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Estimation of uplift and erosion in the Miri area of northwest Sarawak, Malaysia: A multidisciplinary approach

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Abstract: The question of uplift in the Sarawak Foreland is addressed in a multi-disciplinary approach, namely by assigning surface vitrinite reflectance measurements to depth, and by vitrinite reflectance-to-depth conversion using functions from two previous studies. Additional erosion and uplift data were obtained by comparing eroded anticlinal crests with adjacent synclines and their preserved sediments. The combined data pool suggests two types of uplift (I) a regional uplift in the Neogene affecting the entire coastal area, and (II) a tectonically focused uplift. The amount of the latter uplift and erosion is directly linked to rise of anticlinal structures during the Upper Pliocene, with a total uplift ranging from 700 to 4,000 m in areas along prominent regional faults. Within a very short time window major sedimentation, folding, trap formation and trap destruction took place both as a consequence of folding and erosion. Only anticlines in the offshore and the proximal onshore appear to have survived without major crestal erosion. Since the end of the Pleistocene, a rise of foreland sections by some 132 m is recognized. The rapid Pliocene burial and the erosion that consequently removed the overburden thereafter may have negatively affected the petroleum system and hydrocarbon accumulation within the Miri area, which was left largely intact only in the Siwa-Seria anticlinal trend. All anticlines were targeted by petroleum exploration. However, only the Siwa-Seria trend has proved to be economically successful. This has highlighted the significance of overburden in relation to depth of burial and the thermal effect needed to mature the source rocks capable to generate hydrocarbons.

Keywords: Sarawak, uplift, erosion, Neogene, Miocene, Pliocene, Pleistocene, vitrinite reflectance, South China Sea

INTRODUCTION

The area of this study, the greater Miri area, comprises the onshore part of the Baram Delta, an area of some 7,000 km^2. It is a roughly triangular-shaped feature with its apex located in onshore northern Sarawak and extended to include neighboring Brunei in the northeast (Tan *et al*., 1999; cross-section Figure 1, Jong *et al*., 2017). Only 15 % of the basin is located onshore (Jong *et al*., 2017), and, other than the far larger offshore part, has seen uplift and erosion in selective areas. Sediments are believed to be entirely of Neogene age, ranging in thickness from 7,000 m to 8,000 m, depending on erosion and the interpreted depth of the economic basement. Towards the southeast, the basin fill is increasingly stripped-off by erosion and confined by a thrust front of metamorphic Rajang Group deposits.

The chronology of the earlier exploration history and key events that led to the discovery of the Miri Field have been well documented by Sandal (1996), Tan *et al*. (1999), and more recently by Wannier *et al*. (2011). The geology of the foreland basin is well summarized by Hutchison (2005), mostly citing the pioneering work of the Sarawak Geological Survey. Seismic prospecting added a lot of data in the last 60 years but remained restricted to the coastal rim only. The exploration history of the onshore Baram Delta after 1960 is described by Jong *et al*., 2017. Furthermore, Kessler & Jong (2014) provided a potential explanation for the formation of the Canada Hills by clay injection including an update of the structural interpretation of the Miri Field. Mobility in clay sequences, the Setap Shale, may have played a role in the context of the tectonic deformation in the foreland. At the southern limit of the Foreland Basin a particular phenomenon is observed: slump folding. A review of the Dulit Antiform or Dulit Range (Giraldo, 2017) geometry suggested a detached fold associated to gravity-gliding processes.

Quite often, geoscience studies tend to be carried out in isolation, and the authors address readers in highly specialized fields and topics. Only now and then have authors strived to provide a synopsis of all available geoscience data. In Sarawak, this applies in particular to Liechti *et al.* (1960), Doust (1981), Hazebroek & Tan (1993), Sandal (1996), Tan (1999), Madon (1999), Hutchison (1989, 2005), Kessler (2010) and Kessler & Jong (2015a). Examples of data integration are further offered by Gou & Abdullah

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(2011) and Wan Hasiah *et al*. (2013). In these Labuan Island studies, geochemical arguments are integrated with stratigraphic and structural understanding. Following this line of thought, we attempt to reconcile petroleum prospection and geochemical data with emphasize on vitrinite reflectance, and tectonic analysis. There is a significant amount of geochemical analyses related to source rock properties and maturity, including inorganic chemical properties of sediments, that should be combined with structural and stratigraphic analysis.

STRUCTURAL AND TECTONIC SETTING

Structuration in NW Sarawak and Brunei is complex. The Baram Delta province evolved during the Middle Miocene to present day from a foreland basin to a shelf margin. Erosion and uplift impacted the onshore hinterland more than the coastal foreland and the offshore Baram Delta, where up to 10,000 m of sediment had accumulated (Figure 1).

In the area of study, the deposited sediments is likely thinner, in the order of 7,000 – 8,000 m thickness (Morley *et al.*, 2003; Figure 2). Episodic folding events affected the region, causing uplift of the hinterland, delta progradation, and inversion of gravity-related faults (Morley *et al*., 2003). Existing models place the N–S- and NE–SW-trending folds in a strike-slip transpressional setting. In the Late Miocene, around 7.5 Ma, (Watters *et al*., 1999, Morley *et al*., 2003) NE–SW striking inversion folds developed, located mostly

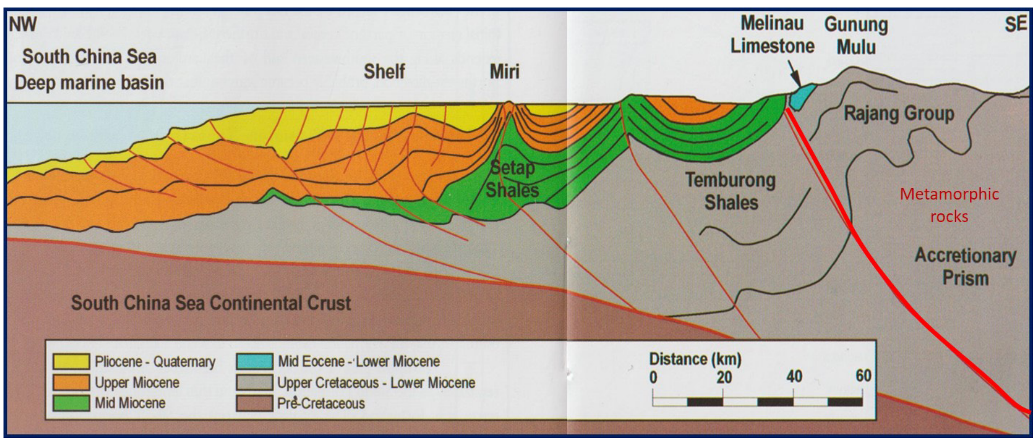


Figure 1: Geologic section through the Foreland Basin and the Baram Delta modified after Wannier *et al.* (2011), partly based on unpublished Shell material. The Rajang Group/Accretionary prism, which is formed by anchi-metamorphic deep water turbidites, likely constitutes a separate tectonic unit and does not form the basement beneath the foreland basin

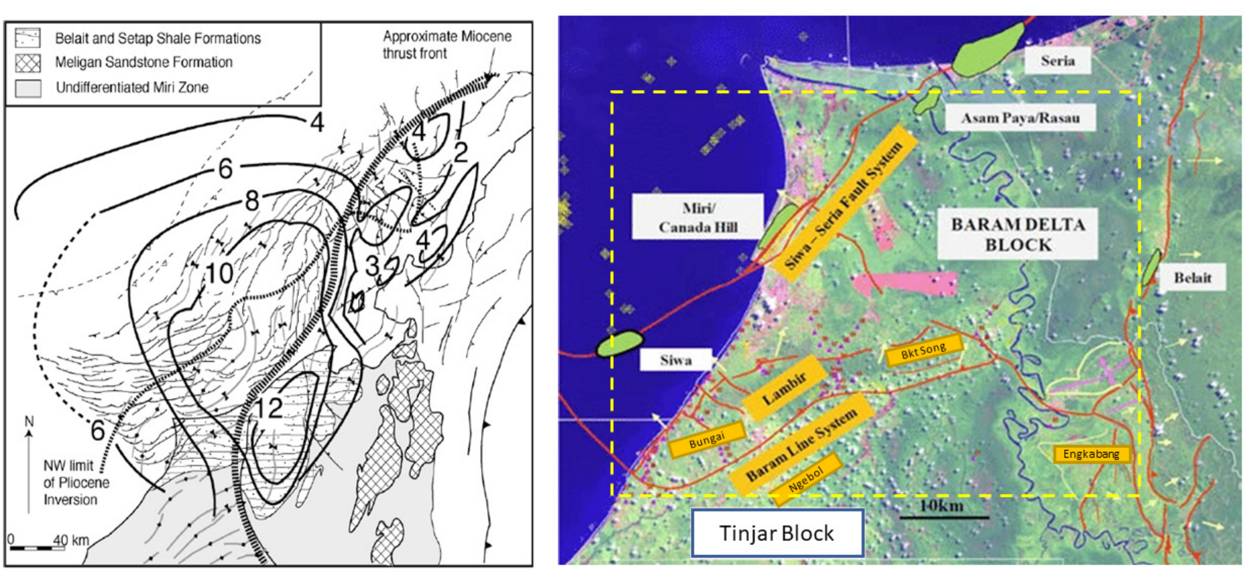


Figure 2: Structural map of NW Sarawak and Brunei with estimated sediment thickness in kilometers, (Morley *et al.*, 2003) left. Right: Tectonic summary map of the greater Miri area, with the outline of the study area marked by a dashed yellow line.The tectonic features are superimposed on a satellite picture.

over early counter-regional faults and associated reactive diapirs. Folds verge towards the NW when underlain by counter regional faults, and towards the S or SE when underlain by regional faults.

