

# Organic petrographic characteristics of the Crocker Formation, NW Sabah, Malaysia

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**Abstract:** The deep marine Crocker Formation in NW Sabah, Malaysia has been well studied in terms of sedimentology, stratigraphy and structural geology. However, not much is known about its potential as a petroleum source rock. This study partly addresses this subject by means of petrographic analysis to characterise the Crocker sediments in terms of its organic matter content and thermal maturity. Crushed rock samples mounted in resin blocks were examined under reflected white and ultraviolet light. Petrographic analysis indicates that the Crocker Formation samples have low phytoclast content (<2%). The mostly indigenous phytoclasts (microscopic plant fragments) can be divided into 4 groups based on their reflectance values; vitrinite with dark inclusions (lowest reflectance), vitrinite, oxidised vitrinite and inertinite (highest reflectance). These phytoclast groups exhibit a reflectance profile of 0.6, 0.8, 1.0 and 1.2%Ro respectively. Such an approach (measuring the reflectance of different phytoclast groups) can aid the petrographer to evaluate and validate vitrinite reflectance measurements in samples such as the Crocker that has a variable phytoclast assemblage. The average vitrinite reflectance is 0.82%Ro, which indicates that the Crocker sediments analysed were once buried to a depth of 4.1 km on average. Although its thermal maturity is within the oil generation window at present day, the Crocker Formation is considered a poor petroleum source rock because it is poor in phytoclast content (<2%) and appears to lack oil-prone liptinitic macerals. However, favourable source rock units could exist within the Crocker in the form of slump or mass-transport units, if the organic or phytoclast content is high enough and oil-prone organic matter is sufficiently present. Further geochemical analysis and regional data need to be incorporated for a more comprehensive analysis and assessment of the Crocker as a petroleum source rock and/or an analogue for subsurface geological units.

**Keywords:** Sabah, Crocker Formation, organic petrography, petroleum source rock

## INTRODUCTION

The Crocker Formation that outcrops in the NW Sabah coastal area has been extensively studied for more than half a century. In the last few years, a lot of work has been carried out to describe the characteristics of the Crocker Formation, particularly on its characteristics and suitability as a deepwater analogue for the deepwater turbidite petroleum reservoirs offshore NW Sabah. Most of the analyses carried out to date mainly cover the sedimentological, stratigraphic and structural aspects, whereas the petroleum geochemistry and petroleum systems aspects are very limited.

The hydrocarbon generating potential of the various facies (e.g. carbonaceous turbidite sands, deepwater shales, mass transport deposits) available in the Crocker Formation outcrops have not been subjected to detailed petroleum geochemistry study. Related data from the various fieldwork carried out by oil and gas companies operating in the region, if any, are not readily available to the general public.

This study will provide some insight into the characteristics of the Crocker Formation derived from petrographic analysis on 23 samples of various lithologies, including sandstones, siltstones, mudstones and 1 'scaly clay matrix' (melange) sample, all collected from quite an extensive area (Figure 1). The lithological descriptions of these samples are shown in Table 1.

The emphasis of the analytical data presented in this paper is on the organic matter (phytoclast) content and thermal maturity of the sediments. It is hoped to answer

**Table 1.** Lithological description of the Crocker Formation samples analysed in this study.

No.	Sample ID	Lithological description
1	26-05-07-B	Dark grey silty mudstone
2	26-05-07C	Structureless dark grey mudstone
3	26-05-E	Structureless dark grey mudstone
4	26-05-F	Dark grey siltstone, very compact
5	26-05-G1	Fine laminated sandstone, carbonaceous laminae 2-3 mm apart
6	26-05-H	Structureless dark grey mudstone
7	26-05-I	Fine sandstone, well sorted
8	27-05-C	Structureless dark grey mudstone
9	27-05-E	Fine yellowish sandstone, well sorted
10	27-05-K	Structureless dark grey mudstone
11	27-05-L	Fine laminated sandstone, cut by quartz (?) veins
12	27-05-M	Structureless dark grey silty mudstone
13	27-5-F	Structureless dark grey mudstone, slightly reddish/brownish
14	27-5-I	Structureless dark grey mudstone
15	27-5-J	Fine-medium sandstone + carbonaceous sandstone
16	28-05-A	Light grey siltstone
17	28-05-E	Fine yellowish sandstone, well sorted
18	28-5-D	Structureless dark grey mudstone, appears to have some preferred texture orientation
19	29-5-A	Scaly clay matrix (melange)
20	29-5-B	Structureless dark grey mudstone
21	29-5-C	Dark grey silty sandstone
22	29-5-D	Dark grey mudstone, slightly lustrous
23	29-5-E	Fine light grey structureless sandstone

some of the questions on the petroleum generating potential of the Crocker Formation or equivalent/similar units or facies. Such data might also provide some clues on the characteristics of the actual source rock intervals contributing to the hydrocarbon accumulations offshore NW Sabah.

The analysis was carried out at the Geology Department, Faculty of Science, University of Malaya in Kuala Lumpur, Malaysia.

## GENERAL/REGIONAL GEOLOGY

The term Crocker Formation was first introduced by Collenette (1957) to describe the sedimentary rocks on which the Crocker Range in NW Sabah is built. Bowen & Wright (1957), in Liechti *et al.* (1960), divided it into the East and West Crocker Formations. In this paper, the term “Crocker Formation” is used whenever possible to refer to both subdivisions. The terms West and East Crocker Formation will only be mentioned when referring to previous published work. The differences between these two Crocker sub-divisions will not be discussed here.

The Crocker Formation that outcrops in the NW coastal area of Sabah forms the landward margin of the Greater Sabah Basin, which consists of the Inboard Belt, Baram Delta, Outboard Belt and Thrust Sheet areas (Figure 2). A detailed onshore geological map is also shown in Figure 3. The Crocker Formation is considered part of the 25,000 km<sup>2</sup> Crocker Fan system that extends from Padas Valley to the northern tip of Sabah (Crevello, 2002).

The West Crocker Formation consist mainly of coarse-grained sandstones interbedded with shale (William *et al.*, 2003). This formation is classified as turbidite deposits and considered an unattractive exploration target due to its poor quality reservoir sands and lack of hydrocarbon (Crevello, 2002). However, recent studies also suggest that the West Crocker Formation is not entirely turbidites but includes debris flows, slumps and submarine transport deposits (Bakar *et al.*, 2008a, 2008b).

