Bulletin of the Geological Society of Malaysia, Volume 72, November 2021, pp. 47 - 62
DOI: https://doi.org/10.7186/bgsm72202105

Facies analysis of the Late Eocene deep-marine middle- to outer-fan sequence of the Crocker Formation in Tenom District, Sabah, Malaysia

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Abstract: The Crocker Formation, Late Eocene to Middle Miocene in age, was deposited in a deep-marine environment by a turbidity current. Most of the facies identified in the field are related to the sedimentary bed-form structures belonging to Bouma sequences. These prominently include unit divisions such as T_a referring to grading sand, T_b for parallel laminae, T_c for cross laminae, T_d for mud laminae, and T_e referring to hemipelagic mud. Five facies have adequately been identified using Bouma sequence implications, namely Facies 1 (F1: T_a-T_b layers), Facies 2 (F2: T_a-T_e layers), Facies 3 (F3: T_b-T_e layers), Facies 4 (F4: T_b / T_c-T_e layers), and Facies 5 (F5: T_d-T_e layers). Based on the Crocker Formation facies analysis, three distinct groups of facies associations were recognised: Deep-Marine Channel-Lobe Association (Type A1), Deep-Marine Channel-Levee Association (Type A2), and Distal Lobe Association. These facies associations precisely revealed that the Crocker Formation's depositional environments were likely deposited in the middle-fan with associated outer-fan settings.

Keywords: Submarine fan, turbidite, Tenom, facies analysis, Late Eocene

INTRODUCTION

The study area lies in the west of Sabah and extends from 115º47'to 115º57' east and 5º00'to 5º15' north, about 40 km to the north of Tenom (Figure 1). Topographically, the area is mountainous and reaches 1,000 meters above sea level. The picturesque Tenom gorge naturally forms part of the Crocker range's backbone in the western part of Sabah. In fact, Wilson & Wong (1985) properly described the study area having the most significant exposure of the Crocker and Temburong formations. The area is also closely related to the potential exposure of nature valley topography, with mountain ridges formed as a possible consequence of the deformation folding and faulting processes trending northwest-southeast.

Generally, the study area consists of Tertiary and Quaternary sediments (Figure 2). The Tertiary sediment in the study area is composed of various formations such as the Crocker Formation and the Temburong Formation. The alluvium terrace appropriately represents the Quaternary deposits, typically forming the gorge topography around the Tenom District area. The Crocker Formation's main lithology, as explained by Hutchison (2005) based on Stauffer (1967), could be concluded as flysch sequences with laminate sequences, red and green mudstones mass-flow sandstones, and slumped zones. Lithofacies analysis of this formation has properly recognized its belonging to turbidite characteristic facies. There is no type section uniquely representing a complete sequence of this formation. However, Wilson (1964) stated that the Crocker Formation's outcrops exposed in Tenom Gorge were the most accessible and likely to provide the best-exposed cross-section of the Crocker Range in Sabah.

Microfossil analysis, as explained by Rangin *et al.* (1990), Basir *et al.* (1991) and Sanudin & Baba (2007), concluded that the Crocker Formation was deposited in the Late Eocene. Therefore, the main goal of this study is to clarify the characteristics of the facies in a different perspective way and facies associations of a deep-marine depositional model in the Late Eocene of the Crocker Formation in Tenom District.

MATERIAL AND METHOD

Facies analysis was carried out properly using the parameters described by Selley (1988), Tucker (2003), Sanudin & Baba (2007), which consist of geometries, lithologies, sedimentary structures, fossils, and paleocurrent measurements. However, the geometries and sedimentary structures are the best and most accurate parameters to

