Tertiary Uplift and the Miocene Evolution of the NW Borneo Shelf Margin

Franz L. Kessler[1*] and John Jong[2]
[1] *Independent Geosciences, Oil and Gas Consultant*
[2] *JX Nippon Oil and Gas Exploration (Deepwater Sabah) Limited*

**Corresponding author: franzlkessler32@gmail.com*

ABSTRACT

NW Borneo, of which the shelfal margin extends from the West Baram Line in the southeast to the Balabac Line in the northwest, encompasses an area of active hydrocarbon exploration since the 1970's. A large number of the earlier oil and gas finds are located in shelfal reservoirs of Neogene age. In this study, we portray the development of the Miocene shelf from the standpoints of stratigraphy, sea-level fluctuations, hinterland uplift and sediment recycling; mobile clay tectonics and, last but not least, the impact of the monsoon climate. Balancing the different viewpoints, we believe the transition from a muddy Mid-Miocene shelf to an unusually sandy one can be attributed to two independent factors, which are:

1. *The rise of the Borneo part of Sundaland in the Middle to Late Miocene, caused by tectonic compression, in combination with the influence of the monsoon climate, and*
2. *The availability, through erosion of the Rajang/Crocker system, of massive amounts of sand delivered to the basin in geologically short time intervals.*

The Early to Mid-Miocene Cycle III/Stage III "Setap Shale" and other sediments in the Baram Delta appear characteristically lean in sand in most areas. The available data suggest that the first massive regional sand pulse originated at the same time in the Baram Delta, Brunei and Sabah, during Cycle IV/Stage IVA (Serravallian), post-MMU/DRU times. Continued sand supply established a shelf edge that remained almost stationary throughout Mid Cycle V/Stage IVC. As compression and uplift continued, the Middle to Late Miocene Cycles IV/V (Stages IVA-E) shelf saw local modification by hydraulic clay injection. During Cycles V/VI, and also in the Stages IVD-F, we see a further major expansion of the shelf. The question, as to which of these pulses can be linked to sea-level fluctuations, remains open; though it appears that the Borneo uplift has "outrun" rising sea-level at least since the Late Pleistocene.

Keywords: *evolution, NW Borneo, Miocene, uplift.*

INTRODUCTION

The purpose of this paper is to summarize the results of studies, both published and unpublished, that help to explain the transition from a mud-dominated, low-energy deeper water shelf in Cycle III/Stage III and leading to the sand-prone, post-MMU/DRU (Mid-Miocene Unconformity/Deep Regional Unconformity) large shelfal margins from Cycle IV/Stage IVA onwards. However, there remains the question, which is yet to be fully resolved, how shelfal sediments underlying the Cycle IV/Stage IVA sand pulses are related to each other in NW Borneo. These are:

1. The gray Setap Shale/Sibuti Formation in Sarawak (Central Luconia, Balingian Province), a sequence of marls, and fine silt to sandy turbidite beds with carbonate shoals developed in places.
2. The Setap Shale underlying the Baram Delta, a clay-dominated sequence with the occasional thin sandstone beds; at the top, just beneath the unconformity to Cycle IV/Stage IVA, there are glauconite-rich green sands with a rich foraminifera fauna.
3. The Temburong Formation (Brunei, Limbang and Sabah), clay-dominated with thin sandstone beds.
4. The Kudat Formation, formed by clay and thin sands in NW Sabah.

Mazlan (1994) investigated the relationship between the Temburong Formation and the Setap Shale on Labuan Island, and came to the conclusion that the Temburong and Setap are *de-facto* time-equivalent depositional sequences. Based on different burial history, metamorphism and uplift, it can be argued that the Rajang/Crocker Basin is tectonically and stratigraphically distinct from the NW Borneo

(Baram-Balabac) Basin. The apparent lithological similarity between the Temburong and the Crocker commented in some studies might therefore be coincidental.

Regionally, the South China Sea corresponds to a former area of Cenozoic crustal extension, flanked by the Asian continent (Vietnam, China), the Philippines, and the Sundaland continent (areas of Java, Borneo, and Peninsular Malaysia). The area saw periods of compression, manifested in strike-slip (and occasionally thrust) movements along major lineaments (Hutchison, 2014: Jong et al., 2014 and 2015). Underlying the different sedimentary fills of variable thicknesses, the basement is formed predominantly of strongly to moderately attenuated continental crust.

Figure 1 shows a summary map of the study area of the South China Sea bounded by the major lineaments of West Baram Line in the southeast and the Balabac Line in the northwest. An index map of important outcrops and offshore locations studied is shown in Figure 2.

An interesting (and economically important) phenomenon observed in our study is the sudden appearance of sandy shelves in Cycle IV/Stage IVA, and related turbidite families in the deepwater. In Sarawak / Brunei area, the early development of the Baram Delta may be sub-divided into three phases in Brunei and Limbang (Sandal, 1996). The first, probably Lower to Middle Miocene age, is called the Meligan Delta and was a precursor pulse of sand which accumulated in a foreland basin. Phase II is known in Brunei as the Mid-Miocene Champion System. As in Phase I, these sands are strictly localized in Brunei, and cannot be found anywhere else. Phase III forms the third and major sand pulse starting with Cycle IV, which shaped the sandy shelfal margins in Sarawak, Brunei and Sabah.

STRATIGRAPHY AND SEISMIC EXPRESSIONS OF SHELF EDGES

Stratigraphic nomenclatures

The simplified stratigraphic scheme for NW Borneo used in this study is presented in Table 1, with detailed description of the "Cycle" and "Stage" concepts in Sarawak and Sabah provided by Doust (1981) and van Hoorn (1997), respectively. In addition, Besems (1992) also gave a good description of the Cycle concept with special references to Cycles I, II and III. A brief summary on the nomenclature evolution of the Tertiary sediments in NW Borneo is given below, which basically reflects increasing area knowledge and the change in focus of the exploration activities.

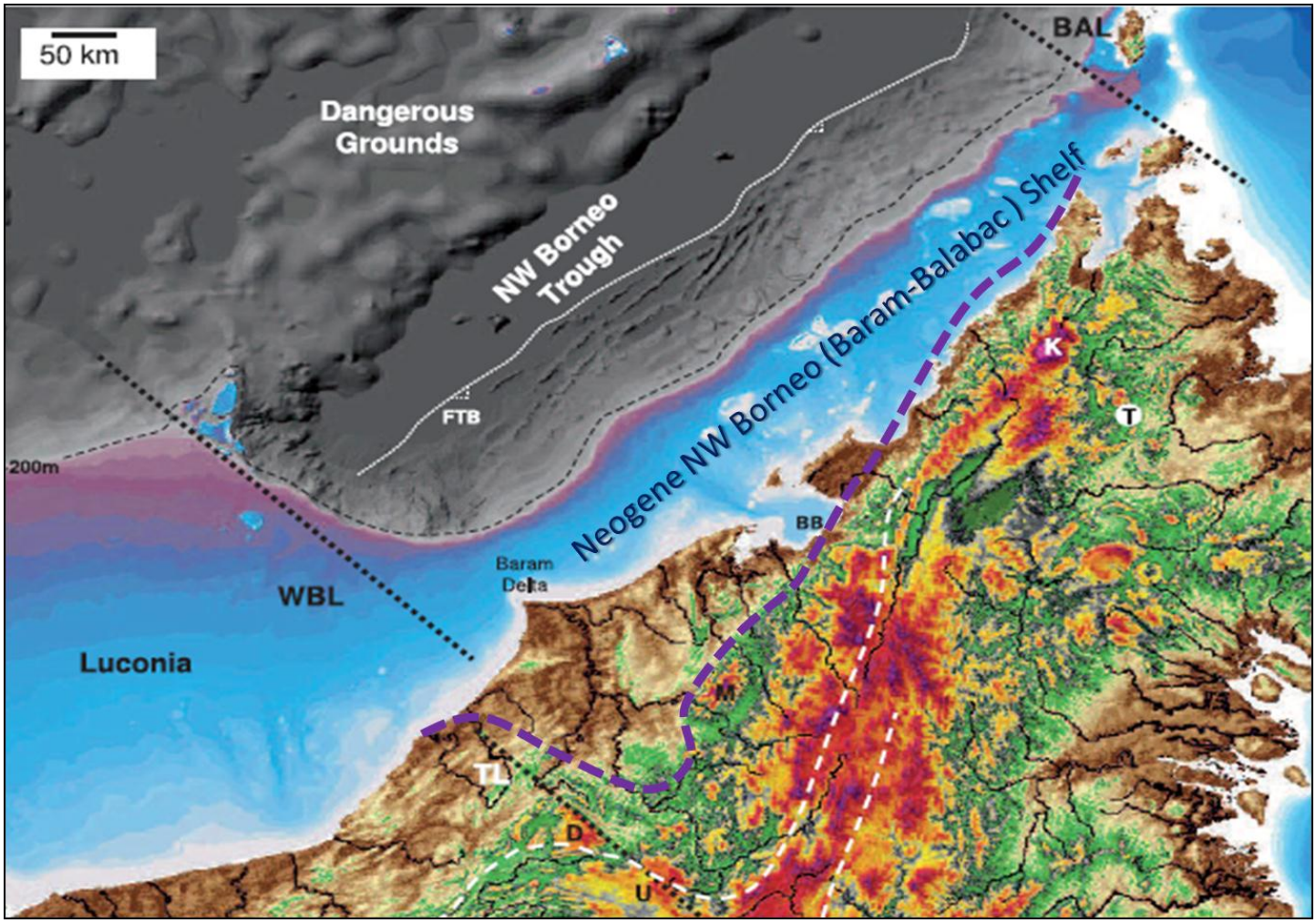


Figure 1. *Tectonic overview map of NW Borneo from Cullen, 2010. The exact course and significance of the Balabac Line (BAL) and West Baram Line (WBL) remain controversial.*

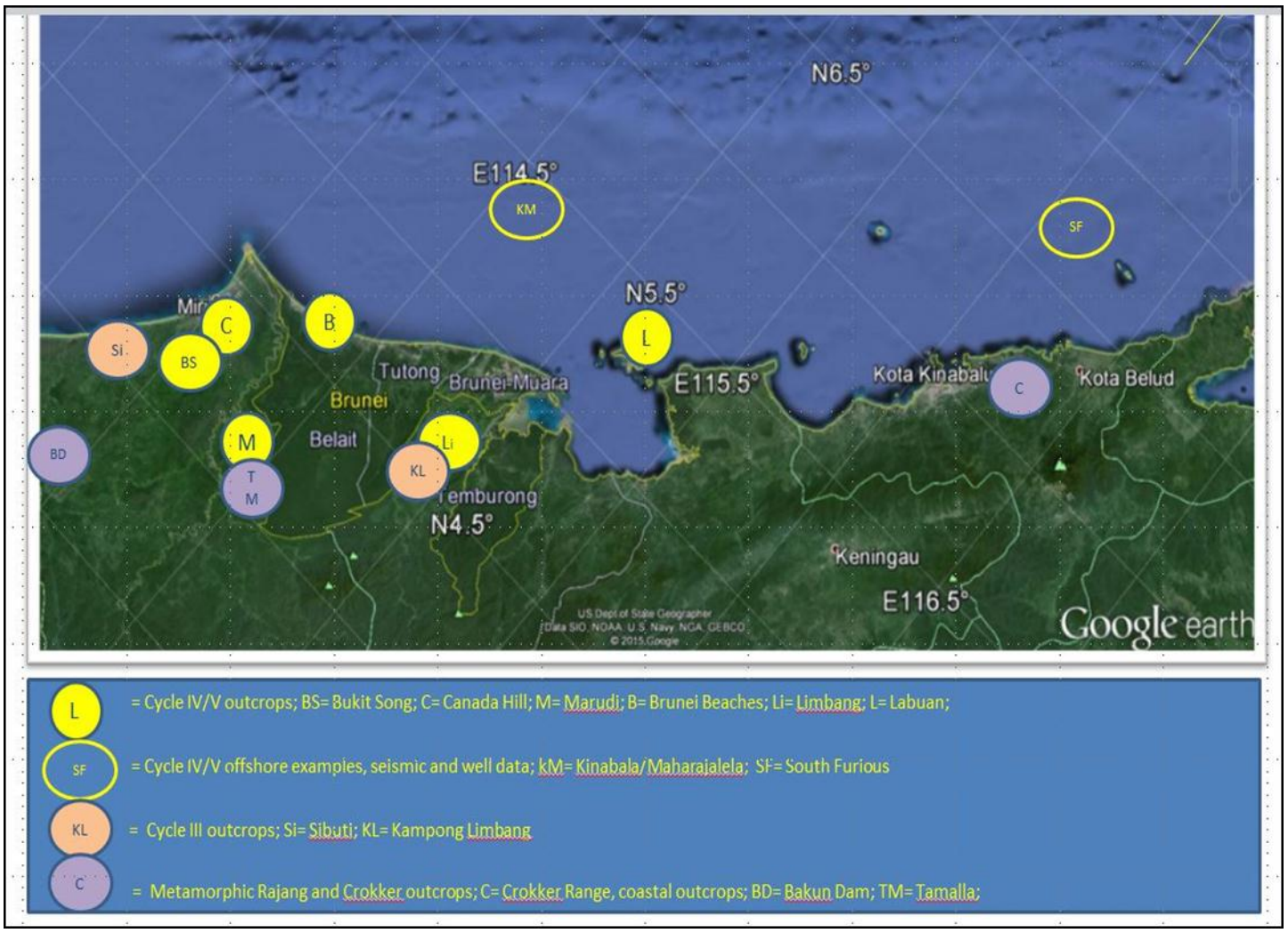


Figure 2. *Summary index map showing the location of outcrop locations and seismic offshore examples.*

The stratigraphic subdivision of Tertiary rocks in Sarawak and Sabah has evolved through various phases of nomenclature. During the early stage of exploration, a large number of local formation names were used (e.g., Belait Formation; Liechti et al., 1960), which proved to be of limited regional application since this approach is impractical in the offshore area, where different formations are difficult to recognize on the basis of lithology. In addition, the great thickness (up to 6s TWT or approximately 7300 m) of the offshore sequences does not allow proper definition for litho-stratigraphical definition due to a lack of well penetration. The proliferation of Tertiary formation names in NW Borneo led to the introduction of a regional subdivision into two major units; a Palaeogene geosynclinal phase, followed by a Neogene regressive phase, the latter being subdivided into six (later eight) regressive cycles.

