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Deep Marine Turbiditic Belaga Formation of Late Cretaceous–Late Eocene in Central Sarawak, Malaysia: Implications for Sediment Transport and Distribution of Total Organic Carbon (TOC)

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Abstract

Turbiditic black shale samples were collected from the fresh road-cuts and outcrops of Late Cretaceous to Late Eocene Belaga Formation of Rajang Group from Central Sarawak, East Malaysia. The samples were analyzed for their total organic content (TOC) using Eltra CS800 (Carbon-Sulphur determinator). The main objective of this study is to categorize and pinpoint the distribution of organic matter content for these deep marine turbiditic shales and to relate them with the depositional setting. The results show that the overall values of TOC for all five members of the Belaga Formation range from 0.14 to 7.22 wt%. Sandy or silty fine-grained shales have low values of total organic content, while higher values are recorded in blackish finer-grained mudstone/shale beds. In Layar Member, for shales belonging to the distal plain or lobe fringe environment, the TOC values vary from 0.29 to 1.39 wt%. For Kapit Member, which belongs to the distal lobe or distal lobe fringe, with few having features matching to that of crevasse splay deposits, the range of TOC values is from 0.14 to 2.37 wt.%. The samples from the Pelagus Member displayed a greater and broader range of TOC values ranging from 0.32 to 7.22 wt.%. Owing to the fact that the sediments went through a large distance during the phase of transportation prior to deposition, which resulted in the low TOC values of the studied samples. Furthermore, oxidation of the organic matter occurs by the transport of sediments through long-shore waves or turbidity flows. Low-energy sediments have a higher organic carbon preservation potential. The TOC values from older stratigraphic members toward younger members are declining considerably, which suggests a corresponding decrease in organic content, respectively. It is suggested that the lower preservation potential of organic matter could also be related to the Eocene volcanic activity in Sarawak.

Keywords: *Turbiditic black shales; Total organic carbon; Late Cretaceous-Late Eocene; Belaga Formation; Rajang Group; Central Sarawak.*

1. Introduction

Fine-grained sediments, with a large amount of organic matter (OM), that has the capability to generate commercial hydrocarbons, are known as the source rock for the reservoir [1-2]. Over the past decades, the paradigm has been shifted towards organic-rich sediments, as they are the main component of hydrocarbon source-reservoir systems [3-6]. Therefore, the initial analysis of the source rock and its characteristics are required to define an area of hydrocarbon generation. The primary criterion for deciding whether a source rock will contain oil, coal, or condensate is thermal maturity. To study the hydrocarbon generation, source rock evaluation is important in terms of organic matter with quality, and richness that is influenced by the composition and concentration of organic matters [7-8]. The geochemical analysis in the petroleum sector is used as the basic science for understanding the properties of source rocks, to identify productive and non-productive areas, oil migration (all resulting in more effective exploration), oil field growth, and sustainable production. Coal as an energy resource for hydrocarbon generation has been widely researched and explored in the Tertiary basins of Malaysia (Sarawak, Sabah, and Peninsula) [9-12]. In Sarawak Basin, the Tertiary sediments of the Mukah-Balingian area consist of the Balingian, Begrih, and Liang formations, which have been considered as the most prolific humic coals producing units in Malaysia, and these are serving as the source rocks for oil and gas hydrocarbon fields [13]. These Tertiary rocks are also overlying the thick marine turbidite Belaga Formation [14]. The Belaga Formation forms the larger areal extent of the Rajang Group in NW, Borneo, deposited in an interval of about 30 Ma, resulting in a thick sedimentary succession of more than 4.5 km [15-16]. This magnificent sedimentary succession is predominantly composed of argillaceous lithology i.e., shales or mudstones, which are exposed at several locations throughout the Central Sarawak.

The calculation of total organic carbon (TOC) is one of the screening methods to determine the hydrocarbon generation capacity of sediments. This study was conducted to examine the distribution of TOC in Central Sarawak's late Cretaceous to Late Eocene deep marine turbiditic black shale sediments and to link the value of TOC to the corresponding depositional as well as tectonic settings. Depositional environment interpretation is adapted from various previous studies [11, 16-24] and is supported by the interpretation of observations and understanding from facies analysis by the author's current research. The distribution of organic matter in the deep marine settings and its relationship to the depositional environment is still poorly known. Furthermore, no such studies have previously been reported for Southeast Asia’s largest ancient deep marine turbiditic shales of Belaga Formation in Central Sarawak, NW Borneo. This paper, therefore, presents the results of a systematic study to measure the organic quality of these turbidite sediments using statistical techniques, to show the spatial distribution of understudy parameters, and to link them to their corresponding depositional environment.

