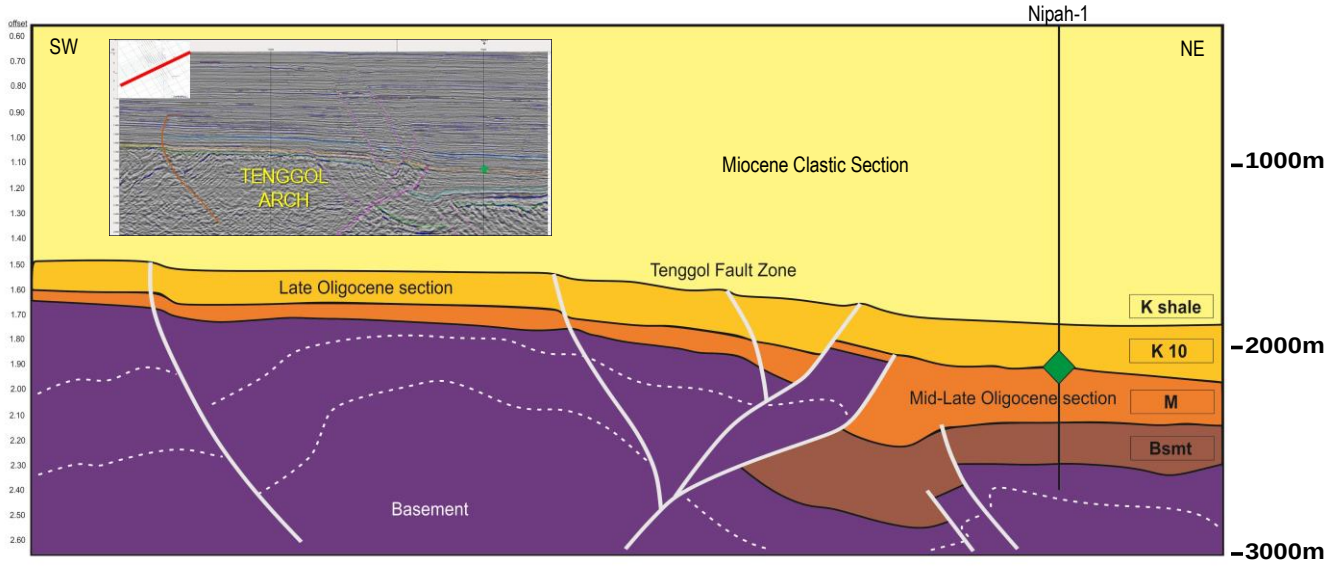
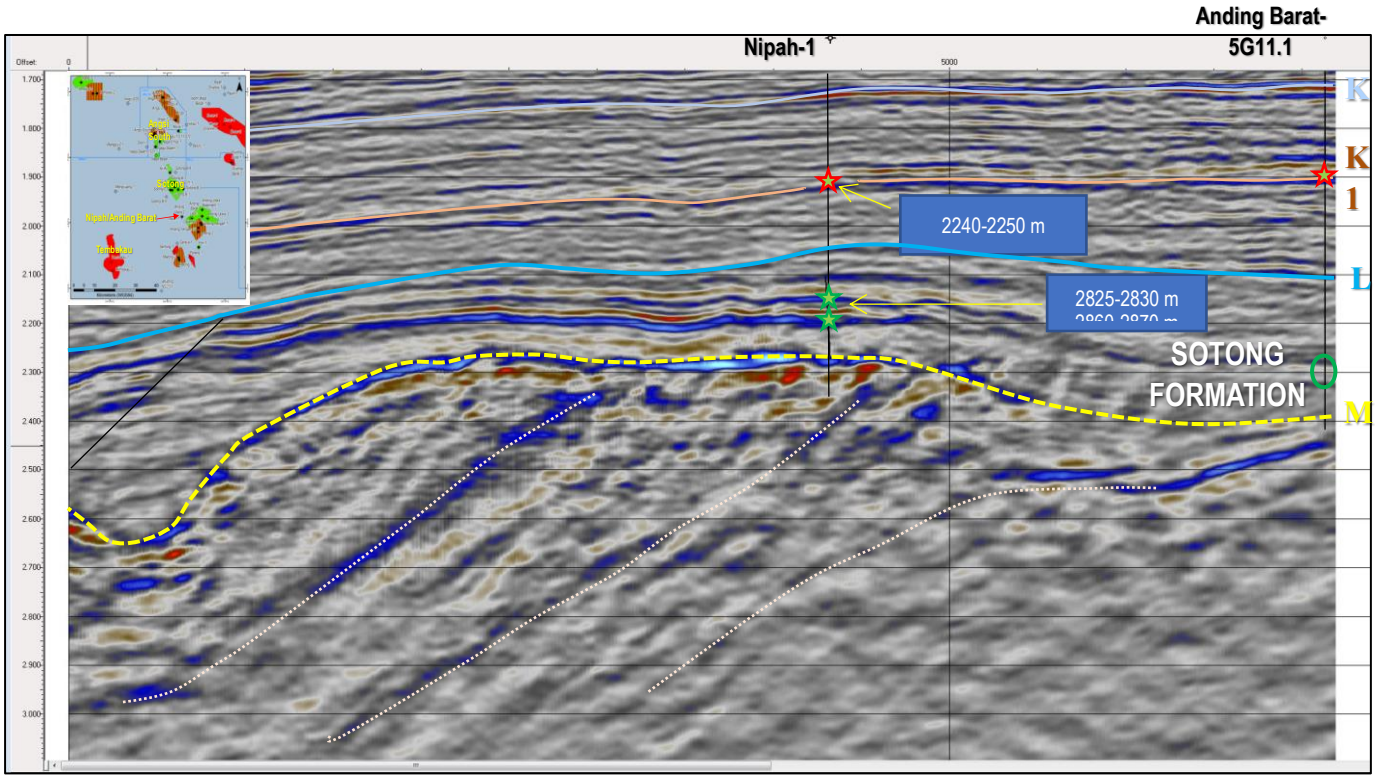