The Cycle concept was first introduced for both Sarawak and Sabah in the late 1960's (Geiger, 1964; Eckert, 1971). At the basis of this cycle concept was the recognition of a number of rapid, widespread transgressions within the regressive sequence, which often coincided with periods of "tectonic unrest" in the Baram Delta area. Each transgression was considered to correspond to the onset of a new cycle, which ideally is composed of a shaly base grading upward in a sandy regressive top. The cycle boundaries were considered to be approximate time lines and isochronous. However, subsequent drilling showed that the criteria, which can be used in Sarawak for the recognition of the cycle boundaries, could not be applied in Sabah because of the presence there of apparently large, diachronous transgressions and regressions. Consequently, a mixture of units of different meaning and magnitude was used, serving as a correlation tool in rather limited areas (Cycle-equivalent; M, N, O units; South Furious Sands; St. Joseph Sands; West Emerald Sands, etc.). These litho-stratigraphic units have been dated using a fairly detailed palynological subdivision into zones and subzones.

Whereas a detailed pollen zonation is acceptable as a correlation tool within limited areas, it is felt that its application for regional correlation is quite often difficult. This is due to the definition of the pollen zones in use, which is mainly based on statistical determinations of the relative abundance of certain types and not on top/bottom occurrences. Furthermore, this relative abundance may be influenced by the distance from the coastline. However, recent work by Morley and Morley (2011) has managed to identify the timing of arrival of specific floras in Miocene SE Asia. Upland floras

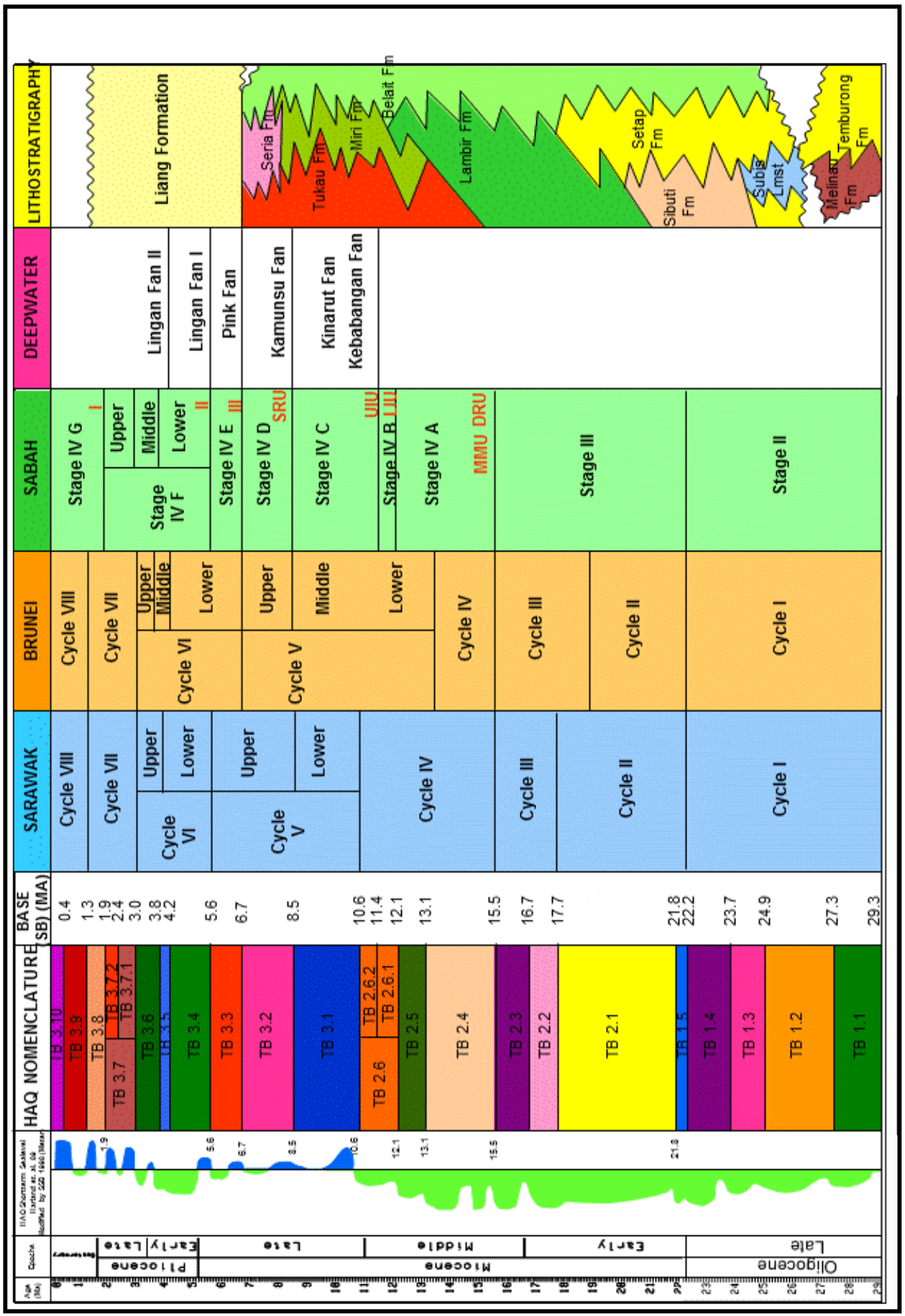


Table 1. *Simplified stratigraphic scheme of the NW Borneo shelf margin from Morrison and Wong (2003), showing correlation of the Sabah, Sarawak and Brunei cycles and stages with SB and TB nomenclatures and Shell deepwater terminology. In the NW Borneo basins, massive sand deposition is seen from 15.5 Ma (post-MMU/DRU) onwards, coinciding with the exhumation and erosion of the Rajang/ Crocker mountain ranges. Litho-stratigraphic units discussed in the text are summarized in the right hand column. For further reference, readers are referred to the updated basin-scale chronostratigraphic correlation chart over the study area (and other Cenozoic and Mesozoic basins of Malaysia), produced by PETRONAS in 2007.*

thrived during sea level low stands, whilst mangroves prospered during high stands in the coastal areas. Obviously, the scale of sea-level changes, being in the order of 20-30 m, must been seen in the context of the much bigger Borneo uplift.

The Stage concept, which recognizes four major Stages (I to IV), separated by unconformities, was introduced for Sabah in the early seventies, and summarized by van Hoorn (1997). The early Mid-Miocene to Pliocene Stage IV sediments are further subdivided into seven sub-Stages (IVA – IVG), each separated by unconformities or their correlatable disconformities. These unconformities [BMU (Base Miocene Unconformity), DRU (Deep Regional Unconformity), LIU (Lower Intermediate Unconformity), UIU (Upper Intermediate Unconformity), SRU (Shallow Regional Unconformity), Hor III, Hor II and Hor I] are the results of both local structural deformation and regional tilting towards the northwest and/or eustatic sea-level variations. In general, they are represented by erosional surfaces in the southeast of West Sabah passing into onlap surfaces or disconformities towards the northwest. However, in detail, the seismic correlation of these stage boundaries between the shelf (Inboard) and the basinal (Outboard) areas remains problematic. Nevertheless, these unconformities remain the best markers for regional seismic correlation in the Inboard area of offshore West Sabah (Lee, 2000, Figure 3).

Both the Cycle and Stage concepts have their limitations. The Cycles are found generally defined by diachronous transgressive surfaces and are not easily recognizable, particularly in deepwater areas. Therefore within the same cycle, distal sedimentary packages may not be necessarily age-equivalent to their shelfal and onshore counterparts, and this hinders the reliable time-stratigraphic correlation of sedimentary sequences across different geological provinces. Furthermore, the prograding/retrograding sedimentary packages associated with second order sea-level fluctuations within the same cycle have not been properly described. The Stage concept on the other hand, suffered from correlation difficulties from shelfal to deepwater area, also in relation to the recognition of the unconformities/disconformities there.

The above shortfalls in Cycle and Stage concepts therefore, warranted a new approach to the subdivision of Tertiary sediments with the application of sequence stratigraphic principles. Recently there is a move towards using the global sequences of Haq et al. (1988) in the regional study of the NW Borneo area (e.g., Morisson and Wong, 2003). Nonetheless, acknowledging their limitations, we believe that the application of the Cycle and Stage concepts remain useful especially for correlating across the shelfal area, where tectonic uplift of the Inboard area plays a more prominent role than eustacy in determining the environments and thus facies of the sedimentary sequences.

It is also worth mentioning that in 2007, a monumental study entitled "Chronostratigraphic Chart of the Cenozoic and Mesozoic basins of Malaysia" was published by the Petroleum Management Unit (PMU), PETRONAS (2007). In the chart, the problem of Sabah stages was also highlighted. The stages as defined by Bol and Thum (1981) have helped in decades of successful exploration. But at present, due to expansion of sections in deepwater exploration, Sabah's stratigraphic nomenclature varies among companies and geoscientists. This lack of uniformity reflects the complexity of Sabah's stratigraphy and the difficulty in taking litho-stratigraphy from the Inboard area and projecting it offshore. Sabah stages offshore are difficult to define; the regressive stages typical of deltaic sequences are not always present due to erosion by time transgressive unconformities as mentioned earlier. Also, similar lithofacies over long periods of geologic time make it difficult to differentiate stages. To help define stratigraphic traps, a more detailed scheme based on biostratigraphy is therefore warranted and timely produced by PMU to facilitate better communications between different companies and geoscientists.

Stratigraphic correlation

Stratigraphic correlation in Sabah offshore areas was, and remains a daunting task. Essentially three approaches have been applied throughout the years, and by various operating companies, with variable success:

- Correlation by means of unconformities and applying the concept of sedimentation cycles; this stratigraphic approach has worked with some success in the Baram Delta, and somewhat less so in Sabah. Results, however, need to be taken with the caveat that cyclicity is not always easy to establish and that certain mapped reservoir units may be of diachronous nature.