2. Study area and geological background

The study area is located in Central Sarawak, NW Borneo, East Malaysia. Throughout geological history, Borneo Island has gone through several tectonic events, including extension (Cenozoic), differently interpreted rotation, uplift and subsidence of different regions, as well as the involvement of basements faults (initiation and regular reactivation) in the deformation of several parts until the Pliocene-Pleistocene. All these are believed to have taken an important part in the geological and tectonic evolution of the region [25-30]. With respect to tectonics, subduction along with the obduction of ophiolites, have a strong controlling influence on the formation of Borneo and the disappearance of paleo-basins. Subsequently, Sunda Plate or Paleozoic core extended in the area because of the collision and welding of several microcontinental fragments as well as island arc with the continental part [18-19, 28, 31-33], now consisting of two basins known as Sabah and Sarawak at the NW, Borneo (Fig. 1). Within the regional tectonic framework, the Sarawak region consists of three main geological zones, including Miri Zone, Sibu Zone, and Kuching Zone (Fig. 1). Each zone can be marked by its explicit stratigraphic variations, depositional backgrounds, and structural patterns [17, 27, 34, 35]. Lupar Line separates Kuching Zone from Sibu Zone, which is a strike-slip fault that might have re-activated many times until Eocene [36]. The area between the Bukit Mersing Line and the Lupar Line is known as Sibu Zone [21, 26, 37, 38]. Active during most of the Tertiary period (Eocene till Middle Miocene), Bukit Mersing Line also played a crucial part in the deformation of areas of Central and Northern Sarawak.

Sibu zone and partially Miri zone consist of Rajang Group, also known as “Rajang Fold-Thrust Belt, which is mostly composed of the flysch turbidites of Upper Late Cretaceous to Late Eocene sediments. Thick deep marine sediments of the Rajang Group represent a major submarine fan and, to some extent, an accretionary prism [21, 39, 40] and is among the world's major ancient submarine fans. The 95% of Rajang Group covered with the Belaga Formation at the central Sarawak. Belaga Formation is the most widespread and better-known formation of the Rajang Group in the lower Rajang area (Central Sarawak). The Belaga Formation (Late

Cretaceous to Late Eocene age) is believed to reach a great exceptional thickness of more than 4.5 km (estimated), excluding the repetitive sequences through folding and thrusting [15]. As this typical rock unit is the prominent part of the Rajang Group, therefore, it had been studied directly or indirectly by various researchers having some interest in the geology of SE Asia and Borneo. It has gone through different perspectives concerning tectonics, stratigraphy, and sedimentology [16-18, 21, 23, 39, 41-49]. Previously, the formation was divided into members mostly on the basis of paleontological distinctions along with little sedimentological differences. Members of Belaga Formation are arranged in the order from oldest to youngest, as follows: (1) Layar Member, (2) Kapit Member, (3) Pelagus Member, (4) Metah Member (of Sibu Zone), and (5) Bawang Member (Miri Zone's lower part) [48, 50] (Fig.1). The younging direction is northwards, i.e., from the Lupar Line towards Bukit Merging Line [17, 22].