At a closer look, the greater Miri area is divided by the Baram Line, a system of wrench and thrust folds which dissects the area of studies and may have triggered the rise of pop-up structures such as Bukit Lambir (Jong & Kessler, 2019 and Figure 12 in this paper). North of the Baram Line we see a strongly folded terrain form of deltaic deposits and very few carbonates. South of the Baram Line lies the Tinjar/Central Luconia Block, which appears to have reacted more rigidly in respect to compression containing many carbonate buildups in the sub-surface.

In respect to the sedimentary and tectonic evolution of the greater Miri area, the following timelines (see also Jong *et al*., 2017) are noteworthy:

- 15.5 Ma: Mid-Miocene Unconformity. Stop of spreading at the center of the South China Sea and progradation of shelfal clastics; a change from clay-dominated neritic to sand-dominated clastics in the Miri area (Kessler & Jong, 2023); shelfal conditions prevailed through late Miocene and Pliocene time; areas of enhanced subsidence and deposition are developed.
- 5.5 Ma: Start of inversion/uplift in synclinal areas alongside of prominent regional faults; strike-slip movements cause folding and anticlines begin to emerge.
- 4.0 Ma: Inversion processes stop. Anticlines are being largely (Engkabang, Ngebol, Pantai) or partly (Lambir, Miri) eroded; peneplanation of the foreland occurred under shelfal and tidal conditions.
- 15550 years- recent (Kessler, 2023): The greater Miri area is uplifted by some 110-132 m; the Miri anticline rises by an additional 80 m probably due to clay injection (Kessler & Jong, 2014).

PREVIOUS GEOCHEMICAL STUDIES

In 1999, Scherer *et al*. studied source rocks and biomarkers in the West Baram Delta and the eastern part of Central Luconia. Although limited rock samples were available, several source rock types could be distinguished including a variety of marine and terrigenous source rocks. Several biomarkers from hydrocarbon fluids in the area suggested a wide range of source rocks from marine to predominantly terrigenous origin. The study found variations in geochemical composition, oil densities and oil/gas fractions vary within approximately 20 to 50 km. Tan *et al*. (1999) provided a comprehensive write up on the geology and hydrocarbon occurrences of the West Baram Delta which include facies model based on outcrop studies as well as offshore stratigraphy. The latter is characterized by coastal to coastal-fluviomarine sands deposited in a northwestwards prograding delta since the Middle Miocene (from Cycle IV onward). It was reported (Tan *et al.,* 1999) that Cycle V (Middle to Upper Miocene) to Cycle VII (Upper Pliocene) are well developed, prograding over thick diachronous pro-delta shales which were mapped as the Setap Shale Formation onshore. These regressive coastal plain and fluviomarine sediments were reported to possess generally good reservoir characteristics. Occurrence of organically lean intervals (rarely exceeding 2.0 wt.% TOC) within Cycle V and VI were cited in their studies. A characterization of organic matter based on biomarker distributions indicate that the main organic matter contributions in the source rocks extracts are higher land plants (i.e. flowering plants and angiosperms). Tan *et al*. (1999) also produced a thermal maturity profile of selected West Baram Delta wells which in general suggest that the top of oil window (early mature) is reached between 4,000-5,000 m.

In a Labuan study focused on coals, Wan Hasiah *et al*. (2013) described the island Cenozoic coal-bearing sedimentary strata as representing different periods and depositional environments as observed in Labuan outcrops. Coal macerals were identified in the laboratory based on their organic petrographic characteristics using photometry microscope equipped with Diskus Fossil software for maceral analysis and measurement of vitrinite reflectance under oil immersion (%Ro; commonly abbreviated as VR i.e., the proportion of normal incident light reflected by a polished surface of vitrinite). In this study some sedimentological aspects such as the depositional environment were correlated with the organic petrological characteristics of the coals. Based on the organic petrographic features and the thermal maturity as determined by vitrinite reflectance, new stratigraphic associations had been identified. From petrographic characteristics and vitrinite reflectance from this study, at least four distinct units associated with coal-bearing sediments were recognized. The analyzed coals are predominantly mangrove-derived and considered to be oil-prone as suggested by the common occurrences of oil haze, and hydrogen-enriched macerals such as suberinite, bituminite, exsudatinite and perhydrous vitrinite.

Gou (2014) attempted to estimate maximum burial temperature and depth of sediments of the outcropping Paleogene Rajang/Crocker formation in Sabah, and the overlying Neogene Belait Group. The sedimentary environment and geochemical properties of the Crocker Formation are discussed in Anuar *et al.,* 2003 and Bakar *et al.,* 2008a & b.

The vitrinite reflectance analysis performed on these surface sediments were used to derive the maximum burial temperatures that the rock and phytoclasts were subjected to, using the equation of Barker & Pawlewicz (1986), in Allen & Allen (2005):

$$\textit{Maximum burial temperature in } ^\circ C = \frac{(\ln(\%Ro)+1.4)}{0.0096}$$

Subsequently, the maximum burial depth (in km) can be estimated by dividing the difference between the maximum burial and surface temperatures (in °C) with the geothermal gradient (in °C/km):

$$\text{Maximum burial depth (in km)} = \frac{\text{Maximum burial temperature in °C} - \text{Surface temperature in °C}}{\text{Geothermal gradient in °C/km}}$$

In Gou´s Sabah evaluation of the Crocker Formation, the average vitrinite reflectance is 0.82% Ro, which indicated that the sediments analysed were once buried to a depth of 4.1 km on average. That 4.1 km layer of rock has been removed by erosion, based on the vitrinite reflectance and the derived maximum burial temperature data. However, the actual thickness of removed overburden could range between 2.7 and 6.5 km, depending on the geothermal gradient and paleo-surface temperatures used in his calculations. Gou cautioned that the estimation of maximum burial depths are sensitive to geothermal gradients used in the calculations.

In 2017, Togunwa & Abdullah published a study on some outcrop samples of Lambir, Miri and Tukau formations, which are of stratigraphically equivalent to the petroleum bearing Cycles (IV and V) intervals in the offshore West Baram delta province in Sarawak. The investigated mudstone samples proved to be fairly organic-rich with a total organic carbon (TOC) content of more than 1.0 wt.% based on the classification by Peters & Cassa, 1994. Unfortunately, not all data points could be used in the current uplift study due to inconsistencies in position of the sample points as some of the coordinates were wrongly cited. Nevertheless, all of the analysed samples displayed similar geochemical characteristics in thermal maturity, depositional conditions and source input showing a strong contribution of terrigenous organic matter deposited in oxic to suboxic conditions. The reported mean vitrinite reflectance (%Ro) ranges from 0.39% to 0.48%. This means that all of these samples are thermally immature and may have yet to enter the oil generation window.

Further mapping campaigns and inorganic chemical research projects were carried out at the Curtin University of Sarawak (Nagarajan *et al*., 2017a; b), with focus on the Sungai Rait area south of Miri. The geochemical studies focused in particular on rocks of the Tukau Member 3 unit (“Chicken Farm outcrop ”). These were classified as shale, wacke, arkose, lithic sandstone consisting of quartz, illite, feldspar, rutile and anatase, zircon, tourmaline, chromite and monazite. Many of these minerals are highly mature and were derived from a moderate to strongly weathered source area, the metamorphic Rajang Group. The zircon geochronology showed that the crystals in the Tukau samples are of Cretaceous and Triassic origin. The presence of chrome spinels and their chemical composition pointed to a minor share of mafic and ultramafic rocks present in the Rajang Group.

In 2021, a comparative analysis on source rock properties has been carried out by Osli *et al*. on the Miocene-Pliocene formations and Quaternary terrace deposits of the Muara district, Brunei. In their study, Rock–Eval pyrolysis was performed as well as organic petrography and biomarker analysis. The coaly organic matter was shown to be composed of Type III (gas prone) and Type II-III (mixed oil- and gas-prone) kerogen. Organic matter in all studied formations originated from a terrigenous source, proven by the abundance of huminite. Organic petrographical and biomarker studies suggested that the coals and lignitic sand samples were deposited in a mangrove-type lower delta setting, under mostly oxic settings. All the studied samples were found to be thermally immature to early mature, as exhibited by the *T*max values that range from 300 to 437 °C and vitrinite reflectance data from 0.22% to 0.46%.

A recent study by Tavakoli (2021) evaluated results of petrological and geochemical analyses, performed on 13 outcrop samples from Bukit Song (Sarawak, SE of Miri). In terms of thermal maturity based on vitrinite reflectance, the results of the mentioned publication are similar to previous studies within the Miri Zone (Abdullah *et al*., 2011; Togunwa & Abdullah, 2017) where samples were found to be thermally immature or early mature. Although the mean vitrinite reflectance values measured by Tavakoli (2021) ranges between 0.35% and 0.58%, there are indications that some measurements were probably made on reworked phytoclasts. The lower values are most likely affected by bitumen impregnation as highlighted by Abdullah *et al*. (2011). In the study by Tavakoli (2021), the Ph/nC_{18} versus Pr/nC_{17} data showed that the majority of samples can be correlated with a peat coal environment, whilst two samples were associated with anoxic marine depositional environment. The organic matter content was dominated by terrestrially derived precursors and, overall, with a dominance of vitrinite maceral. Although the quality of the source rock based on TOC parameter indicated values above 2 wt. % for the majority of samples, this study shows that the hydrocarbon-generating potential of rocks from Bukit Song in Sarawak are generally low.