- A slightly more recent approach spearheaded by Shell attempted to apply sequence stratigraphy based on global sea-level changes (e.g., Morrison and Wong, 2003); however this approach faces the difficulty of applying eustacy in an area which is known both for rapid changes in subsidence, and tectonic uplift, respectively. For this and other reasons such as difficulties in seismic correlation from mini-basin to mini-basin over structural highs, the sea-level curve-based stratigraphy failed to produce reliable results. It turned out to be almost impossible to map sequence boundaries (SB) and third order sequences (TB sequences) of Haq et al. (1988) regionally, with the consequence they were often mis-applied as seismic horizons on interpretations instead of true sequence boundaries. By doing so the information that is vested in seismic data was discounted. In a nutshell, sea-level changes might have only played a minor role in shaping

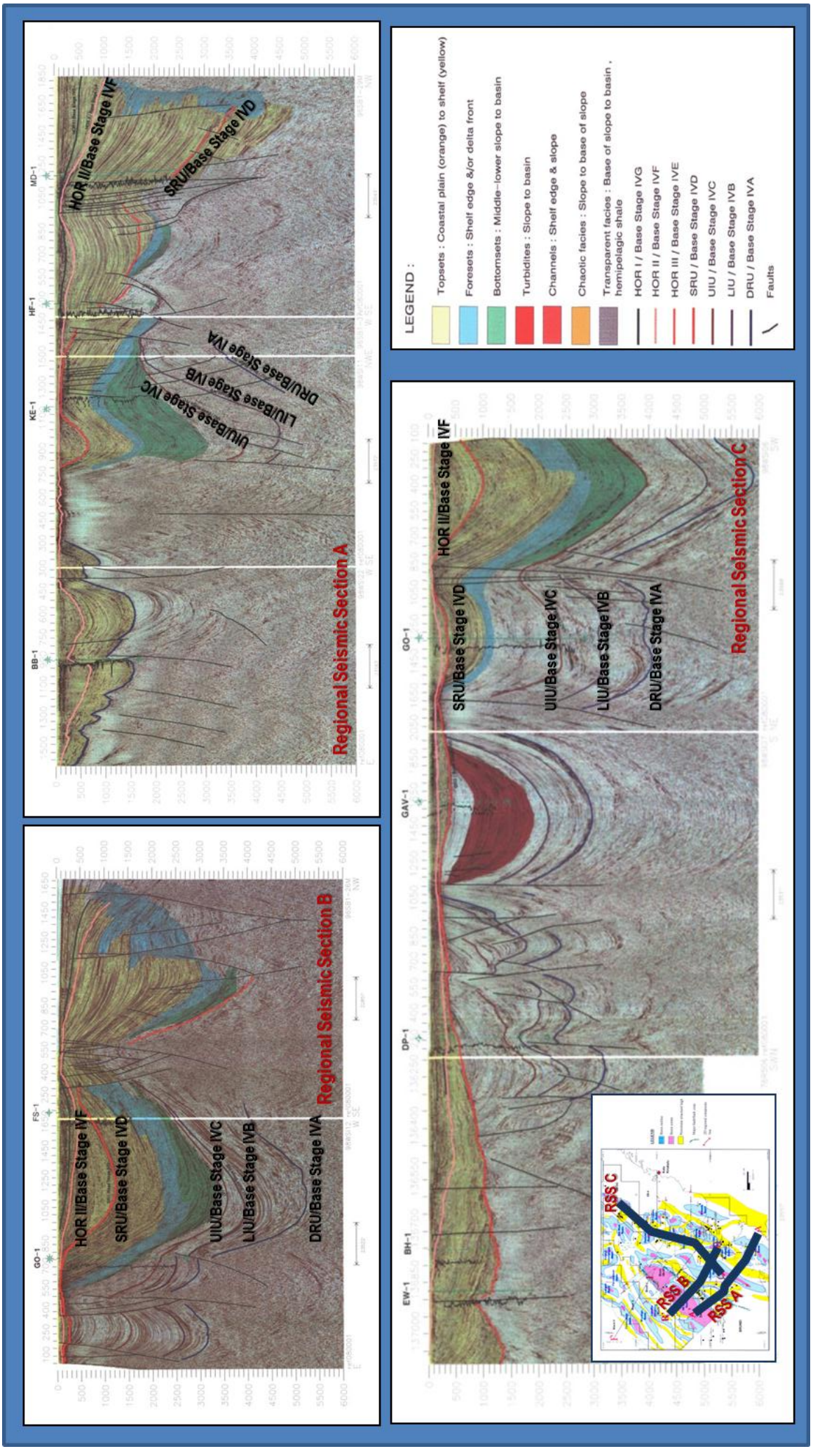


Figure 3. *Regional seismic sections (RSS) A, B and C located in offshore Sabah Inboard area. Note the difficulty in correlation the seismic events both on strike and dip directions as a consequence of significant uplift and erosion experienced in the area (from Jong and Ho, 2000).*

stratigraphy in the offshore Sabah shelf margin, and should be treated accordingly.

• Another approach was to develop local stratigraphy in a given theater, such as the Sabah shelf or the Sabah deepwater. Although such approaches lead to practical solutions, it did not resolve correlation of sediment bodies over large distances. Looking back on some 50 years of stratigraphy in offshore Sabah, the original approach of describing sequences by unconformities (DRU, LIU, etc.) has stood the test of time, whereas the intra-unconformity sequences encountered might be described best by local parameters. The problem of correlating sediments in Sabah also stems from the rather unique geology attributed to Borneo Island and the surrounding offshore. The NW Borneo Foredeep offers four distinct belts that need to be put in regional context:

• *The exhumed Rajang/Crocker Basin*, formed by meta-sediments of Upper Cretaceous (KU) to Lower Tertiary (TL) age, in the hinterlands and on the shallow shelf north of Kota Kinabalu.

• *The Sarawak/Brunei/Sabah Shelf*, Cycles IV/V (Stages IVA-E) strongly inverted in part, and mainly formed by deltaic sand/claystone sequences. These sequences have been drilled by many (albeit commonly "old") exploration wells, but on seismic lack good, correlative reflectors.

• *The Slope*, with only a few well penetrations; these wells here were often abandoned early in the light of significant overpressure being encountered, and forcing an early well TD; seismic is often poor in these areas too.

• *The Deepwater*, formed by a pile of tectonic imbricates with turbidite fans and mass transport complexes, encountered within the imbricates ("older systems"), as well as enveloping these as post-tectonic sediments.

Seismic examples

On the following pages, we discuss various aspects of the development of the shelf – slope transition zone or shelf edge in these areas:

• In northern Sabah, the Middle to Late Miocene shelf lay essentially parallel to the present-day coastline; however there were indentations and outliers of the shelf edge linked to strike-slip tectonics and clay injection (Figure 4).

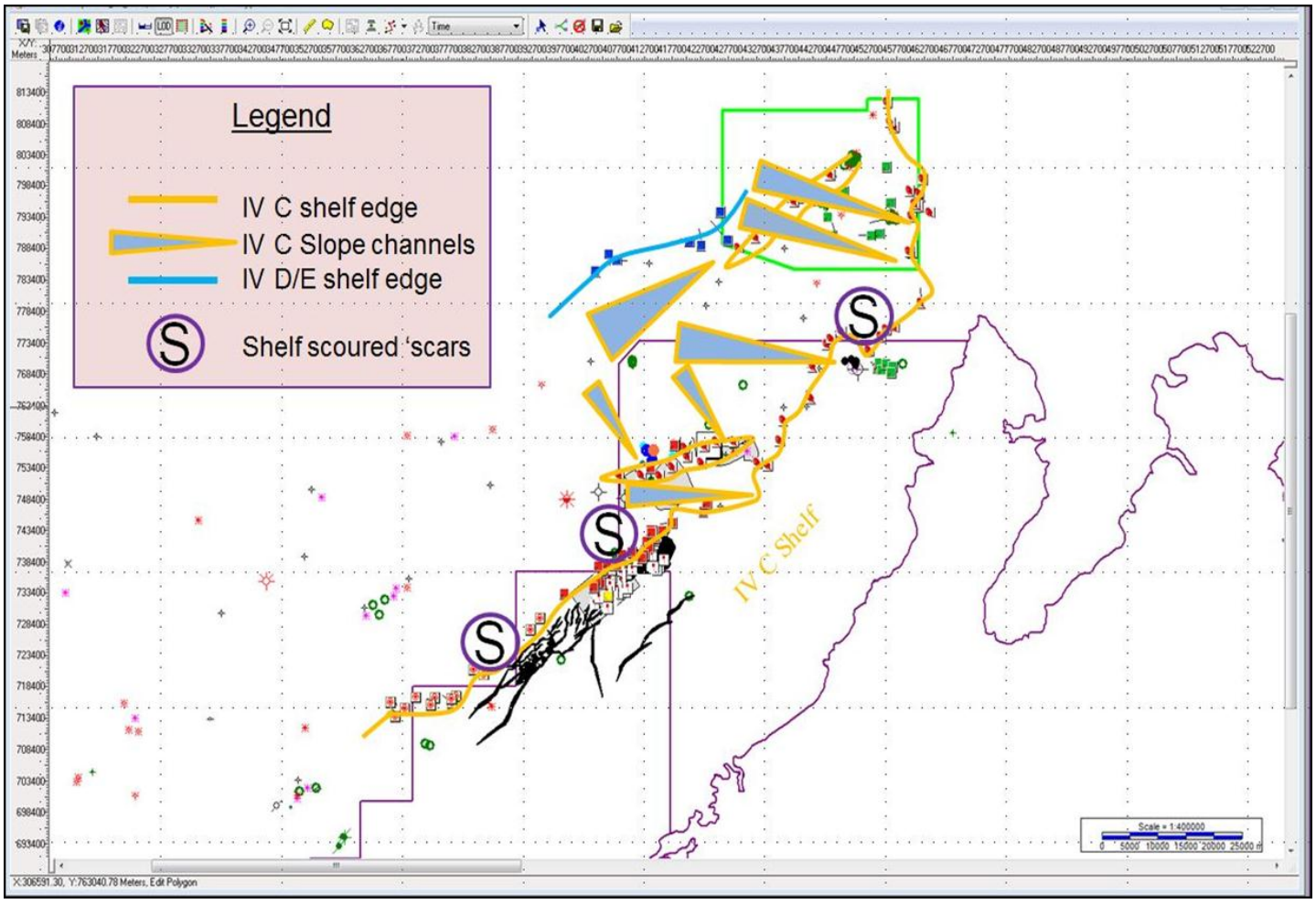


Figure 4. *Map showing the Stage IVC shelf edge, slope scars and locations of associated slope canyons in NW Sabah. The palaeo-shelf edge ran in parallel to the present-day coastline; however we see local "anomalies" caused by strike-slip tectonism as well as clay diapirism. Note the rapid NW progradation to the Stage IVD shelf edge. The coloured dots represent points, where the transition from topset facies to foreset (sigmoidal onlap facies) was picked on seismic.*

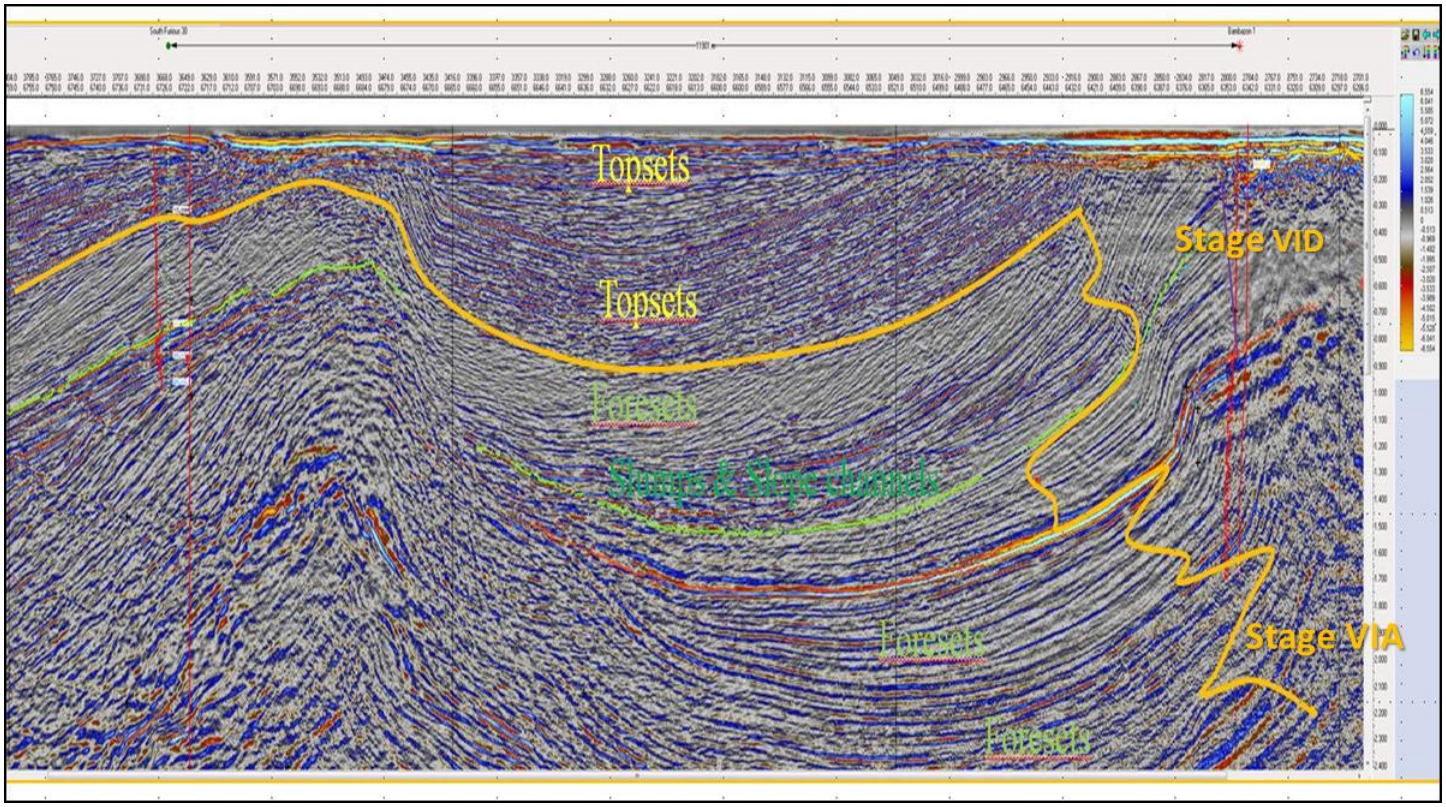


Figure 5. *Seismic profile from the greater South Furious Field area showing the geometries of the shelf edge (orange line) in the interval from Stages IVA-D. The sediments in the syncline between the two clay-cored highs contain very little sand.*

The shelf edge remained more or less stationary during Stages IVA to IVC (Cycles IV to Mid Cycle V) times (Figure 5).

