Carbonate banks and ramps on the northern shore of Palaeogene and Early Neogene Borneo: Observations and implications on stratigraphy and tectonic evolution

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Abstract: Following the intense Palaeocene-Early Eocene Sarawak Orogeny (around 40-36 Ma), the South China Sea engulfed the northern shore of Borneo in present-day NW Sarawak, enveloping both the Luconia/Tinjar terrains and also rimmed the recently emerged and eroding Rajang Group hinterlands on the northern Borneo shore. With prevailing inner neritic depositional environment at that time, benthic foraminiferal limestone banks and ramps developed on sheltered shoals, separated from each other by clastic fairways with turbiditic channel deposits. By Early-Middle Oligocene times, carbonate deposition slowed as a consequence of increased subsidence and or, less likely, of a strongly global rising sea-level. After a pause in which clastics dominated the area, a second carbonate system formed during the Early-Middle Miocene times. These carbonates contain the first hard evidence of small bioherms, mainly corals and coralline algae. However, in the study area, there is not a single outcrop or well which shows an uninterrupted carbonate sequence from the Palaeogene to the Neogene. In addition, it is believed that the palaeo-edge of the platforms today lies somewhat masked by tectonic events, in particular, by a Late Miocene to Early Pliocene fold and thrust belt. Consequently, we believe, that both the Eo-Oligocene and Early-Middle Miocene carbonate systems are independent, not linked or vertically interconnected. Arguably, the presence of carbonates in two distinct systems points to a deepening, and later shallowing in a mega cycle. Within the mentioned hypothesis, the Eo-Oligocene carbonate system was formed during the deepening of the NW Borneo foredeep, whereas the Lower-Middle Miocene carbonates originated as the foredeep shallowed. The latter eventually disappeared with the establishment of a shallow, clastic shelf.

Keywords: Borneo, Eocene, NW Sarawak, Oligocene, paleogeography, platform carbonates, tectonics

INTRODUCTION

This paper serves as a short review of both exposed outcrops, and key wells of the carbonate systems drilled in the Sarawak Foreland Basin. Well results, and biostratigraphic studies carried out in the context of oil and gas exploration, together with environmental research, has allowed the reconstruction of a stratigraphic basin development during Late Eocene to Middle Miocene times. Hutchison (2014) described, that hundreds of carbonate build-ups dot the southern South China Sea (SCS). These are concentrated mainly in two areas, with more than 600 presently active reefs in the Spratly Islands and more than 200 buried build-ups in the Central Luconia Province. Most begun their growth at Langhian time (13.65-15.97 Ma, the Middle Miocene Unconformity). The build-ups within the Sunda Continental Shelf (Central Luconia carbonates) remained in shallow water and were buried by an Upper Miocene clastic sediment influx from the nearby Sarawak hinterland. Build-ups within the continental rise, where crustal attenuation and subsidence was arguably greater, may have been drowned by rapidly deepening water and even draped over by a thin layer of post-carbonate overburden sedimentation.

The onshore Sarawak carbonate setting, though closer to the palaeo-coastline, appears to be contradictory; only a few outcrops bear the characteristics of a shallow shelf, whilst others appear to be of neritic origin. A recent study by Kessler & Jong (2016a) suggests two relatively independent carbonate platforms have evolved in the study area during the Late Eocene to Oligocene (Priabonian to Chattian), and then again during the Early to Middle Miocene. However, it was noted that no outcrop or well has shown a vertical continuity of carbonate deposits from the Late Eocene to the Middle Miocene. Therefore, the authors considered these two platforms as being genetically independent, albeit exhibiting some similarities in lithofacies.

The Eo-Oligocene stratigraphic sequence in the study area of NW Sarawak is relatively poorly constrained, due to the rarity of well penetrations in this older section. Hence the (unpublished oil industry) palaeo-geographic models proposed in the past, focussed on the Upper Oligocene and younger sections (from 27 Ma).

A summary by Hutchison (2005, p. 99) is based mainly on outcrop studies and limited well information. Our approach for deducing the palaeo-geographic evolution is based on an integration of both outcrop and well studies including an updated view from the recent Engkabang West-1 results (JX Nippon, 2014), and also from gravity and seismic facies interpretation (based on 2009/2010 2D seismic data acquired by JX Nippon).

GEOLOGICAL SETTING AND STRATIGRAPHY

A summary of the geological setting in the study area is provided in Kessler (2009) and Jong *et al*. (2016). From a tectonic standpoint, the study area encompasses the hanging-wall Baram Delta Block and the adjacent foot-wall terrain of the Luconia/Tinjar Block. The hanging-wall

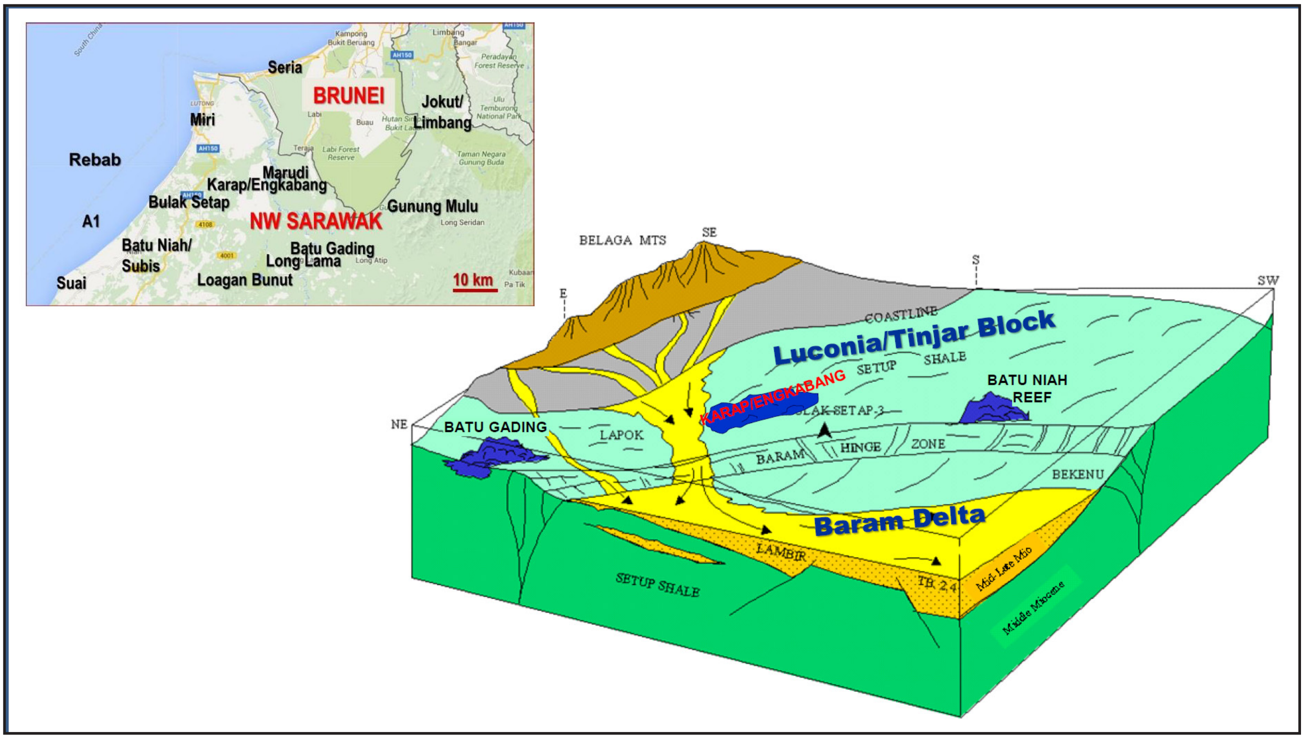


Figure 1: Schematic block diagram of NW Sarawak with a regional perspective of Late Miocene/Pliocene times. Luconia/Tinjar Block constitutes the foot-wall. The Baram Delta is in the hanging-wall NW of the Baram Hinge Zone (West Baram Line). Given the folding of areas such as the Belait-Badas Syncline, Lambir Hills, Miri etc., NW Sarawak serves as an example of relief-inversion (from Kessler, 2009; Jong *et al*., 2016). Inset map shows locations of studied outcrops and wells.

Baram Delta Block was rapidly subsiding by loading of clastic sedimentation, whilst the foot-wall terrain of the Luconia/Tinjar Block had a lower subsidence rate. Being only moderately folded, this terrain is characterized by a number of synclines with minor overthrusting (Figure 1). The West Baram Line (or Baram Line) acted as a tectonic discontinuity that links the relatively stable Luconia/Tinjar Block to the mobile and siliciclastic-dominated Baram Delta Block. The simplified chrono-stratigraphic summary for NW Sarawak and Brunei covering the study area is shown in Figure 2.

Figure 3 shows the location of the carbonate outcrops of the northern shore of Palaeogene and Early Neogene Borneo (present-day NW Sarawak), and selected onshore and offshore well penetrations. Gravity and magnetics south of Miri suggest that a number of undrilled carbonate anomalies may be present in the Tinjar Block (Jong *et al*., 2016). The original contact between the Palaeogene carbonate shelf and the inner Borneo Island core has been tectonically at least partly superimposed by the Late Miocene collision front. According to Hutchison (2005), the Late Eocene and younger NW Sarawak stratigraphy is wholly comprised of molasse. The strata were deposited in non-marine terrestrial to inner neritic marine conditions. Observed unconformities are possibly a result of long-ranging thin-skinned compressional tectonics. The oldest part of the molasse basin can be seen along the basin edge, and is formed by slates that overlie Late Cretaceous anchi-metamorphic flysch/meta-turbidites of the Rajang Group. The nature of the basement beneath the molasse/foreland basin however is unknown to-date. Nonetheless, the results of the Engkabang wells and a seismic-based structural modelling exercise conducted by Jong *et al*. (2016) suggest that the Rajang Group may not be present beneath the basin, and might have been thrusted over the foreland basin altogether (Figure 4).

HISTORY OF CARBONATE RESEARCH IN SARAWAK

The history of carbonate studies in the area can mostly be categorized by three generations of workers. The first being the pioneering ‘old guard’ explorers of the Sarawak Geological Survey; their work was later explicitly summarized in the publications by Charles S. Hutchison, particularly in Hutchison (2005). Data points chosen for these studies were located exclusively in the onshore realm.

During the 1970’s until the 1990’s, the second generation of petroleum geologists and stratigraphic specialists published selected data from offshore carbonate-reservoir gas fields, mostly in the context of reservoir characteristics in venues of regional conferences. Some oil companies also made attempts to review the large outcrops of Gunung Mulu and Batu Niah in the preparation of field excursion guides (e.g., Sulaiman, 2008; Lesslar & Wannier; 1998; Wannier *et al*., 2011).

More recently, the NW Sarawak carbonate outcrops have attracted a new generation of carbonate researchers with particular interests such as stratigraphic-tectonic context, bio-stratigraphic revisions, palaeo-climate, and palaeo-

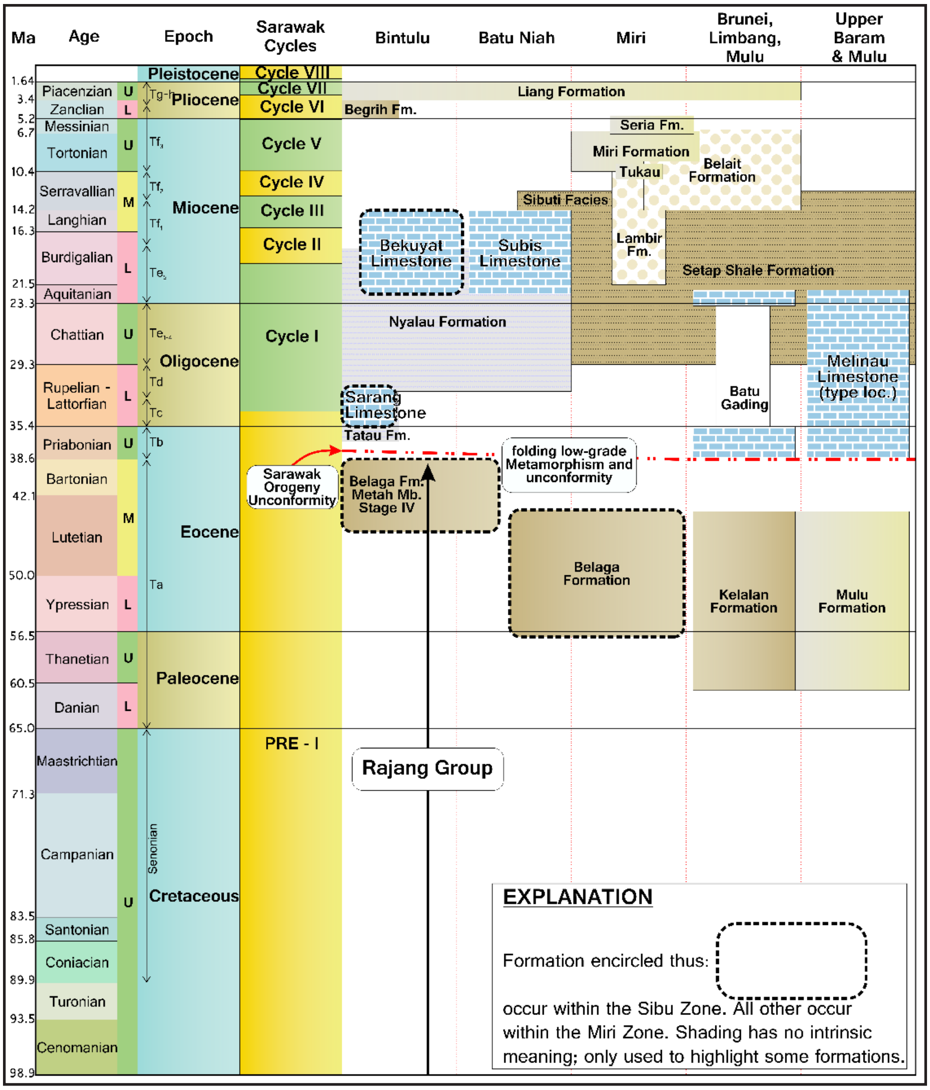


Figure 2: Chrono-stratigraphic table of the major formations of the Miri Zone covering NW Sarawak and Brunei. The Upper Cretaceous to Upper Eocene Rajang Group (flysch) forms the Sibu Zone and underlies the Miri Zone. The Sarawak Orogeny caused low-grade metamorphism and strong folding characterized by steep dips of the Rajang Group. The overlying formations (molasse) are much less deformed, and un-metamorphosed, except in localized shear zones. After Kesslar & Jong (2016a) and modified after Hutchison (2005, Figure 22).

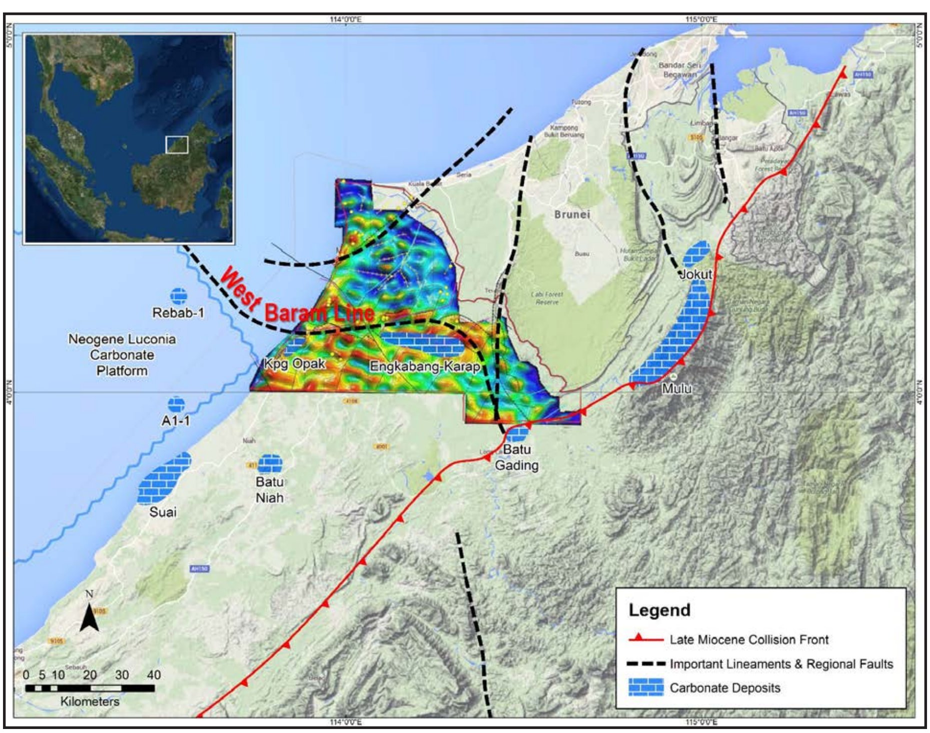


Figure 3: Distributions of carbonate deposits in NW Sarawak. Overlaid on the topography map is the gravity data acquired by JX Nippon (Jong *et al.*, 2016) with Engkabang-Karap highlighted as positive anomalies, and Kampung Opak outcrop also lies in area of positive anomalies. The West Baram Line as annotated subdivides the stable Tinjar/Luconia Block from the subsiding Baram Delta to the north.