The NE-SW trending elongated basin in which the West Crocker sediments were deposited was created by the perpendicular NW-SE compression in the Late Cretaceous-Early Eocene, and is related to the opening of the Southwest sub-basin of the South China Sea Basin (Tongkul, 1994). The sediments were probably derived from the south, as indicated by consistent northwards palaeocurrent direction (William *et al.*, 2003). An eastward source is considered unlikely, as it is insufficient for the Crocker Formation and Rajang Group (Crevello, 2002). More recent studies point to a local or nearby source for the Crocker Fan (Hall, 2002; Hall & Morley, 2004; van Hattum *et al.*, 2006) in contrast to earlier publications that suggested a source from mainland Asia (Hall, 1996; Hamilton, 1979; Hutchison, 1996; Métivier *et al.*, 1999).

The Crocker Formation is Upper Eocene-Oligocene in age (van Hattum *et al.*, 2006). In the Sipitang, Beaufort and Tenom Gorge area, an Oligocene-Lower Miocene age was recorded (Hutchison, 2005). The unconformity at the base of the Crocker Fan is attributed to the Eocene Sarawak

Orogeny (Hutchison, 1996). The thickness of this formation is estimated to be not less than 6,000 m (Lee *et al.*, 2004). The stratigraphic position of the Crocker Formation in relation to the other geological units is shown in Figure 4.

## METHODOLOGY

### Sample preparation

The clastic sedimentary rock samples were dried and crushed to approximately 2-4 mm in size using a porcelain mortar and pestle. The crushed samples were then mounted and let to harden in resin. The hardened resin blocks containing the sample were then gradually polished with abrasive paper and liquid alumina until a smooth and near scratch-free surface was produced. Isopropyl alcohol (2-propanol) was used as lubricant throughout the polishing process.

### Petrographic and reflectance analysis

The polished resin blocks containing the samples were analysed under oil immersion using a Leica DM600M petrographic microscope under normal white and ultraviolet reflected light at 50x objective magnification.

The amount of the different phytoclasts (microscopic plant fragments) and other components observed were estimated with the aid of volume percentage estimate charts. Calibration for reflectance measurements was carried out on a sapphire standard that has a reflectance value of 0.589% under oil immersion. Parts of phytoclasts that were relatively homogenous and free from contaminants were subjected to reflectance measurements. Reflectance measurements were carried out on all suitable phytoclasts, not just the typically measured vitrinite. Reflectance measurements are reported as %Ro (% of reflectance under oil immersion).

### Estimation of maximum burial temperature and depth

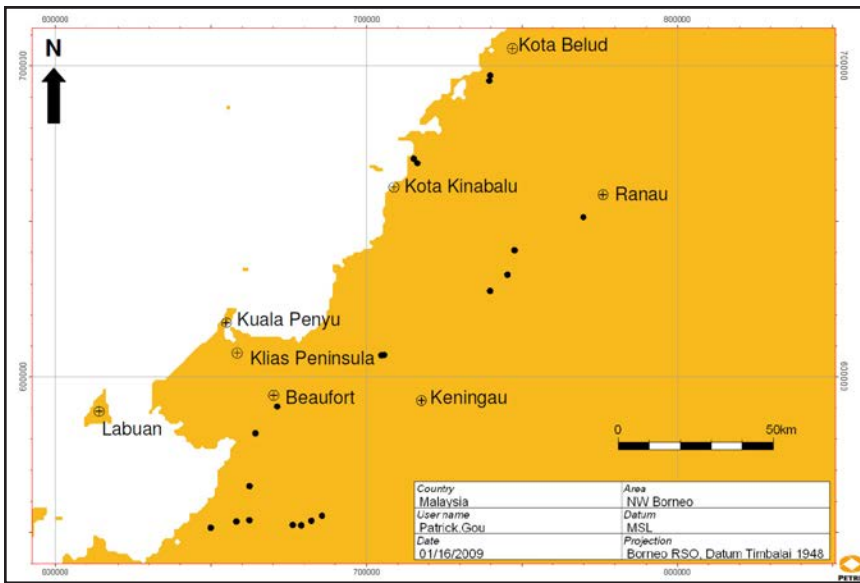
Vitrinite reflectance data was used to derive the maximum burial temperatures that the rock and phytoclasts were subjected to, using the equation of Barker & Pawlewicz (1986), in Allen & Allen, (2005). This is shown as follows:

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

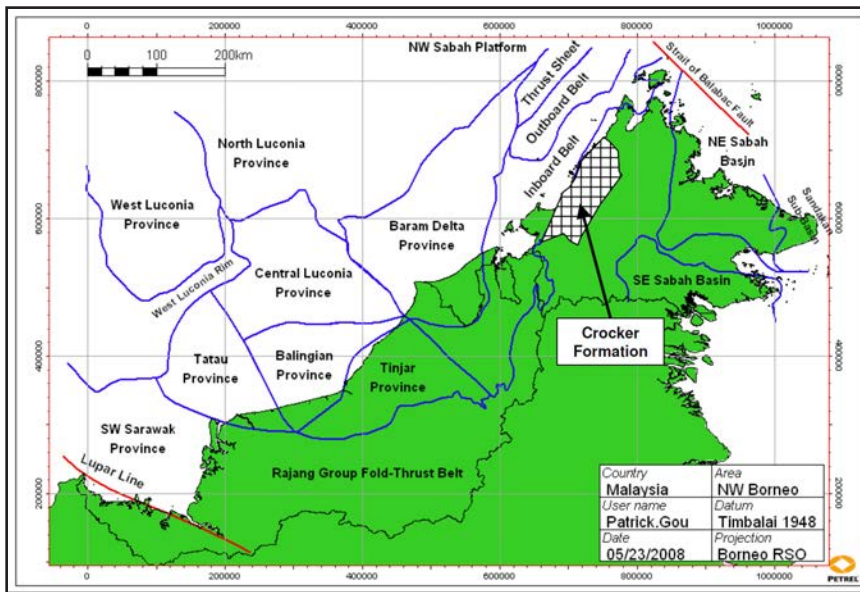
Subsequently, the maximum burial depth (in km) is estimated by dividing the difference between the maximum burial and surface temperatures (in  $^{\circ}\text{C}$ ) with the geothermal gradient (in  $^{\circ}\text{C}/\text{km}$ ).