- At the central Sabah edge, distal shelf deposits are often trapped in mini-basins, and the shelf edges are formed by truncation/onlap against clay-cored anticlines (Figure 6).

- In the area of the Sabah/Brunei border, the margin is controlled by faults and minor depo-centers (Figure 7).

THE SEDIMENTS IN OUTCROPS

Field and outcrop data complement seismic observations, and NW Borneo is rich in fresh (un-weathered) outcrops associated with new road cuts and construction sites. In such way a link between the areas of sediment supply, the older (and often reworked) stratigraphy, shelf and deepwater sediments can be attempted.

Sources of sand

The Rajang and Crocker meta-sediments are at the core of an inverted turbidite basin that formed in KU-TL times under deep marine conditions (Hutchison, 2005). The Crocker appears to be formed by distal fan complexes (Figure 8), not unlike the Rajang Group beds (Kelalalan/Belaga Formation, Figures 9-10).

There are several good onshore outcrop locations which enable completion of the picture described in the previous section. During the Mid-Miocene, the shelf was formed by muddy sediments, generally referred to as Setap Shale (Figure 11). They are commonly lean in organic matter and contain minor turbidite sequences, as well as carbonate shoals (Sibuti Formation). This can lead in places to the development of oyster reefs and marly mud-wackestone sequences (Simon et al., 2014). The narrow sandy shelf that may have existed in Sarawak (but which has never been found), was located well in-land some hundreds of kilometers from the present coastline. In the Long Lama area of Sarawak (TM in Figure 2), the Setap Shale contains many slumped folds and the occasional slump block of sandy material (Kessler, 2009). In Limbang (Li in Figure 2), outcrops show a thin-bedded turbidite sequence (Figure 12). So far, not a single good oil and gas reservoir has been found in Cycle III deposits.

Sediments of Cycles IV and V (Stages IVA to IVE)

Seen from a reservoir standpoint, the Middle to Late Miocene shelfal sands of the Cycles IV/V sequences look very similar; indications of calcite cementation being seen only at the eastern limit of the Sabah shelf. Otherwise the lithologies encountered are clean sandstone and (often coaly) shale. The first commercial oil field discovered in shelfal deposits was the Miri Field. In addition to penetrations in many Sabah and Sarawak wells, the Lower Cycle V (Stage IVA) sequence is well exposed in coastal outcrops in Sarawak (Figure 13).

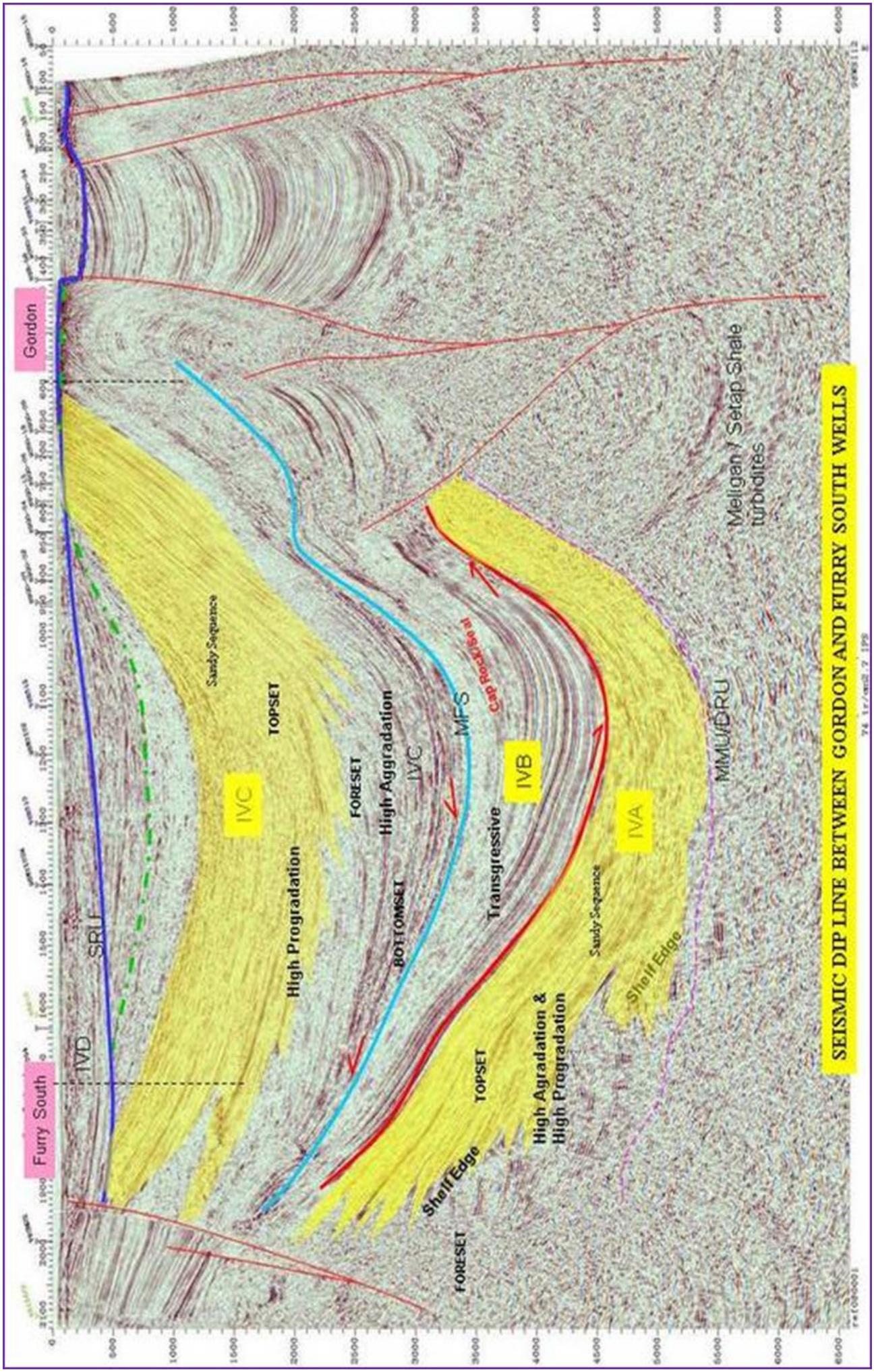


Figure 6. *Interpreted seismic profile on the central Sabah shelf between Gordon and Fury South, with a mini-basin showing a stacked shelf edge. Expansion of the shelfal to foreset sequence in the mini-basin is evident.*

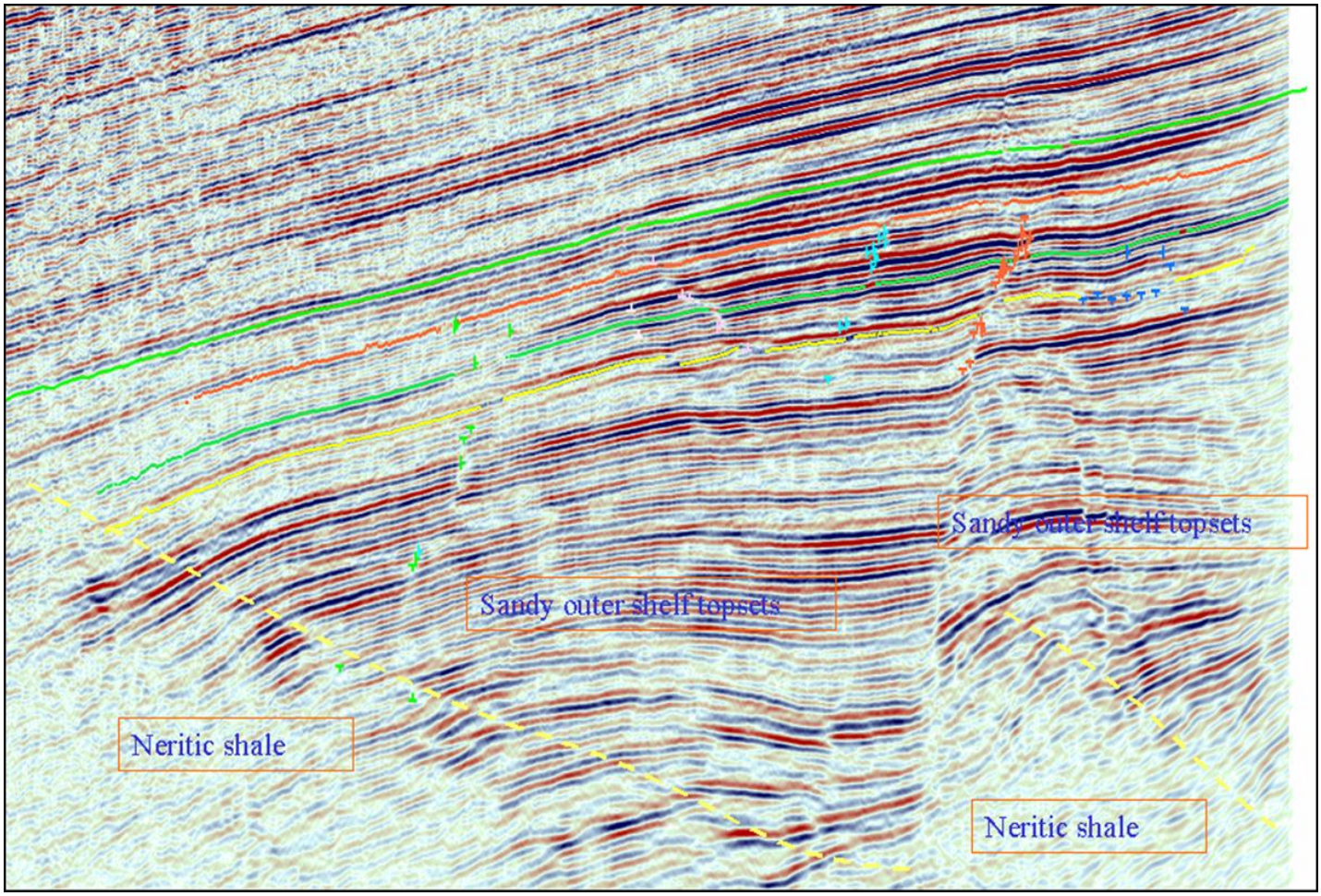


Figure 7. *Portion of a seismic profile through outer shelf deposits near to the Sabah/Brunei border. The seismic line runs NE-SW slightly obliquely through the Stage IVC (TB 3.1) outer shelf depocenter in the Kinabalu Field hanging wall block. The Stage IVC sequence (below upper green marker, and down to broken yellow facies-divide line) reaches here a thickness exceeding 1300 m. Such distal shelf deposits are mostly fine-grained, and clay content within the gross package exceeds 60 %.*



Figure 8.

Originally anchi-metamorphic, but now strongly weathered sandstone/shale sequences belonging to the ?Eocene West Crocker unit qualify as the most likely candidate as the source for Middle to Late Miocene sands on the Sabah shelf.