Figure 8: Seismic-derived SW-NE geological section through the Tenggol Fault Zone, at the edge of the Malay Basin near to the wells Nipah-1 and the Anding cluster, which penetrated pre-Oligocene sediments. The fault originated as a growth-fault, with an overprint of wrenching and thrusting initiated during the Late Oligocene – Early Miocene time (?). Low gravity oil inclusions in quartz are seen on the K-10 level (green diamond), indicating oil migration and entrapment in quartz cement within this important carrier bed. From Maga et al. (2015).



Zone 2872-2962 m in Anding Barat-5G11.1 showed 60 m of cut/fluorescence and high C_1-C_4 gas readings. The section was tested with 12 RFTs but proved to be tight. Conclusion in the well report being, that the reservoir zone is cemented, low-permeable and with dead, unmovable oil.

Zone correlated to K10 in Nipah-1, there is an oil show with fluorescence, gas (C_1 and some C_3). The MDT evaluation indicates oil for 2231-2237 m (0.373 psi/ft) and 2266-2283 m (0.406 psi/ft), but no saturation on logs. In Anding Barat -5G11.1, petrophysical evaluation reports 2.15 m of gas/condensate; 5 % (max 48 %) gas in mud with some C_2,C_3, but logs and RFT indicate water (0.42 psi/ft)

Composite log indicates oil shows in Nipah-1 (gas peak C_1 – C_3) from 2825-2830 m, and from 2860-2870 m, RFTs indicate mud (0.5 psi/foot) and lost sealing capacity.

Figure 9: Nipah and Anding wells were drilled to test Oligocene, Eocene and basement plays. The well records suggest a thinned Oligocene layer above Upper Eocene that only present in sags and half-grabens. Oil shows are observed in the Sotong Formation sandstones.