environments. For example, Wannier (2009) introduced for Gunung Mulu the concept of a wedge-top basin. This refers to a setting, in which carbonates developed on top of siliciclastic and tectonized wedges (Figure 5). Mihaljević *et al*. (2014) reviewed some of the onshore NW Sarawak outcrops in the context of marine biota evolution. The Indo-Pacific marine biodiversity hotspot originated between the Late Eocene and the Early Miocene. Its origin coincides with an increase in availability of shallow-marine habitats driven by the opening of the SCS and the collision of Australia with the Pacific arcs and the SE Asian margin. The authors of the cited paper stressed the need to better understand the distribution and diversity of past Indo-Pacific marine habitats. They examined Upper Eocene to Lower Miocene marine shallow water carbonate deposits from six localities in two limestone formations: the large ramp-like Melinau carbonate platform (Middle Eocene to Early Miocene) and the unattached Subis carbonate platform (Early Miocene, Figure 6). Deposits examined in their study represent palaeo-environments and reveal an increase in habitat diversity from the Eocene to the Miocene. Mesophotic to oligophotic low-energy environments were stated as typical for the Eocene sites. Coral first appeared in the Oligocene deposits, but genuine reef depositional settings were not observed until the Miocene (Wilson & Rosen, 1998; Wilson, 2008). The study provided both insight into the evolution of the

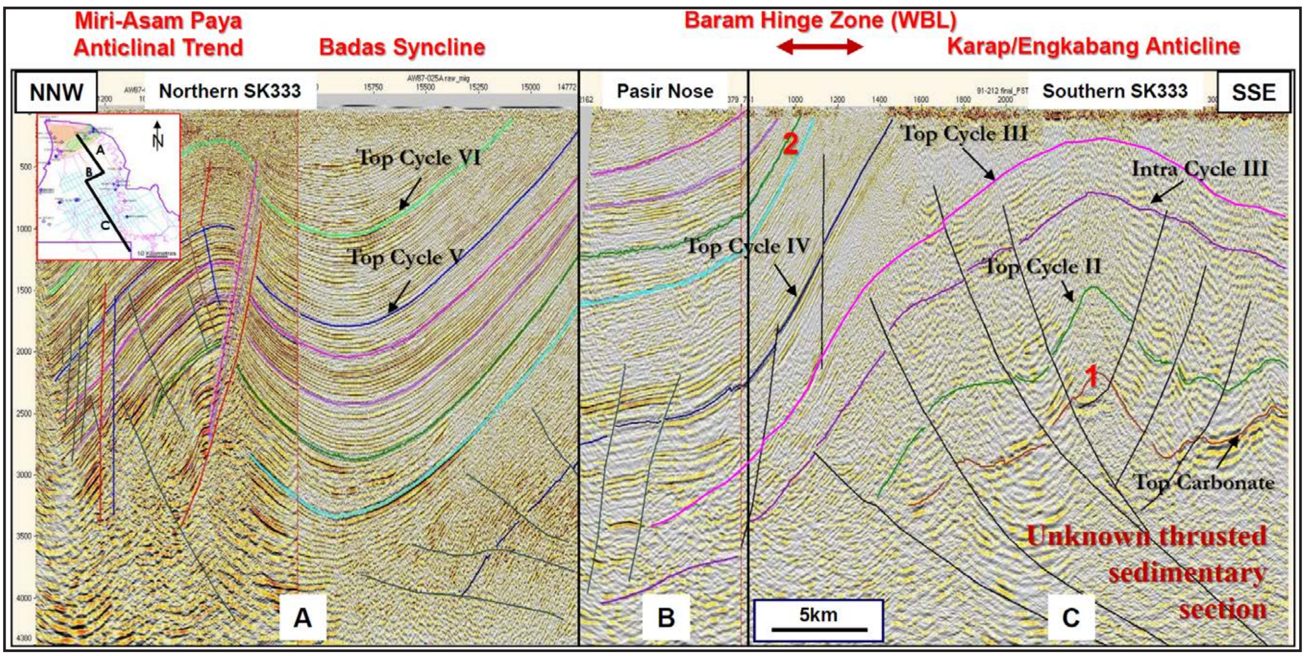


Figure 4: A NNW-SSE seismic correlation of onshore Baram Delta in Block SK333 and interpreted sequences. The numbers 1 and 2 in red annotate the deformation events of Late Oligocene to Mid Miocene wrench movement and related folding, and the Mid Pliocene to Recent uplift and compressional folding, respectively as described by Jong *et al*. (2013 & 2015). As annotated also is the approximate location of the West Baram Line (WBL).

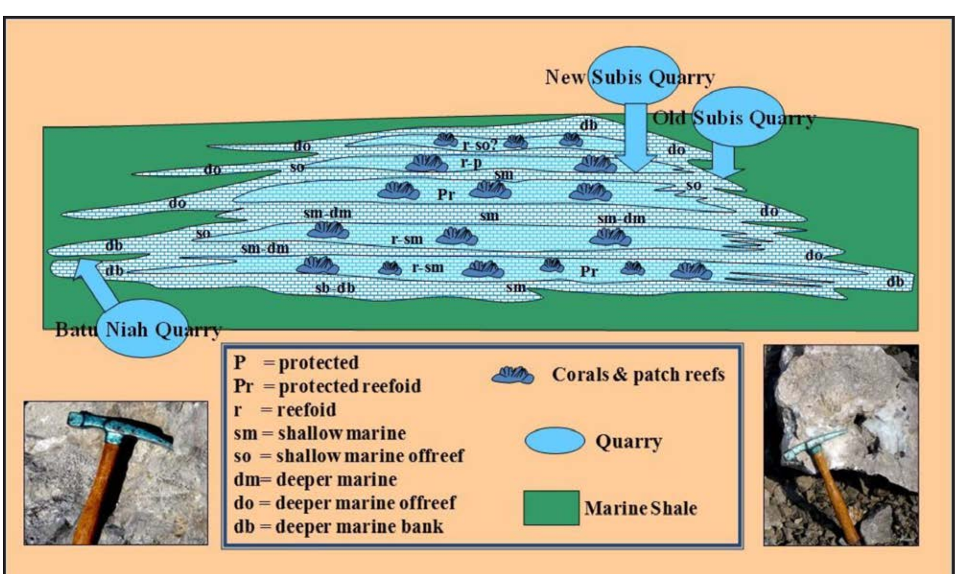


Figure 6: Schematic model of the Subis Limestone Complex (after Sulaiman, 2008). The section shows the Early Miocene carbonate platform. Inset photos: (left) Coral stock in Batu Niah that appears to be formed by a particularly pure limestone, (right) Larger coral stocks have frequently undergone freshwater-phreatic diagenesis leading to particularly clean clusters of calcite mono-crystal. Carbonate stringers, probably off-reef facies and neritic in nature, are also seen in the Oligocene section of the nearby well Subis-1.

carbonate platform environments along the NW Sarawak margin, and context for the origin of the Indo-Pacific marine biodiversity hotspot. The authors concluded that:

1) The Eocene study sites are characterized by foraminiferal-algal associations characteristic of mesophotic-oligophotic environments;
2) The first coral fragments were recorded at an Oligocene site deposited in a fore-reef environment;
3) Miocene deposits (in some parts of the section) show a high abundance of corals associated with fossil reefs;
4) The Middle Eocene to the Lower Miocene limestone deposits from NW Sarawak show an increase in habitat diversity accompanied by a decrease in foraminiferal abundance and an increase in coral abundance through time;
5) The observed pattern of faunal turnover shows that corals were already increasing in abundance during the Oligocene.

In the same year, Lunt (2014) reviewed the Melinau Limestone in the Mulu National Park (Figure 7), focussing on the continuous Melinau Gorge section, and reassessed the taxonomic concepts of Adams (1965). The new data supports the Adams (1970) observation of a Mid-Oligocene disconformity within the Melinau Limestone likely within Td stage (Figure 2). A quantitative indication of this disconformity shows that the Tb and Tc carbonates measured

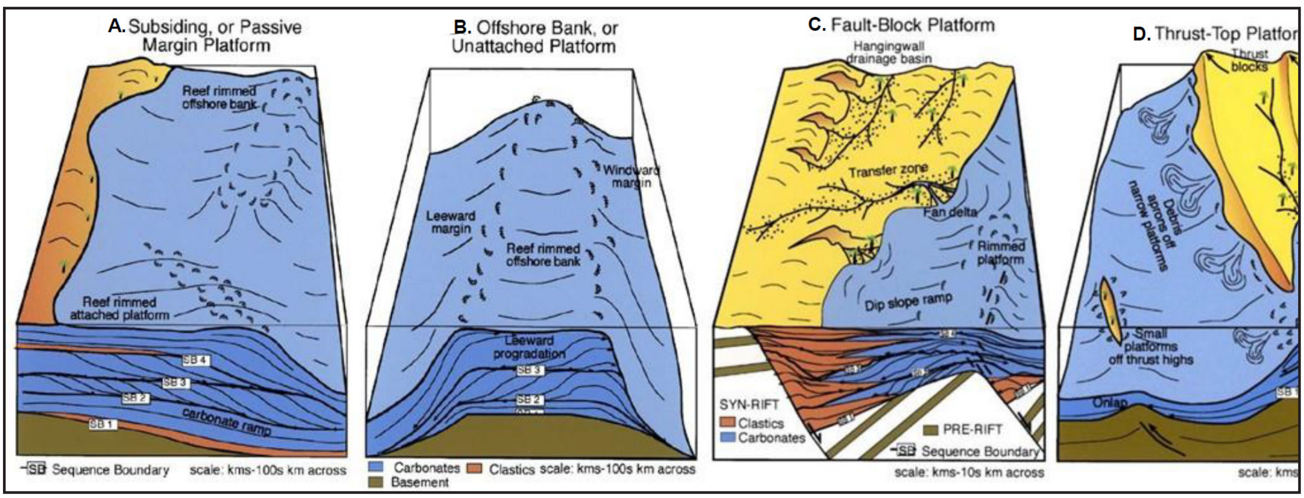


Figure 5: Basinal and tectonic settings of carbonate platforms. Platform types can be genetically linked to their basinal and tectonic setting, basin type and basin history. Platform occurrence, size, overall morphology, and the large-scale stratigraphic features, depositional sequences, and diagenetic overprints that are likely to develop, vary as a function of platform type (after Bosence, 2005).

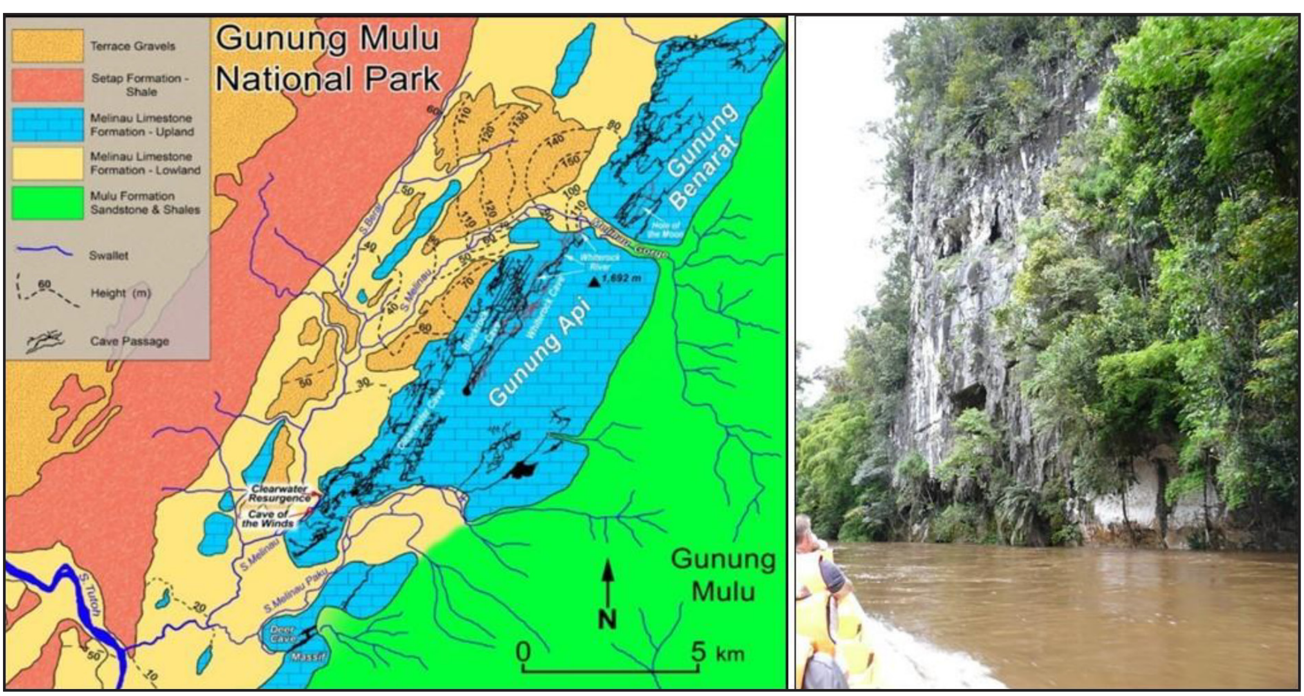


Figure 7: Left - Geological map in the vicinity of Gunung Mulu national park (after Liechti *et al*., 1960). Right – Photography of a carbonate outcrop of Gunung Api.

by Adams (1965) accumulated at rates close to 200m/Ma, but the thin Td is represented by only 11m/Ma, suggesting a significant hiatus and possibly erosion. Observations on the termination of the Melinau Limestone agree with those of Adams (1965, 1970) and Wannier (2009), with an initial event near the Oligo-Miocene boundary (Te4 to Te5 stage boundary; Figure 2) and the youngest limestones dated as Te5, about 20.3Ma in the Lower Miocene Burdigalian.

The Oligocene and Early Miocene saw carbonate sedimentation clustered in shoals. The present-day Sarawak Shelf was a relatively stable, regionally extensive shelf system that was established during the Late Eocene to early Late Oligocene and reached its maximum extent during the earliest Miocene (Adams *et al*., 2014). In the Early Miocene (~18-20 Ma), the clastic shelf system possibly retreated to the southwest due to sea-level rise, and consequently widespread carbonate deposition occurred in the distal shelf area. According to the same authors, two environments of deposition (EOD) had developed with:

1) a pronounced high-relief ‘Barrier Reef’ platform margin along the shelf edge, and

2) a proximal mixed carbonate-siliciclastic back-barrier shelf system. Primary reservoir quality of these two EOD types are distinct with argillaceous limestones dominating the back-barrier shelf, whereas high energy deposits including grainstones and coral-rich deposits have been documented for the ‘Barrier Reef’ platform margin. Furthermore, the Lower Miocene ‘Malaysian Great Barrier Reef’ was affected by varying tectonic events. Extensional and transtensional faulting, as well as major uplift occurred in northern Borneo (Sarawak and Sabah) coastal areas, whereas passive margin subsidence took place in the southeast.

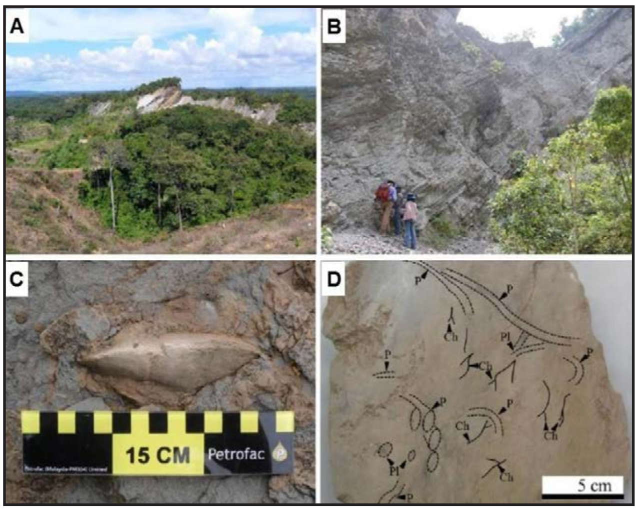


Figure 8: Kampung Opak Limestone outcrop photos. (A) The limestone stands out as an approximately 800 m long ridge surrounded Sibuti Formation shales. (B) Approximately 44 degrees dipping beds of alternating limestone-marl. (C) Internal cast of a bivalve measuring 11 cm wide is oriented perpendicular to the limestone bed. (D) Polished limestone block showing *Cruziana* ichnofacies; *Chondrites* (Ch), *Palaeophycus* (P) and *Planolites* (Pl). After Khor *et al*. (2014).