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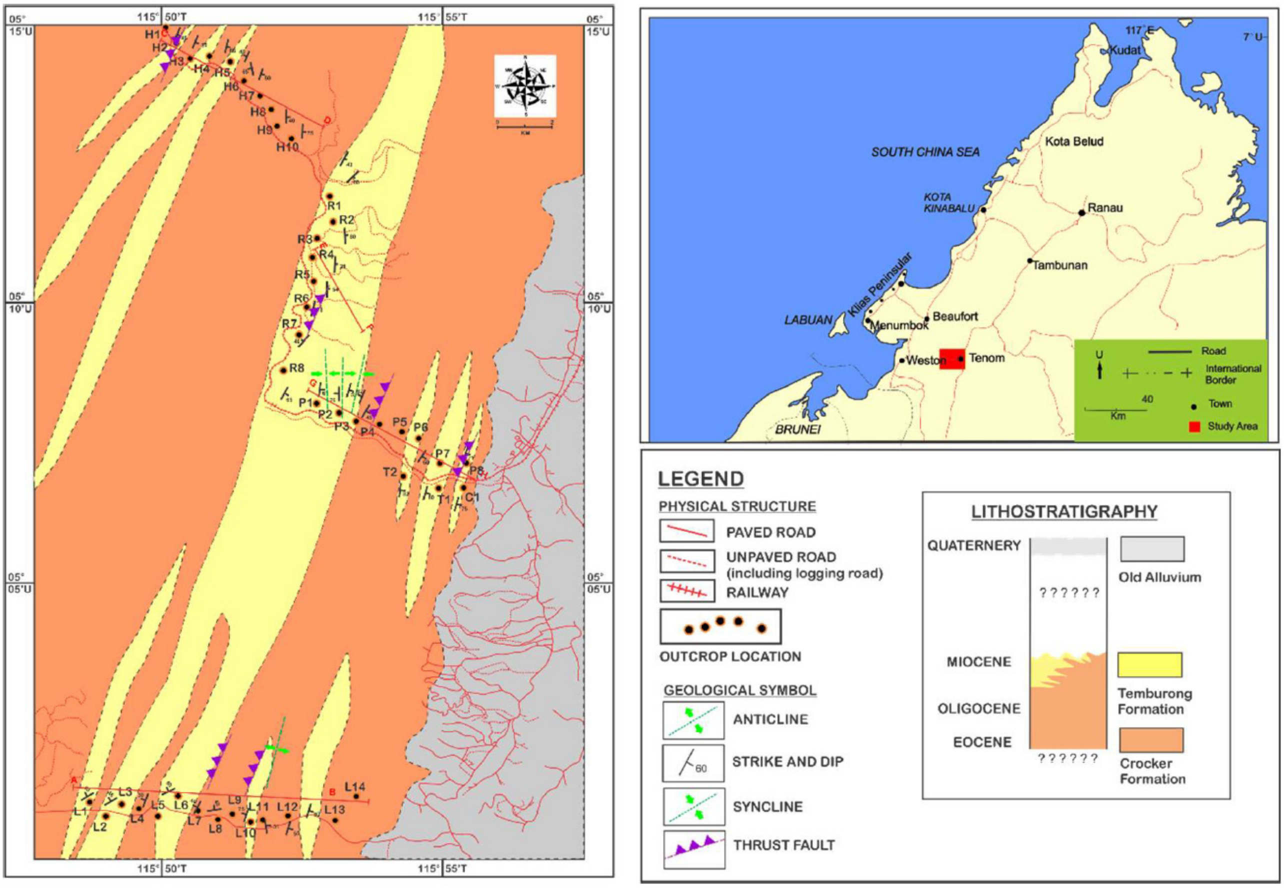

Figure 1: Location Map of the study area in Tenom, Sabah. This map prominently shows lithological units represented as Crocker and Temburong formations. The geological map also shows sampling locations. Modified geological map from Wilson & Wong (1985).