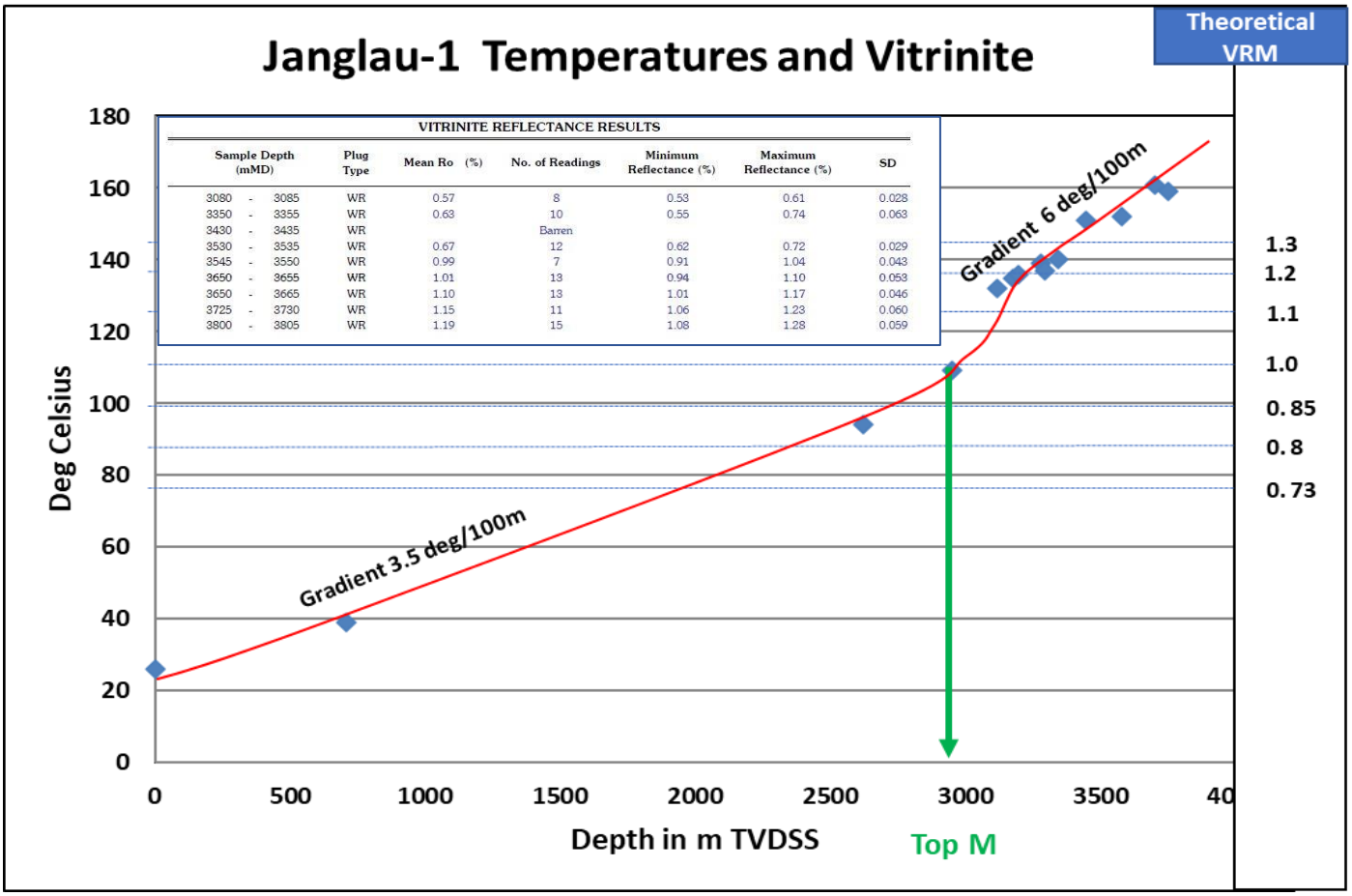


Figure 10: Janglau-1 temperature versus depth plot. Top M appears as a boundary of thermal conductivity VRo readings indicate a hot temperature in the past. However, the reason for the change in temperature regimes remains poorly understood.

Top N corresponds to a shift from thin-bedded gas-bearing sand-and-clay sequences to thick claystone.

- *Top O = Near top Middle Eocene, ca. 41 Ma = near Base Lower Penyu = intra early synrift = Intra-Rift3 (Figures 6 and 7).* The pick for this unconformity in Janglau-1 is at 3477 mMDRT (Figure 7) on seismic, whereas based on palynomorphs it is only at 3435 m. On the log, the unconformity indicates a shift from thin-bedded claystone, siltstone and some sand to massive siltstone/claystone.
- *Base Tertiary (= Base Eocene) Unconformity/Base Tertiary Unconformity (Madon et al., 2020)/Top Mesozoic (? Lower Jurassic) sequence (Figures 6 and 7).* This unconformity is picked, in line with palynomorph data, at 3560 mMDRT (Figure 7). Here, we observe the first occurrence of carbonates in the well.
- *Basement.* Crystalline Basement was not reached. The well reached TD at 3820 m MDRT in thin-bedded rock, composed by claystone, little sand/siltstone and carbonate rock.

