Eocene sediments: precursor deposits to the Oligocene expansion of the South China Sea?

Franz L. Kessler^{1#}, John Jong², Mazlan Madon³

¹Geologist and Geophysicist, Trainer, Glattbach, Germany

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

³Department of Geology, Universiti Malaya, 50630 Kuala Lumpur, Malaysia

Corresponding author: franzlkessler32@gmail.com

ABSTRACT

The stratigraphic record of Eocene in the Malaysian waters of the South China Sea is scarce; the few deep petroleum exploration wells and outcrops are located on the fringes of the SCS. Yet, despite the paucity of data we observe a variety of sediments that cover the range from fluvial to (at least) neritic marine deposits. Whilst fluvial deposits dominate the Western Rim (Penyu, Malay basins), the Southern Rim (Sarawak) is characterized by deposits of a narrow and rapidly deepening shelf, with fluvial, shallow marine clastics and carbonates passing seawards to outer shelf deposits. Possibly, the Eocene underlies additional areas of the SCS, but there is to-date insufficient well data to confirm this. The Eocene marine carbonate facies, which occurs in several places in Sarawak is a strong indicator of subsidence. An association with an early phase of extensional and/or transpressional tectonism, could be related to the onset of rifting of the crust underlying the SCS.

Keywords: *Eocene, Oligocene, Malay and Penyu basins, Sarawak, Stratigraphy, Unconformities, South China Sea.*

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INTRODUCTION

The nature of the oldest Tertiary sediments of the South China Sea (SCS) remains to-date a terra incognita. Yet, from previous stratigraphic basin studies there is a good comprehension down to the Oligocene level. Continental grabens were forming on thinning continental crust, and strike-slip faulting occurred in branches of the evolving sub-basins. These tectonic tensions, that led to an Oligocene seafloor spreading and rift propagation in the SCS were overprinted on an earlier phase of regional extension (Cullen et al., 2010).

Bouguer gravity (Figure 1) anomalies, from which crustal thickness (e.g., Vijayan et al., 2013; Gozzard et al., 2019) is derived, are indicative of a dichotomy of the SCS:

- The western portion of the SCS is formed by a little or moderately attenuated Sundaland continental crust, which reaches a calculated thickness of some 25-30 km; this value stems from a study carried out in the Dangerous Grounds and Sabah area (Vijayan et al., 2013). Gravity modeling of selected profiles indicated that the Sabah Trough (Figures 1 and 2) in the southern margin is underlain by a thinned continental crust 20-25 km thick, representing a continuation of the equally thinned Dangerous Grounds rifted continental terrane (Madon, 2017).
- A triangular-shaped section widening towards the east, formed entirely by oceanic crust with thinned continental crust flanking the oceanic crust on either side.

Figure 1: Bouguer gravity map of the western, south-western and southern margins of South China Sea (modified from Madon, 2017). The map shows a clear divide in the SCS, separating areas of differential crustal parameters. The eastern part of the SCS (in green and blue colors) show signs of attenuation, with a prominent low gravity feature striking SW-NE and coinciding with the Sabah Trough, a feature which may already have originated during Eocene time.

Morley et al. (2011) and Shoup et al. (2012) have shown that the stratigraphic successions in the western SCS, such as the Pattani, Malay, Penyu, West Natuna and Nam Com Son basins shared many features in common (Figure 2), with a generalized succession driven by comparable regional

Figure 2: Area index map – satellite imagery of SE Asia. Basins that originated during the Paleogene are shown in black dashed line with light green fill. Key basins mentioned in this paper include Malay, Penyu, West Natuna, Nan Con Son, Songkhla, Krabi, Chumphon, Mae Sot, Mea Tun, Hongsa, Pearl River Mouth and Taixinan. Eocene sequences have been confirmed in the Penyu and Malay basins by wells Anding Barat-5G, Ara-1 and Janglau-1 (Table 1), and onshore Sarawak. The areas of oceanic crust and strongly thinned continental crust flanks are bounded by the red line Red River Fault System and the Baram Line (BL) (Kessler, 2010; Jong et al., 2014; Kessler and Jong, 2016).

tectonics (Figure 3). Each basin shows a Late Eocene-Early Oligocene extension (rightly or wrongly called the synrift phase), which was followed by post-rift deposition from the Late Oligocene onward. Doust and Sumner (2007) have summarized the extensional relationship of the western and south-western SCS sub-basins (Figure 4). Further northwest, a marine transgression maximum can be detected in the Malay Basin's Oligocene to Early Miocene sequences, in the form of the regionally extensive anoxic K-shale sequence that shows a marginally marine signature (Madon et al., 2019). On the southern margin of the SCS, however, fully marine sequences were deposited as early as in the Middle to

Late Eocene (Kessler et al., 2021). This leads to the view that the Eocene SCS was not a single connected marine basin, but rather formed arrays of isolated and localized basins of which some had an enhanced early subsidence component, possibly connected to the Early Tertiary Pacific Ocean.

