Structural Development, Deposition Model and Petroleum System of Paleogene Carbonate of the Engkabang-Karap Anticline, Onshore Sarawak

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ABSTRACT

To further investigate the hydrocarbon potential of the 400 km^2 large Eocene - Oligocene carbonate body of the Engkabang-Karap Anticline, onshore Sarawak, high-resolution 2D seismic data, aero-gravity and magnetics were acquired by JX Nippon in 2009 and 2010. Interpretation of the latter confirmed the existence of a large carbonate-cored anticline, previously drilled by Shell in 1959-1960 and proving sub-economic gas in a massive 272m section of tightly cemented and dolomitized limestone, with little or no matrix porosity/permeability retained.

Recent drilling results of Engkabang West-1 by JX Nippon confirmed the presence of gas in tight carbonate reservoirs, consisting of mainly mudstone and wackestone, but DST flow rates proved to be un-economic. The latest biostratigraphic analyses of the Engkabang wells indicate the presence of a number of key stratal events related to regional unconformities and hiatuses, suggesting that the basin ramp area saw periods of compression, inversion and/or uplift. The new seismic data indicate significant structural deformation, including strike-slip tectonism and local overthrusting, not seen on older seismic, nor noticed from the interpretation of surface geology. There is also seismic evidence of a low-angle detachment plane, linked to a zone of increased tectonism commonly referred to as the Baram Line. Other than in the nearby Lambir Hills, there is hardly any visible sign of major deformation on the surface, whilst biostratigraphic data of the Engkabang wells suggest the last folding event occurred during the Pliocene. Associated with elements of compressive folding, thrusting and strike-slip movements, the study area seemed to have undergone strong tectonic stresses caused by movements along the nearby Baram Line and Belait Wrench system.

This resulted in active mud volcanism, with the active Karap mud volcano located to the southwest of Marudi Township. Post-folding, peneplanation truncated the anticline, followed by a cover of Quaternary alluvial deposits. The proposed structural model, an overthrust system rooted in a low-angle detachment plane, explains the occurrences of both shallow oil and deep gas, including mud volcanism. This trapping mechanism may also be present in other areas of onshore Sarawak and can be considered as a new hydrocarbon play. Although the petroleum system is relatively well-established with significant potential upside, technical challenges remain to further derisk the carbonate play. The tight reservoir facies encountered in both wells suggest well-developed fracture systems will be needed to improve flow rates, but fracture orientation can only be mapped with properly designed 3D seismic coverage.

Keywords: *Baram Line, Biofacies, Engkabang-Karap, mud volcanism, overthrusting, strike-slip.*

REGIONAL TECTONIC SETTING

The Karap area southwest of Marudi Township along the Baram River in North Sarawak, is formed by low-lying swamp lands, bordered in the north by the Lambir Hills, and to the east by an array of prominent block-faulted foot hills, among these is Bukit Engkabang. It is located in the north-eastern extremity of the Luconia/Tinjar Block (Figure 1), in which the sedimentary sequence consists predominantly of Paleogene claystone (Setap Shale) and carbonates. The stratigraphy of the area is known from outcrops at the edge of the foreland basin such as Batu Gading (Adams & Haak, 1962) and from well data of Engkabang-1 (EK-1; Shell, 1959-1960) and the recently drilled Engkabang West-1 (EKW-1; JX Nippon, 2013-2014). It is noted that, whilst Eocene carbonates in Batu Gading form surface outcrops, the time-equivalent level in Engkabang-Karap carbonate is

buried at a depth of *ca.* 3000m. The well data and existence of the Karap mud volcano (Kessler et al., 2011) confirms overpressures in the subsurface, probably due to under-compaction.

The Baram Line, including the Belait Wrench system, forms the boundary between Luconia/Tinjar and the Baram Delta located to the north and northeast (Kessler, 2009a; Figures 1, 2). Beyond this tectonic boundary, the sediments consist mostly of Neogene clastics belonging to the Belait Group and Setap Shale (Figure 3a). Several wells have penetrated the Neogene clastics, often encountering a hydrostatic regime in sandstone-dominated rock, with minor oil shows. However, overpressures were observed in the deeper, clayey sequences.

A tectonic reconstruction based on 2009-2010 onshore 2D seismic suggests that the Baram Line represents a strike-slip zone with components of reverse faulting/thrusting (Kessler, 2009a, b), a compressional system with the maximum horizontal stress in an angle of less than 90° to the strike-slip zone causing the thrust elements.

Vitrinite reflectance measurements (VRM) on surface coals (Kessler, 2009b), as well as VRM studies of EK-1 samples, carried out on behalf of Shell in the 1960's, suggest uplift and truncation in the order of 500 – 700m. It is believed that this erosion, observed on either side of the Baram Line, may have occurred at various stages of the Late Miocene? to Plio-Pleistocene (Kessler & Jong, 2015).

STRATIGRAPHY OF THE STUDY AREA

The simplified lithostratigraphy for the onshore Baram Delta, as understood prior to the most recent regional study (Core Laboratories, 2010, 2011) and based mainly on outcrop studies, is shown in Figure 3a. In this earlier interpretation the Engkabang carbonate is assigned to the Melinau Formation of broad Late Eocene - Early Miocene age. However, these earlier determinations were broad and limited by the scarcity of well penetrations and age-calibrations made using biostratigraphy techniques limited to foraminifera only. Based on these pre-existing interpretations the regional compilation by PETRONAS (2007, Figure 3b) suggests that the Engkabang carbonate can be subdivided into Engkabang Upper Reefs of Late Oligocene age and a Late Eocene - Early Oligocene section called the Engkabang Lower Reefs.

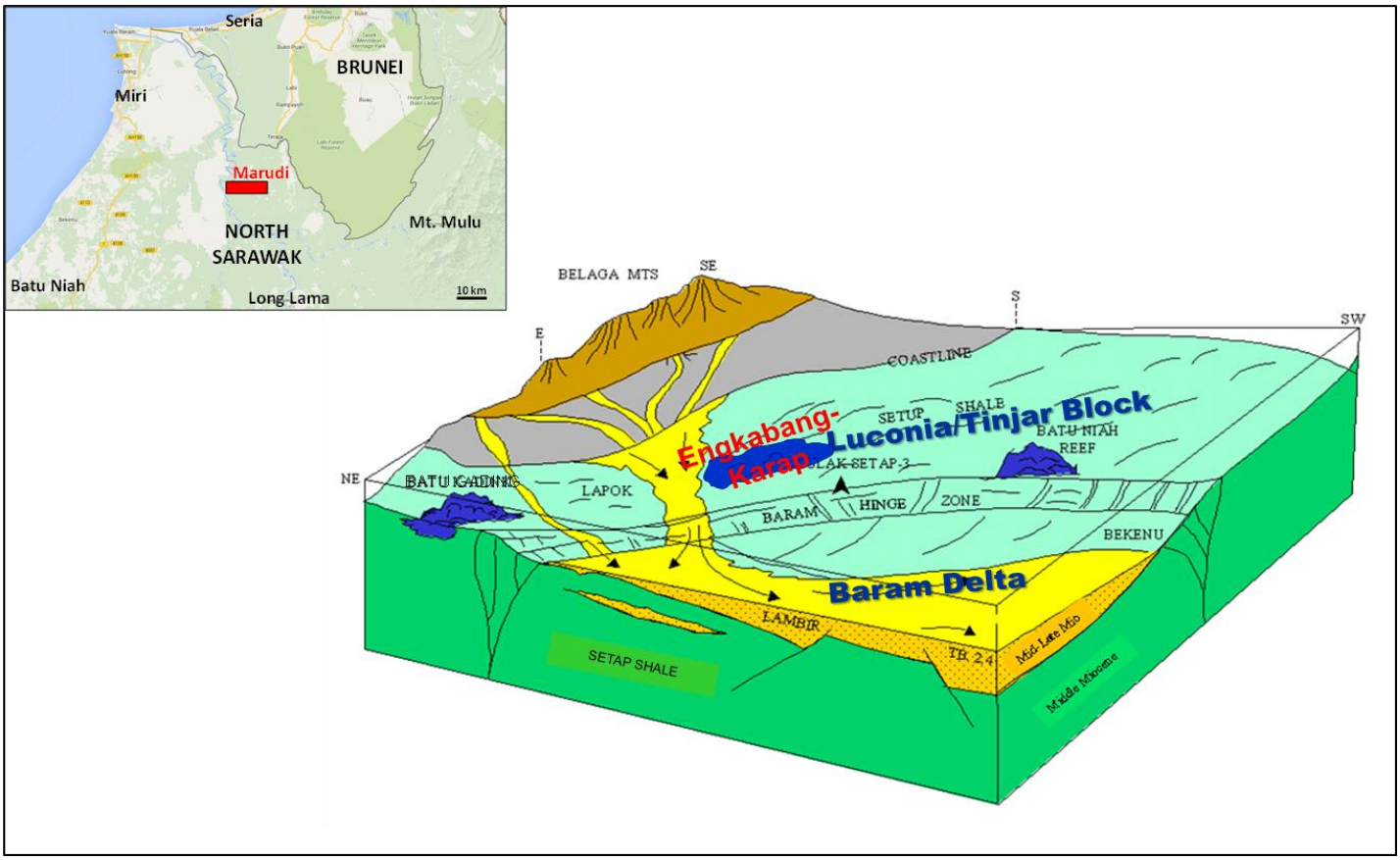


Figure 1. *Schematic block diagram with a regional reconstruction of Late Miocene/Pliocene times. The Luconia/Tinjar Block constitutes the footwall, the Baram Delta the hanging NW block of the Baram Hinge Zone (Baram Line). The latter constitutes an important facies boundary (carbonates dominate in Luconia/Tinjar, clastics in the Baram Delta block). Inversion features Lambir and Miri Hills, Engkabang-Karap and Batu Gading are seen along the lineament (after Kessler, 2009a). Top left inset map shows the region of North Sarawak and neighbouring Brunei with the red rectangle indicates the approximate location of the study area.*

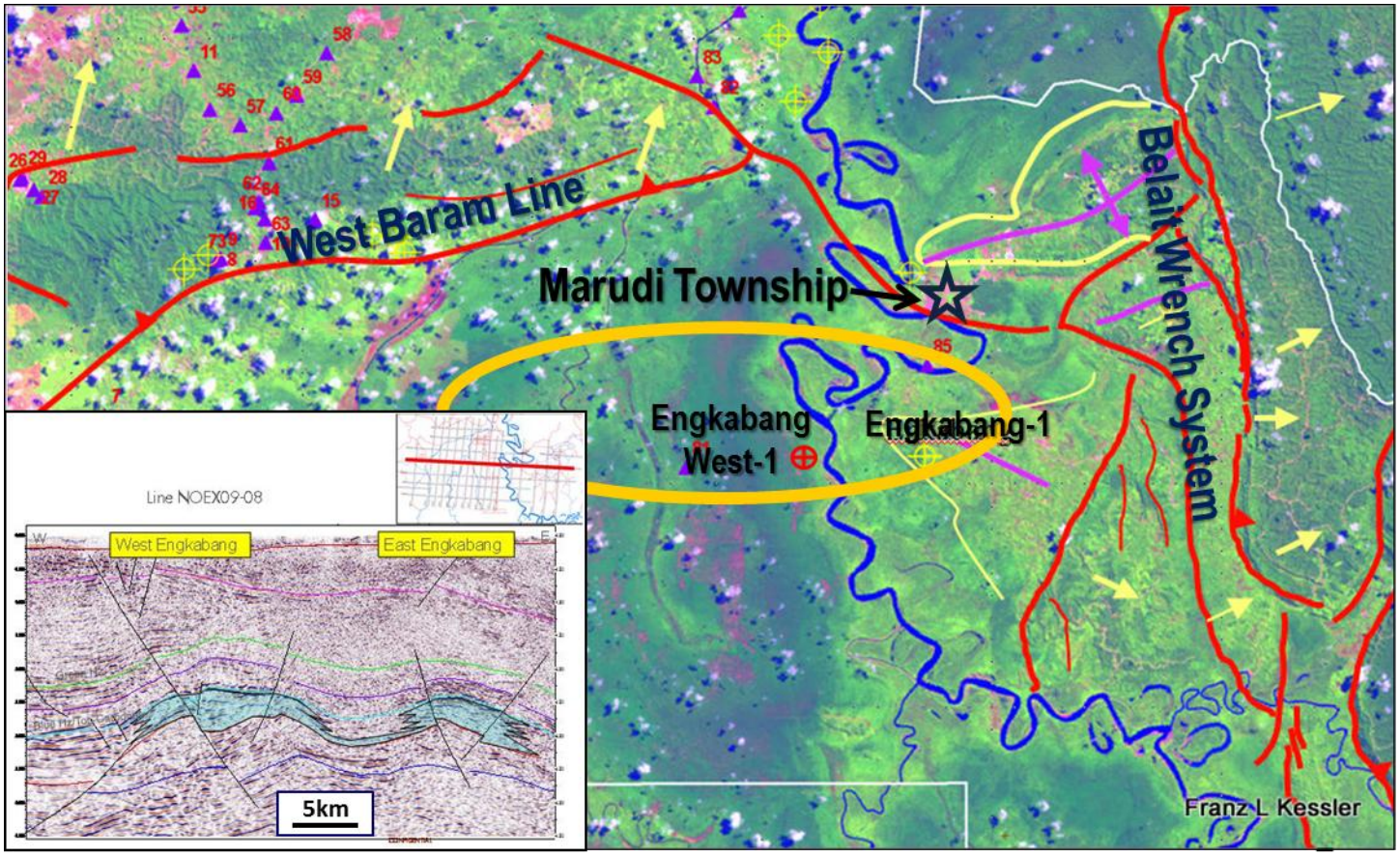


Figure 2. *Tectonic overview map of the Greater Engkabang-Karap study area (enclosed in yellow oval) near Marudi with converging regional structural lineaments of Baram Line and Belait Wrench system. Inset figure shows the new 2D seismic strike section illustrating the East and West Engkabang culminations with carbonate development.*