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

This maximum burial depth is equivalent to the thickness of eroded section as all of the samples collected are at the surface at present day. A surface temperature of  $10^{\circ}\text{C}$  is assumed, which is probably close to the sea bottom temperature when the deepwater Crocker Formation was deposited. If a higher surface temperature is used, the



**Figure 1:** Location of samples analysed in this study are marked as dark circles. Samples were collected from areas mapped as the Crocker Formation. Coordinates are in metric metres.



**Figure 2:** Sedimentary basin of Sabah and Sarawak. The approximate boundary of the Crocker Formation (including the East and West Crocker) is marked by the polygon with square patterns. Basin boundaries traced from PETRONAS (1999).

**Table 2.** Estimation of maximum burial depth or thickness of eroded section of the Crocker samples from vitrinite reflectance data. The equation used to estimate maximum burial temperature are from Barker & Pawlewicz (1986), in Allen & Allen, (2005). A surface temperature of 10°C was assumed.

Sample ID	Vitrinite reflectance (%Ro)	Maximum burial temperature (°C)	Maximum burial depth/thickness of eroded section (km)								
			Geothermal gradient (°C/km)					Minimum	Mean	Maximum	Standard deviation
			19	25	30	35	40				
26-05-G1	0.864	130.64	6.3	4.8	4.0	3.4	3.0	3.0	4.3	6.3	1.3
27-05-C	0.760	117.25	5.6	4.3	3.6	3.1	2.7	2.7	3.9	5.6	1.2
27-05-K	0.858	129.88	6.3	4.8	4.0	3.4	3.0	3.0	4.3	6.3	1.3
29-5-C	0.895	134.28	6.5	5.0	4.1	3.6	3.1	3.1	4.5	6.5	1.4
27-05-L	0.775	119.28	5.8	4.4	3.6	3.1	2.7	2.7	3.9	5.8	1.2
27-5-J	0.784	120.46	5.8	4.4	3.7	3.2	2.8	2.8	4.0	5.8	1.2
Minimum	0.76	117.25	5.6	4.3	3.6	3.1	2.7	-	-	-	-
Mean	0.82	125.30	6.1	4.6	3.8	3.3	2.9	-	-	-	-
Maximum	0.90	134.28	6.5	5.0	4.1	3.6	3.1	-	-	-	-
Standard deviation	0.06	7.14	0.4	0.3	0.2	0.2	0.2	-	-	-	-

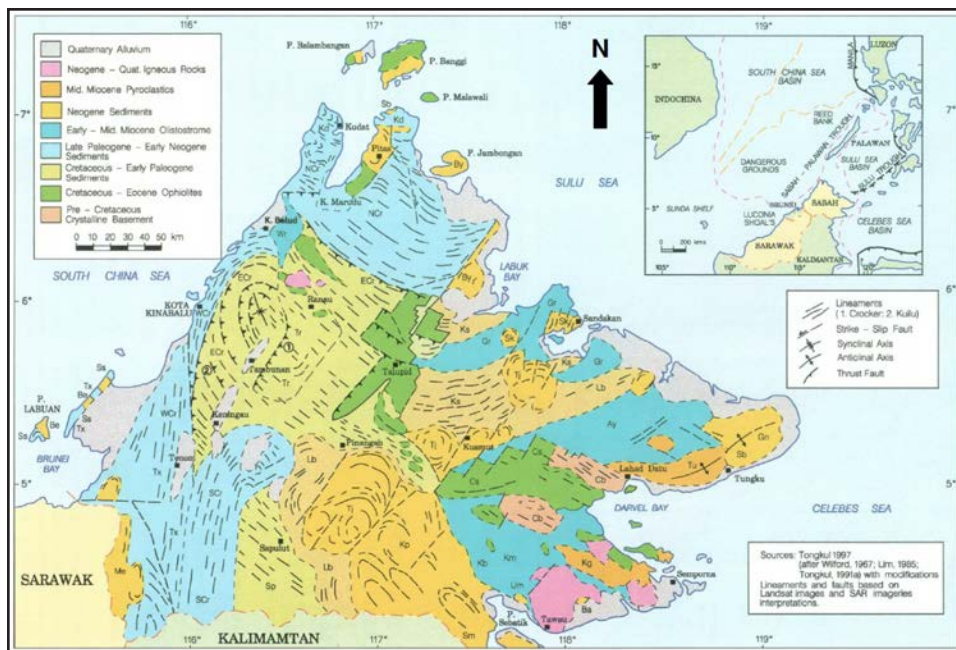


Figure 3: Geological and tectonic map of Sabah (modified after Tongkul, 1994; 1997, in PETRONAS, 1999). Samples were collected from the Crocker Formation, which includes the West (WCr) and East (ECr) Crocker sub-divisions.