WORK OBJECTIVE AND APPROACH

In this paper, we attempt to develop an improved uplift and erosion model for the greater Miri area. The approach is multi-disciplinary and combines geochemical results with seismic imaging and structural/regional geological arguments.

DATA

A calibration of the vitrinite reflectance values of the Miri Field wells is problematic (see following section in the text on the Miri hanging wall). Wannier *et al*. (2011) noted that Miri wells did not encounter any mature source rocks in the Miri Field. This might place the top oil window (VR 0.65%) slightly beyond the total depth (TD) of the deeper “younger” Miri wells at ca. 2,900 m. It is noteworthy, that the Miocene Miri Fm. is here at surface. VR values from Miri well 604 (Tan *et al*., 1999) appear to be of good quality. This said, the overburden sediments, namely Pliocene clastics of the Tukau/ Seria fms, have been eroded in the Miri Field area, and hence their thickness can only be estimated. These Pliocene overburden deposits are preserved in nearby Tudan wells 1, 2 and also in the Pujut and Lutong coreholes (Artis, 1941 cited in Wannier *et al*., 2011), with an estimated thickness in the order of 500 - 700 m.

A calibration of biomarkers in the Baram Delta was carried out by Scherer *et al*. (1999). He indicated oil expulsion took place at a VR of 0.8% at a depth of 4,000 m with a notional temperature gradient of 25°C/1000 m.

In a recent compilation of Baram Delta temperature data by Madon & Jong (2021), they indicate a mean geothermal gradient of 28.6°C/km, but many points plot also in the field between 23°C and 27°C. Possibly, we see an increase of the temperature gradient towards Central Luconia (Scherer *et al*., 1999) further west, where oil expulsion may already have occurred shallower at 2320 m. In the same paper, expulsion of condensate in the Baram Delta offshore well Laila-1 (VR 0.9% at a burial depth exceeding 4,000 m) is mentioned. These data points were used to construct a regression curve anchored by a near-surface value of VR 0.2% in the nearby Brunei Muara location (Osli *et al*., 2021). There are also additional VR values from the Miri and offshore fields plotted in Tan *et al*., 1999.

Other data are measurements on coaly deposits sampled at surface locations (Figures 4 and 6). The following surface vitrinite data points (here averaged) are quoted from the literature, with approximate coordinates. The measured vitrinite reflectance (%Ro) are shown in Table 1.

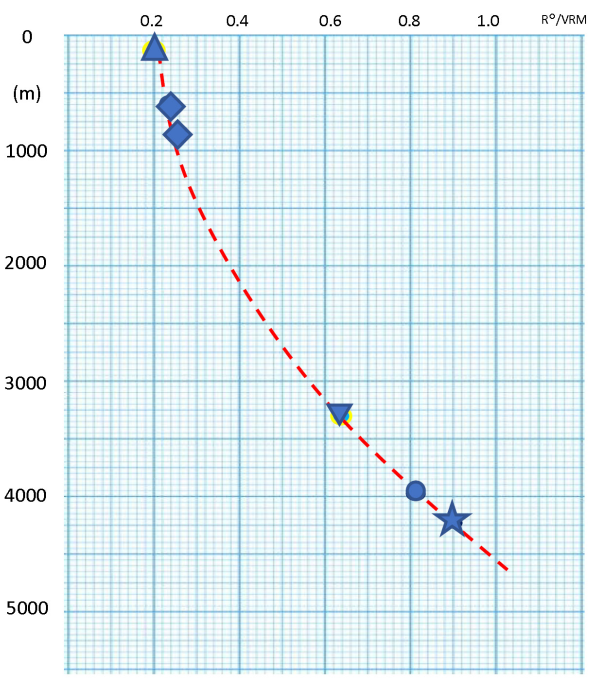


Figure 3: A VR regression curve (conventionally measured vitrinite) is generated from a few data points from the Baram Delta and one Brunei datapoint; an additional data point represents the deep wells in the abandoned Miri Oil Field, corrected for uplift (reverse triangle); two points (diamonds) are from the well Tanjong Baram-1 (Tan *et al*., 1999). Further two points are from the proximal offshore Baram Delta: circle = Western Baram Delta; star = Laila. The standing triangle = Liang Formation, Muara Brunei. The red dashed regression curve can be used to estimate the Sarawak foreland vitrinite-values and related depth in the proximal onshore Baram Delta. The regression curve is associated with a temperature gradient of 25 °/1,000 m.

METHODOLOGY AND RESULTS

Both the methodology and the results are presented and discussed below.

Construction of a regression curve for estimation of missing overburden using limited calibration data

Maturity of organic material in a sedimentary basin is essentially a function of heat flow/temperature and conductivity of the deposits (Allen & Allen, 2005). Clastic depocenters in the South China Sea (SCS) of Neogene age such as the Malay Basin, the Penyu Basin, the Sarawak Foreland Basin and the Baram Delta are composed of Neogene sand and clay sequences. They are normally

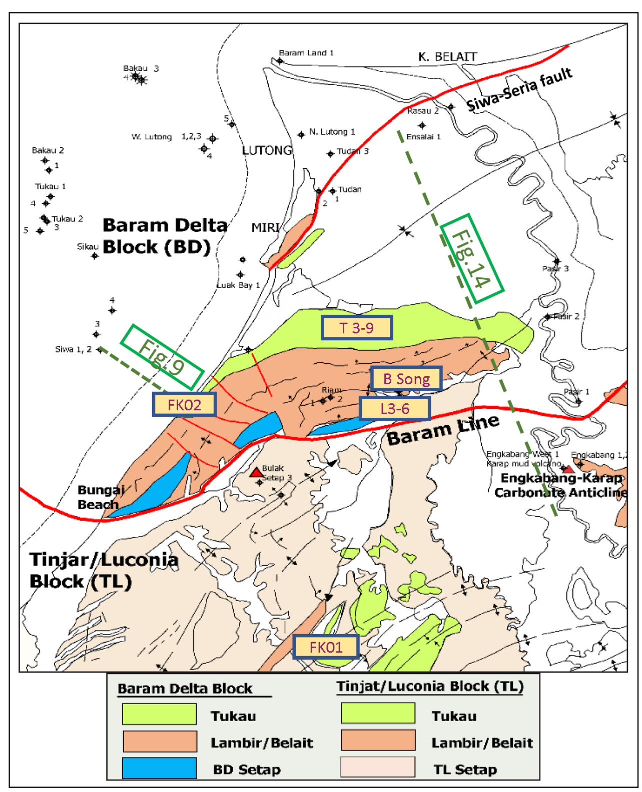


Figure 4: Geologic index overview map showing structural elements and approximate vitrinite sample points.

Table 1: Measured vitrinite reflectance consequence of organic thermal maturation on the Sarawak surface samples after authors: 1 Togunwa & Abdullah (2017), 2 Tavakoli (2021), 3 Kessler & Jong (2015a). Additional Northwest Borneo vitrinite reflectance information was published from the Muara area in Brunei (Osli *et al.*, 2021), and from Labuan Island (Wan Hasiah *et al.*, 2013). Those data can be used in the context of regional comparison.

Sample	Author	Northing (Latitude)	Easting (Longitude)	Formation	Lithological description	Average vitrinite reflectance (% Ro)
T-03-09	1	refer to publication	refer to publication	Tukau	"Mudstone"	0.44
L 3	1	refer to publication	refer to publication	Lambir?	"Mudstone"	0.39
Bkt Song	2	refer to publication	refer to publication	Lambir	Sandstone	0.48
FK 1	3	3°52.571´ N	114°5.4´ E	Tukau	In-situ coal	0.43
FK 2	3	4°7.078´ N	113°49.6´E	Tukau	Coal clasts in sandstone	0.42

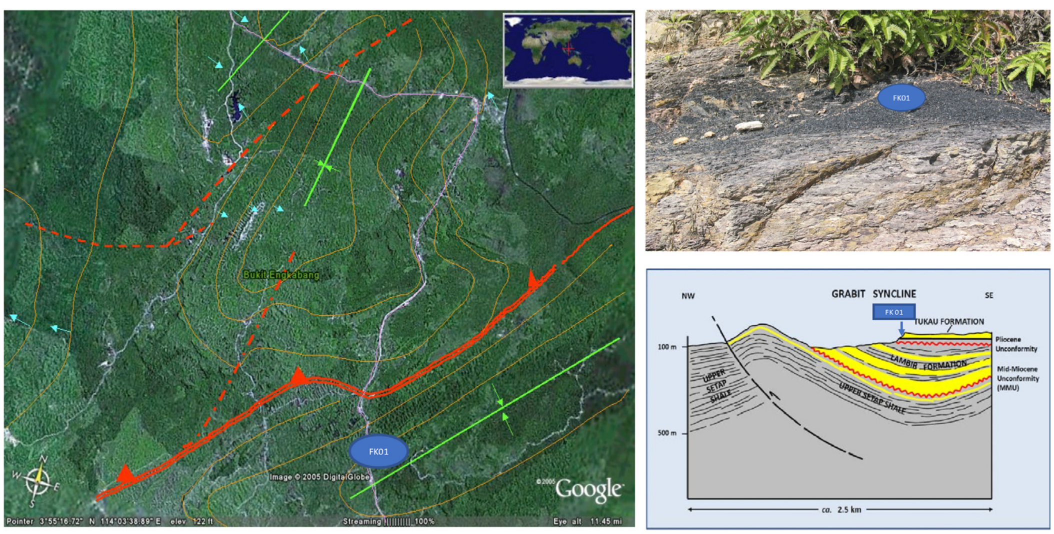


Figure 5: Formline map of the Bakong/Beluru area, with the Long Lama road running North-South. The area is characterized by synclines, often with overthrust contact (left). The Grabit syncline (lower right) contains a residual Tukau sequence, and at least one coal bed of ca. 80 cm thickness at outcrop FK01. This outcrop was destroyed as a consequence of rebuilding the Long Lama road.

pressured with the exception of the deeper basin (Paleogene to Lower Miocene) sections which are overpressured. These and other subbasins in the periphery of the SCS offer temperature gradient characteristics mostly in the range of 25 - 27.55°C/km. However, in selected places they go up to 35°C and beyond. According to Scherer *et al.* (1999), a temperature gradient of 25°C/km is applicable to the proximal part of the Baram Delta.