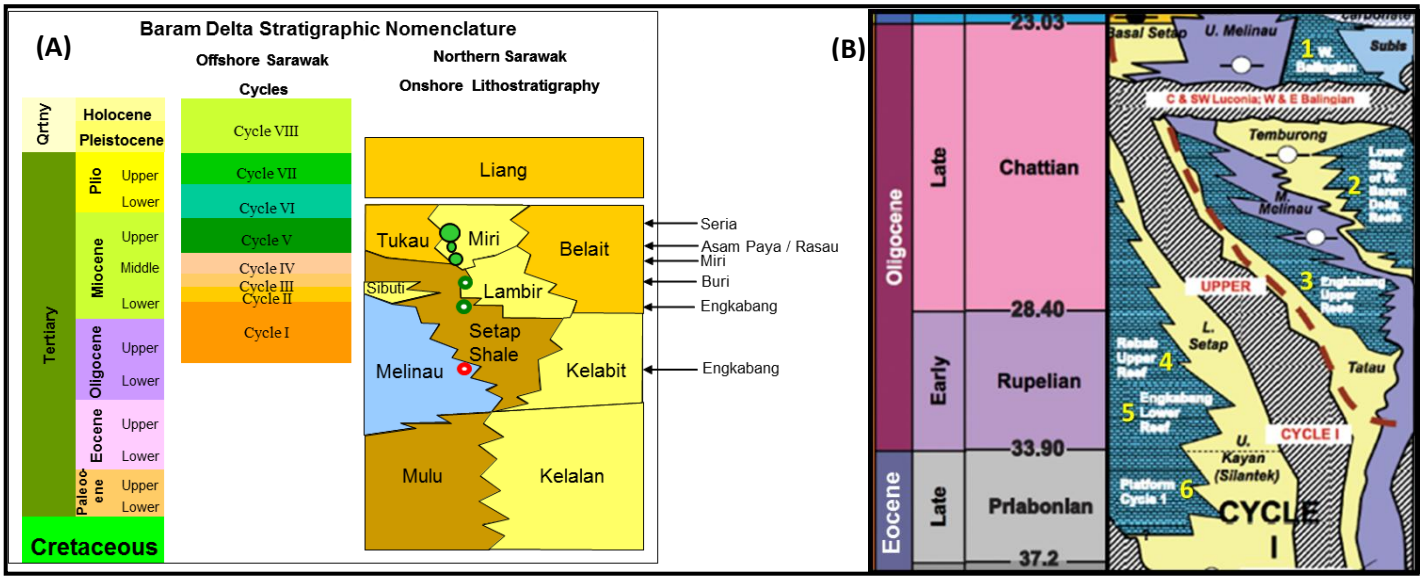


Figure 3. *(A) Baram Delta stratigraphic nomenclature and schematic onshore lithostratigraphy of the study area (generated by JX Nippon), with the Engkabang carbonate assigned to the Melinau Formation; (B) Chronostratigraphic chart for the Eo-Oligocene section of the Sarawak Basin (modified from PETRONAS, 2007, ages in Ma). The various carbonate sections annotated include analogues from 1) West Balingian, 2) Lower section of West Baram Delta Reefs, 3) Engkabang Upper Reefs, 4) Rebab Upper Reefs, 5) Engkabang Lower Reef and 6) Platform Cycle I.*

A new and higher-resolution age model for the Engkabang carbonates was determined during the recent work by Core Laboratories (2010). In this study new samples were selected for detailed biostratigraphic analysis (foraminifera, nannofossils and palynology) of the carbonate section penetrated in the EK-1 well. Unfortunately sample material from this well was limited in

volume and somewhat degraded. To compensate for these limitations, ditch cuttings samples were carefully composited to maximize biostratigraphic recoveries; this was an important stage in analysis for this legacy sample material, ensuring that samples stored since 1959 yielded effective biostratigraphic results. Some core material was also subsequently made available for analysis (Core Laboratories, 2011). The combined results indicated a late Middle Eocene to Late Oligocene age range for the Engkabang carbonates (Figure 4). The basal section of EK-1 represents some of the oldest carbonate rocks penetrated by any wells in the region. The onset of carbonate deposition in the Engkabang Lower Reefs section within Middle Eocene time is older than shown in the PETRONAS (2007) publication, but is similar to that of the Melinau Formation outcrop section of North Sarawak, previously investigated by Adams (1965), and as re-studied by Lunt (2014).

After the 2010 and 2011 biostratigraphy studies, new cuttings samples of the EKW-1 well, drilled in 2013-2014 by JX Nippon were analyzed for biostratigraphy. Age-control and correlation to the EK-1 section was facilitated by onsite foraminifera analysis (N and P zones), followed by laboratory analysis of nannofossils (NP zones) (Figures 4, 5).

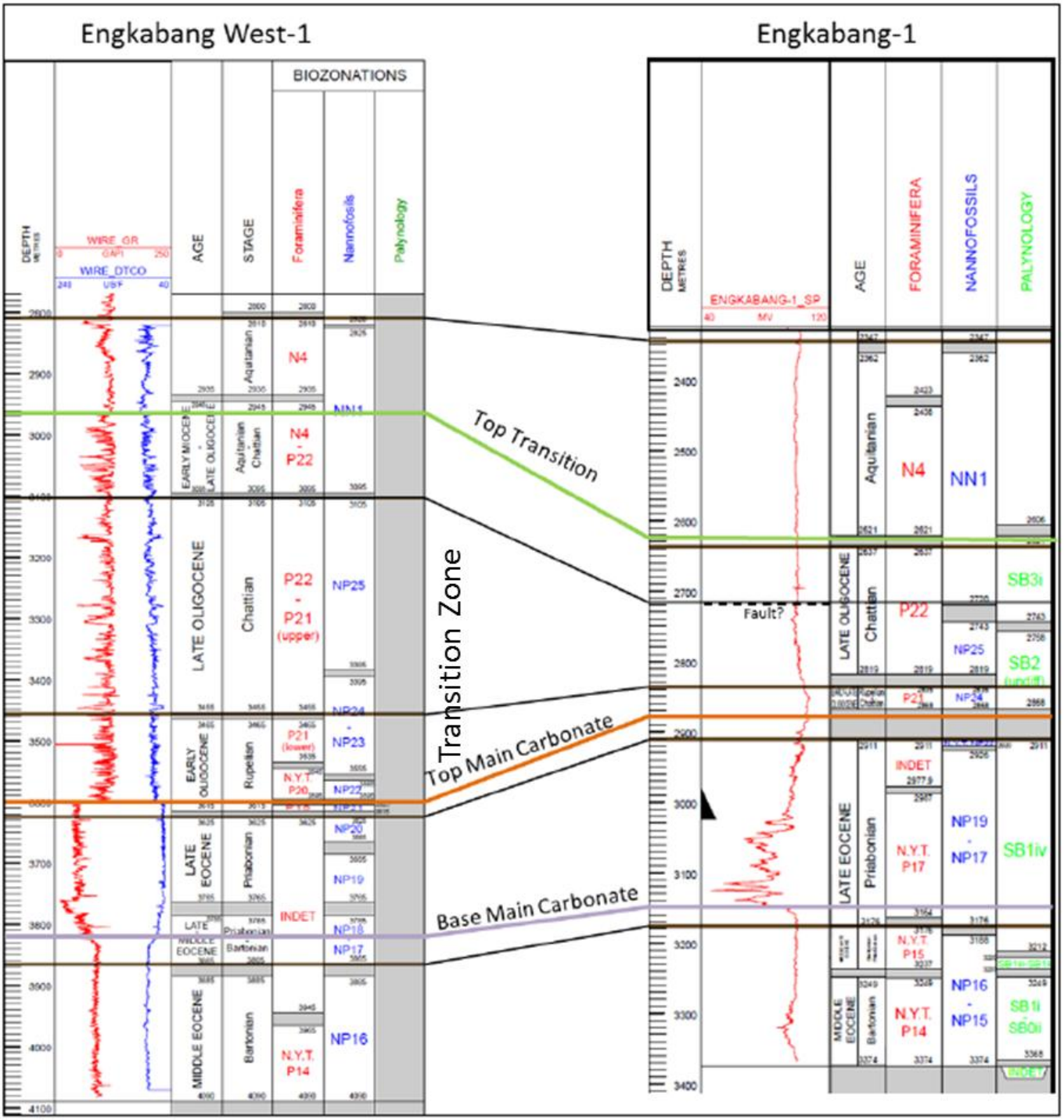


Figure 4. *Engkabang West-1 to Engkabang-1 well correlation after JX Nippon (2014). The reanalyzed biostratigraphic results of EK-1 indicated an age range for the carbonates of late Middle Eocene to Late Oligocene, representing some of the oldest carbonate rocks penetrated by any wells in the region (Core Laboratories (2010, 2011). EKW-1 biostratigraphic investigation by Core Laboratories (2014) confirmed similar-age range for the Engkabang-Karap carbonate section in the well.*

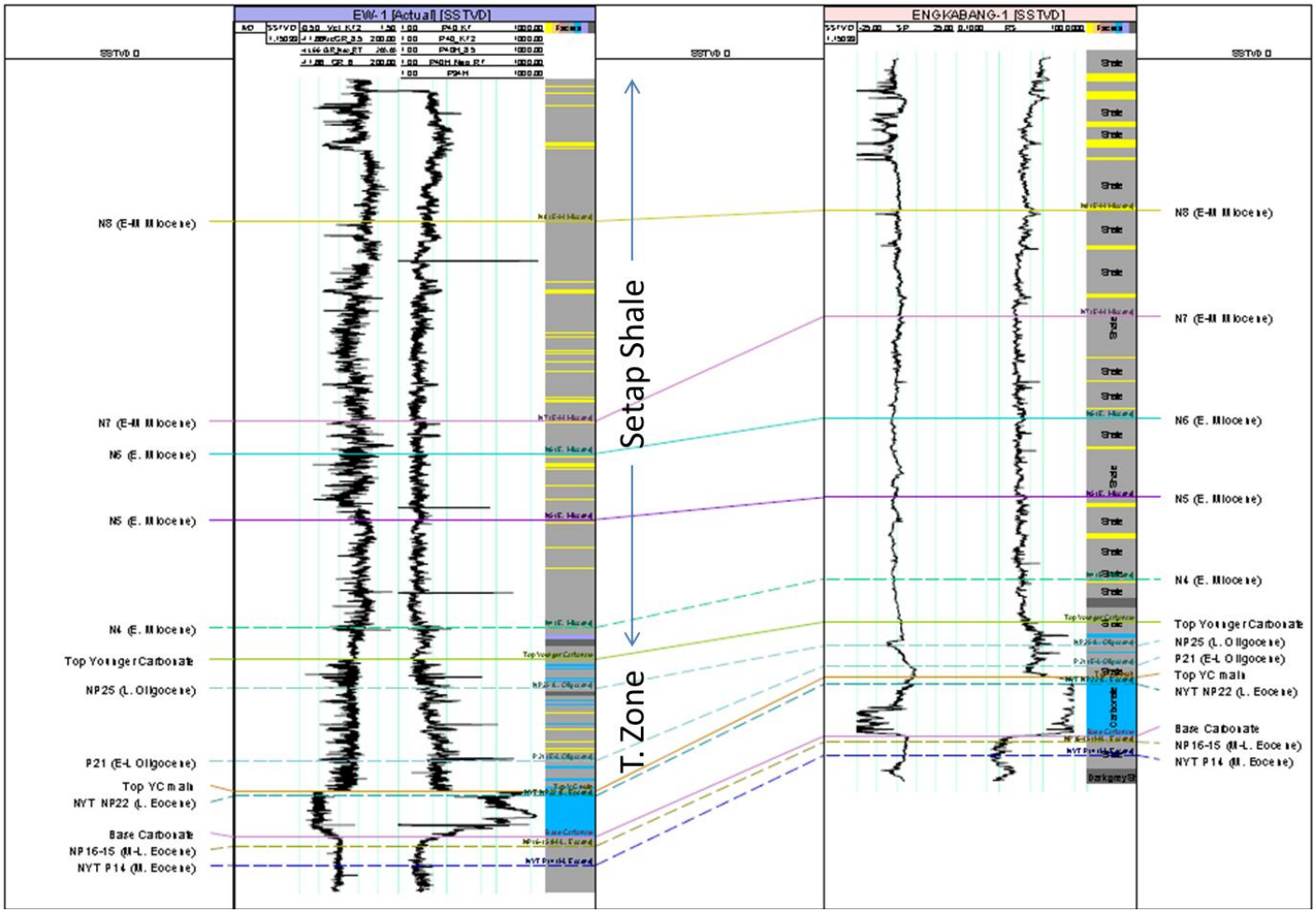


Figure 5. *Engkabang West-1 and Engkabang-1 well correlation based on planktonic foraminifera (N and P zonations) and nannofossils (NP zones) after JX Nippon (2014). It is noted that the "Transitional Zone" (T. Zone) in EKW-1 is an expanded section suggesting possible intra-Oligocene erosion and/or a depositional hiatus at the EK-1 location.*

The lithology and age range of the Early Miocene Setap Shale section in EKW-1 was found to be reasonably similar to EK-1. Biostratigraphic correlations proved to be invaluable, as lithology-only comparison is very difficult due to the homogenous nature of the formation. The top of the Younger Carbonate transitional facies (top Melinau Formation) is defined by lithofacies (the first downhole occurrence of limestone intercalations) and in both wells is coincident with the top of planktonic foraminifera zone P22, the top of regional North Borneo palynology zone SB3i, indicating an age of *ca.* 23 Ma, and the top of the Late Oligocene (Figure 5). The transition lithofacies ("Transition Zone") in both wells consists of silty claystone with intercalations of sandstone and limestone and ranges in age from Early to Late Oligocene in both wells. In EKW-1 the transitional lithofacies is approximately 350m (in TVD) thicker than in EK-1, where the interpreted paleo-environments are similar. A likely interpretation for the difference in thickness could be the presence of depositional hiatuses at the EK-1 location, which might have been subject to slightly shallower environments of deposition than EKW-1 during the deposition of the Transition Zone. In EKW-1 the age of the main part of the Younger Carbonate (Melinau Formation) is Late Eocene on biostratigraphic evidence, which is consistent with the same main carbonate in EK-1. The claystone interval below the carbonate ("Engkabang Marl") is of Middle Eocene age, based on biostratigraphic evidence in both EKW 1 and EK-1. EK-1 penetrated approximately 208m of this shaley interval), whilst EKW-1 penetrated approximately 250m (in TVD) of what appeared to be an equivalent formation.