Based on evaluations of the Integrated Ocean Drilling Program (IODP) and other research wells, Huang et al. (2019) suggested that the SCS opening was probably related to strike-slip faults inherited from Late Mesozoic structures onshore-offshore of the SE Cathaysia Block, and Rhomb-shaped extensional basins probably developed

Figure 3: Sub-basins of the Western Rim. A comparison of formations, nomenclature and aspects of stratigraphy in four SCS sub-basins – Malay, Penyu, Natuna and Nam Con Son (from Shoup et al., 2012). In the shown scheme depositional cycles from shelf to bathyal have been placed into a numeric chronostratigraphic framework with individual cycles attributed the suffix VIM (Vietnam, Indonesia, Malaysia), building on the initial framework of Morley et al. (2011). The green color highlights a transition from synrift to postrift deposits.

in a similar way as *en-echelon* pull-apart on thinned Eurasian continental crust. Obviously, nature and timing of crustal thinning/break-up are important for the understanding of subsequent basin formation. A combined analyses of deep tow magnetic anomalies and IODP Expedition 349 cores showed that initial seafloor spreading started around 33 Ma in the northeastern SCS but varied slightly by 1–2 My along the northern continent-ocean boundary (Li et al., 2014). In the eastern part of the SCS, the discovery of magma-poor margins has raised fundamental questions about the onset of ocean-floor magmatism and has influenced the interpretation of seismic data across many rifted margins, including

since it has shown more marine influence than other basins and may have subsided earlier. This observation not only permits the age of stratigraphic packages to be better constrained by using marine fossils, but also points to a shallowing trend westward from the centre of rifting.

DATABASE

We acknowledge the paucity of well data, notably in the central parts of the SCS. Though even in areas, where wells have been drilled, the stratigraphic record of the bottom-hole sections may be poor or ambiguous. Therefore, we are presented with data gaps that cannot be bridged but infilled with published information by various

the highly extended northern SCS margin (Larsen et al., 2018). The possible onset of rifting in the east should also be reflected in the stratigraphic basin-fill records throughout the SCS. In a study on Vietnam's Nam Con Son Basin, Morley et al. (2011) considered the basin as the 'distal end' of the basin succession

Figure 4: Three SCS sub-basin sections located at the Western and South-western rims. Summary stratigraphy of a typical proximal basin, the Gulf of Thailand, a typical distal basin, the Northwest Java Basin and a typical intermediate basin, and the South Sumatra basin (from Doust and Sumner, 2007). In the above shown sections, only the South Sumatra and Northeast Java basins appear to contain Eocene deposits. 1 = Early synrift lacustrine petroleum system, 2 = Late synrift transgressive deltaic petroleum system, 3 = Early post-rift marine petroleum system, 4 = Late postrift regressive deltaic petroleum system.

authors around the margins of the SCS.

Our database contains two main sources of information: published studies based on petroleum exploration well data, and geological studies of outcrops. For practical purpose, we subdivide areas surrounding the SCS as follows (Figures 1 and 2):

- The **Western Rim** is formed by a string of sub-basins starting from

Peninsula Malaysia to Hainan Island and southern China. Eocene deposits in the Penyu and Malay basins have been described and discussed by Kessler et al. (2020).

- The **South-western Rim** sub-basins are located in the eastern coast of the Sumatra and Java islands. As in the Western Rim, there is good seismic coverage and wells for calibration.
- The **Central SCS** covers a significant part of the discussed

Well or Outcrop	Age Range	Lithofacies and Fossils	Sediment Facies/Characteristics	Remarks
Janglau-1 (Penyu Basin)	Late Eocene (2925-3245m bkb, WN12a) Middle Miocene (3245-3520m bkb, WN13a)	Clastic deposits, with palynomorphs	Non-marine. Mostly immature clastics, poor sorting; occ. Tuffite.	Strongly diagenetically altered, traces of oil.
Ara-1 (Penyu Basin)	Late Eocene (3405-4020m bkb, WN11a, 11b, 12) Middle Miocene not confirmed	Clastic deposits, with palynomorphs	Non-marine. Mostly immature fine clastics, poor sorting.	Strongly diagenetically altered, traces of oil.
Anding Barat-5G (Malay Basin)	Late Eocene (3002m bkb - ?) Middle Eocene not confirmed	Clastic deposits	Non-marine. Mostly immature sediments, occ. conglomerates.	Strongly diagenetically altered, traces of oil.