The Baram Delta regression (Figure 3) is used here to estimate the Sarawak foreland vitrinite reflectance and related depth for the proximal onshore Baram Delta. Rough estimates of the missing overburden are based on surface vitrinite reflectance data as shown in Table 2.

Critical remarks in respect to this methodology and results

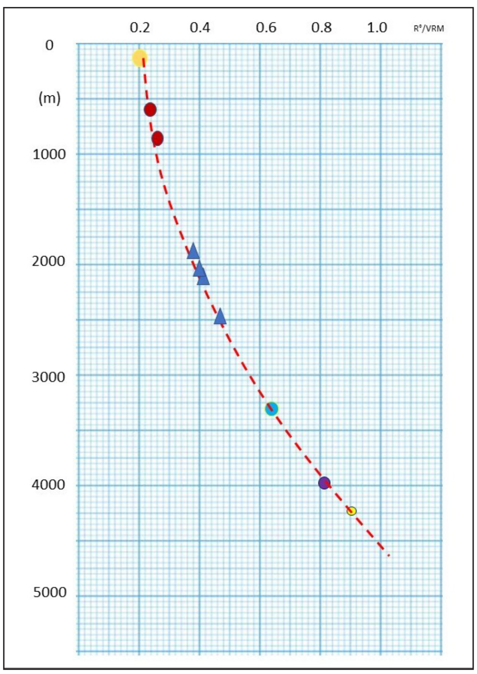
The Baram Delta regression curve is poorly calibrated particularly in the interval between near surface down to 3,000 m. There are no hard data to constrain the surface temperature, and the temperature gradient.

Vitrinite reflectance and uplift estimates from surface (outcrop) samples using the Barker & Pawlewicz method, (as described in a Sabah project by Gou, 2014)

In this approach, Sarawak vitrinite reflectance data are converted to maximum burial temperature using the Barker

Table 2: Estimates for uplift and erosion using surface vitrinite reflectance data taken from the Sarawak Baram Delta regression curve of Figure 3.

Sample	Author	Formation	Lithology	Vitrinite reflectance VR (% Ro)	Estimated erosion/ uplift using the Baram delta regression
T-03-09	1	Tukau	"Mudstone"	0.44	2350 m
L 3	1	Lambir?	"Mudstone"	0.39	2050 m
Bkt Song	2	Lambir	Sandstone	0.48	2600 m
FK 1	3	Tukau	In-situ coal	0.43	2300 m
FK 2	3	Tukau	Coal in sst	0.42	2250 m



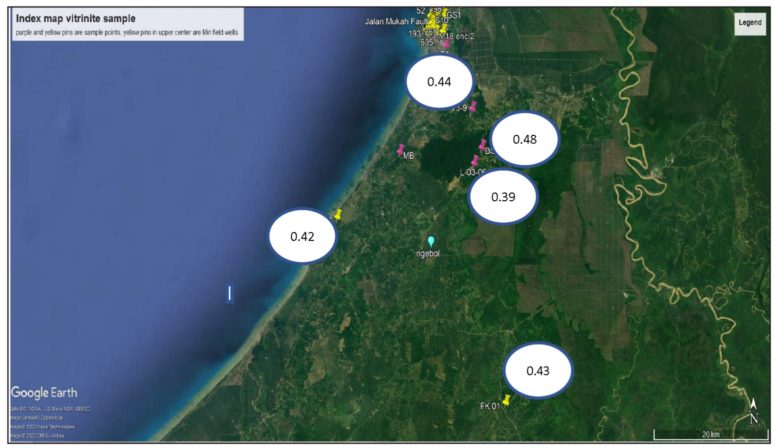


Figure 6: Left: Vitrinite /depth regression curve for the greater Miri area including values of the surface vitrinite samples (triangles on graph). These were calculated with the Walisczek *et al*. (2021) conversion algorithm. There is a good concurrence with the regression curve. Right: Index map for the sampled vitrinite; yellow pins and purple pins indicate the approximative sample locations, with vitrinite relectivity values attached. For the precise vitrinite location coordinates, please be referred to the respective literature. In the upper central part of the picture, some well locations of the Miri Field are shown.

Table 3: Estimates for uplift and erosion using surface vitrinite reflectance data and the Barker & Pawlewicz (1986) formula.

Sample	Author	Formation	Lithology	Vitrinite Reflectance (% Ro)	Max. burial temperature	Estimated erosion/ uplift
T-03-09	1	Tukau	"Mudstone"	0.44	60° C	1810 m
L 3	1	Lambir?	"Mudstone"	0.39	48° C	1310 m
Bkt Song	2	Lambir	Sandstone	0.48	69° C	2175 m
FK 1	3	Tukau	In-situ coal	0.43	58° C	1720 m
FK 2	3	Tukau	Coal in sst	0.42	56° C	1620 m

& Pawlewicz (1986) formulas, applying a temperature gradient of 25°C/km and an estimated surface temperature of 15°C (sea bottom, shelf). The range of estimated erosion/ maximum burial depths for the Crocker Formation was then calculated (Table 3) and discussed.

Critical remarks

The Barker & Pawlewicz (1986) formula is strongly influenced by the assumed paleo-surface temperature, and to a lesser degree also by the temperature model (gradient). Considering the rapid sedimentation during the Neogene, it appears possible that a lower temperature gradient prevailed relative to a potentially higher present-day regime. This appears to be a reasonable assumption for a shelfal seabed in a tropical climate. Madon & Jong (2021) quote a temperature range of 14.5°C to 30°C on the SCS shelf and proportionally to water depth. Using a higher water temperature typical for very shallow tropical shelf settings could lead to considerably lower thickness computations.

Calculation of missing overburden using the Maximum Temperature and Ro relationship and conversion making use of a low-temperature model from the Carpathian Basin, Hungary

Although there is a considerable scatter in the data (Evenick, 2021) there seems to exist a positive correlation between Tmax and Ro. A clear trend was found in the mean, median, and mode values for each Tmax/Ro pair represented by the equation Ro = (0.013 x Tmax) - 5.0 (see Figure 7).

Furthermore, there is a good empirical correlation between VR, Maximum Temperature, and paleo-temperatures such as shown in the example from the Carpathians. The conversion formula below may be applicable in other regions with similar geological settings, such as Sarawak, where a kerogen Type III-dominated shale formation exists in the fold-and-thrust belts, followed by rapid tectonic burial under a low geothermal gradient, (Waliczek *et al*., 2021).

Conversion using the above method is shown in the table below (Table 4), quoting overburden figures with the uncertainty of three different temperature scenarios.

Critical remarks

The above conversion model contains a large amount of data and shows a solid relationship between maximum temperature, rock temperature, and vitrinite reflectance (%Ro). Like in the other models, there is a considerable uncertainty relative to the paleo-surface temperature, and the temperature gradient.

DISCUSSION OF RESULTS AND COMPARISON OF VITRINITE REFLECTANCE-TO-DEPTH CONVERSION MODELS

In Table 5, results of the three vitrinite reflectance-to-depth methods are compared. Interestingly, all three methods produce similar results.

The number obtained via the Baram Delta regression may be giving a fair indication of erosion and uplift, although significant uncertainties remain in the poorly calibrated shallow to middle section, and we do not know the precise heat flow history during the Miocene basin period. Madon & Jong (2021) quote a mean contemporaneous geothermal

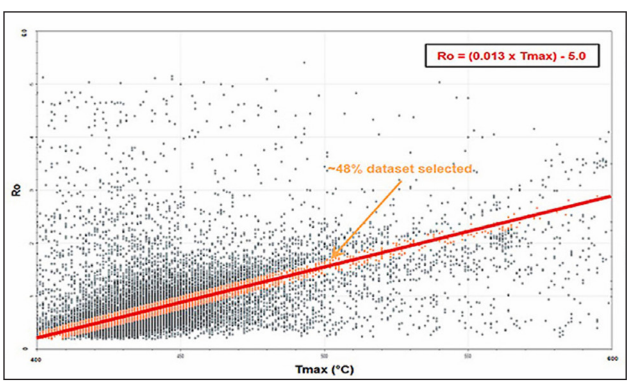


Figure 7: Empirical relationship between Tmax and VRM (after Evenick, 2021) with conversion formula.