Another publication by Khor *et al*. (2014) provided a detailed palaeontological review of the very muddy Opak Limestone/marl in the outcrop near Bekenu. The Kampung Opak Limestone, which is considered part of the Sibuti Formation, represents an approximately 44 m thick succession of regularly interbedded limestones and marls. The Kampung Opak Limestone is mainly composed of mudstone and wackestone (Figure 8), and described by the authors as follows:

“*The relatively thicker limestone beds (~20-50 cm) are interbedded with thin marls (~1-5 cm). The depositional environment is interpreted as a shallow marine shelf, in waters less than 40 m deep, based on sedimentary facies, ichnology and palaeontology. The fine-grained facies indicates a low energy setting. The presence of the Cruziana ichnofacies in the limestone suggests a shallow marine*

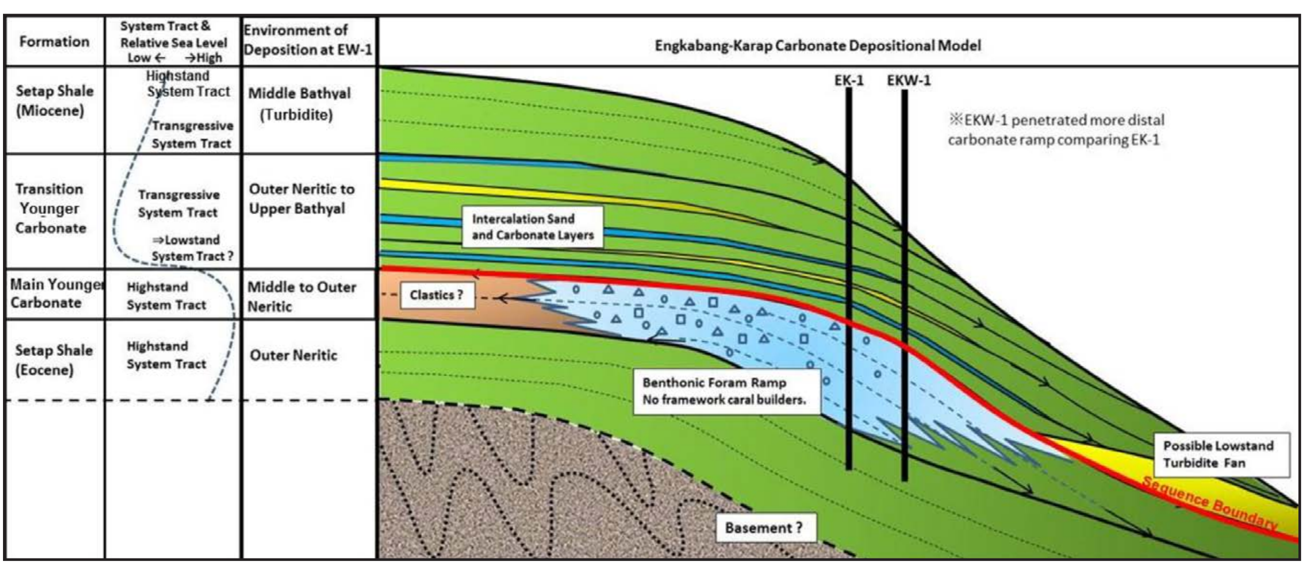


Figure 9: Postulated depositional model of the Karap/Engkabang carbonates with development of benthonic foram bioherm ramps (after JX Nippon, 2014). Note the Main Young Carbonate section penetrated was dated Late Eocene while the Older Carbonate section developed on the Melinau Limestone level remained untested.

Figure 10: Top - Subis Limestone Complex, a highly elevated feature in comparison to the surrounding lowlands indicating the development of the carbonate build-up complex within the surrounding basinal sediments of the Setap Shale. However, the build-up topography is significantly altered by subsequent exposure and erosion. Bottom - Slump deposits of deep marine Setap Shale with beds of detrital limestone fragments located along the road to Sepupuk *ca.* 1 km from junction to Batu Niah (after Sulaiman, 2008).

shelfal environment. The abundance of pelagic foraminifera suggests access to the open sea with high productivity. D/T ratio of Amphistegina sp. specimens from the limestone indicates a water depth of less than 40 m. Twelve species of planktonic foraminifera were identified from the Kampung Opak Limestone. The microfossil assemblage gives a Middle Miocene age (Globorotalia peripheroronda zone – Globigerinoides subquadrata zone, Tf stage). The Kampung Opak limestone probably represents the upper part of the Sibuti Formation. This further extends the age range of the Sibuti Formation from Early Miocene to late Middle Miocene age."

With so much, and sometimes divergent materials being available, we felt the need to combine and compile research results with detailed well and outcrop data for a more holistic evaluation to establish a better regional understanding of the carbonate development in the study area. These include, in particular, data and interpretations of the onshore Baram Engkabang wells (Figure 9), that produced valuable data points filling the knowledge gaps between outcrops (Jong *et al*., 2016), and nearby offshore wells A1-1 and Rebab-1 that reportedly penetrated similar-age carbonate sequences. Simply speaking, we can distinguish between a carbonate period reaching from the Eocene until the Middle Miocene,

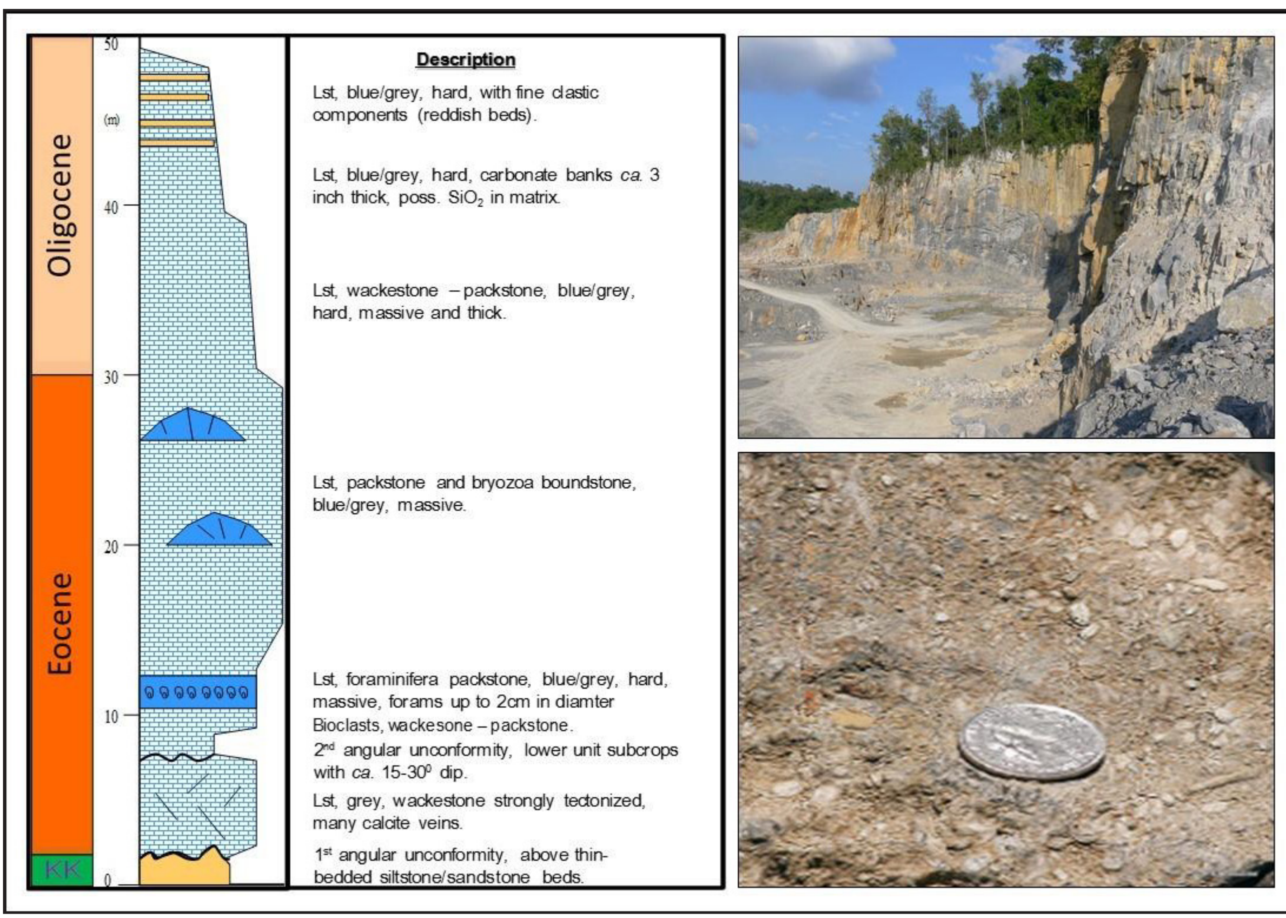
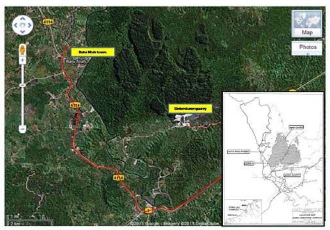
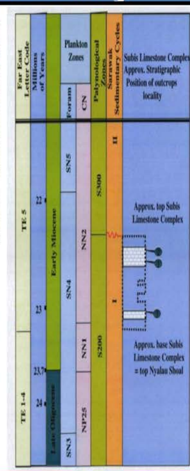


Figure 11: Vertical profile of Batu Gading limestones (Hollystone quarry, after Kessler, 2013). Top right: The Hollystone quarry is located in the vicinity of the discussed Baram-Luconia/Tinjar tectonic segments, imbricated between older Kelalan metamorphics. However, there is no indication that the Batu Gading limestone has undergone metamorphism. Bottom right: Foraminiferal packstones in Batu Gading limestones of a ramp facies. These carbonates appear to contain always some clay component.

Template A : Batu Niah - Quarry and Well Summary

Situated in Niah [3°46'21.18"N 113°47'42.17"E] (WGS84), approximately 17.47 km from Niah Town.





Introduction: Stratigraphy and Depositional History

The Subis Limestone Complex has been interpreted as an isolated bioherm/shoal reef that grew in clear, shallow, shelf waters (down to a depth of some 60m). The carbonate platform initiated growth on a substratum of fine sands of the "Tangap Formation" on pre-existing highs by settling down of coralline algae and large foraminifera (Dedeche *et al*., 2013).

Vertical changes in bioherm growth and development observed in outcrops can be attributed to relative sea-level changes. Eventually the reefal development was interrupted and the bioherm overlain by deep marine marls and shales (Sibuti Formation and Setap Shale).

Abundant benthonic foraminifera date the Subis Limestone in outcrops as Early Miocene (Te5) age. In well Subis-2, the stratigraphically deeper limestones were dated as Te1-4. An important time hiatus seems to separate the carbonate sediments from the overlain clastics.

Palaeontology and Age Determination

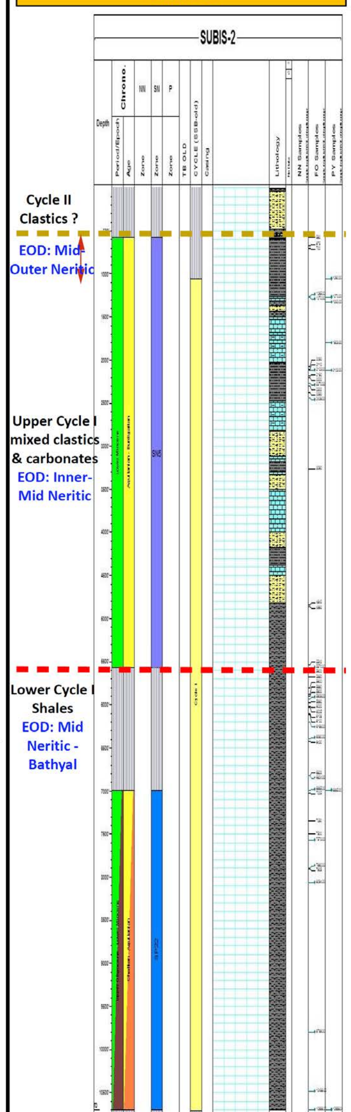
The fossil content of the Subis Complex limestone has been studied on thin sections and polished rock surfaces. The generic determinations are based on Haak (1955, cited in Adams, 1965). The combined occurrence of *Miogypsina (ss)*, *Eulepidina* and frequently *Spiroclypeus* (Haak, 1955; Adams, 1965), is considered as indicative of Zone Te5. This association is commonly found in samples from the Batu Niah and the Subis quarries.

Planktonic foraminifera in shale samples collected at outcrops to the south of the Subis Complex are indicative for the interval *Catapsydrax dissimilis-stainforthi* zone of *Globigerina binaiensis* zone. Palynological analysis of shale samples from the same sediments indicates Zone S300.

The shales deposited to the west of complex are considered as contemporaneous with the lower to middle part of the Subis Limestone and their planktonic foraminiferal content places them within the *Globigerina binaiensis zone* (based on the combined occurrence of *G. binaiensis* and *Globigerinoides* spp.).

Based on these biozonal assignations the deposition of the limestone can be bracketed as within the lower part of the Te5 interval, which is considered as equivalent to upper Cycle 1 of Sarawak stratigraphy and corresponds to the earliest Miocene or latest Oligocene.

Subis-2



Template B : Suai-5 Onshore Sarawak

[03`44'22.052" N, 113`25'26.616" E] (WGS84)

Introduction

Between the 1920-1950's, geological mapping, acquisition of land gravity and seismic were conducted by Shell around the coastal areas around Batu Niah. The belt between Suai and Bulak was covered with 483 line-km of single fold land seismic in 1952/53. Several wells were drilled in the onshore part of the Tertiary basin around the coastal belt. The Suai 1-3 core holes drilled in 1952-53 reached Middle Miocene (Cycles I/II) interbedded shales and sandstones. The Suai-3 well produced oil at a rate of 27 bopd from an isolated channel sandstone, which was abandoned at total depth of 1286 feet (359m) within the Lower Miocene after a gas blow out. In 1955 three more wells (Suai 4-6) were drilled nearby.

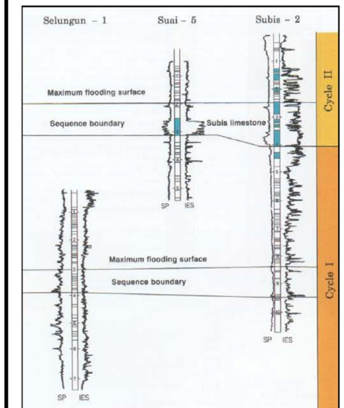
Stratigraphy

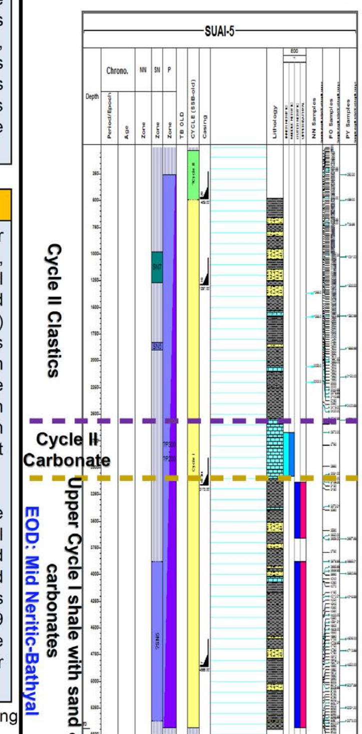
These wells penetrated deeper into Lower Miocene (Cycles I/II) interval comprising the Subis Limestone, and interbedded sandstones and shales. The limestone represents deep marine and off-reef facies, whilst the higher sections are mixed clastics and carbonates comprising thinner, 30 foot (10m) limestone, interbedded with a mixture of shale, sandstone and calcareous sands. At well locations the calcareous and argillaceous sandstone intervals show only marginal reservoir properties (Por. 8-20 %; permeability up to 2.8 mD). A DST within the reservoir intervals recovered only traces of gas and water.

Other Carbonate Wells in Tinjar Province

Located about 25 km northeast from the Suai wells, the other onshore well in the near coastal areas in the Tinjar Province, Subis-2 was spudded in 1956. The well encountered several Lower Miocene intervals of thinner limestone in a mixed carbonate unit of between 1200 – 4000 feet (365-1220m) thickness. The porosities in the deeper marine bank deposits are all very low. Fabrics are mostly wackestone-packstones with no major reefs or grainstones observed. Carbonates are argillaceous, dense limestones and dolostones. Dolomitisation did occur but did not improve porosity. No leaching has been observed and DST's show the amount of hydrocarbons at Subis-2 was insignificant.

The final well, Selungun-1, was drilled in 1956 in the area more towards Bintulu. The Selungun-1 well drilled into an anticlinal feature and spudded into Oligocene (Cycle I) shales, silts and thin sands and 150 – 400 feet (46-122m) of shallow marine and coastal plain sandstones. The porosity of the sandstones varies between 3 to 10%, but improves near the surface to between 9 and 24%. Due to erosion after strong uplift of the structure, the Cycle II Subis Limestone objective in Selungun-1 was never encountered.





Top right: Well correlation from Selungan-1, Suai-2 and Subis-2 showing the Subis Limestone. Text after Ismail & Abu Hassan, 1999.

followed in NW Sarawak and Sabah by a clastic period from the Middle Miocene until present. The evolution of the clastic Sarawak and Sabah shelves as they developed in the late Middle to Late Miocene was described in Kessler & Jong (2015a), and the Pliocene to Quaternary uplift history summarised in Kessler & Jong (2014, 2015a & b, 2016b).

SUMMARY TEMPLATES OF OUTCROP AND WELL DESCRIPTIONS

In this section, we attempt to summarize the most important carbonate facts of outcrops and well penetrations, which are presented in template format -Templates A to I. Our data points for age control and facies determination in this study include:

The Batu Niah cliff/Subis-1 (Lesslar & Wannier, 1998; Dedeche *et al*., 2013; Mihaljević *et al*., 2014; Template A):

A predominantly Miocene aged reef complex (Figure 6), now standing free in the landscape as a weathered-out (inselberg) remnant, is fringed by neritic Setap Shale clastics (Figure 10). The complex is situated on the culmination of a northeast-southwest trending anticline that is reverse faulted along the fold axis. The southeastern part dips towards the southeast while the northwestern part gently dips to the northwest. According to the study by Sleumer (1976), the age of the complex is Te5 (Early Miocene) as evidenced by the combined occurrence of *Eulepidina* sp and *Miogysina* sp. Shales of the Setap Formation deposited contemporaneously with the limestones belong to the *Globigerina binaiensis* zone (combined occurrence of *Globigerinoides trilobus/immaturus* group and *G. binaiensis)*, also of Early Miocene age. The Subis complex is an isolated carbonate development underlain, surrounded and covered by clastic sediments. It apparently formed on a palaeo-high resulting from slight tectonic uplift. The coast at that time was nearby and located to the south or southwest.