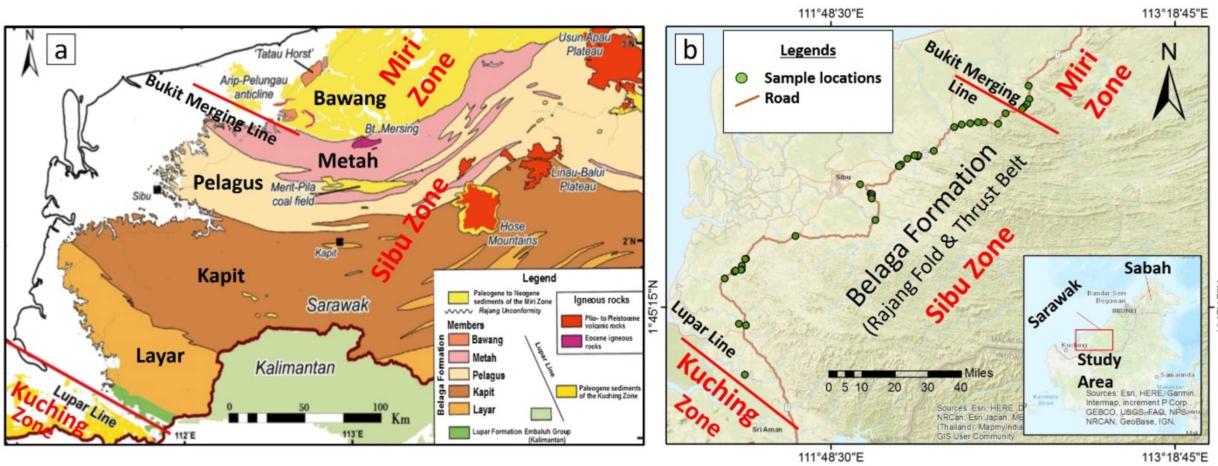

Figure 1. (a) Geological distribution of five members of Belaga Formation, and (b) sample locations for TOC distribution

Galin *et al.* [21] subdivided the Belaga Formation into four units based on zircon geochronology and depositional provenances. They have placed the Lupar Formation, Layar Member, and lower part of Kapit Member in Unit 1 (Late Cretaceous-Early Eocene); upper part of Kapit Member and Pelagus Member in Unit 2 (Early to Middle Eocene); and the previous fourth Metah Member in Unit 3 (Middle to early Late Eocene). Bawang Member, the fifth member of the Belaga Formation (in Miri Zone) was named as Unit 4 and proposed that either it is comparable to Unit 2 of Early to Middle Eocene age or a lesser extent probably with the base of Unit 1 (Lupar Formation- Late Cretaceous).

The oldest Layar Member (Late Cretaceous, based on [21] is located in the westernmost part of the study area and is exposed in and around the areas of Betong (Jln Lubuk Antu) and Roban (Sebangkoi Country Resort) in Central Sarawak. The prominent lithological composition of this member is shale with intercalations of thin siltstones and sandstones, where the sandstones are massive with scoured bases [17].

The second Kapit Member (Paleocene-Early Eocene), is generally composed of turbidites and made up of metamorphosed shale usually dark grey (carbonaceous), dark green, reddish or purple in color interbedded with siltstone and sandstone with dips of about 60°-90° of which sandstones are about less than 10% of the total assemblages. The 3rd member, Pelagus (Middle Eocene) characterizes the Sibu area along the Sibu-Bintulu road, consists of massive sandstone beds several meters thick interbedded with grey shales and thin sandstones and siltstones. Shales of this member are mostly exposed in the middle part and few outcrops towards the contact with the fourth member. The Metah Member (Middle to Late Eocene) occurs as a belt to the north and is conformable to some extent with the Pelagus. Unlike the Pelagus Member, it shows the dominance of shale, which are interbedded with thin layers of sandstone and siltstone and mudstone with a decrease in arenaceous content.

The Bawang (Late Eocene), previously reported as the youngest member, was introduced by Wolfenden [51] and consists of blue-grey to grey-black shales, occasionally slaty but soft with thin beds of fine-grained sandstones and occurrences of calcareous shale. It is extensively seen outcropping in the Sg Arip area and along the Tatau Horst area with exposures near the Tatau town [18, 23]. In a much recent study of Hennig-Breitfeld *et al.* [49], Bawang Member (turbiditic part or Unit 4 of [21] has been added under a new group of "Unit 4 of Miri Zone". As discussed by them, Unit 4 now include igneous rocks of late Middle Eocene (Bukit Piring, Arip Volcanics), Arip Limestones (confirmed late Middle Eocene age based on biostratigraphy!), some part of previous Bawang Member which is exposed between Arip River and Bukit Mersing Line (i.e., the lowermost part of the Tatau Formation of Wolfenden [51]. Bukit Piring is E-W trending granitic to granodioritic rocks that are exposed to southwest of Tatau village, and according to Wolfenden [51], this has been intruded in turbiditic rocks. Whereas, Arip Volcanics are igneous rocks that are exposed along the Arip ridge with an overall thickness of 450m [15]. A simplified geological map (Fig. 1) shows the various members of Belaga Formation, which are described as Flysch sediments assigned to the Rajang Group, modified from [21] and [49].