Table 1: Summary of wells having penetrated Eocene deposits in the Malay and Penyu basins (well locations in Figure 2), with descriptions of these deposits are shown in Kessler et al. (2020).

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 and oceanic crust with several remnants of rafted continental crust.

- Sabah, Sarawak, and the adjacent offshore basins form the **Southern Rim** of SCS. 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 were described and discussed in Kessler et al. (2021).

THE WESTERN RIM

The Western Rim of the SCS (Figures 1 and 2) corresponds to the Gulf of Thailand and offshore peninsular Malaysia, as well as contemporaneous shelf areas of Thailand, Vietnam, and southern China. In Malaysian waters there are two basins: the large Malay

Figure 5: Seismic traverse and stratigraphic interpretation of the Songkla Basin (location in Figure 2). It shows a bottom layer of speculative Eocene deposits (in the interpretation below), with Oligocene-Miocene forming distinctive seismic facies (from Morley and Racey, 2011). The overwhelming part of the Songkla basin, Oligocene and younger, belongs to the postrift stage.

Figure 6: NW-SE seismic line from Nam Con Son area (location in Figure 2) with stratigraphic interpretation suggesting the existence of Eocene sequences in the deep half-graben with interpreted horizon in red marked as Top Basement (from Nguyen et al., 2016).

Basin and its smaller twin, the Penyu Basin (Figure 2). At least five petroleum exploration wells in those basins were drilled deep enough to encounter Eocene rocks. In a previous publication, we described the Paleogene stratigraphic record of the above basins (for more detail, please refer to Kessler et al., 2020). A summary of the well records is shown in Table 1.

The Eocene to Lower Oligocene deposits of the Penyu and Malay basins are formed by fluvial lacustrine deposits with some marine influence in the latter. The sequence consists mainly of siltstone, with intercalations of fine-grained sandstone 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 or earlier, rather than Oligocene as traditionally and commonly stated in the literature.

By correlation, and as seismic character suggests, Eocene sediments also appear to exist in the deeper, undrilled parts of the Malay Basin, pointing to a Mid-Eocene or earlier age of basin initiation. In the Penyu Basin, a prominent near-Base Oligocene Unconformity can potentially be correlated to the Base Tertiary Unconformity mapped by Madon et al. (2020) in the adjacent Malay Basin, however the latter term implies all Tertiary sequences, including potential Paleogene deposits lie above the unconformity. Besides, we also observe intra-Eocene unconformities, called the Top N and Top O (Kessler et al., 2020).

The presence of Eocene strata could be associated with an early phase of extensional, and perhaps also transpressional tectonism, and are probably related to the onset of rifting of the SCS continental crust. Eocene deposits may also be present in some Gulf of Thailand basins such as the Songkhla Basin (Figure 5, see location in Figure 2) and offshore Vietnam's

Figure 7: Across the border from main Malay Basin (location in Figure 2), a seismic transect across a NNW-trending Paleogene graben bounded by steep strike-slip faults and half grabens confined by more gentle dipping WNW-trending normal faults that link up with the strike-slip faults at depth. The presence of Eocene synrift section is also inferred in the cross section and discussed by Fhyn et al. (2010).

Nam Con Son Basin (Figure 6, see location in Figure 2). The Vietnamese part of the Malay Basin comprises a large and deep Paleogene pull-apart basin formed through Middle or Late Eocene to Oligocene left-lateral strike-slip along NNW-trending fault zones (Fhyn et al., 2010; Figure 7, see location in Figure 2). In the West Natuna Basin (Figure 2), Hakim et al. (2008) has also suggested an Eocene-age synrift stratigraphy for the basin.

We will discuss further occurrences of possible Eocene deposits in the Sundaland region in a later section.

THE SOUTH-WESTERN RIM

The South-western Rim encompasses basins south of the Natuna archipelago and are located adjacent to Sumatra and Java. These basins, which include the Sunda and Asri basins (Figure 2) are relatively small, monoclinally steep to

Well or Outcrop	Age Range	Lithofacies and Fossils	Sediment Facies/Characteristics	Remarks
Batu Gading	Late Eocene to Oligocene	Bedded limestone with foraminifera	Shallow marine carbonates contaminated by clastics	Age of overlying sequence uncertain
Engkabang-1	Middle to Late Eocene, and younger	Nannoplankton NP16-23	Neritic carbonates wedges between neritic fine clastics	Overlain by fine clastic Oligocene
Engkabang West-1	Middle to Late Eocene, and younger	Nannoplankton NP16-23	Neritic carbonates wedges between neritic fine clastics	dtto
Nuang-1	? Paleocene, Eocene, Oligocene and younger	Data published by Morley et al., 2020	Data published by Morley et al., 2020	dtto
Kuching-Bako	? Eocene	Mostly barren	Fluvial sandstone	Strongly compacted

Table 2: Important investigated well and outcrop results of the Southern Rim along the Sarawak margin, with detailed descriptions of the Eocene deposits shown in Kessler et al. (2021). Nuang-1 well location in Figure 2 and see locality 1 in Figure 8 for Engkabang well locations.

