BERITA SEDIMENTOLOGI

ISSN 0853-9413 (print)
ISSN 2807-274X (online)

Indonesian Journal of Sedimentary Geology

BERITA SEDIMENTOLOGI · Volume 47 · Number 2 · September 2021
https://journal.iagi.or.id

Publisher:
Indonesian Sedimentologists Forum (FOSI)
The Sedimentology Commission of
The Indonesian Association of Geologists (IAGI)

Jl. Ciledug Raya Kav. 109 Cipulir, Kebayoran Lama,
Jakarta Selatan, Indonesia

Berita Sedimentologi

Indonesian Journal of Sedimentary Geology

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,

We embarked on a new journey starting from this issue onward as **Berita Sedimentologi** is now officially an online journal with an additional ISSN 2807-274X. Berita Sedimentologi Online Journal is now hosted at our parent organization’s scientific publication server at https://journal.iagi.or.id, which utilizes Open Journal Systems software application. Converting Berita Sedimentologi into a proper online journal is actually a long overdue plan because we have been consistently publishing our print version on FOSI website since Berita Sedimentologi No. 20 in 2011. This transformation also marks the first step of our long-term objectives where we want to have Berita Sedimentologi accredited and listed in some leading, journal indexing databases. The ultimate aim is to be improve the quality and standing of Berita Sedimentologi as a scientific journal and to attract more authors to publish with us.

The Editorial Team, Reviewer and Advisory Boards have also been restructured in order to help us achieve our future objectives. Sukiato Khurniawan (University of Indonesia), Barry Majeed Hartono, Gabriella Natalia (Trisakti University), Visitasi Femant (Pertamina) and Desianne Kinanthi joined us recently as Editors. Dr. David Gold (CGG) also joined our core External Reviewer Team, while the Advisory Board now consists of Prof. Yahdi Zaim, Dr. Robert J. Morley and Mrs. Harsanti P. Morley. Please join me in welcoming and supporting them so that we can keep delivering high quality articles punctually and consistently.

In this issue, we include five articles with two articles on Java, one on South China Sea Eocene sediments, one on Basement play in Sumatra and the last one is a short communication about Indonesian Stratigraphic Nomenclature revision.

We plan to publish the next issue of Berita Sedimentologi (Vol. 47 No. 3) in December 2021. This issue will focus on Sulawesi Island, therefore we invite potential contributors or researchers on Sulawesi to submit articles. Manuscripts are accepted from now until early November. Please contact me at minarwanx@gmail.com or visit our journal website for more information.

See you again next time.

Minarwan
Editor-in-Chief

Cover Photograph:

Fine-coarse-grained turbidite sandstones, mixed with volcanoclastic fragments, Mid-Late Miocene Cinambo Fm. Location: Cilutung River, Buniasih, Majalengka (photo by courtesy of Erlangga Septama).

Berita Sedimentologi

- Publisher: FOSI (IAGI), Jl. Ciledug Raya Kav. 109, Cipulir, Kebayoran Lama, Jakarta Selatan, Indonesia
- For paper submission and advertising rates, please send your inquiries to bs.fosi@gmail.com or minarwanx@gmail.com.
- ISSN 0853-9413 (print), ISSN 2807-274X (online)

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 September 2021:

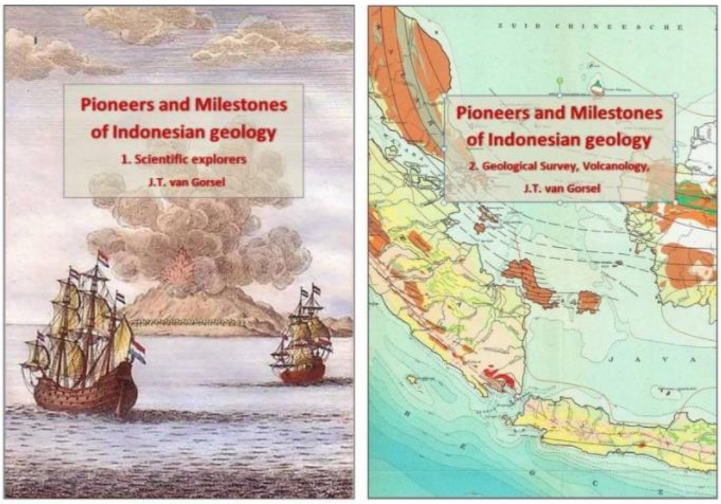
1,009 members

Including Yudistira Effendi and 213 other connections

+210

J.T. (Han) van Gorsel • 1st
Geologist- Biostratigrapher
1mo •

The book that I have been working on for more than two years is finally finished, and the Department of Geological Engineering of the Institut Teknologi Bandung has kindly agreed to publish it. Marketing will h ...see more



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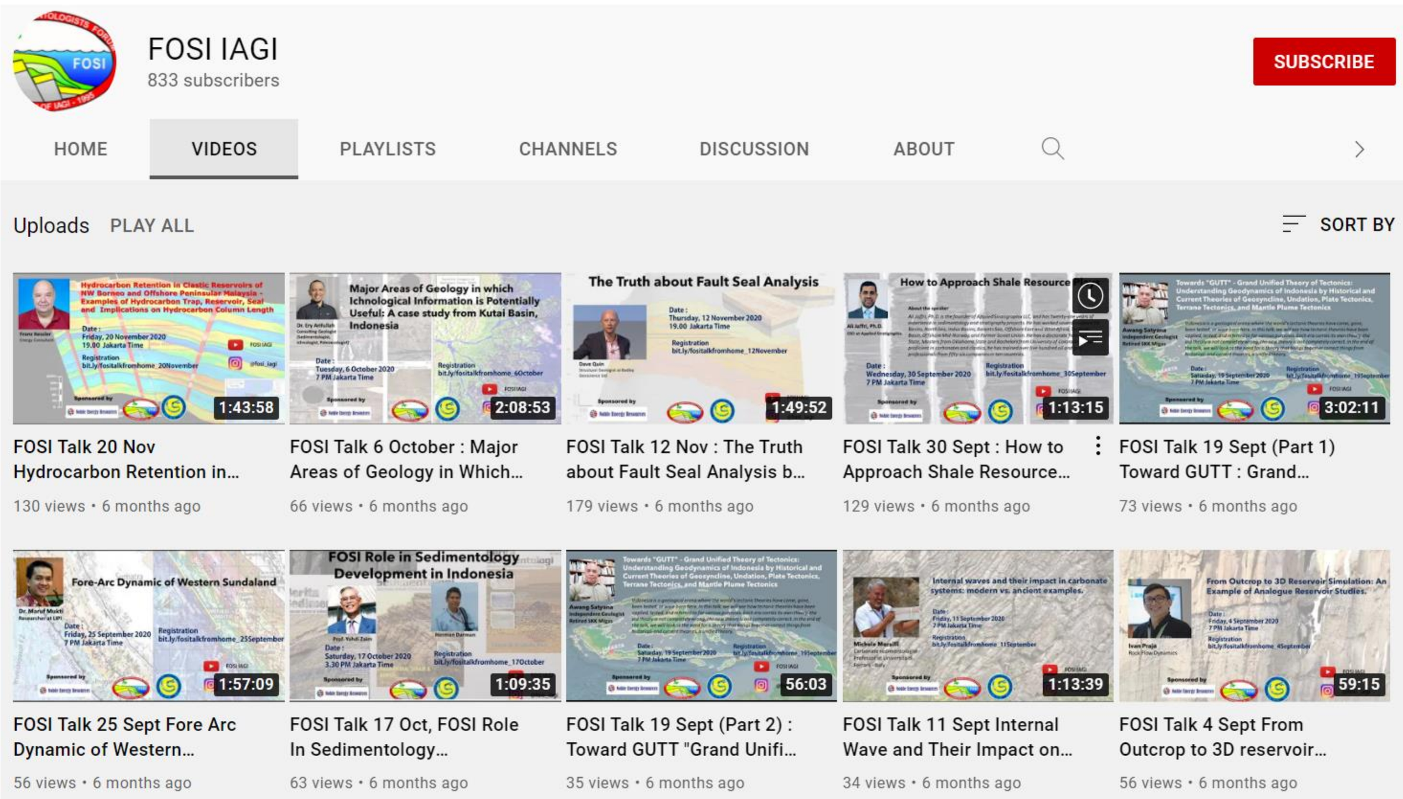
FOSI TALK

A regular webinar presented by well-known experts in theirs fields, delivered via ZOOM. Previous FOSI TALK video collections are available at: https://www.youtube.com/channel/UCquqaq7MTuUTYaiWJmciMDA/featured



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

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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 fluviatile 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 fluviatile, 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.*

Manuscript received July 3rd,2021, revised manuscript received August 14th, 2021, final acceptance August 21st, 2021.

DOI: 10.51835/bsed.2021.47.2.319

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 (Viyayan 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.

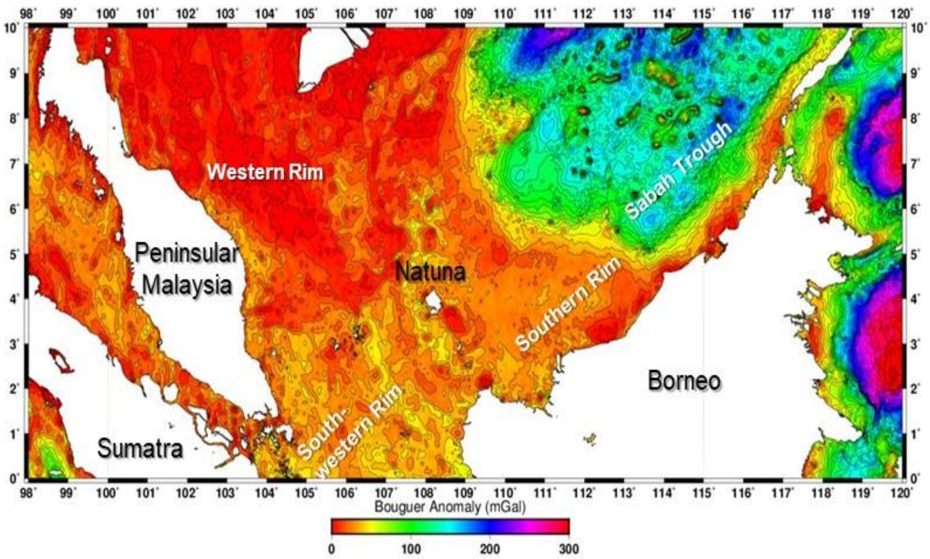

Figure 1: *Bouguer gravity map of the western, south-western and southern margins of South China Sea (modified from Madon, 2017). The map shows a clear divide in the SCS, separating areas of differential crustal parameters. The eastern part of the SCS (in green and blue colors) show signs of attenuation, 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

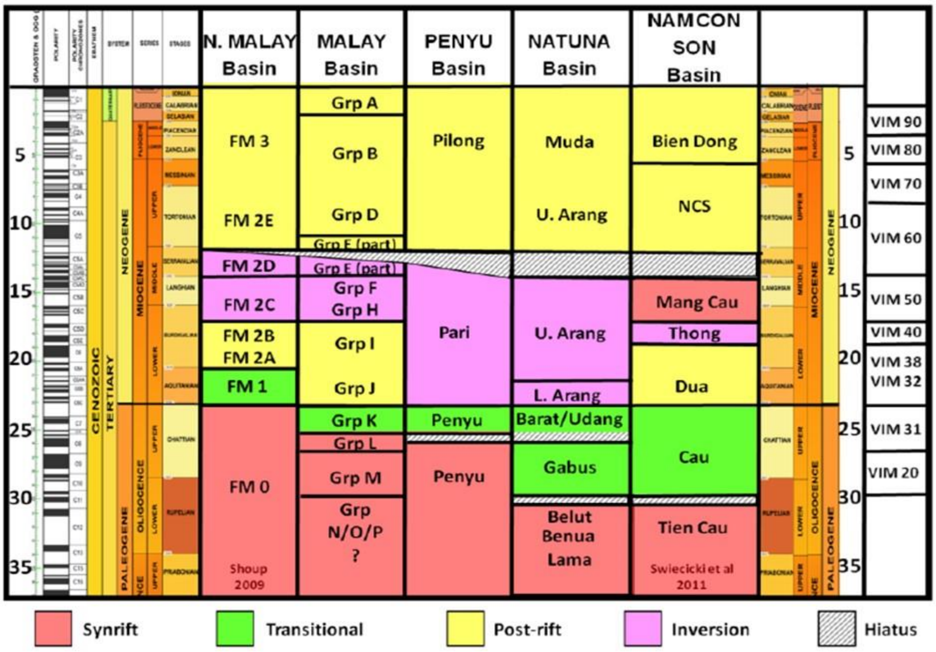

Figure 3: *Sub-basins of the Western Rim. A comparison of formations, nomenclature and aspects of stratigraphy in four SCS sub-basins – Malay, Penyu, Natuna and Nam Con Son (from Shoup et al., 2012). In the shown scheme depositional cycles from shelf to bathyal have been placed into a numeric chronostratigraphic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

in a similar way as *en-echelon* pull-a-part 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 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 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

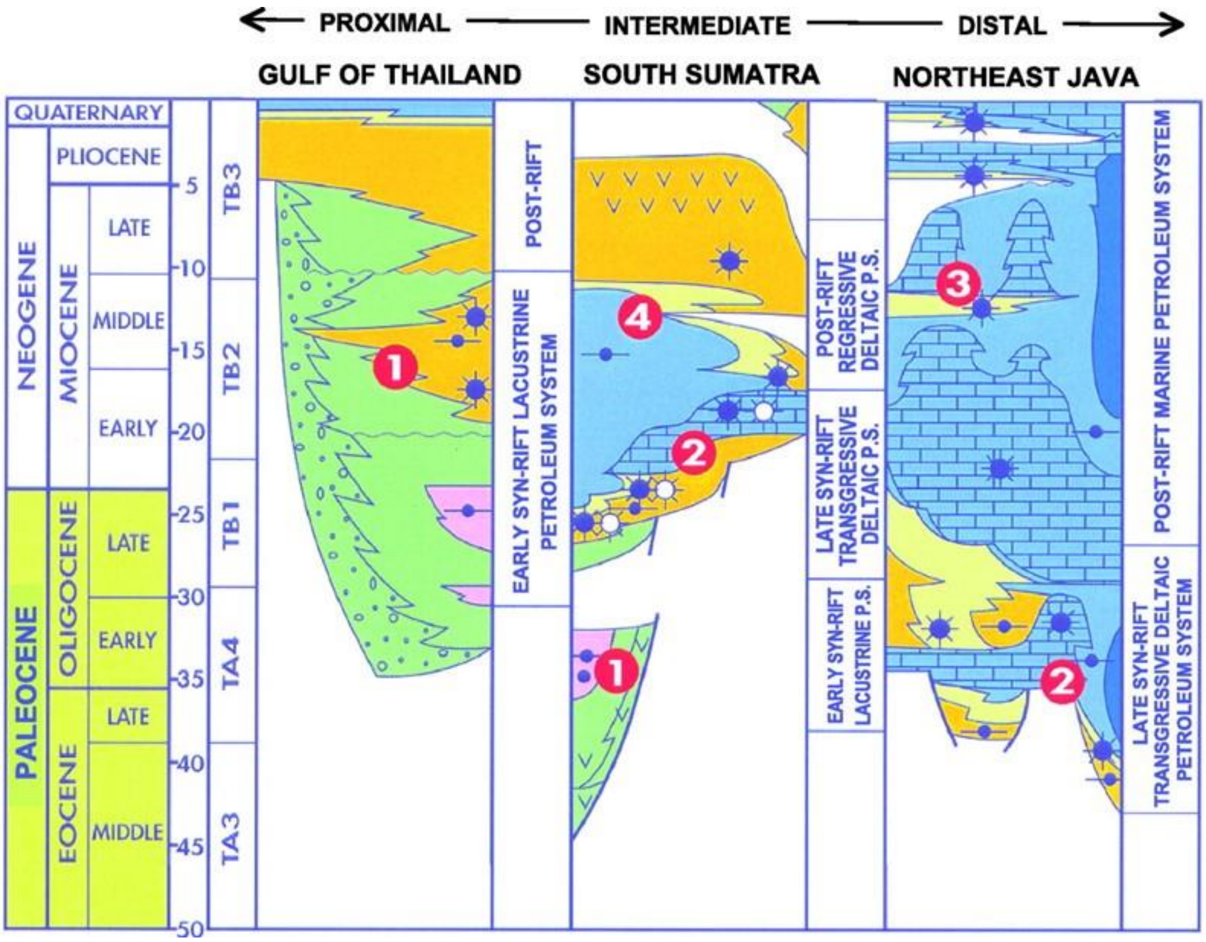

Figure 4: *Three SCS sub-basin sections located at the Western and South-western rims. Summary stratigraphy of a typical proximal basin, the Gulf of Thailand, a typical distal basin, the Northwest Java Basin and a typical intermediate basin, and the South Sumatra basin (from Doust and Sumner, 2007). 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

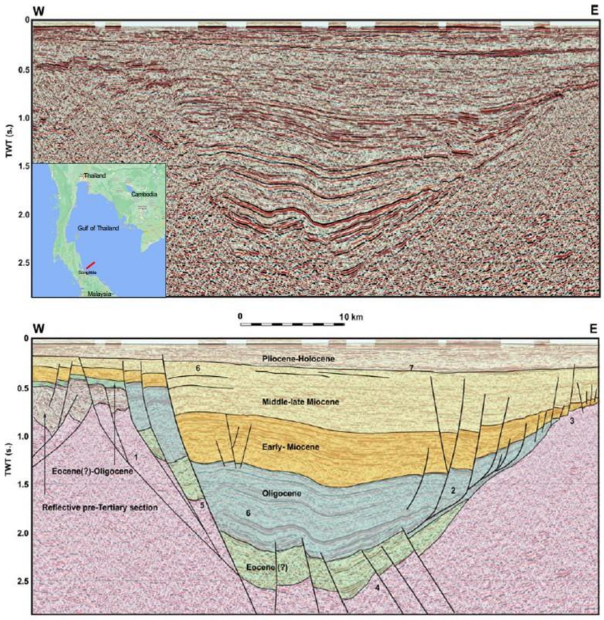

Figure 5: *Seismic traverse and stratigraphic interpretation of the Songkla Basin (location in Figure 2). It shows a bottom layer of speculative Eocene deposits (in the interpretation below), with Oligocene-Miocene forming distinctive seismic facies (from Morley and Racey, 2011). The overwhelming part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

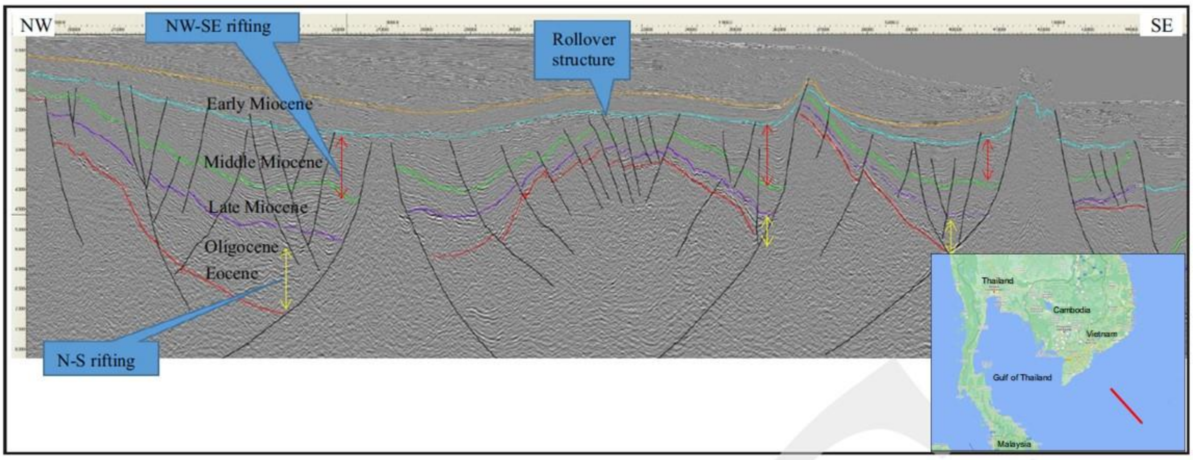

Figure 6: *NW-SE seismic line from Nam Con Son area (location in Figure 2) with stratigraphic interpretation suggesting the existence of Eocene sequences in the deep half-graben with interpreted horizon in red marked as Top Basement (from Nguyen et al., 2016).*

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

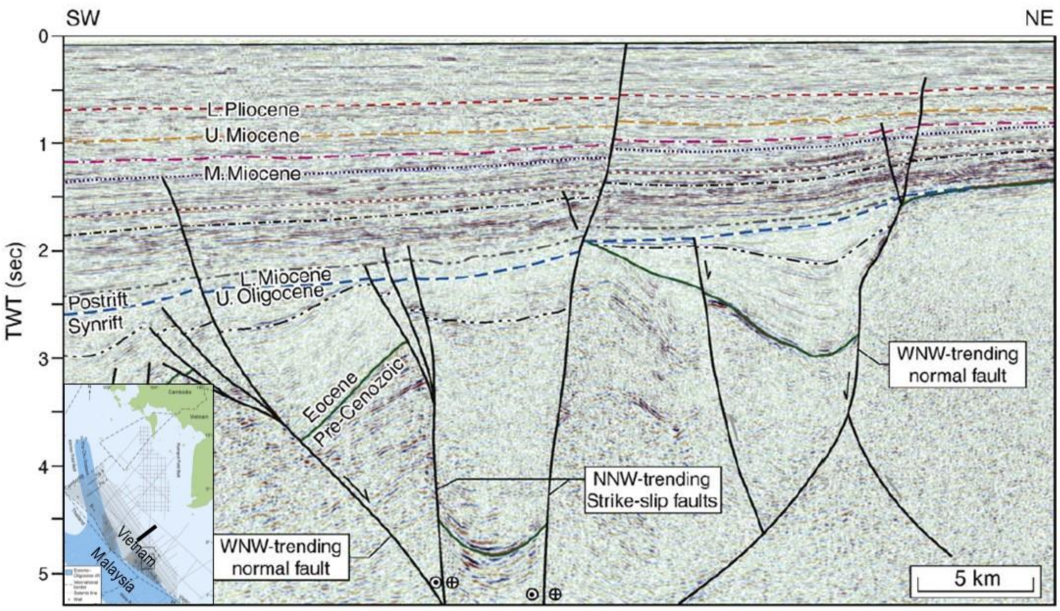

Figure 7: *Across the border from main Malay Basin (location in Figure 2), a seismic transect across a NNW-trending Paleogene graben bounded by steep strike-slip faults and half grabens confined by more gentle dipping WNW-trending normal faults that link up with the strike-slip faults at depth. The presence 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, monoclinal 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.*

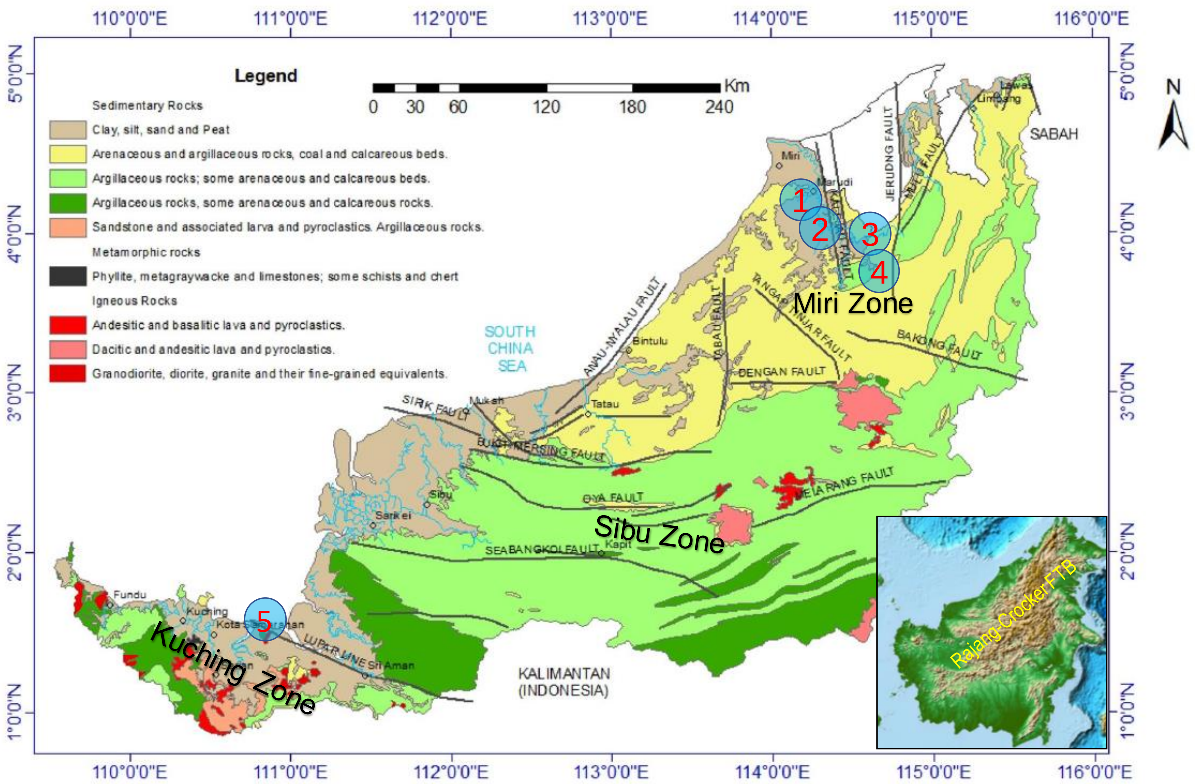

Figure 8: Lithologic map of Sarawak modified after Adepehin et al. (2019), serving as location index. Annotated are the investigated areas with Paleogene carbonates – (1) Engkabang wells, (2) Bata Gading, (3) Limbang River headwaters, (4) Mulu (Miri Zone). (5) Engkilili Formation (Kuching Zone). Marine 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, Sibu 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 approximatively 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 approximatively 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	Aquitanian	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

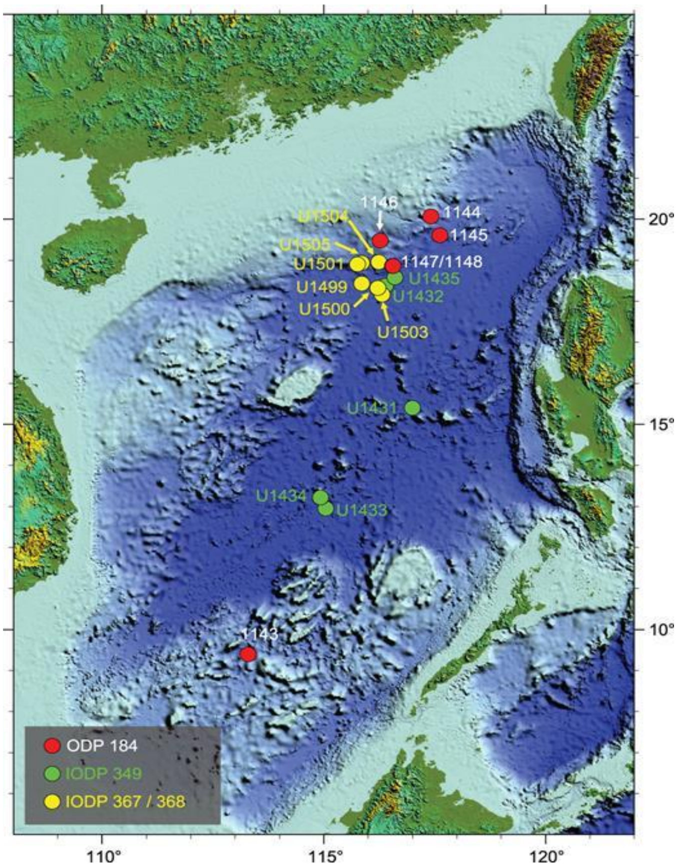

Figure 11: *Additional scientific ocean-drilling sites in the South China Sea: ODP 184 in 1999, East Asian monsoon history; IODP 349 in 2014, SCS tectonics; IODP 367/368 in 2017, IODP 368X in 2018, SCS rifted margin (from Wang et al., 2019). Note that most if not all of the scientific wells in the SCS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

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).