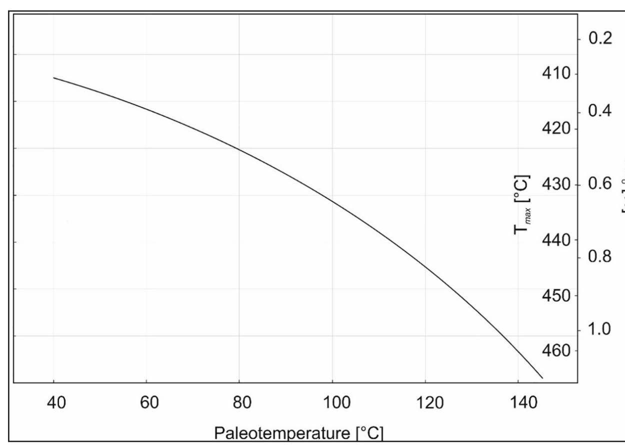


Figure 8: Conversion function between VRM (%Ro), Tmax and rock temperature after Waliczek *et al*. (2021).

Table 4: Erosion/uplift estimates using the Waliczek *et al*. (2021) conversion model with three temperatures gradient schemes. The 25°C/1000 m in the middle is seen as the most likely scenario.

Sample	Calculated paleo-temperature °C	Overburden @ 20° C/ 1000 m	Overburden @ 25° C/ 1000 m	Overburden @ 30° C/ 1000 m	VR (% Ro)
T-03-09	70	2700	2200	1800	0.44
L 3	61.5	2300	1850	1500	0.39
Bkt Song	78	3100	2500	2100	0.48
FK 1	68	2700	2100	1700	0.43
FK 2	66.5	2500	2300	1675	0.42

Table 5: Comparison of missing overburden results using three different methods of conversion, but the same paleo-surface temperature (15°C) and the same temperature gradient (25°C/ km).

Sample	Baram Delta regression curve; depth in (m)	Barker & Pawlewicz (1986) formula; depth in (m)	Waliczek *et al*. (2021), 25°C/km; depth in (m)	VR (%Ro)
T-03-09	2350	1810	2200	0.44
L 3	2050	1310	1850	0.39
Bkt Song	2600	2175	2500	0.48
FK 1	2300	1720	2100	0.43
FK 2	2250	1620	2300	0.42

gradient of 28.6 °C/km for the Baram Delta wells, but the gradient might have been historically lower during Miocene-Pliocene times as a result of rapid clastic sedimentation and the associated cooling effects. The numbers obtained based on the Barker & Pawlewicz (1986) formula deliver lower erosion estimation values compared to those obtained via the Baram Delta regression. The results obtained via the Waliczek *et al*. (2021) conversion are remarkably similar to the Baram Delta regression results.

At this stage, any of these results cannot be excluded. It is, however, possible to make additional arguments based on geographic sample position in the context of field measurements. For example, the three confirmed Tukau data points T3-9, FK-01 and FK-02 are located on the edge of synclines, and the Tukau sediments are only partly removed. Hutchison (2005) gives a thickness estimate of 2,700 m for the entire Tukau thickness. A water well drilled in 1999 in the center of the Badas syncline penetrated and confirmed some 1,500 m of Tukau deposits, without reaching the Lambir/Miri formation beneath. Data (borehole temperature, vitrinite reflectance etc.) from old wells in the greater Miri area would help to obtain better measured points and further constrain the erosion/uplift figures.

MATERIAL BALANCE: COMPARISON BETWEEN ERODED ANTICLINES AND ADJACENT SYNCLINES

Material balancing is a further approach in trying to quantify uplift and erosion. Already in 1933, the Shell field geologists Braendlin, Trumpy and Waite discovered that anticlines such as Miri´s Canada Hill were deeply eroded whilst, other areas, such as the Liku (now called Liku- Badas or simply Badas) syncline contained a mighty sequence of unconsolidated sand-and clay deposits called the Pliocene or Tukau formation (Wannier *et al*., 2011). Excellent field mapping exercises were carried out by geologists such as P. Eiber in 1924, Figure 13 (fragment of a lost Sarawak Oilfields report). Early and later fieldwork also helped to establish a better notion of tectonic timing. An important phase of folding and perhaps even thrusting appears to have affected the greater Miri area between 5.5 Ma and 4 Ma, these events occurred during the Late Miocene, Messinian, and Pliocene, Zanclean (Jong *et al*., 2017) and Figure 14. During this time span, the Engkabang anticline rose, and subsequently Late Miocene to Pliocene deposits on its crest were eroded. Equally, a first pulse caused the rise of the pop-up structures of Bukit Lambir, as well as Miri´s Canada Hill.

Whether the tectonic activity, leading to uplift along the Siwa-Seria fault were strictly synchronous with the rise of Engkabang, Ngebol and Lambir/Bungai on the other regional faults, cannot be assessed at present.

The coastal area near Pantai Bungai

An old 2D seismic line (see Figure 9) which was shot perpendicular to the coast between Tusan Beach and Pantai Bungai, indicates the presence of an offshore low, the Siwa Depression (Figure 2), a southwestern extension of the Liku-Badas syncline. It holds some 1.9 seconds (1WT= 0.95 seconds = roughly 2,350 m, assuming a 2,450 m/sec interval velocity) of sediment, that belongs partly to the present and partly ´missing Tukau´ sediments which are not fully represented onshore. Arguably, the Siwa Depression has not been incorporated in the inferred uplift and erosion, which may have occurred onshore during the Late Pliocene, and the sediment record may include the entire Neogene sequence.

The Liku-Badas syncline

The slightly asymmetrical Liku-Badas Syncline is an onshore continuation of the Siwa depression and lies between the Canada Hill (Miri) and Bukit Lambir (Figures 2, 10). The area may have suffered little erosion if the presence of a reasonably thick Tukau Fm is considered.

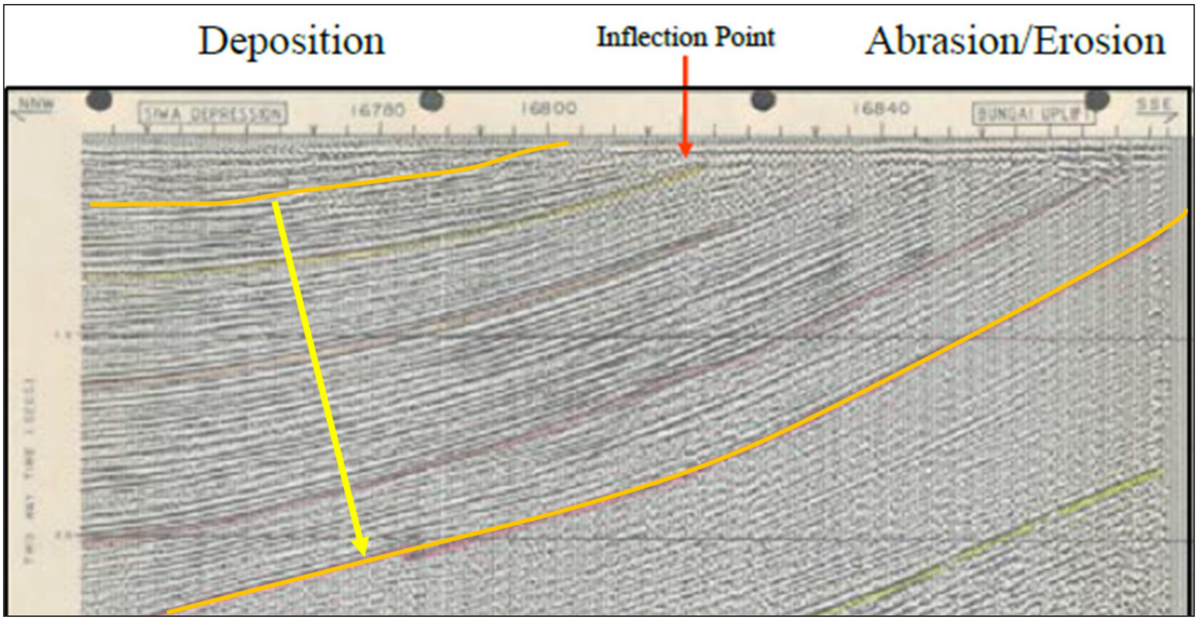


Figure 9: Old offshore seismic line, running perpendicular to the coast line. The onshore line ending (right) is located near to the Tusan cliffs, and lies close to the coal clast sample point of FK 02. The seismic picture shows significant abrasion in the shoreface section. The interval between the two orange interpreted horizons is assigned to the Tukau formation, 1.9 seconds of seismic 2wt (yellow arrow). The highlighted seismic interval section coresponds to a total Tukau thickness of about 2350 m (@ assumed interval velocity= 2450 m/sec).