Figure 8: Lithologic map of Sarawak modified after Adepehin et al. (2019), serving as location index. Annotated are the investigated areas with Paleogene carbonates – (1) Engkabang wells, (2) Bata Gading, (3) Limbang River headwaters, (4) Mulu (Miri Zone). (5) Engkilili Formation (Kuching Zone). Marine carbonates within the Eocene sequence point to increased subsidence and possible rifting. Inserted is the topography map of Borneo with location of Rajang Fold-Thrust Belt annotated.

box-shaped, and are situated far away from the centre of rifting/spreading of the Eastern SCS.

A summary of Sunda Basin features is given by Ralanarko et al. (2020) and we observe the following tectonic signature:

- A very prominent fault-induced half-graben flank.
- A maximum depression and subsidence, with the basin axis located near to the fault escarpment.
- A sedimentary sequence gradually growing in thickness towards the basin axis.

Although marine conditions were established during Late Oligocene time, full marine conditions took control of the East Java basins only during the Miocene. The South-western Rim basins clearly indicate an early pulse of rifting, predating the mainly Oligo-Miocene rifting and spreading events that took place in the SCS. Eocene deposits in the lowermost part of these basins remains a possibility, so far unconfirmed.

Figure 9: Eocene Batu Gading Limestone outcropping on the Baram River NW of Long Lama (locality 2 in Figure 8). Benthonic foraminifera are indicating a shallow water environment. Nummulites and other large foraminifera occur in two horizons.

THE SOUTHERN RIM

Sarawak

On the Southern Rim of the SCS (Figures 1 and 2), the Eocene is recorded in three exploration wells, and there are a few good outcrops along the escarpment that form the boundary between the coastal basin and the Rajang Basin. Based on our work on the Eocene of the Southern Rim (Kessler et al., 2021), we summarized the available data for purposes of calibration in Table 2.

Paleogene rocks in Sarawak are found in three tectono-stratigraphic zones – Miri, Sibü and Kuching presenting three depositional settings (Madon, 1999; Figure 8):

Miri Zone: Outcrops and deep exploration wells in the Miri Zone indicate shelfal clastics, shelfal to neritic carbonates, and clay-dominated neritic sediments (Kessler et al., 2021). In Batu Gading, Limbang and Mulu areas (Figures 9 and 10), there are outcrops of Eocene to Oligocene age

which can be tentatively correlated with the clastic and carbonate section of the Engkabang wells (Table 3; locality 1 in Figure 8), which also forms the most complete stratigraphic record:

- A shelfal carbonate sequence, rich in foraminifera, can be logged in the Batu Gading quarry (Kessler and Jong, 2017; Figure 9, locality 2 in Figure 8).
- The Melinau Limestone of the greater Mulu area (locality 4 in Figure 8) represents a mighty sequence of platform carbonates, ranging from Priabonian (Late Eocene) to Aquitanian (Lower Miocene age) (Hutchison, 2005; p. 88-91).
- Further northwest, in upper Limbang area and along the deeply incised Limbang river, outcrop the strongly slumped and tectonized series of slates and neritic limestones, called Keramit and Selidong limestones (Figure 10; locality 3 in Figure 8). These sequences appear to be distal, neritic equivalents of the above mentioned Melinau Limestone and

Figure 10: Slumped and tectonized sequence of the Paleogene Kerimit Limestone, which formed in a neritic environment (locality 3 in Figure 8). Headwaters of the Limbang River, Jokat quarry, Limbang, Sarawak. The sequence is inferred to be a distal equivalent of the carbonate sequence as encountered in the Engkabang wells.

are of approximately the same age (Hutchison, 2005; p. 90).

Sibu Zone: In the Sibu Zone (Rajang Fold-Thrust Belt, Figure 8), Late Cretaceous to Late Eocene deep marine clastic-sediments indicate upward shallowing of the depositional sequence, which was later buried to great depths and possibly metamorphosed.

However, the tectonic relationship between the Rajang and the sedimentary sequences of the Miri Zone, both laterally and vertically, remains a controversial topic.