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

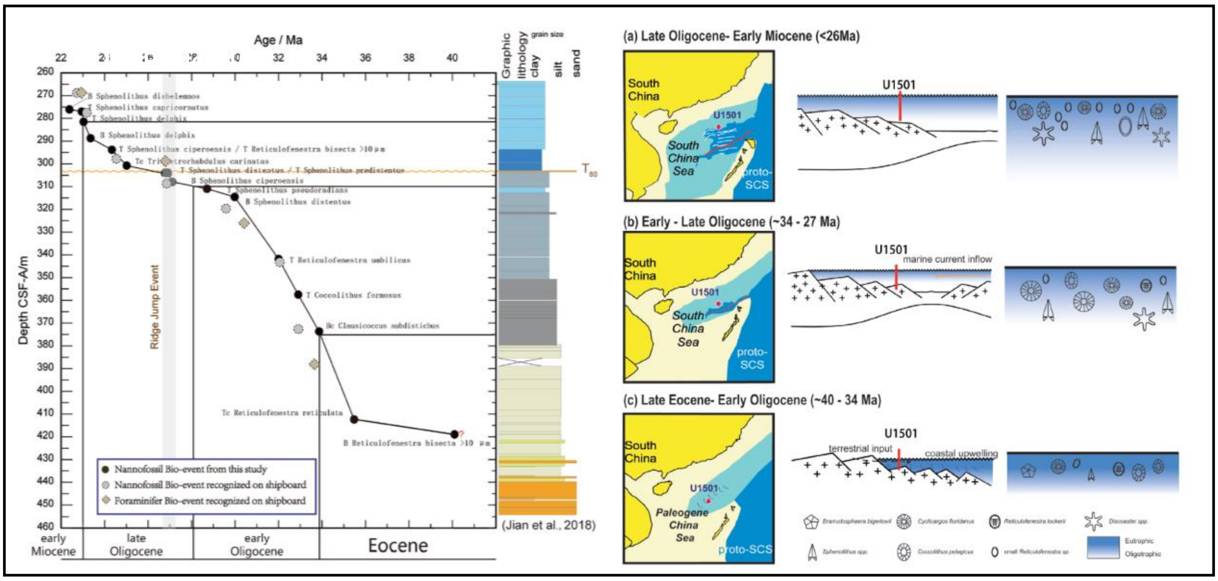

__Figure 12:__ Based on calcareous nannofossil biostratigraphy research for the Late Eocene to Early Miocene sediment section at IODP Site U1501, the regional seismic reflector T_{60} at ~26.8 Ma was dated, corresponding to the final stage of the Ridge Jump Event, which marked the onset of accelerated 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; Nantasin 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

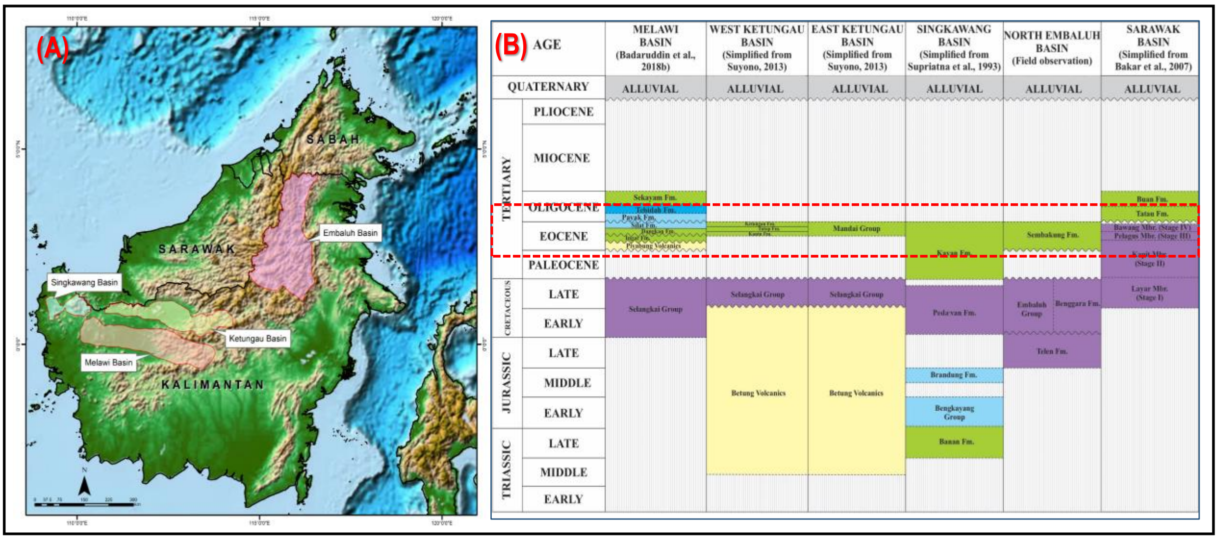

Figure 13: *(A) Location of Singkawang, Melawai, Ketungau and Embalah basins with Eocene fluvio-deltaic deposits, onshore Kalimantan Borneo. (B) Stratigraphic comparison of the four basins with Sarawak onshore basin with the equivalent Eocene Pelagus and Bawang members of Belaga Formation (modified from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

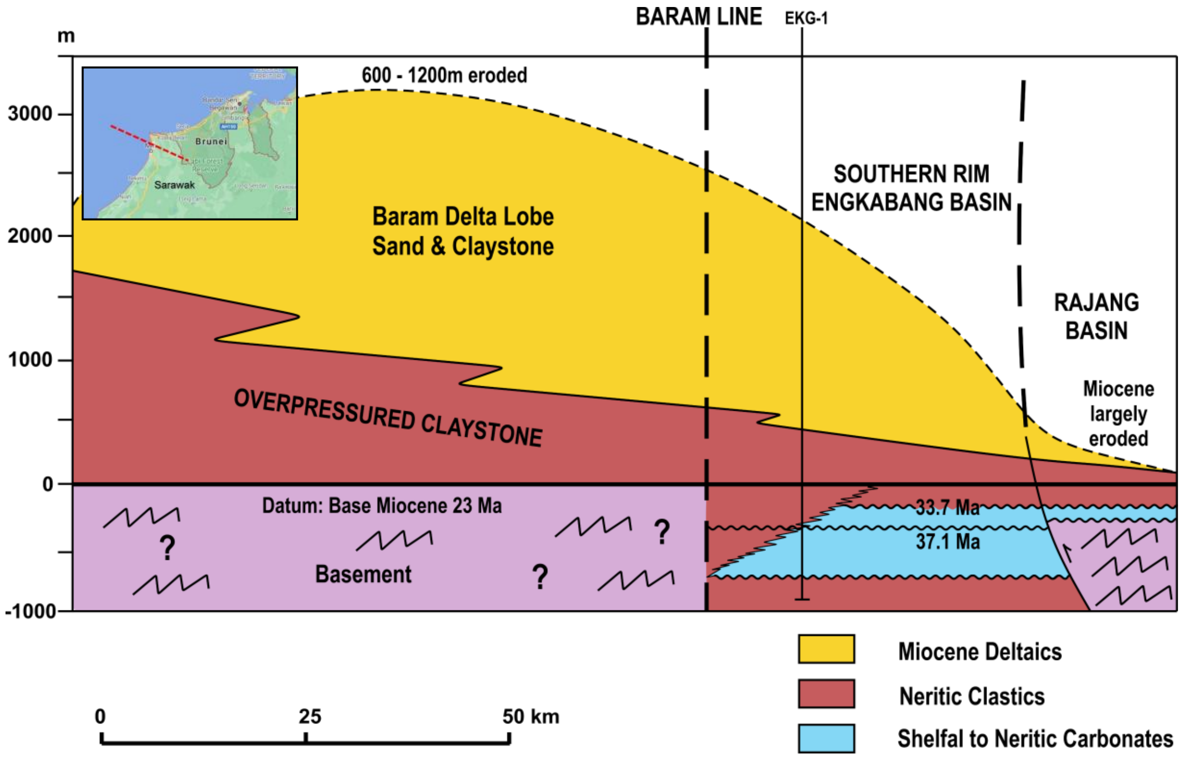

Figure 14: *NW-SE schematic section through the nearshore and onshore portion of the Sarawak Basin. The datum of the sketch is placed at the Base Miocene Unconformity (23 Ma). The section features the Engkabang sub-basin, which saw subsidence during Late Eocene time coeval with a prominent marine ingression. 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.

ACKNOWLEDGEMENT

This study is based on the expanded research of the Penyu, Malay and Sarawak foreland basins conducted over the last few years by the authors as summarized in Kessler et al. (2020, 2021). The research has benefited greatly from the discussion and published work of past and present authors who contributed to the ideas presented in this paper, and to whom we are indebted. Fruitful discussion with exploration colleagues in the petroleum industry is gratefully acknowledged, and our gratitude is also extended to our reviewers for offering constructive comments, which helped to improve the quality of this paper.

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The hidden sedimentary basin underneath the Quaternary volcanic unit in Bogor and Kendeng area

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ABSTRACT

Java Island is part of an active volcanic arc that experienced several volcanism episodes, which gradually moved from South to North from the Late Oligocene to Pleistocene, following the subduction of the Indian Ocean-Australian plate underneath the Eurasian plate. During the Eocene, the southern and northern parts of Java were connected as one passive margin system, with the sediment supply mainly coming from Sundaland in the north. During the Eocene–Oligocene, the subduction along Sunda-Java Trench created compressional tectonics that led to the formation of a flexural margin and a deep depression in the central axis of Java Island, which later acted as an ultimate deep-sea depocentre during the Neogene period. In contrast to the neighboring Northwest and Northeast Java Basins in the Northern edges of Java Island, the basin configuration in the East-West trending depression in the median ranges of Java (from Bogor to Kendeng Troughs) are poorly imaged by seismic due to the immense Quaternary volcanic eruption covers.

Five focus areas are selected for this study. A total of 1,893 km of seismic sections, 584 rock samples, 1569 gravity and magnetic measurements, and 29 geochemical samples (rocks, oil, and gas samples) were acquired during the study. Geological fieldwork was focused on the stratigraphic unit composition and the observable features of deformation products from the outcrops. Due to the scarcity of exposures of Paleogene deposits in the Central-East Java area, rock samples were also collected from the mud volcano ejected materials in the Sangiran Dome.

Manuscript received August 1st,2021, revised manuscript received August 31st, 2021, final acceptance September 18th, 2021.

DOI: 10.51835/bsed.2021.47.2.323

The distinct subsurface configuration differences between Bogor and Kendeng Troughs are mainly in the tectonic basement involvement and the effect of the shortening on the former rift basins. Both Bogor and Kendeng Troughs contain active petroleum systems with Type II /III kerogen typical of reducing environments organic material derived from transitional to shallow marine environments. The result suggests that these basins are separate from the neighboring basins with a "native" petroleum system specific to the palaeogeographical condition during the Paleogene to Neogene periods, whereas the North Java systems (e.g., Northwest and Northeast Java Basin) were characterized by oxidized terrigenous Type III Kerogen.

Keywords: Bogor Trough, Kendeng Trough, sub-volcanic, volcanic arc

INTRODUCTION

Java Island is a segment of the east-west trending Sunda volcanic arc, which begins in Sumatra and ends in East Nusa Tenggara, and continues into the Banda arc (Figure 1). The arc and thus the island elongation orientation is parallel with the trend of the subduction zone. This volcanic arc formed since the Late Oligocene due to the orthogonal subduction of the Indo-Australian beneath the Eurasian Plate (e.g., Katili, 1973; Katili, 1975; Hamilton, 1979; Hall, 1996; Smyth et al., 2005; Pubellier and Morley, 2013; Metcalfe, 2017; van Gorsel, 2018). In general, the volcanic arc consists of several episodes of volcanism that become sequentially younger northward (from Late Oligocene to Pleistocene), following northward movement and subduction of the Indian Ocean-Australian plates. This movement is also believed to create subsequent northward thrusting and

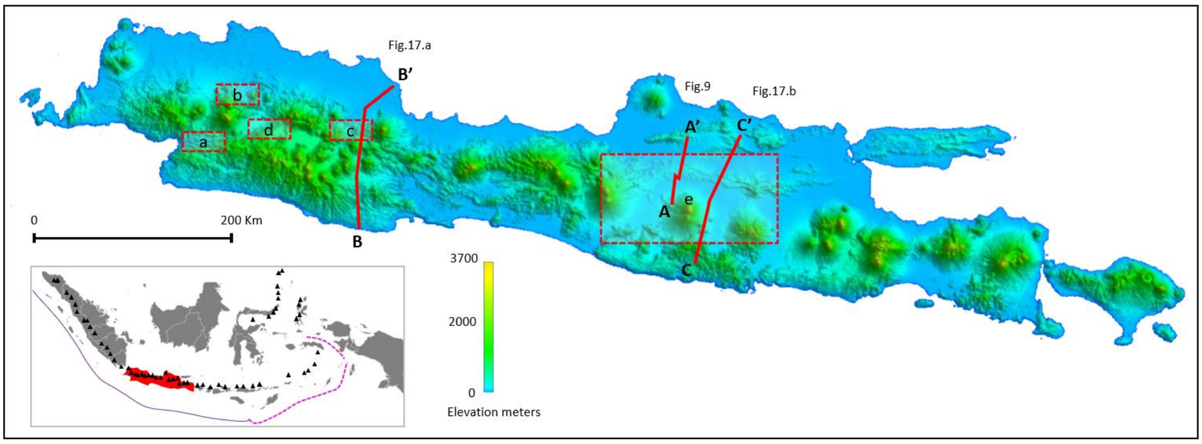


Figure 1. *One arc second resolution shaded relief SRTM map of Java Island shows a cluster of active volcanoes and immense volcanic material covers over the study area in (a) Sukabumi, (b) Bogor, (c) Majalengka West Java, (d) Rajamandala, and (e) Kendeng zone Central and East Java. The index map shows the main volcanoes chain (black triangle) and Java Island (red) in respect to Sunda Arc (solid blue lines) and adjacent Banda Arc (purple dashed lines). Line A-A' is the gravity and seismic section in Fig.9, lines B-B' and C-C' are interpreted regional geological section in Fig.17a. and Fig.17b.*

folding of the volcanic arc (Clement et al., 2009) that explicitly affects the structural style in the study area.

The basin development of the east-west trending depression in the central axis of Java (from Bogor to Kendeng Troughs) is not so well understood, in contrast with the NW and NE Java Basins in the coastal plain and adjacent offshore along the Northern edges of Java Island, which are well known and well-studied. A major challenge is seismic imaging, due to the structural complexity of the over thrusted shallow Neogene stratigraphic units, as well as the thick Quaternary volcanic cover. These deposits form an acoustic masking that makes imaging of the underlying basin configuration almost impossible.

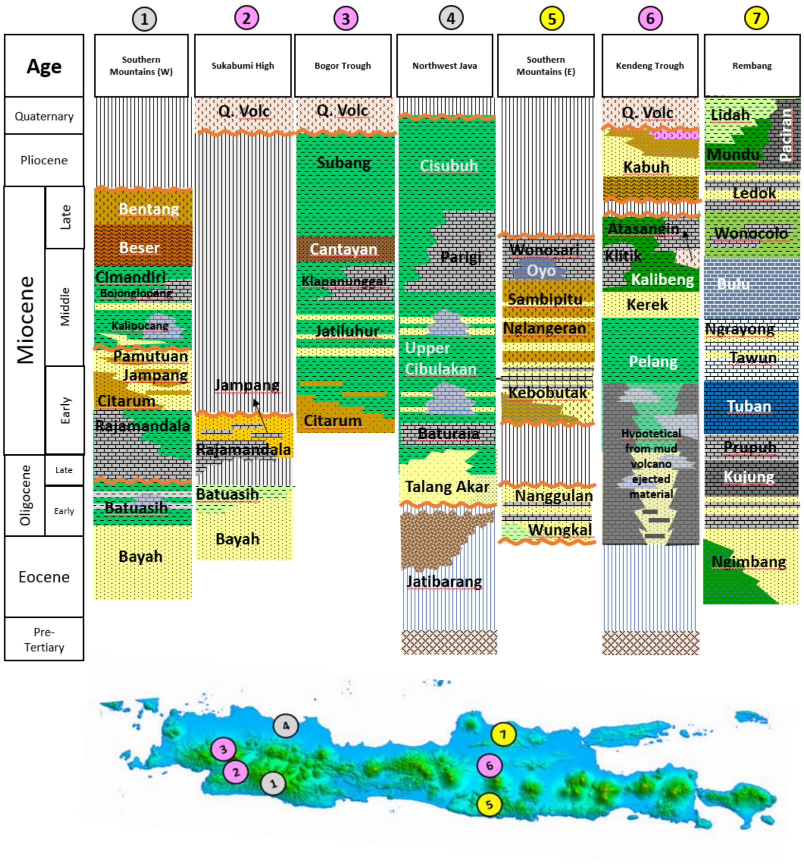


Figure 2. Regional stratigraphy of Java focused on several localities based on specific physiographic positions (see the circle number for the location and text for details)

Common oil and gas seepages are present around the northern and central parts of the island (Doust and Noble, 2008; Satyana, 2014; Doust, 2017), some of which are reported to produce quite voluminous hydrocarbons, confirming active petroleum generation in the area. Although the exact petroleum sources are unknown, this phenomenon led to the hypothesis that petroleum generation is likely derived from Paleogene stratigraphic units underneath the volcanic covers. The hydrocarbons were expelled and transferred through the southerly dipping thrust fault or via e volcanic dyke remnant pathways (Satyana, 2014). This paper will mainly discuss prospect generation in the poorly understood Java volcanic arc frontier area.

REGIONAL STRATIGRAPHY

As the flexural margin of Bogor and Kendeng Troughs formed later in the Early Miocene, for the general purposes to denote the depositional history ranging from Paleogene to Neogene, we use the terminology of Bogor zone and

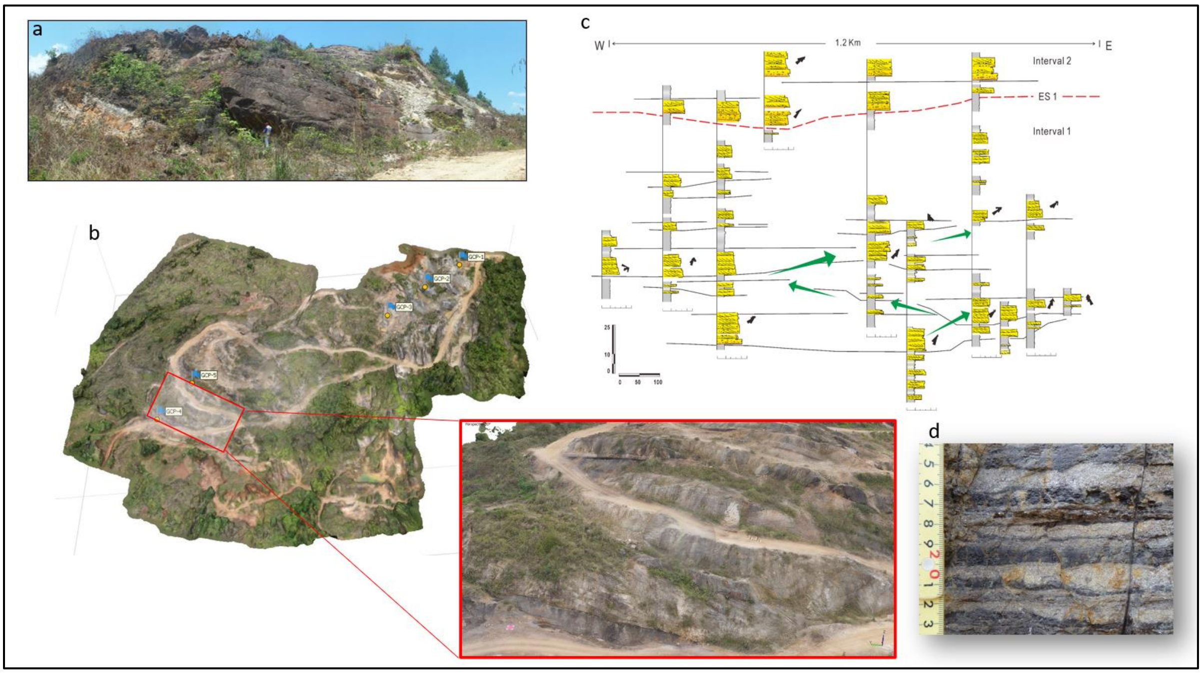


Figure 3. *The Bayah Fm. outcrop in the Cibadak and Sukabumi High area shows stacking of Paleogene (Eocene to early Oligocene) fluvial channels with a total thickness of 915 meters. a) the most upper part of the fluvial unit shows a typical single channel story with a thickness of 9-11 meters. b) The digital outcrop models (DOM) of the fluvial sand exposure in the Kadupugur quarry area, near Cisaat with the inset taken parallel to the bedding, shows a lateral accretion package (LAP) with the paleocurrent direction toward the southwest. c) the interpretative measured section log correlation in Sekarwangi outcrop showing the channel migration evolution mainly toward south-southwest and few to south southeast direction suggests the major fluvial flow direction southward. d) The interbedded shale with a typical lacustrine deposit character. This shale unit contains abundant freshwater algae (see also Figure 4) and has a high total organic carbon content (Adhiperdana, 2018; UNPAD – Pertamina, 2020).*

Kendeng zone. This section will focus on the stratigraphic succession in the Bogor and Kendeng zones compared to neighbouring basins or sub-basins (Figure 2).

The oldest rocks found in three complexes in the southern part of Java Island are Mesozoic metamorphic rocks, grading from phyllite to schist and gneiss. The age extracted from zircon dating from schist or eclogite ranged between 124-102 Ma in the Luk Ulo complex, 98 Ma in the Jiwo Hills and 55-38 Ma in the Ciletuh area (Satyana, 2014). These rock units are mostly buried and only exposed in limited areas such as Bayat, Karang Sambung, Bayah, and Ciletuh and are overlain by Paleogene or Neogene deposits elsewhere.

West Java

During the Eocene epoch, the West Java area was dominated by fluvio-lacustrine to the fluvio-deltaic depositional system of the age-equivalent Bayah and Walat Formations (Fm.). The Bayah Fm. is

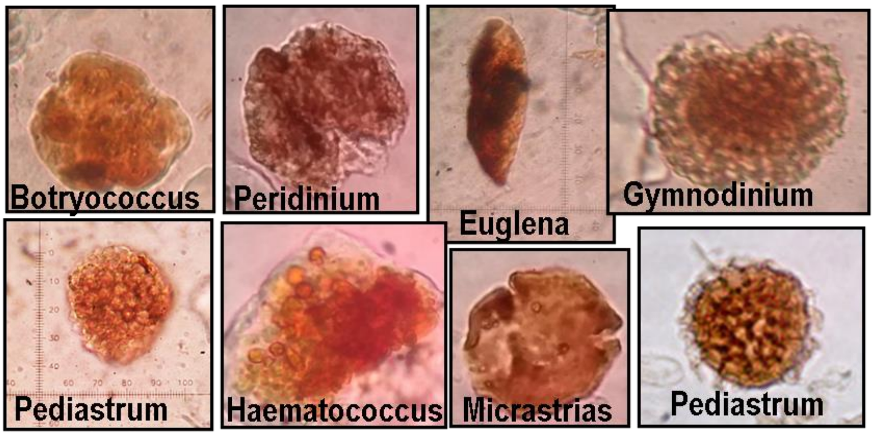


Figure 4. *The freshwater algae from Eocene Bayah Fm. shale suggest periods of lacustrine deposition occasionally occurred during the fluvial deposition period (UNPAD – Pertamina, 2020).*

found in several localities in the Sukabumi high area and is dominated by quartz sandstone, barren in marine fossils with some occurrences of spores and pollen, indicating a Late Eocene age in the lower part from palynological zonation of *M. nayarkotensis, P. operculatus* and *P. kutchensis* (Morley, 2012) and Early Oligocene from *F. trilobata, M. medius and V. usmensis* (Baumann et al., 1973; Martodjojo, 1984) in the upper part. The outcrops in the Cibadak area, Sukabumi reveal a stack of the thick fluvial deposits of up to 915 meters thick, with a significant paleo-current direction toward South-Southwest and Southeast suggest the deposition of the major fluvial system from North to South (Adhiperdana, 2018) (Figure 3a-d). Some intra-fluvial successions show a typical lacustrine character with layered shale units (Figure 3d) containing many freshwater algae such as *Botryococcus*, *Peridinium, Pediastrum, Haematococcus, Euglena*, and *Gymnodinium* (Figure 4). The interbedded fine-grained units in this formation also contain organic-rich coaly beds and shales units.

In the upper interval, the Bayah Fm. was capped with transgressive shale and marl of the Batuasih Fm. which is dominated by calcareous mud with locally interbedded clastic and patchy limestone. This formation has marked the end of the terrestrial depositional period of Bayah Fm., which was dated around nannoplankton zone CP18 and planktonic foraminifera zone P19 (within Early Oligocene) (UNPAD-Pertamina, 2020).

The Rajamandala Fm. limestone growth in the Late Oligocene generally consists of two major depositional sequences, namely layered pack stone to boundstone with a local reef mound in the lower interval, which gradually changes upward into deeper marine facies of marl and calcilutite. This formation becomes deeper northward (Koesoemadinata and Siregar, 1984), likely controlled by the paleo-high configuration during the reef growth. The benthic foraminifera analysis indicates that this formation is deposited in inner to middle neritic environments (e.g., Irwansyah et al., 2011; Sekti, et al., 2011; Wibowo and Kapid, 2014; Gani et al., 2020).