Figure 9. *Distal turbidites of the Belaga Formation, which appear to be chevron-folded, Baram River near Long Lama. The sand is mostly fine-gained. The folding appears to be mainly the result of compressive tectonic.*



Figure 10. *Quartzitic and very hard heterolithic conglomerate, which may have originated as a debris flow. Top right inset is a sample from the rock face. Scale in cm.*



Figure 11. *Middle Miocene sequences (Cycle III, TB 2.2, 2.3) below the Late Miocene are characterized by mainly shale-dominated outer neritic environments. These occasionally contain thin-bedded Bouma-type turbidite silt and sandstone beds, as shown here in an outcrop from Kampung Limbang (KL).*



Figure 12. *Outcrop of gray Setap Shale (~ Sibuti Formation) with two prominent turbidite sand beds ca. 5 cm and 12 cm thick, respectively, on the old Beluru Road, Bukit Peninjau, in Sarawak. This sequence is typically lean in sand, containing only few isolated, thin-bedded and distal turbidites. Occasional calcareous fossils are found. The Setap Shale underlies fluvio-deltaic sediments of the Lambir Formation, Cycle IV (Stage IVA) in Sarawak.*

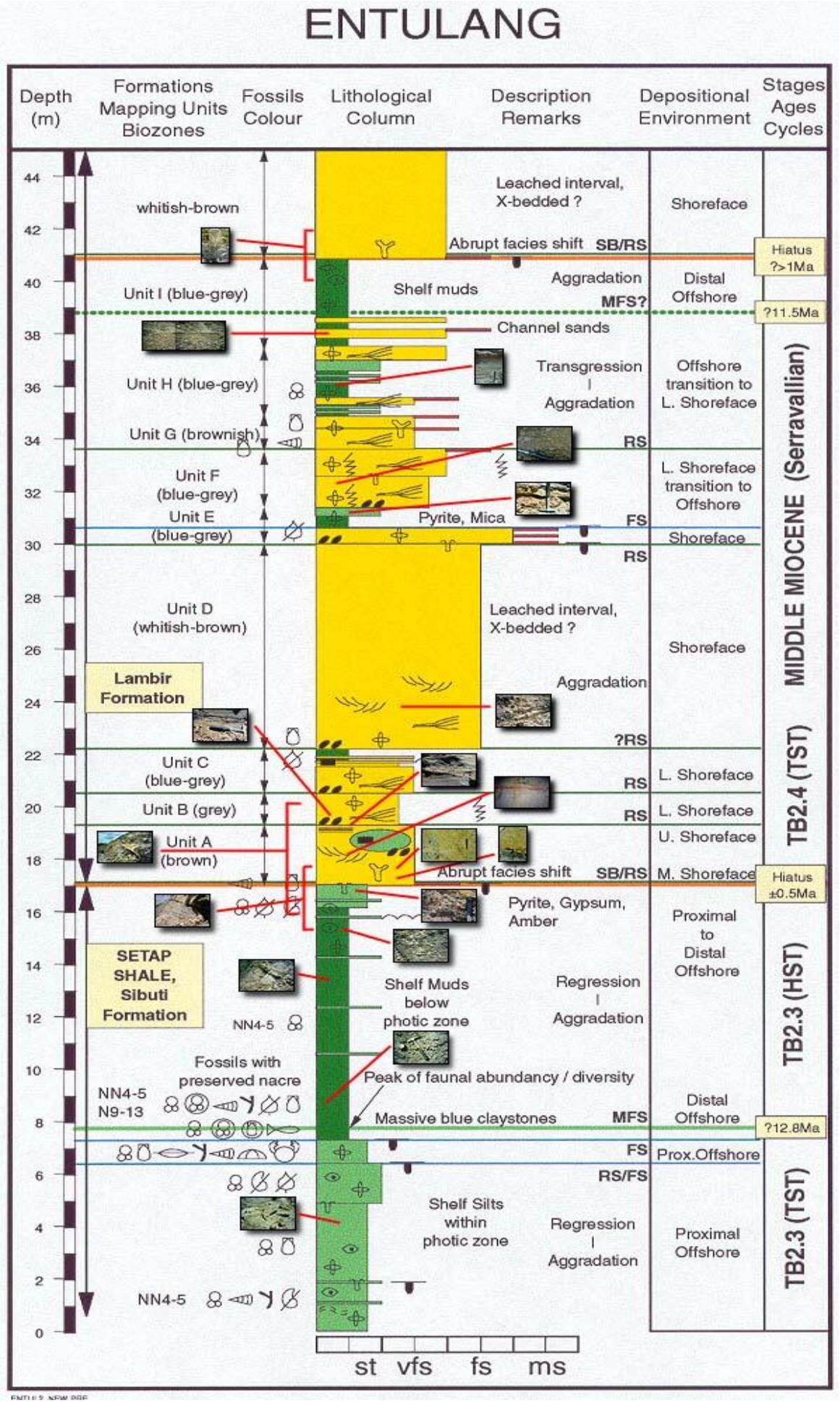


Figure 13. *Stratigraphic log of measured outcrop section at Entulang showing the transition from a very fossiliferous Sibuti Formation (after Wannier, 2011, p. 160) to the sandy Lambir Formation [(Lower Cycle V (Stage IVA), Serravallian]. There is an unconformity at the base of the sand, with a tentative hiatus of 0.5 Ma.*

The reservoir facies in Cycles IV/V (Stages IVA to IVE) can be divided as follows:

- Lower coastal plain. On low resolution seismic, these beds often appear as sheet sands. In reality and on sub-seismic scale however, there is widespread channeling, which can lead to unexpected lower reservoir continuity than one would foresee. This facies is characterized by tidal channel fills, mouth bar and beach deposits, very often rich in peats and coals. Channel sands often display cross-bedded geometries (Figures 14-16).

- Inner to middle shelf deposits are characterized by relatively continuous sheet sands, and grain-size is usually fine; these are stacked with siltstone and shale packages that can form sealing barriers between sandstone units (Figure 17).

- Following a rapid transition from the inner to the outer neritic shelf, the sand content of the Cycle IV/Stage IVA interval drops very rapidly; the shelf break can be defined here as the point at which topset seismic facies is replaced by sigmoidal onlap.

Figures 18-19 show potential distribution of sand on the NW Borneo shelf during Stage IVA (Cycle VI) and Stage IVC (Mid Cycle V), respectively.

Characterization of reservoirs

The presence of reservoir sandstones in NW Borneo hinges on the processes that led to their formation; this relationship and their properties can be seen in Table 2. Dykstra-Parsons coefficient of permeability variation is a common descriptor of reservoir heterogeneity. It measures reservoir uniformity by the dispersion or scatter of permeability values. A homogeneous reservoir has a permeability variation that approaches zero, while an extremely heterogeneous reservoir would have a permeability variation approaching one.

The provenance of sand

Although it was proposed above that the Cycles IV/V (Stages IVA to IVE) sands are essentially reworked metamorphics from the Rajang/Crocker hinterlands, the question poses itself from where these sand prone clastics came from in the first place. According to van Hattum et al. (2013), there is good evidence, based on heavy mineral assemblages, that the origins of most if not all Rajang/Crocker deposits are located in the greater Schwaner Mountains area of south-western Borneo. They proposed therefore, that the Crocker Fan sandstones were derived from nearby sources in Borneo and nearby SE Asia, rather than from distant Asian and Himalayan sources. The Crocker Fan sandstones have a mature composition, but their textures and heavy mineralogy indicate they are first-cycle sandstones, mostly derived from nearby granitic source rocks, with some input of metamorphic, sedimentary and ophiolitic material. In the Eocene sandstones, Cretaceous zircons dominate and suggest derivation from granites of the Schwaner Mountains of southern Borneo. According to the same authors, the provenance of the Tajau Sandstone Member of the Lower Miocene Kudat Formation in north Sabah is strikingly different from other Miocene and older sandstones. This sediment was derived mainly from granitic and high-grade metamorphic rocks.



Figure 14.

Eastern slope of Canada Hill in Miri (Location M), Lower Cycle V (Stage IVA), with normal faulting. The rock face shown belongs to a section of the Miri Oil Field that was uplifted, and exhumed in Late Pleistocene-Holocene time. Some sand layers still contain traces of residual oil.



Figure 15. *Upper Cycle IV/Lower Cycle V (Stage IVA) sequence from Bukit Song (Location BS, Lambir Hills, Sarawak) showing a stacked sequence of sandstone and shale layers. Minor channeling is seen within the thick sandstone units. Sands are mostly fine- to medium-grained, but larger pebbles can be found in rare conglomeratic beds.*



Figure 16. *A rare cross-bedded conglomeratic bed is seen in Cycle IV deposits at Bukit Song. The conglomerate pebbles are mainly composed of white quartz, possibly originating from quartz dykes in the Rajang Group.*



Figure 17. *?Cycle IV-V sequence in Labuan, Location L, with predominantly fine-grained sandstone deposited in lenses between continuous claystone beds. Layered sequences of fine-grained sandstone and claystone are often interpreted as shelf margin deposits. The sediment composition is being investigated by A/Prof. Dr. Nagarajan, Curtin University Sarawak.*



Figure 18. *Potential distribution of sand on the NW Borneo shelf during Stage IVA (Cycle IV) based on the study of depositional environments, from Kessler and Jong, 2012. Light yellow = coastal plain (sand-rich topsets), light green = outer shelf/slope (clay-dominated), dark green = bathyal (mainly clay). Highlighted yellow are slope fans.*

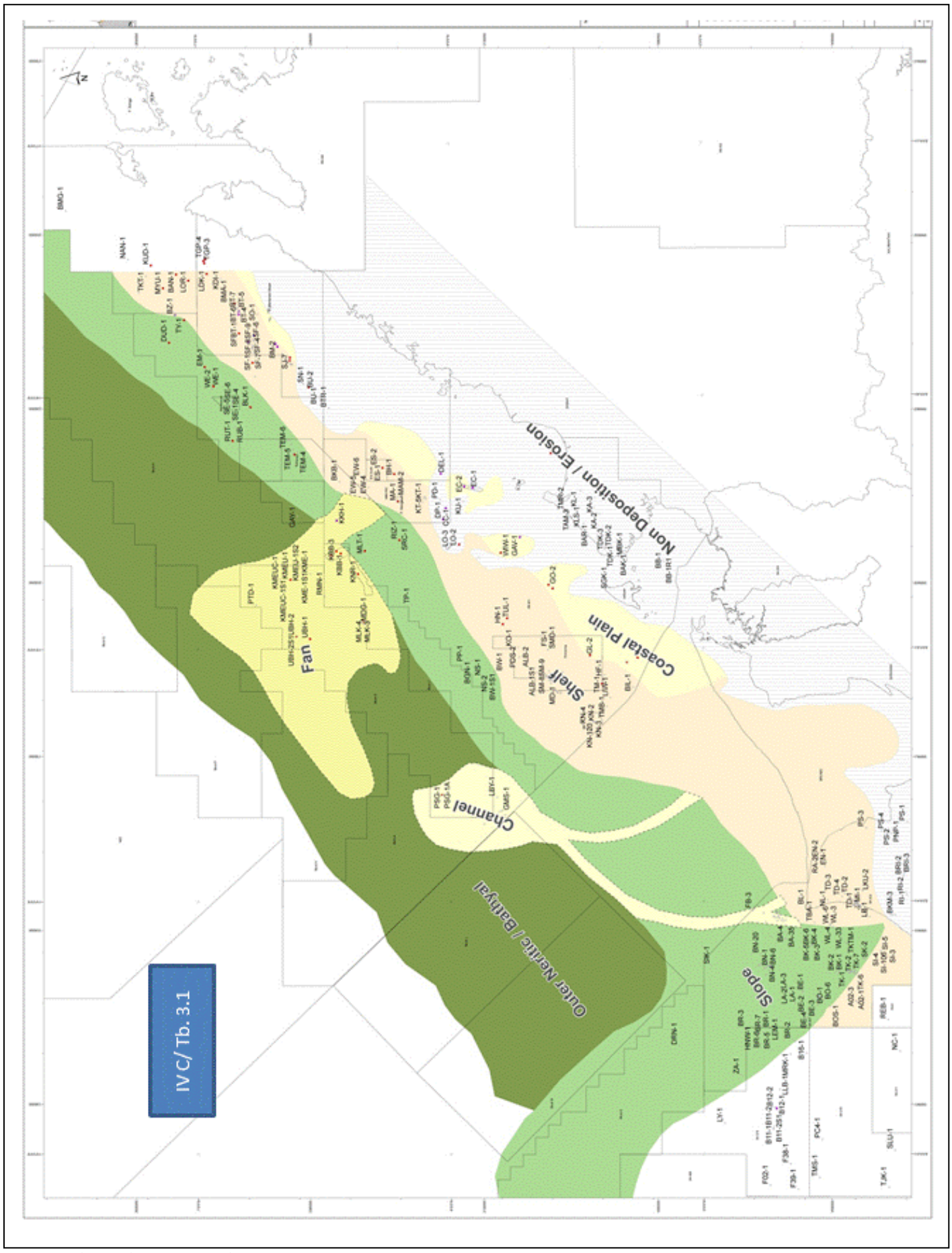


Figure 19. *Potential distribution of sand on the NW Borneo shelf during Stage IVC (Mid Cycle V) based on the study of depositional environments, from Kessler and Jong, 2012. Light yellow = coastal plain (sand-rich topsets), light pink to green = outer shelf/slope (clay-dominated), dark green = bathyal (mainly clay). Highlighted yellow are slope fans.*

Type Reservoir	Process	Parsons-Dykstra Index*	Reservoir Connectivity	Clay content in net reservoir
Deltaic Topset	Coastal currents	Low	poor	high
Deepwater channels	Gravity flow	variable	variable	low
Deepwater fans	Gravity Flow	variable-high	high	low
Shelfal point source	Inversion, Gravity	variable	high	variable
Contourite deposit	Contourite currents	high	high	high

Table 2. *Summary of reservoir characteristics of shelfal and deepwater sand reservoirs. Reservoir connectivity addresses the extent of hydraulically connected reservoir cells; in deltaic topset reservoirs these are mostly < 1 km², and mostly > 10 km² in basin floor fans. *The Parsons-Dykstra index describes the statistical distribution of porosity and permeability in a reservoir.*

No such rocks existed at the surface in Borneo during the Early Miocene, but potential metamorphic sources from an elevated region are present on Palawan, to the north of Borneo and could have supplied sediment to north Sabah. If so, this may indicate that the Lower Miocene Kudat Formation (usually the deepest formation drilled in Sabah offshore exploration) has not received any recycled clastics from the Crocker, which in turn suggests that the latter had not been uplifted and exhumed yet.