Kuching Zone: In the Kuching Zone, the Kayan and Plateau sandstones represent a fluvial-dominated non-marine depositional setting. Allochthonous, shallow-marine limestone blocks of the (?) slumped Engkilili Formation (locality 5 in Figure 8) of Paleocene to Eocene age are found also (based on a rich fauna of foraminifera and nannofossils; Hutchison, 2005), but the original carbonate shelf from which these

blocks were derived appears not to have been preserved.

Again, the tectonic relationship between the Rajang and the sedimentary sequences of the neighboring Kuching Zone remains a controversial topic.

Noted there are two major unconformities within the Paleogene deposits of Sarawak: the Rajang Unconformity, dated as approximately 37 Ma, and the younger near-Top Eocene (aka Base Oligocene) Unconformity of 33.7 Ma (Table 3). As mentioned earlier, the presence of these Eocene strata in the margins of Sundaland point to an early phase of regional extension that is probably related to the onset of rifting in the South China continental crust.

Sabah

The geology of Sabah is notoriously complex, and the tectonic divide between Rajang/Crocker and the younger Sabah basins (Figures 1 and 2), runs parallel to the coast. On Kudat

Biofacies Unit	Engkabang West-1	Engkabang -1	Series name	Stage Name	Composite zonal ranges
EJ	Present	Present	Early Miocene	Burdigalian - Aquitanian	NN2 N5
EI	Present	Present	Early Miocene	Aquitania	NN1 N4
Sequence Boundary 23.0 Ma (boundary between Miocene and Oligocene)					
EH	Present	Present	Late Oligocene	Chattian	NP25 P22
EG	Present	Not present (approx. 3 my erosion or hiatus?)	Late Oligocene	Rupelian	NP25 - NP24 P22 - Upper P21
EF	Present	Present	Early Oligocene	Rupelian	P21 (Lower) NP24 - NP23
Sequence Boundary 33.7 Ma (boundary between Oligocene and Eocene) Possibly up to 2 my "missing" in Engkabang -1					
EE (Main carbonate)	Present	Present	Late Eocene	Priabonian	NP21 - NP19
Possible Tectonic Erosional event related to SB at circa 37.1 Ma (approx. top Middle Eocene). Up to 2 my "missing" in Engkabang-1?					
ED	Present	Not present (approx. 2 my erosion or hiatus?)	Middle Eocene	Bartonian	NP17 - NP16
EC	Not penetrated	Present	Middle Eocene	Lutetian	NP16 - NP15

Table 3: Established Palaeogene biofacies of Engkabang wells (locality 1 in Figure 8). The Eocene biofacies units EJ to EC denote the local "Engkabang" biofacies. The absence of biofacies units EG and ED in Engkabang-1 is likely due to erosion and/or depositional hiatus, with three significant erosional events were observed at 37.1 Ma (approx. Rajang Unconformity), 33.7 Ma, and 23.0 Ma (from Jong et al., 2016). Foraminifera zonation (left side) and nanno-plankton zonation (right) are annotated.

Peninsula, some smaller carbonate outcrops have been logged, but there is so far no evidence for the presence of Eocene rocks (Mansor et al., 2021). Petroleum exploration wells located offshore in the Sabah Basin did not penetrate pre-Oligocene sequences before reaching TD in mostly turbiditic deep-water sequences of Early Miocene age. Therefore, whether there are Eocene deposits beneath the evaluated well sections, remains an open question.

The Rajang and Crocker Conundrum

The Rajang Group consists of a several thousand meters of mostly

anchimetamorphic deposits in the central part of Borneo Island, which became folded during the Sarawak Orogeny. Field observations and investigations by the authors suggest that the Rajang Group forms an entity of its own and is separated from the SCS foreland basins by a tectonic contact, in which the metamorphic Rajang (nappe, block or sub-basin) overthrusts the latter. Whether the Rajang metamorphic are allochthonous or are *in situ*, remains an open question.

Interestingly, there are no sediments equivalent to the Rajang in the foreland basin: the youngest deposits of the

Figure 11: Additional scientific ocean-drilling sites in the South China Sea: ODP 184 in 1999, East Asian monsoon history; IODP 349 in 2014, SCS tectonics; IODP 367/368 in 2017, IODP 368X in 2018, SCS rifted margin (from Wang et al., 2019). Note that most if not all of the scientific wells in the SCS were drilled in the oceanic crust region.