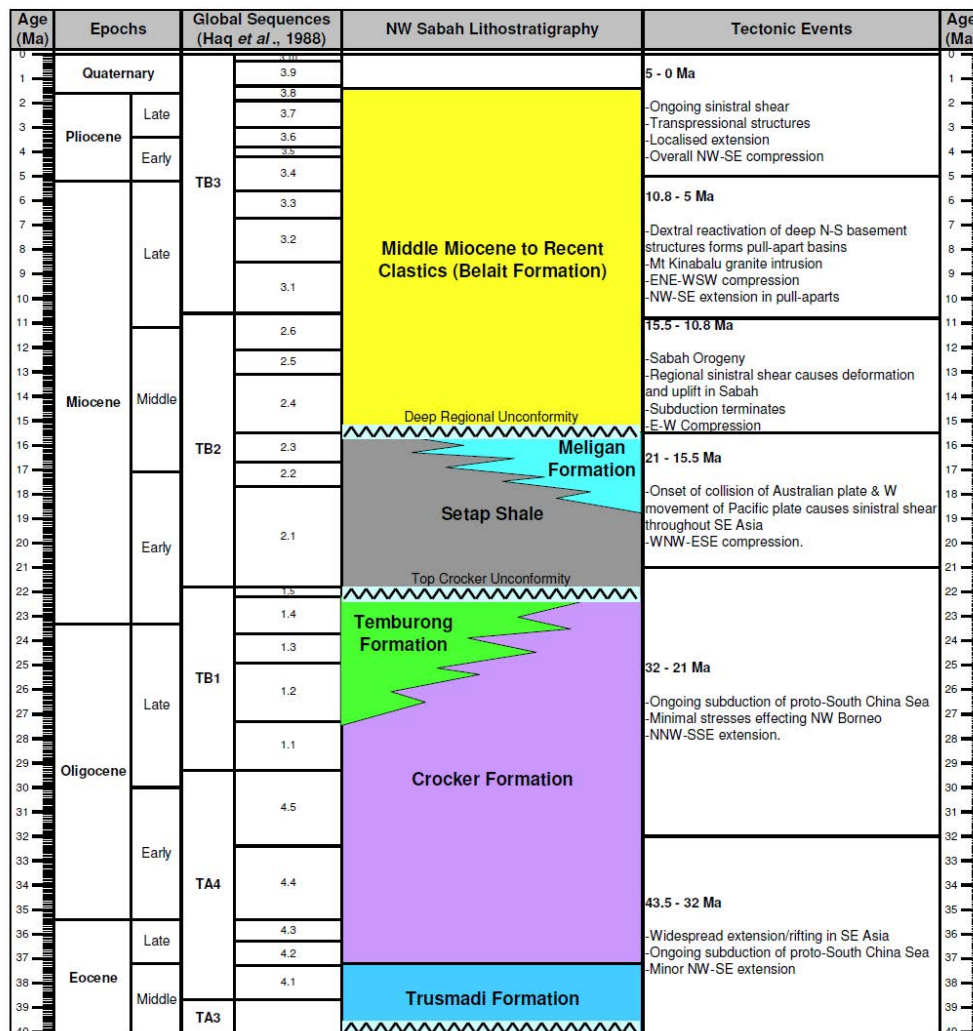


Figure 4: North Sabah stratigraphy. Modified after Morrison & Wong (2003) and van Hattum et al. (2006).

calculated burial depth will be less, as a similar burial temperature will then be encountered at a shallower depth.

## RESULTS AND INTERPRETATION

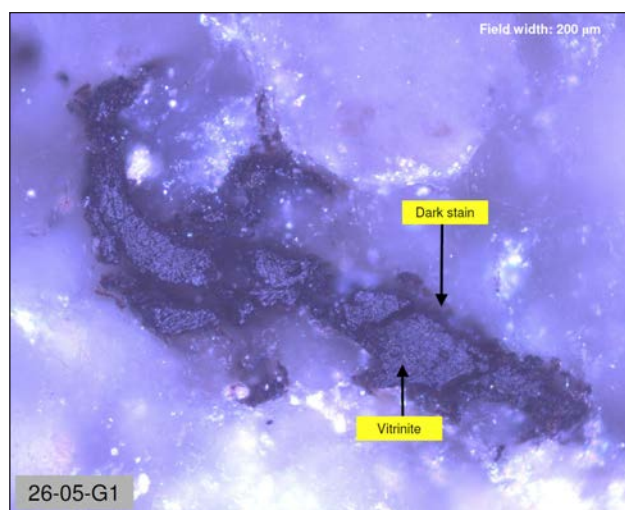
### Petrographic description of Crocker Formation samples

The petrographic analysis reveals that the Crocker Formation samples contain 2% or less (by volume) of phytoclast/visible organic matter. Only 2 out of the 23 samples did not have any phytoclasts. Most of the phytoclasts are sub-angular to angular in shape, with sizes between 10 and 30  $\mu\text{m}$  most common. In one carbonaceous sandstone sample, the phytoclasts are as large as 200  $\mu\text{m}$ . Most of the phytoclasts are indigenous, based on the existence of weak dark/brownish staining that rims them. This stain might be bitumen, but examination under UV light did not produce the typical fluorescence commonly associated with strong bitumen or hydrocarbon stains. An example of indigenous vitrinite phytoclast seen in the Crocker samples is shown in Figure 5.

The classification of the phytoclasts into maceral groups (i.e. vitrinite, inertinite and liptinite) is challenging due to their very small size, low abundance and oxidised nature of some. Phytoclast identification could only be made with a reasonable level of certainty at maceral group level (vitrinite, inertinite and liptinite). More detailed maceral classification is difficult or impractical for the purpose of this study.

More than half of the samples analysed have the vitrinitic phytoclasts as the major phytoclast constituent (Figure 6). Only one of the samples (28-5-D) has a phytoclast composition that is totally made of high-reflecting inertinites. Liptinitic oil-prone macerals were not observed in any of the samples. Even so, there is a possibility that the minute dark inclusions observed within vitrinite phytoclasts are liptinitic macerals (e.g. resinite). However, due to the lack of fluorescence or other liptinite characteristics, these inclusions will be referred to as 'dark inclusions' in this article. Further supporting analysis (e.g. Fourier Transform Infrared Spectroscopy or FTIR) is required to ascertain their true compositions.

Pyrite is seen in most of the samples in quantities of 1% or less. About half of the samples analysed have framboidal pyrite, which occurs as globular particles (see Figure 7). One hypothesis to explain the globular framboidal pyrite occurrence is surface tension effects; certain bodies like fluids tend to exist as spheroids that have minimum surface areas (Butler *et al.*, 2000). Laboratory experiments have demonstrated that framboidal pyrite forms directly via the oxidation of  $\text{FeS (aq)}$  by  $\text{H}_2\text{S}$  in the absence of molecular  $\text{O}_2$ , magnetic intermediates or biological intervention (Butler & Rickard, 2000). However, it is still unclear if the framboidal pyrites seen in the Crocker samples could be precipitated by a mechanism where fluid (hydrocarbon) droplets serve as nucleation sites. Framboidal pyrite formation has also been linked to pyritisation of individual bacterial and bacterial colonies (Schneiderhohn, 1923; Love, 1957, in Butler & Rickard, 2000), or on organic particles or colloids (Papunen,



**Figure 5:** Example of angular-subangular indigenous vitrinite seen in the Crocker Formation. A (slight) dark stain rims it.

1966; Kalliokoski & Cathles, 1969; Kribek, 1975; Raiswell *et al.*, 1993, in Butler & Rickard, 2000).