The provenance of sands and muds of the Miocene Sibuti Formation was studied by Nagarajan et al. (2013), based on the mineralogy, major and trace element geochemistry data. The X-ray diffraction (XRD) and scanning electron microscopy-energy dispersive spectrometry (SEM-EDS) data revealed that the sandstones and mudstones contain abundant in quartz, pyrite, clay, and heavy minerals such as zircon, rutile, and some detrital cassiterite. Elemental ratios such as La/Sc, Th/Sc, Cr/Th, La/Co and Th/Co suggest sediments to be derived from the felsic rocks. Also, the provenance discrimination diagrams suggest that these clastic sediments are of a recycled continental nature and are mostly derived from a meta-sedimentary source (of the Rajang/Crocker Formation). Discriminant-function diagrams for the tectonic discrimination of siliciclastic sediments revealed that the sediments of Sibuti Formation were derived from a collision zone, which is consistent with the geology of the study area as described by van Hattum et al. (2013). However, a turbidite reservoir potential within this sequence could never be demonstrated.

HOW MUCH UPLIFT CAN BE ESTABLISHED FOR THE BORNEO HINTERLAND?

- Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite gravity (Figure 20) images show a strong regional anomaly of the Earth's geoid in SE Asia, pointing to crustal uplift. Possibly, this area of crust started to rise when subduction commenced in the Late Cretaceous off Java, leading to accretion of terranes, and thickening of the crust between Sundaland and Australia (Hall, 2013). Areas of Borneo as well as others, such as New Guinea and in particular Sulawesi (pers. comm., Robert Hall) have seen spectacular uplift especially since the Pliocene.

- Recent research sponsored by JX-Nippon, and carried out by Curtin University Sarawak has indicated that the Sarawak coastline rose by some 75 m in the Miri area (on Miri's Canada Hill 150 m) since the Late Pleistocene, when including and compensating for the Holocene sea-level rise (Kessler and Jong, 2014a and 2014b). This makes a case for a recent uplift, probably including a much longer and older component. The recent uplift is dwarfing sea-level changes by a factor of 3:1. The coastline south of Miri is elevated by some 20 m above the current sea-level (Figures 21-22).

- Vitrinite samples (VRM 0.42) obtained from coaly Pliocene Tukau sediments, now 30 m and 50 m above sea-level; suggest that some 600 m of sediments have been removed during the last couple of million years.

- A comparative study (vitrinite, seismic and other) on Bukit Enkabang near Marudi (Table 3) concluded that this area saw a Pliocene uplift in the order of 500 m. From folding considerations, it is commonly assumed that folds and thrusts of sedimentary basins commonly originate in the shallow subsurface, given it is easier to create folds and thrusts when the overburden is minimal. The nature of folds also implies steep dips in the core sections, and smaller dips in the crestal (top) section. This means that a deeply eroded fold-core will show steeply dipping beds (such as the Tudan dome north of Miri, for instance), whilst weak dips would emphasize a section of the roof, with the implication that erosion has only stripped-off flat overburden, and a bit of the anticline's roof. The Enkabang-1 well summary report quotes dipmeter readings of 5 - 10^0 in the shallow section, with dips increasing with depth. Following the above argument, it indicates that only a minor roof section plus some overburden have been eroded. In comparison with other folds in the area, this might be indicative for a removed overburden in the order of 300 to 1200 m.

- Most likely, the uplift had started much earlier. Hutchison (2005) recorded phyllite in the Belaga Formation (of the Rajang Group), and this has been corroborated by observations of the authors in Batu Gading. Phyllite requires a minimum pressure of 1000 bar and a temperature of 300 ^{0}C. Assuming a temperature gradient between 30 and 40 ^{0}C / 1000 m, one would expect a minimum uplift (followed by erosion) of 6000 m.

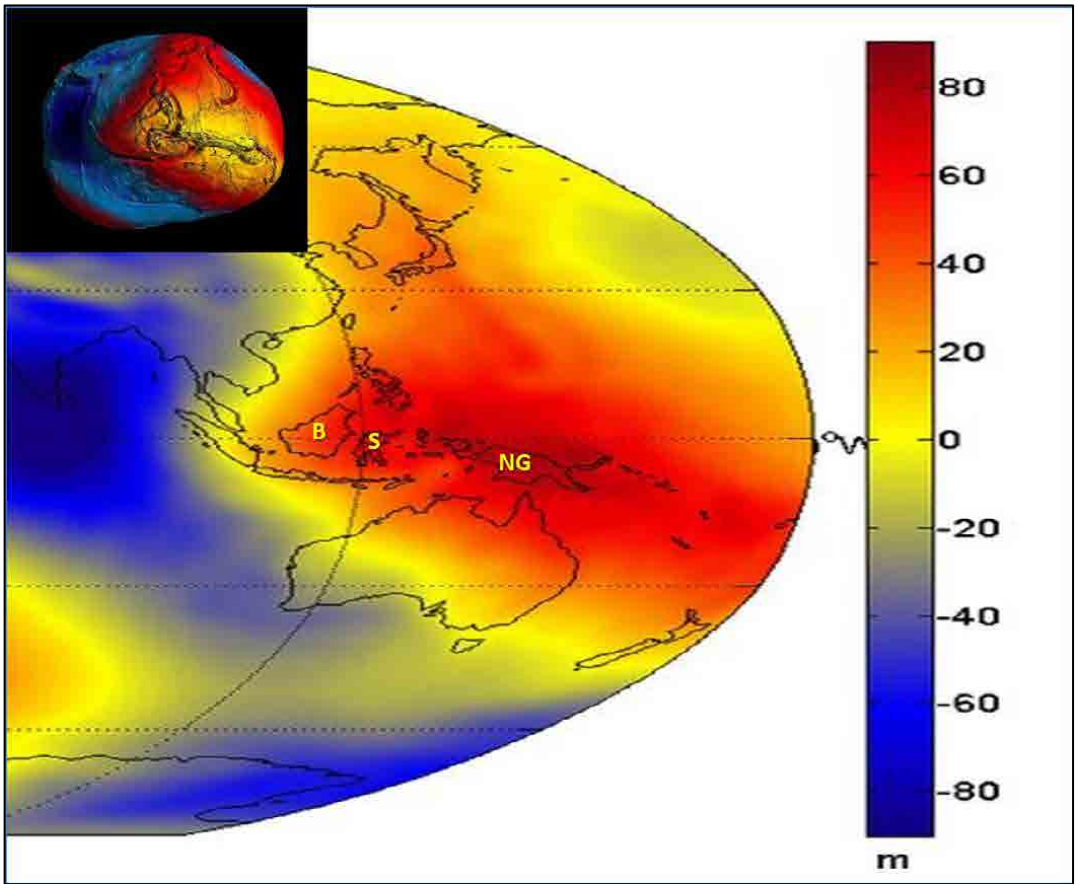


Figure 20. *GOCE satellite gravity. There is a strong positive anomaly in the SE Asia Geoid, reaching from Borneo (B) via (S) Sulawesi to New Guinea (NG). This can perhaps be explained by a buoyant and thickened continental crust, which is isostatically rising leading to strong uplift and erosion. Image processed by ESA. The picture shown has an escalation factor of 10000. Given the anomaly stretches over a large part of East, South-East Asia and Oceania, one might speculate that the uplift could be triggered by the large rainfall (monsoon), and strong erosion in the area.*



Figure 21. *Cycles IV/V outcrops along the shoreline between Miri and Bekenu. It shows the elevation of the coastal plateau, and cliffs. Recent radiometric dating of littoral terrace deposits suggest that the shown coastline here has been uplifted by ca. 20 m since the end of the Pleistocene (not counting the effect of a rising sea-level that has occurred simultaneously).*



Figure 22. *Deltaic sediments of ?Cycle V near Tusan Beach Head are wave-cut at a Late Pleistocene unconformity. The unconformity is now located some 20 m above mean sea-level, and makes a case for hinterland uplift. The flat-lying paralic sediments above the unconformity are composed of coaly sands and were C14-dated as Late-Pleistocene to Holocene age (Kessler and Jong, 2014a). The inclination seen in the older section must have been originated in the Plio-Pleistocene when folding occurred, leading to a syncline, the axis of which is located a few kilometres offshore.*

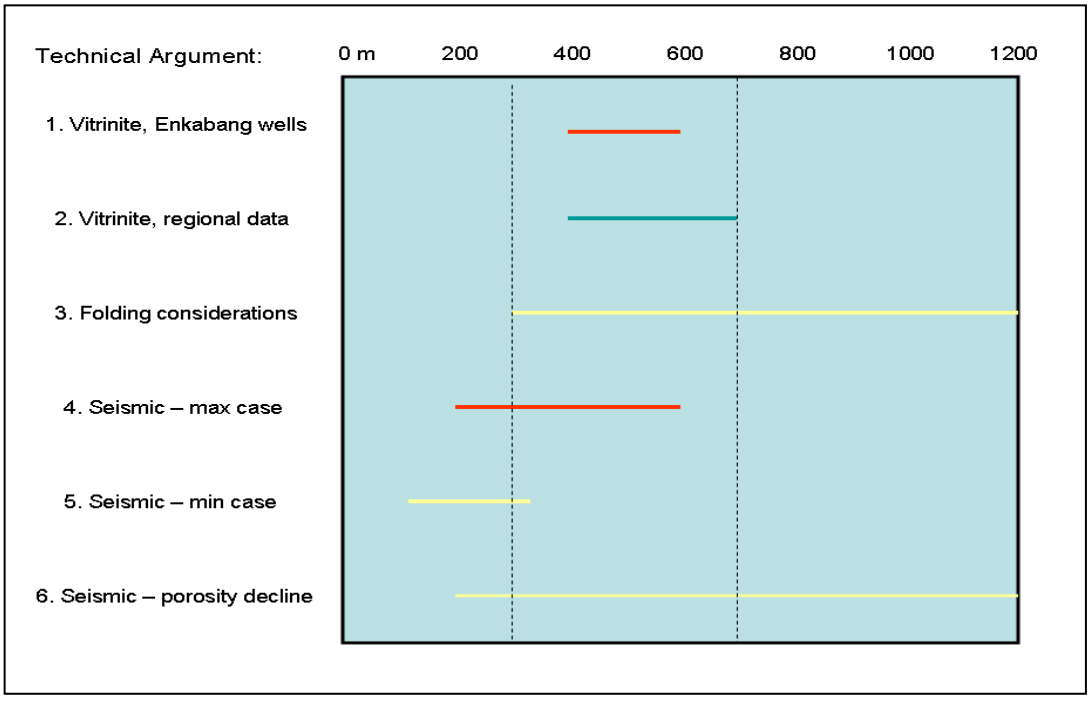


Table 3. *The different parameters shown here were used to assess the magnitude of uplift in the area of Bukit Enkabang. A comparison of methods suggests a Pliocene uplift and sediment removal in the order of 500 m. The porosity argument is purely indicative, and relates to compaction of the clastics if compared to adjacent wells.*

- The Rajang Group sediments also contain clear quartz mono-crystals in the Belaga Formation of Tamalla, nested in vugs or growing on sandstone surfaces; this requires temperatures > 200 ^{0}C which also suggests removal of 6000 m plus of sediments.