In a review by Dedeche *et al*. (2013), the Subis Limestone is a member of the Tangap Formation. It is Late Oligocene to Early Miocene in age. It is divided into two sequences, which are different in depositional setting and architecture. The lower sequence is Late Oligocene in age, generally deep marine depositional environment and is for the most part in the subsurface. The upper sequence is Early Miocene in age, with shallow marine reefal depositional enviroment and forms a spectacular limestone hill that reflects the original carbonate platform. The carbonates of shallow marine back-reef characteristics are comprised of foraminiferal-algal packstone-grainstone; algal fragments, larger foraminifera, with presence of gastropod. Within the grainstone facies, we observe patches of *in-situ* coral reefs. The lagoonal facies are tight and slightly argillaceous ranging from bioturbated wackestone-packstone to fine-grained wackestone with stylolites and calcite veins; cemented corals, algal fragments, and larger foraminifera (Sulaiman, 2008). The old Subis-1 well (Shell, TD 3185 m) penetrated a carbonate section older than Miocene, likely to be time-equivalent to the younger carbonate section of the Karap/ Engkabang Anticline (Jong *et al*., 2016).

The coastal Sarawak Suai-5 well (Template B):

Drilled by Shell in the 1950's near Bintulu, this old well penetrated possible Early Miocene to Middle Miocene platform carbonates, which are potentially time-coeval with the Subis Limestone. There are, however, currently no better data available in absence of further onshore exploration in the area. A well (Bulak Setap-3**)** south of the Lambir Hills on the Luconia/Tinjar Block penetrated some 3353 m of Oligo-Miocene claystones, but without intercepting any major turbidite sandstones, carbonates or source-rock levels. The well is noteworthy for leaking methane-rich gas at the corroded wellhead located within a current oil palm plantation, which possibly points to the existence of a deep and highly mature source rock (of coaly Eocene interval?).

The Batu Gading quarry (Ngau, 1989; Hutchison, 2005; Kessler, 2013; Template C):

An Eo-Oligocene section overlies a strongly chevron-folded, and slightly metamorphosed clastic basement with Late Cretaceous deepwater fauna (Figure 11). Above this, the Batu Gading quarry exhibits a sequence of foraminiferal packstones leading to thin-bedded mudstones of Te2 - 4 stages. In one section of the quarry, now removed, one could see clusters of small Bryozoan limestone-boundstone patches, surrounded by foraminiferal packstone. The lower section of the packstone beds also contains a significant percentage of detrital quartz grains. However, controversy remains regarding the age of the upper stratigraphic section. According to Peter Lunt (pers. comm.), the Oligocene is not 'entirely absent' as indicated by Hutchison (2005, p.87; possibly miss-citing older data). According to Lunt's (2014) revised foraminifera dating, the area was therefore exposed for most of the Oligocene, and was transgressed only in the

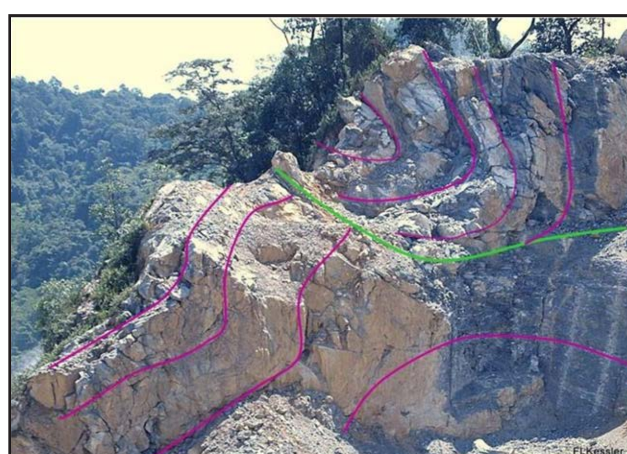
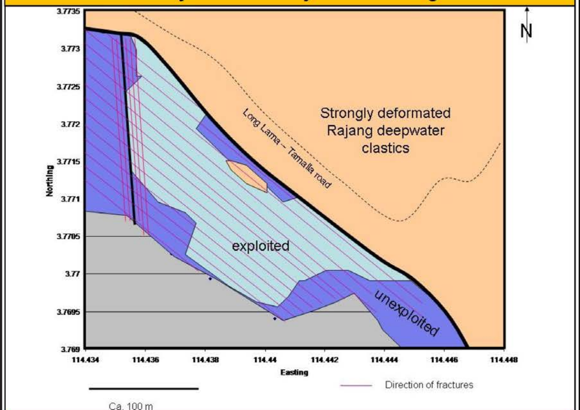


Figure 12: The Jokut Quarry is located NE of the Mulu Massif and forms probably the northernmost known occurrence of carbonates in this part of NW Sarawak. The exposed carbonates (called Selidong and Kerimit Limestones) are intensely folded and fractured, and float within an even more intensely folded and tectonized mass of shales and slates (after Kessler, 2012).

Template C : Batu Gading, Hollystone Quary

Near Long Lama Town
[3° 46' 24.23"N, 114° 26' 21.31"E](WGS84)

Hollystone Quarry Batu Gading



Rock Description/Sedimentology

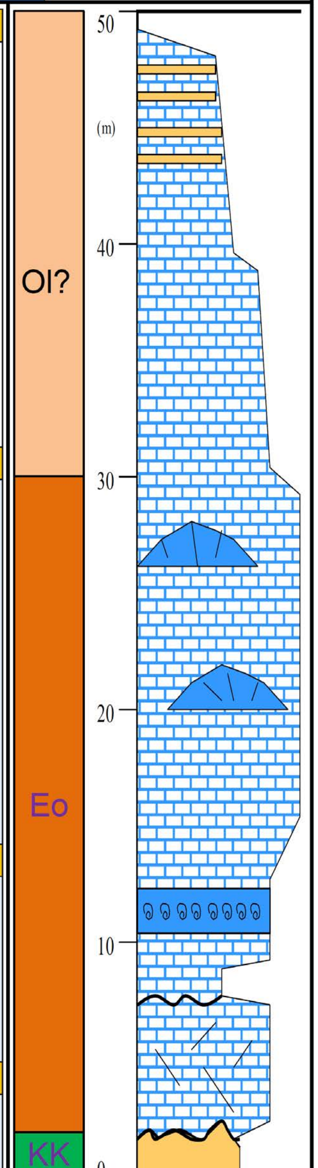
Batu Gading foraminifera were studied by Liechti *et al.* (1960), Adams & Haak (1962) and later by Ngau (1989). A very good summary of the stratigraphy is also given in Hutchison (2005), p. 87. According to these authors, the lower carbonate body is of Upper Eocene age, whereas the limestone above the 2nd unconformity was dated as Lower Miocene. This said, the upper limestone body (above 2nd unconformity) in the studied location appears to be far more prominent compared to literature. Only the upper carbonate body could be studied and logged in detail. The sequence starts with foraminiferal wackestones/packstones and indicates a moderate energy environment of fully marine conditions. The central sequence is formed by patch reefs (this time not well exposed) surrounded by packstone/grainstone facies. We see here a high-energy environment with good sorting and marine-phreatic cementation. The uppermost, platy limestone sequence may, subject to confirmation by microfacies analysis, an outer shelf – neritic carbonate sequence. The Batu Gading matrix rock appears to be relatively tight (Por. < 10%?), with potentially better matrix porosity/permeability preserved within the high energy carbonates combination with fracture porosity.

Age

According to Hutchison (2005), who summarizes older stratigraphical work carried out in the sixties, the Batu Gading sequence is formed by two limestone bodies on top of each other: An Eocene unit, superimposed by a Lower Miocene unit in apparent concordance, with the Oligocene time section being missing. A review by P. Lunt (pers. comm., 2016) suggests however, that the upper part of the limestone sequence is of Upper Oligocene age. and that the Lower Miocene may be missing. However, there is no sign of karstification seen. In summary, the age and lithology context should be further investigated.

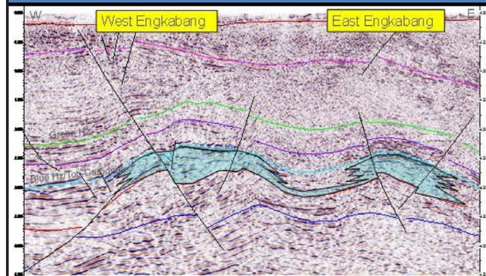
Unconformities (fieldwork 2011; see Kessler, 2013)

The only (angular) unconformity between carbonate bodies lies near to the base of the carbonate column below the large foraminifera (nummulite) horizon. A disconformity/unconformity between the massive limestone and the overlying slaty limestones could not be located.



Template D : Engkabang-1 Onshore Sarawak

[04`07'21.893" N, 114`19'14.732" E]
(WGS84)



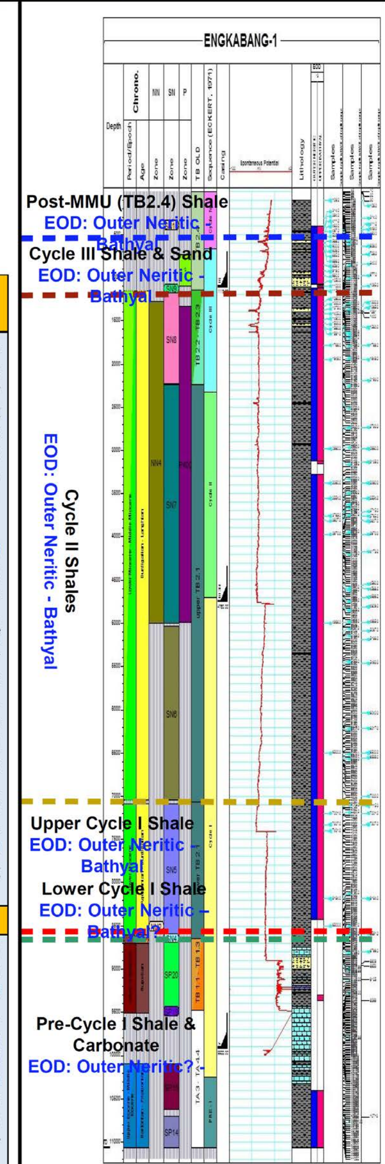
Introduction: Engkabang-1 and Engkabang West-1 (Jong *et al.*, 2016)

The Engkabang-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 of ?bioherms. 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. Carbonate porosity was only 3%, but a 40 hour test produced gas at 211,000 scf/day through 2⅞" tubing (75% methane, 25% CO_2) and 71 bbl/day water with low salinity (Chlorite 2500 ppm).

Uncertainty around the Engkabang-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. The well penetrated 210m TVD of massive carbonate of mudstone and wackestone, which was about 60m thinner than the equivalent section in Engkabang-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 DST 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.

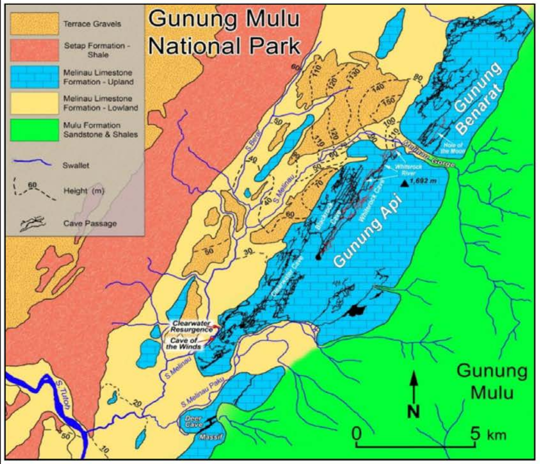
Stratigraphy and Age Determination

A massive section of shaly sequence overlaid the targeted carbonate section and the Engkabang wells penetrated deep into Middle Eocene stratigraphy based on updated biofacies reviews of the wells conducted by Corelab in 2014. The recent studies suggest the Karap-Engkabang carbonates are some of the oldest carbonates dated onshore Sarawak. A number of Sequence Boundaries and erosional events have been identified at 23Ma (boundary between Miocene and Oligocene) and 33.7Ma (boundary between Oligocene and Eocene) and 37.1Ma. The latter two events have up to 2 My missing section recorded.



Template E : Gunung Mulu Carbonates

Gunung Api [4°6'3.89"N, 114°53'35.27"E] (WGS84), more than 10 km from Mulu Town. Accessible through boat and walking about 7-10 Hours.



Stratigraphy and Facies

Above the Mulu Formation lies the Melinau Limestone Formation. This unit consists of a 2.1km thick sequence of massively bedded, strong, pale grey limestones of Late Eocene-Lower Miocene age. These were laid down in a shallow sea between 20 and 40 million years ago. Because of the steep dip to the west (at around 60-70°), the Melinau Limestone now outcrops to the west of Gunung Mulu, forming a narrow, lenticular outcrop culminating in Gunung Api. The limestone also underlies the alluvial plain to the west where occasional steep sided limestone towers (*batus*) project through the alluvium.

Overlying the Melinau Limestone is the Setap Shale, which consists of a sequence of mudstones with occasional marly bands and thin sandstone beds. These rocks were lain down in deeper water during the Middle Oligocene – Early Miocene period, some 20-30 million years ago. These outcrop to the west of the park, forming a small escarpment. Although generally younger that the other two rock units, the softer nature of these rocks means they have been preferentially eroded to form the low-lying area to the west of Gunung Api. (Adapted from a recent description by Farrant, 2015, based probably on Liechti *et al*., 1960).

Overall the Melinau Limestone dips fairly steeply NW (averaging 50-80° near base, 20-50° near top). There is a syncline in centre of the outcrop band, roughly along axis of which runs the Melinau River. The high angled reverse fault (Melinau Fault or Iman Fault) located to NW of Melinau River is reported to have a maximum throw of 900m. There are also a number of normal faults. North of the Melinau Fault the sequence dips steeply north. The structure is such that there is significant presence of limestones below the water table. Melinau Limestone forms the line of mountains along strike at the heart of the park and underlies the Melinau and Medalam alluvial plains. The surface area of the limestones is approximately 120km^2. Melinau is the type locality for the formation. It is in apparent structural conformity with underlying sequences; but unconformably overlies the Mulu Formation.

The top of the Mulu Formation is calcareous sandstone grading up into limestone. Note however of report of "schists and slates" at top of Mulu formation in contact with overlying limestones in the Sarawak Chamber. Massive, lenticular body, 2133m thick, 37km long (NE-SW) and approx. 8km wide. The lens thins out to both north and south. It is exceptionally massive throughout, which renders dip and strike difficult to ascertain in the field. The key lithological characteristics are:

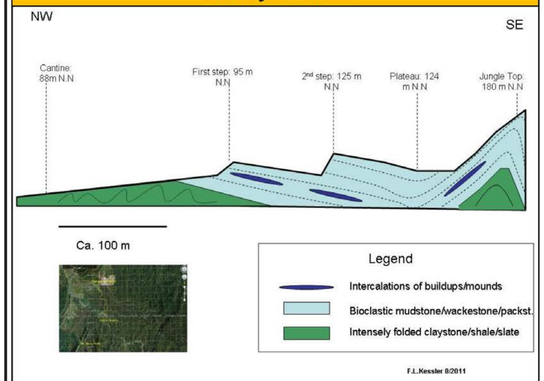
- White or grey uniform limestones
- Massive
- Calcilutites (grains < 1/16mm) or calcarenites
- Locally recrystallized to marble.
- Insolubles less than 1% (i.e. extremely pure)
- Dolomite (mainly primary) ranges from 2-20%. Some outcrops (Bukit Berar) are reportedly of pure dolomite, with sucrose appearance. Fossil content: foraminifera (prolific and some very large), corals, bryozoans, bivalves, gastropods, (all sparse) and algal balls (locally abundant).

Text after Dr. Domique Dodge-Wan, (2012), Curtin University Sarawak. Geological Map after Liechti *et al*., 1960.

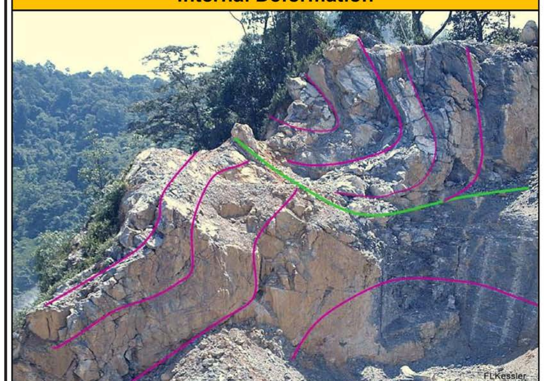
Template F : Jokut Quarry, Limbang

Situated In Limbang [4°22'51.23"N, 114°59'44.66"E] (WGS84)

Quarry Section



Internal Deformation



Introduction

One reaches the quarry after *ca.* 150 minutes under benign conditions from Nanga Nedremit. The quarry belongs to a series of outcrops along the upper Selidong River and her tributaries, and the limestone is referred to as Selidong and/or Kerimit Limestone (Hutchison, 2005).

Outcrops in Sarawak are impermanent features, and this outcrop is no exception. Opened in 2006, the main deposit is almost exhausted. One can approach and access the outcrop from Nanga Nedremit in Limbang.

The Jokut Quarry is located NE of the Mulu Massif and forms probably the northernmost known occurrence of carbonates in this part of Sarawak. The exposed carbonates (called Selidong and Kerimit Lst) are intensely folded and fractured, and float within an even more intensely folded and tectonized mass of shales and slates.