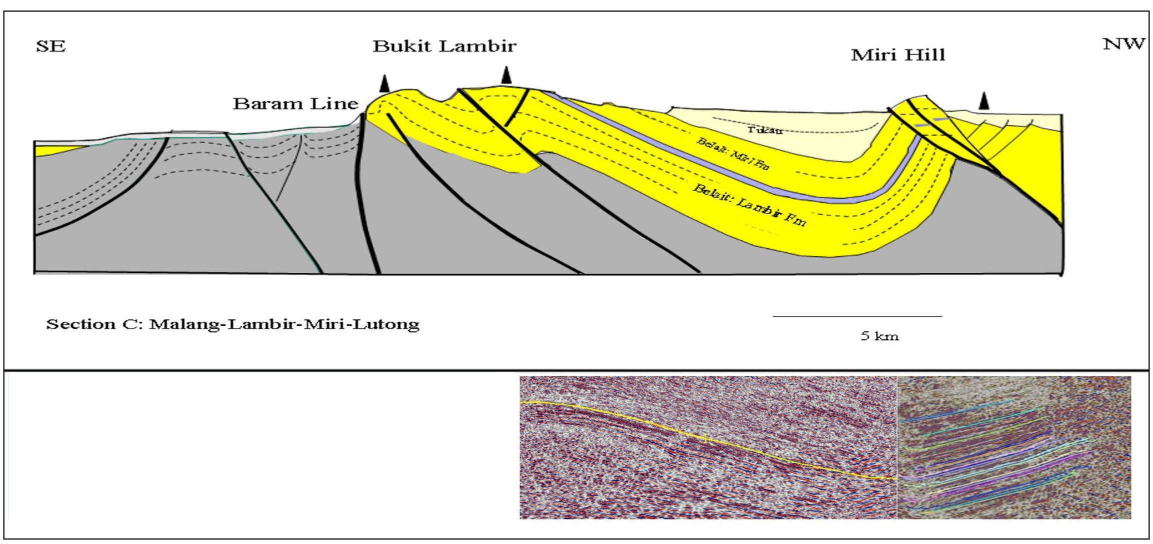


Figure 10: Geologic and stitched-up seismic section through the Liku-Badas Syncline, in which the top Lambir/Miri (or Belait Fm), yellow marker, is overlain by some 2700 m of Pliocene Tukau Fm. Modified after Kessler *et al*., 2010.

The Miri Anticline, the Canada Hill and the Miri Oilfield

Thanks to the persistent work of two generations of Sarawak Oilfields Ltd geologists, there is a good level of knowledge in respect to stratigraphy of Miri´s Canada Hill, which continued to be further evaluated until the present. The exact sequence of tectonic processes, however, remains a matter of discussion. A good summary of the past efforts is provided by Wannier *et al.* (2011), and the Petroleum Museum located on Canada Hill. The Miri anticline lies on a strike-slip fault system which runs from Siwa in the SW to Seria in the NE, and Miri is the only one which saw major uplift/inversion. The other structures (Siwa, Adong Kecil, Asampaya, Seria) have not seen any significant erosion of the overburden sequence (Chapman, 1983; Jong *et al*., 2017).

The Miri Field is located on the hanging wall

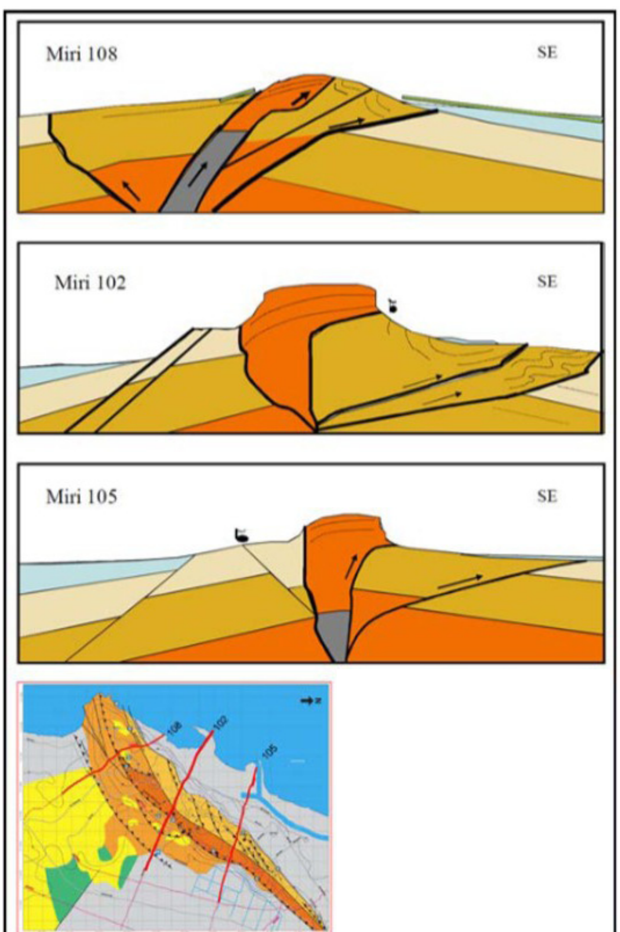
The Miri Field (hanging wall) is separated from the crest of the Canada Hill (foot wall) by the Shell Hill Fault, a feature of significant fault throw forming an escarpment, which can be seen in the field (Figure 11). The contemporaneous relief may be the result of a fairly recent (mostly less than 20,000 years before present) uplift, as suggested by Kessler & Jong (2014). Most of the 612+ Miri Oil Field well heads are located on the hanging wall, whilst only few have been drilled in the strongly truncated foot wall. The Miri Fm appears to be fully preserved in the hanging wall or oil field block, the shallowest level is formed by the Pujut sands. Vitrinite reflectance values of the Miri well 604 (Tan *et al*., 1999) appear to be of good quality. The overburden sediments, namely Pliocene clastics of the Tukau/ Seria fms, have been eroded in the Miri Field area. This is demonstrated by the projected vitrinite reflectance near surface value of 0.52% in well Miri 604. Based on the near-surface vitrinite reflectance values, the amount of eroded overburden in the Miri hanging wall could be as high as 1,800 m. However, it is doubtful that such an amount really was eroded. The Tukau/Seria Fm., the Pliocene overburden, is present in the nearby Tudan wells 1, 2 and also in the Pujut and Lutong core holes (Artis, 1941 cited in Wannier *et al*., 2011), indicating an estimated Tukau/Seria thickness in the order of only 500 - 700 m.

The crest of the Canada Hill is located on the foot wall

Figure 11 shows outcrops of the Miri Footwall structure, the Canada Hill. On the crest of the Canada Hill (foot wall), not only the Tukau Fm is missing, but also a large section of the Upper Miri Fm appears to be eroded and only the lower sandstone series are preserved on the hill side. This means that at least 2,000 m (estimated from formation thickness in Miri wells) of the Miri Fm may have been eroded in the crestal section, and a thin remaining Miri sequence is covering the soft Setap Shale core beneath (see Figure 11). This could mean that the crestal portion of the Canada Hill may have suffered uplift and truncation in the order of 2,500 m or more, namely the combined thickness of Upper Miri and Tukau formations.

The Lambir/Bukit Song and Bungai anticlines

The Bukit Lambir/Bukit Song anticline (Figure 12) is a pop-up feature between two important faults: the Baram



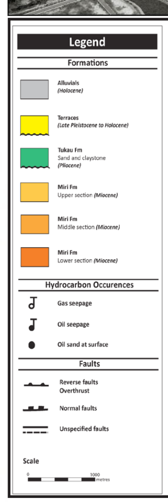


Figure 11: Left: The Canada Hill, cross-sections based on 2011 seismic (Kessler& Jong, 2014). The center of the anticline is defined by a core of mobile clay, which has inflated the structure leading to uplift and a partial erosion of Miri and Tukau formations. Right: View on the Miri Field and the Canada Hill. The Shell Hill fault is shown as an escarpement, covered by dense vegetation and highlighted by two yellow lines. The fault throw measures several hundreds of meters. Originally interpreted as a normal fault, it may have been remodeled by upwelling of diapiric clay beneath the footwall.

Line in the South, and another strike/slip fault accompanied with local overthrusts in the North. Bukit Lambir is an asymmetrical anticline, endowed with a steeply dipping northwestern flank, and a gently dipping south-eastern flank (Figure 10).

The total uplift in Lambir is estimated by adding the topographic elevation (ca. 500 m) to the missing overburden (Tukau Fm., estimated at 2,175 m, in Bukit Song), resulting in a combined figure of 2,675 m. Pleistocene or Holocene sediments were probably never deposited. Lambir is a dipping downwards anticline, the fold axis is seen plunging at the Bungai Beach, ca. 19 km west of Bukit Song. The anticline at the Bungai Beach is deeply eroded down to the Setap Shale. The Coastal Road runs through a valley that has incised the plunging Setap Shale core of the anticline. This segment is also called the Bungai anticline (see Figure 13). In this area, the uplift is summed up as follows: by elevation (100 m), then adding an estimated thickness of the eroded Lambir Fm (ca. 2,100 m, after Hutchison, 2005) plus 100 m eroded Setap Fm. plus the estimated thickness of the missing Tukau Fm (ca. 1,620 – 2,300 m values converted from vitrinite reflectance). The calculated uplift for the SW Lambir anticline could therefore be in the order of above 3,500 m, potentially presenting a case of relief inversion.