### Reflectance measurements of phytoclasts

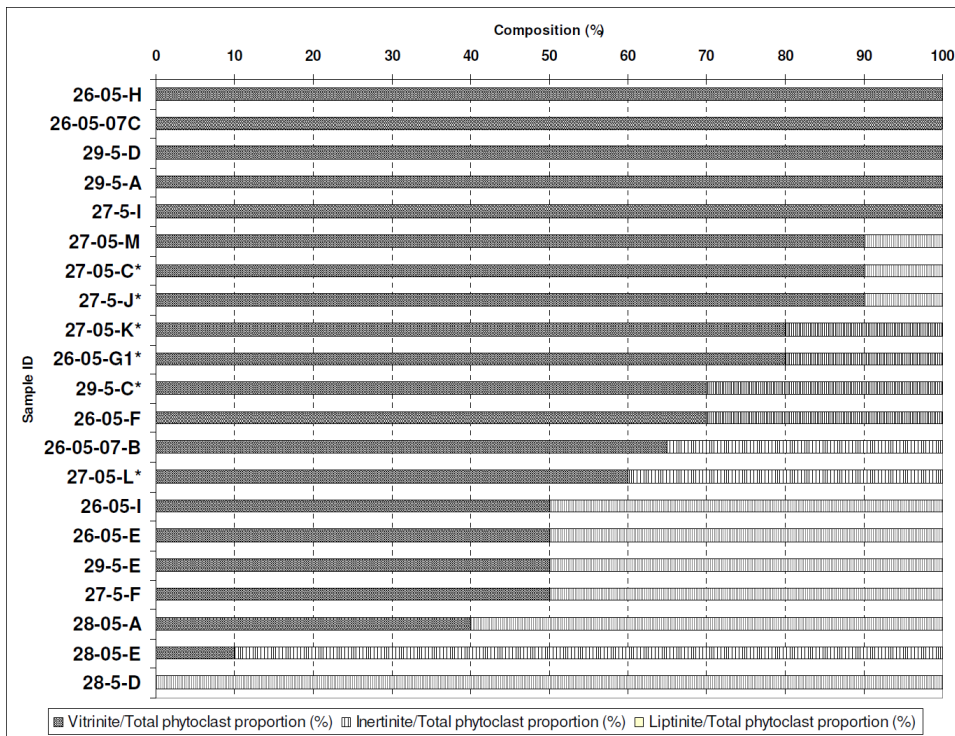
Most of the phytoclasts are poor for reflectance measurements. Only 6 of the 23 samples contain the type of phytoclasts on which reflectance measurements were possible. All of the vitrinite reflectance measurements are considered to be of poor to moderate quality. Nevertheless, the measured values seem reasonable, as they are quite consistent. The mean vitrinite reflectance was 0.82%Ro with a standard deviation of 0.06%Ro from 34 measurements. This suggests that the samples analysed were subjected to very similar temperature regimes throughout their history. This also supports the interpretation that they all belong to the same stratigraphic unit with comparable burial histories.

Other phytoclasts were also measured. Based on the reflectance values and their distribution, it is possible to classify the phytoclasts into 4 different groups, as follows:

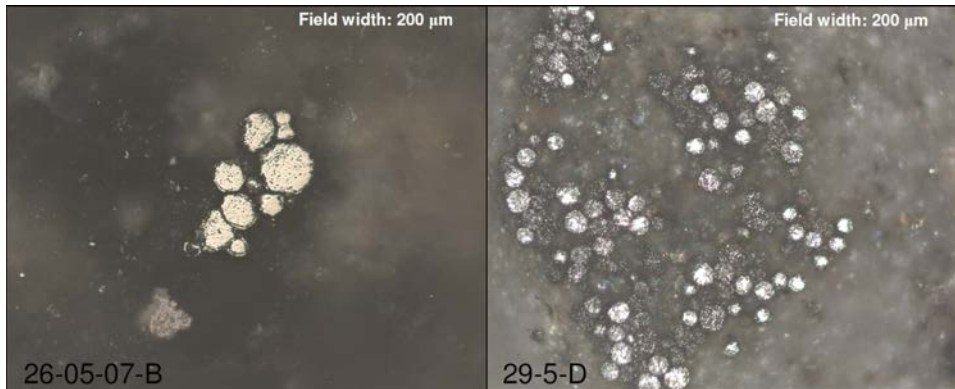
- Vitrinite with dark inclusions: Average reflectance of 0.64%
- Vitrinite: 0.82% (this is the 'normal' type of vitrinite conventionally measured)
- Oxidised vitrinite: 1.02%
- Inertinite: 1.25%

This overall reflectance distribution is illustrated in Figures 8 and 9. It is also noted that the standard deviations of reflectance measurements are slightly higher for the 2 end members (vitrinite with dark inclusions: 0.08%Ro, inertinite: 0.09%), as compared to 'normal' vitrinite. This is probably due to the increased variability and heterogeneity in these 2 end members and/or simply the relatively lower number of reflectance measurements made on them. Figure 10 shows the photomicrographs of the 4 different phytoclasts that were measured for reflectance.

The reflectance values were also analysed by sample ID (Figure 11) to see how the samples compare in their 4-phytoclast reflectance profile. Clearly, the different



**Figure 6:** Maceral group (vitrinite, inertinite and liptinite) composition of the Crocker samples. All of the samples are sandstones, mudstone or siltstones, except sample 29-5-A which is a tectonic melange (scaly clay matrix) deposit. Samples marked ‘\*’ were selected for reflectance measurements. Phytoclasts were not observed in 2 of the 23 samples.



**Figure 7:** Globular framboidal pyrite in the Crocker Formation samples.

phytoclasts groups for each sample exhibit a “0.6 – 0.8 – 1.0 – 1.2” reflectance profile, starting with vitrinite with dark inclusions (lowest, 0.6%Ro) to inertinite (highest, 1.2%Ro).