BIOFACIES INDICATIONS AND ENGKABANG BURIAL HISTORY

Biostratigraphy well reports (Core Laboratories, 2010, 2011, 2014) presented foraminifera, nannofossil and palynology biozones in chronostratigraphic and paleo-environmental context for both the EK-1 and EKW-1 sections. Subsequent work has been completed using high-resolution biofacies and biosequence techniques (Noon, 2015), the details of which will be published separately (Noon, in prep.). The biofacies methodology involves the integration of foram facies, nannofacies and palynofacies. For example, palynofacies involves the detailed interpretation and stratigraphic analysis of "palynosignals". On Figure 6 an example is presented from an Eocene to Early Oligocene section in Southeast Asia (from

Noon, 2015 and in prep.). On this Biostratigraphic Summary Chart each individual sample is displayed as analyzed and interpreted palynosignals are presented. This particular example shows freshwater palynosignals logs in green and intertidal to marine palynosignals logs in blue.

The most important characteristic in terms of how each of the Engkabang Biofacies Units (EJ-EC) were characterized are the trends and surfaces identified by rapid turnover of assemblages between samples, which identify candidate key stratal surfaces as labelled in the figure. The candidate key stratal surfaces identify the boundaries between Biofacies Units. The identification of these key stratal surfaces additionally enable us to identify possible erosion events/unconformities, sediment by-pass events, etc., that are often linked to regional tectonic episodes as well as eustasy-driven sequence stratigraphy. By way of example a potential major tectonic event is identified clearly on Figure 6. For the Engkabang wells the foraminiferal, nannofossil and palynological biozones and paleo-environmental determinations were then reinterpreted in the context of biofacies, enabling the recognition of a number of key stratal surfaces that enabled high-resolution correlations of wireline logs and seismic between the two wells. Key observations based on integrated biofacies and biostratigraphic interpretations were presented recently by Noon (2015, Figure 7).

Biofacies comparison between the two wells is shown on a summary table (Figure 7) on which the key interpreted Biofacies Units in the context of age and biozones (both foraminifera and nannofossil zones) are presented. It is significant that Biofacies Units EG (Late Oligocene) and ED (Middle Eocene) are both recorded in EKW-1 but are apparently absent in EK-1, where they correspond to key stratal surfaces identified on biofacies character. This apparent absence in EK-1 may be due to erosion, and/or a depositional hiatus as proposed in the previous section.

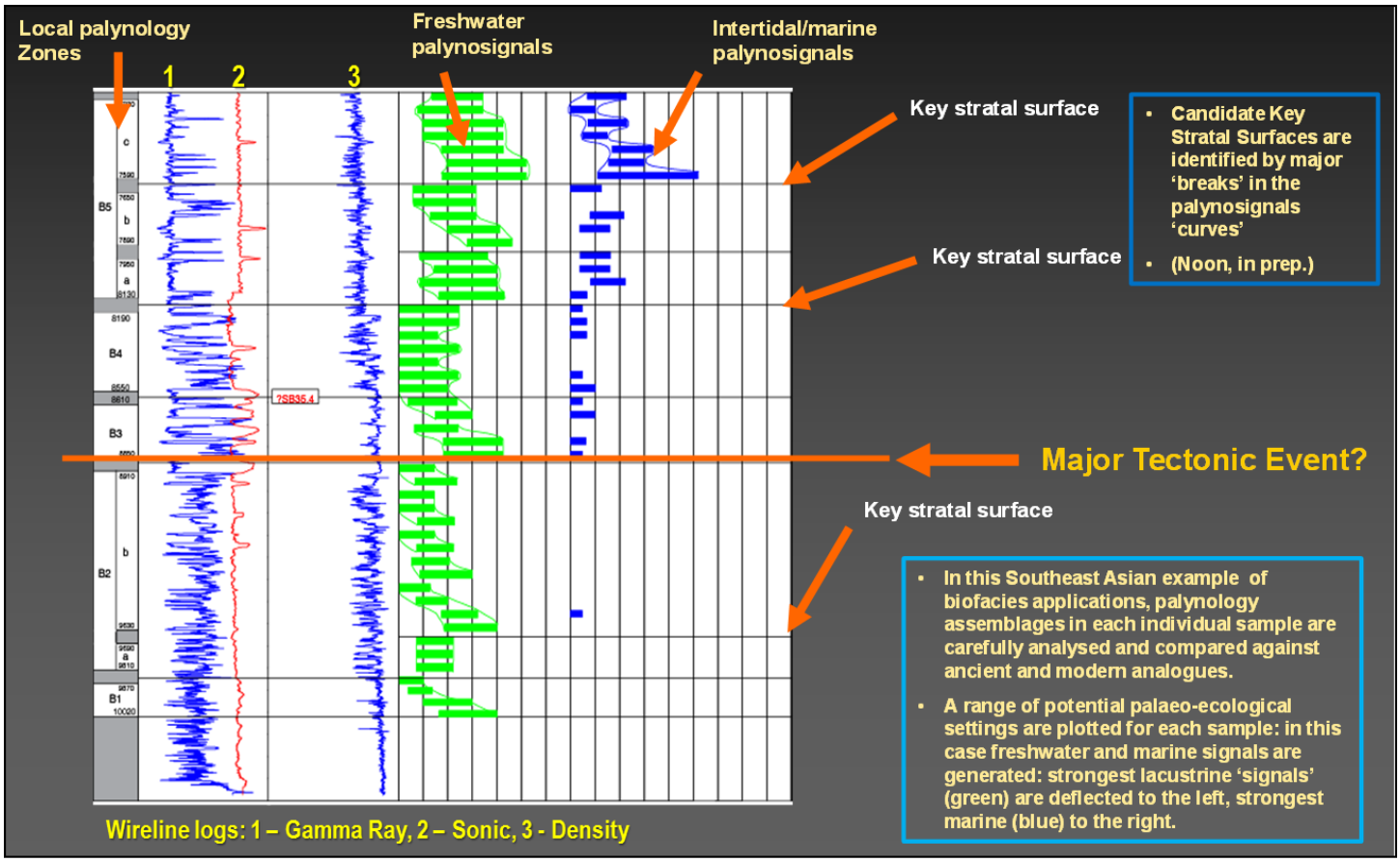


Figure 6. *Example of application of high resolution biofacies technique in establishing key stratal surfaces related to potential tectonic events, showing abrupt change from a fresh water to marine environment, with a generally deepening upward sequences observed (after Noon, 2015). Note detail discussion on the application of biofacies and biosequence techniques, including the study on the Engkabang wells is currently being prepared for a separate publication (Noon, in prep.).*

Preliminary Biofacies Unit (This study)	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

Figure 7. *Paleogene biofacies of EK-1 and EKW-1 (after Noon, 2015). The absence of Biofacies Units EG and ED in EK-1 is likely due to erosion and/or depositional hiatus. Biofacies Units EJ to EC denote the local "Engkabang" biofacies.*

It is of major interest that the key stratal surfaces/unconformities identified by biofacies analysis apparently correspond to major regional tectonic events and Tertiary Sequence Boundaries as discussed in this paper. A burial history profile based on EKW-1 well data was generated (Figure 8), which shows that the multiple inversion intervals/uplifts identified on biofacies characters compare favorably with key regional events (Figures 7, 8):

- Sequence Boundary at 23.0 Ma (Oligocene - Miocene boundary)
- Sequence Boundary at 33.7 Ma (Eocene - Oligocene boundary)
- Possible tectonic erosional event related to Sequence Boundary at *ca.* 37.1 Ma (approx. top Middle Eocene), with its significance in relation to the regional Mid Miocene Unconformity (MMU) and Deep Regional Unconformity (DRU) a current topic of continued research by the authors.

A comparison of the stratigraphy of the Engkabang-Karap area with carbonate outcrops from North Sarawak is currently under way. Data available at this point suggest the greater area subsided from the late Middle Eocene onwards, forming a carbonate ramp with only occasional bioherm development. From the Oligocene to the Middle Miocene, outer shelf environments were established with the deposition of the Setap Shale, occasionally carrying slope turbidites; only in some distinct areas (Batu Niah) and offshore Luconia, carbonate development continued well into the Miocene. Shelfal conditions were re-established in the Middle Miocene, as seen in the Sibuti Formation. From the Late Pliocene onwards, inversion and folding led to an uplift of some 600m (Kessler & Jong, 2015), sometimes truncating the upper part of the Miocene.

RESULTS OF ENGKABANG WELLS

The EK-1 exploratory well was drilled by Shell in 1959-1960 to test 2 targets: sands in the Setap Shale and a deep seismically defined closure (Figure 9). The shallow target was sand-lean and produced oil at 30bbl/day, whilst the deep target found 272m of massive dolomitic limestone with minor shale intercalations.

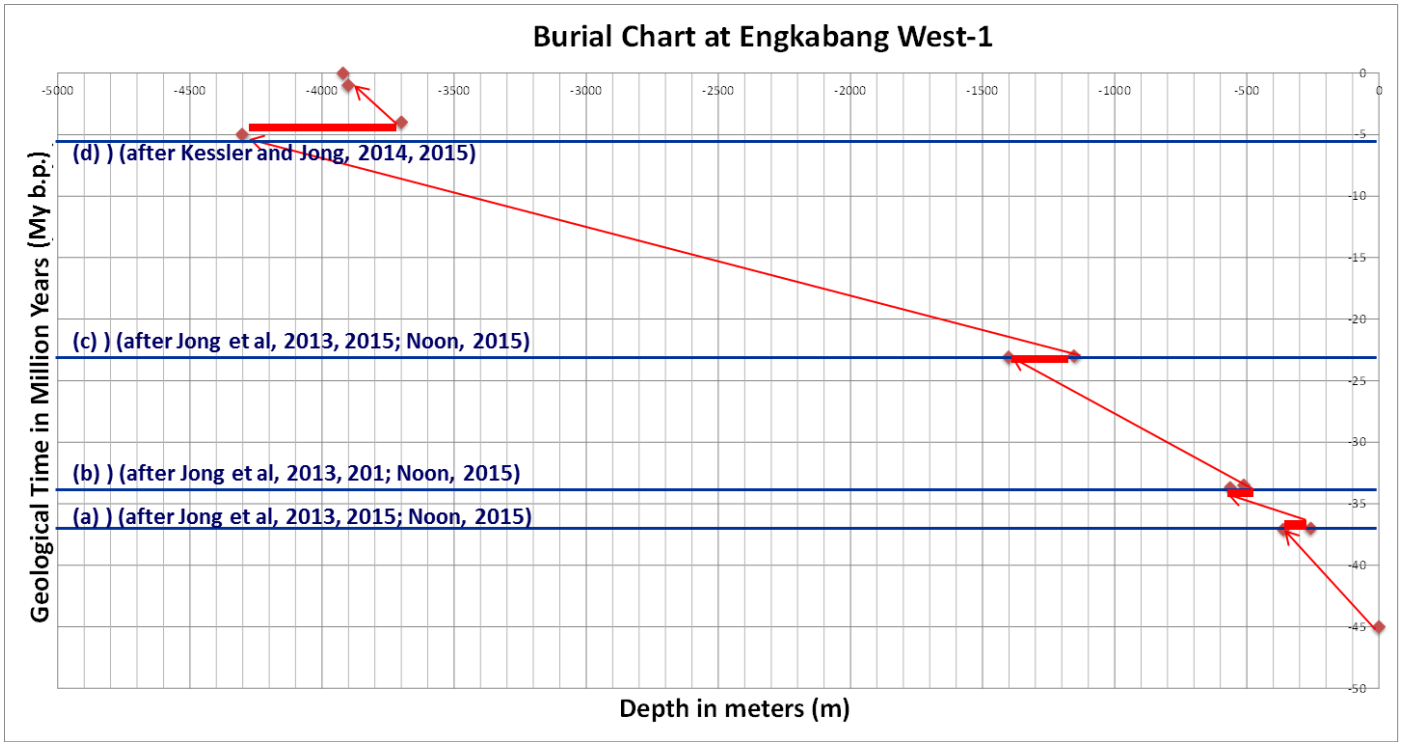
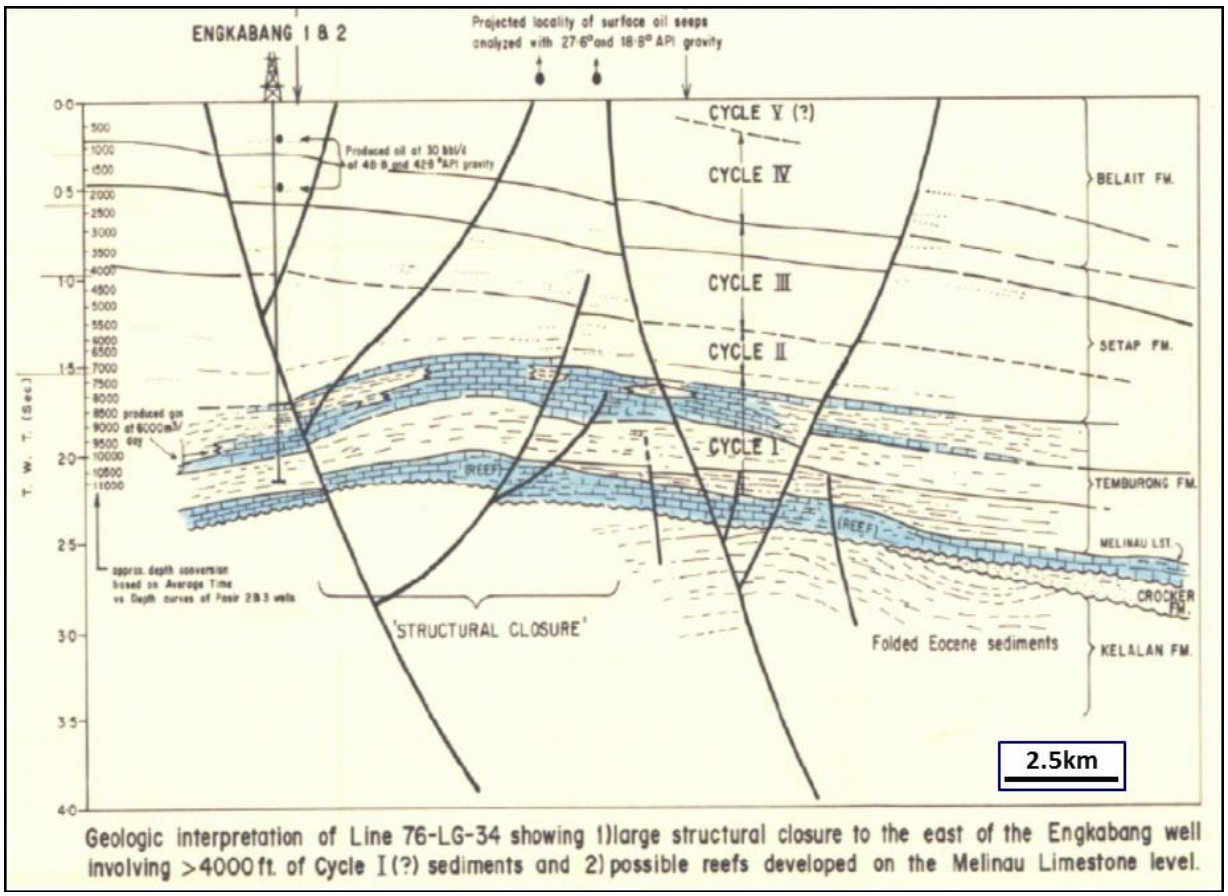