THE CENTRAL SOUTH CHINA SEA: ODP AND IODP WELLS

The central SCS, a deep small ocean basin, has become the subject of scientific drilling research since 1999. Over the last 20 years, a total of 17 sites were drilled and nearly 10,000 m of cores recovered, including 320 m of basement basalt (Wang et al., 2019). Of particular interest are the recent IODP Expeditions 367, 368 and 368X on the northern continental margin, which addressed questions relating to the rifting process and the rift-to-drift transition. The break-up of continental lithosphere and the opening of ocean basins have always been high priorities in ocean drilling, and research in the Atlantic Ocean has yielded basic knowledge of basin formation in passive margins. Two end members have been recognized: volcanic or magma-rich and non-volcanic or magma-poor rifted margins. Volcanic rifted margins can be easily recognized by the seaward-dipping reflector sequences in seismic transects. The primary goal of these expeditions was mostly “testing hypotheses for lithosphere thinning during continental breakup”, rather than establishing stratigraphic control in the

Rajang Group appear to be of Mid-Eocene age, while the oldest Sarawak foreland basin deposits appear to be of Late Eocene age.

The Rajang Basin is also considerably older (Cretaceous age; Hutchison, 2005) and appears therefore to precede basins that have developed on top of the SCS continental crust – with the caveat that the tectonic contact between Paleogene deposits and underlying rock (magmatic and metamorphic basement, (?) Mesozoic sediments) remains poorly understood. For further information in respect to the Rajang Group sedimentary history, readers are referred to the recent publications by Breitfeld et al. (2017, 2018), and by Nagarajan et al. (2020).

Figure 12: Based on calcareous nannofossil biostratigraphy research for the Late Eocene to Early Miocene sediment section at IODP Site U1501, the regional seismic reflector T_{60} at ~26.8 Ma was dated, corresponding to the final stage of the Ridge Jump Event, which marked the onset of accelerated seafloor spreading of the SCS at ~27.14–26.77 Ma. (Left) Summary of well results of well U1501 with age/depth plot of calcareous nannofossil bio-events, shown alongside the lithostratigraphic summary by Jian et al. (2018) (see well location in Figure 11). The paleoenvironmental conditions and the nannofossil assemblages also show stepwise changed in response to tectonic events. (Right) Schematic representations of nannofossil responses to early paleo-oceanographic evolution of the South China Sea from Late Eocene rifting to Early Miocene spreading (paleo-maps modified after Hall, 2012). The well penetrated the northern shoulder of the Central South China Sea rift and found Paleogene deposits on top crust, which is interpreted as continental crust (from Ma et al., 2019).

sediments overlying the magmatic basement rocks.

From the studied well results (U1431, U1433, U1146, U1147, U1148; Figure 11), only U1435 logged Paleogene sediments in locations in proximity to the continental-to-oceanic crust boundary (Li et al., 2014). 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-Mid-Miocene age. Therefore, we cannot expect any meaningful calibration for the Eocene

sediments that were encountered in the basins further to the west. Another to IODP well, U1501, 1502 penetrated Eocene rock on the north-eastern shoulder of the central SCS rift (Ma et al., 2019; Figure 12).

ADDITIONAL DATA POINTS IN THE SUNDALAND NEIGHBOURHOOD

The presence of Eocene strata in the depocentres of Western and Southern rims discussed by Kessler et al. (2020, 2021) points to an early phase of extensional tectonism and one could

anticipate that more Eocene depocentres will be in the Sundaland region.

Eocene tectonic events in SE Asia, marked by extension, strike-slip tectonics, and some thrusting (e.g., offshore Peninsular Malaysia/Gulf of Thailand and offshore Vietnam), are probably associated with strike-slip faulting. The Three Pagodas Fault Zone (TPFZ, Figure 2) in western Thailand, estimated to be more than 700 km in length (Searle and Morley, 2011), represents a Cenozoic structure that developed in response to the India-Eurasia collision (e.g., Lacassin et al., 1997; Morley, 2002; Rhodes et al., 2005). ^{40}Ar - ^{39}Ar dates, obtained from micas in gneisses within the TPFZ, suggest that ductile (left-lateral) slip occurred during the Late Eocene – Early Oligocene along the TPFZ (Lacassin et al., 1997; Nantasini et al., 2012; Simpson et al., 2020), and may have created several smaller pull-apart basins.

Review of basins in Thailand by Morley and Racey (2011) suggests that most basins were initiated in Oligocene, with possible exception of two basins (Mae Tun and Hongsa, Figure 2) that may have an Eocene section. Note that the Hongsa Basin is in Laos, near the border with Thailand. In Mae Sot basin (Figure 2), Ratanasthien (1990) describes the coals as being of Late Eocene–Early Oligocene age, unconformably overlain by Upper Oligocene–Lower Miocene strata.