The carbonates, mainly formed by bioclastic mudstones to packstones contain mounded features. The carbonates appear cherty (concoidal break structures). The outcrop was measured and described during a scouting trip to Limbang in July 2011. Current field data suggest that the Jokut carbonates may be part of a much larger olistostrome complex. In absence of good biostratigraphic data, and the complex gravity tectonics, age of the unit remains uncertain, and perhaps Oligocene?

latest Oligocene time, represented by a sequence of thin-bedded, clayey and cherty limestones. This sequence bears witness to an upwards deepening cycle, and drowning of the shallow water carbonate environment. Strangely though, there is no clear evidence for a pronounced unconformity within the quoted Oligocene sequence, and there is no sign of any karstification. Hence, if there is complexity in respect to stratigraphic ages, there is also complexity in respect of tectonics. The largest carbonate outcrop is called Hollystone Quarry, located within a graben flanked by and above the Rajang Group metamorphics, which was preserved from erosion. Most likely, the extent of Eo-Oligocene deposits was originally much larger, and only small remnants have escaped erosion. Only a few kilometres to the northwest, a tectonic contact between the Rajang Group and the foredeep (Setap Shale) can be mapped. Folding, faulting and perhaps thrusting occurred during the Late Miocene/ Pliocene times, but the area had also likely seen tectonic movements ahead of the Late Miocene, as documented by Jong *et al*. (2013, 2015).

The Engkabang wells (Jong *et al*., 2016; Template D):

Engkabang-1 was drilled by Shell in a 1959-1960 campaign, and penetrated late Middle Eocene to Oligocene carbonates above non-metamorphic clastics of unknown age (which may not be part of the Rajang Group). The well proved sub-economic gas in a massive 272 m section of tightly cemented and dolomitized limestone, initially broadly assigned to a Late Eocene-Early Miocene age. The well Engkabang West-1 was drilled by JX Nippon in 2013-2014 (Figure 9). It penetrated a separate culmination of mainly mudstone and wackestone, and the mapped carbonate reservoirs proved tight (JX Nippon, 2014). Seismic maps of the Karap/Engkabang area, calibrated with biostratigraphic studies in the wells indicate the presence of a number of key stratal events related to regional unconformities and hiatuses. The Karap/Engkabang area was a platform ramp area, which saw periods of compression, inversion and/or uplift. The biofacies study further indicated that the basal section of Engkabang wells represented some of the oldest carbonate rocks penetrated by any wells in the region. It was similar in age to that of the Melinau Limestone outcrop section of NW Sarawak, previously investigated by Adams (1965), and re-visited by Lunt (2014). Should the interpretation of the TD section proved to be correct, it would infer that the molasse of Sarawak Foreland Basin is located in an entirely different tectonic block (no Rajang Group present), with a different and unknown basal sedimentary section.

The Gunung Mulu carbonates (Liechti *et al*., 1960; Lesslar & Wannier; 1998; Wannier, 2009; Template E):

A very large carbonate platform complex, of Eocene to Early Miocene age, which was biostratigraphically reviewed recently by Lunt (2014), and confirmed the age setting proposed by Adams (1965). According to a recent description by Farrant (2015, based probably on Liechti *et al*., 1960):

"Above the Mulu Formation lies the Melinau Limestone. This unit consists of a 2.1 km thick sequence of massive, thick bedded, light grey limestones of Late Eocene to Early Miocene age. These were deposited in a shallow sea between 20 and 40 million years ago. Because of the steep dip to

Figure 13: Top: Proximal turbidite channel, probably of Oligocene to Lower Miocene age, on the road from Long Lama to Long Laput. Turbidite channels like the one above appear to be incised into the Setap Shale and characterize topographic lows and fairways between carbonate platform elements. Middle: Gray Upper Setap Shale with sandstone olistoliths, shown in the middle section of the picture. The outcrop is located near to the road junction leading to the Empresa oil palm plantation. The sandstone slump blocks shown above illustrate the vicinity of a (probably narrow) sandy shelf, as well as the presence of a relevant angle such that mass gravity flow occurs (Kessler & Jong, 2015c). Bottom: Distal turbidite facies on the Long Lama Road near the junction with Miri-Bintulu road. The section is probably time-coeval with the Lower Miocene section in Batu Niah (Subis-1).

the west (at around 60-70°), the Melinau Limestone now surfaces to the west of Gunung Mulu, forming a narrow, lenticular outcrop culminating in Gunung Api (Figure 7). Overlying the Melinau Limestone is the Setap Shale, which consists of a sequence of mudstones with occasional marly bands and thin sandstone beds. These rocks formed in deeper water during the Middle Oligocene to Early Miocene, some 20-30 million years ago. Outcrops to the west of the park are forming a small escarpment. Although generally younger than the other two rock units, the softer nature of these rocks caused preferentially erosion to form the low-lying area to the west of Gunung Api."

The Jokut quarry in Limbang (Kessler, 2012; Template F):

These limestone sequences, known as the Selidong and Keramit limestones, are strongly folded and lie interbedded in dark, probably anchi-metamorphic Setap Shale (Figure 12). The intensity of folding suggests a gravity-driven slumping, and might suggest a transport of carbonate platform segments downslope into deeper water. Both limestone and shale sequences appear to be of Late Oligocene Te age, according to dating by Wilford (1964, citation in Hutchison 2005). The carbonate sequences consist of bioclastic carbonates (mudstones, wackestones, and very rarely packstones). The mudstone-wackestone beds are typically very finely laminated, implying a very low sedimentation rate. Since the coastal areas of NW Sarawak (Miri) and coastal Brunei are essentially covered by Neogene deposits camouflaging older rocks, the Jokut/Limbang area is unique in the sense that the Oligocene basin margin can be studied here both in terms of stratigraphic succession, facies and deformation.

The Kampung Opak quarry (Khor *et al*., 2014; Template G):

The quarry area is part of the Sibuti Formation, a marly to carbonate-rich member within the uppermost 200 m of the 'Gray' Setap Shale (Figure 8). There are several minor outcrops in the area of Bekenu. However, only in Kampung Opak the entire carbonate-rich Sibuti member is expressed as a continuous marly limestone, where the outcrop is formed by layered carbonates of low energy characteristics and with a high clay content. The combination of fine grained facies, *Cruziana* ichnofacies and shallow marine benthic foraminifera indicate a shallow marine shelf depositional environment in water depths of less than 40 m. The biostratigraphic study indicates a Middle Miocene age, based on planktonic foraminiferal zonation. A comparison with the nearby Subis Limestone suggests that the bedded limestone facies of Kampung Opak probably represents the distal and muddy margin of a carbonate platform, which may extend to the Batu Niah area. The Kampung Opak quarry, a lenticular outcrop and a very steeply dipping cliff, allows only limited conclusion in respect of the platform extent. Northwest of the Pantai Bungai beach, however, some large and clearly autochthonous carbonate boulders are formed by oyster rudstone support the interpretation of sheltered tidal to very shallow marine environment.

Figure 14: Transition between gray Upper Setap Shale and Lambir sandstones. Note the colour change from light gray (carbonate debris) of Setap Shale to brownish-gray claystones and the scouring channel sandstones at the base of Lambir Formation (after Kessler & Jong, 2015c).

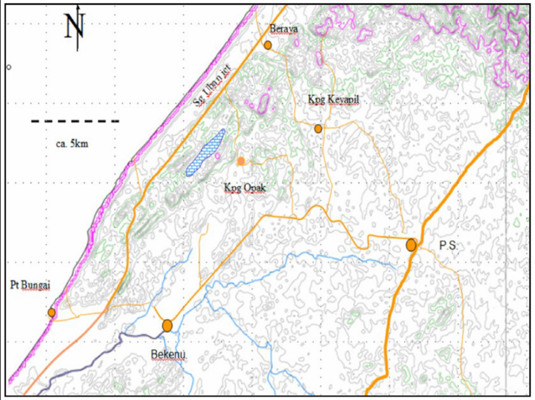
The Loagan Bunut, and Long Lama area outcrops (= clastic sub-basin facies):

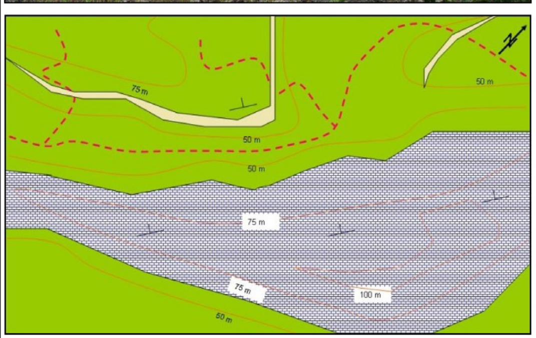
These data points summarised below are important, since they characterize the clastic facies setting between carbonate platform areas, in addition to the Bulak Setap-3 well data. Several data points indicate turbiditic sandstones and siltstones, located within small channel complexes embedded in the Setap Shale claystones. These sandstone-filled channels are usually a couple of metres thick and up to 40 m wide and might belong to the turbidite fairways that bypassed isolated platforms (Figure 13).

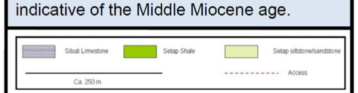
- A profile logged by Kessler & Jong (2015c) describes a rock column spanning probably from Late Oligocene to Pliocene in age. It shows a rarely seen outcrop example, where the profile dissects two major regional unconformities, namely the Middle Miocene Unconformity, separating the ?Early-Middle Miocene Upper Setap Shale from the Lambir Formation (Figure 14), and stratigraphically higher, a pronounced angular Pliocene unconformity separating the folded sand-dominated Lambir Formation from similar but unfolded deposits of the Tukau Formation. The Upper Setap Shale (bottom section of profile) is the most common outcrop rock exposed in the onshore Luconia/Tinjar region. It constitutes a thick bottom-fill layer within a shallowing-upwards mega-sequence of channels that probably accumulated in an upper slope environment. In some areas, the Upper Setap Shale is replaced by marls and limestones of the very shallow-marine Sibuti Formation, not represented in the logged profile; instead we see marly shale with the occasional slumped sand blocks, and thin-bedded levees of turbidite sequences (see below). A few shelfal sandy beds may be interpreted

Template G : Kampung Opak Quarry near Bekenu

Near Bekenu Town
[4° 7' 47.94"N,
113°51'21.91"E] (WGS84)







Introduction

The quarry follows a steep-dipping carbonate rib over a distance of some 1200m. The quarry was opened in *ca.* 1995 and closed in 2005 – the rock proved to be of inferior quality compared to Batu Niah, and work in the quarry was halted. The topographic relief in the quarry is rather impressive – the estimated cliff face could exceed 60m strike/dip throughout the outcrop is in the order of 40/45 NW, and thickness of the carbonate formation may be in the order of some 70m. The latter is somewhat difficult to estimate given that the southeast leg of the limestone rib is covered by dense jungle. To date we are not able to find a good outcrop detailing the base of the carbonates; the transition (gradual, over several meters) from carbonates to the overlying clastics is documented in several rather poor outcrops at the flank of the quarry area.

Stratigraphy

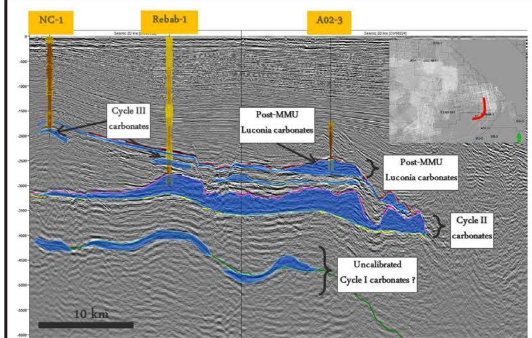
The carbonates belong to Sibuti Formation of the Setap Shale; located some 50-100m below the onset of the Lambir clastics. This interval is occasionally rich in marine stenohaline biota, even though the character of the sediment is commonly marly.

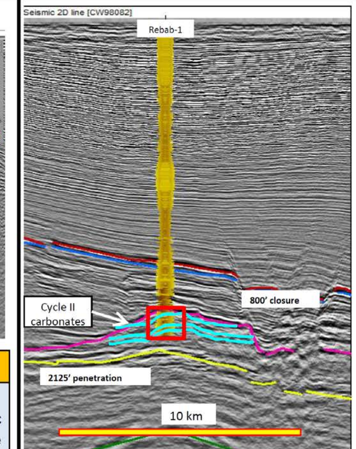
Sedimentary Environment of Deposition

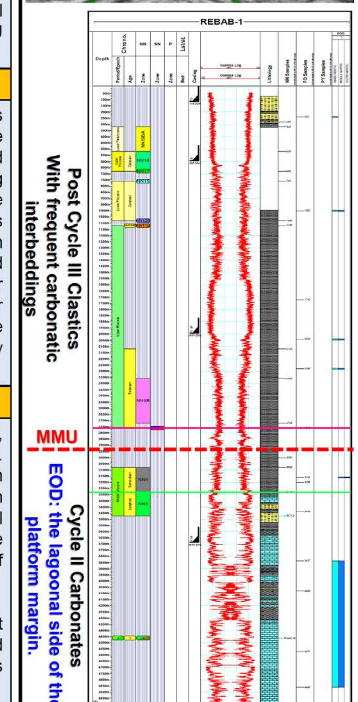
We observe marly mudstones, and the measured clay content lies within 20-40%. The rock contains minor amounts of foraminifera, plus gastropods and bivalves. The absence of wave ripples suggests a sediment environment either to be ultra-shallow, or somewhat below the wave base. Within the neighborhood of Opak (Bungai Beach; above illegal foreigners detention camp; Kampung Sepurau), we observe the occurrence of small oyster patch reefs plus marly beds containing corals, bivalves, and gastropods. Hence it can be argued that the Opak quarry facies may be a particular development in the context of a shallow-marine setting. The fauna in the Opak Limestone was recently reviewed by Khor *et al.* (2014), with the conclusion that the studied molluscs and foraminifera are indicative of the Middle Miocene age.

Template H : Rebab-1 Offshore Sarawak

[04`16'06.616" N,
113`32'04.234" E]
(WGS84)







Introduction

The AGIP (Malaysia) Ltd., Rebab-1 well, was drilled in 1992, about 40km from the coast. The well penetrated a stratigraphic sequence from the Recent-Pleistocene at 120m down to the Early Miocene and possibly older at 4991m (TD). The well remains one of the deepest stratigraphic test of the pre-MMU carbonates in offshore Sarawak.

Stratigraphy and Facies

Drilling was stopped after some 678m of carbonate sequences were encountered without reaching the platform complex base due to pressure constraints. The interval between 4860m and 3620m was dominated by limestones (Cycle II) comprising grainstones and fossiliferous wackstone/packstone facies, while between 3620m and 3471m predominantly clastic lithologies were present. These sediments were dated as Early Miocene in age from the occurrence of Zone NN4/NN5 nannofissils and larger foraminifera referable to Letter Stages Upper Te to Lower Tf. The limestone dominated unit was deposited in an inner neritic setting with the overlying clastics indicating transgressive conditions, having been deposited at deep inner to shallow middle neritic water depths.

Well Outcomes

Gas shows were detected in the target limestone and porosity, mainly vuggy, was observed in cores and confirmed by logs. Porosity ranges between 3 to 10% but shows random distribution along the drilled section. Gas effects developed on logs corresponding to porous zones, and a single pool hydrocarbon column of about 200m was interpreted to have occurred. Permeability in cores were low, with a maximum of 0.3 mD.

Three DSTs were carried out in the target limestone, with gas at non stabilised rates flowed to surface. The gas analysed comprised mainly methane (81%) with about 17% CO_2; H_2S was reportedly detected on the rig.

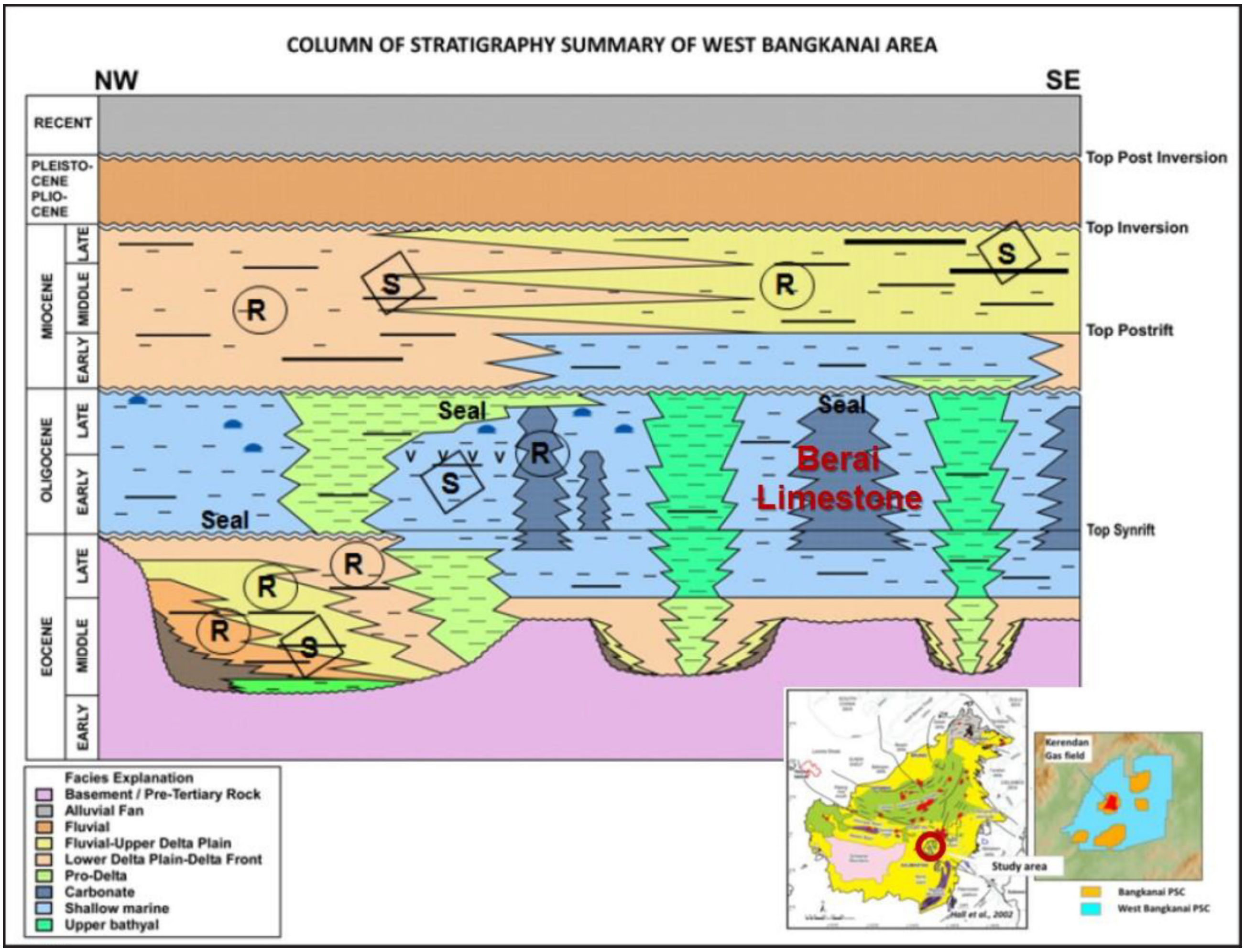


Figure 15: Stratigraphic column of Bangkanai and West Bangkanai area, onshore Upper Kutei Basin (after Subekti *et al*., 2015).

as precursors of the sand-dominated deltaic younger section of the Lambir Formation. Sandy Pliocene deposits of the Tukau Formation sandstones are seen overlying the Lambir Formation above a marked angular unconformity and may have formed in a shoreface environment. The Tukau Formation contains coal measures.