Figure 8. *Burial history profile of Engkabang West-1 area. (a) Possible tectonic erosional event related to Sequence Boundary at ca. 37.1 Ma (approx. top Middle Eocene), coinciding with timing of Rajang Group Uplift in Borneo hinterland? (b) Sequence Boundary 33.7 Ma (boundary between Oligocene and Eocene), (c) Sequence Boundary 23.0 Ma (boundary between Miocene and Oligocene, (d) Pliocene uplift as documented by Kessler and Jong (2014, 2015). The red stripes are indicative for eroded formation, as direct consequences of uplift and/or tectonic inversion (in pulses) affecting the basin ramp.*



Geologic interpretation of Line 76-LG-34 showing 1) large structural closure to the east of the Engkabang well involving >4000 ft. of Cycle I (?) sediments and 2) possible reefs developed on the Melinau Limestone level.

Figure 9. *Original geologic interpretation of Engkabang-1 and -2 penetrated sequences with an interpreted, albeit untested older carbonate section developed on the Melinau Formation level (after Shell, 1960). Note Engkabang-2 was a shallow appraisal well drilled and was located some 36m away from to test the shallow oil-bearing sands discovered in Engkabang-1. Production tests however yielded only small quantities of oil, salt water and gas.*

Carbonate porosity was only 3%, but a 40 hour test produced gas at 211,000 scf/day through 2⅜" tubing (75% methane, 25% CO_2) and 71 bbl/day water with low salinity (Chlorite 2500 ppm) (Shell, 1960).

Uncertainty around the EK-1 well test quality and the potential for a large in-place resource led to the drilling of Engkabang West-1 in 2013-2014 on the western culmination of the Engkabang-Karap Anticline by JX Nippon (Figure 10). The well penetrated 210m TVD of massive carbonate, which was about 60m thinner than the equivalent section in EK-1. The carbonate was also tightly cemented with extremely low k porosity. However, the presence of open fractures with gas was expected from the occurrence of drilling gas up to 21% and from visual fracture zones in the image logs. A Drill Stem Test was conducted, but observed immeasurable small gas flow. Analyses of two fluid samples from gas sample chambers show dry gas with approximately 20% N_2 and less than 1% of CO_2. In the overlying Setap Shale section, minor oil shows were also observed in two thin sandstone beds at around 800m (JX Nippon, 2014).

DEPOSITIONAL MODEL AND RESERVOIR FACIES OF ENGKABANG-KARAP CARBONATE

The estimated paleo-position of Engkabang-Karap carbonate was close to a slightly deeper water area, and some 35 km away from the Rajang coastline, with carbonates occasionally settling on top of a thrusted anticline (Figures 11, 12). Southeast of Batu Gading and Mulu, all rocks appear to be older than Eocene, and this may indicate a different and likely much stronger uplift history compared to the Eocene to Miocene shelfal areas (light blue zone in Figure 11), which saw subsidence at least to the Early Miocene.

Paleo-environment of the Setap Shale is interpreted as upper to middle bathyal in EKW-1, whilst it is outer neritic to upper bathyal in EK-1 according to foraminifera biofacies, suggesting a slightly deeper paleo-environment in EKW-1. The thin sandstone intercalations are considered to be distal turbidite facies.

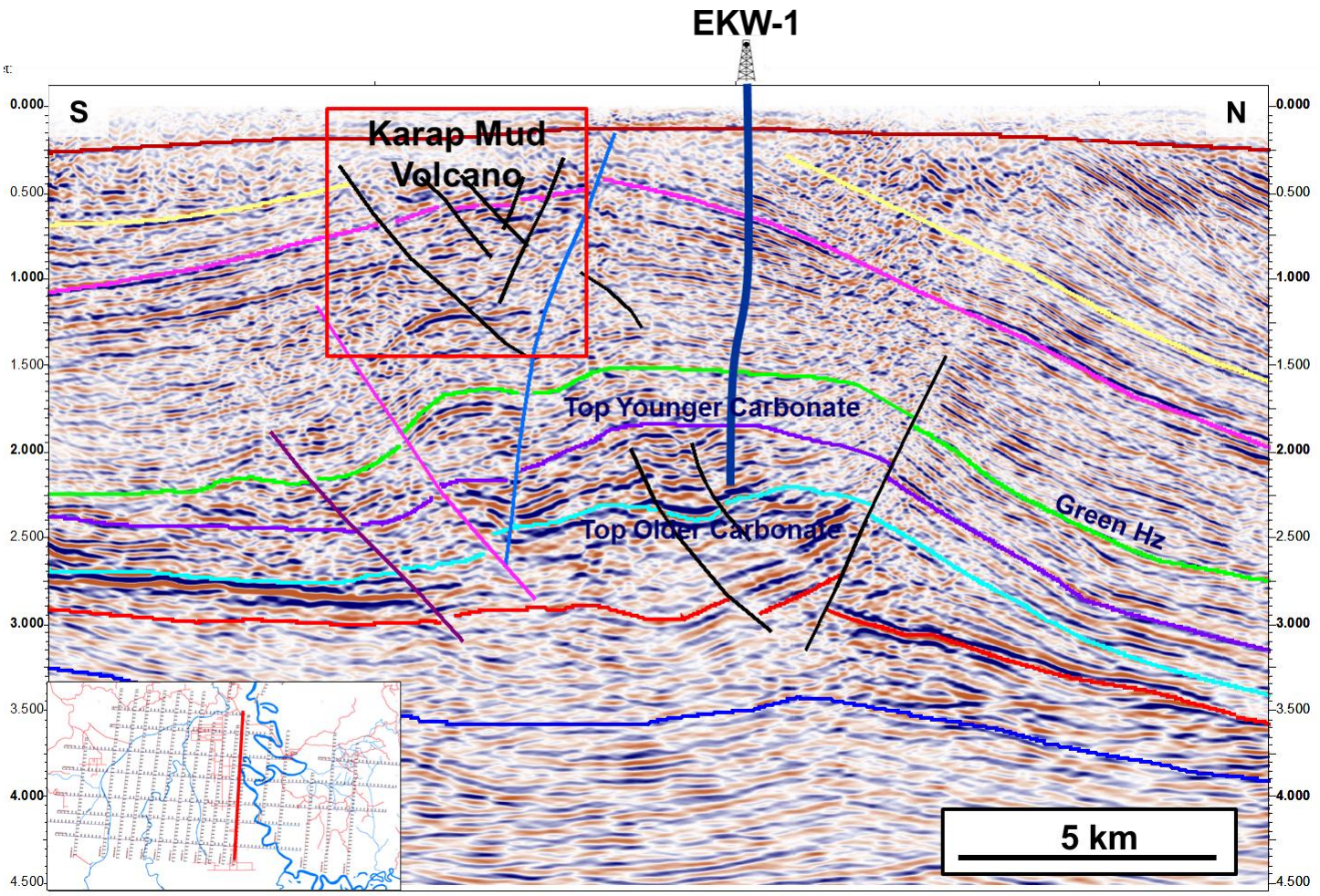


Figure 10. *Location of Engkabang West-1 along Seismic Line NOEX09-23. The well was initially planned to test down to the Older Carbonate interval. However the well managed to penetrate only 210m TVD of Younger Carbonate section and drilled another 270m of shaly sequence before TD was prematurely called because of operational risk due to low kick tolerance below safety margin. Consequently, the presence and quality of the Older Carbonate and its hydrocarbon potential were not assessed. The red square shows the subsurface manifestation of the Karap Mud Volcano.*

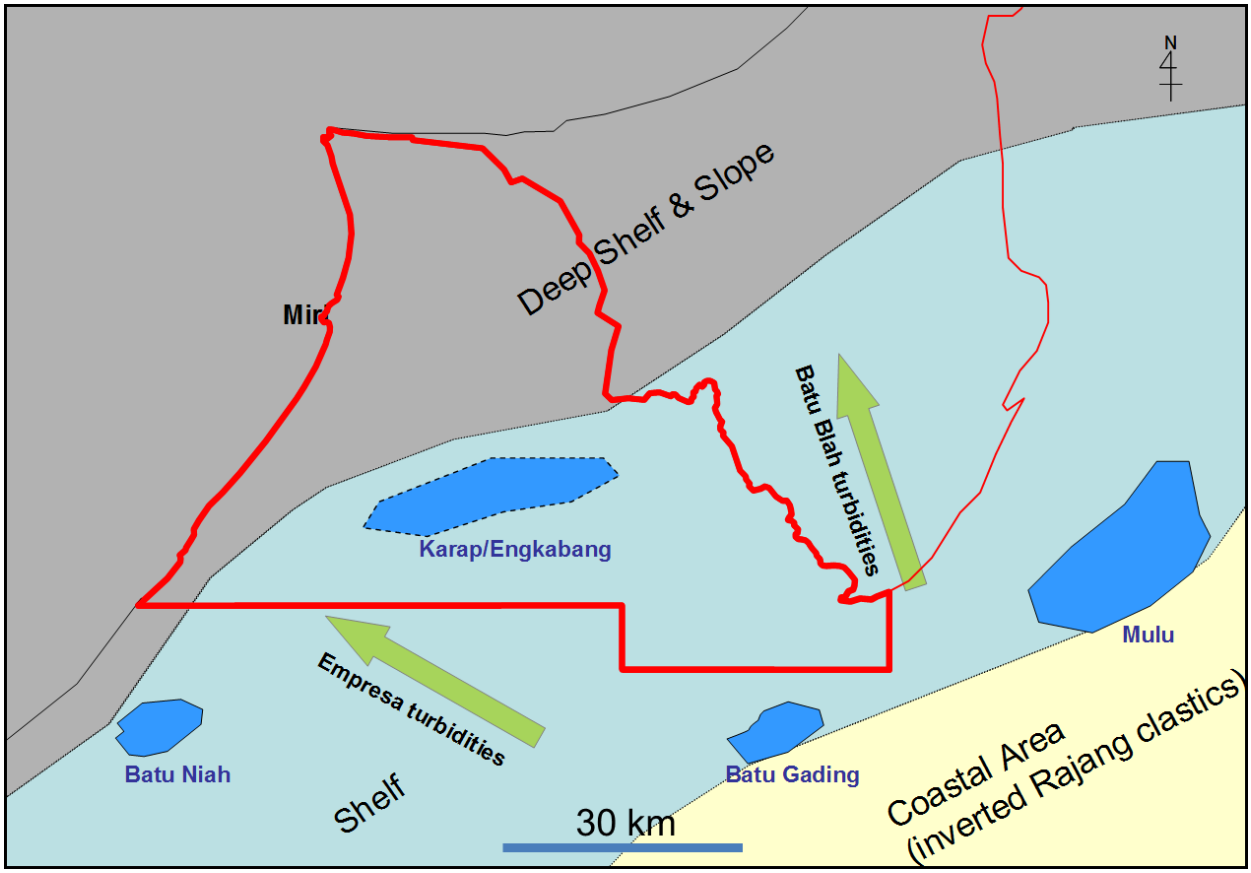


Figure 11. *Schematic Late(?) Eocene paleogeography of North Sarawak. The estimated paleo-position of Engkabang-Karap carbonate is slightly deeper water than the Batu Gading and Mulu carbonates, surrounded by lows which were filled with clay-dominated clastics with occasional turbidite sandstones. The red polygon is Block SK333, operated by JX Nippon from 2008 - early 2015.*