MALAY BASIN: LATE EOCENE AND EARLY OLIGOCENE SEQUENCES AT THE SOUTH-WESTERN MB AREA

The MB is shallower towards the Tenggol Arch, and in the southern-western area we observe a thinning of Eocene and Oligocene beds towards the Arch, which points to a continued, but reduced subsidence of the basin during that time. We note also the occurrence of a distinct strike/slip tectonism with some local compression and over thrusting, most probably related to major strike-slip faulting along the Tenggol Fault, which forms the south-western boundary of the basin with the Tenggol Arch (Figure 8). The presence of sinistral wrenching is also indicated in a generalized stratigraphy proposed by Madon and Anuar (1999).

According to Tan (2009), sediments belonging to the lowermost sequences were deposited in isolated grabens, and characterized by alternating sand- and clay-dominated fluvio-lacustrine

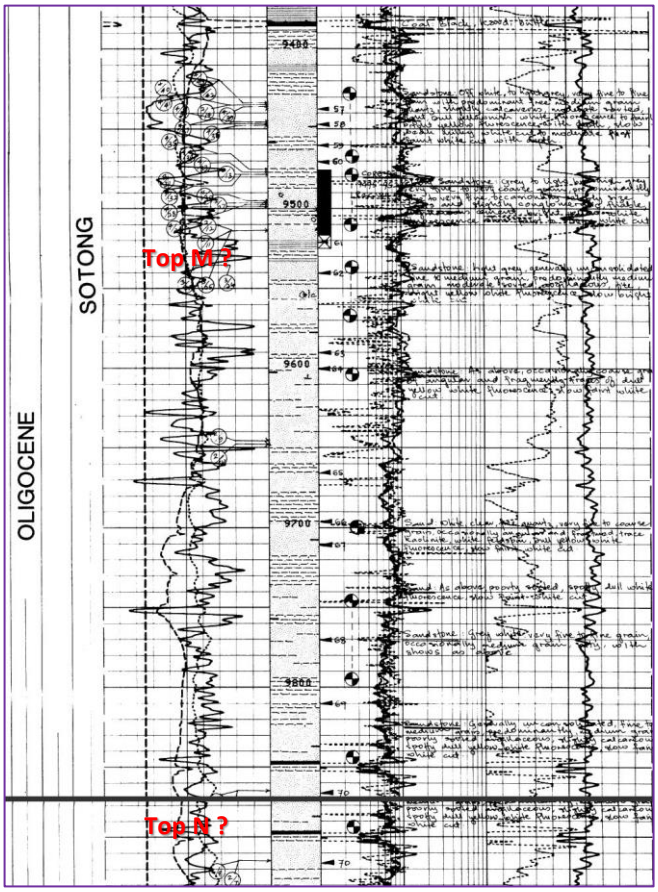


Figure 11: Group M section in well Anding Barat-5G11.1. The Early Oligocene Sotong Formation consists of alternating tight sandstones and claystones. The mostly tight sandstones showed 60 m of cut/fluorescence and high C_1-C_4 gas readings, and the section was tested with 12 RFTs but proved to be tight.

sequences in the Oligocene Groups M, L and K. Group M is estimated to have a thickness of 300 m and consists of sandstone and shale (Fazira et al., 2006). According to the authors, cores from Group M in well Ledang Tengah ST-1 show sandstone deposited in a continental setting, and in an alluvial-lacustrine setting. The authors describe a delta system comprising braided fluvial channel, in-channel bars, lacustrine mouth bars, paleosols and open lacustrine mud. Coarse-grained sands and massive sandstone in channel fills and mouth bars appear to be the best reservoirs. However, there appears to be some uncertainties in respect of assigning stratigraphic ages to the lowest basin-fill sediments (see problem description on p. 185 by Tan, 2009). It is note that Group M is not the lowest sequence in MB. In the early Esso reports, there were groups down to P identified, but over time neglected and ignored. In the chart by Yu and Yap (2019), there is a mentioning of three deeper sequences of Groups N, O, P below M. In the Esso-Petronas Integrated Collaborative (EPIC) Study (1994), the report referred to "Group M and Synrift", implying there is a separate "synrift" below Group M.