Central and East Java

Rapid subsidence marked the Neogene period in the middle of Java Island. The

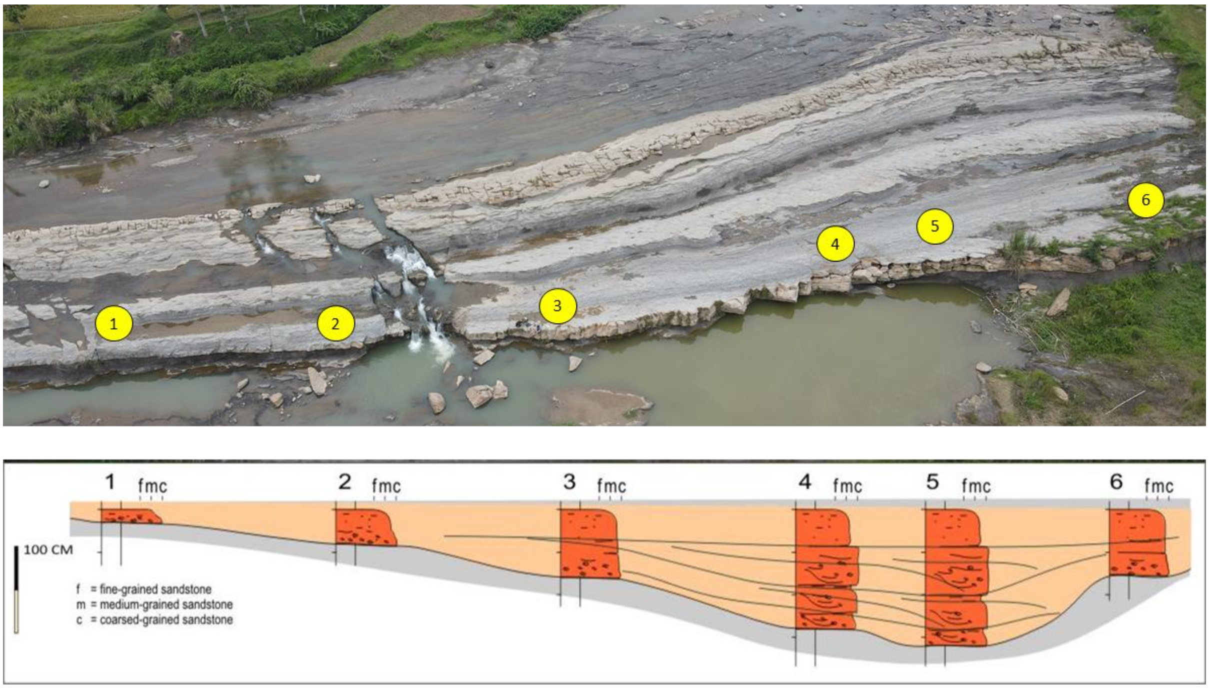


Figure 5. *The drone photograph of the deep-water deposit in Jatiluhur Fm. in Cipamingkis River shows blocky and sheet-shaped characters consistent with Bouma turbidite sequence Ta and Tb. The deposit was 70 meters long and showed a wedge out termination leftward (Southwest direction). This outcrop was interpreted as a coarse-grained slump scar deposit. (Abdurrokhim, 2017; UNPAD – Pertamina, 2020).*

trough deepening was initiated during the early Miocene and was followed by the deposition of deep-sea sediments including the volcaniclastic-rich Jampang Fm. and Citarum Fm. in the Sukabumi high and Bandung areas, then continued by Jatiluhur Fm. in the Bogor area and the Cinambo Fm. in the Majalengka area (Muljana et al., 2012) (Figure 5). The volcaniclastic rich materials show the possible mixed provenance from the older volcanic arc in the Southern Mountains area (Hall and Smyth, 2008; Waltham et al., 2008; Seubert, 2015). The succession gradually changes to the relatively shallow marine environment upward where the limestone of Klapanunggal Fm. developed. The rock unit consisted of coral boundstone and rudstone, skeletal rich grainstone, and locally interbedded wackestone and packstone layer (Abdurrokhim, 2017). This formation growth was taking place in Late Miocene (Martodjojo, 2003).

The Paleogene unit interval was absent, and the occurrence of them in the Kendeng zone surface area remained a mystery. The oldest exposed outcrop accessible for this study is Early to Middle Miocene neritic to upper bathyal Pelang Fm. which consisted of interbedded marl and calcareous sandstone. This formation is only exposed in a limited area at the Juwangi, Pelang River, and surrounding area. The thick marls with a thin bed of calcareous globigerinid-rich sand were found in the Juwangi area and interpreted as shallow marine deposits with a local internalite deposits bed (e.g., in Warren, 2018) (Figure 6a-f). The oldest planktonic

Foraminifera zonation using *G. kugleri* as index fossil and shows an age of N3-N5 (Late Oligocene to Early Miocene). The depositional environment was predicted as lower neritic to upper bathyal environmental.

The mud-volcano ejects material in one location in Sangiran Dome, Surakarta, shows the strong evidence that the older Paleogene sediment exists below the Pelang Fm. The hand specimen observation shows that the ejected rocks had a similar characteristic with Nanggulan and Bayat Fm. Clastic carbonate with Eocene large foraminifera including *Nummulites* like those exposed in the Bayat area is present, together with other older rocks such as conglomerate and metamorphic rock. Although this older unit's existence and configuration in the subsurface are questionable, hypothetically, these Paleogene units were believed to be distributed widely in the lower stratigraphic interval in the Kendeng area.

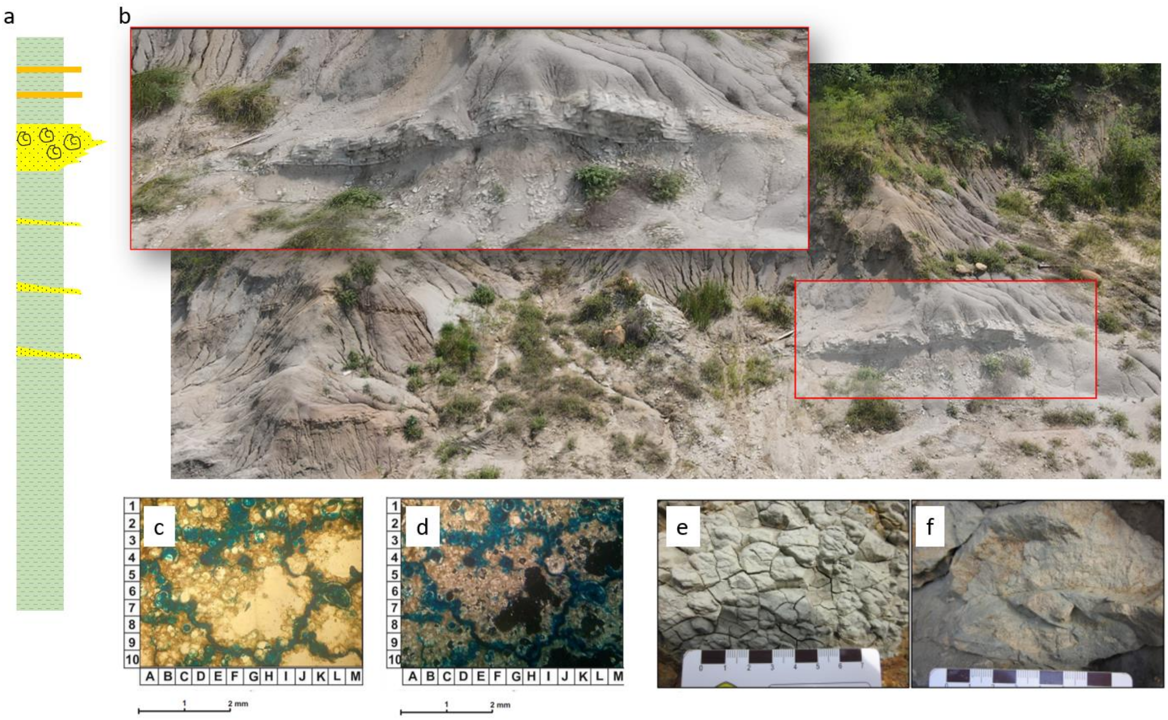


Figure 6. *The Early to Late Miocene Pelang Fm. shows a thick structureless mudstone and marl layer; in the upper section, the thin laminae of evaporite deposit (anhydrite) were found and interpreted as sequence boundary where this unit was once exposed sub-aerially (a). b) the digital outcrop model (DOM) of the outcrop near the provincial road in the Juwangi area, the outcrop length is 70 meters with a total thickness of 20 meters. The inset shows that the globigerinid sand layer in the lower right image is 1.5 to 2 meters thick. The sand layers show a paleocurrent with southeastward direction c) the parallel nicol and d) cross nicol of the photomicrograph of the globigerinid sand layer shows a relatively southeast oriented of the fossil grains interpreted to be formed in the high energy regime such as tidal channel or perhaps internalite deposits? (e.g., in Warren, 2018) e) the marl specimen shows the structureless character with some burrows. f) the globigerinid sand specimen could be classified as packstone.*

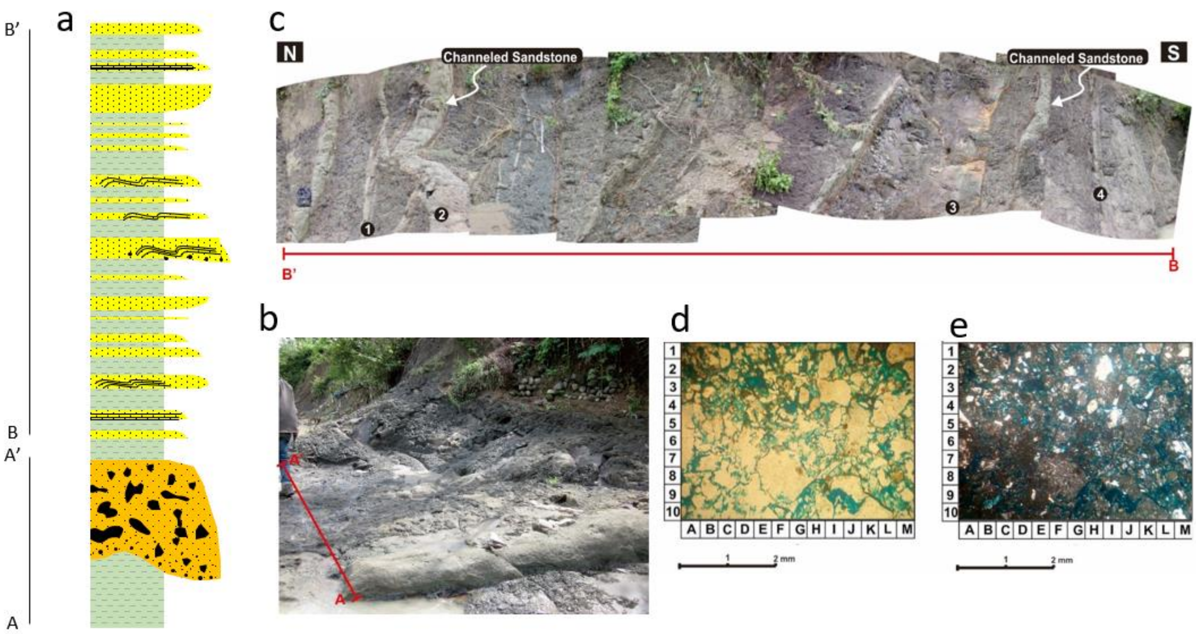


Figure 7. *The middle Miocene Kerek Fm. shows alternating sandstone and shale layers. The measured stratigraphic logs (a) showing an interbedded debris flow deposit in the lower part of the section with a coarse fragment (boulder to pebbles size) deposit as an initial stage sequence, e.g., as a traction carpet in the base of deposition (b). c) The upper section showing a classic Bouma turbidite sequence Ta to Tc coarse to fine-grained sand layer (20-40 cm in thick). d) the parallel and e) cross nicol photomicrograph showing a mixed provenance between quartz and volcaniclastic materials suggest the multi-directional provenance from the north (Sundaland) and south (southern mountain range).*

The carbonate development is intensified in most areas during the transgression periods in Oligocene to early Miocene, followed by the rapid depositional of the deep-sea sediment of Kerek Fm. to Kendeng Trough during a short period in the middle Miocene. The volcaniclastic rich materials confirmed the possible mixed provenance between the quartz arenite dominant provenance from the Sundaland continental margin and the lithic and volcanic rich provenance from Southern Mountains area (Hall and Smyth, 2008; Waltham et al., 2008; Seubert, 2015). The Kerek Fm. consists of interbedded shales and sandstones with some locally calcareous shale layer and conglomeratic layer shows a classical turbidite succession consistent with Bouma sequence Ta-Tc (Figure 7a-e). This formation age is around N13 – N20 or Middle Miocene to Early Pliocene. stratigraphic succession gradually changes to the shallower marine environment upward in Late Pliocene with Klitik and Kapung limestone member in the Kendeng Trough. The formation consists of interbedded mudstone, marl, and calcareous sandstone.

In contrast to the Bogor and Kendeng areas, during the early to middle Miocene, the NW and NE Java Basins became part of a stable shallow shelf area with the deposition of Cibulakan and Parigi Formations in the west and a succession of thick carbonate growth such as Tawun, Bulu, and Ngrayong in

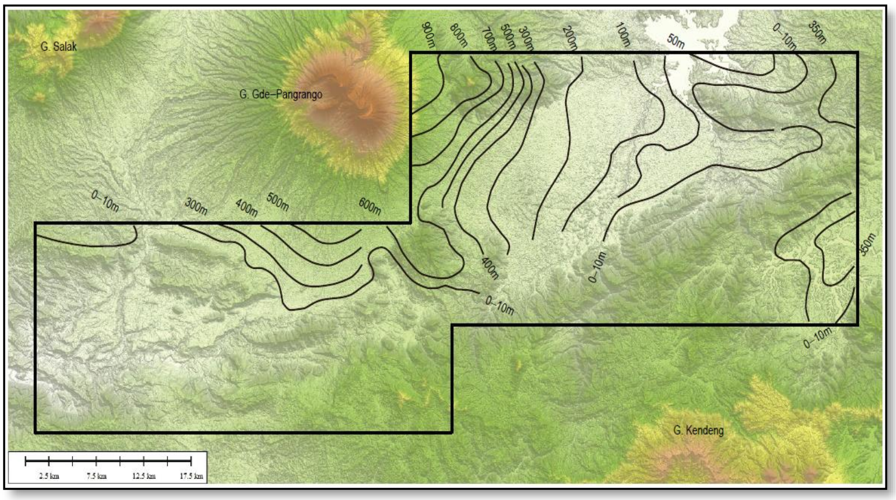


Figure 8. *The extrapolated volcanic covers map is estimated from various data collection such as topographic data, direct outcrop measurement, and water well data, for example, from Mt. Gede-Pangrango foothill, Sukabumi area, contour interval: 100 meters (UNPAD-Pertamina, 2020).*

the NE Java Basin (Simo, 2011; Lunt, 2013; Lunt, 2019).

DATA AND METHODS

Our research study integrated the surface geology sampling and measurement, exploratory subsurface data, geochemical analysis, basin modelling, newly acquired field gravity, magnetic data, and previously available gravity and magnetic data. Four (4) research window areas in West Java and one large extent research window in Central-East Java have been selected. A total of 1,893km measuring sections, 584 rock samples (petrography, micropaleontology, and reservoir rock characterization), 201 stations gravity data, 269 stations magnetic data, and 29 geochemical samples (source rock pyrolysis, oil and gas chromatography, and gas isotope) were acquired during the study. The preserved paleo-current in several exposures (e.g., Bayah Fm., Kerek Fm., Jatiluhur, and Cinambo Fm.) were used to identify the main flow direction, dispersal pattern, geometry, and paleogeographic condition during the deposition period.

The volcanic covers were estimated and measured from compiled data collection such as topographic map, direct measurement in outcrop, or the report from water well rock description in the surrounding urbanized area in the west of study area (UNPAD-Pertamina report, 2020) (Figure 8).

The horizontal and vertical gradient/derivative analysis was performed on field gravity data to clarify the boundary of the sources signal, whether it is caused by a structural boundary (low frequency) or internal basin configuration (high frequency) in Kendeng Trough. The 2.5D geomagnetic modelling was performed by integrating field observation data, surface geology information, fold-thrust conceptual model. The block model construction iterative by trial and error considers the variation of misfit between observed vs. calculated data.

The old exploratory wells and seismic section were used for reference. Geological fieldwork was focused on the stratigraphic unit composition and the observable features of deformation products from the outcrops. We used biostratigraphy, petrography, and paleocurrent analysis to verify the stratigraphy framework's consistency. Due to the Paleogene deposit exposure scarcity in the Central-East Java area, the rock samples were also collected from the mud volcano ejecta materials area for advanced study. Due to the subsurface geochemical data limitation, where there are only two wells available (Toto-1 and Ngawi-1 in East Java area), some parameters such as TOC, HI and Ro are extracted from surface geochemical samples and calibrated to the designated generation depth.

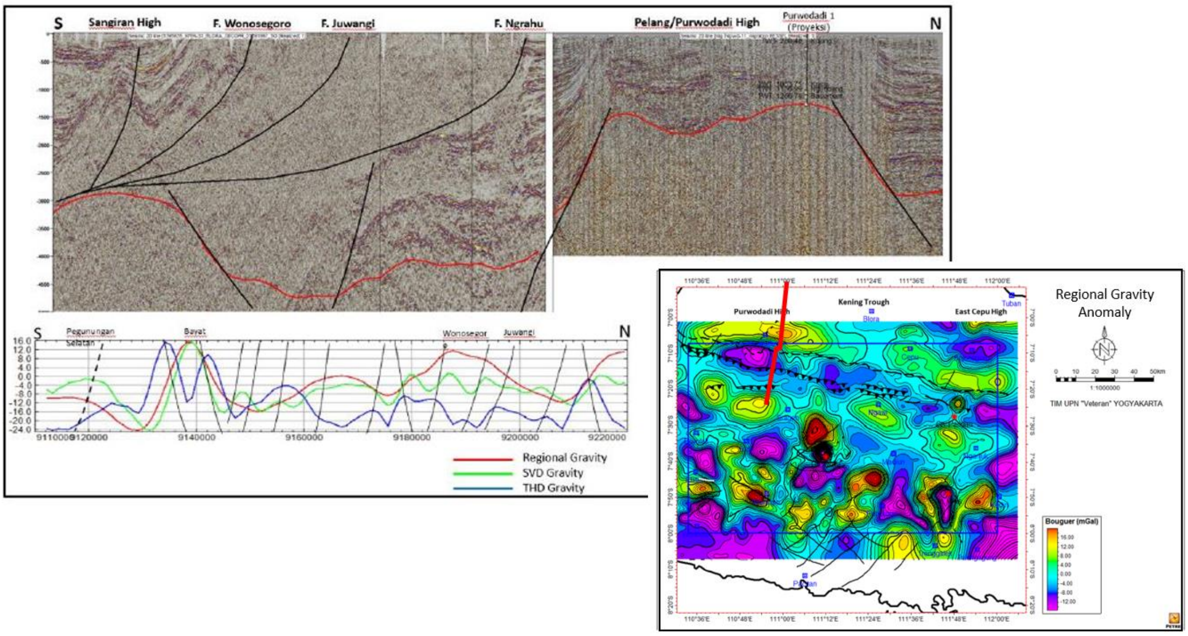


Figure 9. *The surface geological measurement integrates seismic data and existing and newly acquired gravity and magnetic data to reconstruct the basin configuration models in Kendeng Trough, Central - East Java. Index map shows the most updated (2020) regional gravity anomaly data (UPNY-Pertamina, 2020). The red square is the seismic coverage area. See Fig. 1 for the location.*

in the Sangiran Dome area. The comprehensive surface and subsurface data integration are expected to conceal the inferred volcanic covers, structural styles, and sub-basin configurations model (Figure 9).

Furthermore, this model will be used to reconstruct the regional palinspastic section (Figure 10). The 1D and 2D basin modelling approach was used to localize the most favorable prospect

RESULTS AND DISCUSSION

Field Geology and Structural Reconstruction

Bogor Trough: The stratigraphic succession is characterized by a very thick (up to 1000m in outcrops) transgressive sequence from Bayah Formation (Fm.) fluvial deposits in the lower part overlain by conformable paralic deposits of Batuasih Fm. and carbonates facies of Rajamandala Formation.

Bayah Fm. consists of thin to very thick-bedded coarse-grained sandstone, mudstone, and carbonaceous mudstone layers. Some organic matters contain freshwater algae and wooden fragments. Those Paleogene deposits were overlain by a very thick Neogene Volcanoclastic deep-water succession with southward and northward paleocurrent directions indicating multi-directional sedimentation. This process possibly resulted from a big tectonic uplift event that might be responsible for creating the flexural trough and the peripheral paleo-high area (Figure 10).

<u>*Kendeng Trough:*</u> Contrary to the West Java area, the Paleogene stratigraphic unit was absent in outcrops. They could only be found scarcely outside the study windows (e.g., Karang Sambung, Bayat, and Nanggulan).

The oldest stratigraphic unit found in this study window is Pelang Fm. that consists of marl and alternating thin laminae of calcareous sand. The upper section shows a widespread thick deep-sea depositional system of Kerek Fm. consisting of volcanic rich medium to fine-grained sandstone bed alternating with silt and shale. The Kalibeng Fm. is deposited with a dominant marl and shale deposition on the top section with intercalated limestone of Kapung and Klitik Member.

<u>*Structural reconstruction:*</u> Bogor and Kendeng Troughs' significant differences are in the basement and

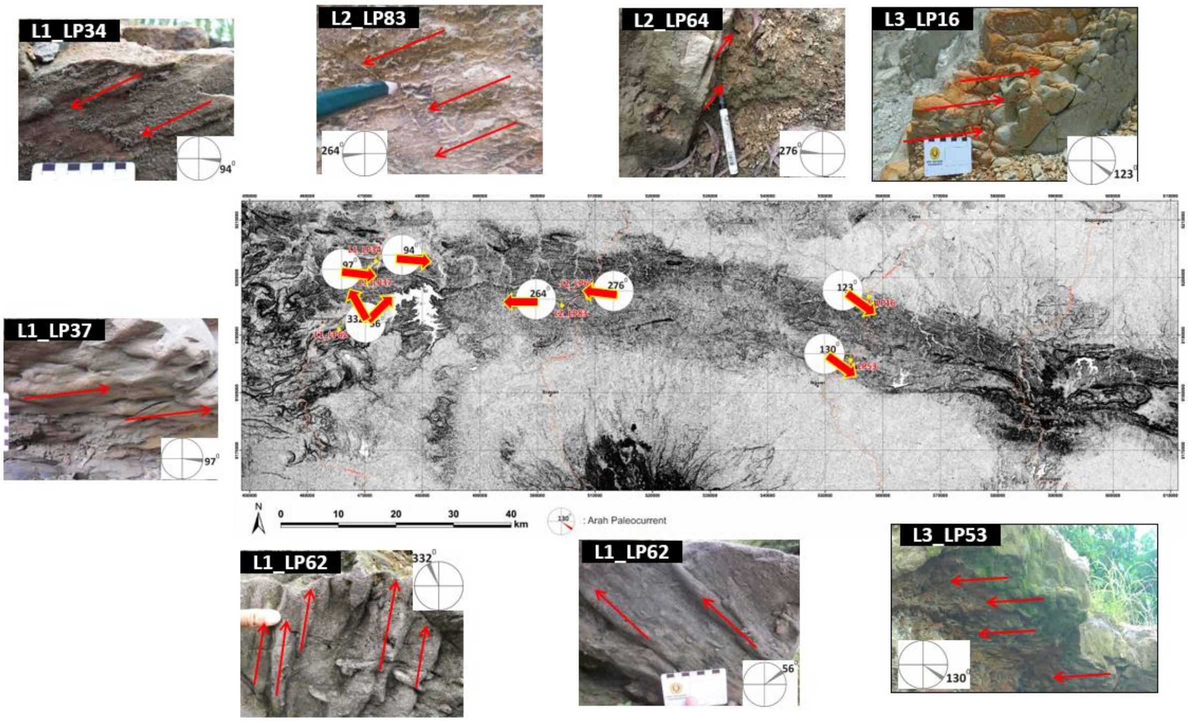


Figure 10. *The paleo-current measurements in the Kerek Formation, Kendeng Trough, shows a multi-directional sediment source that suggests the pre-existing topography during Kendeng Trough deposition in Middle Miocene.*

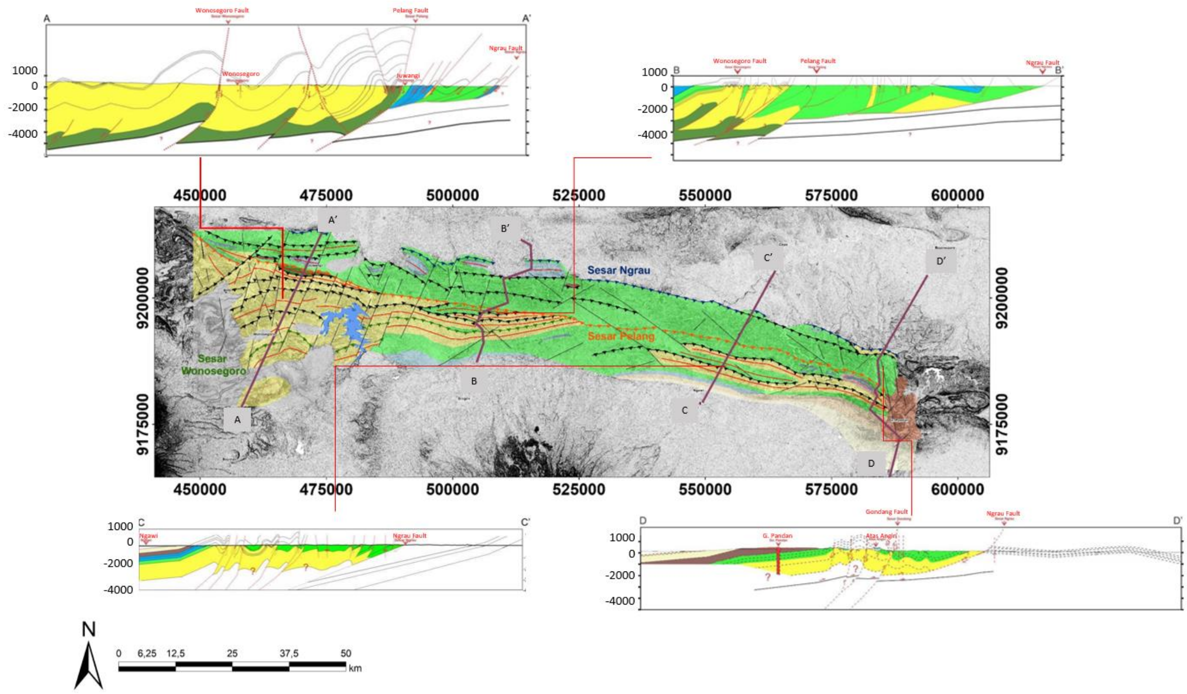


Figure 11. *The structural reconstruction in Kendeng area based on surface geological data measurement combined with the subsurface integration of gravity, magnetic and regional seismic data (UPNY-Pertamina, 2020), grey: volcanic covered area, dark green: Pelang Fm, yellow: Kerek Fm., light green: Kalibeng Fm. and teal: Klitik Fm.*

Paleogene unit thrusting involvement. The palinspastic reconstruction shows that the sediment unit in the West Java section is more intensively shortened than the East Java section. The rifting followed by the thrusting phase is common and observed throughout the southern and central median of Java Island (Satyana and Purwaningsih, 2003; Yulianto et al., 2007; Satyana, 2016). The structural observation and reconstruction in Bogor Trough demonstrate the semi thin-skinned model where the basement act as a decollement and thrusting has overprint the initial rifting phase especially in the northern part, adjacent to the deep-water margin, thus forms an inseparable structure configuration. Kendeng Trough, on the contrary, shows an opposing thick-skinned geometry model with an involved basement fold-thrust belt and shows the remaining rifting phase remnants with thrust sediment packages above it (Figure 11 and 17).