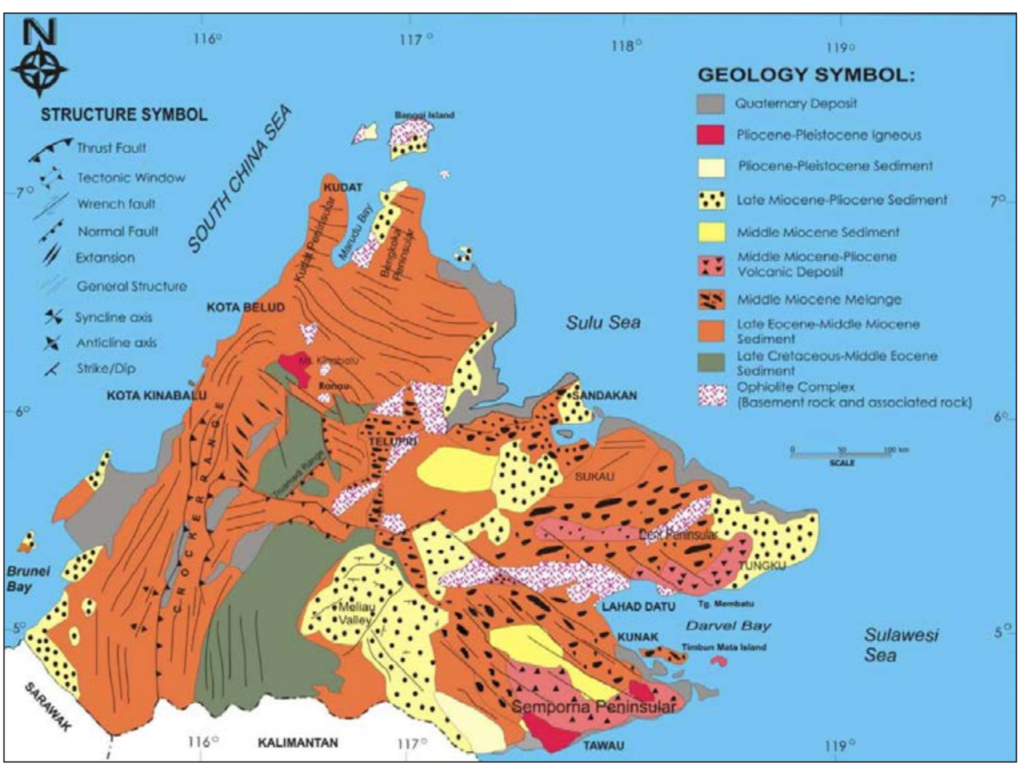

Figure 2: Simplified geological map of Sabah (modified after Yin, 1985).

accurately differentiate facies in the study area. The apparent correlation between similar rock facies using vertical litologs allowed us to further identify facies changes between the Crocker and Temburong formations. Apart from that, paleocurrent data presented in rose diagrams for the analysis of paleoflow direction is also beneficial for establishing a deep-marine environment model.

GEOLOGICAL SETTING

Borneo is the third-largest island in the world; however, its topography is not very high (Hall *et al.*, 2008). It is typically surrounded by three active tectonic plates, namely, the Indo-Australian, Eurasian, and Philippine-Pacific plates (Figure 3), which have been interpreted as the product of the Mesozoic accretion of ophiolitic material, marginal basin fills, island arc material, and microcontinental fragments onto the Palaeozoic continental core of the Schwaner Mountains in the south-west of the island (Hutchison, 1989; Metcalfe, 1996). Previous researchers mostly concluded that, based on seismicity and GPS measurements, Borneo is currently part of the South East Asian or Sunda block moving slowly relative to Eurasia (Cardwell & Isacks, 1978; Rangin *et al.*, 1990; Simons *et al.*, 2007; Hall *et al.*, 2008).

According to Hall (1996), the core of Borneo Island naturally formed a Sundaland promontory in the early Tertiary. He added that Borneo Island, except Sabah and Sarawak, is part of Sundaland since the Cenozoic. Paleomagnetic studies by Fuller *et al.* (1999) evidenced that the Borneo Island had rotated approximately 45° counterclockwise since the Early Miocene. Hence, the Northwest Borneo margin would have been oriented northwest-southeast in Oligocene (Hall & Nichols, 2002). Sabah's Tertiary mountain belt is also considered part of an accretionary prism related to the Palawan Trench (Rangin *et al.*, 1990). This wedge was formed during the Late Paleogene and Early Miocene (Hamilton, 1979) and was associated with the opening of the proto-South China Sea (Holloway, 1982; Taylor & Hayes, 1983).

The Northwest Sabah Basin is one of the main Tertiary depocentres in Northwest Borneo with two distinct periods of basin filling as recorded by prior literature (Leong, 1999; Mazlan Madon *et al.*, 1999). The first period was from