- Several smaller sandy turbidite channels, as well as levee deposits, have been studied along the road from Bukit Peninjau (Petronas Gas station) to Beluru. The levees consist of siltstones, contain trace fossils and possibly imprints of medusae.
- One marked turbidite channel was exposed in the past in the gray Upper Setap Shale along a branch road of the Long Lama road leading to the Empresa palm-oil plantation, but was recently found overgrown by creeper plants.
- Another, but strongly tectonized turbidite channel outcrop was observed on the tributary road from the Long Lama road towards Loagan Bunut. Later research by Kessler & Jong (2015a, b) suggests a proximity to a possibly very narrow and sandy Setap shelf (Figure 13), which is believed to consists of turbidites deposited in a slope to outer shelf environment.
- Another small sandy turbidite channel was found approximately three kilometres along the Long Laput road from the Long Lama road junction.

Rebab-1 (AGIP, 1992) and A1-1 (Shell, 1968) wells (Templates H, I):

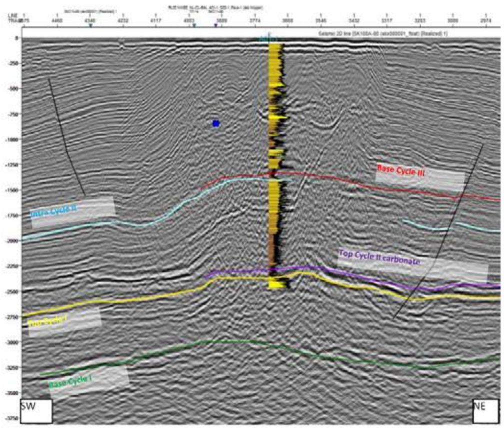
Both wells suggest the presence of Early Miocene carbonate platforms placing them at the base of the younger Early-Middle Miocene carbonate system. Rebab-1 encountered Early Miocene and possibly even older carbonates. Drilling was stopped after some 678 m of carbonates without reaching the base of the platform complex due to pressure problems. The well remains one of the deepest stratigraphic test of the pre-Middle Miocene Unconformity carbonates in offshore Sarawak. The main objective of well A1-1 was the Early Miocene Cycle I carbonate sequence in a seismic- defined structural closure. However, a recent Shell review (Tan Yaw Tzong, pers. comm.) concluded that only late Early Miocene Cycle II carbonate section was encountered.

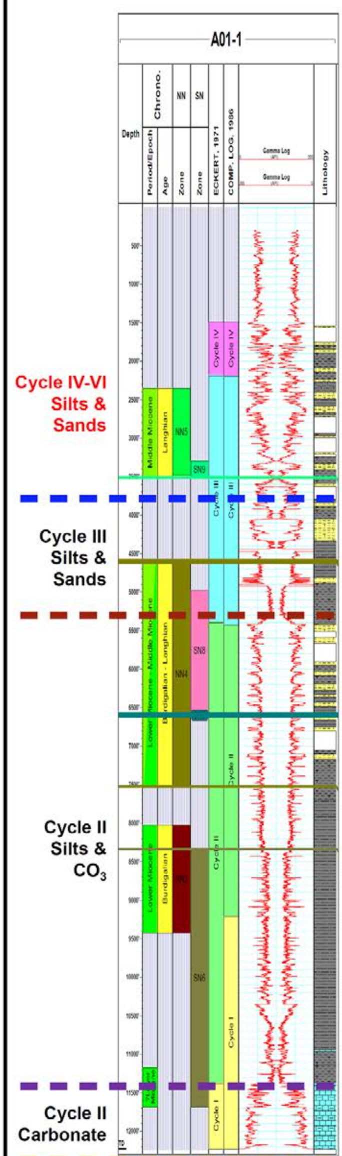
Other outcrops:

Although not investigated in this study, there are additional outcrops, probably not reviewed since Liechti

Template I : A1-1 Offshore Sarawak

[03`57'51.880" N, 113`31'38.208" E] (WGS84)





Introduction

A1-1 located off the coast from Suai was drilled to a total depth of 12,231ft (3,727m) by Shell in 1968 following encouraging results of onshore Suai wells, where Suai-5 well found oil updip on the same structural trend. The well tested a compressional anticline in shallow water of 61 feet (19m). The main objective of the well was Cycle I carbonate in a seismically-defined structural closure. However, a recent review by Shell (Tan Yaw Tzong, pers. Comm.) suggested that it is likely only the Cycle II carbonate section was encountered as illustrated in the above seismic example.

Stratigraphy and Well Outcomes

The well penetrated 800 ft (245m) of tight carbonate with fractures filled with calcite spar (Por. 4 – 8%) and was abandoned before reaching the base Cycle II carbonate with no hydrocarbons found. Cycles II-V clastics above the carbonate section are dominated by silty/shaly stratigraphy of the Setap Shale, apart from sands within intervals 300-4300 ft (91-1200m, Cycles III-IV) and 5400-7500 ft (1645-2286m, Cycle II). The Cycle II carbonate has open marine fauna within a platform margin environment of deposition. Cycle II clastics above the carbonate contain fluviomarine influences, and shallow-up from inner neritic to lower coastal plain. Cycle III shales are holomarine to inner neritic.

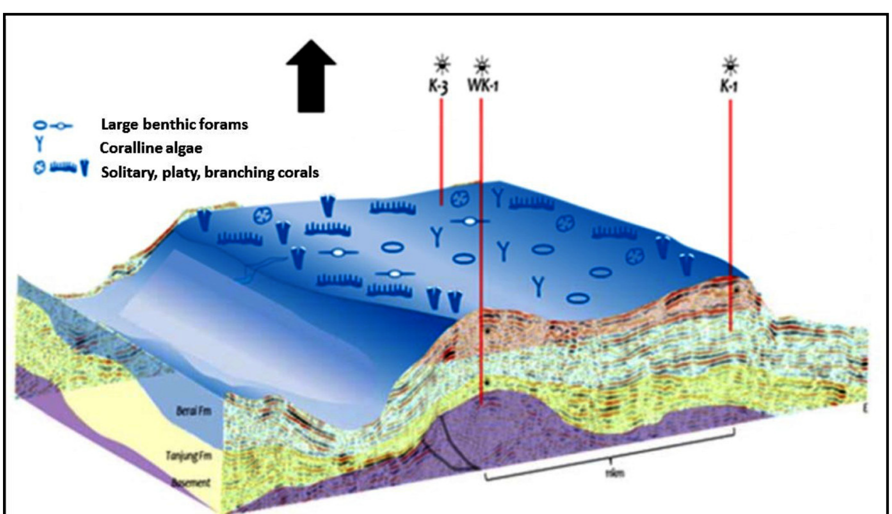


Figure 16: Current model of Kerendan and West Kerendan platform carbonates indicating significant presence of framework builders during the Oligocene (from Subekti, 2015).

et al. (1960): The **Bekuyat Limestone**, formed by Late Oligocene to very Early Miocene foraminiferal limestone; the **Jelalong**, and **Tujoh-Saman** outcrops appear to be of similar Late Oligocene age (Peter Lunt, pers. comm.). These outcrops are located in remote areas of central-northern Sarawak.

ANALOGUE OF OLIGOCENE CARBONATE SYSTEM FROM UPPER KUTEI BASIN

Since the Oligocene, the inner core of Borneo appears to have been an area of erosion with carbonate banks and ramps developed on the shelf. Looking from Sarawak to the opposite side of Borneo, the Kutei Basin, we see another example of how carbonate deposition was established. Subekti *et al*. (2015) described a basin that is bounded to the south by the Paternoster Platform, to the north by the Mangkalihat High and to the west by the Kuching High. Similar to NW Sarawak, only a few wells have penetrated the basement and Eocene and Oligocene sediments have been found along the basin margin or the so-called the Upper Kutei Basin. A gravity map suggests a shallow basement at about 3500 m depth in the basin margin or the Upper Kutei Basin, whilst to the west it is exposed at the surface. In contrast the basement in the depocentre or Lower Kutei Basin is very deep, up to 14 km (Subekti *et al*., 2015). The stratigraphic succession in the Bangkanai and West Bangkanai PSC's started with the Eocene syn-rift sediment of various environments of deposition from alluvial, fluvial, deltaic to shallow marine (Figure 15). The end of Middle Eocene saw a regional uplift followed by erosion creating a regional unconformity of similar timing with Batu Gading in NW Sarawak.

According to the authors of the cited paper:

"Marine conditions were established in the Late Eocene and a deepening/sagging of the basin began. During the Oligocene period, carbonates were deposited on the (land-attached?) basement high in a carbonate platform. During the Late Oligocene, renewed extension and uplift of the basin margin occurred. Subsequently, the uplift of the Central Range of Kalimantan gave rise to delta-fed sedimentation, which from Early Miocene and prograded progressively to the east until the Pleistocene. These carbonates (called Kerendan) are now interpreted as a complex of open marine platform carbonates with some coral build-ups and carbonate sand aprons developed episodically with no lagoon existing between the Kerendan and West Kerendan structures (Figure 16). The Upper Berai carbonate in Kerendan was deposited in a shallow to deep photic water depths, under mainly low to moderate energy conditions within a semi-enclosed marine embayment. From a structural viewpoint, the Oligocene carbonate sequence appears to sit on NNE-SSW trending Palaeogene basement highs or horsts."

The Kerendan High was created by inversion along the former rift faults, which bounded the grabens to the west and east of the high. The above-mentioned study suggests that both carbonate sedimentation and uplift in Kutei originated at the same time with the NW Sarawak area.

CARBONATE FACIES

According to the recent publication by Mihaljević *et al*. (2014), development of a particular strong biodiversity occurred in the Indo-Pacific between the Late Eocene and the Early Miocene. The studied NW Sarawak outcrops suggested a first appearance of corals in Oligocene deposits, but true reef settings are not observed until the Miocene. In Batu Niah we see patches of corals, but they do not form prominent build-ups. The Batu Gading/Besungai quarry section also contains patches of Bryozoans. In a nutshell, the older (Late Eocene) carbonates, as well as those from the Miocene (Batu Niah) are shelfal platform carbonates. The Eocene and some of the Miocene limestones contain strata rich in benthonic foraminifera of the Nummulite family. Beds also contain quartz grains such as in the Batu Gading/Besungai quarry areas. Thus far, no massive reef development has been found from any of the data points. The shelfal carbonates grade upwards into thin bedded

Table 1: Summary of carbonate lithofacies in observed outcrops.

Lithofacies	Description	Locations	Estimated age	Water depth and energy	Comment	Comment
A	Clayey mudstone/marl	Kpg. Opak	Mid Miocene	Shallow shelf, very low energy	In vicinity of oyster reefs	Poor industrial rock
B	Foraminiferal packstone/wackestone	Batu Gading	Eocene	Shelf, mod. energy	Contains quartz sand	Good industrial rock
		Batu Niah	Early Miocene	Shelf, mod. to high energy	Very clean	Good industrial rock
		Gunung Mulu	Oligocene	Shelf, low to mod. energy		
		Bukit Engkabang	Oligocene	Shelf, low energy	Marly limestone	
		Suai	Early Miocene	Shelf, low to mod. energy		
C	Foraminiferal packstone/boundstone	Batu Gading	Eocene	Shelf, mod. to high energy	bryozoan patches	Good industrial rock
		Batu Niah	Early Miocene	Shelf, mod. to high energy	Coral patches	ditto
D	Cherty mudstone	Batu Gading	Oligocene?	Slope, low energy	Some clay content	Waste rock
		Jokut	Oligocene?	ditto	ditto	ditto

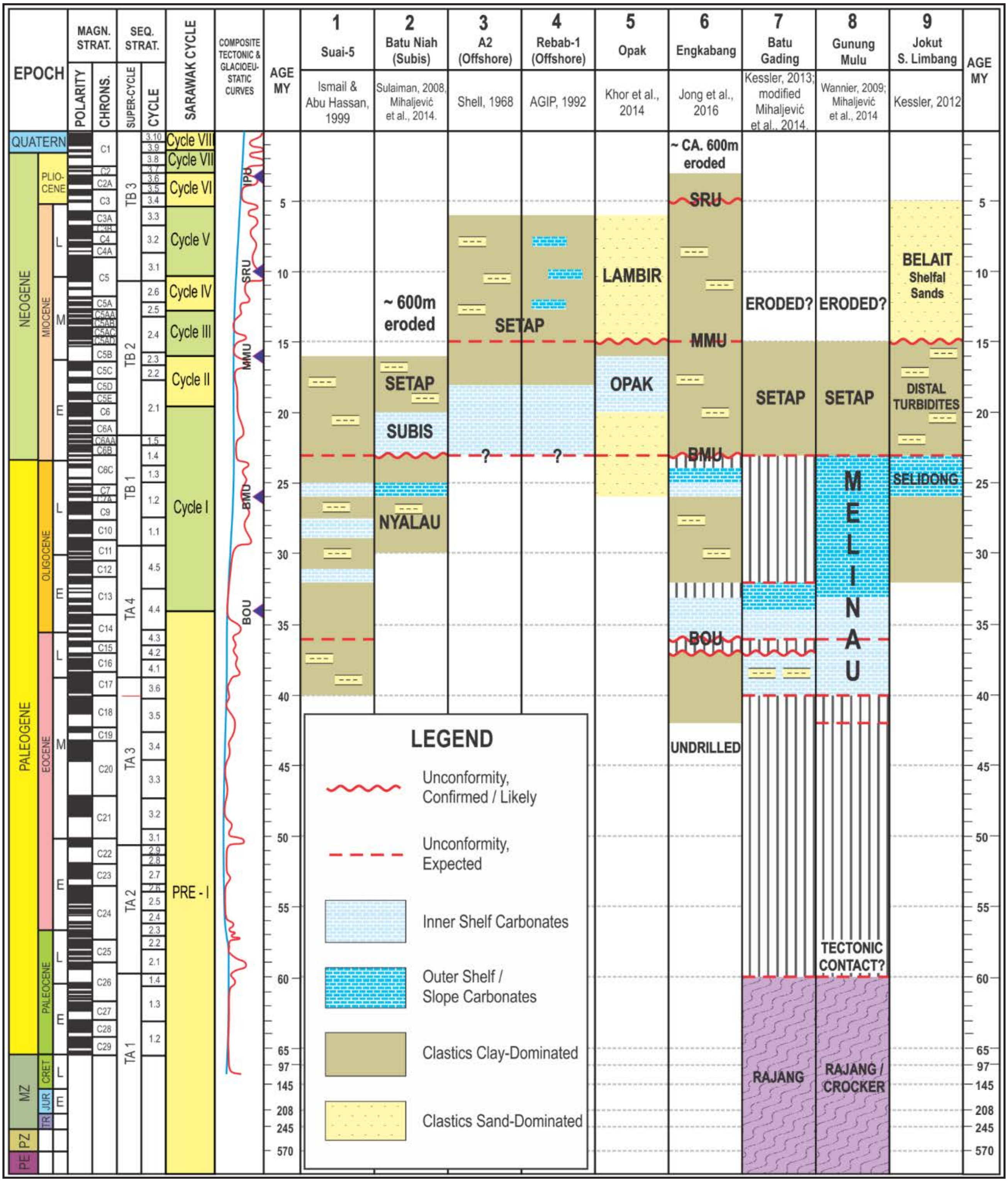


Figure 17: Correlation of important carbonate deposits from well and outcrop investigations in NW Sarawak. The correlation suggests the development of an older carbonate system which was separated from the younger one by the BMU. The tectonic and regional significance of Base Oligocene Unconformity (BOU), Base Miocene Unconformity (BMU), Middle Miocene Unconformity (MMU) and Shallow Regional Unconformity (SRU) as annotated has been discussed recently by Kessler & Jong (2016b).

shaly, and sometimes, cherty limestones. These may have formed in deeper water. The youngest carbonates seen in the area are Middle Miocene shaly platform carbonates of the Sibuti Formation (Khor *et al*., 2014), and are possibly associated with oyster patch reefs.