3. Methodology

Sedimentary facies were recorded, and samples were collected from all five members of the Belaga Formation during the field visit. Numerous new and fresh outcrops have been exposed along the Jalan Sri Aman–Sarikei, Jalan Sibu–Sarikei, and Jalan Sibu–Bintulu highway in central Sarawak. These new road cuts are exposed due to the recent Pan Borneo road expansion and construction project in Sarawak.

The geochemical analysis was conducted on a total of forty-six (46) fresh and representative black shale samples. The samples were washed, dried, and pulverized to achieve homogeneity and a fine consistency and further packaged for various analyses. The samples were initially screened and washed for any possible impurities. Both automatic mortar grinder pulverisette 2 and agate Bowl were used for making the powder to achieve the homogeneity and fine consistency of grains. Later the samples were dried in the oven at 60°C. All the samples were then treated with 10% diluted hydrochloric acid (HCL) to dissolve the inorganic carbon. The samples were analyzed for their total organic carbon (TOC) content. The total organic carbon content of the samples was determined using the Carbon Sulphur determinator (Eltra CS800).

Samples are named based on the name of the member from which they were collected and labeled later by using some representative letters for ease of referencing (i.e. Layar=Ly, Kapit=Kp, Pelagus=Pl, Metah=Mt, and Bawang=Bw). The samples are also arranged according to younging order, i.e., Ly1 is older in age and stratigraphic position than the Bw46. The succeeding number after the member code corresponds to the locality number of the sample (e.g., Kp1 corresponds to the sample taken from the first locality of the Kapit Member).

4. Results and discussion

4.1. TOC values

TOC is the volume of organic matter in rocks; the nature and quantification of the organic matter determine the relative capacity of a source rock to produce petroleum [52]. In the case of shales as effective hydrocarbon sources, minimum initial organic matter content is typically taken at 0.5 percent TOC [53-54]. Table 1 summarizes the lithologies of the samples from all five members of the Belaga Formation as well as the respective TOC values.

Colored lines in Table 1 reflect TOC values above 0.5 weight percent (wt%.) From the findings reported in Table 1, 25 out of 46 samples have TOC values of more than 0.5 wt%. The individual occurrence of samples with a minimum threshold value in each member of Belaga Formation is as: i) seven samples from Bawang Member, ii) four samples from Kapit Member, iii) ten from Pelagus Member, iv) three samples from Metah Member, and v) one sample from Bawang Member as shown in Fig. 2. Table 2 shows the range of TOC values and the source rock potential based on Peters and Cassa [55].

Table 1. Total organic carbon (TOC) content (wt%) of the samples

Serial No.	Sample	Lithology	TOC (wt.%)
Bawang Member			
46	Bw-1	Black Mudstone	0.33
45	Bw-2	Compact shale	0.31
44	Bw-3	Light Black Mudstone	0.32
43	Bw-4	Dark grey Shale	0.47
42	Bw-5	Dark black Mudstone	0.74
41	Bw-6	Mudstone/Clay interbedded	0.22
Metah Member			
40	Mt-1	Shale, light black	0.71
39	Mt-2	Shale/Claystone, thinly laminated	0.46
38	Mt-3	Shale (black)	0.3
37	Mt-4	Mudstone with thin clay layers	0.39
36	Mt-5	Mudstone	0.52
35	Mt-6	Black Mudstone	0.42
34	Mt-7	Dark grey Shale	0.51
Pelagus Member			
33	Pl-1	Compact shale	0.82
32	Pl-2	Mudstone black	0.61
31	Pl-3	Splintery, pebbly Shale	0.53
30	Pl-4	Sandy Mudstone	0.64
29	Pl-5	shale (black, compact)	0.58
28	Pl-6	Shale (black)	0.63
27	Pl-7	Shale (compact)	0.37
26	Pl-8	Splintery Shale	0.4
25	Pl-9	Shale	0.73
24	Pl-10	Coaly Shale	7.22
23	Pl-11	Dull grey Shale	0.52
22	Pl-12	Shale	0.4
21	Pl-13	Mudstone black	0.48
20	Pl-14	Shale	0.37
19	Pl-15	Silty Shale	0.32
18	Pl-16	Shale (black)	0.44
17	Pl-17	Shale	0.72
16	Pl-18	Reddish Shale	0.42
Kapit Member			
15	Kp-1	Light greenish grey Claystone	0.14
14	Kp-2	Light black Mudstone	0.17
13	Kp-3	Shale dark black, fissile papery	0.85
12	Kp-4	Coaly black Shale	0.95
11	Kp-5	Shale (black)	2.37
10	Kp-6	Papery black Shale	0.67
Layar Member			
9	Ly-1	Muddy black Shale	0.87
8	Ly-2	Very compact black Mudstone	0.75
7	Ly-3	Very compact Shale	1.01
6	Ly-4	Black compact Shale	0.86
5	Ly-5	Claystone, greenish grey faintly laminated	0.29
4	Ly-6	Shale (black)	0.34
3	Ly-7	Shale (black)	0.59
2	Ly-8	Shale (black)	1.39
1	Ly-9	Shale (black)	1.04