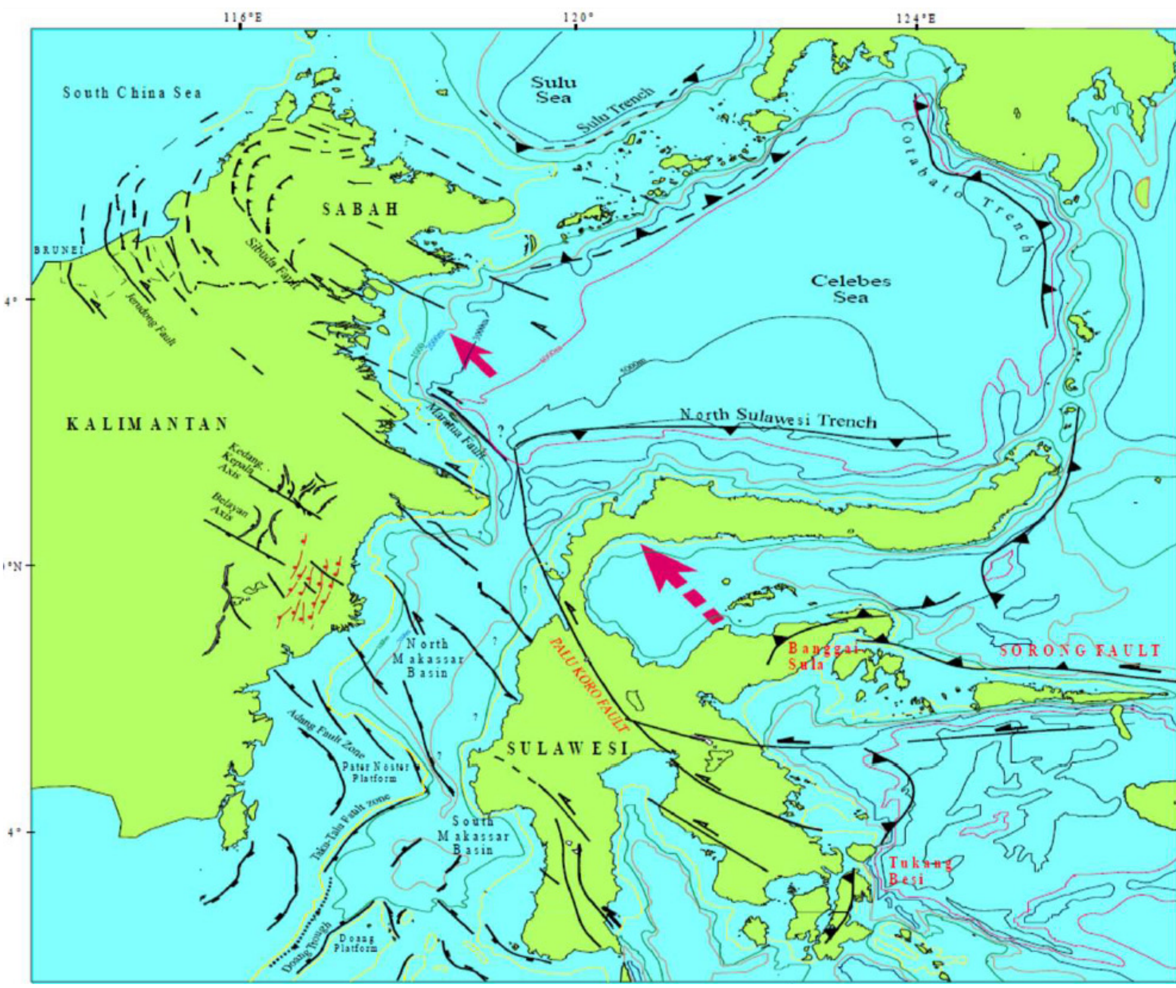

Figure 3: Tectonic framework of Southeast Asia showing the location of Sabah (after Balaguru & Hall, 2009).

Paleocene to Eocene when deep-water sediments of the Rajang-Embaluh Group were deposited, whereas the second period was in the Late Eocene, associated with ongoing subduction and efficient compression of the Rajang-Embaluh Group (Jackson *et al.*, 2009). In northwestern Sabah, the deformed coastal basins were then filled with Neogene sediments, progressively extending along the western front of the Crocker Range in Brunei and offshore Sabah (Hinz *et al.*, 1989).

Bowen & Wright (1957) mapped about six formations within the study area, namely the Liang Formation, Nyalau Formation, Pangi Shale Formation, Temburong Formation (formerly known as Pa Plandok Marl Formation), and Crocker Formation. According to Wilson (1964), the age of the Crocker Formation ranges from Eocene to Miocene; however, Sanudin & Baba (2007) confirmed the age of this formation to be Upper Eocene. Lateral variations between the Crocker and Temburong formations show that they interfinger, overlaid by the Sapulut Formation. Wilson (1964) added that this formation is widely distributed down to Sarawak's border and part of Labuan Island, while the thickness is relatively up to 20,000 feet (Sanudin & Baba, 2007). The most common facies from the Crocker Formation include channel-lobe facies, lobe-migration facies, distal lobe facies, and middle-fan facies; this illustrates that the sedimentary sequence was widely distributed in the Crocker basin.