Geochemical Analysis and Basin Modelling

The oil and gas seeps in the northern and median part of Java Island suggest the hidden active petroleum system underneath the volcanic covers. The hydrocarbon seepages are manifested to the surface from the middle of the depocentre, likely via the conduit from southerly dipping thrust or volcanic intrusions. The organic richness, oxygen index, and maturity plot versus the hydrogen index suggest that most of the samples taken in Bogor or Kendeng Troughs are derived from Type II/III kerogen suggesting the terrestrial transition source rock origin.

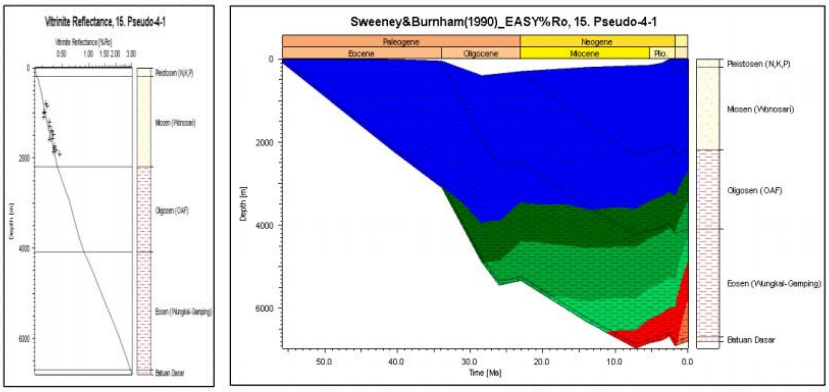


Figure 12. *The geochemical modelling in Kendeng Trough; see text for the explanation. Color legend: blue: immature (0.00-0.55), dark green: early oil (0.55-0.7), green: main oil (0.7-1.00) Light green: late oil (1.00-1.3), red: wet gas (1.30-2.00), orange: dry gas (2.00-4.00).*

The source rocks pyrolysis data from Bogor Trough (Bayah Fm., Batuasih Fm., and Cinambo Fm.) shows a fair to good total organic content (TOC) of 0.9-2.7 %, low hydrogen index (HI) of 3-280 mg HC/gr TOC, indicating the ability of the petroleum system to generate gas. The Tmax value ranges between 429–476 °C, suggests the immature to the early mature stage of hydrocarbon generation. A lower result was observed in Kendeng Trough (Pelang Fm.), where the TOC range is 0.22-0.72 % (poor to fair), Tmax value between 259 – 423 °C, and very low HI of 19-265 mg HC/gr TOC. This suggests that the hydrocarbon should have come from older unit than the Pelang Fm. The maturity analysis from both Bogor and Kendeng Troughs indicates that the hydrocarbon most likely were derived from Eocene stratigraphic unit eq. Bayah Fm. in Bogor Trough and eq. Wungkal-Gamping or Nanggulan Fm. The basin modelling in Kendeng Trough suggests that the early oil generations ranged between 29-22 Ma (Late Oligocene to Early Miocene) and then reached the peak oil generation in approximately 14.5-10 Ma (Middle Miocene) and gas generation in 2-1.5 Ma (Pleistocene) (Figure 12).

Bogor and Kendeng Trough vs NW and NE Java Basin Source Rocks

The source rock pyrolysis and oil and gas chromatograph from both Bogor and Kendeng Troughs indicates the kerogen Type II and III typical to

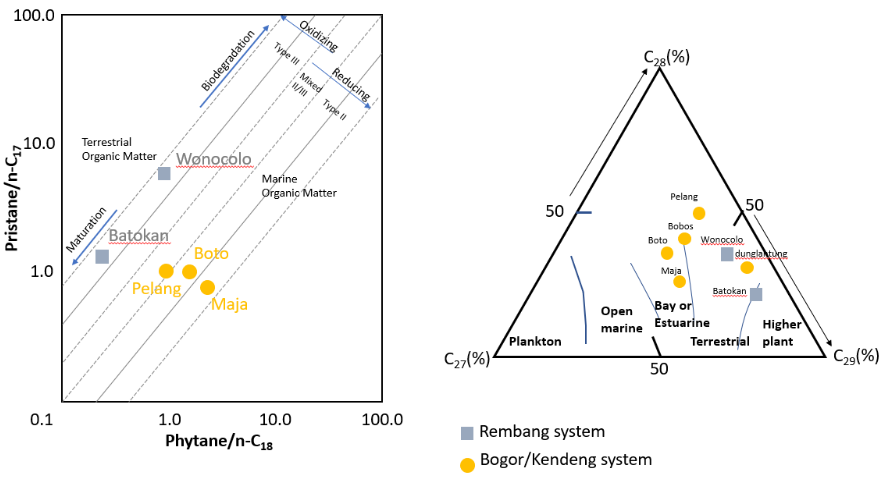


Figure 13. *The Pr/n-C17 vs Ph/n-C18 plots (left) Huang and Meinschein plot of relative amounts of C27, C28 and C29 regular steranes in oil samples as an environmental indicator (right).*

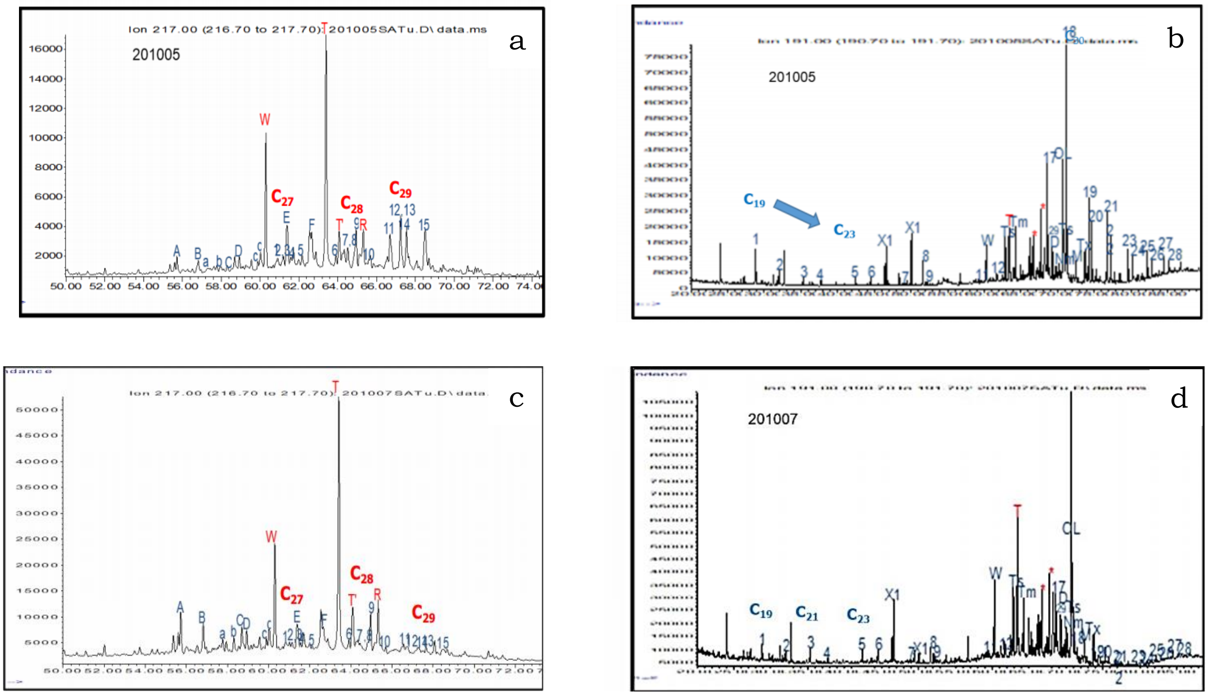


Figure 14. *The comparison between sterane m/z 217 (left) and triterpane m/z 191 (right) fingerprints between Wonocolo well, Rembang zone (above), and Boto seepage, Kendeng Trough (below) (see text for the explanation).*

transition or shallow marine environment. Sample from Boto oil seep (Kendeng zone) shows a high bicadinane with a balanced number of C_{27} vs C_{29} suggest the mixed of terrestrial and transition origin. The equal high of C_{19}, C_{21}, and C_{23} also suggest the strong marine influence (Peter and Moldowan, 1993), where the complete hopane family of C_{19}-C_{35} exhibits the transition environment origin (Figures 13 and 14). The ternary plot of relative amounts of C_{27}, C_{28}, and C_{29} regular sterane in oil samples (Huang and Meinschein, 1979) also supports the above interpretation and suggests that the Kendeng and Bogor Troughs samples are plotted more to the transition depositional environment (Figure 13).

The above result is slightly different from the fingerprint gas chromatography from the Rembang zone, Northeast Java Basin. The chromatograph shows the n-Alkane peak in C_{19} presumably is dominated by freshwater algae organic matter. The cross plot between Pr/n-C_{17} vs Ph/n-C_{18} as an environmental and maturation indicator specifies the Type III Kerogen in a relatively oxidized environment, most likely terrestrial in origin (Figure 13). The gas isotope data shows that the NE Java samples are likely less mature if compared to the Kendeng and Bogor Trough samples. The chromatograph from Wonocolo well, although similarly high in bicadinane, likely shows a higher number of C_{29} with low diasterane, suggesting a terrestrial source origin with poor anoxic clay source rocks (Figure 14).

GROSS DEPOSITIONAL ENVIRONMENT

The hypothetical Gross Depositional Environment (GDE) model was reconstructed based on the integration of the available datasets and literature (Hall et al., 2007; Hall and Smyth, 2008; Lunt, 2013; Lunt, 2019,) with a specific focus area in the Bogor and Kendeng Troughs zones (Figure 15 a-c). We subdivided the major palaeogeographical events into three (3) major stages: Eocene, Late Oligocene, and Middle Miocene.

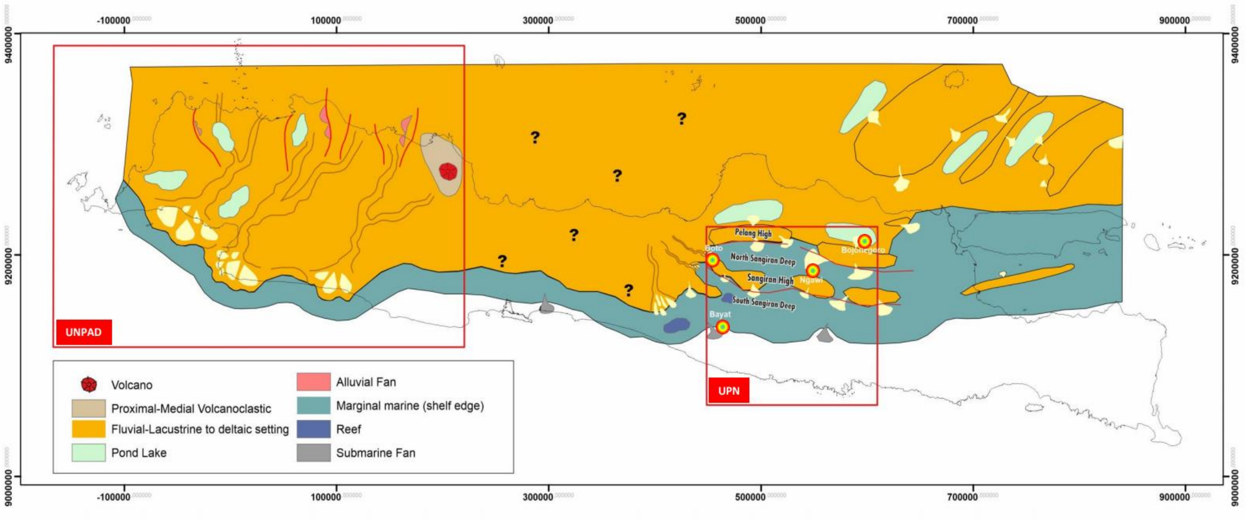
Eocene

During the Eocene epoch, the Bogor zone and Northwest Java basin were one connected passive margin system of the south-southeast edge of Sundaland with the main sediment transport directions southward. This margin shows a deepening trend to the east, probably due to the remnant of the Cretaceous suture zone that creates a low depression area to the east. However, due to the data scarcity in the Central Java area, we skip the interpretation in the Banyumas area and adjust the condition to the nearest location of the West Java area. A terrestrial deposit dominated the depositional in the west area. The intensive phase of rifting during the

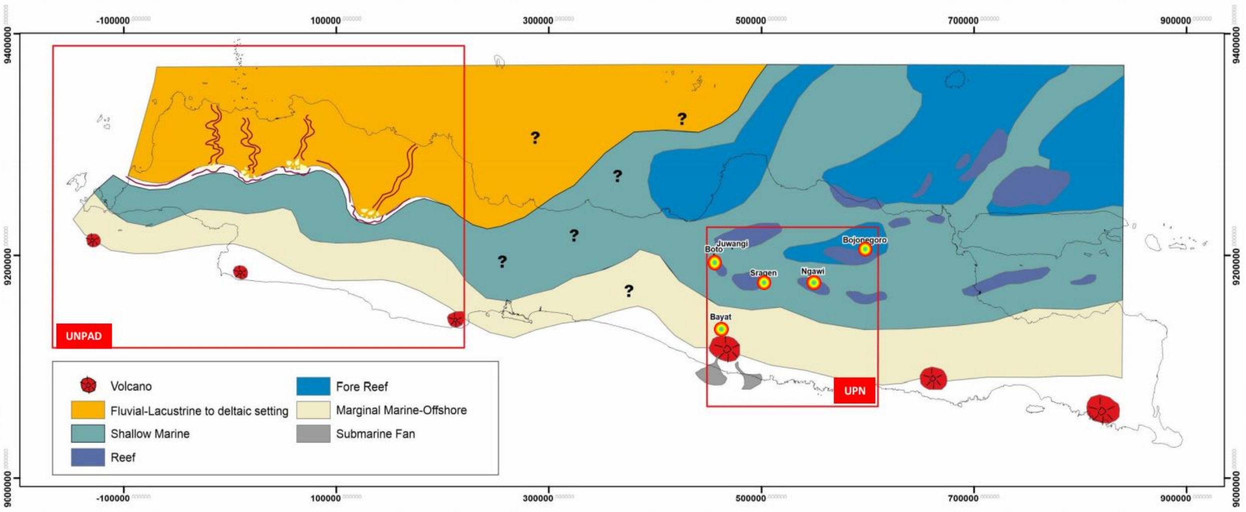
Eocene creates a sub-basin filled by synrift sediment, including a fan delta associated with a marine or lacustrine environment. The fluvio-lacustrine environment was developed with the major river flow orientation to the southwest. These river systems might be partially associated and controlled by the NW-SE-oriented block faulting. During this time, some local depression areas were collecting water and possibly become a localized lacustrine system. At the same time, the Eastern Java area was partly submerged. The Rembang area was established as a terrestrial to transition environment and produced thick deltaic and lacustrine deposits of the Ngimbang Fm. The Kendeng area was becoming a transition area as early as the Eocene epoch with the deposition of deltaic and tidal deposits associated with other shallow marine deposits. This depositional system is likely equivalent to Nanggulan and Wungkal Fm. This study also distinguished a local high area with east-west trending ridges from gravity and magnetic data. This ridge was christened as The Sangiran High, which continues eastward into a promontory shaped Ngawi High. This ridge separates North and South Sangiran Deeps; which is interpreted to have a continuity to B-D ridges in Madura Strait (Sribudiyani et al., 2003; Prasetyadi et al., 2016) (Figure 15a).

Late Oligocene

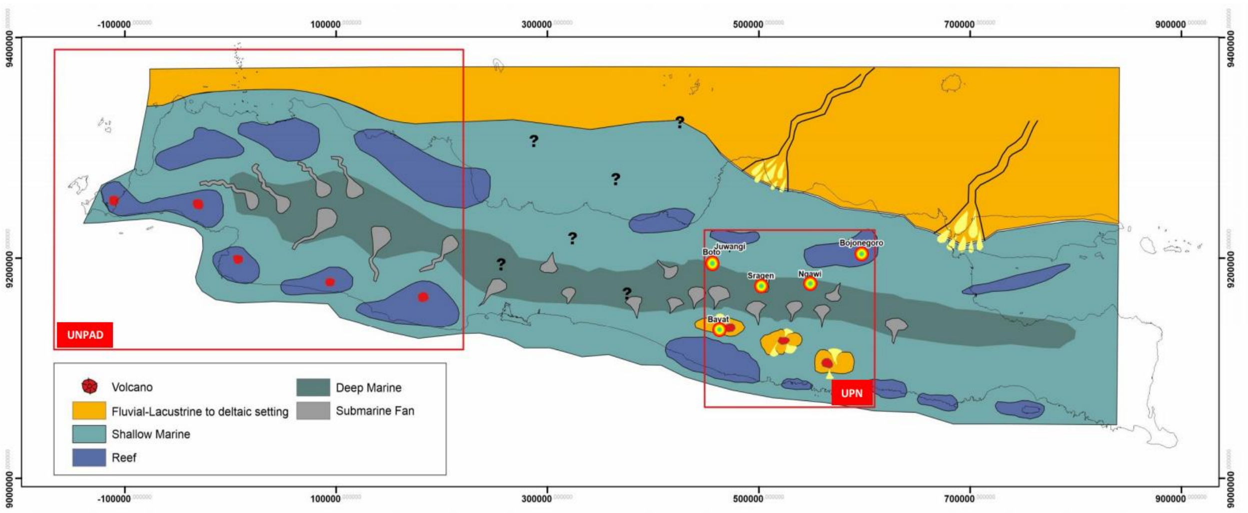
In the Late Oligocene, a regional transgression was initiated, marked by the rapid marine sediment deposition in the eastern Java, producing a thick sequence of the limestone in NE Java and Rembang Basins such as Kujung and Prupuh Fm. and the initial deposition of Tuban Fm. Near the onshore area, Pelang Fm. consists mainly of the various shelf, and transition deposits developed. The limestone unit equivalent to Pelang Fm. was also believed to develop in the Sangiran paleo high area.



Early Eocene



Late Oligocene



Middle Miocene

Figure 15. *The simplified cartoon of the Gross Depositional Environment (GDE) based on data integration from West Java (Bogor Trough area) and East Java (Kendeng Trough area) from a) Early Eocene, b) Late Oligocene, and c) Middle Miocene. These maps also incorporated interpretation from previous publications i.e., Hall et al. (2007), Hall and Smyth (2008), Lunt (2013) and Lunt (2019) (see text for the explanation).*

The exposure of this limestone, with a presence of large *Eulepidina* is once reported in the Mrisi area (van Bemmelen, 1949 in Lunt, 2013), but the recent fieldworks were unable to locate the position of the outcrop and assumed that the exposure probably has long gone by the erosion.

In the northwest Java Basin, the transgression was also marked by the deposition of a thick sequence of limestone of Baturaja Fm. In the Bogor area, at the southern extend, the sea emergence northward and creates a favourable area for shallow marine and transition depositional systems such as Batuasih, followed by Rajamandala Fm. During this time, the southern mountain volcanic arc system was interpreted to be partially submerged as an underwater volcano in the western area. In the eastern area, the volcanic arc continues onshore and align relatively east west in the southern part of Java Island. At this period, the distance between the southern mountain was still considered far away from the Bogor and Kendeng area. This condition continued until the early Miocene. During this period, the Pelang Fm. is deposited as a shelfal deposit in the Kendeng area, whereas in contrast, western Java becomes a deep-sea realm with the deposition of Citarum Fm. (Figure 15b).

Middle Miocene

During the Middle Miocene, the fold-thrust belt deformation was intensified with an average shortening rate of 25-50% from its original form (UPNY-Pertamina, 2020). This deformation created a flexural basin that separated the Bogor and Kendeng Trough from the adjacent basin of the northwest and northeast Java basins. Bogor and Kendeng Trough were started to form as a deep basin with possible multi-directional provenance were the major sediment provenance derived from Sundaland shelf margin in the north, dominated with arenite and volcanic material of southern mountains from the south. This period was marked with the deposition of thick deep-water deposits such as the Kerek Formation in the Kendeng area and the Jatiluhur and Cinambo Formations in the Bogor area. This thick deep-sea deposit was furthermore uplifted and partly thrusted, followed by the deposition of younger shallow marine deposits such as Kalibeng and Klitik in the east and Klapanunggal and Cantayan in the western area (Figure 15c).

"Native" Petroleum System and Geological Risks in Bogor and Kendeng Troughs

Figure 16 shows a compiled table of proposed petroleum elements in Bogor and Kendeng Trough. The prospective source rocks are derived from the

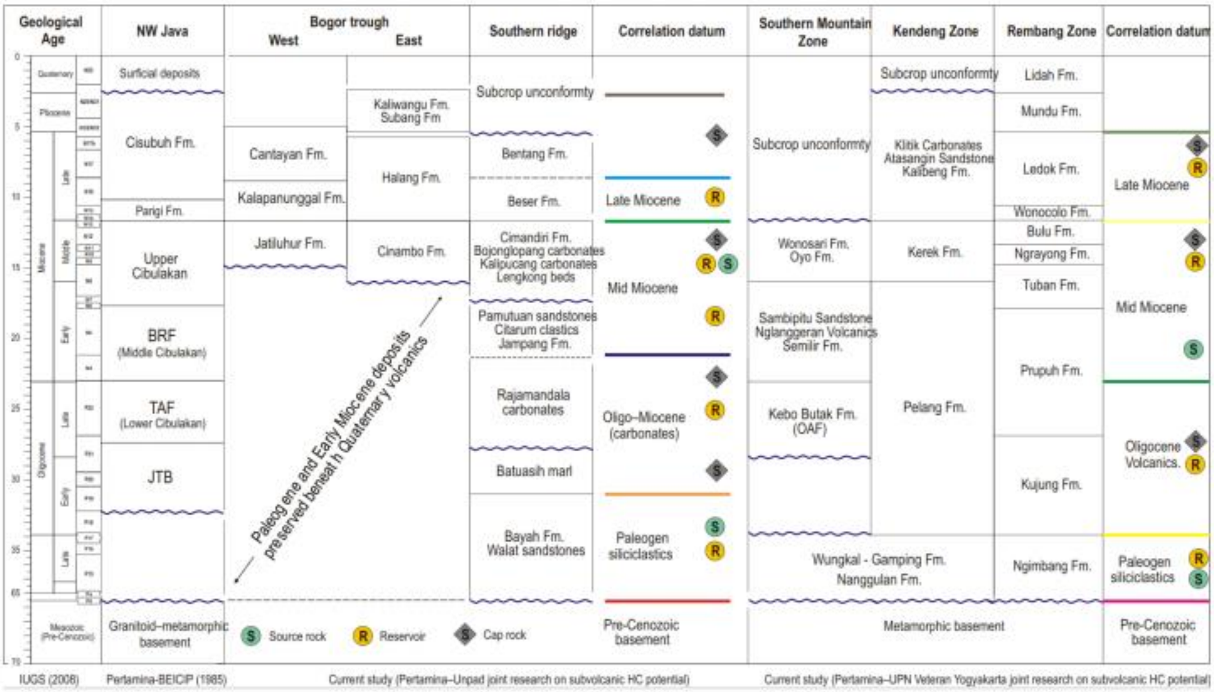


Figure 16. *The proposed petroleum system elements in the Bogor and Kendeng Troughs (see text for the explanation).*

terrestrial and transition environment from Paleogene units in the West Java, such as the Bayah, Walat and Batuasih Formations, which demonstrate mature source rock, with moderate to good TOC with kerogen Type II and III. In addition, the Neogene sample from the Cinambo Formation shows moderate to good TOC (0.72 -1.21 wt. %).

The Paleogene siliciclastic such as Bayah and Walat Fm. and Oligocene Rajamandala Fm. could become a major potential reservoir rock. The other younger siliciclastic and volcaniclastic units (Seubert, 2015) could also be potential as reservoir rocks depend on their preserve porosity and permeability due to the intensive tectonic and burial. Furthermore, the widespread distribution of Subang and Kaliwangu Fm. shale shows their potential to become a regional seal rock.

In Eastern Java, The Paleogene equivalent Wungkal and Nanggulan Fm. underneath the Neogene unit in the Kendeng zone possibly act as primary potential source rock. The sample from the oldest rock exposed in the area, Pelang Fm., is still considered immature. The best candidate for reservoir rocks is included equivalent Wungkal and Nanggulan terrestrial to transition deposit and any sand unit in Pelang Fm. The regional shallow marine shale from Kalibeng Fm. is becoming a good candidate for the regional shale.

The proposed trapping mechanism in this studied basin is mostly a combination of stratigraphic and structural traps. The thrust and fold-belt system have a crucial control to form the structural closure and became a primary hydrocarbon conduit from the source rocks to the reservoir. This southerly dipping thrust system is becoming a major hydrocarbon pathway to the surface (Figure 17). There are still geological risk factors associated with the systems; in the Paleogene siliciclastic reservoir, some risks may be associated with imperfection in structural closures, limited thickness, and the limited extent of the caprock area. Magma intrusion may destroy or compartmentalize trap, and pre-existing fault system and direct contact with magma may "overcook" source rock and loss of hydrocarbon charging. In the Oligo-Miocene Carbonate, long-distance migration, limited carrier beds, and fault conduit and lateral facies change. The other geological risk in the Neogene siliciclastic reservoir is poor porosity development in matrix-rich volcanogenic sandstone.

CONCLUSION

Both Bogor and Kendeng Troughs contain active petroleum systems where HC were generated from Type II to III Kerogen, typical of organic material that were deposited in transition to shallow marine environment. The result suggests that these basins are separate from the neighbouring basins, The Northwest Java and Northeast Java Basins are characterized by more strictly terrigenous Type III Kerogen.