Table 2. Statistical values of TOC (wt%) data by area

	Ly	Kp	Pl	Mt	Bw
Min	0.29	0.14	0.32	0.3	0.22
Q1	0.59	0.295	0.4	0.405	0.3125
Median	0.86	0.76	0.52	0.46	0.325
Q3	1.01	0.925	0.63	0.515	0.425
Max	1.39	2.37	0.82	0.71	0.74

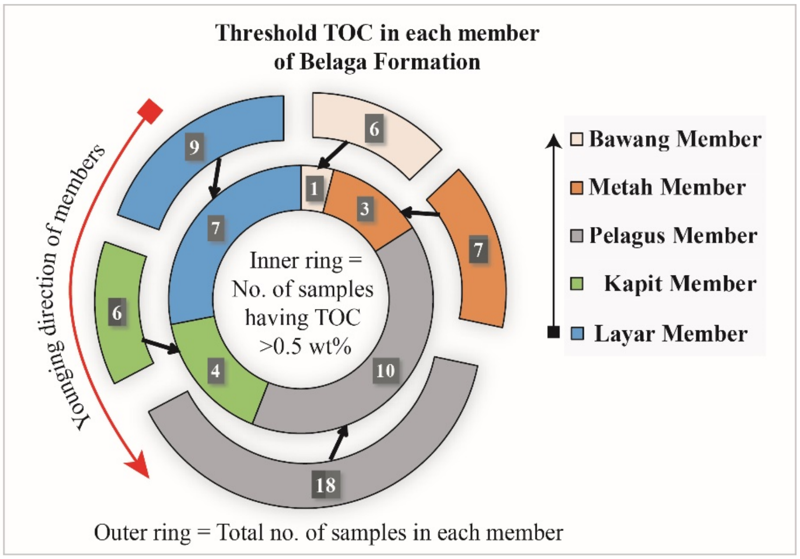

Figure 2. Frequency of the number of the sample having TOC values higher than the threshold range of 0.5 wt% in all five members of Belaga Formation

4.2. Individual value plot (IVP)

An individual value plot (IVP) is developed to analyze and compare the distributions of data from any analysis. An IVP displays a point on the graph for each observation's true value, which makes it easier to find possible outliers and see the spread of the distribution.

This plot functions well where the sample size is under 50 or so. Like a boxplot, an IVP can be used to classify and visualize probable outliers and reveal the data distribution. In comparison to a boxplot, each value is shown independently on an IVP. Relevant values are particularly helpful where very little observation has been made or the impact of individual measurement needs to be measured. The TOC values from the five members of the Belaga Formation are shown in Fig. 3. The sample sizes for Layar, Kapit, Pelagus, Metah, and Bawang members are nine, six, eighteen, seven, and six respectively.

4.3. Spread and distribution

The spread of data at Mt and Bw is comparatively short, meaning that most of the TOC values are at a high level of agreement with each other as compared to TOC values in Pl and Kp where the data in the IVPs are more spread out, suggesting a variation in the distribution of its TOC values. The values of Mt and Bw are less than 1 wt% while Ly, Kp and Pl have values of more than 1 wt%. As it can be perceived from Fig. 3, the overall values from Kp and Pl members are also less than 1 wt%, with the exception that each having only a single value of more than 1 wt% (Table 2).