To summarize, the carbonates can be subdivided into the following lithofacies types, ordered according to water depth and water energy:

A: Clay-rich mudstones (marly limestone) and oyster reefs, deposited in a very low energy environment in estuaries;

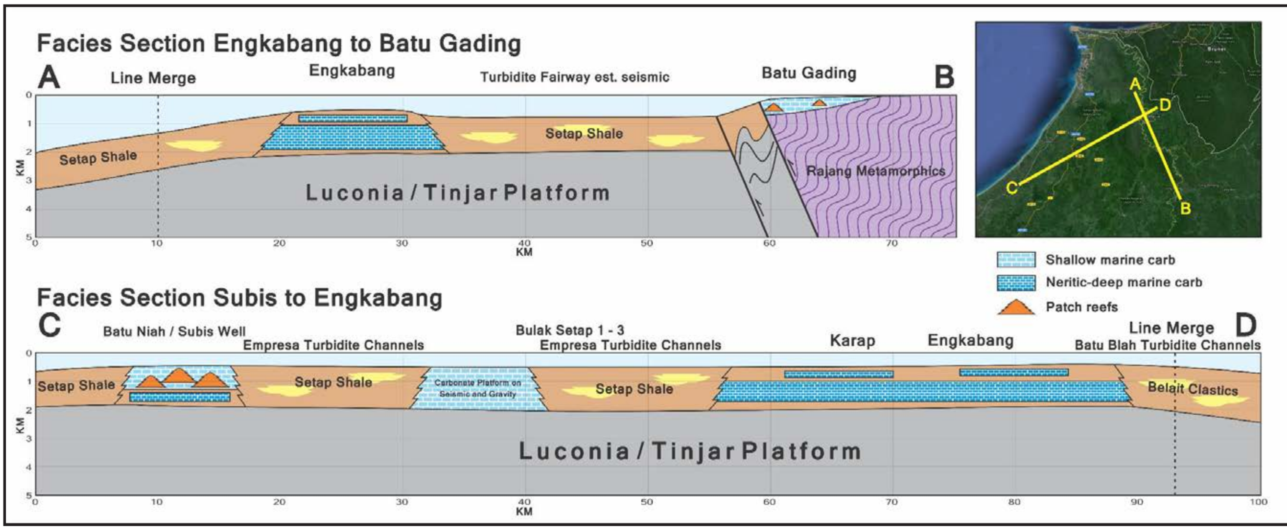


Figure 18: True horizontal-scale geological cross-sections of the study area generated based on inference from seismic interpretation. The younger Late Oligocene to Early Miocene section is better imaged, and we also incorporate well and outcrop studies. These simplified sketches do not differentiate between the older and younger platforms for display reasons. Platform carbonates are shown in blue, proven or potential bioherms in orange; turbidite sandstones are annotated in yellow, within clastic fairways that separate these proven or geophysically-inferred carbonate platforms. Modified after Kessler & Jong (2016a).

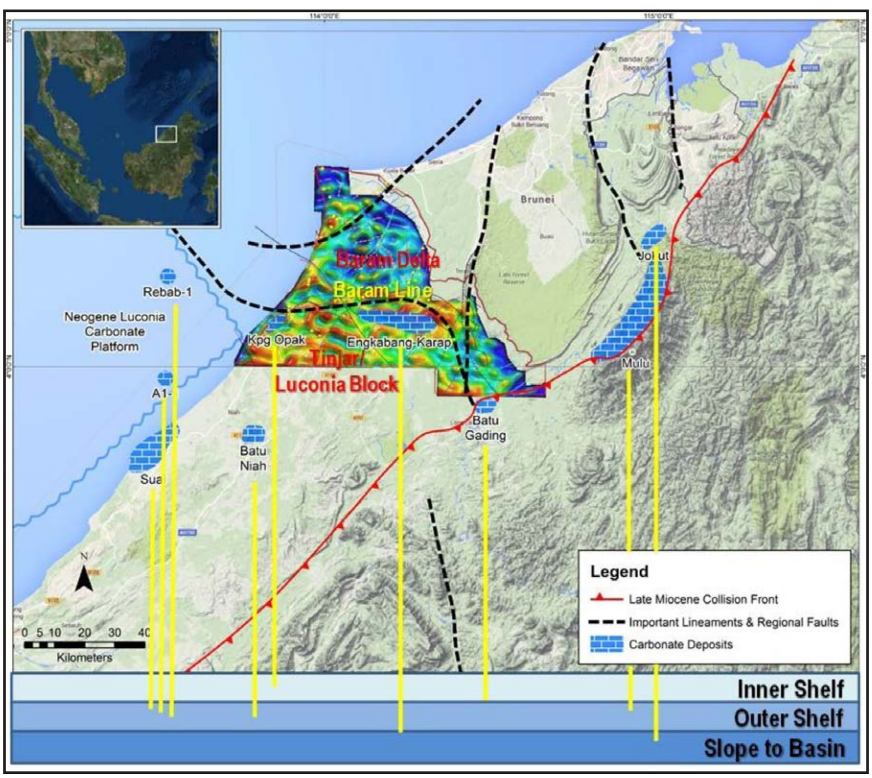


Figure 19: Distributions of studied carbonate deposits in NW Sarawak with inferred water depths of Late Eocene to Early Miocene carbonate sections at various well and outcrop locations. However, water depth uncertainties remain tentative and deserve further studies. Modified after Kessler & Jong (2016a).

B: Foraminiferal packstone/wackestone formed in moderate water energy;
C: Foraminiferal packstone with patches of Bryozoans and corals, formed in high energy water on the shallow shelf;
D: Mudstone with little biota, cherty, deposited in low energy environment on the deeper shelf or slope (drowning sequence).

Based on stratigraphic data, we have grouped the lithofacies types as summarized in Table 1 below. It suggests that the above described facies types are not correlated to specific intervals, but are instead part of a wider carbonate system.

CORRELATION OF DATA POINTS IN THE CONTEXT OF FACIES DEVELOPMENT AND CYCLICITY

A tentative correlation of facies encountered in wells and outcrops is shown in Figure 17. It suggests the existence of two carbonate platforms:

- An older one of Late Eocene-Oligocene age, which was drowned at the end of the Oligocene. It is covered by dark anoxic claystone of the Setap Shale. Frequent slump structures are suggestive of an outer slope environment.
- A younger system, that originated in the Early Miocene, and ended in the Middle Miocene, when fluviatile to shallow-marine clastics of the Belait Group overwhelmed the platforms and adjacent clastic sub-basins. It brought an end to open marine environments. Sediments from the Middle Miocene onwards are either paralic or deltaic. Arguably, this shallowing-upwards cycle might have started at the Oligocene/Miocene boundary and continued to the present. Our previous work also suggests that many areas of Northern Borneo have seen a tectonically derived uplift that overtook the eustatic sea-level rises (Kessler & Jong, 2014; 2015a&b; 2016b).

PALAEOGEOGRAPHY AND TECTONIC BOUNDARIES

To establish a regional lithofacies overview of the study area, two true horizontal-scale cross-sections have been generated (Figure 18):

1) Section A-B correlates the palaeo-facies from Engkabang-1 to Batu Gading and;

2) Section C-D linking Karap/Engkabang to Batu Niah, where we noticed that the younger Late Oligocene to Early Miocene section is better imaged on seismic.

By integrating outcrop data, seismic interpretation and the cross-sections, a preliminary palaeo-geographic evaluation of the Late Eocene to Late Oligocene/Early Miocene interval of NW Sarawak was attempted based on the limited data available. Figure 19 shows inferred water depths of the carbonates at the outcrops and well locations, based on discussion with colleagues and other researchers. However, uncertainties remain and are subject of an on-

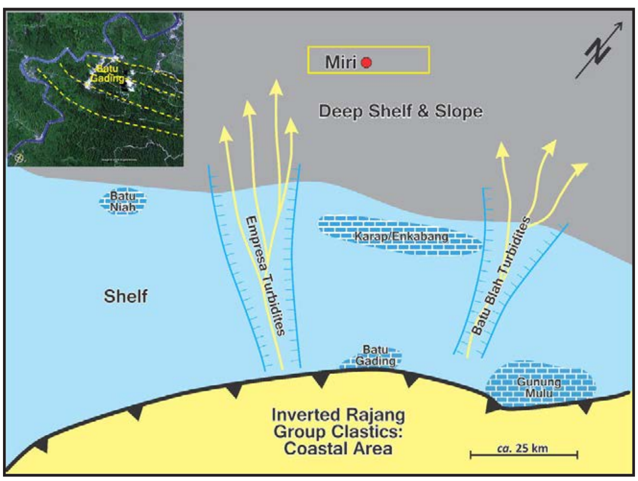


Figure 20: Paleogeography of NW Sarawak from the Late Oligocene to Early Miocene times with major carbonate occurrences. Fairways of turbidite channel systems have been identified, however the precise context between carbonates and turbidites in terms of stratigraphy and facies have not been established to-date. Note the Kampung Opak carbonate was not shown which was dated early Middle Miocene (Khor *et al*., 2014). Inset shows satellite picture of the Batu Gading area, where one can clearly identify the outcrop area (white), and the elongated Rajang fold thrust belt that originated during the Early Eocene, with a tectonic overprint (folding and thrusting, dashed yellow lines) occurring from the Late Miocene-Pliocene times. The West Baram Line dissects the area in N/S direction, just to the west of the limestone outcrops. From Kessler & Jong (2016a).

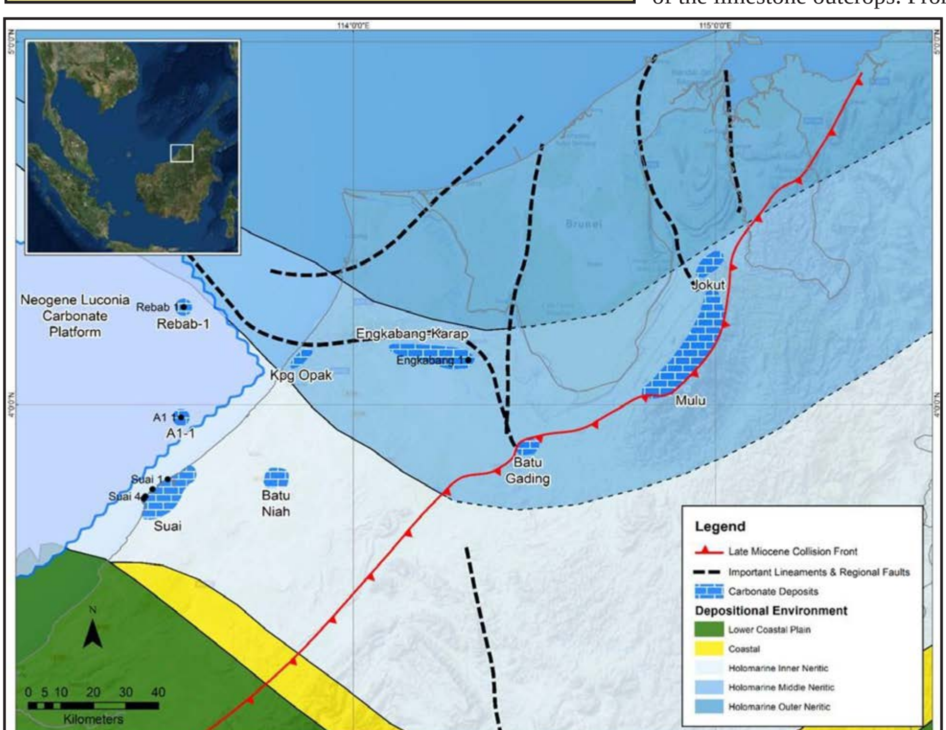


Figure 21: Regional palaeo-environment map of northern shore of Borneo with carbonate distribution discussed in this paper illustrating the variation in depositional environments at Cycle I time (Late Oligocene to Early Miocene), which was extended offshore integrating data from Abdullah *et al*. (2015).

going debate and continuing research. For instance, we noticed that, considering the age differences between the Kampung Opak outcrop (early Middle Miocene), and on the same trend the Karap/Engkabang carbonates (Oligocene in 'Young Main Carbonate'), the *Cruziana* ichnofacies and shallow marine benthic foraminifera suggested a shallow marine inner neritic depositional environment for Kampung Opak (Khor *et al*., 2014), whilst the Karap/Engkabang has been assigned an outer shelf, deeper water depositional environment. With these uncertainties in mind, a palaeogeographic map was generated for the Late Oligocene to Early Miocene interval, supported by seismic correlation of major carbonate occurrence and outcrop data from the Loagan Bunut and Marudi areas (Figure 20).

The map shows an inferred deep shelf/slope area in the vicinity of Miri, a sheltered-shelf area with two or more littoral reef complexes in Batu Niah and Karap/Engkabang that grew seawards, away from the palaeo-coastline, plus two more platform/reef complexes in Batu Gading and Gunung Mulu located proximal to the coastline. In between the carbonate areas, a couple of turbidite sedimentary fairways – the Empresa and Batu Blah acted as conduits of clastic outflow embedded in the Setap Shale. However, the stratigraphic context between the carbonate areas and the clastic fairways remains poorly understood. The considerable thickness of Gunung Mulu suggests a faster drowning of the area, deduced from the carbonates trying to keep pace with a rising sea.

Subsequently, a regional palaeo-environment map of the northern shore of Borneo was generated with carbonate distributions illustrating the variation in depositional environments for Cycle I interval (Late Oligocene to Early Miocene, Figure 21), and extended offshore integrating the data from Abdullah *et al*. (2015). The map shows a northerly transition from inner to outer neritic environment of carbonate deposition.

Given the offsetting effect of the West Baram Line (movements started within the Oligocene), the areas of Karap/Engkabang, Batu Gading and Mulu were located an estimated 50 - 100 km further to the northwest of their current locations, hence Batu Niah and Batu Gading were located closer to each other than they are today. The contact between the inverted Rajang Group and the Tertiary molasse of the foredeep might have been a simple onlap, but this original tectonic boundary is difficult to reconstruct since it coincides with a fold thrust belt that originated at the Miocene/Pliocene boundary. Potentially, this suture can be followed from Sarawak to the Klias Peninsula, and to offshore South Sabah, where it is supposedly better defined by seismic. However, the question of whether or not Neogene compressive tectonics were preceded by older ones, cannot be resolved at this point in time.

DISCUSSION

Our current study shows a picture, in which two relatively independent carbonate platforms had evolved, first during the Late Eocene to Oligocene (Priabonian to Chattian) and then during the Early to Middle Miocene. There are no data showing a vertical continuity of carbonate deposits from the Eo-Oligocene to the Miocene. Therefore, we can consider these two platforms as being genetically independent, albeit exhibiting some similarities in lithofacies:

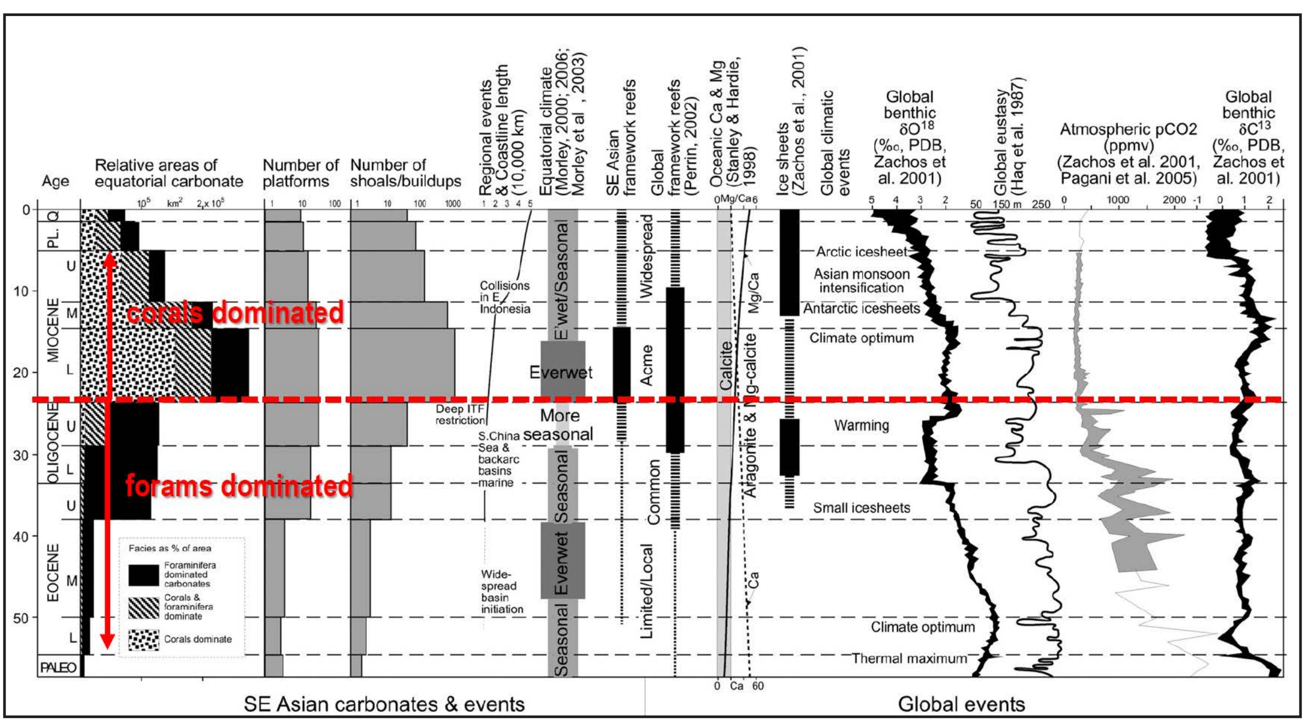


Figure 22: Carbonate biofacies, numbers of platforms/build-ups in SE Asia plotted against regional and global events during the Cenozoic. There is a marked change from larger benthic foraminifera to corals as dominant shallow-marine carbonate producers in SE Asia around the Oligo-Miocene boundary (red dashed line). After Wilson (2008).