Bogor and Kendeng Troughs' ultimate source rocks came from deeply buried Paleogene stratigraphic unit (Bayah Fm. in Bogor Trough and unidentified Pre-Pelang Fm., e.g., equivalent to Wungkal-Gamping and Nanggulan Fm. in Kendeng Trough) with various potential reservoir rock of Paleogene to Neogene deposit. The contrasting

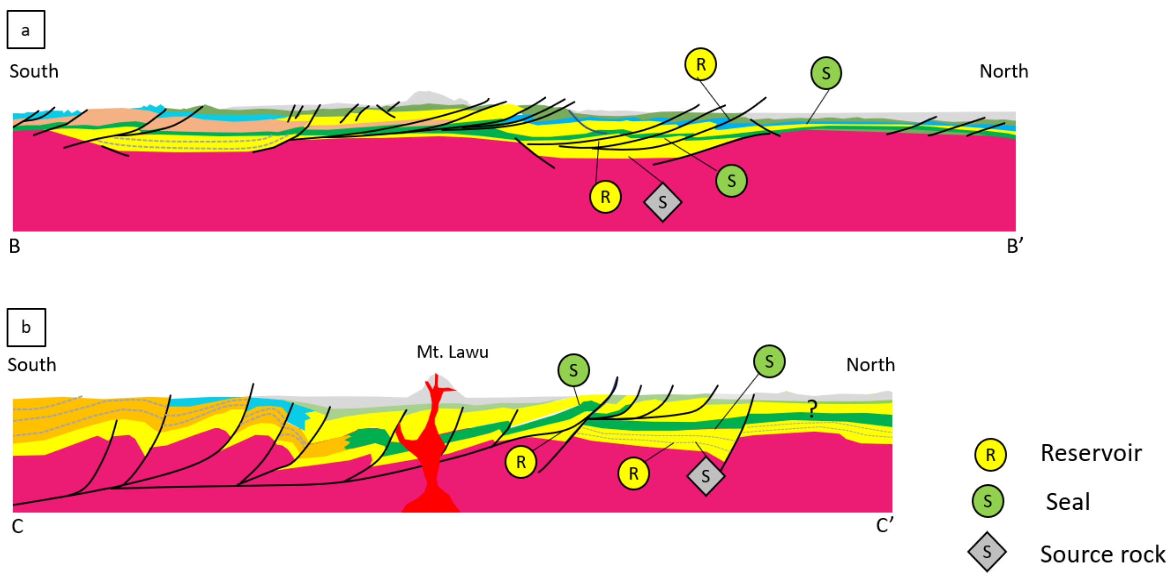


Figure 17. *The cartooned section of structural reconstruction and interpreted regional geology and associated petroleum play a) Cijulang – Indramayu – Kromong section in Bogor Trough west Java and b) Wonogiri- Gunung Lawu - Purwodadi section in Kendeng Trough East Java (UNPAD-Pertamina, 2020; UPN-Pertamina, 2020). See Fig. 1 for the location.*

subsurface configuration between Bogor and Kendeng Troughs mainly concerns the fold-thrust belt basement involvement and the tectonic shortening effect on the formerly rift basin.

The implication for the petroleum play: the sub-thrust and over-thrust plays combined with the stratigraphic play were expected to develop in Bogor Trough. On the other hand, more traditional rift deposits and paleo high limestone development (e.g., equivalent Pelang Fm.) could become the most expected prospective target in Kendeng Trough.

ACKNOWLEDGEMENT

PERTAMINA Research and Technology Innovation (RTI) provided funding and resources for this study through the University ideation program to Universitas Padjajaran (UNPAD) and Universitas Pembangunan Nasional Veteran (UPN Veteran). This manuscript is dedicated to the memory of our dear teacher and advisor, Dr. Rudy Ryacudu, who passed away while this paper was being prepared. May his legacy in regional geology last forever.

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Source rock characterization and oil grouping in the NW Java, Central Java and NE Java Basins, Indonesia

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ABSTRACT

This study reveals the detailed organic geochemistry from crude oils (acquired from wells and seepages) and rock extracts from NW Java and NE Java Basin that have been gathered and compiled from previous publications. The interpretation was conducted from geochemical data value and plot, GC-MS fingerprints, and agglomerative-hierarchical cluster analysis using the Euclidean algorithm. Various source rocks from those basins were deposited under fluvio-lacustrine to the marine environment. Six groups of crude oils are also distinguished. Groups 1, 2, and 6 are oils from deltaic source rocks, Groups 3 and 4 are oils from marine source rocks, and Group 5 is from lacustrine and/or fluvio-lacustrine source rocks. Groups 1, 2, and 6 could be distinguished from the pristane/phytane (Pr/Ph) ratio and C_{29} sterane composition, while Groups 3 and 4 differ from the distribution of C_{27} sterane. The schematic depositional environment of source rocks is also generated from this study and suggests that Group 5 is deposited during early syn-rift non-marine settings, while the remaining groups are deposited in the deltaic (Group 1,2 and 6) and marine settings (Groups 3 and 4). The main differences between those groups are including the distributions of C_{27}-C_{28}-C_{29} steranes.

***Keywords**: organic geochemistry, crude oil, oil seepage, rock extract, oil families, agglomerative hierarchical cluster analysis, Euclidean algorithm.*

Manuscript received May 18th, 2021, revised manuscript received August 5th, 2021, final acceptance September 6th, 2021.

DOI: 10.51835/bsed.2021.47.2.334

INTRODUCTION

A series of back-arc basins in Java within Sundaland (Figure 1) has been known for their prolific oil and gas accumulation. They lie from west to east, from NW Java Basin to NE Java Basin. These basins shared roughly similar tectonostratigraphic history during Cenozoic, which consists of Cretaceous-Early Paleogene? pre-rift, Late Eocene-Oligocene synrift, Early Miocene postrift, and Middle Miocene inversion (Satyana and Purwaningsih, 2003; Doust and Noble, 2008). These similarities caused the similar type and deposition of source rocks which were deposited during early and late synrift basin phases. However, the heterogeneities within individual source rocks might cause the different compositions of crude oil and natural gas. This paper analyses the detailed organic geochemistry of crude oils from various basins in Java based on their composition and biomarker characteristics compiled from various publications.

PREVIOUS WORKS

Previous works on oil-to-source rock correlation in several basins in Java mostly emphasized on conventional geochemical analysis from biomarker and isotope data with quantitative (geochemical bivariate plot) and qualitative (comparing fragmentogram peaks) methods (e.g. Satyana and Purwaningsih, 2003; Wiloso et al., 2008; Devi et al., 2018 in NE Java Basin; Subroto et al., 2008; Praptisih,

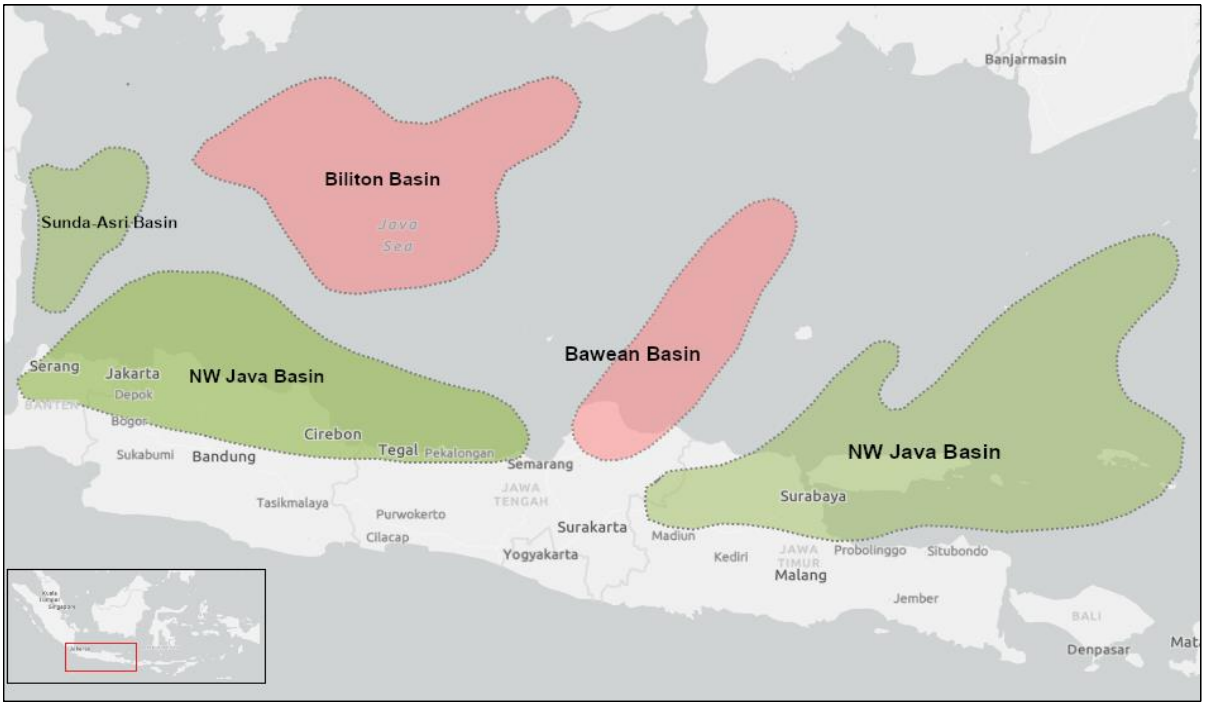

Figure 1. *Back-arc basins in Java, Indonesia. The oil samples for this paper were taken from the NW Java Basin and NW Java Basin (green areas indicate producing basin), while the remaining basins are not studied. Some authors suggest that NW Java Basin is a bigger basin that contains several sub-basins including Sunda-Asri, Billiton, and Ardjuna. In this paper, the classification for the basin in Indonesia uses one from Doust and Noble (2008).*

2018 in Central Java; Ponto et al., 1988; Rahmad (2016) in NW Java Basin]. However, hierarchical clustering analysis (HCA) is rarely performed since not all samples were analyzed using full range geochemistry analysis from bulk composition to stable carbon isotope. The other reason is that not all samples contain a similar biomarker, or the biomarker is co-eluted and difficult to be calculated.

In NW Java, Napitupulu et al. (1997) differentiate three groups of oils from lacustrine, marine shales, and marine carbonate source rocks. In the eastern part of NW Java Basin (near Semarang, Central Java), oil seepage was studied by Praptisih (2018). In East Java, Devi et al. (2018) suggested one oil family from deltaic to marginal marine source rock in NE Java Basin. Satyana and Purwaningsih (2003) discuss the geochemistry of oils and extracts from East Java Basin from 100 wells and seeps (86 crude oils, 35 natural gases, and 57 rock samples from onshore and offshore areas). This study suggests that there are two "classes" of oils based on various geochemistry parameters and plots, however, the hierarchical cluster analysis has yet to be done (Satyana and Purwaningsih, 2003). The classification that they used was one from BP Research Centre (1991, in Satyana and Purwaningsih, 2003) which enables oils to be put into one of five categories: A (marine non-clastic with mixed algal and bacterial input), B (marine clastic with mixed algal and bacterial input), C (lacustrine algae), D (high resin terrestrial) and E (low resin terrestrial), depending upon their bulk properties. Satyana and Purwaningsih (2003) classify oils in East Java into two: Class D1 and Class D2.

Other work that incorporated HCA and principal component analysis (PCA) have been done by Sosrowidjojo (2011) in the Sunda-Asri Basin and Ramadhina et al. (2017) in the NE Java Basin. The HCA and PCA performed by Sosrowidjojo (2011) indicates that oils in the Sunda-Asri Basin can be classified into 6 clusters that reflect their different geographical locations and not due to differences in source rocks. These 6 clusters consist of North Oil Field (2 clusters), Central Oil Field (2 clusters) and South Oil Field (1 cluster) and 1 mixed oil group. In the NE Java Basin, Ramadhina et al. (2017) classify the crude oils from published data into 3 main groups that reflect their subtle differences in API gravity and "final" depositional environment, suggesting the initial source rocks are similar (of non-marine origin) and then possibly were transported and deposited on different places from terrigenous to transition and marine. Unlike the work done by Sosrowidjojo (2011) and Ramadhina et al. (2017), the current study attempts to do HCA on crude oils and source rocks from across several basins.

DATA AND METHOD

Several publications from NW Java Basin and NE Java Basin (Figure 1) that contained geochemistry of crude oil, rock extract, and oil seepages were studied, analysed, and compiled to understand (1) source rock facies and depositional environment, (2) oil geochemistry from those basins, (3) classification and groups of oils based on their geochemistry parameters using hierarchical cluster analysis, and (4) schematic depositional environments of each group of source rock.

In this study, several biomarkers were analysed, including pristane and phytane ratio (Pr/Ph), n-alkanes distribution, C_{27}-C_{28}-C_{29} steranes ternary diagram, and fingerprint of selected steranes and terpanes. Table 1 explains those parameters and their interpretation. Each publication mentioned above has a different range of geochemistry analyses, however, most of them have at least one or two parameters (e.g., pristane and phytane ratio and C_{27}-C_{28}-C_{29} steranes distribution) that are of important source-related biomarker. Therefore, cluster analysis is also used to understand the similarity and/or opposition of each sample based on geochemistry characters and tectonostratigraphy.

Hierarchical Clustering Analysis (HCA) for Oil Grouping

Cluster analysis is one of the common methods for geochemists to classify oils. Peters et al. (1999) used this method to classify crude oil from Eastern Indonesia, Sosrowidjojo (2011) in the Sunda-Asri Basin, and Ramadhina et al. (2017) in the NE Java Basin. In this paper, the geochemical data from various publications were subjected for oil-to-oil correlation. In addition to qualitative and quantitative geochemical analysis, HCA, a common method that have been widely used in many scientific applications (e.g., Gower et al., 1967), was also performed. The goal of HCA is not to find a single partitioning of the data, but a hierarchy (generally represented by a tree) of partitions that may reveal interesting structures in the data at multiple levels of granularity (Balcan et al., 2014). The most widely used hierarchical methods are the bottom-up or the agglomerative clustering technique; most of these techniques start with a separate cluster for each point and then progressively merge the two closest clusters until only a single cluster remains (Balcan et al., 2014). To calculate the distance (d) between two points (p and q), the Euclidean algorithm is utilized and shown in Equation 1:

$$d\ (p, q) = \sqrt{(p-q)^2} \qquad (1)$$

Several samples are selected for the analysis which have at least six parameters, such as Pr/Ph, S%, C_{27}-C_{28}-C_{29} steranes, and oleanane /hopane ratio. Therefore, in this study, HCA was only performed for samples that have multiple geochemical parameters. Various limitations that include the number of geochemical parameters that are not available from all samples from published work, hydrocarbon alteration, and thermal maturation are not discussed in this paper. This study assumed that such factors will not greatly affect the results of HCA. Finally, the HCA was performed using XL Stats software with a high confident level.

Geochemical Parameters	Analysis	Biomarker	References
n-alkanes	GC	The distribution of n-alkanes are indicators for organic matter input, e.g., nC_{27}, nC_{29}, nC_{31} are indicators of terrestrial origin.	e.g., Tissot and Welte (1984)
Pr/Ph	GC	The ratio of pristane and phytane is commonly used for indicator of redox condition. This ratio also distinguishes the source rocks from shales and carbonates. Low Pr/Ph usually indicates source rocks from carbonates under anoxic condition, while high Pr/Ph suggests ones from shales under oxic condition.	e.g., Hughes (1984), Palacas et al. (1984)
C_{27}-C_{28}-C_{29} steranes	GC-MS	The distribution of C_{27}-C_{28}-C_{29} is a source parameter that can be used to differentiate depositional settings. The principal use of the ternary diagrams is to distinguish groups of crude oils from different source rocks or different organic facies of the same source rock.	e.g., Huang and Meinschein (1979), Peters et al. (2004)
Oleanane	GC-MS	Oleanane is a biomarker characteristic of GC-MS angiosperms (flowering plants) found only in Cretaceous and younger rocks and oils	Peters et al. (2004)
Bicadinanes	GC-MS	Bicadinanes are derived from higher plants and GC-MS used as an indicator for terrestrial organic matter input.	e.g., Summons and Jahnke (1992)
Carbon Isotope of Saturates and Aromatics	Carbon Isotope	Combination of stable carbon isotope ratios of Saturates and Aromatics, a sterane ternary Carbon Isotope diagram, and other supporting data was used to classify oil groups and relate most of them to source rock extracts.	Grantham et al. (1988)

***Table 1**. Selected geochemical parameters to understand the various depositional environment, redox conditions, organic matter input and to classify crude oils based on their genetic origins based on various authors.*

GEOLOGICAL SETTINGS AND TECTONOSTRATIGRAPHY

Java island of Indonesia is located in the SE part of Sundaland in which various back-arc basins lie, including NW Java Basin and NE Java Basin (Figure 1) studied in this paper. In nearly all the basins within Sundaland including Java and Sumatra, four stages of tectonostratigraphic evolution could be recognized (Doust and Noble, 2008):

1. Early Synrift (generally Eocene to Oligocene) corresponds with the period of rift graben formation and the following period of maximum subsidence,
2. Late Synrift (Late Oligocene to Early Miocene) corresponds with the period of waning subsidence in the graben when individual rift elements amalgamated to form extensive lowlands that filled with paralic sediments,
3. Early Postrift (typically Early to Middle Miocene) corresponds with a period of tectonic quiescence following marine transgression that covered the existing graben–horst topography,
4. Late Postrift (typically Middle Miocene to Pliocene) corresponds to periods of inversion and folding, during which regressive deltas were formed. Doust and Noble (2008) described the stratigraphy of

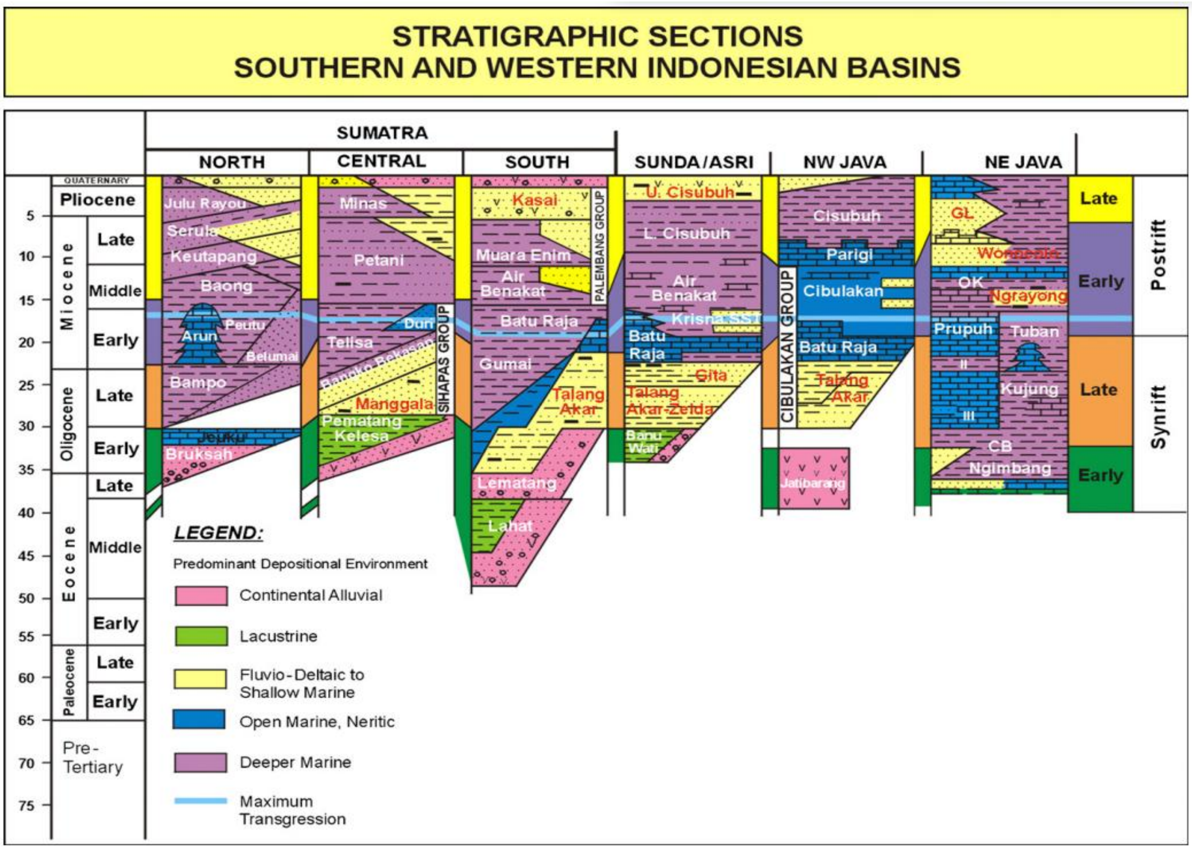

***Figure 2**. Stratigraphic sections of several Indonesian basins from Sumatra including North, Central, and South Sumatra Basins, and Java including Sunda-Asri, NW Java, and NE Java basins. The sequences in those basins are divided into four sections: Early and Late Synrift, Early and Late Postrift (Doust and Noble, 2008).*

Sumatra and Java, suggesting rifting stage during Eocene and terminated in Oligocene, followed by post-rift since Miocene (Figure 2).

The four stages of tectonostratigraphic evolution and their relations to petroleum system elements are summarised in Table 2. To summarise, the Eocene to Oligocene fluvio-lacustrine to paralic/deltaic shales synrift are the main source rocks in Java Basins, including Banuwati (Sunda Asri Basin), Talangakar (NW Java Basin), and Ngimbang formations (NE Java Basin). Howes and Trisnawijaya (1995) also suggest other source rocks from Cenozoic sequences in the NW Java Basin. Reservoirs vary from Oligocene to Miocene syn- and postrifts sediments, including Baturaja, Talangakar, and Kujung formations.

GEOCHEMISTRY OF SOURCE ROCK FROM JAVA

The geochemistry cross plot of stable carbon isotopes from saturates fraction versus Pr/Ph (Figure 3) distinguished three different groups of source rocks namely Banuwati, Talangakar, and Ngimbang formations from Sunda-Asri, NW Java, and NE Java basins, respectively (Figure 3). On the sterane plot, all samples have a predominance of C_{29} steranes suggesting input from terrestrial higher plant organic matter (Figure 4, Table 3; Huang and Meinschein, 1979).

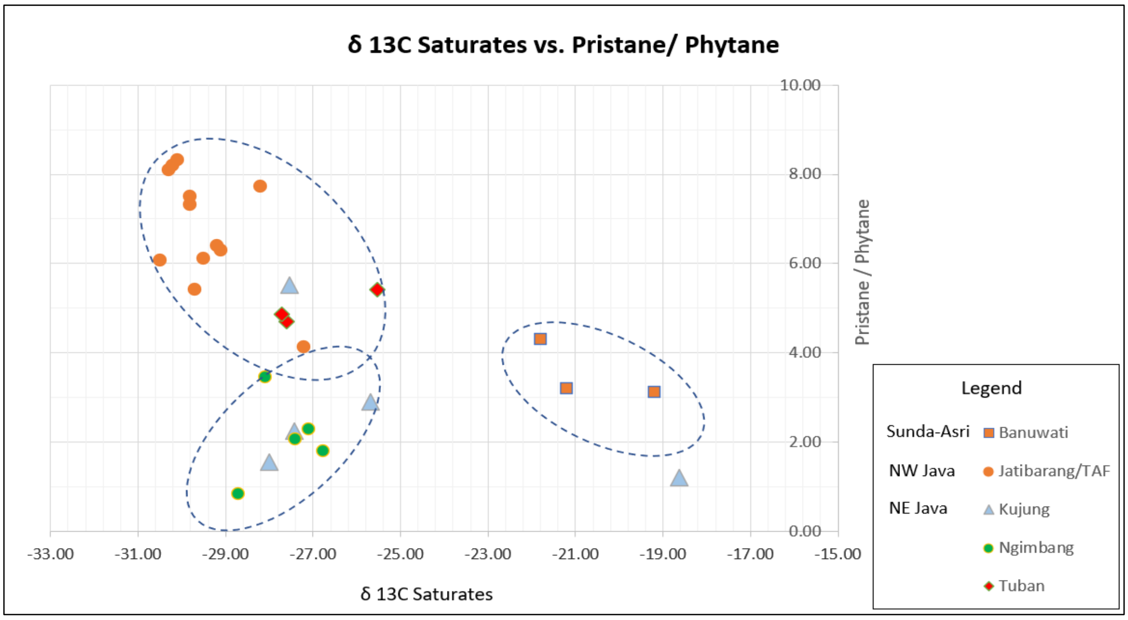

Figure 3*. Cross plot between carbon isotope of saturates and pristane/phytane (Pr/Ph) ratio that suggests different characters of source rocks. In Sunda-Asri and NW Java basins, Banuwati and Jatibarang/TAF source rocks could be distinguished. Banuwati source rock tends to have higher Pr/Ph and lower carbon isotope of saturates. In East Java Basin, all potential source rocks tend to have similarities, however, Ngimbang Formation could be distinguished from the lower carbon isotope of saturates. Sunda-Asri and NW Java data are from Bishop (2000) and Rahmad (2016), and NE Java data are from Satyana and Purwaningsih (2003) and Devi et al. (2018).*

Basin	Tectonostratigraphy in Java Basin				Proven Petroleum System
	Early Synrift	Late Synrift	Early Post rift	Late Post rift	
Sunda -Asri	Oligocene fluvio-lacustrine Banuwati (SR)	Oligo-Miocene fluvio-deltaic Talangakar and Baturaja carbonates (R)	Middle Miocene transgressive marine shales of Airbenakat (C)	Miocene – Quaternary regressive & deltaic sediments of Cisubuh	Banuwati-Talangakar (!)
NW Java	Late Eocene – Early Oligocene lacustrine Jatibarang and deltaic Talangakar (SR)	Oligo-Miocene transgressive fluvio-deltaic to shallow marine Talangakar and Baturaja (R)	Early – Middle Miocene regressive & deltaic clastic of Cibulakan (R), (C)	Late Miocene to Quaternary platform carbonates and regressive clastic of the Parigi and Cisubuh	Talangakar-Cibulakan (!)
NE Java	Late Eocene to Early Oligocene lacustrine to paralic sediment of Ngimbang (SR), (R)	Late Oligocene to Early Miocene marine carbonates of the Kujung and Prupuh (R)	Early to Late Miocene carbonate platforms of Tuban, Wonocolo shales and Ngrayong sands (R), (C)	Late Miocene to Quaternary marine clays, volcaniclastics, carbonates and sands from shallow to deeper water environments	Ngimbang-Ngrayong (.), Ngimbang-Ngimbang (!), Ngimbang-Kujung (!), Cenozoic-Miocene (.), Cenozoic-Pliocene (!) (Howes and Trisnawijaya, 1995).