The more clustered spreading of Mt and Bw data at low values indicate normal distribution while the spreading of data from Pl is concentrated at intermediate values, where this indicates moderate positive skewness. Values of TOC at Ly and Kp are more concentrated at more than 0.5 wt%. Ly also has few values concentrated above 1 wt %. TOC values in Metah and Bawang members are recorded to be similar, whereas in Layar, Kapit and Pelagus members, it differs highly, as apparent by the median value. The median TOC values are centered around 0.86 in Layar Member, 0.76 in Kapit Member, 0.63 in Pelagus Member, 0.515 in Metah Member and around 0.425 wt% in Bawang Member (refer Table 2).

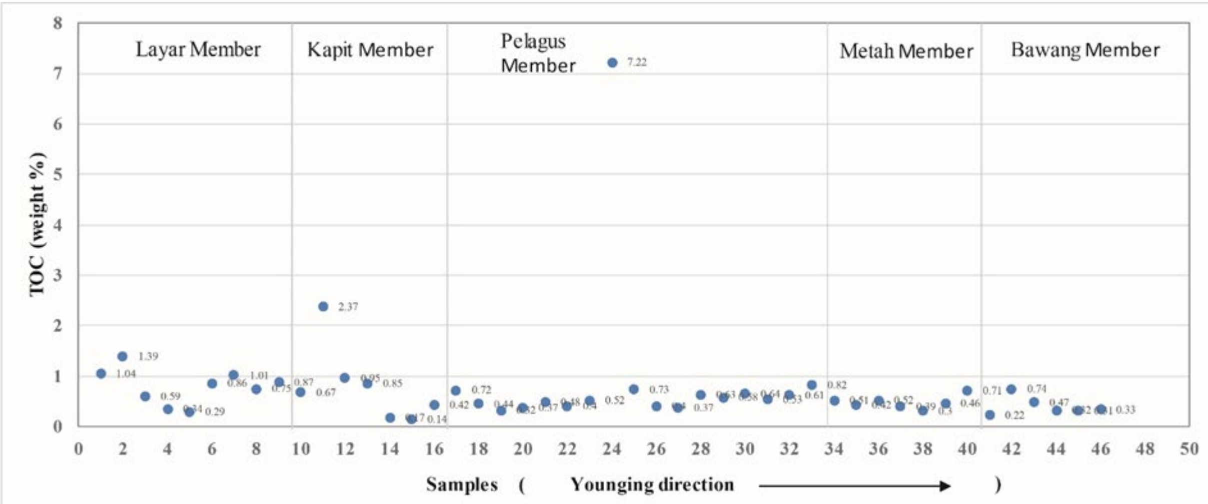

Figure 3. Graph showing the overall values of TOC by samples following the sample numbering in Table 1.

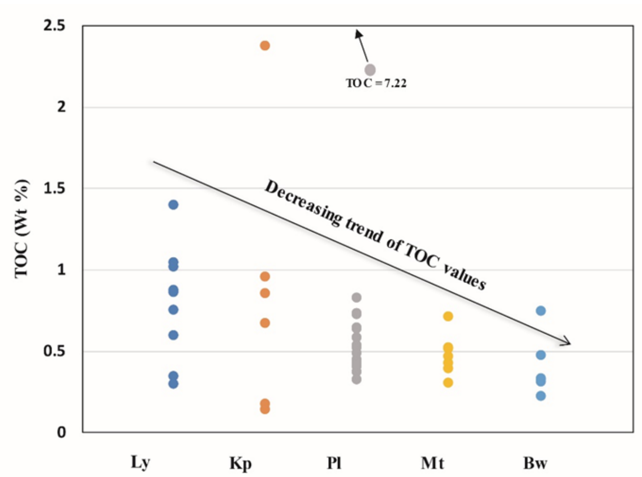

Figure. 4 Individual value plot (IVP) of TOC values for all five members of Belaga Formation

TOC values in all five members show a decreasing trend from older Layar Member to much younger Bawang Member which is evident from IVP Fig. 4 as well as from median values in Table 2. Given the large spread of TOC values in older members (Layar and Kapit), we can interpret a high variation in the amount of TOC while in Pelagus Member, the TOC values center more towards average. This also shows a high concentration of organic matter (TOC values) in shale lithologies from older units as compared to the younger ones.