In the area of Nipah and Anding (Figure 9), a few wells were drilled to test Oligocene, Eocene and basement plays. The well records suggest a thinned Oligocene layer above Upper Eocene that only present in sags and half-grabens. As shown in Figure 11, the Early Oligocene Sotong Formation consists of alternating sandstones and claystone. The mostly tight sandstones layers look immature and are predominantly formed by fine-grained sand with the exceptions of some coarse and even conglomeratic layers. This may indicate a proximal source on the nearby Tenggol Arch.

Some sands are oil-bearing but characterized by tight reservoir above fractured and in partly oil-bearing "basement" rock, formed by metamorphic schists of probably Late Cretaceous age and granitic rocks (Madon et al., 2020). Reservoir quality may be as much influenced by diagenesis compared to sedimentary environment, as shown in the PB (Maga et al., 2015; Kessler and Jong, 2018).

DISCUSSION

The Base-Tertiary Unconformity (BTU; Madon et al., 2020), and undrilled Paleogene Rock in PB: The undrilled Paleogene section in the PB could measure up to 2 km of sedimentary section (counting laterally from Janglau-1 TD), within the graben centre. Most likely, this undrilled deep section may correspond to a Mid-Lower Eocene section, but this remains speculative (Figure 5).

It is noted that the pre-Tertiary "basement" has been addressed by Madon et al. (2020). In that study, the authors define the "basement" as rocks beneath the major erosional unconformity at the base of the Tertiary basin-fill in both Malay and Penyu basins - BTU, which is clearly identifiable in seismic in most places, and is easily recognized throughout the basin as a prominent high-amplitude reflector that marks a significant contrast in acoustic impedance between the Tertiary sediment above and pre-Tertiary basement below (Figure 12). The unconformity is believed to represent the eroded Mesozoic peneplanation surface that existed prior to crustal extension and subsidence during the Early Tertiary. The relationship between the BTU and the intra-Paleogene unconformities is shown in Figure 13. In the Tenggol Arch plateau, the BTU also forms the base of the Paleogene. On the flanks