**DISCUSSION**

**Reflectance measurement values of various phytoclast groups**

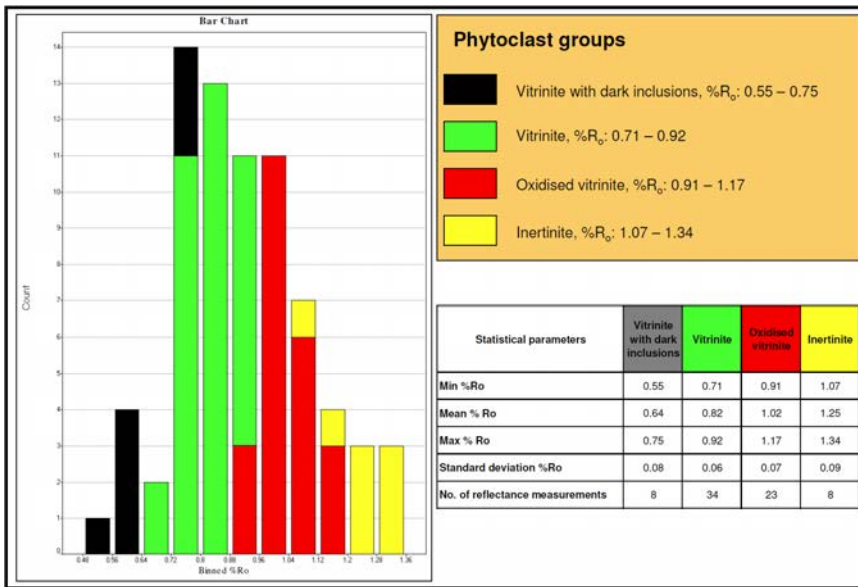
From the reflectance analysis, it was discovered that samples that contain abundant vitrinite phytoclasts did not necessarily provide optimum macerals for reflectance measurements. Large vitrinite phytoclasts sometimes give erratic readings even when the measurements were made on the same piece of phytoclast, due to their internal texture (e.g. pitting) and presence of inclusions. On the other hand, oxidised vitrinite and inertinite tend to have smoother and more homogenous surfaces. This is probably attributed to their mechanical character that is relatively harder and less brittle.

For that reason, it is proposed in this study that reflectance measurements on a sample like the Crocker

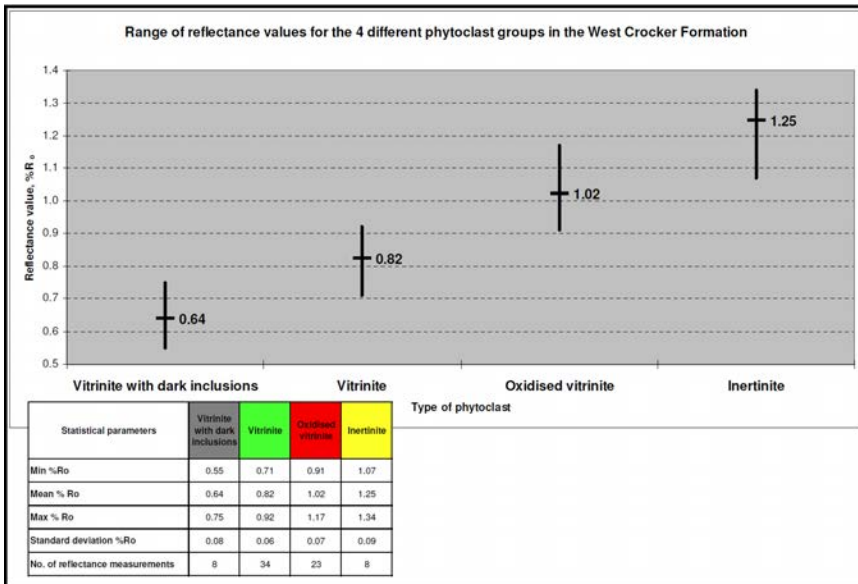
Formation have to include all the different types of phytoclasts. It is only when the measured reflectance data are compiled and statistically analysed could one come to the conclusion on the number of phytoclast populations in the sample before assigning them to their respective maceral groups with greater confidence.

Such an approach was found to be useful to validate the reflectance measurements that are of primary interest, i.e. vitrinite reflectance, especially in a sample where the difference between ‘normal’ vitrinite and vitrinite with dark inclusions or oxidised vitrinite are marginal. For the Crocker samples, it is observed that the difference in reflectance measurements between the 4 phytoclast groups are a constant 0.2%; vitrinite with dark inclusions and oxidised vitrinite are 0.2% lower and higher respectively compared to ‘normal’ vitrinite, while inertinite is 0.2% higher in reflectance than oxidised vitrinite. Figures 9 and 11 illustrate this relationship.

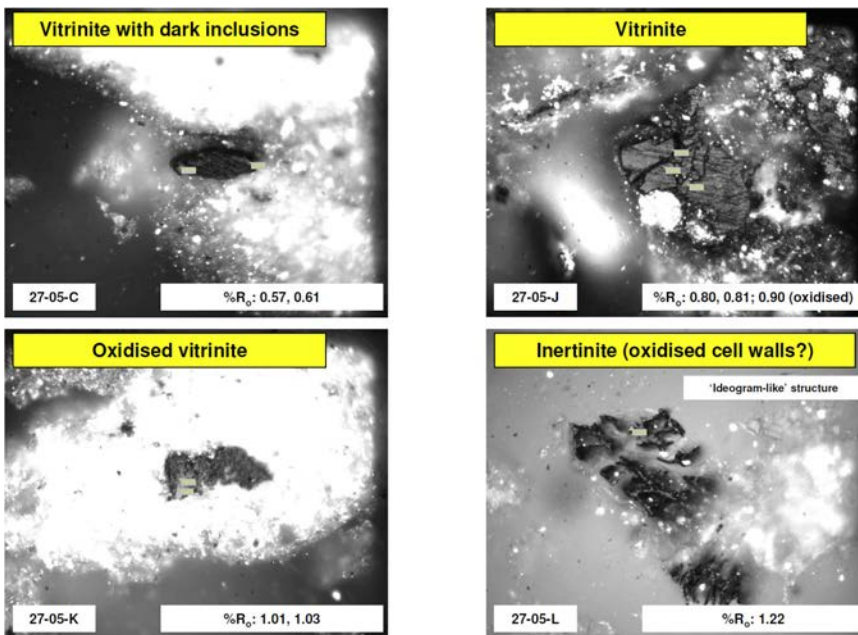
There are some overlaps in the range of reflectance values for the 4 different phytoclast groups. These again illustrate the difficulty in using traditional approaches



**Figure 8:** Distribution of reflectance measurements from the Crocker Formation by phytoclast group. 73 measurements were made altogether.



**Figure 9:** Range of reflectance values across the 4 different phytoclasts types in the Crocker Formation.



**Figure 10:** Four different types of phytoclast observed in the Crocker Formation. They are classified by their reflectance values measured under oil immersion. The reflectance values measured in each photomicrograph are listed at the bottom right corner. Field width is 200 µm.

when analysing a sample with low phytoclast abundance but variable phytoclast types like the Crocker. It is also an indication that one can easily misidentify a phytoclast especially when it has a reflectance that lies on the 'borderline.' Nevertheless, when the reflectance data is plotted as a histogram to show the reflectance distribution, the number of phytoclast populations that exist in the sample become more evident. From the same histogram, one could also specify at what reflectance values a phytoclast can be assigned to a group with greater confidence.