Figure 12: The Crest of the Lambir Hills is formed by sandstone of the Lambir Fm., at the core of the Lambir anticline. The Bukit Lambir/Bukit Song anticline is interpreted as a pop-up structure which rose between two wrench faults, the southern branch belonging to the Baram Line system. The uplift occurred in the Late Pliocene and led to a rapid erosion of parts of the Lambir (Late Miocene) and Tukau (Pliocene) formations. The Lambir Hills indicate a rapid sedimentation and subsequent uplift/erosion (estimated 2,500 m in Table 4) in a relatively short time. This appears to concur with the very high burial rate of about 2,000 to 3,000 m/ma reported by Sandal (1996) for the Baram Delta and Champion delta system of Brunei Darussalam.

The Bukit Engkabang anticline

The Bukit Engkabang anticline is one of the better imaged structures in Sarawak. High-resolution 2D seismic data, aero-gravity and magnetics were acquired by JX Nippon in 2009 and 2010. Interpretation of the latter confirmed the existence of a large carbonate-cored anticline, previously drilled by Shell in 1959-1960 and proving sub-economic gas in a massive section of tightly cemented and dolomitized limestone, with little or no matrix porosity/permeability (Jong *et al.,* 2016). Drilling results of Engkabang West-1 by JX Nippon confirmed the presence of gas in tight carbonate reservoirs, but DST flow rates also proved not to be economic. The anticline is a typical "bald head" structure, with Aquitanian-Burdigalian (Lower Miocene) sediments

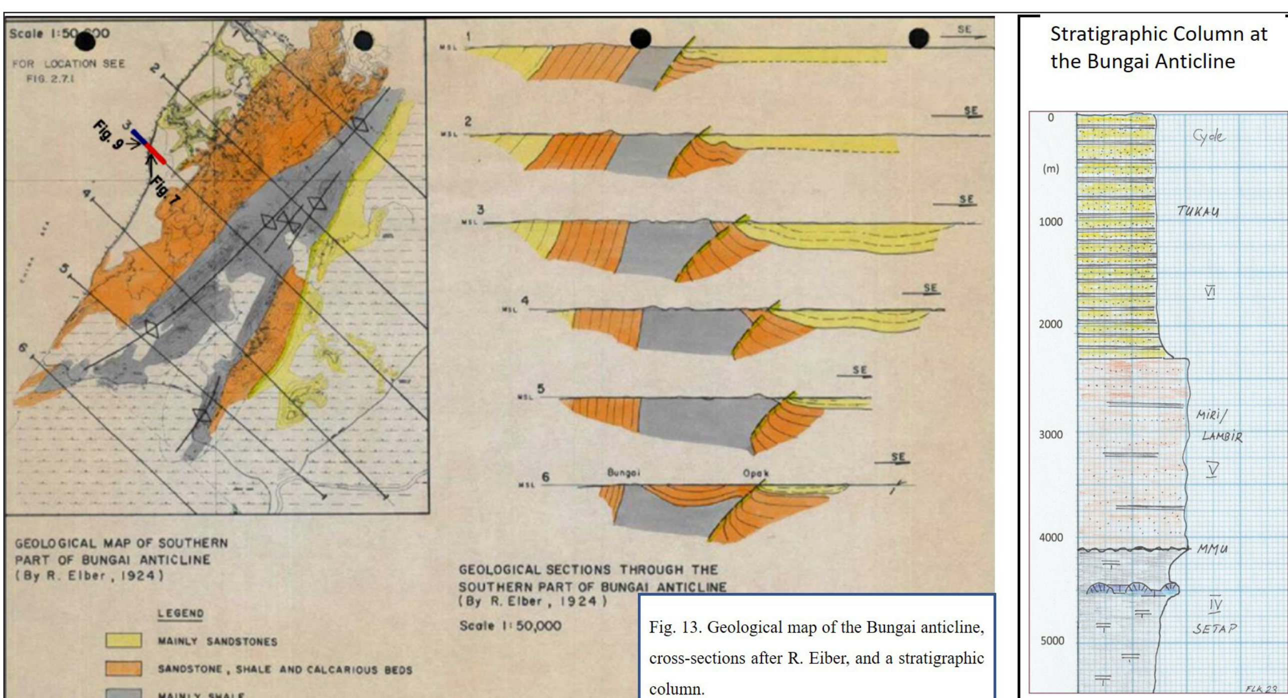


Figure 13: Geological map of the Bungai anticline, cross-sections after R. Eiber and a stratigraphic column.

outcropping at surface. Younger strata have been eroded. A comparison with the syncline adjacent to the North of Engkabang (see Jong *et al*., 2017, and Figure 14) suggests that at least 2 seconds (ca. 2,500 m), but probably more could have been eroded (4,000 m?). This figure is obtained by counting the strata which are seen subcropping beneath a regional intra-Pliocene unconformity surface. Some of the Tukau sediments in the low adjacent to Engkabang might have been deposited whilst the anticline was still rising; hence the Engkabang bald head may have featured as an area of non-deposition. Interestingly, the wells Engkabang-1 and-2 had strong oil shows in the uppermost, near surface sediment section only. This might be seen as an indication that deeper levels in the well are at present postmature for oil. On the top of the anticline, near to the well EW-1 is a prominent mud volcano, called the Karap mud volcano. Volcanoes consist of generally low surface mud mounds, with a crater-like appearance, produced by vertically migrating, cold fluidized mudstones and gasses (Wannier *et al.,* 2011). Mud volcanoes are tiny pressure valves at the surface and are often located above of the crests of anticlines and diapirs, where pressurized gasses and fluidized mud find their way to the surface through areas of least resistance (Tingay *et al.*, 2009; Wannier *et al.,* 2011).

The Ngebol anticline

The Ngebol Anticline appears to be a deeply eroded and peneplanated anticline in Bukit Peninjau. In the center it harbors the mud volcano ´Ngebol´ (Figure 15). Not far from the mud volcano is the well Bulak Setap-3, which

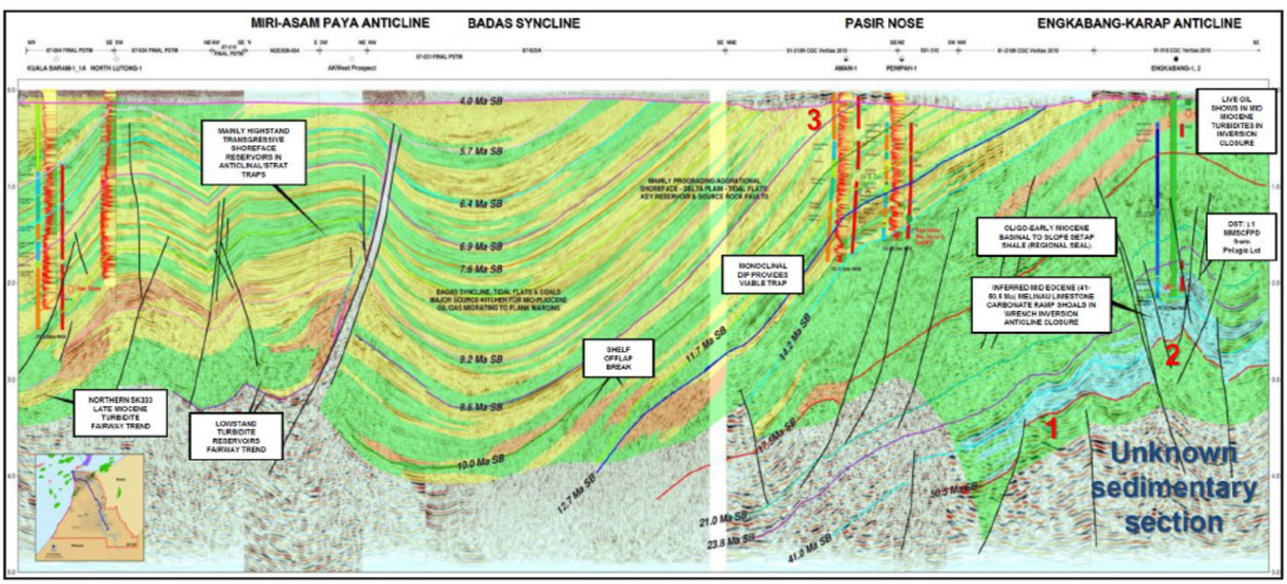


Figure 14: Interpreted seismic section from the Miri-Asam Paya to Bukit Engkabang. The syncline in the center is filled by a prominent Tukau Fm. thickness, deposited between 11.7 to 5.5 Ma and truncated at 4 Ma. The syncline in the center of the section contains multiple sandstone reservoirs. The Engkabang Fm. is deeply eroded and the oil window may be close to surface. The red arrow indicates the amount of sediment, in the order of 4,000 m, which has been eroded in the Bukit Engkabang anticline. After Jong *et al.*, 2017.