FACIES ANALYSIS

The rock units typically consist of a sequence of deep marine clastic rock, adequately classified as the Crocker Formation. According to Wilson (1964), the oldest rock unit was formed from Eocene to Miocene, while Sanudin & Baba (2007) described the age of this formation as Late Eocene. As described by former researchers, the rock units of the Crocker Formation belong to a series of turbiditic sequences. In this study, established codes such as Facies 1 (F1: T_a-T_b) by Bouma sequences (1962) were used as parameters to determine the suitability of lithology types in turbiditic facies. The rock units for the Crocker Formation in the study area can be distinguished as follows:

i) Thick Sandstone Unit
ii) Interbedded Sandstone and Shale Unit
iii) Interbedded Medium Sandstone and Shale Unit
iv) Interbedded Thin Sandstone and Shale Unit

These rock units were precisely defined by Stauffer (1967) and Rodeano (2002) and functionally related to what has been carefully observed in the field. The facies identification at the field basically used normal parameters established by Selley (1988). These include geometry, lithology, sedimentary structure, fossil, and paleocurrent direction. However, the best facies indicator recorded in a rock along history is the sedimentary structure due to the preservation process during the depositional setting. Thus, most of the facies differentiation in the research used the sedimentary structure as the main indicator. The author believe that the different environment yield different sedimentary structures with a particular regime and flow density. Those sedimentary structures is displayed by the Bouma sequence within individual sandstone bedding (Figure 4).

Facies 1 (F1: The T_a-T_b Beds)

Description

Facies 1 is characterised as thick, amalgamated, and channelised sandstones. The bedding thickness typically ranged from twelve metres and up to a hundred metres in the study area with medium to fine grain size (Figure 5). This facies invariably showed an incomplete Bouma sequence with the potential exposure of T_a-T_b sequence only. In contrast, the other Bouma sequences were utterly unobserved. Some sedimentary structures like cross laminations, grooves, and flute casts were obscured in this facies. Apart from that, a soft-sediment deformation with dish and convolute structures was harder to observe in the field.

Interpretation

The possible presence of T_a-T_b beds in thick, amalgamated, and stacked sandstone beds is likely related to the rapid high-density deposition of the sediment. The thicker amalgamated sandstone beds approximately achieved a hundred metres as observed in the study area and were mainly associated with the proximal turbidite deposition (Morris, 1974). Some sedimentary structures (e.g. cross laminations, grooves, and flute casts) were obscured due to the high-energy depositional flow of the sediment laden of the axial channel. As for the grain size

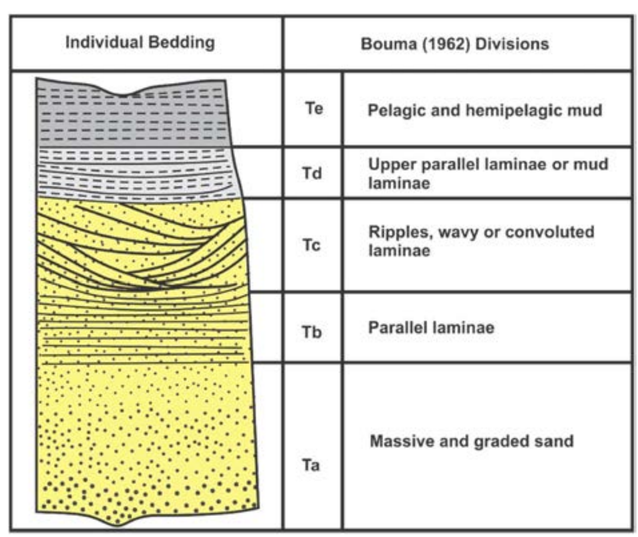

Figure 4: Ideal Bouma Sequence showing T_a to T_e division, the sequence developed of a turbidity current. Modified after Bouma (1962).