Further, Morley and Racey (2011) state: “Unpublished results from one well in the Gulf of Thailand demonstrated that

a Late Eocene dyke encountered in a well was intruded along a synrift normal fault, indicating the earliest rift stage was at least of Late Eocene age. However, this is an interpretation of the seismic and well data, and we do not consider it to be categorical evidence for rifting beginning in the Eocene.”

While such arguments are premised upon the “oldest demonstrable” age of the drilled section, undrilled portions remain. For example, Heward et al. (2000) suggest units as old as the Eocene could be present at the base of the synrift section in the Chumphon Basin (Figure 2). Likewise, indications of potential Eocene sections based on seismic correlation has been noted by Fhyn et al. (2010), Nyugen et al. (2016) and Kessler et al. (2020) in the Western Rim of SCS. Moreover, vertebrate fossils are also reported from Eocene (continental) deposits, as documented by Benammi et al. (2001) and Chaimanee et al. (2013) in the Krabi Basin (Figure 2).

Eocene deposits have also been reported in recent publications on the northern SCS. Ge et al. (2017) summarized the tectono-stratigraphic evolution and hydrocarbon exploration in the Eocene Southern Lufeng Depression, Pearl River Mouth Basin (Figure 2) and was followed-up by Ge et al. (2019) discussing the controls of faulting on synrift infill patterns in the Eocene PY4 Sag, Pearl River Mouth Basin. In the north-eastern portion of the SCS, a study on specific intervals of deep-water wells 7-1-1 and L-29 was carried out by Zhang et al. (2015). The study confirmed a marine sequence containing Eocene foraminifera and

Figure 13: (A) Location of Singkawang, Melawai, Ketungau and Embaluh basins with Eocene fluvio-deltaic deposits, onshore Kalimantan Borneo. (B) Stratigraphic comparison of the four basins with Sarawak onshore basin with the equivalent Eocene Pelagus and Bawang members of Belaga Formation (modified from Hartono et al., 2021).

spores of algae in the Taixinan basin (Figure 2). Overall, the discovery of marine Eocene sediments in the northern SCS has been well-documented by Jian et al. (2019).

In the quest for further hydrocarbon exploration and the search for Paleogene source rocks of Indonesian onshore Borneo basins, field studies conducted by Hartono et al. (2021) in the lesser known Melawai, Ketungau, Singkawang and Embaluh basins, also suggest the presence of Eocene deposits (equivalent to central Sarawak's Pelagus and Bawang members of Belaga Formation) in eastern Sundaland (Figure 13).

DISCUSSION

In the context of seafloor spreading and basin formation we may subdivide the Paleogene basin sequence of the SCS into two sub-sequences (Figure 14),

analyze the common elements and state the differences:

- **Extensional basins.** The older basin sequences were labeled synrift (Doust and Sumner, 2007), and are of Oligocene and possibly Mid-Late Eocene age. The basal deposits may have formed during the confirmed onset of rifting at *ca.* 35 Ma, or perhaps earlier. Comparing the individual Paleogene basin fill sequences, one cannot put forward a simple transgressive trend from east to west, and subsidence rates appear to have varied considerably from one sub-basin to another. This may point to transpressional tectonism, which has been proved for selected areas of the Penyu Basin (Kessler et al. 2020). So-far, there is only a record of Eocene deposits overlying continental crust.
- **Eocene unconformities.** The intra-Late Eocene Unconformity of

Figure 14: NW-SE schematic section through the nearshore and onshore portion of the Sarawak Basin. The datum of the sketch is placed at the Base Miocene Unconformity (23 Ma). The section features the Engkabang sub-basin, which saw subsidence during Late Eocene time coeval with a prominent marine ingress. The Engkabang sub-basin is bordering by tectonic contact the Baram Delta Block in the northwest, an area which saw expansion only during the Oligocene and Miocene time, and also the Rajang Basin, which was inverted at the end of the Middle Eocene. The section also points to a shift of the expansion axis from the Southern Rim (Engkabang sub-basin) further north, where the final break-up of the South China Sea continental crust occurred during Oligocene and Miocene time.

37.1 Ma as seen in the Engkabang wells (Sarawak), as well as the top Mid Eocene event *ca.* 41 Ma in the Janglau-1 well (Penyu Basin) may correspond to periods of reduced subsidence followed by pulses of enhanced extension affecting the continental crust, but only at 33.7 Ma did tensions lead to a complete crustal breakup of the SCS further to the east. Currently, we do not know how well one can correlate the intra-Eocene unconformities from sub-basin to sub-basin; this

can only be done if the tectonic causes are properly understood.