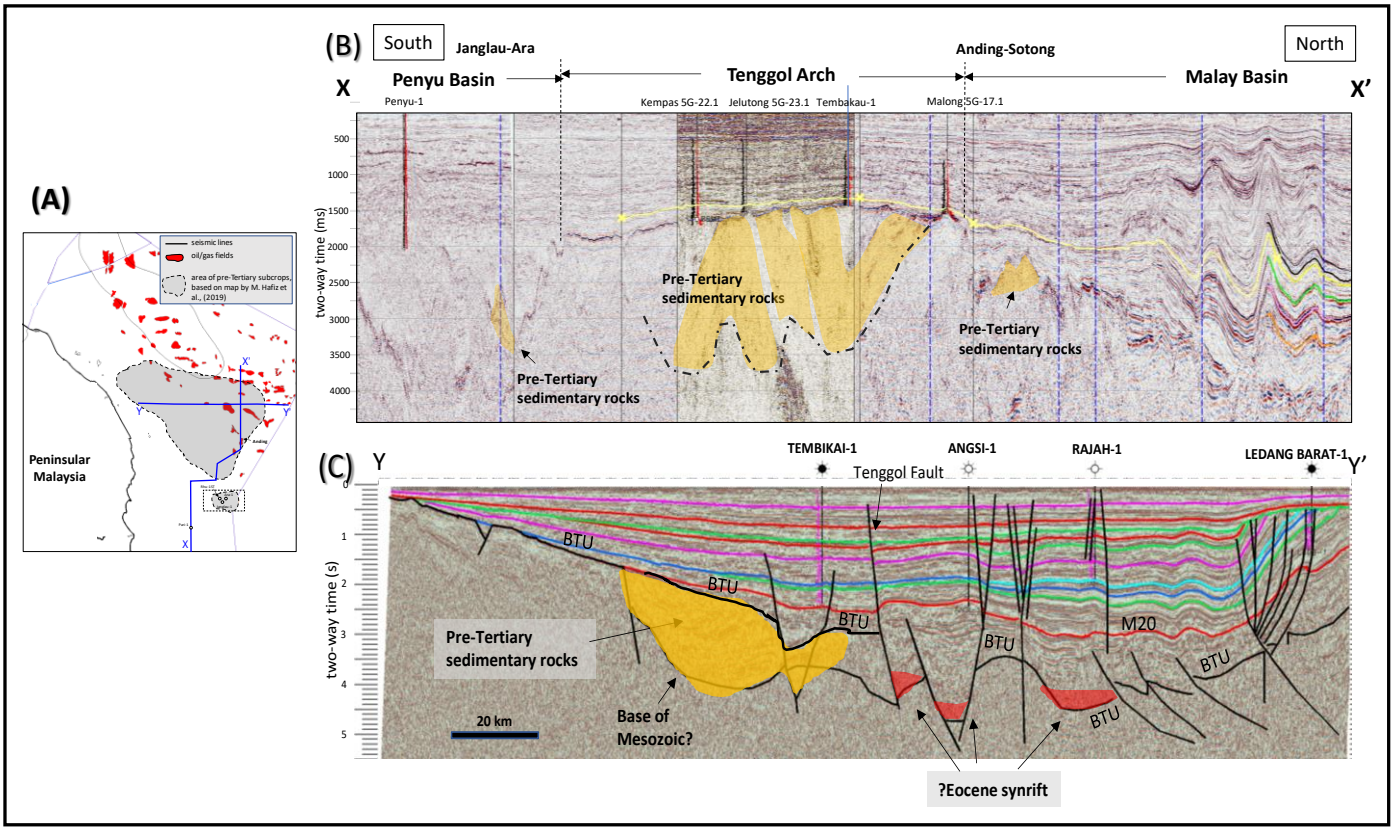


Figure 12: (A) Area of pre-Tertiary subcrops in the Malay and Penyu basins (shaded area represents area of pre-Tertiary subcrops, based on M Hafiz et al., 2019). (B) Long composite seismic profile XX' from Penyu to south Malay Basin with highlighted areas identified as underlain by pre-Tertiary sedimentary rocks over a large area of the Tenggol Arch as well as in Janglau-Ara (Penyu Basin) and Anding-Sotong (Malay Basin). (C) Line YY' crossing the Tenggol Arch and south-western part of the Malay Basin into the central basin area where a compressional anticline is clearly observed. The BTU is clearly seen as strong reflector starting in the western end of the line to around 60 km where it starts to be less obvious. The orange highlighted area is pre-Tertiary sedimentary rocks (proven by well data and gravity models) beneath the BTU. Probable Eocene sediments (red highlighted areas) are inferred to be present in the deep grabens beneath the Oligocene sequence (the top of which is marked by M20 marker, red horizon). Adapted from Madon et al. (2020) with seismic profile YY' from Yu and Yap (2019).

of the Arch, the BTU merges with Top M, N and O unconformities.

Reservoir potential: There is a common misunderstanding that sandstone means reservoir. With temperatures far above 100 ^{0}C, the onset of quartz recrystallisation, the Eocene sequence in PB underwent a strong imprint of several phases of diagenesis, altering the rock fabric profoundly by destroying porosity and permeability (Maga et al., 2015; Kessler and Jong, 2018). Therefore, future exploration should select proximal flank areas (edges of the Tenggol Arch, Pahang Platform, and local high zones). This said, only a better understanding of diagenesis could also help to locate sweet spots in otherwise strongly cemented rocks.

The Top M and Top N unconformities: The most important unconformity in PB are the Top M and Top N unconformities, and both erosional events may have incised into the lowermost Oligocene and Eocene sediments, respectively. Based on the palynomorph data from Janglau-1, the hiatuses

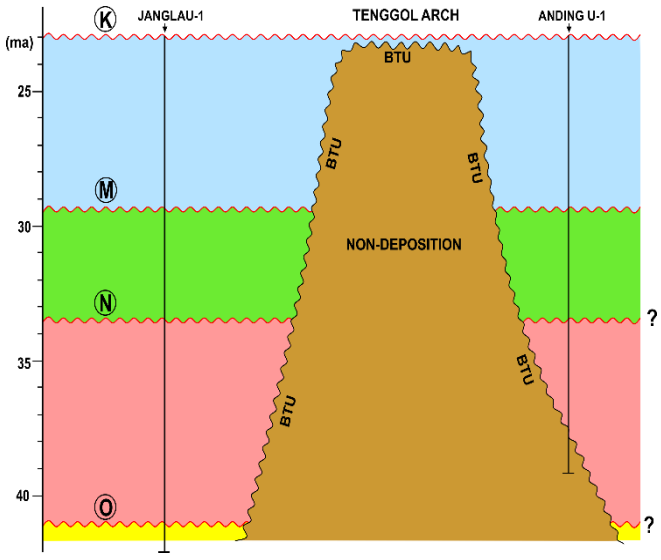


Figure 13: Schematic summary of relationship between Top K, M, N and O unconformities and the BTU on the Tenggol Arch plateau. The BTU forms also the base of the Palaeogene, and on the flanks of the arch, the BTU merges with Top M, N and O unconformities.