The next step is to test if the reflectance profile described can also be observed in other Crocker outcrops and different formations of equivalent age and geology in the area and region, particularly the North (NCR) and South Crocker (SCR) Formations, as shown in Figure 3.

### Estimation of maximum burial depth and amount of erosion from vitrinite reflectance data

Regional offshore data indicate that the geothermal gradient in the NW Sabah Basin at present day range between 19 and 40°C/km (The International Heat Flow Commission, 2008). The geothermal gradient from the nearest offshore well measurement to where the Crocker outcrops in NW Sabah is 36°C/km (see Figure 12). The extrapolation of these offshore well data into the onshore areas of NW Sabah suggests that the geothermal gradient is higher than 36°C/km onshore. However, this extrapolation of geothermal gradient has to be handled with caution, as there are no calibration points in the NW Sabah coastal area.

For the estimation of maximum burial depth or eroded section thickness, several geothermal gradient scenarios ranging from 19 to 40°C/km were considered to cater for the huge uncertainty in the thermal regime of the area. Table 2 shows the predicted maximum burial depths or eroded section thickness of the Crocker sediments, calculated from vitrinite reflectance measurements and derived maximum burial temperatures, using the relationship described by Barker & Pawlewicz (1986), in Allen & Allen, (2005).

Based on 6 average vitrinite reflectance measurements and 5 geothermal gradient scenarios, 30 different possible maximum burial depths/thicknesses of eroded sections were calculated. A surface temperature of 10°C was assumed. The estimated amount of eroded section of the Crocker sediments range from 2.7 to 6.5 km for the geothermal gradients between 19 and 40°C/km. The standard deviation of the predicted eroded section thickness for all of the samples for each geothermal gradient scenario are less than 0.5 km. In contrast, for similar samples the standard deviations range between 1.2 and 1.4 km when different geothermal gradients are applied. This implies that the geothermal gradient used in the calculations has a bigger influence on the predicted maximum burial depths or thickness of eroded sections; variations in vitrinite reflectance measurements itself have a lesser impact.

These estimations imply that it is quite likely that on average, 4.1 km of sediments were eroded before the present day Crocker Formation was exposed to its present

configuration. The uncertainty is quite large though with a standard deviation of 1.17 km (based on the 30 predicted values). The data in Table 2 is illustrated in Figure 13.

### The Crocker Formation as a petroleum source rock

Although the maturity indicated by average vitrinite reflectance (0.82%Ro) puts the Crocker Formation within the oil generation window and close to the peak oil generation stage at present day, no indicators of hydrocarbon could be observed petrographically. The low (2% or less) phytoclast content makes the Crocker Formation unfavourable in terms of organic matter quantity.

Even if it had generated hydrocarbons, gas instead of oil would be the main hydrocarbon generated, due to the absence of liptinitic material that is more prone to produce liquid hydrocarbons like oil. Nevertheless, the possibility of liquid hydrocarbon generation at an earlier stage of burial cannot be totally discounted as liptinitic macerals might have been depleted by the generation of oil itself. Similarly, the absence of bitumen fluorescence under UV light excitation might be due to the maturity of the sediments that are within the oil generation window at present day.

However, isolated sedimentary units, such as the debris flow shales in the West Crocker Formation can be enriched in organic matter (Total Organic Carbon or TOC) as high as 68.62% (Anuar *et al.*, 2003). However, the quality and type of organic matter were not mentioned in that article. More in-depth analysis is needed as the role and contribution of slump and mass-transport sediments as petroleum source rocks has generated some interest recently, as they could partly explain the transport of land plant organic matter from the delta or shallow marine areas into deeper waters. Such transport mechanisms have been proposed by Longley (2005) for NW Borneo, while Gee *et al.* (2007) have described a massive landslide from seismic data in neighbouring offshore Brunei that was estimated to involve sediment movement by gravity of 30 to 120 km.

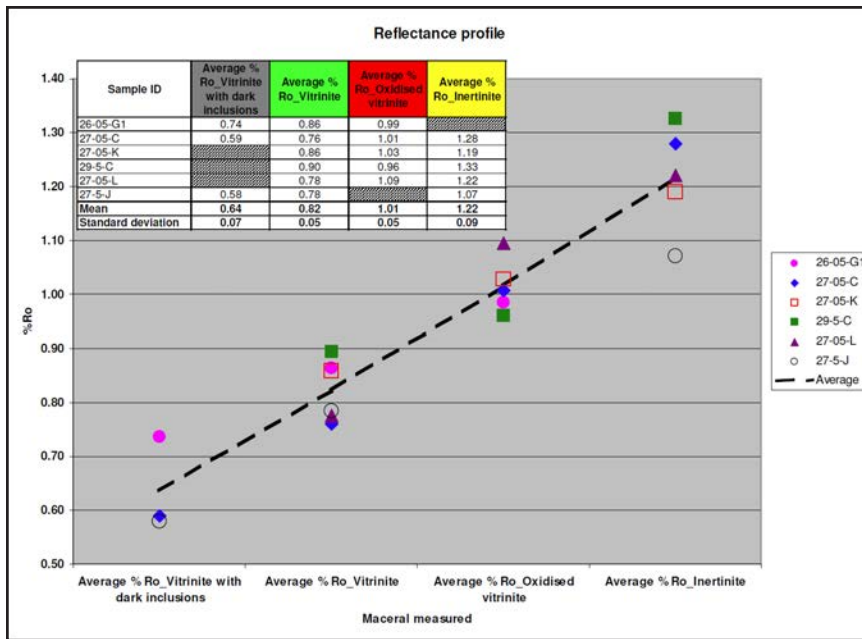
The vitrinite reflectance values of the Crocker Formation presented in this study are lower than preconceived by many, as it is generally thought to be thermally overmature. This could make the Crocker a potentially good analogue for source rock layers offshore NW Sabah that have a similar facies and are within the oil generation stage.