- **Strike patterns of sub-basins, lineaments.** The dominant strike direction in the Sarawak-Sabah Trough, Penyu Basin and Java Sea is northeast-southwest. The strike direction of Eocene grabens in the Malay and Natuna Basin area may have an east-west component, but this awaits further clarification, the tensions also led to an initiation of lineaments such as the Lupar Line, the Red River/Baram Line system (Figure 2), the latter dividing the

SCS into areas of strong and moderate crustal stretch.

- **The post-break-up sequences.** Present in post-rift, extensional-to-strike-slip basins of the latest Eocene, Oligocene, and younger ages, formed after the extensive crustal thinning that took place and led to mostly SCS-wide marine conditions during Late Oligocene to Early Miocene time.
- **Unconformity correlation.** The 33.5 Ma Top N Unconformity (Penyu Basin; Kessler et al., 2020), and the 33.7 Ma unconformity (Engkabang wells; Jong et al., 2016) may be one event, given age uncertainty and diachronism. It marks the end of the early phase of basin formation. The presence of the unconformities, as expressed on the Western and the Southern rims ties well with the 35 Ma statement by Wang et al. (2019), for a “start of spreading” in the eastern portion of the SCS, and a measured sediment age of 33.43 Ma (above ocean crust basalt) in IODP 1435. We believe that the *ca.* 33.5 Ma unconformity may serve as a good regional correlation event. The diachronous nature of the unconformity, as well as uncertainty, however, need to be further investigated.
- **Crustal thinning.** Based on basis of the stratigraphic record, we assume a significant crustal thinning of the continental crust, with a pulse of subsidence occurring at *ca.* 23 Ma, and well documented on the Southern Rim. Later in the Miocene, crustal thinning and subsidence continued but slowed, and compressive

tectonism took over during Late Miocene time. The Sarawak and Sabah foreland basins gave way to a zone of deep water, the Sabah Trough (Figures 1 and 2), which is an area of thinner continental crust, compared to the Sabah Shelf and the Dangerous Grounds on either side of it. The basins fringing the Borneo coastline may have undergone a unique evolution history. We observe a significant Eocene subsidence along the Sarawak margin, leading to marine sequences as logged in the Engkabang wells (Table 3). There is also sedimentary continuity from the shallow marine Eocene to the neritic Oligo-Miocene sequences. In the adjacent Rajang Basin, however, we note a major break in Mid-Eocene – the Rajang Unconformity (Sarawak Orogeny), following which there was deposition of fluvio-marine and coastal plain sediments (Cycles I and II) before the shallow marine environment was re-established.

- **The post-rift evolution.** This corresponded with the development of deep-water environments of the outer neritic and basin floor realms. Interestingly, the axis of thinning (= basin axis) is not clearly related to the centre of crustal thinning in the eastern SCS (Wang et al., 2019), and one may speculate that the Sabah Trough evolved as a separate rift, with an associated crustal thinning in the order of 5 km, already occurring during Eocene time.

The question of whether a subduction (a Benioff-zone in southeast direction)

existed beneath Sabah remains controversial. Neither in the Late Eocene, nor during Oligocene, the rock record does not show any signs of compression. If subduction had taken place since the Early Miocene, it could be expected to have left a trail of seismic foci seen up to the present time. Nor do we encounter specific volcanic extrusive typical for subduction areas on deep imaging seismic data. This said, several recent deep seismic tomography studies have identified or provided geophysical evidence of the presence of a “proto-South China Sea” lithospheric slab beneath northern Borneo, which seems to lend support to earlier findings by Hall and Spakman (2015) and studies conducted by Hall and Breitfeld (2017), Wu and Suppe (2018) and Lin et al. (2020). In a nutshell, the question about a proto-South China Sea crust beneath Borneo has not been conclusively resolved yet. Accordingly, one should collect further information from all disciplines with different angles to come to a conclusive answer.

CONCLUSIONS

Despite an overall paucity of Paleogene data, fluviatile to (at least) marine neritic deposits of this age are recognized around the SCS. While fluvial deposits dominate the Western Rim (Penyu and Malay basins), the Southern Rim (in Sarawak) is characterized by deposits of a narrow and rapidly deepening shelf, with fluviatile, shallow marine clastics and carbonates leading seawards to outer shelf and neritic deposits. Among the observed Paleogene unconformities, only the near-Base Oligocene event offers scope for a SCS-wide correlation.

Where present, Eocene strata in the margins of Sundaland are associated with continental crust and appear to have originated in an early phase of extensional and/or transpressional tectonism. Possibly, such early movements were precursors related to the onset of rifting of the SCS continental crust. Among the studied sub-basins of SCS margins, the Sarawak and Sabah basins distinguish themselves by a history of early subsidence and marine ingression, for instance in the Sabah Trough, which may have originated as a failed rift – a topic that warrants further investigation.

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