4.4. Relationship between TOC and depositional environment

The sediments of Belaga Formation are the deep marine strata of the Late Cretaceous – Late Eocene age [17-18]. Table 3 below summarizes the TOC values of samples from each member along with the interpretation of source rock potential (the type of organic matter). It also displays the range and average values of each member.

Table 3. Range of TOC values and classification of members based on the classification of Peters and Cassa [51]

Member	Range of TOC (wt%)	Average	TOC% classification
Bw	0.22 - 0.74	0.3983	Poor
Mt	0.3 - 0.71	0.4729	Poor - Moderate
Pl	0.32 – 7.22	0.9	Poor - Moderate
Kp	0.14 – 2.37	0.8583	Poor - V good
Ly	0.29 - 1.39	0.7933	Poor - good

Based on the TOC range, Layar and Kapit members show high organic matter content, classification after Peters and Cassa [55]. Previous studies have suggested a general deep marine environment for all Belaga Formation. The same is true for the older Layar Member as well, except that the authors have inferred an overall mud dominated lobe/fan depositional environment. Based on facies analysis sediments from Layar Member were predominantly deposited in a distal plain or lobe fringe depositional sub-environment. Low terrigenous input along with high organic influx in Cretaceous could be the possible cause of high organic matter content in this member.

Kapit Member of the Paleocene to Eocene age also have a very high content of organic matter that is evident from the range of TOC as well as from the average values of 0.8583 wt%. Kapit Member has relatively more siliciclastic (sand) content compared to Layar Member, but still, it is also mud dominant. Facies analysis of this member reveals that most of the shales in Kapit Member belong to the distal lobe or distal lobe fringe, with few having features matching to that of crevasse splay deposits. Eocene deep marine sediments of Belaga Formation (i.e., Pelagus, Metah and Bawang) show much less content of organic matter. There could be several factors for low values, including these are more sand dominated turbidite units, naturally with less organic content. Either the organic matter was not producing and/or preserving at that time, or very less organic matter was reaching to deep marine fans/lobes of these younger members. As mentioned by Biscara *et al.*, [56], in the canyon and lobes, turbidites show generally low TOC content (0.5 wt. %) and OM is oxidized. The source of the OM of such deposits can be defined as both marine and terrestrial, with a higher input from continental sources compared to marine sources. The extensive siliciclastic content is transported covering long distances before deposition, due to which the low TOC of materials. Transport by long-shore waves and/or turbidity flows contributes to the oxidation of the OM.

The area between the Bukit Mersing Line and the Lupar Line is known as Sibu Zone [17-18, 21, 26, 57, 58]. Active during most of the Tertiary period (Eocene till Middle Miocene), Bukit Mersing Line played a crucial part in the deformation of areas of Central and Northern Sarawak. Therefore, the Eocene regional tectonic involvement might have affected the occurrence and preservation of organic matter in the Northern region i.e Lower Miri Zone.

5. Conclusion

The TOC values of the samples from the study area range from 0.14 to 7.22 wt%. In Layar Member, the TOC values range from 0.29 to 1.39 wt% for the shales belonging to the distal plain or lobe fringe environment. TOC values range from 0.14 to 2.37 wt.% in the Kapit Member and based on facies analysis these shales belong to the distal lobe or distal lobe fringe, with few having features matching to that of crevasse splay deposits. Pelagus Member showed a higher and wider range of TOC values ranging from 0.32 to 7.22 wt.%. Sandy or silty fine-grained shales show low values of organic content, while higher values are recorded in blackish finer-grained mudstone/shale sediments. Zones with high TOC values show higher variations in the TOC distributions and vice-versa. Transportation of sediments takes place in deep marine deposits covering long distances before deposition, due to which the low TOC of materials is obvious. Also, the transport of sediments by long-shore waves and/or turbidity flows contributes to the oxidation of the OM. Grain size and weathering also influence the preservation of organic matter in sediments, as well as the depositional energy because low-energy sediments have a higher organic carbon preservation rate. There is a prominent decline in TOC values from older members toward younger members which implies the decrease in organic matter likewise. Involvement of volcanic activity in Eocene in Sarawak can also have some effect on the availability and preservation of OM.

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