### RECOMMENDATIONS FOR FURTHER RESEARCH

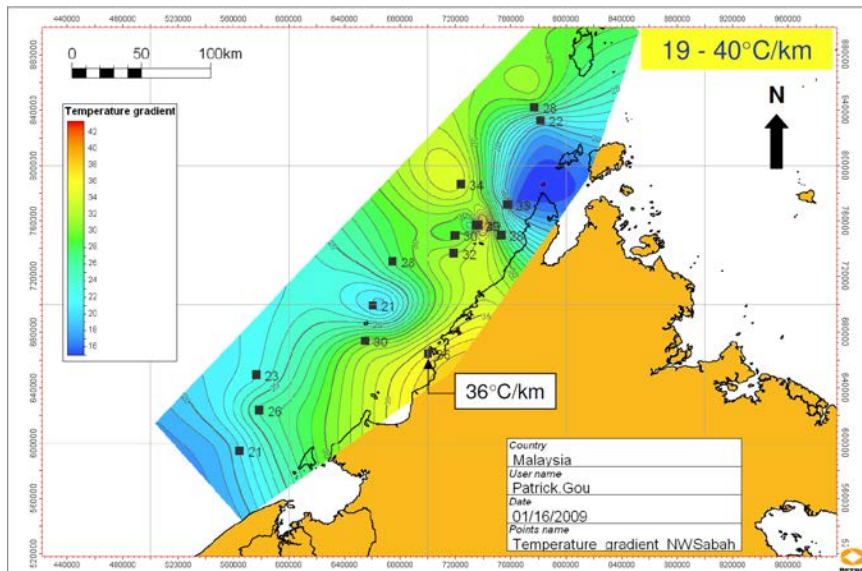
This study would benefit from detailed geochemical characterisation of the organic matter that could be derived from analysis such as Rock-Eval, FTIR (Fourier Transform Infrared Spectroscopy) and GC-MS (Gas Chromatography-Mass Spectrometry). However, such analysis can only be optimised by sampling specific organic-rich layers, which was not the main objective of the fieldwork from which the samples came from.

Ultimately, the onshore outcrop data has to be compared with offshore subsurface data (e.g. core and well

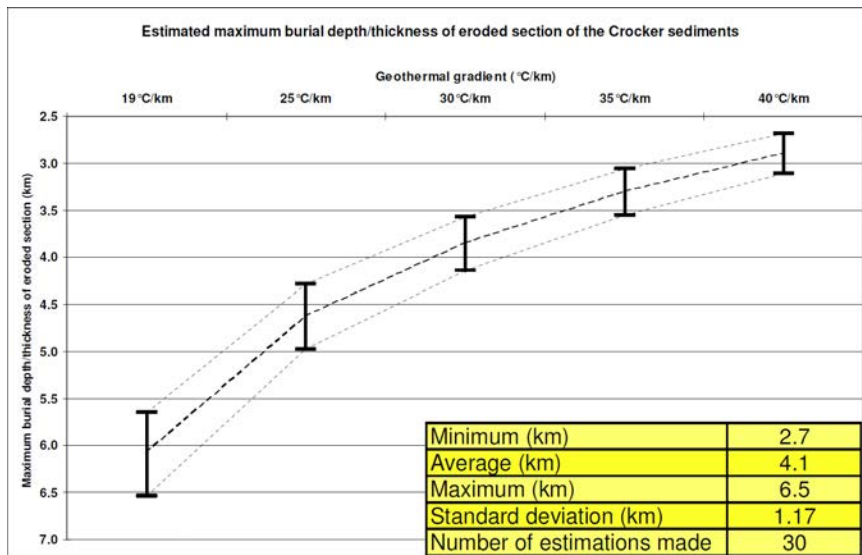




**Figure 11:** Average reflectance profile for the Crocker Formation, plotted by sample ID. A reflectance profile of “0.6 - 0.8 - 1.0 - 1.2” is observed for the 4 groups of phytoclast. The dashed line represents the average reflectance profile.



**Figure 12:** Geothermal gradient map for the NW Sabah Basin. Map gridded with data from the International Heat Flow Commission (2008). The nearest well measurement indicates a gradient of 36°C / km for the NW Sabah coast, where most of the Crocker Formation outcrops.



**Figure 13:** Range of estimated maximum burial depth/thickness of eroded section derived from vitrinite reflectance data and calculated maximum burial temperatures. Geothermal gradients between 19 and 40°C / km were considered to estimate the final maximum burial depth/thickness of eroded section. A surface temperature of 10°C was assumed.

cutting samples) to establish if certain correlations can be established. Only then one could make a better decision whether the onshore outcrop data is a suitable analogue for the petroleum systems in the NW Sabah offshore area.

### CONCLUDING REMARKS

Petrographic analysis reveals that the Crocker Formation samples analysed are low in organic matter content, judging by their low phytoclast content (<2%). Most of the phytoclasts are indigenous and can be classified into 4 groups based on their reflectance values (vitrinite with dark inclusions, vitrinite, oxidised vitrinite and inertinite).

Six of the samples provided reflectance measurements of poor to moderate quality. The average vitrinite reflectance of 0.82%Ro puts the Crocker Formation within the oil generation phase. The Crocker Formation as a whole has a reflectance profile of 0.6, 0.8, 1.0 and 1.2%Ro for the 4 different phytoclast groups; vitrinite with dark inclusions (lowest), vitrinite, oxidised vitrinite and inertinite (highest). The reflectance measurements on the various phytoclast groups were found to be useful to evaluate and validate vitrinite reflectance measurements in samples such as the Crocker that has a highly variable phytoclast assemblage.

Liptinitic macerals were not observed, although dark inclusions seen within some of the vitrinite phytoclasts could be liptinite (resinite) that do not fluoresce intensely under UV light as they might have undergone changes during earlier hydrocarbon generation. Weak bitumen staining was observed around indigenous phytoclasts, but no other direct indicators of hydrocarbon could be identified from petrographic analysis. Framboidal pyrites that might represent remnants of hydrocarbon globules are commonly seen, although the total pyrite content is always less than 1%.

An average of 4.1 km of sediments that once overlaid the Crocker Formation were eroded, based on the vitrinite reflectance and derived maximum burial temperature data. However, this could range between 2.7 and 6.5 km, depending on the geothermal gradient used in the calculations.

Because of its low organic matter content (judging by the amount of phytoclasts) and lack of macerals usually associated with liquid hydrocarbon generation, the Crocker is considered as a poor/insignificant petroleum source rock. On the positive side, its present day maturity falls within the hydrocarbon generation window. To find and solve the remaining piece of the puzzle, geological facies in the Crocker Formation (such as slump or mass transport deposits) that might have features absent in the current set of samples (high organic and oil-prone organic matter/macerals content) need to be found, studied and analysed.

Further integration with other methods of geochemical analysis and regional data, including subsurface offshore data is required to further validate and improve the findings described in this study.

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