***Table 2**. Tectonostratigraphy and its relation to petroleum system elements in several basins within Java (Doust and Noble, 2008). The symbols SR, R, and C are for source rock, reservoir, and caprock or seal, respectively.*

Rock Extracts	$\delta^{13}C$ Saturates (‰)	Pr/Ph	C_{27} steranes (%)	C_{28} steranes (%)	C_{29} steranes (%)	Authors
Jatibarang/TAF	-29.70	5.40	25.00	25.00	50.00	Bishop (2000), Rahmad (2016)
Jatibarang/TAF	-29.50	6.10	31.00	22.00	47.00	Bishop (2000)
Kujung	-28.00	1.56	34.00	36.00	30.00	Devi, *et al.* (2018)
Kujung	-25.68	2.90	25.00	29.00	46.00	Satyana and Purwaningsih (2003)
Ngimbang	-26.77	1.80	34.00	21.00	45.00	Devi, *et al.* (2018)
Ngimbang	-27.40	2.07	29.00	29.00	42.00	Devi, *et al.* (2018)
Ngimbang	-28.10	3.44	30.00	20.00	50.00	Devi, *et al.* (2018)
Ngimbang	-27.10	2.30	30.00	25.00	45.00	Devi, *et al.* (2018)
Tuban	-25.54	5.40	5.00	39.00	56.00	Satyana and Purwaningsih (2003)

***Table 3**. Source rock extracts from NW Java Basin and NE Java have a significant amount of C_{29} steranes, an indicator of the higher plant from the terrestrial origin. The high Pr/Ph ratio (more than 1) indicates sub-oxic to oxic conditions. Two samples from Kujung and Ngimbang (Devi et al., 2018) and one from Tuban (Satyana and Purwaningsih, 2003) have higher C_{27} and C_{28} steranes indicating a predominance of marine and lacustrine organic matter, respectively.*

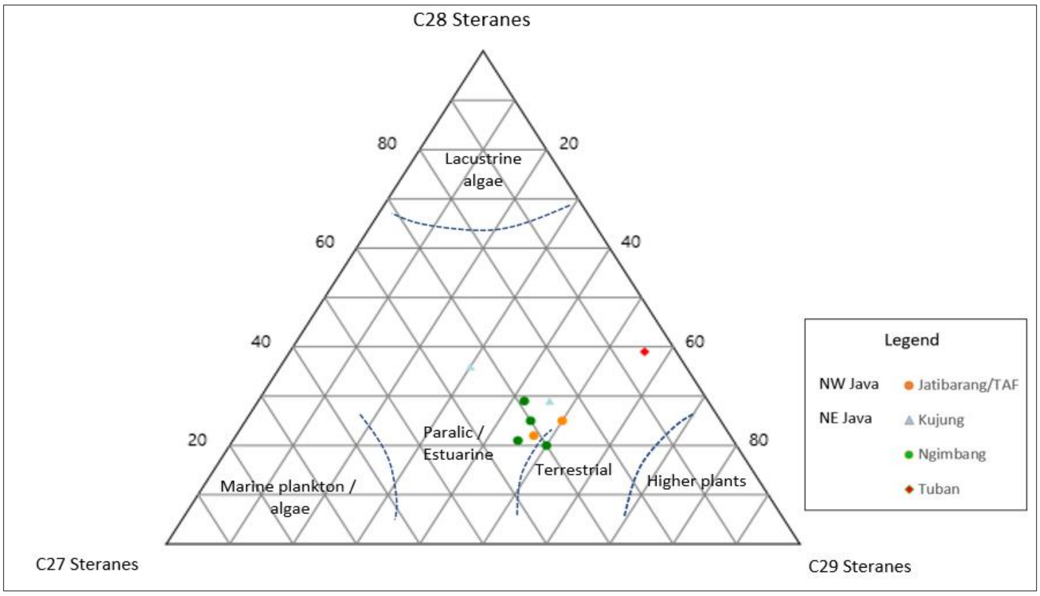

***Figure 4**. The distribution of C_{27}-C_{28}-C_{29} steranes is presented in the ternary diagram. All samples indicate the same location with a significant number of C_{29} steranes. Huang and Meinschein (1979) studied the importance of steranes as indicators for the depositional environment, where a high abundance of C_{27}, C_{28}, and C_{29} steranes suggest marine, lacustrine and terrestrial environments respectively. NW Java data are from Bishop (2000) and Rahmad (2016), and NE Java data are from Satyana and Purwaningsih (2003) and Devi et al. (2018).*

Group	Classification	Dissimilarity with other groups	Pristane/ Phytane	S	C_{27} steranes (%)	C_{28} steranes (%)	C_{29} steranes (%)	Oleanane / Hopane	Oils
1	Deltaic-sourced oil	Higher in C_{29} steranes than Group 2	3.95 - 9.81	0.07 - 0.35	11 - 17	21 - 28	55 - 63	0.12 - 0.51	NE Java Basin
2	Deltaic-sourced oil	Lower in C_{29} steranes compared to Group 1	2.40 - 7.72	0.00 - 0.68	16 - 24	26 - 32	45 - 55	0.04 - 2.19	Mostly NE Java Basin
3	Marine-sourced oil	$C_{27} > C_{28} > C_{29}$. C_{27} is a biomarker from marine plankton or algae	4.10 - 13.77	0.07 - 0.43	40 - 48	25 - 33	18 - 28	0.22 - 0.43	NW Java Basin and NE Java Basin
4	Marine-sourced oil	C_{29} Steranes is the lowest compared to C_{28} and C_{27}	3.95 - 9.75	0.00 - 0.25	38 - 47	38 - 46	6 - 18	0.36 - 0.76	Mostly NW Java Basin
5	Lacustrine or Fluvio-lacustrine-sourced oil	$C_{28} > C_{29} > C_{27}$. C_{28} is an indicator for lacustrine oils	0.00 - 11.70	0.09 - 0.42	23 - 34	42 - 49	19 - 28	0.10 - 0.46	NW Java Basin and NE Java Basin
6	Deltaic-sourced oil, potentially from coal or carbonaceous shale	Higher in Pr/Ph compared to Group 1 and 2	3.82 - 16.25	00.00 - 1.19	22 - 36	29 - 37	31 - 41	0.00 - 0.37	NW Java Basin

Table 4. *Six groups of oils are observed in this study. Groups 1, 2, and 6 are crude oils from deltaic source rocks, Groups 3 and 4 are crude oils from marine source rocks, and Groups 5 are crude oils from lacustrine and fluvio-lacustrine source rocks. Pr/Ph ratio, S (sulfur, wt%), C_{27}-C_{28}-C_{29} steranes (%), and oleanane/hopane are the parameters for conducting the HCA analysis in this study.*

The Banuwati Formation is an excellent deep lacustrine Type I source rock in the Sunda-Asri Basins, with TOC of up to 8 wt% and a hydrogen index (HI) of up to 650 mg HC/g TOC (Doust and Noble, 2008; Ralanarko et al., 2020). In the Ardjuna sub-basin (NW Java Basin), the Talangakar Formation is known as the source rocks, with TOC of 40-70 wt% in coals and 0.59 wt% in the shales and HI of 200–400 mg HC/g TOC (Ponto et al., 1988), indicating that the source rock is oil- and gas-prone (Bishop, 2000). Noble et al. (1991) distinguished three facies of Talangakar Formation, which are delta plain (coal facies), delta plain (shale facies), and marine-influenced interdistributary bay. Delta plain coals have higher TOC and HI of 62.7–72.2 wt% and 348–406 mg HC/g TOC, respectively. Napitupulu et al. (1997) observed the occurrence of Botryococcane in the oils from NW Java Basin that indicate they were derived from lacustrine source rocks. In NE Java, Ngimbang Formation has TOC from 0.79–40.15 wt% and HI from 107–282 mg HC/g TOC (Devi et al., 2018).

OIL FAMILIES IN THE NW JAVA AND NE JAVA BASINS

Oil grouping in NW Java and NE Java basins is conducted using hierarchical cluster analysis where the main parameters are sulphur content, Pr/Ph ratio, oleanane/hopane ratio, and distribution of C_{27}-C_{28}-C_{29} steranes (Tables 4 and 5). Other geochemistry plots are also used to understand the correlation between each group.

Based on those methods, six oil groups in NW Java and NE Java basins are classified (Table 4) and presented in a dendrogram (Figure 5).

Group Interpretation	Oil / Seepage	S	Pr / Ph	Oleanane /Hopanes	C_{27} steranes (%)	C_{28} steranes (%)	C_{29} steranes (%)
Group 1	Kawengan	0.25	5.30	0.50	14.00	28.00	58.00
	Nglobo	0.07	5.60	0.60	17.00	25.00	58.00
	Wonocolo	0.13	4.70	0.50	14.00	28.00	58.00
	Kertageneh	0.13	5.00	0.51	16.00	21.00	63.00
	Lerpak	0.10	5.00	0.38	16.00	25.00	59.00
	poleng(JS 20-4)	0.10	6.15	0.29	16.00	27.00	57.00
	JS 1-1	0.17	5.80	0.29	11.00	26.00	63.00
	JS 2-1	0.34	6.21	0.13	16.00	26.00	59.00
	JS 14A	0.20	9.81	0.21	11.00	26.00	59.00
	JS 19-1	0.25	6.65	0.12	16.00	26.00	59.00
	JS 20-4 (Poleng)	0.14	3.95	0.31	16.00	27.00	57.00
	Poleng A-3	0.14	5.28	0.29	17.00	28.00	55.00
Group 2	NWJ-21	0.00	2.40	0.15	24.85	29.58	45.57
	Banyuasin	0.28	5.00	1.88	19.00	28.00	53.00
	Semanggi	0.15	5.90	0.62	19.00	26.00	55.00
	Lidah	0.05	5.00	0.59	21.00	29.00	50.00
	Gegunung	0.07	5.60	0.62	20.00	29.00	51.00
	Kuti	0.13	5.00	2.19	17.00	32.00	51.00
	Arosbaya	0.13	3.50	0.36	23.00	26.00	51.00
	KE 6-3	0.38	2.69	0.95	16.00	31.00	53.00
	L 46-1(SE Kangean)	0.68	4.19	0.04	23.00	29.00	48.00
	L 46-1 (SE Kangean)	0.68	4.19	0.04	23.00	29.00	48.00
	L 46-2 (SE Kangean)	0.09	7.72	0.09	18.00	32.00	50.00
Group 3	NWJ-2	0.43	4.10	0.22	48.19	25.71	26.10
	NWJ-7	0.07	9.65	0.43	40.92	30.63	28.45
	NWJ-8	0.15	13.77	0.30	41.25	31.09	27.66
	NWJ-13	0.08	11.56	0.29	43.50	32.91	23.59
	NWJ-19	0.12	9.03	0.37	47.90	33.32	18.78
Group 4	Suci-B	0.00	3.94	0.00	47.10	46.20	6.70
	NWJ-10	0.24	5.28	0.40	38.41	42.79	18.80
	NWJ-12	0.20	6.54	0.44	42.89	38.30	18.81
	NWJ-14	0.25	5.12	0.76	38.94	43.98	17.08
	NWJ-16	0.08	9.75	0.36	42.73	40.87	16.40
	NWJ-18	0.05	7.54	0.45	43.65	45.45	10.90
Group 5	Sekarkorong	0.19	11.70	0.10	31.00	44.00	38.00
	NWJ-3	1.14	9.63	0.43	23.47	48.78	27.75
	NWJ-5	0.16	7.62	0.30	25.47	44.02	30.51
	NWJ-9	0.13	6.07	0.39	31.94	45.80	22.26
	NWJ-11	0.42	0.00	0.46	31.11	49.75	19.14
	NWJ-20	0.09	7.74	0.41	34.57	42.86	22.57
Group 6	Mudi-1	0.36	3.54	0.00	33.90	34.70	31.50
	KE 9	0.32	3.82	0.15	22.00	37.00	41.00
	JS 44-A1	0.70	5.15	0.28	26.00	34.00	41.00
	NWJ-1	1.19	4.88	0.05	34.20	34.65	31.15
	NWJ-4	0.11	7.68	0.39	24.66	34.37	40.97
	NWJ-6	0.00	8.12	0.24	27.21	34.89	37.90
	NWJ-15	0.02	14.40	0.26	36.01	29.48	34.51
	NWJ-17	0.02	16.25	0.37	31.76	32.65	35.59
	NWJ-22	0.08	7.77	0.31	34.11	34.74	31.15

Table 5. *This study distinguished six groups of oils. Oil geochemistry in this study is compiled from NW Java Basin (Napitupulu et al., 1997) and NW Java Basin (Satyana and Purwaningsih, 2003).*

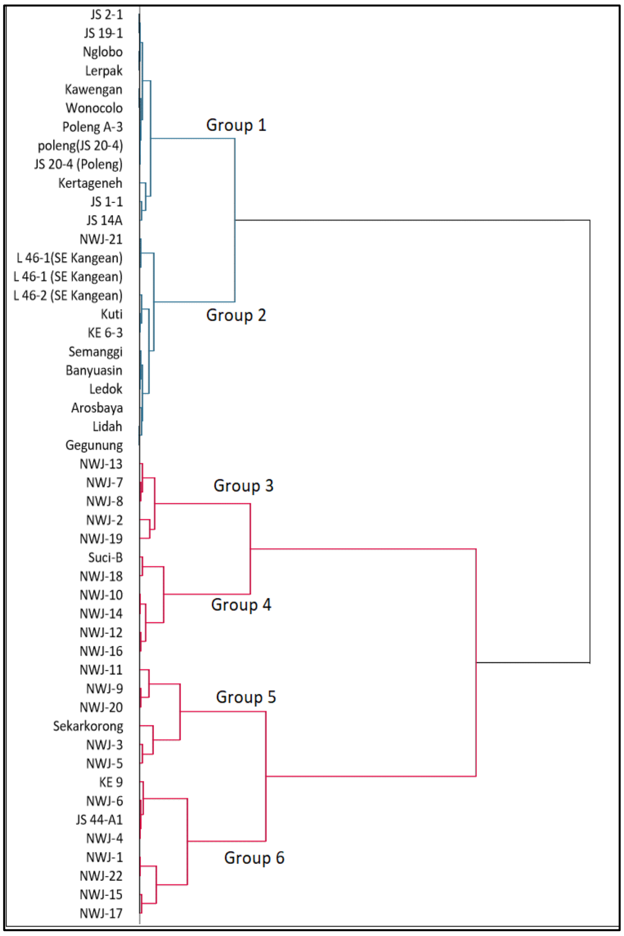

***Figure 5**. The dendrogram resulted from HCA from oils from Java, including NW Java and NE Java Basins, where six groups were distinguished. Group 1, 2, and 6 are from marine-sourced oils, Group 3 and 4 are from marine-sourced oils, and Group 5 is from lacustrine-sourced oils. Group 1, 2, and 6 can be distinguished from the number of pristane/phytane (Pr/Ph) ratio and C_{29} sterane, while Group 3 and 4 differ based on the distribution of C_{27} sterane.*

Most oil groups show significant numbers of Pr/Ph ratio (higher than 1, see Table 4) and predominance of C_{29} sterane indicating that these crude oils were derived from source rock which was deposited under suboxic-oxic with predominance input from terrestrial organic matter. The crude oils also contain oleanane, a biomarker from angiosperm which is an indicator from Cretaceous and younger (Peters et al., 2004).

Group 1 and 2 are crude oils derived from deltaic shale facies, where the main difference is the distribution of C_{29} steranes and Pr/Ph ratio. Group 3 and 4 are crude oils derived from a marine shale source rock based on the distribution of C_{27} sterane (Huang and Meinschein, 1979; Figure 6 and Table 4) that ranges from 40-48% and 38-47%, respectively. Group 5 is oil from the lacustrine and fluvio-lacustrine source rocks based on the high distribution of C_{28} sterane (Huang and Meinschein, 1979; Figure 6 and Table 4) that ranges from 42-49% (Table 4). Group 6 has the same characteristics

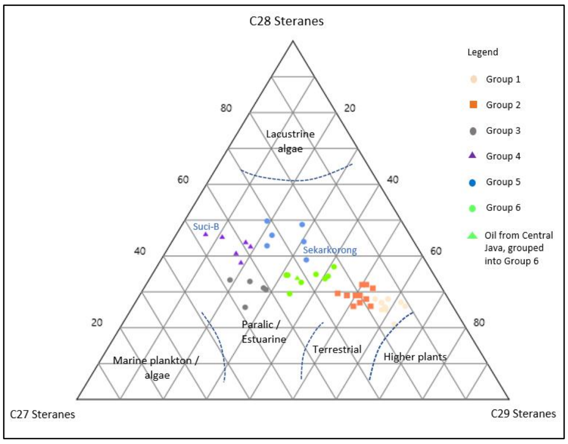

***Figure 6**. Sterane distribution of six oil groups in Java, Indonesia indicating depositional environment from fluvio-lacustrine to shallow marine (after Huang and Meinschein, 1979). Oil grouping of Java Oils shows a good correlation with C_{27}-C_{28}-C_{29} steranes. One oil from Semarang, Central Java is obtained from Praptisih (2017) and categorised as Group 6 in this study. This sterane distribution is analyzed from various publications including NW Java Basin (Napitupulu et al., 1997) and NW Java Basin (Satyana and Purwaningsih, 2003).*

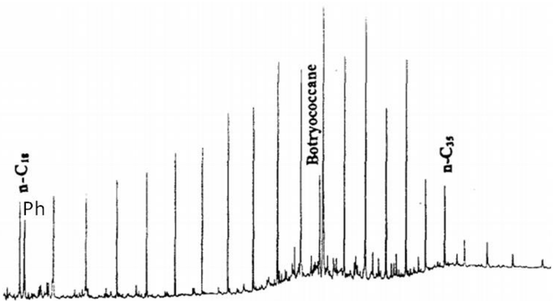

***Figure 7**. The distribution of n-alkanes and isoprenoids that contains Botryococcane from NWJ oils (Napitupulu et al., 1997). Botryococcane is a biomarker derived from Botryococcus braunii, colonial Chlorophycean algae that only live in the lacustrine environment (Peters et al., 2004).*

as Group 1 and 2 but has a higher Pr/Ph ratio (up to 16.25) indicating oils from coal measure source rocks, in which Wang et al. (2019) defined coal measure source rocks as those which include coal, carbonaceous shale, and grey shale.

Lacustrine and Fluvio-Lacustrine Group

The crude oils from this group are characterized by the abundance of C_{28} steranes (C_{28}> C_{29}> C_{27} steranes) that are typical of lacustrine-sourced oils (McKirdy et al., 1984). The deltaic sourced oils tend to have a slight dominance of C_{29} over C_{28} and C_{27} steranes (Noble et al., 1991). Huang and Meinschein (1979) suggest that C_{28} sterane are derived from lacustrine algae. Only one group (Group 5) is categorised as lacustrine/fluvio-lacustrine group. Group 5 consists of five oils from NW Java Basin and one oil from NE Java Basin (Sekarkorong oil). Oils from NWJ-3 and NWJ-5 also contain Botryococcane that is observed on the chromatogram (Figure 7, Napitupulu et al., 1997). Botryococcane is a saturated, irregular isoprenoid biomarker produced by the lacustrine, colonial Chlorophycean algae *Botryococcus braunii*, an organism that thrives only in fresh/brackish water lacustrine environments (Peters et al., 2004). Botryococcane is also an age-related biomarker, indicating oil from Cenozoic (Peters et al., 2004). In the NE Java Basin, Botryococcane is not detected.

The gas chromatograph from NWJ oil from NW Java Basin (Figure 7) shows high concentration of nC_{21+} and peaks in nC_{29}, nC_{31}, nC_{33} alkanes. Group 5 also has relatively low sulphur, low oleanane/hopane, while the Pr/Pr ratios are varied from low to high indicating input from terrestrial organic matter in the fluvio-lacustrine settings (Table 4).

Deltaic-sourced Groups

Group 1, 2, and 6 are crude oils from deltaic source rocks that typically have slight dominance of C_{29} over C_{28} and C_{27} steranes (Noble et al., 1991). Group 1

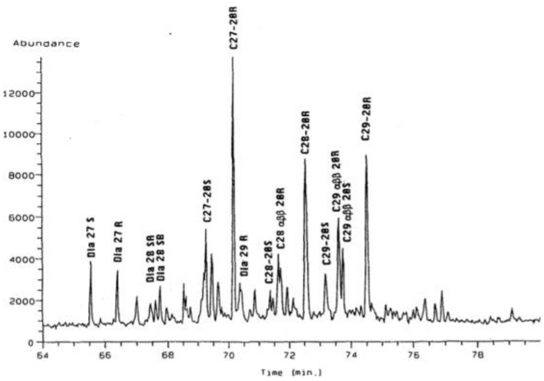

***Figure 8**. Partial m/z 217 fragmentogram from crude oil retrieved from NWJ-1 (Napitupulu, et al., 1997).*

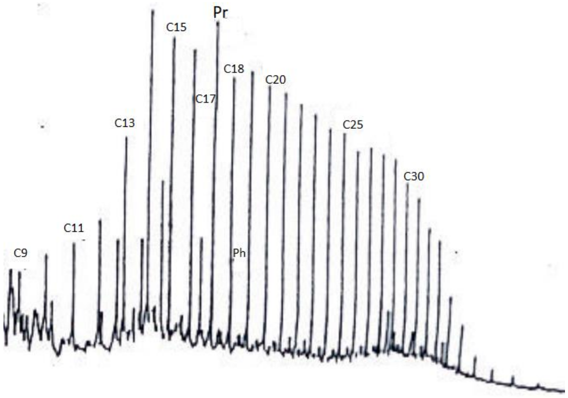

***Figure 9**. The distribution of n-alkanes and isoprenoids from KE-9 oil, NE Java (Satyana and Purwaningsih, 2003). Pristane (Pr) > phytane (Ph) indicate an oxic condition in the fluvio-deltaic environment (e.g., Peters et al., 2004).*

and 2 consists mostly of oils from NE Java Basin while Group 6 consists of oils from NW Java Basin. These groups have a predominance of C_{29} over C_{28} and C_{27} steranes. The considerable dissimilarities between three groups are from the number of C_{29} sterane and Pr/Ph ratios. Group 1 is relatively high in C_{29} sterane, Group 2 is less C_{29} sterane, and Group 6 has the highest value of Pr/Ph. The steranes plot (Figure 6) shows that Group 1 has more terrestrial organic matter input from higher plants compared to Group 2 and 6, while Group 6 has more marine influence than Group 1 and 2 (Figure 2) that is indicated from high C_{27} sterane (Figure 8). One oil from the eastern part of NW Java Basin (oil seepage from Semarang) is categorised as Group 6 (Figure 6).

From Group 6, the gas chromatograph from KE-9 shows a high peak of pristane compared to phytane (Figure 9; Satyana and Purwaningsih, 2003). Compared to the chromatograph in the lacustrine and fluvio-lacustrine group, the deltaic group has a lower chain of n-alkanes, from nC_{9+} and peaks in nC_{14} to nC_{16}.

From Group 6, NWJ-1, the partial m/z 217 fragmentogram (Figure 8) shows a C_{27} > C_{29} > C_{28} steranes and high C_{19} and C_{20} tricyclic terpanes (Figure 10). Some tricyclic terpanes are terrigenous indicators (Noble, 1986) including C_{19} and C_{20} tricyclic terpanes that are derived from vascular plants (Barnes and Barnes, 1983).

Marine-sourced Groups

Groups 3 and 4 are crude oils from marine source rocks as they differ from lacustrine and deltaic source rocks from their high distribution of C_{27} sterane (Table 4 and 5, Figure 5) and low molecular n-alkanes distribution (Figure 11). Groups 3 and 4 are similar in terms of the abundance of C_{27} sterane and typically have sterane distribution as follows: C_{27} > C_{28}> C_{29} steranes. Group 4 differs from Group 3 in its lack of C_{29} sterane (Table 4), indicating oils from marine source rocks.

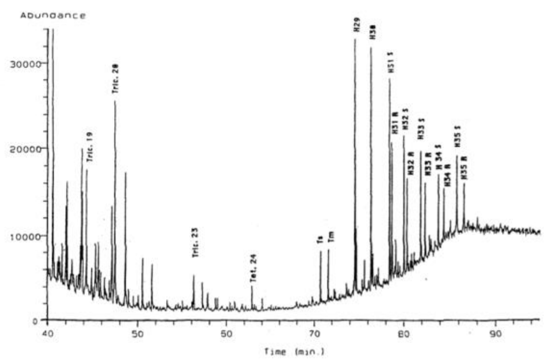

***Figure 10**. Partial m/z 217 fragmentogram from crude oil retrieved from NWJ-1 (Napitupulu, et al., 1997).*

Groups 3 and 4 are dominated by crude oils from NW Java Basin, although one oil from NE Java Basin, Suci-B oil is categorised into Group 4 as it differs from other oils from NE Java Basin. Suci-B has the lowest composition of C_{29} sterane (6.70) indicating a low influence of organic matter from terrestrial higher plants (based on Huang and Meinschein, 1979), and high in C_{27} and C_{29} steranes indicating an oil from the marine source rock.

Napitupulu *et al.* (1997) suggests that two oils, NWJ-1 and NWJ-2 are derived from marine source rocks from their low molecular weight n-alkanes (nC_{11} to nC_{17}, Figure 11), low diasterane /sterane ratio, hopane/sterane > 2, C_{23} tricyclic terpane higher than C_{24} tetracyclic terpane, C_{35}/C_{34} homohopane ratio > 1, a high homohopane index, C_{29}/C_{30} hopane > 1 and an intermediate to high sulphur

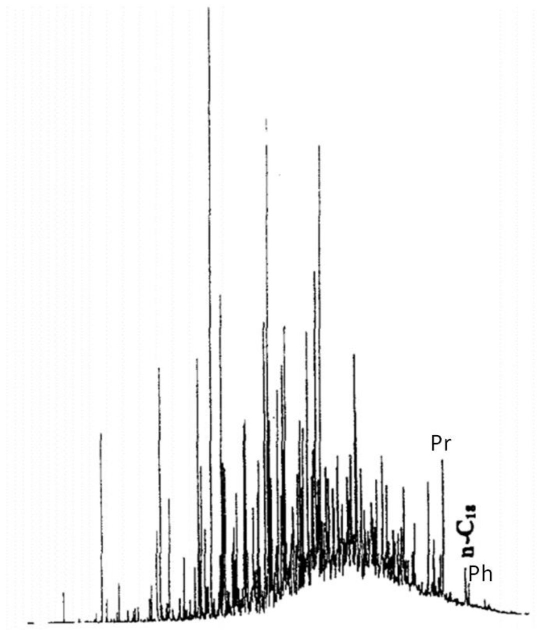

***Figure 11**. The n-alkanes and isoprenoids distribution from NWJ oil suggesting marine source rock (Napitupulu et al., 1997).*

content. This study supports that NWJ-2 is from a marine source rock yet suggests that NWJ-1 is from deltaic source rock based on its sterane distribution (Figure 6), Pr/Ph ratio, and HCA analysis (Figure 5).

INTERPRETATION OF SOURCE ROCK DEPOSITIONAL ENVIRONMENT BASED ON OIL GROUPING

During early rifting, the early synrift deposit of fluvio-deltaic rocks (Figure 12a) were deposited under terrestrial depositional environments. Several rock facies were deposited including an alluvial fan, braided fluvial channel, and lacustrine shales. The lacustrine shales are the main source rocks in this setting. This type of source rock generally types I oil-prone with high hydrogen index. In this study, Group 5 oils are derived from this lacustrine source rocks.

During late rifting, the depositional environment ranges from deltaic to marine settings, where the deltaic source rocks (Group 1, 2, 6) and marine source rocks (Group 3, 4) were deposited (Figure 12b). Group 1, 2, and 6 are generally from terrestrial organic matter where Group 6 is potentially high in carbonaceous and coaly material. Group 3 and 4 are oils from marine source rocks that are potentially generated from siliciclastic source rocks. During early postrift, deltaic and marine rocks are also potential source rocks (Figure 12c), especially in the NE Java Basin, however, the late postrift are generally non-source rock potential (Figure 12d).