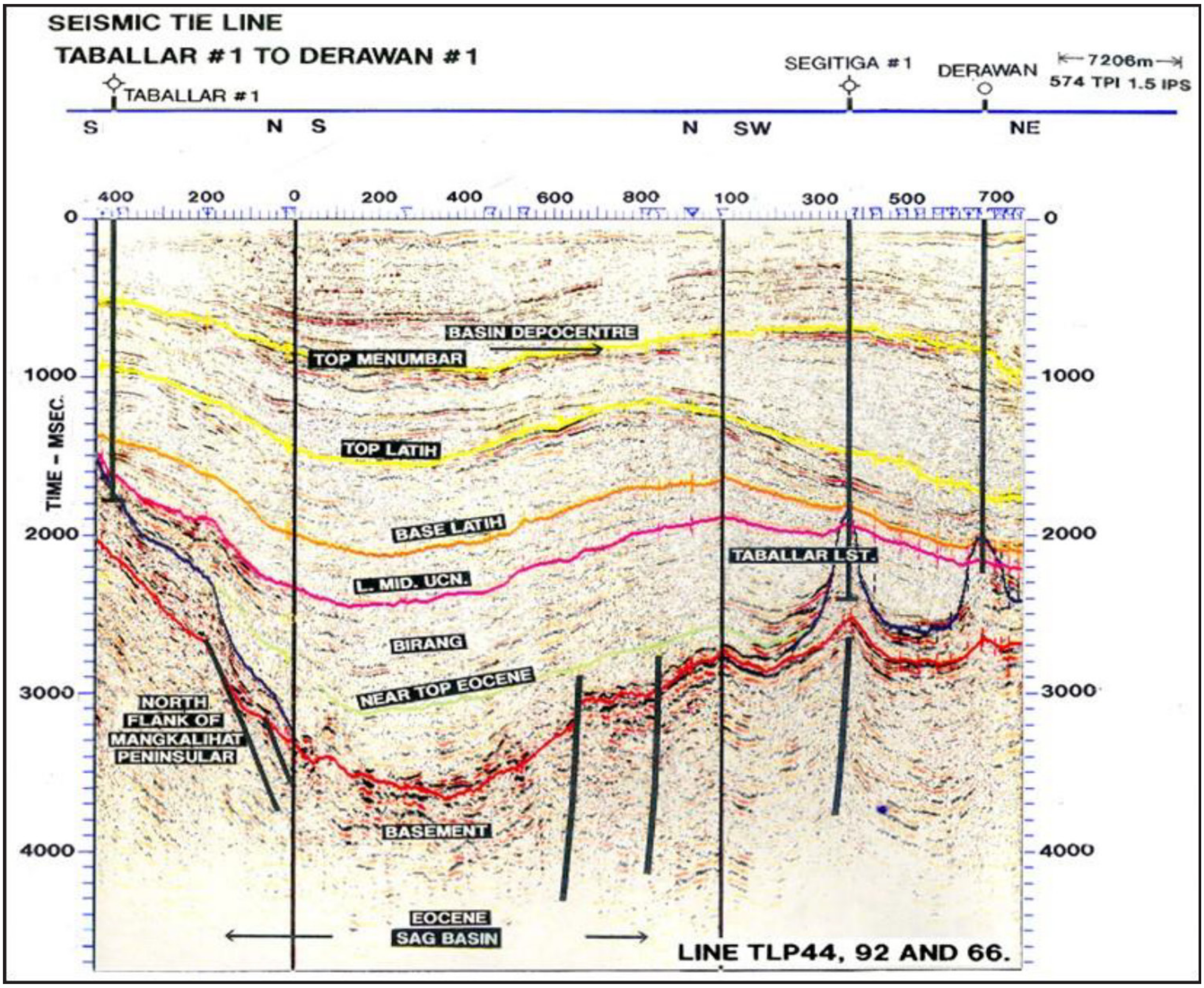


Figure 23: Oligocene reefal carbonate development of Taballar Limestone in offshore SE Sabah, Tarakan Basin. Dated on the presence of *Nummulites fichteli* throughout, with *Lepidocyclina (Nephrolepidina)* and *Eulepidina* present in the upper part of the limestone [Tc and Td stages].

- The Late Eocene to Oligocene carbonates appear to be more continuous compared to the younger, rather patchy Miocene system and are mostly foraminifera-dominated platform ramp carbonates. The extent of the platform is not well-known, but might have covered up to 70 % of the Sarawak Foreland Basin areas (between coastline and the Rajang Group Mountains). Locally, smaller stocks of bryozoan colonies have been reported within the often slightly muddy carbonates in Batu Gading, but do not seem to have formed large patch reefs.
- In the Neogene and Early to Middle Miocene carbonate system, we observe foraminifera-dominated platform carbonates together with isolated coral reefs, that in places could have led to patch reef development. Patch reefs such as seen in Batu Niah appear to have formed on local highs, whilst areas off-platform are characterized by clays and distal silts with a few sandy turbidite deposits.
- Hence, it is likely that both carbonate intervals have evolved due to relatively high sea-level flooding the northern Borneo margin during the mentioned periods. This is considered an important conclusion in the context of tectonic movements affecting segments of Borneo (Jong *et al*., 2016). Evidence for historic and recent uplift of segments of the Borneo Island has been shown in earlier papers by Kessler & Jong (2014, 2015a&b, 2016b), and Jong *et al*. (2016).

Other aspects to consider for the interpretation of the deposition of the carbonate sequences include the impact of atmospheric and oceanic changes in the water chemistry and species evolution. The former approach was taken up by Mihaljević *et al*. (2014) as mentioned earlier. Other possibilities are evolutionary trends during the Tertiary with the re-establishment of corals as reef builders as discussed by Wilson (2008). The author noted that there is a marked change from larger benthic foraminifera to corals as dominant shallow-marine carbonate producers in SE Asia around the Oligo-Miocene boundary (Figure 22). Key aspects of Wilson's (2008) conclusions integrating our observations can be summarised as follows:

"Regional and global controls, including changing CO_2, regional tectonics and oceanography, nutrient input and precipitation patterns are inferred to be the main cause of this lag in equatorial reefs such as the discussed Late Eocene to Oligocene carbonate system. It is inferred that moderate, although falling levels of CO_2, Ca^{2+} and Ca/Mg when combined with the reduced salinities in humid equatorial waters, all contributed to reduced aragonite saturation hindering reefal development compared with other warm and more arid regions during the Late Eocene to Oligocene. By the Early Miocene, atmospheric CO_2 levels had fallen. Although this was a relative arid phase globally, in SE Asia palynological evidence indicates that the Early Miocene experienced ever wet, but more stable and less seasonal conditions than periods before. It is inferred that aragonitic reefs were promoted where previously the waters had been more acidic, more mesotrophic, more turbid, and less aragonite saturated. Extensive reefal development resulted in an order of magnitude expansion of shallow-carbonate areas through build-up and pinnacle reef formation in the Early Miocene."

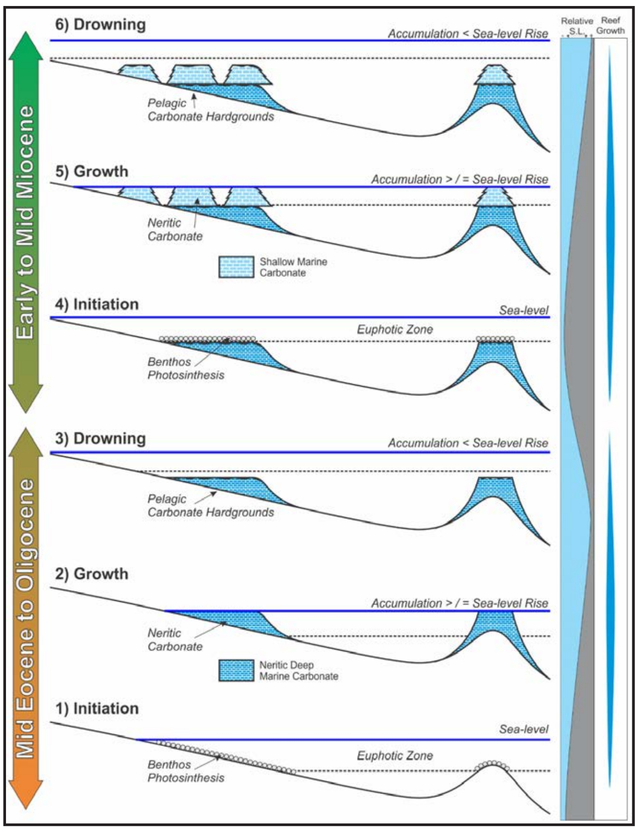


Figure 24: Schematic summary of the phases of evolution and drowning of the carbonate reefs/platforms from the Mid Eocene to Mid Miocene in the study area.

Wilson's (2008) hypothesis was used by Jong *et al*. (2016) to explain the lack of the reef framework builders in the Late Eocene – Oligocene, foraminifera-dominated carbonate facies in the Engkabang wells, which were compared to the Tunisian nummulites/discocylines ramp model of Vennin *et al*. (2003) by Jong *et al*. (2013, 2015). However, our discussion with field researcher Peter Lunt (pers. comm.) suggests that in offshore SE Sabah, well-dated Early Oligocene reefs have been observed in the Tarakan Basin, north of the Mangkalihat Peninsula (Figure 23), in addition to the Oligocene reef section presented by Subekti *et al*. (2015) in the Upper Kutei Basin (Figure 16). In the example shown in Figure 23, the mudstone that covers the flanks of the reefs is deep marine, with good planktonic faunas without *Globigerinoides* (evolved at base Miocene) and with the distinct Oligocene marker *Globigerina sellii*. That is, the reefs were extinct, had undergone a high degree of subsidence, and were being onlapped by a new clastic source before the end of the Oligocene. The very crests of the highest relief reefs were not covered until early Middle Miocene times. These analogues suggest that there exist some local variations to the global events summarised by Wilson (2008), as corals continued to thrive throughout the Oligocene in some areas of Borneo. Also according to Wilson (2015), it is likely that we are currently grossly underestimating Oligo-Miocene biodiversity on a basin-wide and probably a system-wide scale, perhaps more so for the Oligocene interval.

Our own fieldwork did not contradict Wilson's (2015) observations and indicated that corals are exclusively seen in the Neogene carbonates, although the host rock appears particularly low in clay and sand content (Batu Niah). Adding

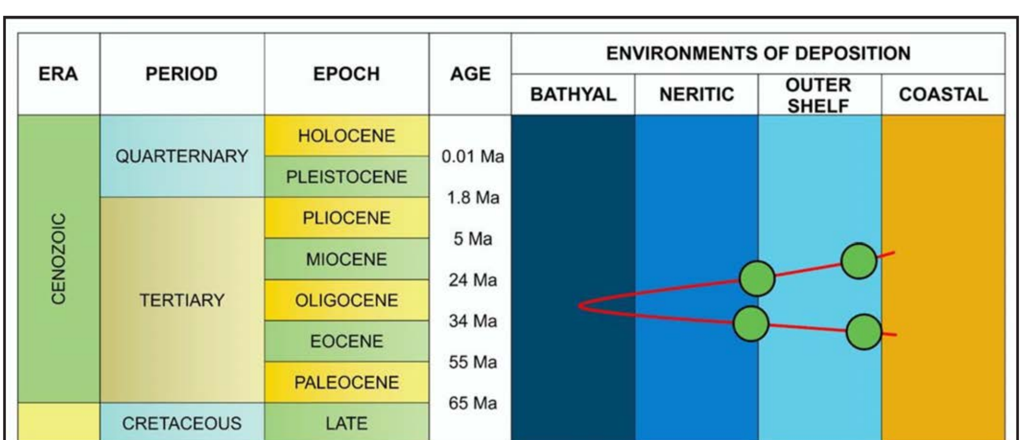


Figure 25: Estimate of sea-level change (red line) from Late Eocene to Mid Miocene inferred from water depth indications of studied carbonate deposits. Green circles show the occurrence of carbonates as the foredeep area drowned, and later re-emerged.

to this, the Palaeogene platform carbonates contain often a significant amount of sand and clay, suggesting a muddy benthonic environment unfavourable for the growth of corals and other framework-building organisms. This brings us to the question of palaeo-water depths. With the relative paucity of outcrops and wells, quality of data (cuttings mostly and only a few cores) the following conclusions remain tentative:

In Suai, and Batu Niah, Oligocene carbonates consist of discontinuous stringers and were most likely deposited in a slope setting. The Jokut Limestone and the thin-bedded limestone sequences in the upper portion of the Batu Gading quarry are cherty and fine-grained and could reflect a neritic to bathyal environment. Core material from Engkabang-1 contains plenty of echinoderm remains (Peter Lunt, pers. comm.), supporting an interpretation of neritic environment. Only the lower (Eocene) sequence in Batu Gading and Gunung Mulu, appears to have been formed in relatively shallow water. In both Batu Gading and Gunung Mulu, we see deepening-upwards trends, suggesting that the Eo-Oligocene platforms have gradually drowned, and hence created an environment unfavourable for shallow marine reef builders. This said, we regard this conclusion still as tentative with many remaining questions.

Therefore, we considered an alternative to explain variations in the carbonate facies evolution from the Late Eocene to Middle Miocene. We place both carbonate systems in the context of major global sea-level changes, and more, likely relative changes due to tectonic movements. We can observe that the older Late Eocene to Oligocene carbonate platform developed during a deepening-upwards cycle, whereas the younger Early-Middle Miocene platform represents a shallowing-upwards sequence.

The sequence of platform initiation, growth, drowning, re-initiation, growth and subsequently re-drowning is schematically depicted in Figure 24. Drowned platforms are common in the geologic record (Schlager, 1981; Chappell, 1983), and there are many good examples for carbonate platform initiation/growth, as well as drowning as a direct response of sea-level fluctuations with possible environmental influences summarised in literature. Such examples include studies of the Porong carbonate build-ups (Kusumastuti *et al*., 2002) and Kujung platforms of East Java (Posamentier *et al*., 2010), the Kutei platforms of Kalimantan (Saller *et al*., 2010), the Miocene platforms of Luconia Province (Zampatti *et al*, 2004; Zampetti, 2010) and the Malampaya platforms of the Philippines (Warrich *et al*., 2010). Noted some studies are specifically focussed on the history of coral reef development in the Quaternary (e.g., DiCaprio *et al*., 2010; van Woesik *et al*., 2015 and references providing therein).

For comparison with our observation of carbonate development and drowning history in the study area, the results of the following selected studies of Oligo-Miocene carbonate platforms in the SCS are summarised:

- Tectonical subsidence drowning of carbonate platforms is known from central SCS areas. Ding *et al*. (2015) describes drowning of an Oligo-Miocene carbonate platform in the Reed Bank at *ca.* 17 Ma after more than 10 Ma of stable carbonate platform growth.
- Fyhn *et al*. (2013) described a model of carbonate platforms development in offshore central Vietnam. The growth was initiated during Early Miocene and continued until Middle Miocene when regional uplift led to subaerial exposure, termination of platform growth and karstification. Carbonate growth thrived during Early and part of Middle Miocene. A massive, clean Lower and Middle Miocene carbonate succession covered the Triton Horst and the Qui Nhon Ridge. During the Middle Miocene, partial drowning resulted in the split-up of the Triton Carbonate Platform. Repeated partial drowning events throughout the Middle and Late Miocene resulted in westwards retreat of platform growth and eventual platform drowning and termination of carbonate deposition.

CONCLUSIONS

The NW Sarawak sequence may comprise of two carbonate platforms and clastic levels forming one mega-cycle characterized by initiation, growth and successive drowning. A maximum water depth was reached in Oligocene. This was followed by gradual uplift of the area leading to renewed carbonate deposition. The carbonate sequences may have started to form when water depth and temperature conditions were ideal for the formation of carbonates - as the water deepened during the Eo-Oligocene interval, and then again during the Early-Middle Miocene. This model is shown in Figure 25. The amplitude of the sea-level change appears to be far too large to be created by global sea-level oscillations, but rather prompted by tectonic movements in the context of the NW Borneo foredeep tectonic evolution, from shelf to slope/basin, and back to a shelf setting.

Both approaches (habitat evolution, mega-cycle concept) appear to have merit and are not necessarily in conflict with each other. However, with the relative paucity of outcrops and wells in onshore NW Sarawak and the poor quality of data, we believe that the inboard Sarawak Foreland Basin is not well suited to bring clarity to the subject of marine species evolution. There is, however, sufficient evidence to make a case for tectonically-induced sea level fluctuations.

ACKNOWLEDGEMENTS

This study has benefited from the research funding support of Mr. Hideki Kitagawa and Mr. Hajime Kusaka, the MD and GM Exploration of JX Nippon in Miri from 2009-2011 for sponsoring and endorsing field studies, which is gratefully acknowledged. We appreciate the technical support from and discussion with A/Prof. Dr. Nagarajan, Curtin University Malaysia. Our gratitude is extended to Mr. Alvin Alexander Idin for providing assistance to finalise the studied outcrop sections and figures accompanied this paper. We thank Peter Lunt for a good exchange of ideas, his view of key data points, and a comparison of our carbonate data bases. We also thank our reviewers Dr. Mike Scherer and Dr. Doug Gillies for their constructive comments that enhanced the quality of this manuscript, and our colleague Mr. Steven M. Barker for improving language and final presentation of the paper.

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Manuscript received 6 June 2016
Revised manuscript received 23 August 2016
Manuscript accepted 3 October 2016