- Gou (2014) carried out vitrinite reflectivity assessment on samples of the Crocker Formation in Sabah, and calculated a removal of 4100 m of sediment (=0.82 VRM). Some of the VRM data he studied are > 1; hence there remains some ambiguity about which number is the more likely, if either.

- Material balance. A material balance exercise carried out by the authors, equating the thickness post-Oligocene sediments with the amount sediment stripped off from central Borneo along major river catchment areas, equally suggests that 6000-7000 m of sediment must have been removed.

- The conundrum of the Bario salt. The latter is found in Tertiary rocks of undated age in the Bario Highlands. The salt contains (unconfirmed) lithium chloride, which suggests the salt is derived from high mountain salinas such as those known from the Himalayas or Andes. Highland salt encountered in tropical regions suggests a local dry micro-climate in the shadow of the monsoon.

- A study by Grant (2005) linking the Sabah deepwater depositional systems to the Inboard erosional area suggested an uplift of some 6000 m. More recently, estimations of 4000 – 6000? m of uplift in the Brunei Inboard area was obtained from the study by Gratrell et al. (2012, Figure 23), while study of the Belait Field area conducted by ISIS Petroleum Consultants also generated similar estimates of uplift in Brunei's hinterland (pers. Comm., Peter Barber).

SHELF AREAS MODIFIED BY CLAY INJECTION

The idea that clay injection can raise or modify anticlines is far from new (e.g., Venezuela, Trinidad), and has also been advocated in a number of older (1950's) internal Shell reports in Borneo. We place the clay injection in the context of regional compression and basin dynamics as described by Kessler and Jong (2014a and 2014b) and demonstrated on Miri's Canada Hill. A number of Brunei and Sabah anticlinal oil fields also appear to be clay-cored, and this mobile phase may have affected or even controlled charge, reservoir and seal aspects of the petroleum system.

As shown in the Miri example (Figure 24), and also NW Sabah (Figure 25), clay reacts as a hydraulic medium and transfers fluids from the areas of maximum pressure (basin center) to areas of minimum pressure (via faults, shale diapirs, etc.).

THE INFLUENCE OF CLIMATE ON UPLIFT AND EROSION

The influence of climate parameters on uplift and erosion during Late Cenozoic time has been demonstrated by Shroder and Bishop (2009) on the Nanga Parbat Himalaya. The authors hypothesize that the Nanga Parbat pop-up structure was initiated at *ca.* 10-12 Ma. (comparable to the almost co-eval age of uplift and shelf development in Borneo) before present, with un-roofing on-going at least until the Late Pleistocene. Furthermore, in other parts of the world it has been shown by Whipple (2009), that the internal dynamics of actively deforming collisional mountain ranges are influenced by climate in other parts of the world as well.

Triggered by a climate-driven increase in erosion rate, friction-dominated mountain ranges are expected to show a number of simultaneous responses: a decrease in the width of the range, a temporary increase in sediment yield, a persistent increase in the rate of rock uplift and a reduction in the subsidence rate of surrounding basins. The most convincing field evidence for such a coordinated response of a mountain range to climate change is made by Whipple (2009) on examples from the European Alps and the St Elias range of Alaska.

Such recent and rather ground-breaking research poses the question as to what extent the uplift in the Borneo hinterland, as well as of the mountainous regions of Sulawesi, New Guinea and other areas of SE Asia, could have been prompted by climate changes.

DISCUSSION

Answering the question as to what prompted the establishment of widespread sand-dominated shelf areas is rendered difficult by the simple fact that there are no contemporaneous analogs of the latter in the tropical regions. The contemporaneous North Sea shelves are at least partly sand-prone, but have developed within an unusually strong tidal regime; similar conditions cannot easily be argued for in the Miocene NW Borneo shelves. This said, sandy shelves must depend on two essential factors, namely:

i. high load of sediments from the hinterlands combined with a massive, unprecedented outflow of clastic sediments. Supply is likely to have stemmed from multiple sediment outputs in both Sabah and Sarawak, as well as

ii. persistent long-shore currents that can carry sand over large distances.

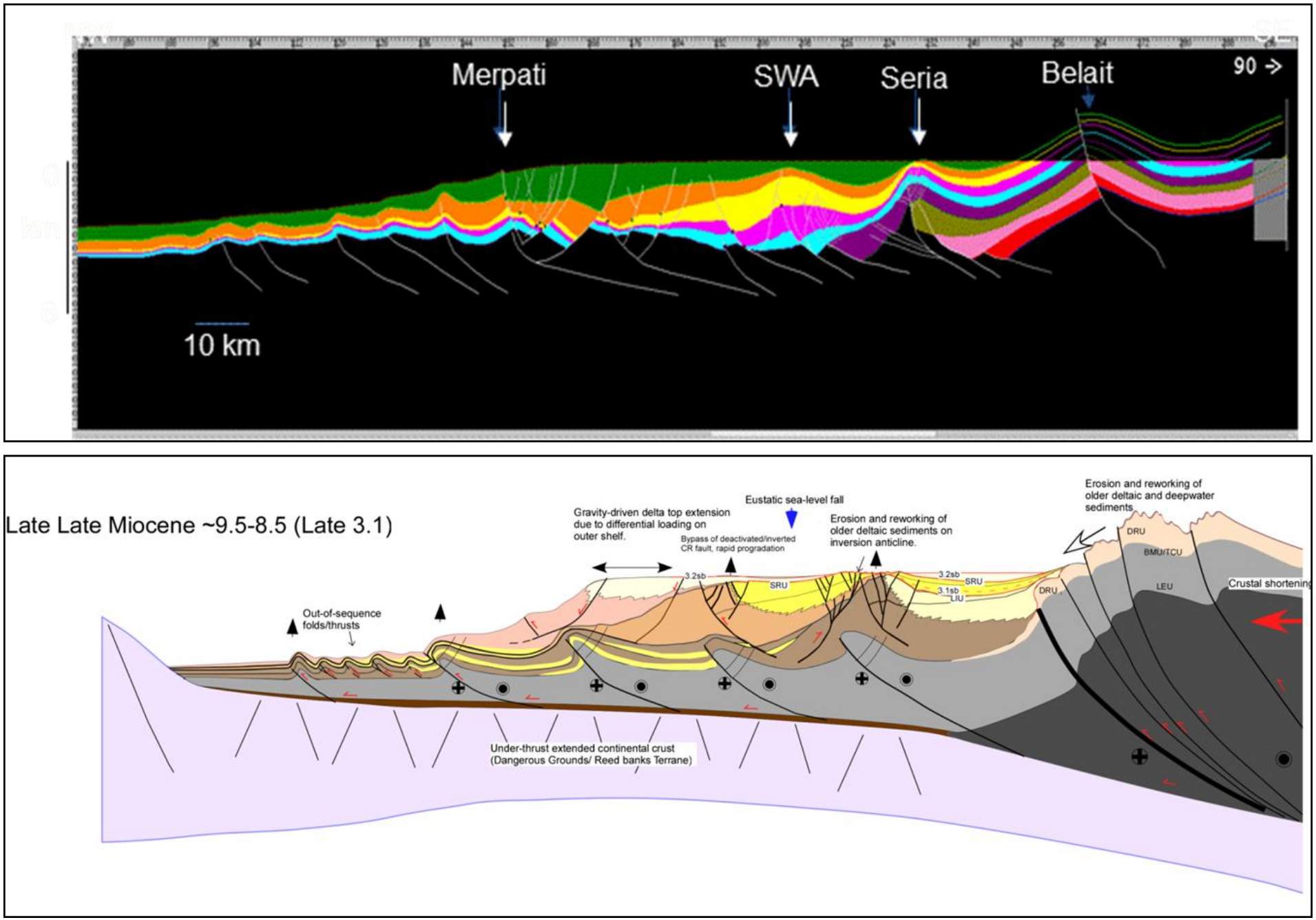


Figure 23. *(Top) onshore-offshore structural reconstruction of West Brunei from ~2.0 Ma to Present-day suggesting an uplift of up to 6 km in the Belait area. The various coloured zones represent mapped tectonic event sequences (SB) from the Late Miocene. (Bottom) a reconstruction of the tectono-stratigraphic features of onshore-offshore Brunei in the Late Miocene, from Gartrell et al. (2012).*

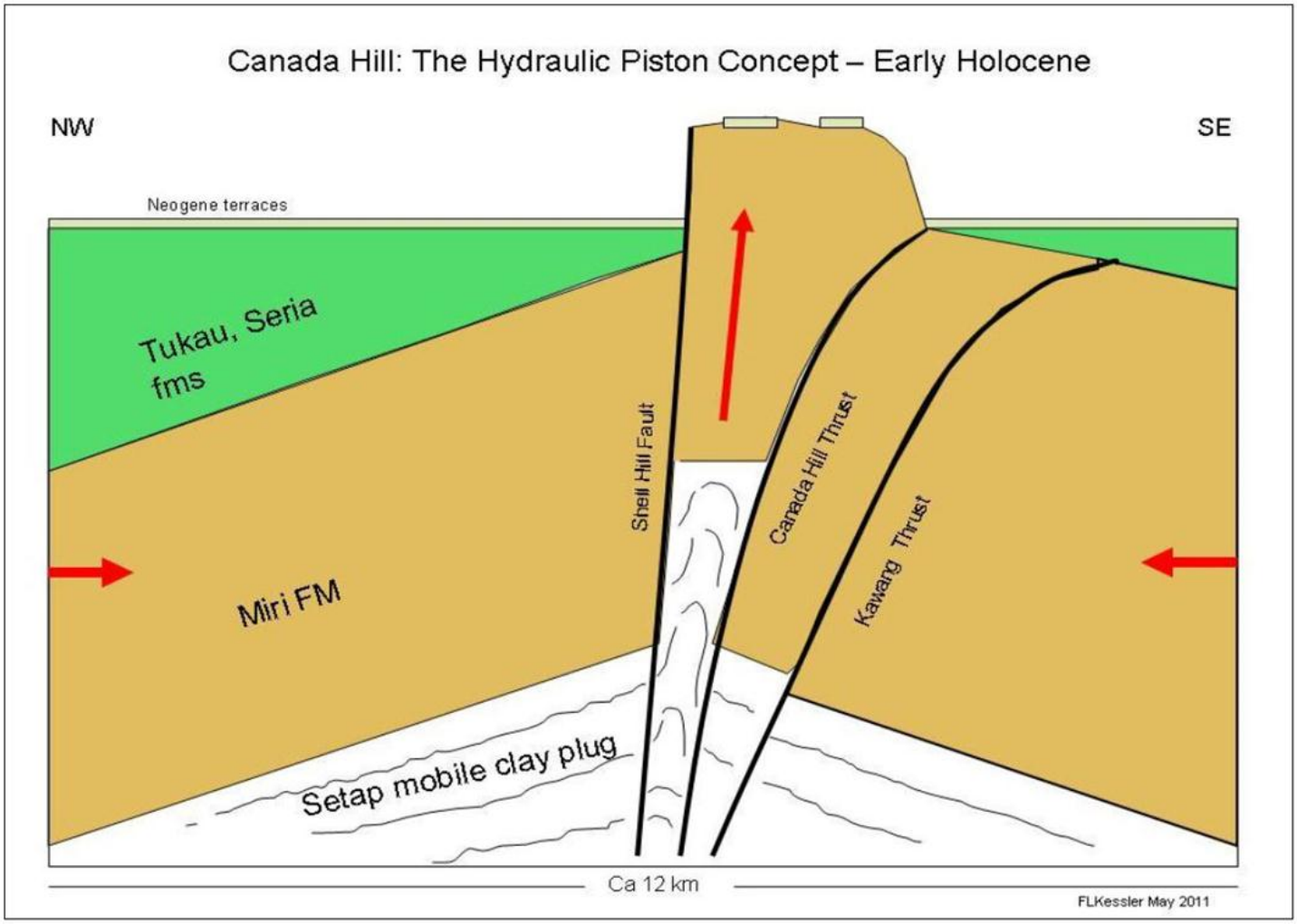


Figure 24. *Parts of the Canada Hill section in the Miri anticline are interpreted to have been uplifted by a pressurized mobile clay core acting as hydraulic liquid, from Kessler and Jong (2014b).*