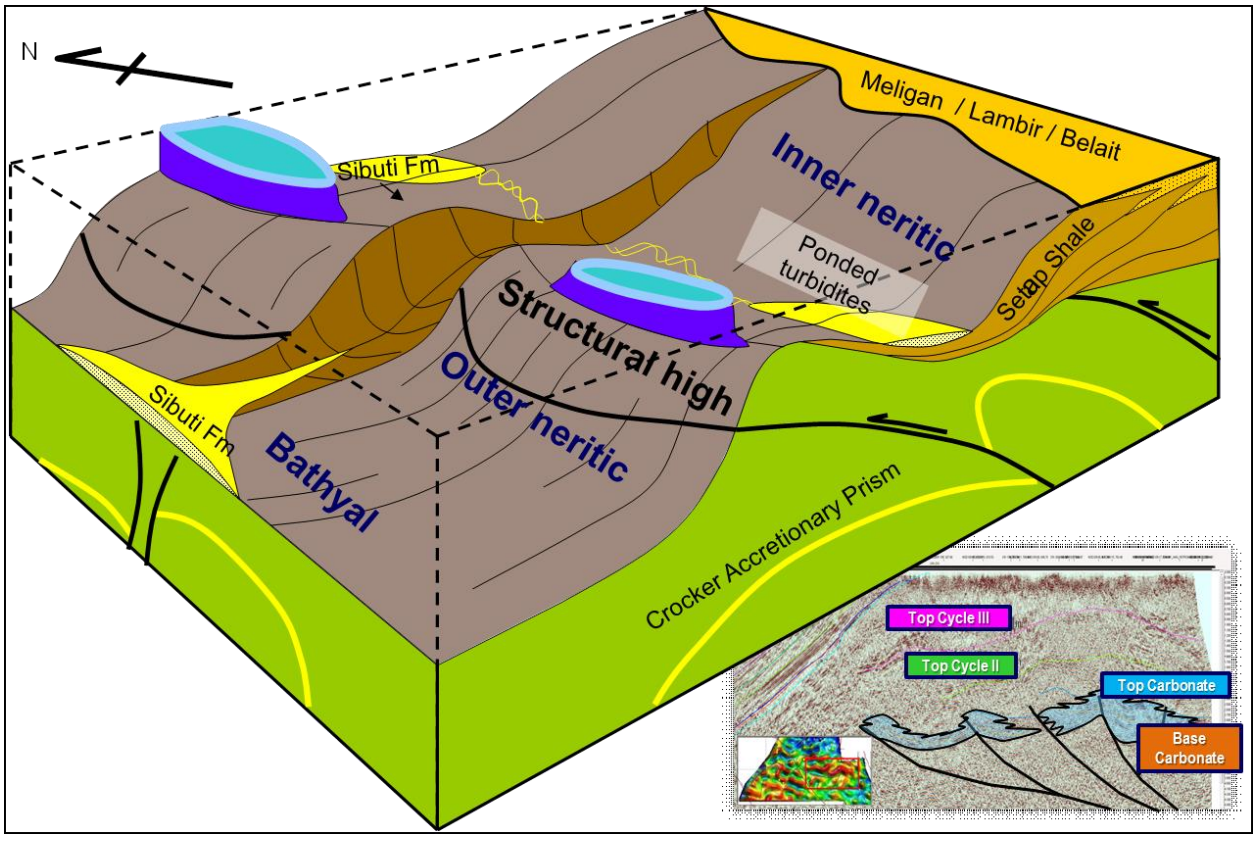


Figure 12. *Structural and depositional model of Late Oligocene - Early Miocene Cycles I-III in southern SK333 illustrating carbonate development on structural highs with shaley clastic sedimentation of Setap Shale in shallow to deepwater areas. Topographic lows are sometimes filled with younger sandier clastics such as the Sibuti Formation. Inset shows seismic example of Engkabang-Karap Anticlines with carbonate zones annotated.*

Paleo-environment of the intermediate Transition Zone is interpreted to be outer neritic to upper bathyal, suggesting slightly shallower depositional environment than that of Setap Shale. The main Younger Carbonate is interpreted to be middle neritic to outer neritic environment, though its reliability is low due to barren foraminifera occurrence. The observed carbonate lithology was mudstone – wackestone (Dunham, 1962) indicating the relatively deeper water depositional environment for the carbonate (Figure 13).

Although the seismic events around EK-1 are chaotic, without showing any meaningful stratigraphic features due to the poor quality of seismic data, the equivalent interval around EKW-1 shows seismic facies interpreted to be stacked mounds of calcareous bioherms of Eo-Oligocene age. This was the basis of expectation for EKW-1 that perhaps more porous and massive carbonate might develop without transition zones in the western culmination. It should be noted that these benthic foram bioherms are not reefs as originally suggested, as coral framework builders did not fully evolve until Oligocene or even Early Miocene times in SE Asia, as observed within the Melinau Formation succession of Sarawak (Wilson & Rosen, 1998).

CARBONATE DIAGENESIS

Diagenesis can reduce porosity and permeability, or it can increase them. In general, though, the trend is towards progressive loss of porosity and permeability with increases time and depth and burial, and that shift is commonly quite substantial. According to Scholle & Ulmer-Scholle (2003), preserved porosities of non-hydrocarbon bearing ancient carbonates are generally less than 10%. The muddy carbonate facies as recorded in the Engkabang wells are not particularly conducive for porosity/permeability enhancement. The well data also suggest that likely no vadose and/or karstification ever occurred.

The relatively deep burial of carbonates has led to partial dissolution of grains and formation of stylolites. Mobilized carbonate (calcite) likely filled fractures and prevented major fracture porosity systems. For comparison purpose, a time-equivalent section of Late Eocene/Oligocene carbonate rock exposed in the Batu Gading outcrops, *ca.* 36 km southeast of the buried Engkabang-Karap carbonate was investigated. The matrix rock there is very tightly cemented and dissected by major and minor fault and fracture systems. These fractures strike at some 120^0, and interestingly this direction seems to be the only major regional fracture orientation, with some faults show slickensides indicating normal fault movements (Figure 14). In addition, both faults and fractures display calcite re-mineralisation (Figure 14), implying that there is little or no fracture permeability retained.

However, EK-1 saw hydrothermal diagenesis. Kaolinite-family alumino-silicates are reported from EK-1 from the interval 1450-2490m, an Early to Middle Miocene section (*Globigerina 17 A* zone). The alumino-silicates are of hydrothermal origin, requiring a minimum P/T threshold of 200 ^{0}C and 2000 psi. It is concluded the Engkabang-Karap area was subject to one or more hydrothermal heat pulses after deposition. A preferred candidate for this type of mineralization is the switch from extensional (dextral) to compressive (sinistral) movements at the Miocene/Pliocene boundary. This event may have led also to hydraulic fracturing of the shallow oil reservoirs. Most likely however, the diagenetic impact was of local nature.

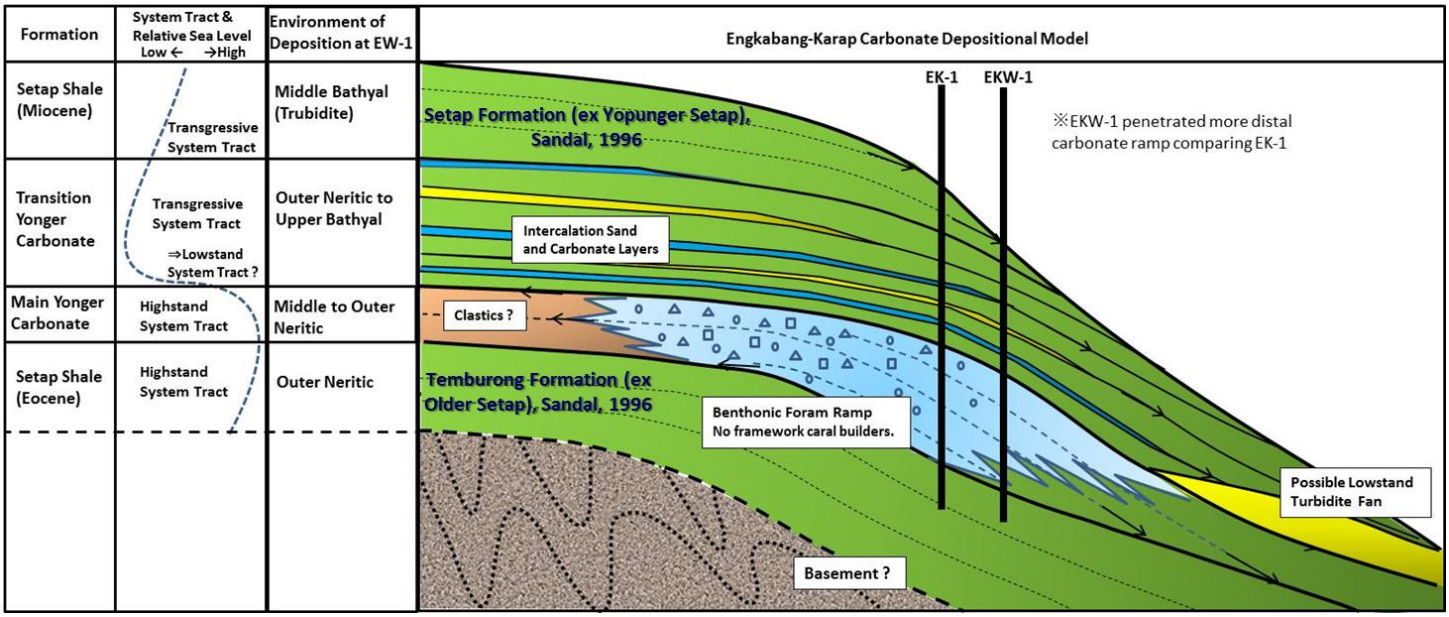


Figure 13. *Postulated depositional model of the Engkabang-Karap carbonate with development of Middle - Late Eocene - Oligocene benthonic foram bioherm ramps (after JX Nippon, 2014). Note Sandal (1996) defined the Miocene Setap Shale as Setap Formation, and Eocene Setap Shale as Temburong Formation.*



Figure 14. *(a), (b) Faulting occurred along several cleavage planes with polished, striated rock surface of slickenside (S) observed. (c) Calcite re-mineralisation in faults and fractures.*

Nonetheless, current circumstantial evidences point to porosity/permeability occluding diagenetic processes could be more prevalent in affecting carbonate reservoir quality. It will be however, an interesting challenge to document the potential porosity enhancing processes related to meteoric diagenesis associated with uplift events and subsequent exposure of the carbonate in connection with the burial history discussed earlier. In particular, the most likely point where uplift could have affected the carbonate fabrics would be the lowest interval namely the Eocene/Early Oligocene section. The realm of sedimentation at the time was, in comparison to the Lower Miocene section above, relatively shallow and could be affected by sea level changes and/or uplift. The Lower Miocene and clastic-dominated section however, saw deeper (slope?) depositional environment, hence even a major sea-level drop or uplift without exposure would have little diagenetic impact on the carbonate fabrics.

Although burial diagenetic play a critical role in porosity reduction, elevated pore fluid pressures and early hydrocarbon generated could have reduced the impact of both mechanical and chemical burial diagenesis. Nonetheless, apart from the observed elevated pressures encountered in the penetrated carbonate sections of the wells, so-far we lack the direct microscopic evidence that diagenetic rock alteration associated with uplift events could have happened. In addition, the effect of dolomitisation for secondary porosity enhancement is also not well-established and need further investigation. Currently the complex diagenetic history of the Engkabang-Karap carbonates remains poorly understood and therefore a recommended topic of further research.

PETROLEUM SYSTEMS OF ONSHORE BARAM DELTA

Sequence stratigraphic investigation of the onshore Baram Delta suggests that the sedimentary section of study area has been affected by three major tectonic episodes of deformation: (i) Late Cretaceous-Eocene (79.5-36 Ma) block faulting, (ii) Late Oligocene-Mid Miocene (30-20.5 Ma) wrench movement and related folding, followed by (iii) Mid Pliocene-Recent (4.0-0 Ma) uplift and compressional folding (Jong et al., 2013, 2015, Figure 15).

These tectonic episodes have resulted in subdivision of the onshore Baram Delta into two major anticlinal trends or provinces: the Engkabang-Karap Anticline in the south, separated from the northern Miri-Asam Paya Anticlinal Trend by the large Badas Syncline (Figure 15), which in turn has resulted in two distinct petroleum systems and related hydrocarbon zones:

1. A southern overmature gas system sourced from deeply buried Eo-Oligocene basinal shales, charging wrench induced traps in the southern area such as at the Engkabang-Karap Anticline, which were later overprinted by compressional folding. The surface expression of this petroleum system is manifested by an active mud volcano on the western Engkabang-Karap Anticline axis, the Karap mud volcano which emits thermogenic C_1 gas (Kessler et al., 2011). Burial history modelling indicates that an earlier oil charge probably occurred during deep Oligocene burial, preceding basin reversal during the Pliocene-Recent inversion episode, with wrench-induced anticlinal closure subsequently being charged by late stage gas.

2. An onshore, SK333 permit-wide oil and gas system sourced from peak stage mature Mid-Late Miocene carbonaceous shales and coals in the synclines, charging inversion and compressional fold structures along the northern Miri-Asam Paya Anticlinal Trend area (Figure 16), and also the Miocene section at the Engkabang Anticline (Setap Shale section) (Figure 16). Expulsion and charge of traps commenced during the Late Miocene and is continuing to the present-day (Jong et al., 2013, 2015).