do not seem to be significant in terms of duration. Top M is also a boundary of thermal conductivity which is shown in Figure 10, and VRo readings indicate a high temperature in the past. However, the reason of the high temperature gradient is poorly understood. Furthermore, Top M appears to be the onset of wrench tectonism along the Tenggol Arch area. These early strike/slip movements are better documented in the MB (Anding area), rather than in PB (the TPFZ and faults bounding the Merchong Graben are clearly strike-slip faults).

The Tenggol Fault is clearly a strike-slip fault based on the recent interpretation by Madon et al. (2020), but has always been assumed, erroneously, to be a normal fault. However, as shown as in Figure 8, the strike-slip mode has locally caused the crystalline basement of the Tenggol Arch to overthrust the southwestern MB in the Anding area. These movements occurred during the intra-Late Eocene to Early Oligocene time span. Both Top M and Top N and possibly also Top O are seen here as regional marker unconformities. The scheme on Figure 13 exemplifies the relationship of the mentioned unconformities with the BTU.

Eocene deposits: The presence of Eocene strata in the margins of Sundaland is likely related to an early phase of extensional tectonism, probably related to the onset of rifting of the South China Sea continental crust. It is noted that coeval Mid-Eocene sediments also occur in Sarawak, but more importantly, there is a well-documented Mid-Eocene unconformity marking the "Sarawak Orogeny" (Hutchison, 1996), as marked by the Middle to Late Eocene fluvio-marine Ketungau Group unconformably overlying fluvio-deltaic Late Cretaceous Kayan Group (Breitfeld et al., 2018). Breitfeld et al. (2017) called the Mid-Eocene unconformity in Sarawak the "Rajang Unconformity". This Mid-Eocene Unconformity appears to be correlated with the BTU in MB and PB, suggesting a regional event affecting the entire area from East Peninsular Malaysia to Sarawak. With additional data points from the Eocene or older deposits, a review of paleogeography of the SCS region on the eastern margin of Sundaland is thus needed to better refine the Eocene-Oligocene paleogeographic evolution of the south-western SCS. The authors suggest and plan to expand the current study to other areas of the SCS, such as Malaysian Borneo margin.

CONCLUSIONS

The Eocene to Lower Oligocene deposits of the Penyu and Malay basins are formed mainly by fluvial-lacustrine deposits. The sequence consists mainly of siltstone, with several intercalations of thin, mostly fine-grained sand and volcanic tuff. In comparison, the MB also experienced significant marine incursions with transgressive shale deposition that resulted in better sealing capacity. In the PB, a prominent near-Base Oligocene Unconformity can potentially be correlated to the BTU in the adjacent MB. However, it is noted that the BTU, which marks the base of the Tertiary basin, is less prominent and more difficult to track on seismic in the PB. In addition, we also observed intra-Eocene unconformities, called the Top N and Top O. On the Tenggol Arch plateau, the BTU forms also the base of the Paleogene, and on the flanks of the arch, the BTU merges with Top M, N and O unconformities.

Based on well data, there exist Mid-Upper Eocene sediments in PB in the deeper parts of the half-grabens and sub-basins, which implies that the age of basin initiation is at Mid-Eocene, rather than Oligocene as traditionally and commonly believed. Similarly, in the neighboring MB, by correlation and as seismic evidences show, Eocene sediments also exist in the deeper, undrilled parts of the MB. Again, the observation suggests that, at the latest, a Mid-Eocene age of basin initiation in the study area.

The presence of Eocene strata in the margins of Sundaland is associated with an early phase of extensional tectonism, probably related to the onset of rifting of the South China Sea continental crust. Paleogeographic reconstruction of the western/southern SCS margins should incorporate these elements of Eocene sedimentation history, by assessing additional data points from the Eocene or older deposits, such as those from Malaysian Borneo margin.

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