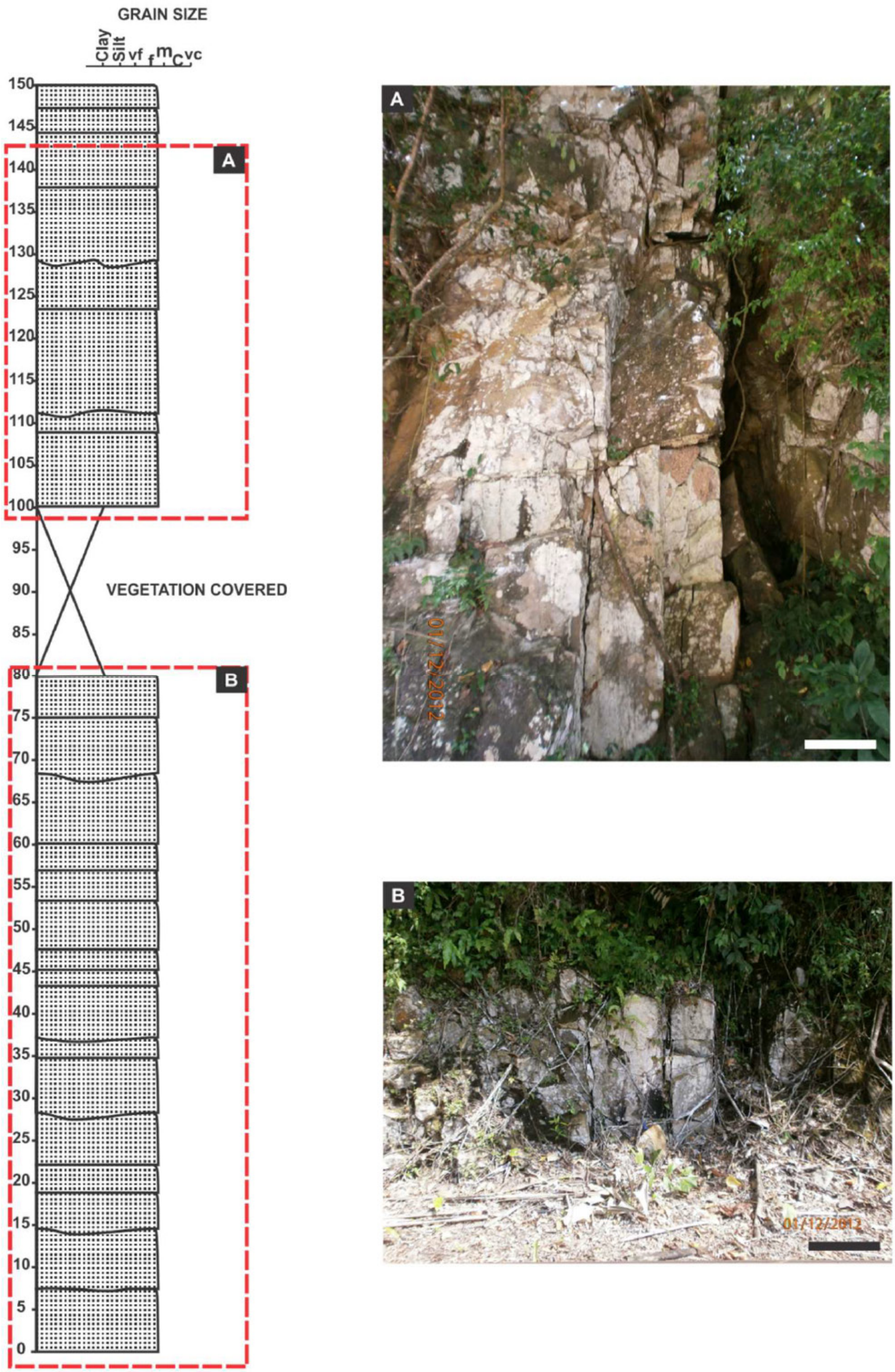

Figure 5: Facies 1 represents thick and amalgamated sandstone, channelise geometry, and estimated to have a thickness of about twelve meters and up to a hundred meters in the study area.

observation, it could be clarified that the possible source of the sediment came from a large prograding delta. The lack of soft-sediment deformation occurred on a bed, suggesting that the deposition did not take place in a slope setting but a more distal basin floor depositional environment. Based on these explanations, Facies 1 was interpreted as a deep-marine channel.