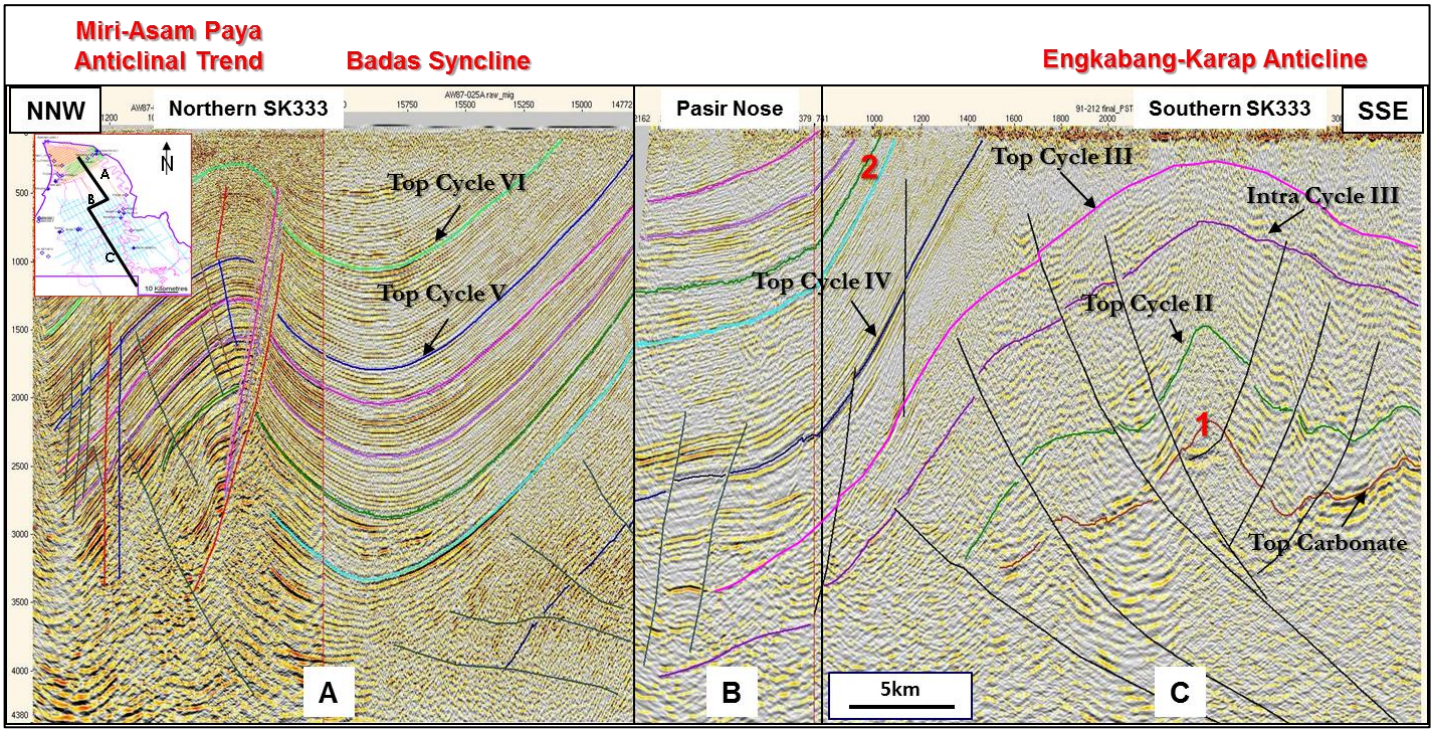


Figure 15. *NNW-SSE seismic correlation of onshore Baram Delta in SK333 and interpreted sequences. The numbers 1 and 2 in red annotate the deformation events of Late Oligocene to Mid Miocene wrench movement and related folding, and the Mid Pliocene to Recent uplift and compressional folding, respectively as described by Jong et al. (2013, 2015).*

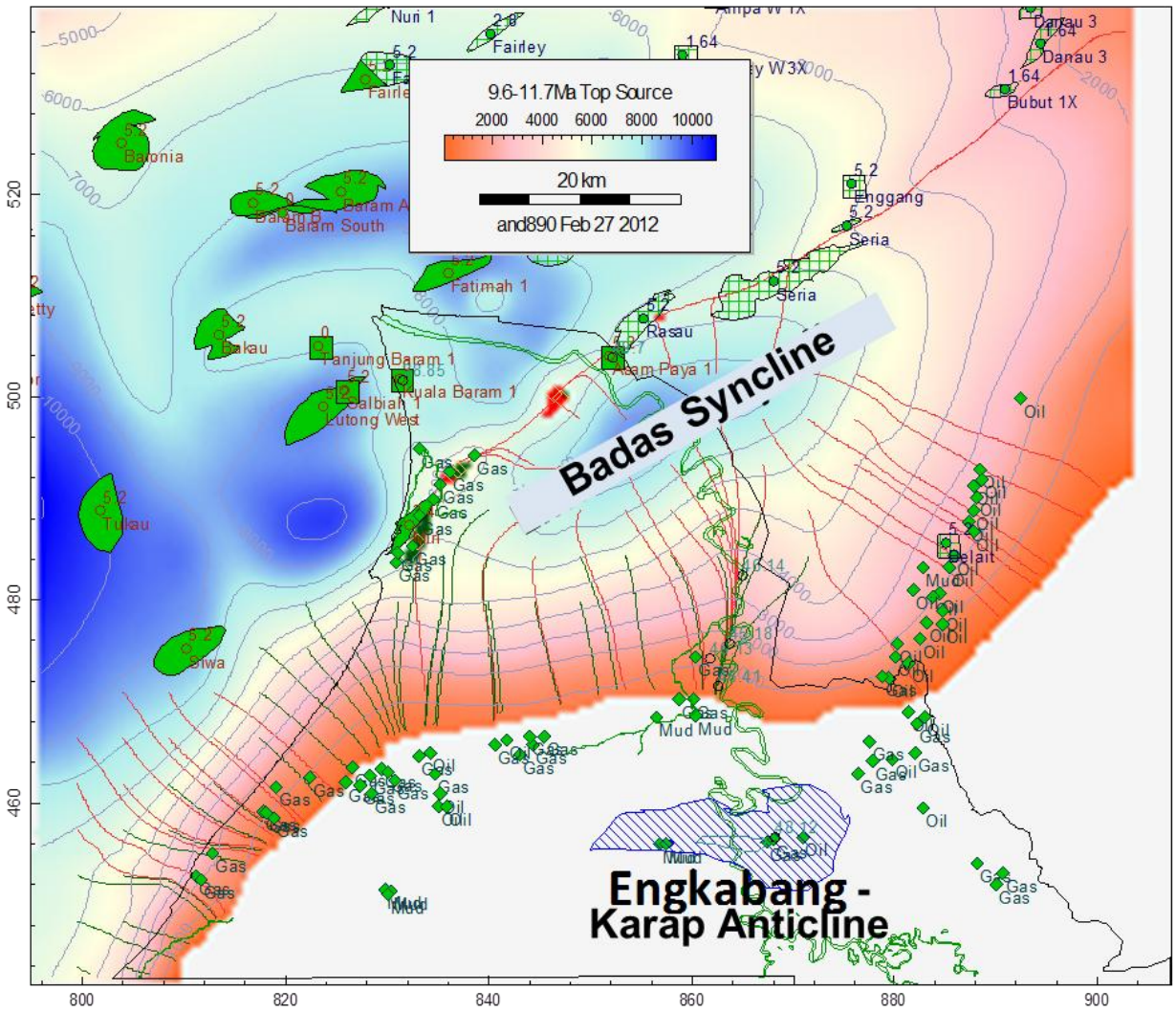


Figure 16. *Hydrocarbon charge and migration modeling of a postulated Mid Miocene Cycle V source rock, indicating hydrocarbon could be expelled from the mature source rock kitchen area of Badas Syncline, and migrating south and updip towards the Engkabang-Karap structure charging the overlying Setap Shale section.*

BOUGUER GRAVITY ANOMALIES AND SUBSURFACE MODELLING OF THE ENGKABANG-KARAP ANTICLINE

The onshore Baram Delta was covered by an airborne gravity and magnetic survey flown by Sander Geophysics Limited for JX Nippon in 2008, with data processed and interpreted in 2009. The gravity data provided good-quality imaging of the known major structures, including the Miri-Rasau Anticlinal Trend, the Badas Syncline, the Belait Syncline and the Engkabang-Karap Anticline (Figure 17).

The basic Bouguer gravity data and the vertical gradient of the Bouguer gravity data show various additional gravity high trends that are considered likely to be caused by anticlinal features. Whilst many of these have already been recognized from earlier geological and seismic mapping, many new gravity highs have been identified that could be due to previously unknown structures, particularly those located to the west of the study area. Nonetheless, the elongated positive anomaly observed on Bouguer gravity over the Engkabang-Karap Anticline (Figure 17) was confirmed on seismic 2D data (Figure 18). The anomaly is imaged as a complex anticline, likely combined with elements of patchy Eo-Oligocene bioherms (Core Laboratories, 2010, 2011).

Initially, prior to good seismic data, it was thought that the Engkabang-Karap anticlinal zone could be interpreted as a string of bioherms only. However, based on the 2009 high resolution 2D seismic data, it became obvious that "stratigraphic thickening" within the Eocene - Oligocene carbonate section could neither fully explain the shape of the anomaly, nor the uplift history seen in the EK-1 and EKW-1 wells. Subsequently, seismic structural interpretation and a recent subsurface modeling carried out in the study area with PETREL software further corroborated a model emphasizing a combined strike-slip faulting and folding with a decollement surface (Figures 18, 19). A (blind) overthrust plane (Figure 18) was located at 4-4.5 seconds (TWT). The folding occurred very late, as only a thin series of unconformably overlying near-surface layers of young (?Plio–Pleistocene) sediments is not involved in the folding.

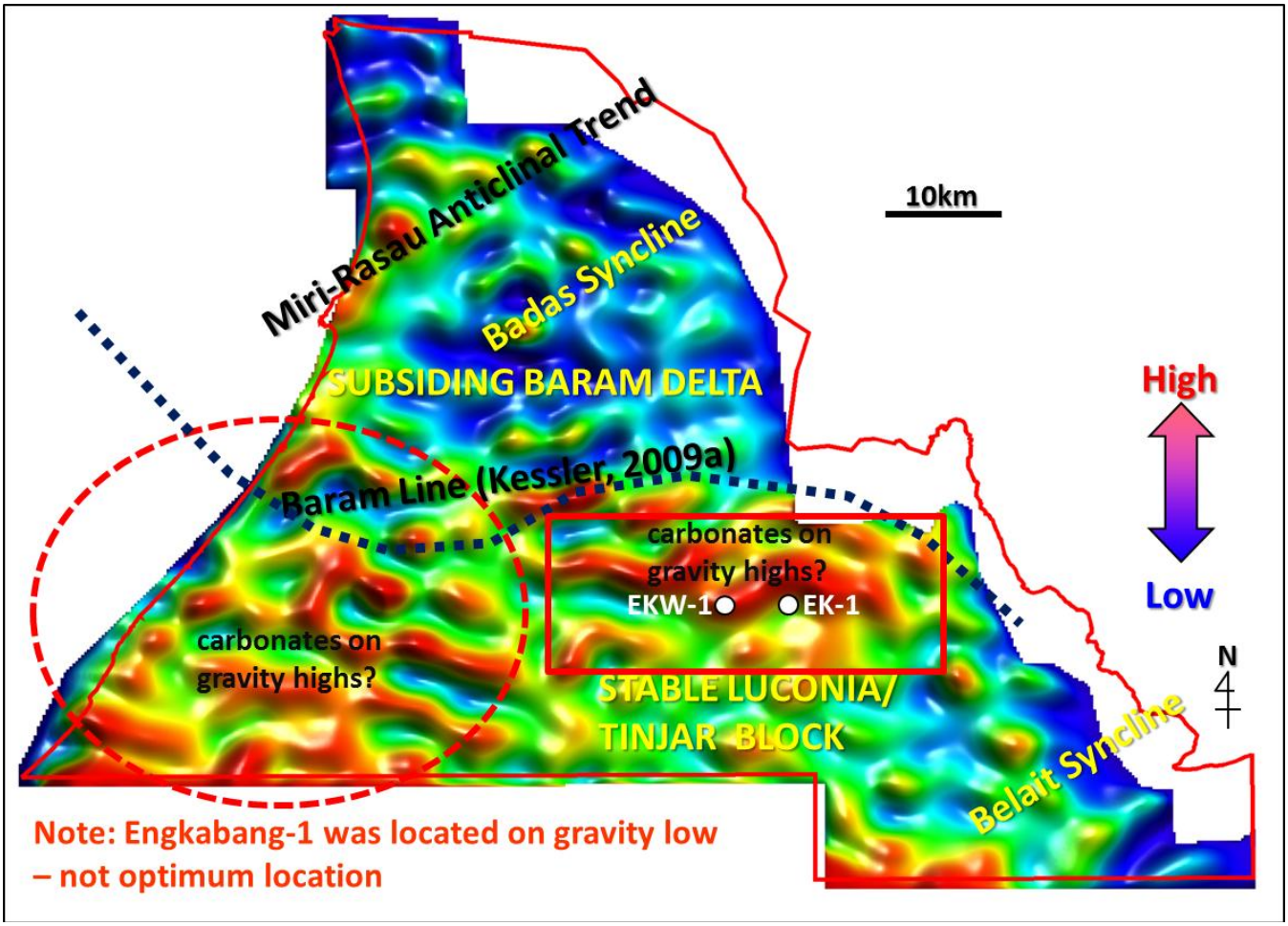


Figure 17. *Airborne gravity map showing positive Bouguer anomalies over the Engkabang-Karap structure (red rectangle), where the data suggest that the EK-1 well was not optimally located to test the main carbonate feature. The red dashed circle suggests further presence of Engkabang-like structures/bioherms to the west of the study area (after Jong et al., 2013, 2015).*