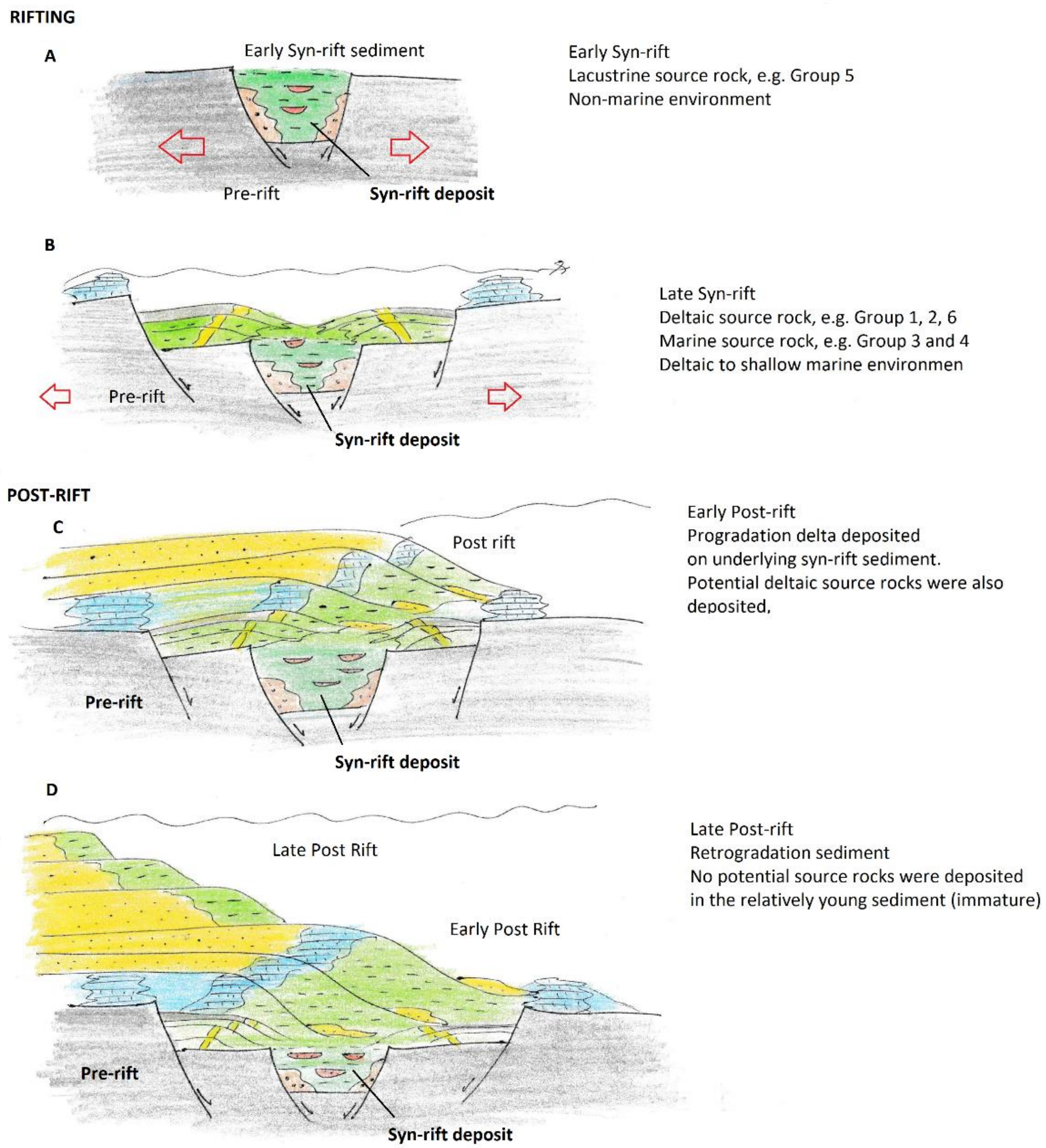

Figure 12. *The schematic depositional environment during rifting and post-rift where the source rocks are mainly deposited during syn-rift, both early (Group 5) and late (the remaining groups). The early post-rift sediments may also be potential source rocks mainly in NE Java Basin, while the late post-rift has no potential source rocks.*

CONCLUSIONS

This study reveals different groups of potential source rocks in NW Java and NE Java basins based on various geochemical parameters including Pr/Ph and $\delta^{13}C$ of saturate fraction (Figure 3). Banuwati Formation differs from Talangakar Formation from its high $\delta^{13}C$ of saturate. Oil extracts from Tuban Formation are relatively similar to Talangakar Formation based on its Pr/Ph and $\delta^{13}C$ of saturate. Ngimbang and Kujung formations relatively have Pr/Ph less than 4 and $\delta^{13}C$ of saturate less than -26‰ (Figure 3).

The agglomerative-hierarchical cluster analysis using the Euclidean algorithm is utilised in this study to classify various oils NW Java and NE Java oils, where several geochemical parameters are performed such as sulfur content, Pr/Ph, C_{27}-C_{28}-C_{29} steranes, and oleanane/hopane. Six oil groups are determined from this analysis. Group 1, 2, and 6 are oils from deltaic source rocks, with a significant number of C_{29} sterane. These groups differ from each other in their C_{29} sterane concentration, where Group 1 has the highest C_{29} steranes, followed by Group 2 and Group 6. Group 5 is oil from lacustrine and/or fluvio-lacustrine source rock where C_{28} steranes are more dominant than C_{27} and C_{29} steranes. Some crude oils from NW Java in this group (NWJ-3 and NWJ-5) also contain Botryococcane (Napitupulu et al., 1997), an isoprenoid biomarker formed from precursors in *Botryococcus braunii* that only live in fresh/brackish water lacustrine environment (Peters et al., 2004). Finally, Group 3 and 4 are oils from marine source rocks where they are dominated by oils from NW Java oils, and only one oil from NE Java (Suci-B) that has very low C_{29} steranes and high C_{27} steranes.

The schematic depositional environment of source rocks is also described in this study (Figure 10). Group 5 is deposited under a non-marine lacustrine early synrift environment, while the remaining groups are deposited in the deltaic (Group 1, 2, and 6) and marine settings (Group 3 and 4). The main differences between those groups are including the distributions of C_{27}-C_{28}-C_{29} steranes.

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Undiscovered Potential in the Basement: Exploring in Sumatra for oil and gas in naturally fractured and weathered basement reservoirs

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This paper was first published in GEOExPro magazine, Vol. 18, No. 1, 2021, both in print and electronically (Koning et al., 2021) and is republished with permission from GEOExPro. For Berita Sedimentologi, we have made various changes to the existing text and figures by including further results from our ongoing in-depth research into the geology of basement oil and gas plays in Sumatra.

INTRODUCTION

This paper provides and up-to-date and in-depth review of the status of exploration for oil and gas in naturally fractured and weathered basement throughout Sumatra. Also reviewed is the status of oil and gas production from Sumatra's basement fields. In this paper's section on Economic Impact, we emphasize the major positive contribution to Indonesia's economy resulting from gas produced from basement reservoirs in the South Sumatra Basin.

Manuscript received August 4th,2021, revised manuscript received August 9th, 2021, final acceptance August 10th, 2021.

DOI: 10.51835/bsed.2021.47.2.320

Sumatra, Indonesia is the sixth largest island in the world covering an area of 445,000 sq km. The first significant oil discovery in Asia was found in 1885 at Telaga Said in North Sumatra. Telaga Said was the foundation asset of Royal Dutch Shell. Sumatra has been a major producer of hydrocarbons and has current total discovered resources of almost 28 billion barrels of oil equivalent (BBOE) based on the North Sumatra Basin with 6 BBOE, Central Sumatra Basin with 15 BBOE (Darwis et al., 2007 and Meckel, 2013, and this paper) and our estimate for the South Sumatra Basin with 6.7 BBOE. Although Sumatra is now viewed by many as a mature hydrocarbon province, a major gas discovery by Repsol in February 2019 in fractured basement rocks highlights that there is still significant potential for further discoveries of oil and gas in Sumatra.

Repsol's discovery well was the Kaliberau Dalam (KBD)-2X well, drilled on the Sakakemang Block in the South Sumatra Basin and encountered at least 2 TCF of recoverable gas and condensate. The well targeted the basement reservoirs that are highly gas productive in the nearby Corridor Block operated by ConocoPhillips. This was the largest hydrocarbon discovery in Indonesia in 18 years since the ExxonMobil Cepu oil discovery in 2001 in Central Java (Wood Mackenzie, 2019). The KBD-2X well was reported to have flowed gas at 45 MMCF/d. Repsol as operator has a 45% interest in the discovery along with partners Petronas with 45% and Mitsui with 10%.

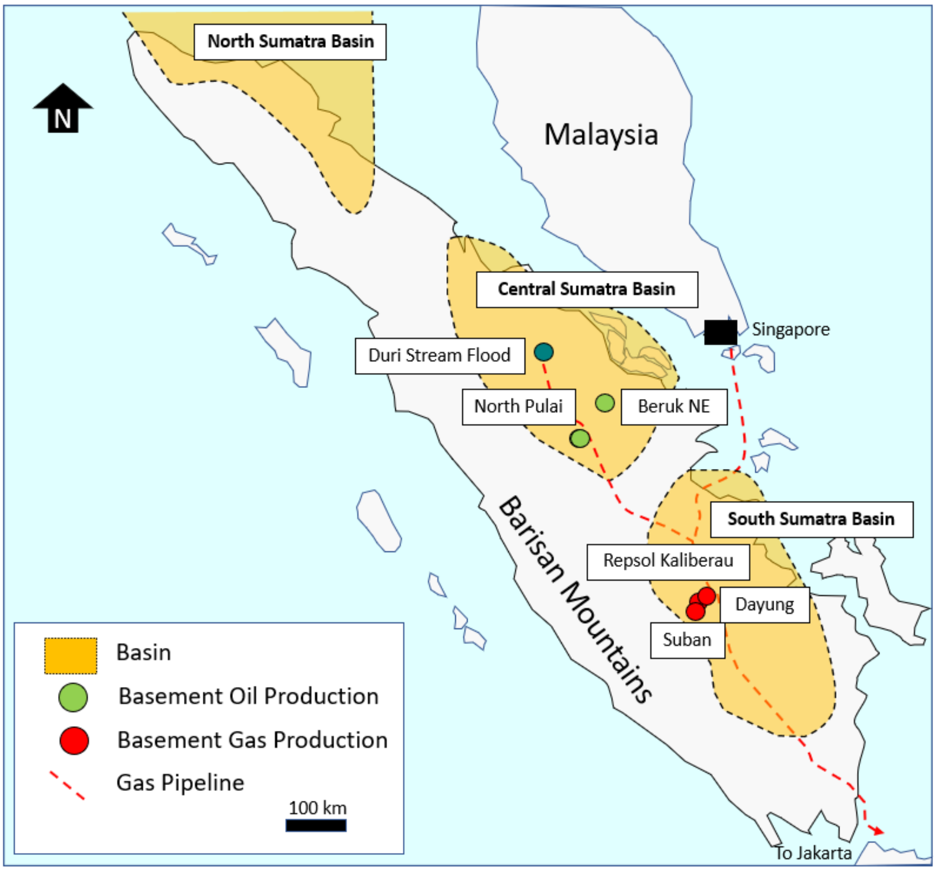


Figure 1. *Location of the discussed basement oil and gas discoveries. More detail on basement hydrocarbon occurrences in the South Sumatra Basin is provided in Figure 2.*

During the many decades of exploration in Sumatra, little attention was placed on exploring for oil or gas in basement. This lack of interest in basement is due to a general perception of the industry worldwide that basement is typically "tight" and did not warrant investigation. Most discoveries of oil and gas in basement were made "by accident" rather than by deliberately exploring the basement. Giant oil discoveries in naturally fractured and weathered basement in Venezuela in 1953, Libya in 1965 and Vietnam in 1975 (Koning, 2020) encouraged more exploration worldwide in basement. However, exploration in basement in Sumatra remained minimal until 1991 when the first major basement gas discovery was made in the South Sumatra Basin.

SOUTH SUMATRA BASIN

Oil was first discovered in the South Sumatra Basin in 1896 in the Kampong Minyak field (van Bemmelen, 1949). In the Palembang sub-basin of the South Sumatra Basin, oil and gas in basement was discovered in 1913 in the Kluang Field (Martin, 1952). The Sei Teras pool (Tiwar and Taruno, 1979), which was discovered in 1977, flowed a minor amount of oil and gas from basement. In 1988, Pertamina discovered oil and gas in basement in the Kuang area in the ASD-1 well which flowed oil at 1,824 BOPD from granodiorite (Sardjito et al., 1991). Subsequent wells were less productive

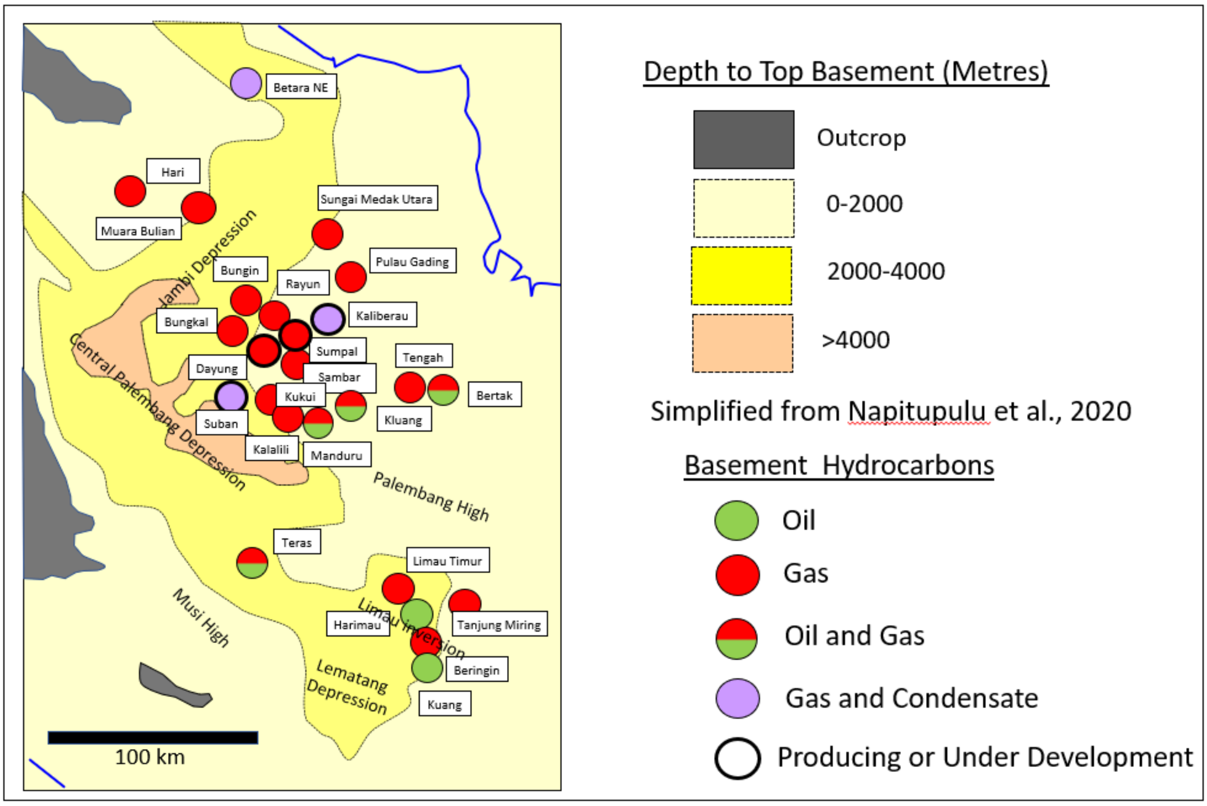


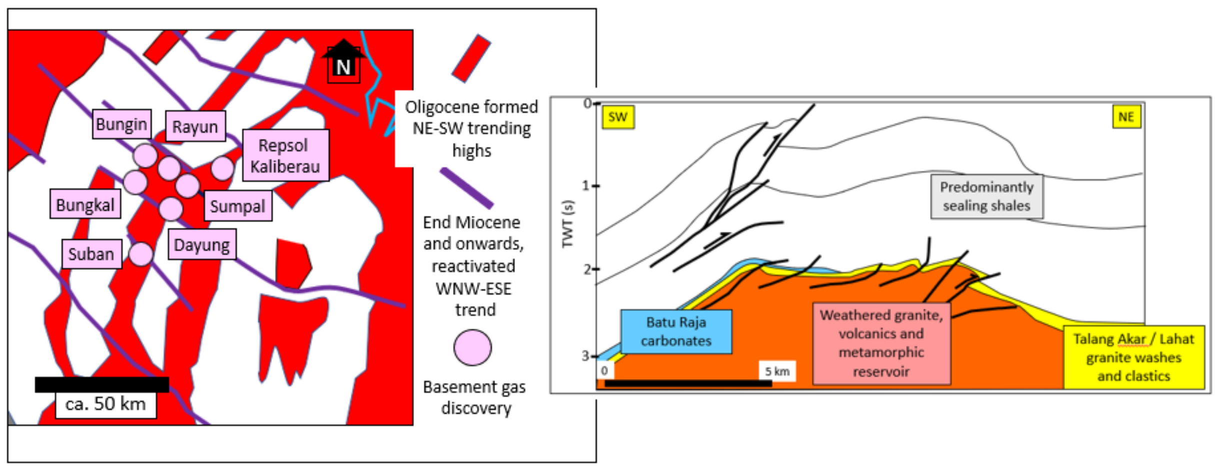
Figure 2. *South Sumatra Basin basement hydrocarbon occurrences. Their pattern is suggestive of a dominant hydrocarbon expulsion direction up-dip eastwards out of the source bearing depocentres. Clearly demonstrated by Napitupulu et al, (2020) is the ideal location of the Suban region to trap large volumes of migrating hydrocarbons owing to the proximal location of the depocentres and, more critically, the exceptional vertical relief of the structures.*

with oil flow rates between 6 – 88 BOPD from basement.

This abruptly changed in 1991 with the discovery by Gulf Indonesia (legacy Asamera Oil) of a major gas field in basement at Dayung-1. This well in the Gulf-operated Corridor Block was rapidly followed up by seven more major basement gas discoveries that culminated in 1998 with the finding of the Suban Field with 5-7 TCF of gas and condensate reserves. The gas reserves of these eight discoveries were estimated at 15 TCF (Zeliff, 2001). Repsol's discovery in 2019, now called the Kaliberau Field, is the first major discovery of gas in basement reservoirs in the last two decades in the South Sumatra Basin.

A more recent discovery of gas in a basement 'buried hill' was the NEB-X-1 exploration well drilled by China National Petroleum Corporation (CNPC) in 2017 on the Jabung Block which tested gas at 2.1 MMCF/d and condensate at 240 BCPD (Ming et al., 2019). Though our records remain incomplete, Figure 2 demonstrates that basement hydrocarbon shows are surprisingly widespread throughout the South Sumatra Basin.

The basement reservoirs comprise Jurassic granites and metasediments whose ages range from Carboniferous to Jurassic (Barber and Crow, 2005). The complexity of the play is illustrated by the lithologies of the Dayung Gas Field where the host rock which includes Permian marbles is invaded by hydrothermally altered granites (Darmadi et al., 2013 and Sagita et al., 2008). As is apparent from Figure 3a, the gas discoveries lie at the intersection of two trends. These are: 1) NE-SW running, rift related highs formed during the Oligocene and 2) late Miocene and younger, WNW-ESE aligned, compressional features formed above Mesozoic lines of weakness (Figure 3b). Maximum fracturing is likely in such settings. The rift created



a) Basement gas discoveries are associated with trend intersections (simplified from Ginger and Fielding, 2005)

b) Suban Gas Field viewed in the dip directions is an evolving compressional structure (simplified from Hennings et al., 2012)

***Figure 3**. Structural influences on the South Sumatra Basin basement gas discoveries.*

Formation	Oil (Bboe)	
Late Miocene Muara Enim	0.2	
Middle Miocene Air Benakat	0.6	
Early Miocene - Middle Miocene Gumai	0.1	
Early Miocene Batu Raja	1.0	
Early Miocene - Late Oligocene Talang Akar	2.0	
Basement gas found including Kaliberau	2.8	(17 TCF)
Estimated yet-to-find basement gas	0.8	(5 TCF)
Total oil and gas	7.5	

Table 1*. South Sumatra Basin: estimated ultimate oil and gas production.*

highs which survived as "buried hills" in the Miocene before being covered by Gumai sealing shales. They were subject to deep weathering and are the origin of Talangakar reservoirs sands and granite washes. The gas was sourced from the Talangakar and Lahat succession (Clure, 2005).

Wells with sustainable flow rates more than 200 MMCF/d have been reported such as in the Sumpal Field. Most of the Corridor Block fields have clearly defined gas-water contacts and the basement traps are filled to spill-point. In the Suban Field, the gas column rests on water and has a height of 1,450m. In some Suban wells, granitic basement is deeply weathered with up to 155m of weathering (Hennings et al., 2012) thereby creating a thick section of reservoir rock at the top of basement. The excellent gas deliverability of the basement reservoir is illustrated by Suban-11 which had an Absolute Open Flow (AOF) rate of 1 BCF/d and deliverability rate of 150 MMCF/d. Well trajectories are critically important since wells must be drilled perpendicular into the dominant fracture orientations to maximize gas production (Hennings et al., 2012). The highest flow rates are associated with active fracturing and tracking their location is a critical factor in optimizing the field's development (Schultz et al., 2014 and Figure 2b).

Data on the composition of the gases in basement in the Corridor Block fields are limited. Abdurrahman et al. (2015) reported carbon dioxide (CO_2) ranges from 32 – 90%. Suban is distinctive in having a much lower CO_2 content of only 5.5% (Gulf Indonesia, 1999). This field supplies more than 70% of the gas production from the Corridor Block (Mohede et al., 2014). The CO_2 must be removed prior to the gas being exported by pipeline.

Table 1 presents our estimate of the basin's ultimate oil and gas production. It was prepared from various sources including Bishop (2001) and Darwis et al. (2007).

A 'super basin' is defined by the American Association of Petroleum Geologists (AAPG) as a basin that has produced at least 5 billion barrels of oil equivalent (BBOE) and contains at least another 5 BBOE future production (Fryklund and Stark, 2020). Based on our analysis, the South Sumatra Basin is on the verge of becoming a super basin due to the continued impact of the basement gas play. We consider it reasonable to assume that at least a further 5 TCF of basement gas could be discovered given pattern of expulsion suggested by Figure 2. Our estimate of 5 TCF entails finding, for example, no more than one more Suban or five Dayung-sized fields.

CENTRAL SUMATRA BASIN

The Central Sumatra Basin has produced prodigious volumes of oil since the Duri oil field commenced production in 1944. This basin is classified as a super basin. Except for the small North Pulai and Beruk Northeast basement oil pools, all the production in this basin has been from Oligocene and Miocene clastics. The giant Duri heavy oil field was discovered in 1941 and has produced 2 billion barrels of oil. The giant Minas oil field, discovered in 1944, is the largest oil field in S.E. Asia, has 9 billion barrels original oil-in-place and has produced to date approximately 5 billion barrels of oil.

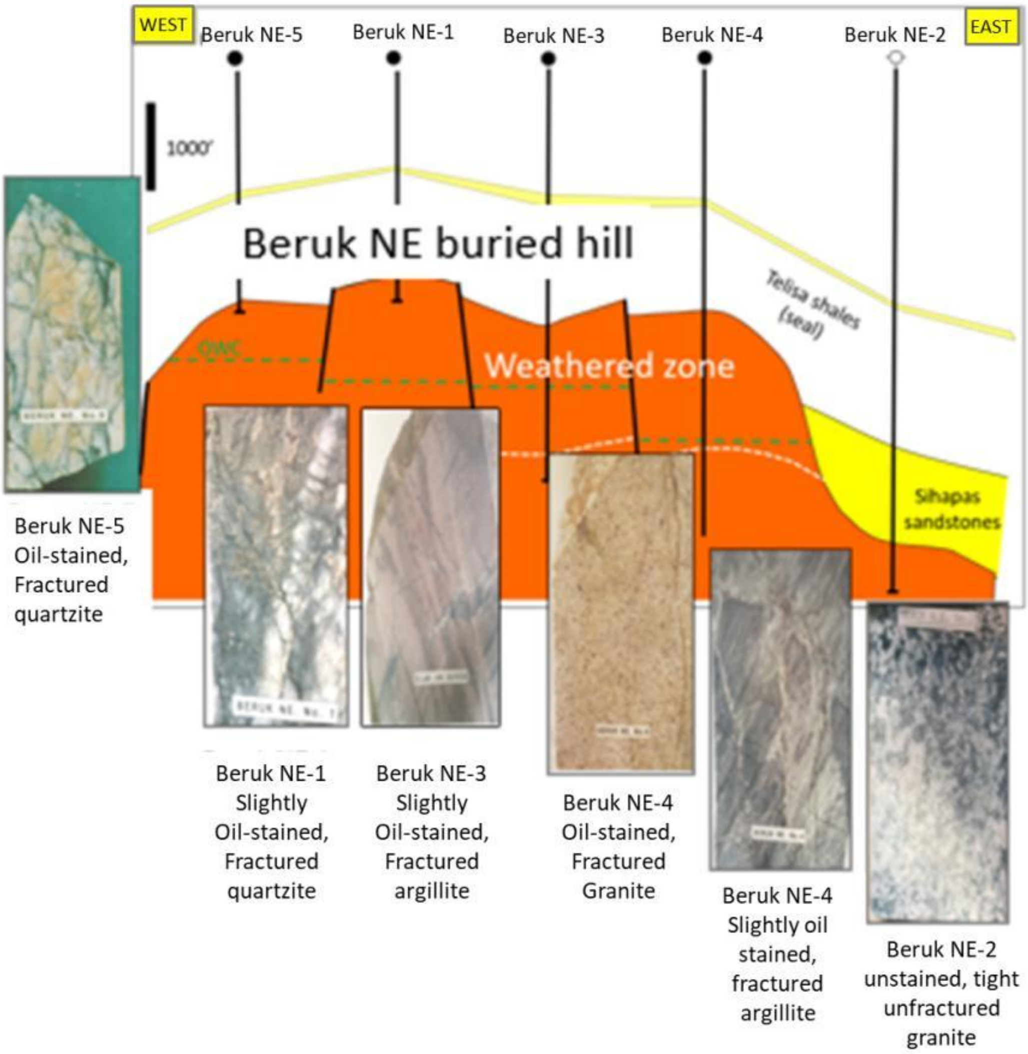


Figure 4. *Beruk Northeast oil field cross-section and basement cores. All the cores were taken at the bottom hole, and each are about 15 cm long (modified after Koning and Darmono, 1984).*

The first discovery of oil in basement in the Central Sumatra Basin was the small North Pulai field found in 1951 within a faulted anticline located on the Lirik Trend (Clure, 2005). The basement reservoir consists of Pre-Tertiary quartzites which is overlain by late Oligocene Lakat sandstones. A 49.5m oil column occurs in basement and the overlying Lakat sandstones have a 74.0m oil column. Net pay in basement was 4.3m and in the Lakat was 7.9m (Courteney et al., 1991). Cumulative oil production up to 1990 from North Pulai was 37.5 MMBO with presumably half (19 MMBO) from basement and the other half from the Lakat. Pertamina is the operator of the North Pulai field.

In 2011, Pertamina drilled exploration well Nira-1 located geologically on-trend with North Pulai. Nira-1 penetrated 350m of metamorphic basement and discovered noncommercial biodegraded heavy oil in basement and was abandoned (Wahyudin et al., 2015). From the same trend, Setiawan et al. (2013) described the 1982 basement discovery in the S-2 well. This well produced oil, but only limited information is available. The records point to a marginal oil discovery, perhaps a single well oil pool. We suspect the primary reason for the lack of success in this well is the presence basement rocks consisting of greywackes, argillites, phyllites and volcanics, which are rock types that tend have only tight fracture systems and are not conducive to deep weathering.