Facies 2 (F2: The T_a-T_e Beds)

Description

Facies 2 has a broad distribution in the study area. However, the exposed outcrops are intermittent. The upward sequence of the outcrop achieved 40 meters high vertically and 60 meters horizontally. Individual sandstone beds ranged from 20 to 110 centimetres thick (focused on one outcrop in Halogilat (locality H1), see Figure 1), and were thicker in the lower part and became thinner upwards (Figure 6). The lower part of the sequence was overlain by thin layer shale in a 2:1 ratio, while the facies graded upwards into Facies 4. Some beds, mostly the thicker ones, displayed complete Bouma sequences of T_a-T_e units. Based on field observations, Facies 2 showed a variation in thicknesses - the T_a units were up to 1 meter thick and scoured (Figure 7 (a), (b), and (d)), the T_b units 3 were 10 centimetres thick (Figure 7 (a) and (c)), the T_c units were 20 centimetres thick (Figure 7 (a) and (e)), the T_d units were 10 meters thick, and the T_e units were 15 centimetres thick (Figure 7 (b)). The facies could equally be seen at other locations like locality L8 (see Figure 1) where the outcrop is thick and inclined (Figure 8 (a)). This location consists of some exposure of trace fossils such as *cosmorhaphe sp*. and *Helminthopsis sp.* (Figure 8 (d), (e), and (f). Various syn-sedimentary structures were formed in Facies 2, for instance, the T_b unit represents parallel laminae, the T_c unit is cross-laminated, and the T_d unit is mud-laminated (obscure). Other structures, such as flute casts and grooves, were the most common structures in Facies 2 (Figure 8 (b), (c), and (g)) as well as dewatering structures (Figure 8 (h)).

Interpretation

Interbedded sandstone and shale have been interpreted to indicate a reversal of velocity, convection currents, and sedimentation processes (Pickering & Hiscott, 1992). Complete Bouma sequence units with various sedimentary structures, starting from T_a to T_e units in an outcrop were due to the repeated current alternations from a high density of deposition to a low density of deposition. This facies is accurately distinguished from other facies by the occurrence of complete sedimentary structures (complete series of Bouma units) and the geometric sequence of rock units (Showed channel-levee). Based on the criteria above, this facies can be described as channelised sandstones and interpreted to have been deposited at the middle-fan system in the Crocker Formation.

Facies 3 (F3: The T_b-T_e Beds)

Description

Facies 3 is distributed locally around the study area, such as in specific localities H1, H7, and H8 (Figure 1). Facies 3 typically consists of thick interbedded sandstone and shale, which infrequently occurred after Facies 2 within one outcrop (Figure 9). The bedding showed a thickening-upward sequence and sharp contact with the underlying shales. Overall, the bedding measured from the outcrops averages approximately 5 metres where individual bedding ranges from 50-cm to 1-m thick. According to the petrographic observation of some samples collected in the study area, this facies yielded fine to medium grain size with poorly sorted and grained coarsening-upward sequence. Bouma sequences were incompletely exposed within the beds where the possible exposure included merely T_b (parallel laminae), T_c (cross lamination), T_d (mud laminae), and T_e (hemipelagic mud) units, respectively. The T_b unit was easy to observe compared to other units due to the obvious parallel laminae in sandstone beds; however, other units exist intermittently in several beds of outcrops. Meanwhile, a trace fossil was moderated and exposed in localities H1 and H7 only.

Figure 6: Photo showing parts of Facies 2 outcrops in the Crocker Formation. The arrow indicates the younging direction.

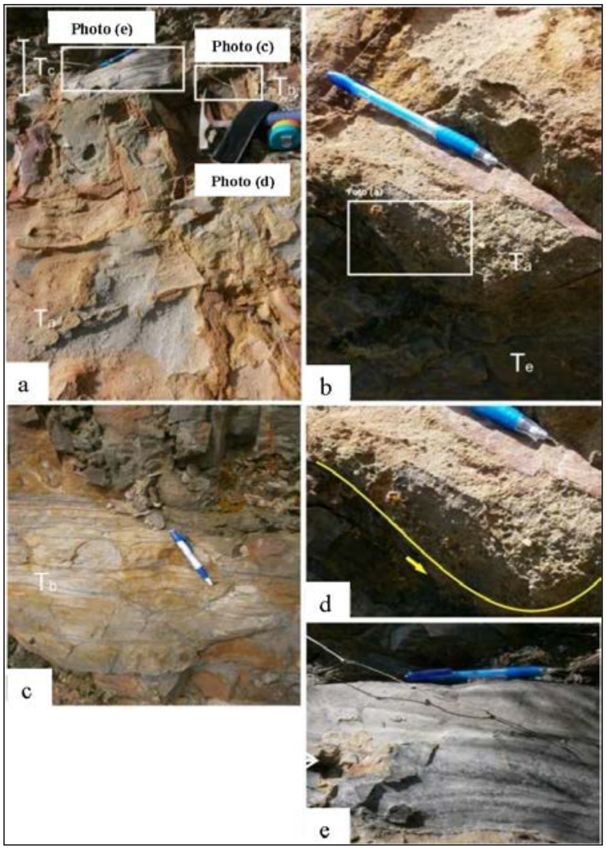

Figure 7: Outcrop showing exposed sedimentary structures in Facies 2. (a) Proper exposure of complete Bouma division (i.e. sedimentary structures) on individual bedding. Hammer as scale. (b) Scoured base showing granule size of channelise sandstone. (c) The T_b unit is showing parallel laminae in sandstone bed. (d) An enlargement of scoured base of sandstone from photo (b). (e) An enlarged view from (a) accurately representing cross lamination referring to T_c.