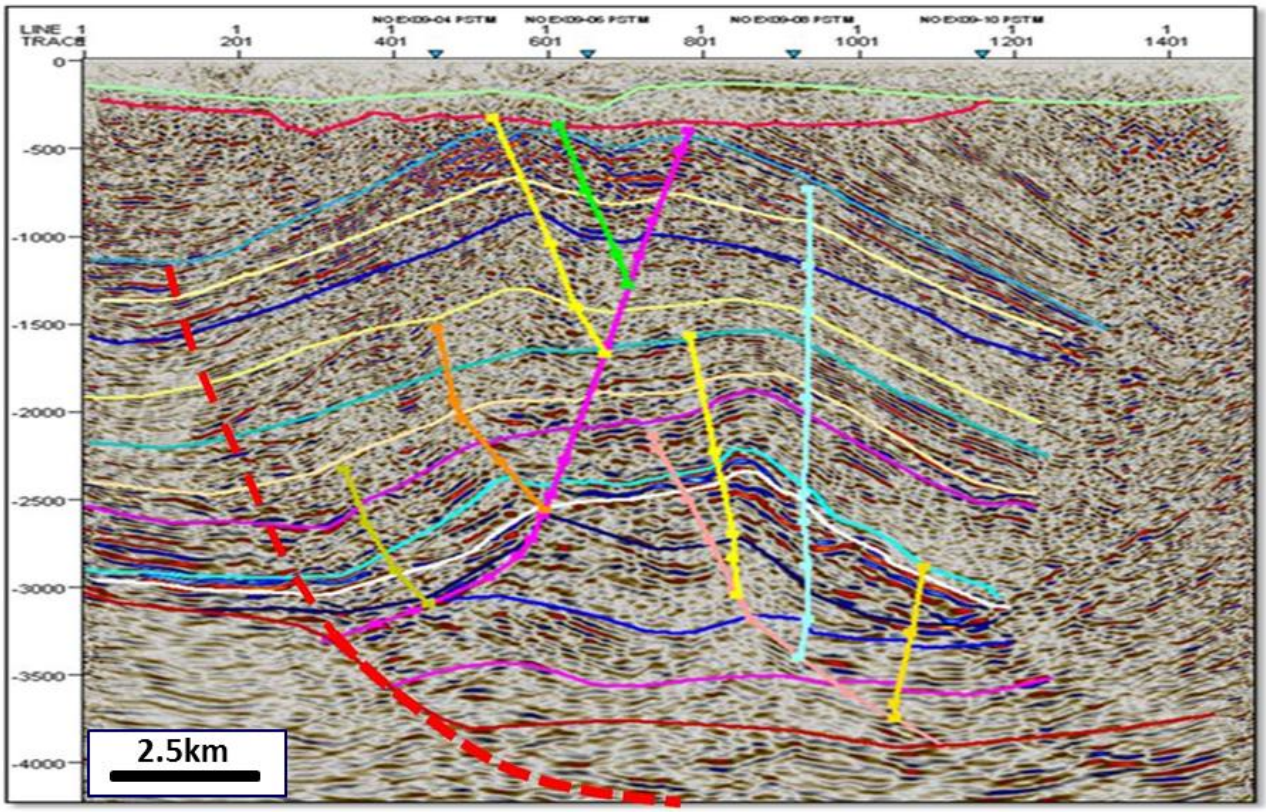


Figure 18. *Seismic section through the Engkabang-Karap Anticline, showing complex folding caused by a decollement zone (red interrupted line), interpreted as a branch of the Baram Line.*

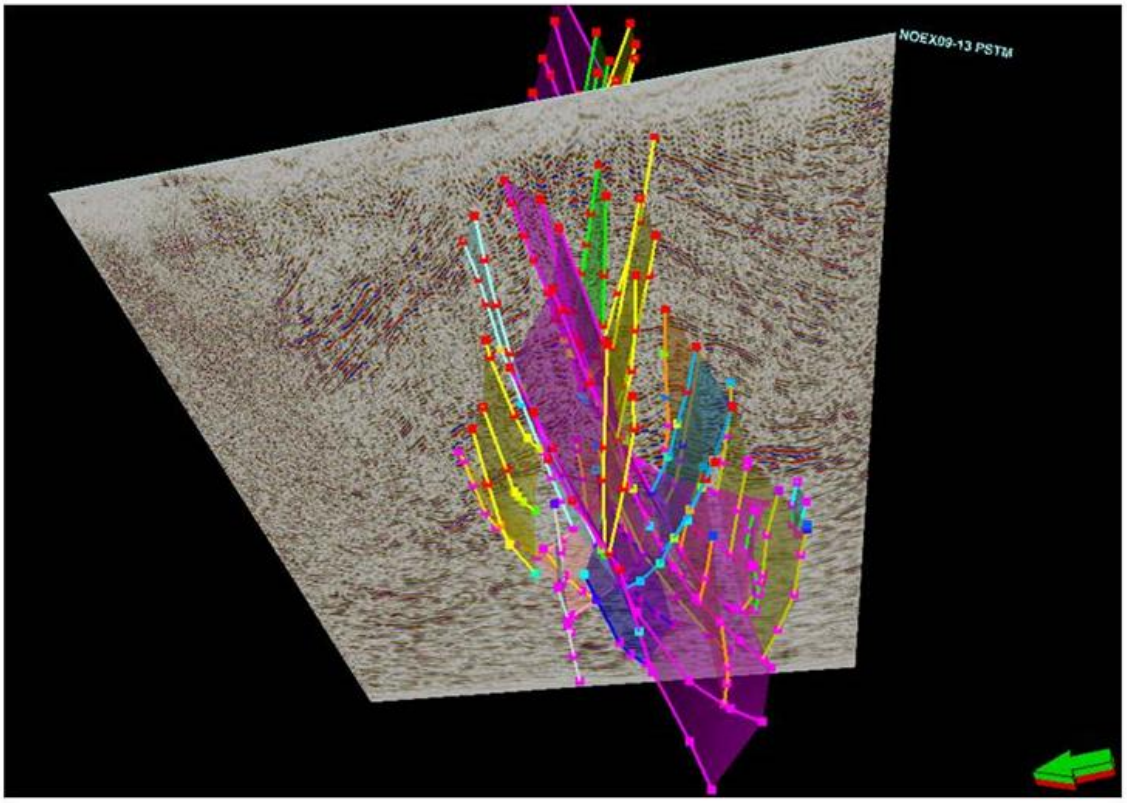


Figure 19. *A PETREL structural model of the study area suggests a conjugated pair of strike slip planes (purple and blue) and characterizes the mechanism of deformation inside the anticline.*

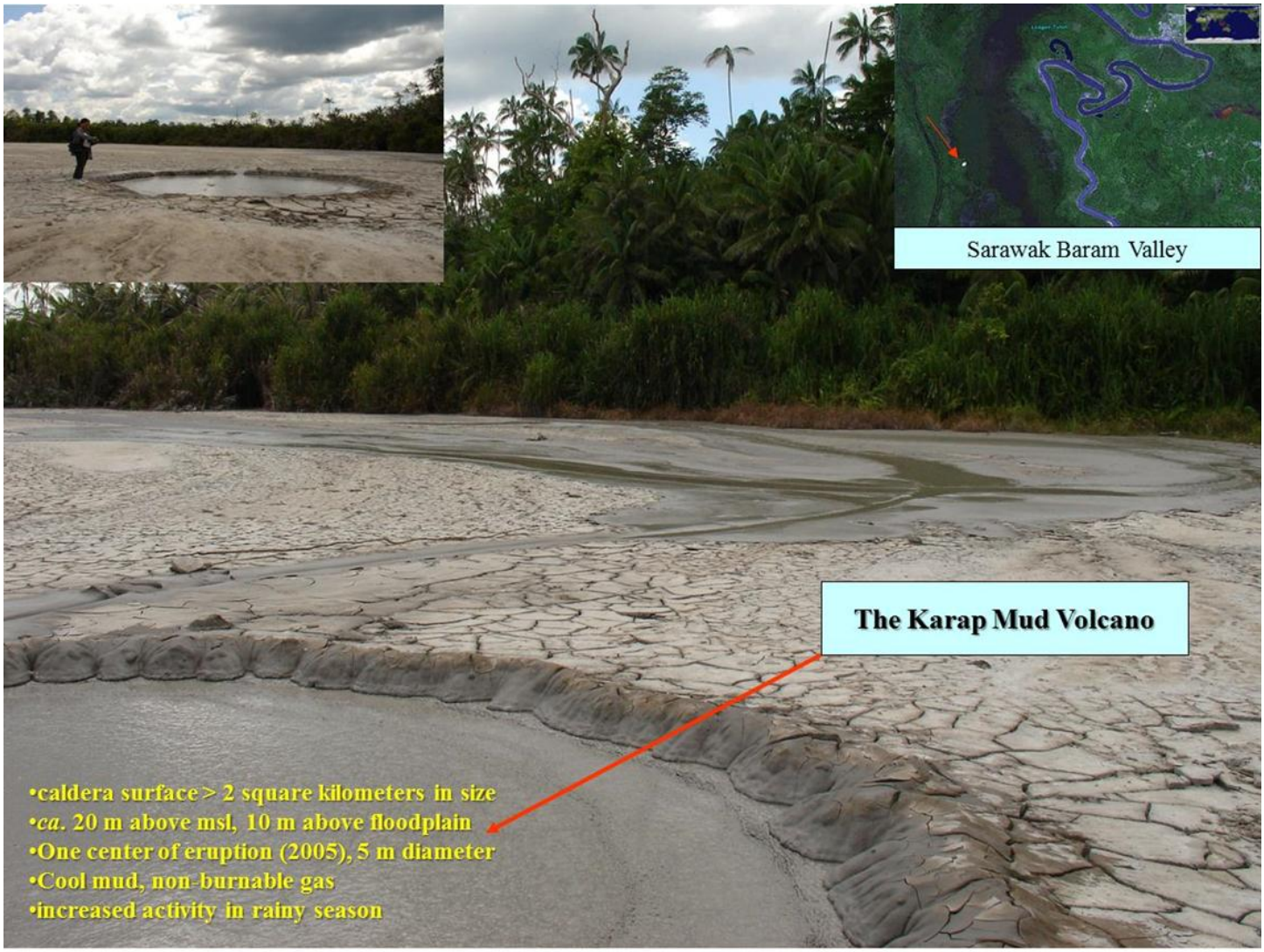


Figure 20. *View on the central caldera perimeter of the Karap mud volcano. Insets on top left show the centre of eruption and top right the Google satellite image with the small white dot representing the location and size of the volcano (after Kessler et al., 2011).*

MUD VOLCANISM

Hutchison (2005) described Sarawak mud volcanoes as: "cold mud volcanoes occur where the county rock is rich in mudstone. They are not numerous but an example occurs about 2km south of the main road between Batu Niah and Miri. Large bubbles of presumably methane gas slowly break the surface and a mud cone is slowly built up. There is no connection with petroleum, but the actual cause, whether it may be a relationship to an underlying fault, remains unknown." New 2D seismic data clearly images the subsurface structures of the Engkabang-Karap Anticline, and the cause of mud volcanism was explained by Kessler et al. (2011). From many studies of young basins (Sabah Foredeep, for instance) it appears that mud volcanoes originate in areas of:

- Overpressured and semi-liquid mobile clay;
- Compressive tectonism, such as inversion, strike-slip faulting, and thrusting.

In the study area, these components all appear to be present; a thick overburden of Setap Shale and younger overpressured sections have both been encountered above the EK-1 and EKW-1 carbonate section, with compressive elements such as folding, thrusting and strike-slip faulting. The study-area will have endured structural movements along the nearby Baram Line and Belait Wrench system (Figure 2), triggering dewatering of the overpressured sediments and hence active mud volcanism.

There are currently two active mud volcanoes: Ngebol in Bukit Peninjau and Karap southwest of Marudi (Kessler, 2007; Figure 19). In between, there are a number of "calderas" possibly belonging to presently inactive mud-volcanoes, all located in difficult-to-access jungle and swamp areas. The authors hereby suggest using the term "caldera", since those are not real volcanoes. All mud-volcanoes and calderas seem to be aligned roughly in E-W direction, offset by several km from the contact of the Baram Line. The Karap volcano is an impressive feature, *ca.* 1 km in diameter, elevated *ca.* 10m above the Baram flood plain (Kessler et al., 2011; Figure 20). At present, the caldera harbours one central crater feature, and eruptions occur once in every few minutes. On seismic, the mud volcano is located above the edge of the Engkabang-Karap bioherm complex (Figure 21). The volcano's vent reaches *ca.* 1250m into the block-faulted rock, and can be described as a complex fault-segmented vent that is rooted in a prominent strike-slip system, possibly a branch of the Baram Line.