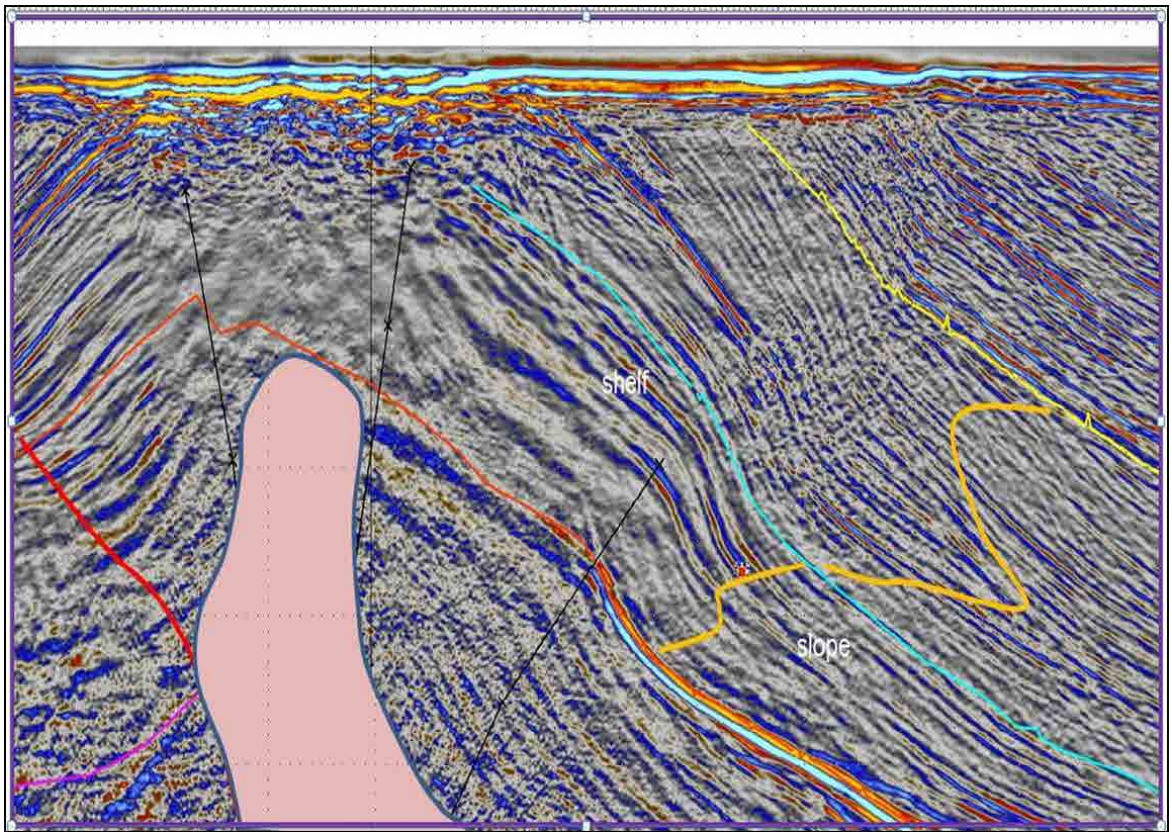


Figure 25.

Seismic example of a presumed clay-cored structure in the South Furious area of NW Sabah. The red marker is the unconformity separating the Stage IVA shelf edge (below) from the Stage IVC (above). The rising clay (pink colour) may have impacted the position of the shelf edge over time and, by providing a sealing mechanism, have influenced hydrocarbon migration.

There are, however, still questions that need to be answered. Next to the Baram and Champion Deltas, and again in Sabah there were areas where carbonates grew, apparently completely unaffected by the enormous influx of clastics and long shore currents. It is noted that a contemporaneous juxtaposition of carbonates and sands also occurs off the extremities of the Mahakam Delta in East Kalimantan. Topography may play an important role here. These shelfal areas were equally close to high mountains in the hinterlands subject to erosion in a tropical monsoon climate. Could it be that the clastic load reached deeper portions of the basin through canyons by-passing the Luconia shelf?

To discuss the origin of the widespread Mid-Miocene sandy shelf areas of Borneo, we could therefore imagine the following sequence of events:

1) Areas of the Eo-Oligocene Sundaland are stretched, as a rift is formed in the Central South China Sea, where oceanic crust is established.

2) A collision between the southern portion of Sundaland and the Australian Plate leading to Early to Mid-Miocene compression/inversion in the greater Borneo area.

3) Segments of the previously thinned continental crust are re-compressed, the Borneo hinterland rises, and a hinge zone develops between Borneo and its NW foredeep. The Rajang/Crocker is exhumed providing massive amounts of sand in a short time span.

4) Under the influence of the monsoon, erosion is accelerated and triggers additional un-roofing as a result of isostatic rebound. High mountain ranges form, potentially crowned by ice caps, and salt lakes are established in the shadow of the monsoon.

5) With a slowing compression at the end of the ?Pliocene, erosion exceed the climate-induced uplift and mountains are eroded to their current roots.

6) The mentioned climatic influence remains hypothetical up to now, and relies heavily on analogues from areas that are both better researched and better understood.

CONCLUSIONS

Here, for Borneo, we have attempted to portray the origin of the Middle to Late Miocene Borneo Baram-Balabac shelf margin from a variety of viewpoints. In particular, we tried to reconcile information obtained from fieldwork and outcrop studies with interpreted seismic and regional correlation data from the offshore areas. In a nutshell, there is sufficient evidence to believe that the key driver for a switch from a muddy to sandy shelf development is vested in the timing and magnitude of uplift. From the current data, we infer:

- A coastal uplift of 20 or more meters in areas of Sarawak since the end of the Pleistocene,
- A semi-regional uplift in coastal areas of Sarawak in the order of 500 m since the Late Pliocene, and
- A total cumulative uplift of some areas of Sarawak and Sabah of some 6000 m since the Eocene.

Furthermore, uplift may have been strongly enhanced by monsoonal impact, consequent erosion and isostatic rebound, a speculation subject to further studies and evidence. In particular, it would be important to compare the Borneo uplift with adjacent young tectonism and monsoon climate. Such work might clarify, if the spectacular Borneo uplift remains a singularity, or applies also to other areas such as New Guinea and Sulawesi.

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. However, any mistakes or shortcomings remain the responsibility of the authors. Fruitful discussions with our ex-colleagues in Shell and JX Nippon are gratefully acknowledged, and our gratitude is also extended to our reviewers for offering constructive comments, which helped to improve the quality of this paper.

REFERENCES CITED

Besems, R. E., 1992. The Cycle concept in NW Borneo with special references to Cycles I, II and III, a review. SSB XGS Stratigraphic note No. 12 (unpublished report).

Bol, A.J. and Thum, I., 1981. Exploration history in offshore Sabah, Sabah Shell Petroleum Company Ltd., Exp. R. No. 70131 (unpublished report).

Cullen, A., 2010. Transverse segmentation of the Baram-Balabac basin, NW Borneo: refining the model of Borneo's tectonic evolution. Petroleum Geoscience, 16, p. 3-29.

Doust, H., 1981. Geology and exploration history of offshore central Sarawak. AAPG Studies in Geology 12: Energy Resources of the Pacific Region, p. 117 – 132.

Eckert, H. R., 1971. The Cycle concept in NW Borneo: definitions and applications. SSB Exp. R. 1870 (unpublished report).

Gartrell, A., Torres, J., and Hoggmascall, N., 2012. A Regional approach to understanding basin evolution and play systematics in Brunei - unearthing new opportunities in a mature basin, adapted from oral presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, 2012.

Geiger, M. E., 1964. Stratigraphy and palaeogeography of the NW Borneo basin. Geological Report No. 866 (unpublished report).

Gou, P., 2014. Organic petrographic characteristics of the Crocker Formation, NW Sabah, Malaysia. Bulletin of the Geological Society of Malaysia, 60, p. 65-75.

Grant, C. J., 2005. Sequence boundary mapping and paleogeographic reconstruction: the keys to understanding deepwater fan deposition across the NW Borneo active margin, adapted from Oral Presentation at 2005 SEAPEX Exploration Conference, Singapore, 5-7th April.

Hall, R., 2013. Contraction and extension in northern Borneo driven by subduction rollback, Journal of Asian Earth Sciences, 76, p. 399–411.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, In: C. K. Wilgus et al., (eds.), Sea-Level Changes - An Integrated Approach, SEPM Special Publication, 42, p. 71-108.

Hutchison, C.S., 2005. Geology of North-West Borneo. Elsevier, the Netherlands, 421 p.

Hutchison, C. S., 2014. Tectonic evolution of South-East Asia. Bulletin of the Geological Society of Malaysia, 60, p. 1-18.

Jong, J. and Ho, F., 2000. A regional overview of the NW Borneo margin, NW Borneo, Malaysia. Sarawak Shell Berhad/Sabah Shell Petroleum Company Ltd., Exp. R. No. 51121 (unpublished report).

Jong, J., Barker, S., Kessler, F. L. and Tan, T. Q., 2014. The Sarawak Bunguran fold belt: structural development in the context of South China Sea tectonics. Processing 8th International Petroleum Technology Conference, Kuala Lumpur, Manuscript 18197-MS.

Jong, J., Barker, S. and Kessler, F. L., 2015. A comparison of fold-thrust belts in eastern Sundaland: structural commonalities and differences on the circum-Borneo margin. Proceedings Indonesian Petroleum Association, 39th Annual Convention & Exhibition, Jakarta.

Kessler, F. L., 2009. Observations on sediments and deformation characteristics of the Sarawak Foreland, Borneo Island. Warta Geologi, 35 (1), p. 1 -10.

Kessler, F. L. and Jong, J., 2012. Critical drilling and play parameters of oil and gas prospection in offshore Sabah, Deepwater Block R and surrounding areas. JX Nippon Oil and Gas Exploration (Deepwater Sabah) Ltd., Kuala Lumpur (unpublished report).

Kessler, F. L. and Jong, J., 2014a. Habitat and C-14 ages of lignitic deposits along the northern Sarawak coastline. Bulletin of the Geological Society of Malaysia, 60, p. 27-34.

Kessler, F. L. and Jong, J., 2014b. The origin of Canada Hill – a result of strike-slip deformation and hydraulically powered uplift at the Pleistocene/Holocene border? Bulletin of the Geological Society of Malaysia, 60, p. 35-44.

Lee, C., 2000. Regional seismic horizon, offshore west Sabah, SSPC Exp. R. 70619 (unpublished report).

Liechti, P., Roe, F. W., and Haile, N. S., 1960. The Geology of Sarawak, Brunei and the western part of North Borneo. British Territories of Borneo, Geological Survey Department, Bulletin (Two volumes), 3, 360 p.

Mazlan B. Hj. Madon, 1994. The stratigraphy of northern Labuan, NW Sabah Basin, East Malaysia, Bulletin of the Geological Society of Malaysia, 36, p. 19-30.

Morisson, K., and Wong, C. L., 2003. Sequence stratigraphic framework of Northwest Borneo. Bulletin of the Geological Society of Malaysia, 47, p. 127-138.

Morley, R. J, Morley, H. P., 2011. Neogene climate history of the Makassar Straits, In: R. Hall and M. Wilson (eds.), South East Asian Gateway Evolution, Spec. Pub. Geol. Society of London, 198, p. 319-332.

Nagarajan, R., Armstrong-Altrin, J.S., Kessler, F. L., Hidalgo-Moral, E.L., Dodge-Wan , D., and Taib, N. I,, 2015. Provenance and tectonic setting of Miocene siliciclastic sediments, Sibuti Formation, northwestern Borneo, Arabian Journal of Geosciences, February 2015.

PETRONAS, 2007. Chronostratigraphic Chart of the Cenozoic and Mesozoic basins of Malaysia. PMU publication No 9: 71 p.

Sandal, T. (ed.), 1996. The geology and hydrocarbon resources of Negara Brunei Darussalam, Brunei Shell Petroleum Co. Sdn. Bhd. and Brunei Museum, 243 p.

Shroder, J. F., and Bishop, M., P., 2009. Unroofing of the Nanga Parbat Himalaya. In: Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya, M.A Khan et al. (eds.), Geological Society of London Special Publication, 170, p 163-179.

Simon, K., Hakif, M., Barbeito, M. P. J., 2014. Sedimentology and stratigraphy of the Miocene Kampung Opak limestone (Sibuti Formation), Bekenu, Sarawak. Bulletin of the Geological Society of Malaysia, 60, p. 45-53.

van Hattum, M.W.A, Hall, R., Pickard, A.L, and Nichols, G.J, 2013. Provenance and geochronology of Cenozoic sandstones of northern Borneo, Journal of Asian Earth Sciences, 76, p. 266–282.

van Hoorn, B., 1997. Tectonics and hydrocarbon habitat of SSPC's contract area, offshore Sabah, Malaysia, SSPC Exp. R. 70054 (unpublished report).

Wannier, M., Lesslar, P, Lee, C., Raven, R., Jorkhabi, R., and Ibrahim, A., 2011. Geological excursions around Miri, Sarawak. Ecomedia, Miri, 279 p.

Whipple, K. X., 2009. The influence of climate on the tectonic evolution of mountain belts, Nature Geoscience, 2, p. 97 – 104.

AUTHOR BIOGRAPHY----------



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.



John Jong

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.