Figure 15: Overview of Ngebol with the Bulak Setap-3 well head location and the Ngebol mud volcano caldera. In the brownish green area surrounding Ngebol an older generation of palm oil plants has just been cut. Upper left: The Bukit Peninjau road junction. Left upper corner: excerpt from a geological map, 1958 Sarawak Oilfields Limited (SOL), showing a strongly folded area (anticlines in red, synclines in green), and the light blue-colored area corresponds to outcropping Setap Shale. The exploration well Bulak Setap-3 was drilled near to the crest of a deeply eroded anticline.

vents methane and formation water at irregular intervals. This exploration well was drilled in 1951 and abandoned dry in 1953 at a TD of 11,633 feet and at a cost of USD 4,200,000 including the road construction, which took two years to complete (Sarawak Gazette Nr. 1142). The well was a big disappointment, given it did encounter neither oil nor reservoir from surface to TD. The penetrated formation is called Setap Shale, mostly Lower Miocene claystone, which is found often overpressured and occurs in large parts of NW Sarawak and Brunei (Chapman, 1983). Surprisingly, there are surface oil seepages reported in Ngebol (Wannier *et al*., 2011), and a gas-rich brine is seen escaping from the corroded well head of Bulak Setap-3. Could this indicate that the near- surface layer of sediment were in the oil window, or might it be a gas-rich brine associated with biogenic methane? Unfortunately, we lack sufficient outcrops for better information. In addition, human activity (palm plantations, multiple bulldozing) has largely obliterated the natural morphology of the crater valley. Consequently, a determination of missing formation and uplift in Ngebol appears more difficult than in other areas. We do not know the thickness removed by erosion in Ngebol, but one can try to estimate the former formation thickness by interpolation of better-established figures from the neighborhood. Hutchison (2005) quotes a thickness of the Lambir Fm. as 1,600-2,100 m. This said, the Lambir Fm. appears to be thinner south of the Lambir Hills, beyond the Baram Line. Furthermore, in the profile of FK-1 (Kessler & Jong, 2015b), only 345 m of Lambir Fm. were measured. The Tukau Fm in the Grabit Syncline may just reach a thickness in the order of 100 m (diameter of the Grabit Syncline = 7.0 km, very small bed inclination). The vitrinite reflectance (VR 0.43 % Ro) of the coal bed of FK-1 pointed to a missing overburden of some additional 2,100 m of Tukau deposits. Such an amount of sediment may also have been eroded in the Ngebol anticline, plus a few hundred meters of Lambir, and certainly some unroofing of the Setap Shale as well. Possibly, the erosion in Ngebol speculatively reached even deeper. With 3,000-4,000 m of overburden being removed, Ngebol is obviously a prime location for escaping fluids as seen in the above-mentioned mud volcano. Unfortunately, we are lacking chemical analyses of the methane gas which is sizzling from the corroding Bulak Setap-3 well head in the Ngebol caldera.

Critical remarks

Obviously, material balancing as carried out under Work Objective and Approach requires extensive extrapolation of stratigraphic data, and the results are simply estimates. However, it was possible in one location to calibrate actual sediments of the Siwa depression with uplift/erosion figures at the adjacent coast line. The old seismic offshore line (Figure 9) indicates a low with additional sediments, west of the inflection point in the order of 1.9 seconds TWT = 2,350 m (assumed interval velocity of 2,450 m/sec). The area between the two orange horizons of Figure 9 corresponds to the Tukau formation. The nearby VR sample point FK 2, located onshore at the Coastal Road in Tukau sediments, indicates uplift and erosion of some 1,620-2,300 m of sediment, respective to the VR conversion method applied, in broad concurrence to the thickness calculation based on the seismic section. A tabulation of results is shown in Figure 16, which summarizes the main results of this paper:

(i) There was a significant intra-Pliocene uplift, followed by erosion, affecting anticlinal areas only.

(ii) In respect of the vitrinite reflectance conversion methods used, they delivered comparable results. Arguably, a well-calibrated regression curve should be the conversion method of choice.

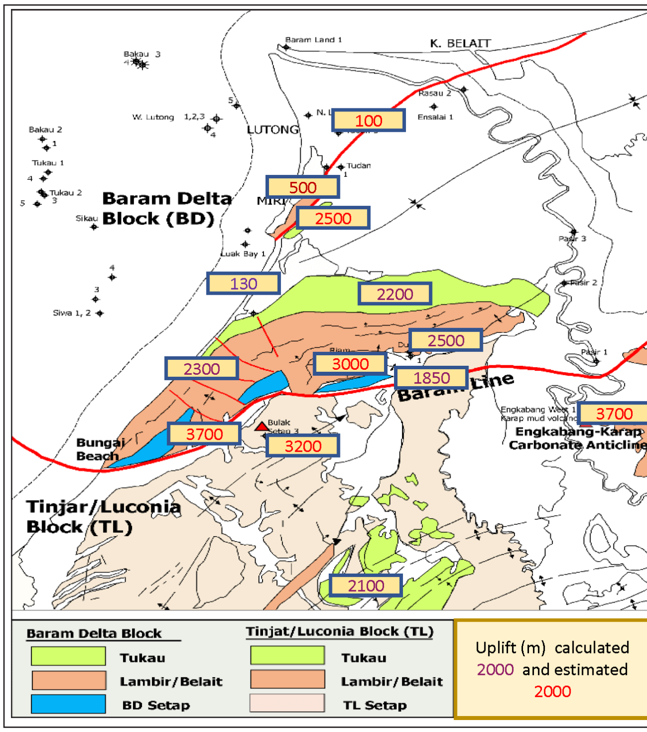
(iii) Material balance estimations carry a high amount of uncertainty and should only be used if other methods are not available.

IMPLICATION OF THE UPLIFT ON THE PETROLEUM SYSTEM

In the Bungai, Lambir, Engkabang and Ngebol anticlines, the Setap Shale is outcropping near to surface, and the oil window is very shallow in absence of several thousands of meters of Neogene overburden. Hence these bald-head anticlines may lack either sufficient charge or a contiguous reservoir/seal assembly to trap hydrocarbons. On the other hand, there are synclines that are less affected by tectonics with some Tukau source rocks of moderate quality, dominated by Type II-III kerogen, and perhaps also some deeper source in the Lower Miri shale and the associated sandstones. The Miri and Lambir formations are known to contain oil-prone kerogen as reported by Abdullah *et al*. (2011) and Tavakoli (2021). With a maximum burial of perhaps 3,000 - 4,000 m, these source rocks are at best marginally mature, and considering the relatively low geothermal gradient applied. Indeed, there is some evidence for charge from the Liku-Badas syncline: The Siwa field is a marginal oil discovery; JX Nippon´s well Miri East 1 X (Jong *et al*., 2017) reported wet gas shows; and some of the Sarawak Oilfields Ltd wells Buri and Riam, located in the Lambir Anticline encountered also minor amounts of immovable oil in poorly constrained traps. In a nutshell, there is proof of hydrocarbon charge, but the amount expelled may be insufficient in the context of an economic hydrocarbon accumulation.

CONCLUDING REMARKS

Following a period of sustained subsidence and continued sedimentation of shallow marine/brackish clastics, a pulse of faulting and folding affected the greater Miri area along wrench faults belonging to the Baram Line system. This led to partial uplift of the area, and the following anticlinal areas were impacted: (i) Siwa-Miri-Adong Kecil-Asampaya-Seria (partially uplifted only); (ii) Bungai-Lambir; (iii) Engkabang; (iv) Ngebol. Whilst the anticlines



Area/ Point	Type	Setap eroded, m	Miri/Lambir, eroded, m	Tukau, eroded, m	Total uplift, m
T-03-09	Syncline	0	0	2200	2200
L 3	Anticline	0	0	1850	1850
Bkt Song	Anticline	0	0	2500	2500
Lambir E	Anticline	0	300?	2700	3000
Lambir W (Bungai)	Anticline	100-250 m	1000 or more	2300	3700
FK 01	Syncline	0	0	2100	2100
FK 02	Syncline	0	0	2300	2300
Siwa Depression	2300 m Tukau	0	0	0	0
Engkabang	Anticline	200?	2000	1500 ?	3500
Miri Field	Hanging Wall	0	0	500	500
Canada Hill Miri	Foot Wall	0	2000	500	2500
Ngebol	Anticline	300?	600	2300	3200
Liku- Badas Syncline center	2700 m Tukau	0	0	?	130
Tudan	Edge syncline	0	0	100?	100?

Figure 16: Summary of uplift calculations and estimates.

rose, synclines were minimally affected by the tectonic movement, and only saw a Pleistocene-to-recent uplift in the order of 110-132 meters (Kessler, 2023). The magnitude of uplift in the Sarawak Foreland anticlines is addressed in a multidisciplinary approach, namely by assigning surface vitrinite reflectance measurements to depth by a regression curve, and by vitrinite reflectance-to-depth conversion using the Barker & Pawlewicz (1986) and Waliczek *et al.* (2021) functions. Additional erosion and uplift data were obtained by comparing eroded anticlinal crests with adjacent synclines, and the preserved sediment record within, in a mass-balancing effort. The combined data pool suggests the amount of uplift and erosion are directly linked to rise of anticlinal structures during the upper Pliocene, with total uplift/erosion ranging from 500 to 4,000 m. Within a very short time window, a major sedimentation phase, folding, trap formation, trap destruction and final erosion took place. Only anticlines in the offshore and in the coastal onshore escaped the tectonic movements without a major crestal erosion. The rapid Pliocene burial and the erosion that consequently removed the overburden in the other anticlinal areas may have negatively affected the petroleum system, specifically hydrocarbon charging and accumulation mechanisms. While all of these were targeted by petroleum exploration, only the Siwa-Seria trend has been proven to contain significant petroleum accumulations because the overburden and top seal remained at least partly intact. This has highlighted the significance of overburden thickness in relation to depth of burial and the thermal effect needed to mature the source rocks to generate and expel economical amounts of hydrocarbons.

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AUTHORS CONTRIBUTION

F-LK is the main author who prepared the manuscript and figures. WHA provided support on the aspect related to organic geochemistry. Both authors reviewed the results, did the interpretation and final write-up of the manuscript.

DECLARATION OF COMPETING INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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