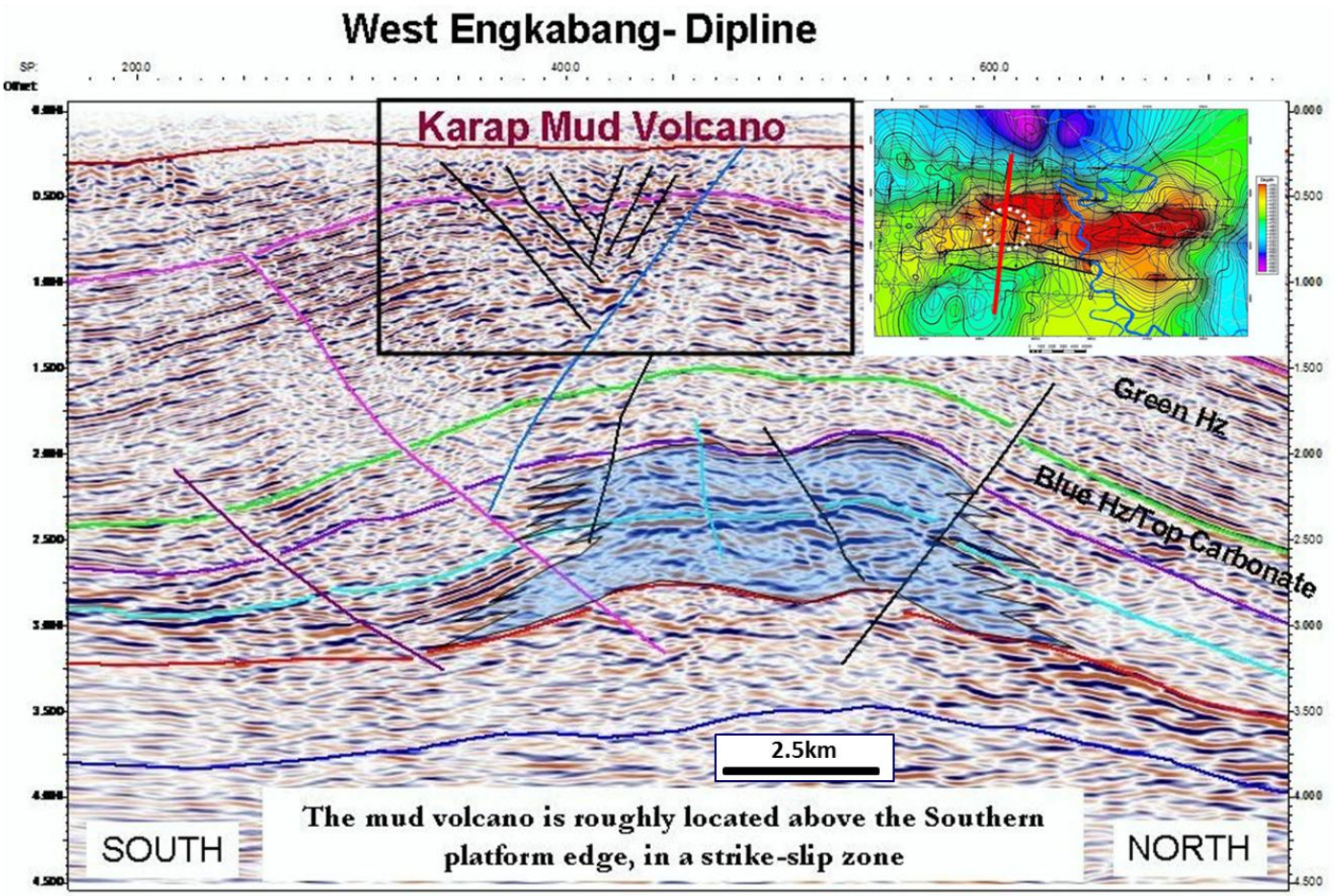


Figure 21. *The Karap mud volcano is located on the SW platform edge, and rooted in a regional fault system. Insert map shows structure of Top Carbonate sequence, with location of the Karap mud volcano (white dashed circle). The decollement overthrust is not present on this level, but creates the southern edge of the culmination (after Kessler et al., 2011).*

IMPLICATIONS FOR OIL AND GAS SETTING IN ENGKABANG-KARAP AREA

The proposed structural and depositional models described in previous sections are schematically summarized in Figure 22, which could help explaining several observations in the study area, namely:

- The occurrence of oil in EK-1 at shallow depth, a possible result of seal failure with the thrust faults acting as conduits for updip migration of deeper hydrocarbons.

- The occurrence of gas in a deeper carbonate section of the well, without any significant source rock found in the well; in fact, the slightly south-dipping overthrust plane could have acted as a regional conduit of gas originating from deeper levels of Baram Delta clastics located just north of the Baram Line.

- Associated mud volcanism, acting as a temporary release valve to overpressured sediments; overpressured but mainly with non-flammable gases (N_2 or CO_2) and sediment-laden liquids percolating upwards along prominent faults.

DISCUSSION AND CONCLUSIONS

Although structural development of the Engkabang-Karap Anticline formed a major theme of the study, the associated investigations of the carbonate depositional environment and the subsequent diagenetic alteration of the reservoir facies are no less significance in providing a better understanding of the petroleum system of the study area. Interestingly, biostratigraphic correlation of marker taxa and biofacies determinations of the Engkabang wells has enabled the identification of a number of key surfaces/unconformities, with the ages of these surfaces determined from biozones that might be directly related to the regional tectonic uplift events experienced in North Sarawak.

The burial history of EKW-1 was investigated in this study, and the inferred uplift events seemed to correlate well with the outcomes of biostratigraphic investigations. Nonetheless, significant questions remain with respect to the burial history of Engkabang-Karap carbonate and neighboring outcrops. In the Batu Gading outcrop Eocene carbonates overlie Rajang metamorphic rocks, but not in Engkabang, where clastic sediments were found at well TD. Does this suggest that there is a tectonic boundary separating inner Borneo from the carbonate ramp area, with the latter forming the southern fringe of the South China Sea, from the Eocene onwards? Furthermore, it is intriguing that on biostratigraphic and biofacies evidence the carbonates appear to represent an overall deepening-upwards sequence until the Early Miocene, with some uplift later, whilst Borneo hinterlands appear to have seen uplift already by then (Kessler & Jong, 2015).

In aspects of the hydrocarbon habitat, both EK-1 and EKW-1 proved a working petroleum system, but with tight carbonate reservoirs. Interestingly the gas contaminants seem to show local variations, e.g. CO_2 is low in EKW-1 in comparison to EK-1. The wells likely penetrated bioherm ramps with marginal reservoir properties, with the observed carbonate facies dominated by mudstone-wackestone, and gas flow rates remained sub-economic. There is no indication for porosity enhancement by processes such as vadose diagenesis and/or karstification. So-far no reservoir sweet spots could be discovered within this carbonate sequence, although admittedly the complex diagenetic history of the carbonates remains poorly understood and a recommended topic for further research. Fractures, on the other hand in a tectonically stressed area could be well-developed but they will need a properly designed and oriented 3D seismic to better image potential subsurface fracture development.

In conclusion, new, high resolution onshore 2D seismic data acquired by JX Nippon in the area of Marudi indicates complex structuration unseen previously on surface geology, with seismic interpretation and PETREL structural modeling indicating the existence of a low-angle detachment overthrust plane, linked to a zone of increased tectonism, the Baram Line. Mud volcanism, as observed in Karap is also believed to be associated with the elements of folding, thrusting and strike-slip faulting. The inferred overthrust faulting, rooted in a suggested low-angle detachment overthrust, could help explain the occurrences of both shallow oil and deep gas and mud volcanism, and points towards a trap model that may be present also in other areas of onshore Sarawak.

ACKNOWLEDGEMENTS

This study has benefited greatly from the discussion and published work of past and present authors who have contributed to the ideas presented in this paper, and to whom we are indebted. Earlier discussions with our ex-colleagues in Shell, in particular with Dr. Mike Scherer and Dr. Andrew Cullen, and contributions from our colleagues in JX Nippon and Core Laboratories are gratefully acknowledged. We appreciated the drafting assistance provided by Mr. Fairy Dasun, and our gratitude is also extended to our reviewers for offering constructive comments, which helped to improve the quality of this paper.

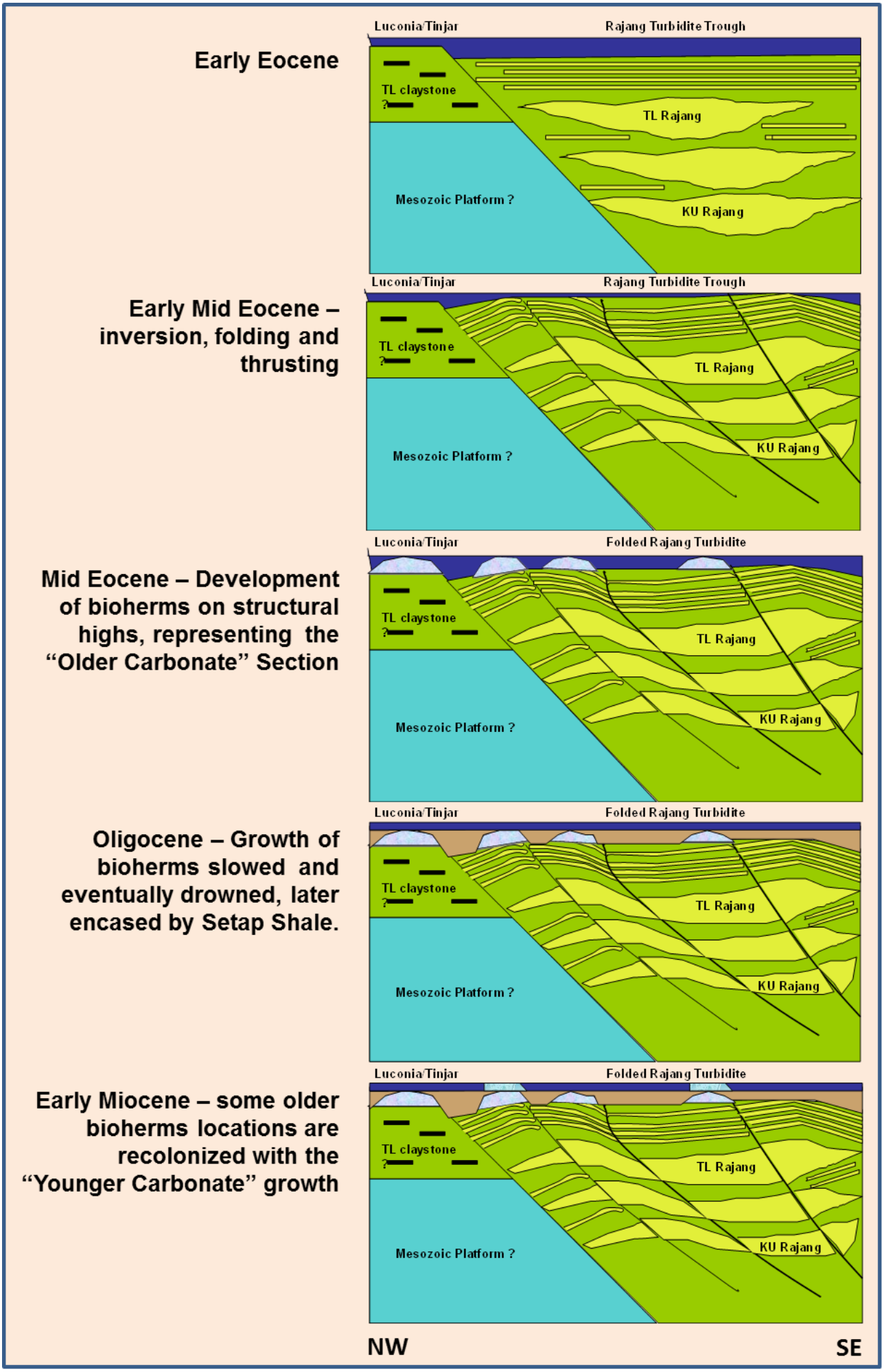


Figure 22. *Model of structural evolution and carbonate development in area of Engkabang-Karap Anticline (TL = Lower Tertiary, KU = Upper Cretaceous).*

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Dr. John Jong has 20 years of international working experience in the oil and gas industry. He started his geoscience career with Shell in the mid 1990s as an Exploration Geologist and later worked in different roles including Project Planner and Regional Geologist with Shell International in Houston from 2002-2004. In late 2006, John joined Tap Oil where he was involved in the company's NV and exploration evaluation efforts in SE Asia, and he left Tap Oil in 2009 to join JX Nippon for onshore Baram Delta exploration. Currently he is the Exploration/New Venture Manager based in the KL office. John is currently a member of AAPG, EAGE, PESA and SEAPEX.



Franz L. Kessler

Dr. Franz Kessler has over 25 years of working experience in the oil and gas industry, and is currently an Independent Oil and Gas Consultant. Previously he was the Regional Geologist with Lundin Malaysia and had worked as a Subsurface Manager/Geological Consultant for Petrotechnical Inspection Sdn. Bhd. From 2009-2013, he was the A/Professor and Department Head of Geosciences in Curtin University Sarawak in Miri, where he explored and mapped areas of Sarawak and has published a number of papers on the origins of West Baram Line and Canada Hill. In earlier years he carried out a variety of functions as Geologist, Seismologist and Interpreter in some 16 Shell global ventures.



Steve Noon

Since graduating in 1979 Steve has had wide experience working as a geologist on all continents (except the very cold one!). His career has progressed from wellsite geology, through MSc Micropalaeontology, to Senior Palynologist/Stratigrapher and latterly as Technical Director Stratigraphy for Core Laboratories in Asia Pacific based in Kuala Lumpur. After six years working worldwide for Exploration Logging Inc. Steve decided the “bugs” in the sample trays were deserving of special attention and so decided on a year of focussed study at Hull University which included a thesis on palynology from Hong Kong. A two month assignment in Southeast Asia for Core Laboratories became permanent and he has remained there ever since, working on hundreds of wells and numerous multiwall and regional studies worldwide. Steve is particularly interested in the stratigraphic applications of microfossils with emphasis on integration with broader geology and sequence stratigraphy; constantly developing new skills and techniques to achieve this.



Tran Quoc Tan

Tran Quoc Tan has 15 years of working experience. He started his career with Tiberon, a Canadian company (based in Vietnam) in 1999 as an Exploration Geophysicist. He joined PetroVietnam Exploration & Production Corporation (PVEP) in 2003 where he was involved in the company's new venture opportunity screening in SE Asia & Middle East and later worked for exploration projects as Senior Geophysicist in SE Asia. In early 2008, Tran joined JX Nippon in Miri as a Senior Geophysicist, in charge of seismic interpretation as well as land & marine seismic acquisition projects, and he is currently the Exploration Manager/Senior Geophysicist based in KL office. Tran has special interests in seismic acquisition, seismic interpretation, seismic sequence stratigraphy and reservoir characterizations. He is currently a member of EAGE.