More significant was the discovery of oil in basement in the Beruk Northeast oil pool. BNE-1 was drilled by Caltex (Chevron & Texaco) in 1976 and tested oil at 1,600 Bpd from fractured quartzite (Koning and Darmono, 1984 and Figure 4). Beruk Northeast was placed on production in 1981 and experienced rapid influx of formation water. Cumulative oil production has been only 2.6 MMBO. The disappointing results are due to poorly defined thin oil columns in basement and the high variability of the basement lithologies.

Noteworthy also is that more recently Caltex drilled a few wells into the basement high beneath the Minas oil field. We have learned through informal communications that those wells were water-bearing. The failure of these wells is attributed to the absence of a sealing shale overlying basement.

Beruk NE well	Lithology	Age	Oil flow rate (Bpd)
BNE-1	Quartzite	Permian	1600
BNE-2	Granite	Jurassic	Tight
BNE-3	Argillite	Cretaceous	200
BNE-4	Granite	Triassic	200
BNE-4	Argllite	Cretaceous	200
BNE-5	Quartzite	Undated	2252 (34% water cut)

Table 2. *Beruk Northeast pool. Basement lithologies and initial oil production flow rates.*

Although exploration in Pre-Tertiary basement in the Central Sumatra Basin has been discouraging, the lack of success is also because there has been little serious and deliberate exploration for oil and gas in this basin. Most wells in the basin only "tagged" into the top of basement and may have "left behind" significant oil or gas fields. In many parts of the Central Sumatra Basin, the organically rich, world class Pematang Formation Brown Shales rest directly on basement and could feed oil or gas directly into underlying or adjacent fractured or weathered basement. The Brown Shale would serve as both a source and seal.

NORTH SUMATRA BASIN

The geology of the North Sumatra Basin has been published on by many researchers including Cameron et al. (1980). The North Sumatra Basin is the least oil-productive of Sumatra's three basins. However, it does contain the super-giant Arun gas field with reserves of 15 TCF gas (Meckel, 2013). No oil or gas has been reported from definite basement in this basin, although in the literature hydrocarbons within the Eocene-aged, Tampur carbonates are often referred to as basement occurrences (for example Wahyudin et al., 2015). Our opinion is that this basin has the geological ingredients required to contain significant, true basement hosted, oil and gas deposits. Especially favorable is the deep succession below the Arun region with its narrow horsts and deep Bampo source grabens (Meckel, 2013).

WHY JUST THE SOUTH SUMATRA BASIN?

It remains unclear why only the South Sumatra Basin has yielded significant

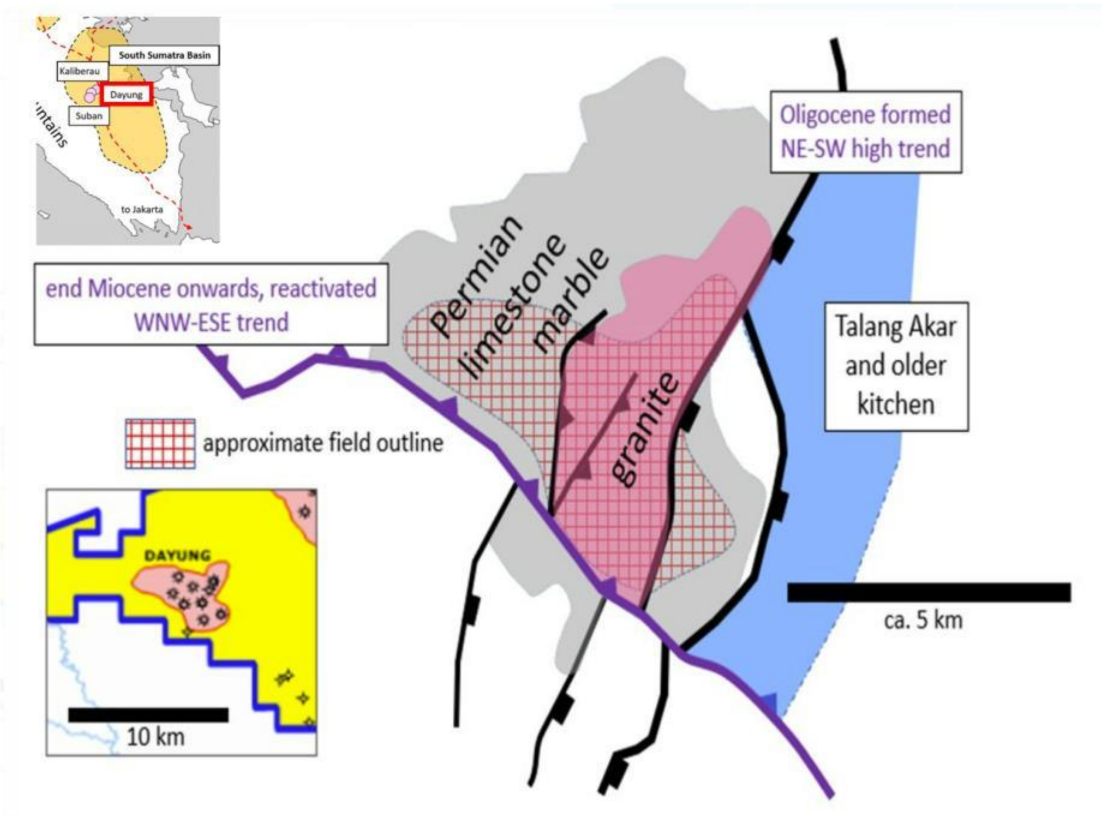


Figure 5*. Dayung Field outline and top basement surface. Modified after Sagita et al. (2008) and Permana et al. (2016).*

basement finds when the geology of the Central and North Sumatra basins with their rich source succession is optimal for their presence given the island's long history of basement disruptive tectonics. One reason may be a lack of deeper basement intersections as top basement shows are not uncommon as is evident from Figure 2. For the South Sumatra Basin, two other factors are in play. The first is that the cross-cutting fault sets are prominently developed at the gas discovery locations. The second and perhaps critical one is, following the publication by Sagita et al. (2008) of Tertiary radiometric ages from the hydrothermally altered granites at Dayung, is that rather than fractured, Pre-Tertiary basement, it is altered granites and their hydrothermal aureoles that are supplying prolific pay zones. Furthermore, it could be that intrusions are focused on the fault set intersects resulting in the further enhancement of porosities. Such a possibility is evident in the figures provided by Sagita et al. (2008) and combined to form Figure 5.

It is these granites and their aureoles that we consider will yield the bulk of the additional 5 TCF yet-to-find gas for this basin. Given the induced, hydrothermal nature of the porosity, conventional structural traps may not be required, provided there is access to migrant hydrocarbons and top seal exists. Smaller finds may now be economic since the infrastructure for their development already exists. Wood Mackenzie (Anon, 2019) regard the economic cut off as 300 BCF for satellites to producing fields. However, in the past year the price of gas in Asia has increased dramatically mainly due to significantly increased imports of LNG (Liquified Natural Gas) by China. Accordingly, gas fields with considerably less than 300 BCF may now be economically feasible. Finding such small volume bodies will be limited by the ability of seismic or any other exploration tool to discriminate potential pay.

With growing concerns relating to increasing atmospheric CO_2, higher CO_2 yielding discoveries are becoming globally less attractive. Already sequestration, always an expensive option, to Suban has been proposed as the means of disposing the 26% CO_2 present at Kaliberau (Energy Voice, 2021). A consequence is that low CO_2 plays such as that associated with the Suban granite may become the preferrable target. An attraction here is the size of this discovery compared to hydrothermally related fields such as Dayung. Weathered granite plays, as they tend to form "buried hills", such as at Beruk Northeast, will be simpler to locate.

ECONOMIC IMPACT

The economic impact for Indonesia of South Sumatra's gas production is highly significant. For example, following the development of the Corridor Block's basement gas fields, in 2001 Singapore signed a 20-year agreement with Indonesia to buy 2.3 TCF gas from South Sumatra for $9 billion. The agreement called for Indonesia to export 350 MMCF/d through a 500 km pipeline constructed between the two countries. Total gas production from South Sumatra was assessed by Abdurrahman et al. (2015) to be 1.9 BCF/d, almost 70% of which was supplied by ConocoPhillips. Deliveries are to the Duri Steam Flood, Singapore, and Java. Further exploration for gas in the South Sumatra Basin is strongly supported by the Indonesian government which is aiming to double the nation's gas production in the next 10 years and become one of the top global gas exporters (Harsono, 2020).

However, in the short-term Indonesia is faced with a looming natural gas deficit estimated to happen in 2025 when consumption is greater than domestic supply. To partially mitigate this deficit, in 2019 Pertamina signed a long-term contract with Anadarko Petroleum to buy 1 million tonnes per year of LNG for 20 years from the yet-to-be-constructed Mozambique LNG terminal (Tan, 2019). On February 10, 2020, Indonesia's Downstream Oil and Gas Regulatory Agency (BPH Migas) announced that Indonesia would stop gas exports to Singapore in 2023 to meet the ever-increasing domestic demand for gas. The announcement said that this would create added value for Indonesia's natural gas by using gas to replace oil for power generation and reduce its trade deficit as the use of gas would lessen the consumption of expensive imported oil. The gas is also much needed by industries in Indonesia such as petrochemicals, fertilizers, ceramics, and steel. The government strongly encouraged Repsol to fast track the development of Kaliberau so it can be producing gas by 2024 – 2025 (Evans, 2020). This has resulted in positive action with Repsol having now re-entered KBD-2XST1 and completed the well as a production well. The first infill well has also been drilled and completed as a gas producer (Energy Voice, 2021).

Accordingly, it is our view that there is potential for more gas discoveries in Sumatra such as the Kaliberau basement gas discovery which will be much welcomed by Indonesia's government and economy.

ACKNOWLEDGEMENT

Mike Crow provided guidance on the nature and origin of the igneous bodies in the Suban and Dayung fields. We also wish to acknowledge MapStand for the use of their maps of Sumatra.

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Indonesian Stratigraphic Nomenclature Revision: The first progress report

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ABSTRACT

A team was formed by the Indonesian Association of Geologist (IAGI) in early 2021 to revisit the Indonesian Stratigraphic Nomenclature which was issued in 1996. After 25 years many experts find that the document needs to be updated. The team is a mix of geologists with both academic and industry background. Several representatives from the Geological Agency who are involved in the Stratigraphic Lexicon document were also invited in the discussion. The team meeting was set on a regular basis to evaluate the existing nomenclature and look on areas for improvement. In each meeting the team will discuss a certain section of the nomenclature document. A three-years work programme was set and reported on this article. In the first year the team will investigate areas for improvement, followed by revising necessary content in the second year. Implementation and promoting the nomenclature are planned for the third year.

This short communication aims to engage a wider community on the process in revisiting the Indonesian Stratigraphic Nomenclature. Several examples of discussion topics in the meetings were included in this article. Readers will see potential areas for improvement and the team are open for suggestions.

Keywords: Indonesian Stratigraphic Nomenclature, Stratigraphic Lexicon, volcanostratigraphy, lithostratigraphy, lithodemic

Manuscript received July 28th, 2021, revised manuscript received August 10th, 2021, final acceptance August 12th, 2021.

DOI: 10.518535/bsed.2021.47.2.39

INTRODUCTION

In January 2021, the leadership of the Indonesian Association of Geologist (IAGI) formed a team to update the Indonesian Stratigraphic Nomenclature (Sandi Stratigrafi Indonesia or SSI for short). The letter was signed by IAGI former president, Sukmandaru Prihatmoko, and IAGI active president, Muhammad Burhannudinnur. The SSI team is composed of Herman Darman (INDOGEO Social Enterprise, currently with PETRONAS in Kuala Lumpur), Dwandari Ralanarko (Pertamina OSES, Jakarta), Sugeng Sapto Suryono (Gadjah Mada University, Yogyakarta), Hill Gendoet Hartono (Institut Teknologi Nasional Yogyakarta), Dwiharso Nugroho (Institute of Technology, Bandung), Dewi Syafitri (Trisakti University, Jakarta) and Abdurrokhim (Padjajaran University, Bandung). The main task of this team is to revisit the existing Indonesian Stratigraphic Nomenclature which was issued in 1996 (Martodjojo and Djuhaeni, 1996). After 25 years, there is an unofficial consensus among many Indonesian geologists that some parts of the nomenclature need to be updated and improved. The new SSI needs to comply with the International Commission on Stratigraphy and to include recent development in geoscience. The improvement should make the guide clearer for application by geologists in Indonesia.

The 1996 document is a revised version of the 1973 SSI. Soejono Martodjojo was the team lead of the 1973 SSI, which was published by IAGI and he also led the 1996 revision team. The SSI document provides rules and guidance in giving names to specific rock units in Indonesia. It also useful for defining the boundary of a particular stratigraphic unit, provide the procedures in describing a new stratigraphic unit and help in ranking the hierarchy of the stratigraphic units. The rock grouping is based on similarity in their characteristics such as lithology and age. The lithological basis of grouping will generate lithostratigraphy and the age based of grouping is called chronostratigraphy. When the age

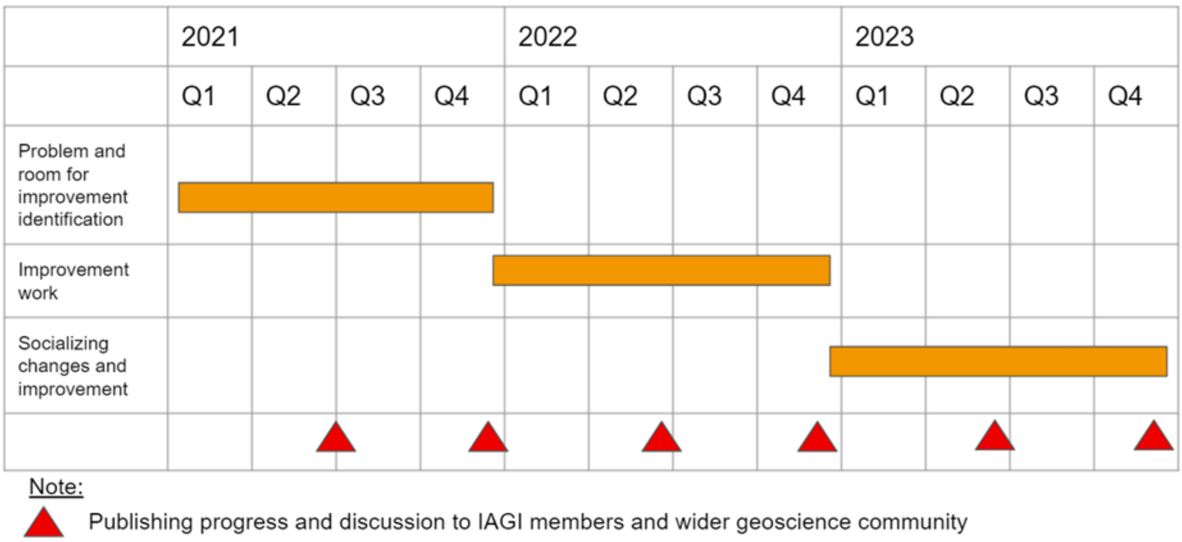

Figure 1. *SSI team working plan, 2021-2023*

grouping is based on their fossil content, it is called biostratigraphy. There are many more methods developed to subdivide the rock units, including seismic stratigraphy, which is splitting the rock units based on their seismic character and, chemostratigraphy, which is based on chemical composition. In the 1996 edition, volcanostratigraphy, sequence stratigraphy and lithodemic have also been included.

The stratigraphic nomenclature provides guidance for Indonesian geoscientists to name the rock formation they observed in the field. The document will go hand-in-hand with the Stratigraphic Lexicon of Indonesia. The first lexicon was prepared by P. Marks and published in 1957 by the Indonesian Geological Agency (Pusat Djawatan Geologi; Marks, 1957). In 2003, the lexicon was updated by the Geological Agency (Harahap et al., 2003) and is currently available online in the following link: https://geology.esdm.go.id/lexicon.

WORK PROGRAMME

The current SSI team has organized several monthly online meetings to review the 1996 SSI. Although the discussions are ongoing, it will probably be worth sharing the team's progress to the IAGI community. The team is expecting input, suggestions, and comments from a wider community, especially from IAGI members.

Starting in July 2021 the SSI team also invited experts from the Geological Agency who deal with updating the Stratigraphic Lexicon; represented by Asep Permana, Rina Zuraida and Ruly Setya. They have been involved in evaluating groups of rocks and assigning official names. In their activities they encountered several issues related to the SSI application, such as applying consistencies among researchers in giving formation names or rock groupings in general. For this task they require an updated SSI which should be in line with the guidance provided by International Commission on Stratigraphy. The SSI team may also provide suggestions

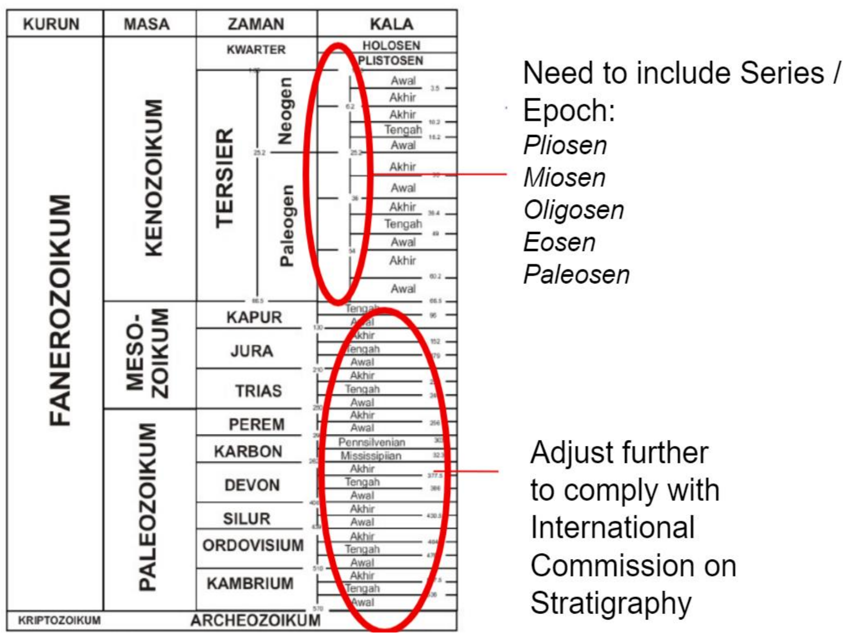

Figure 2. *Stratigraphic table in SSI 1996. Red circles indicate areas for improvement which should follow the International Commission on Stratigraphy.*

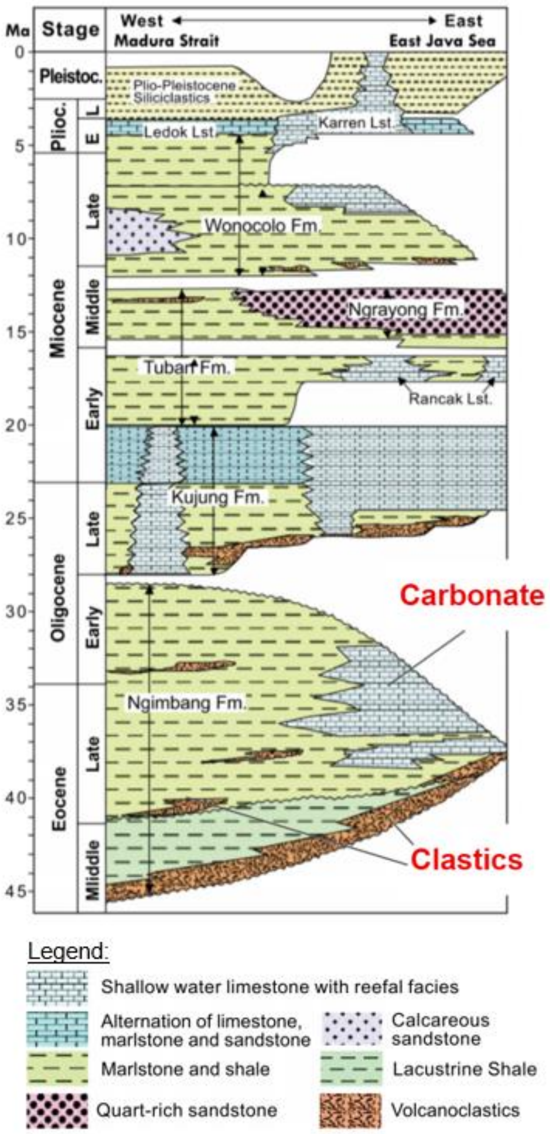

Figure 3. *Generalized stratigraphy of the Cenozoic sediments in North East Java Basin (Syah et al., 2019, simplified from Mudjiono & Pireno, 2001) using updated absolute ages (Ogg, Ogg and Gradstein, 2016). The following abbreviations are used: Fm., Formation; Lst., Limestone.*

to Geological Agency in improving the lexicon.

The SSI team has designed a 3 years' work programme to achieve its target in revising the 1996 SSI as shown in Figure 1. In the first year, the team will identify problems and potential improvement on the 1996 SSI. The team will work on the improvement in the second year and provide cases where the improvement can be applied. The team will socialize the changes in the third year (Figure 1).

DISCUSSIONS

During the last 3 online meetings, the team has discussed four key problems and indicated room for improvement. Firstly, the current Indonesian stratigraphic nomenclature needs to comply with International Chronostratigraphic Chart which is published by the International Commission on Stratigraphy. Therefore, the stratigraphic scheme in the document needs to be adjusted accordingly. Secondly, most publications in Indonesia will refer to Epoch which is currently not included in the stratigraphic scheme. The subdivision of Mesozoic and Palaeozoic and absolute age of each chronostratigraphic boundary also needs to be refined and updated. The consistency between Indonesia and International Chronostratigraphic Chart is the main reason why the 1996 SSI document needs to be adjusted. Figure 2 shows the chronostratigraphic chart in the 1996 SSI and the red circles indicate the room for changes.

The Ngimbang Formation in East Java was discussed as an example of the second problem. This formation is of Eocene to Oligocene in age (Syah et al., 2019; Figure 3) and it contains both clastic and carbonate units, which are commonly called Ngimbang Clastic and Ngimbang Carbonate Formation, respectively. The naming of this formation is against the

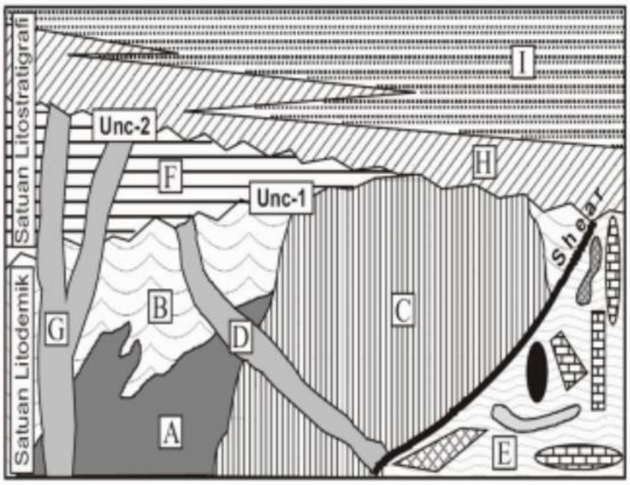

Figure 4. *Lithodemic unit types in the 1996 SSI. The caption is written as follow: A, B, C, D, E and G are lithodemic units. AB is suite one, CD is suite two. ABCD are grouped as supersuite. FHI are Lithostratigraphic units (Modified from NASC, 1993). The rock types need to be mentioned in the caption to give better understanding on how the lithodemic differentiate itself from lithostratigraphic unit.*

lithostratigraphic principle because they have clearly different lithology. This formation is also known as a major source of hydrocarbon supply but has not been comprehensively assessed in terms of its role as a source rock and a reservoir (Pandito et al., 2017). Therefore it is important to name them properly according to the SSI guidance and the SSI Team also saw a requirement to change the lithostratigraphy of formations which contain petroleum system elements.

The third problem discussed is about the lithodemic which is discussed in Chapter II Articles 21-25 in the 1996 SSI. Lithodemic is defined as a group of rocks or bodies of rock whose character is not ruled by the Law of Superposition. A lithodemic unit is a three-dimensional body composed of one or more intrusive, highly deformed or highly metamorphosed rock types, distinguished and delimited on the basis of rock characteristics. This chapter has included a figure (Figure 4), which is adopted from the North American Stratigraphic Code (1983). More detailed explanation of the figure is required to further describe the rock types such as igneous and metamorphic. The igneous rock in the diagram should be defined further as volcanic complex, intrusion, and dike. The SSI may need to set a rule on how it will be defined in map legends as well.

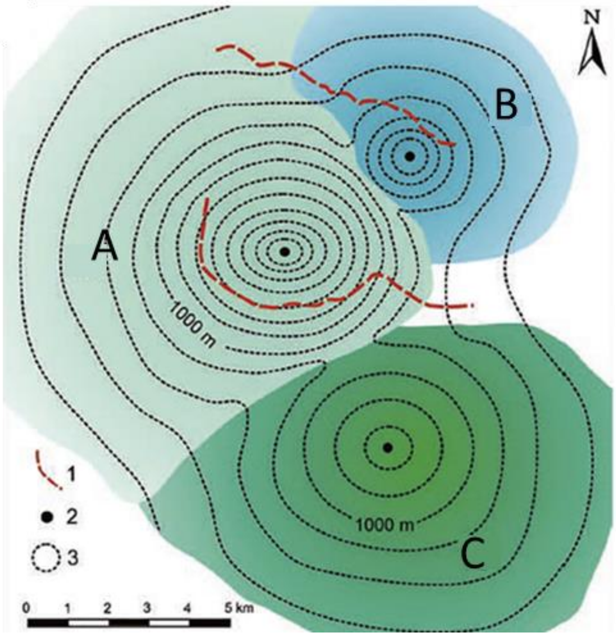

Figure 5. *Distribution map of volcanostratigraphic units (A, B and C) which are derived from their sources, description and genetic. 1) Valley rim; 2) summit vent; 3) contour line (equidistance). This figure could be inserted in the coming SSI edition to explain more on the volcanostratigraphy. Adopted from Marti et al. (2018).*

Volcanostratigraphic nomenclatures are also discussed in Chapter III of 1996 SSI and this is another problem which needs refinement. The volcanostratigraphic units are systematically defined according to source, description and genetic. To give a better understanding on how to apply it on geological mapping or evaluation projects, at least a diagram needs to be included. Figure 5 shows an example of the map which is useful to explain that the volcanostratigraphic units are derived from their source.

CLOSING REMARKS

The SSI Team will continue with regular monthly meetings to discuss more on areas of improvement observed in the 1996 SSI. The examples discussed above shows where the team may work on to come up with an updated better SSI. The team is also expecting active participation from IAGI members and the wider geoscience community. Any suggestion or contribution is welcome to improve the existing 1996 SSI, by sending their comments and concerns to the correspondence author of this article

Engagement with a wider audience will be arranged through webinars organized by IAGI or its sections such as the Indonesian Sedimentological Forum (FOSI) yearly. In case there is an urgent topic to be discussed with the geoscience community, a special event can be arranged.

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ISSN 2807-274X

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