Interpretation

Abundant evidence of thick-bedded sandstones shows that the sediment was typically derived from the main channel moving rapidly ahead to create a normal fan lobe. The possible source of the sediment could also be derived from the reworking of sand either the delta lobe migration or sand shelves environment (Nichols, 2009). The continuous and robust current in this condition allows sand to have properly sorted and removed mud and silt particles and finally leaving dominant sand with a limited amount of mud. The sediment was subsequently transported onward as a coarsening-upward trend and progressively eliminated the T_a division by the time of transportation. As such, Facies 2 did not exist simultaneously with Facies 3 within a sequence. Trace fossils were moderately exposed due to the time and the condition is not extremely favourable for a living organism to survive.

Facies 4 (F4: The T_d-T_e Beds)

Description

Facies 4 typically consists of shale and thin fine-grained sandstones (Figure 10 (a)). The shale is more abundant than sandstone and the beds range up to 1 meter thick (in one outcrop). Generally, the sandstone sequence indicated a thickening-upward sequence at a small scale (Figure 10 (b) and (c)). Some outcrops displayed trace fossils and bioturbation on beds; however, they were not extremely abundant. The Bouma divisions described only the T_d-T_e units that properly represented mud laminae and hemipelagic mud.

Interpretation

Thin sandstones with thick shale are evidence for slow currents in a deep basin. According to Hesse (1992), the

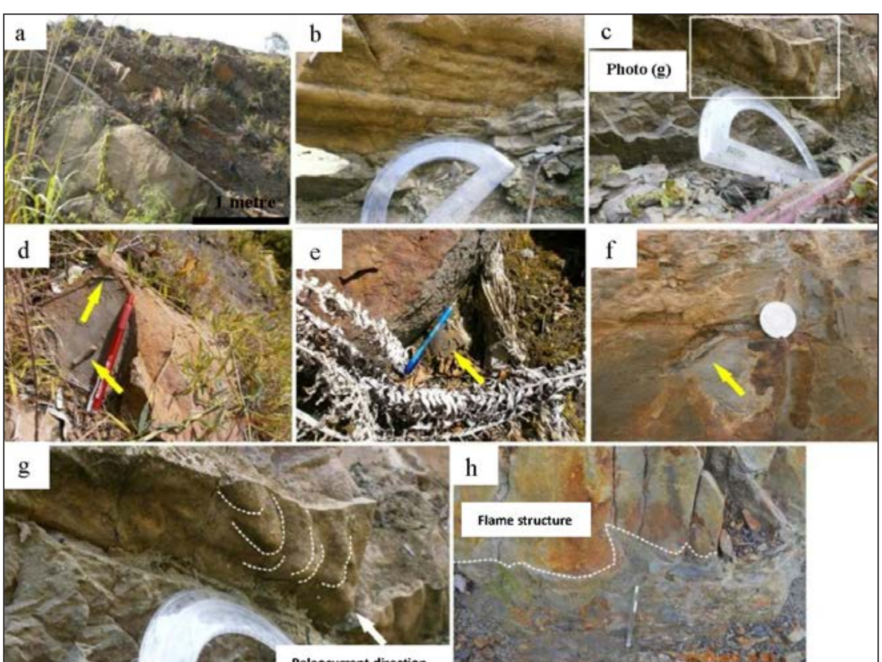

Figure 8: (a) The outcrop of Facies 2 shows inclined bedding and coarse to fine-grained size (b) A groove cast typically exposed on the bottom of sandstone bed. (c) A flute cast typically exposed at the bottom of sandstone bed. (d) The trace fossil of *Cosmohaphe* sp. (e) and (f) The trace fossils of *Helminthopsis* sp. (g) Flute cast (an enlarged view from (c)) and its paleocurrent direction. (h) The dewatering structure yields a flame-like structure on the sandstone bedding.

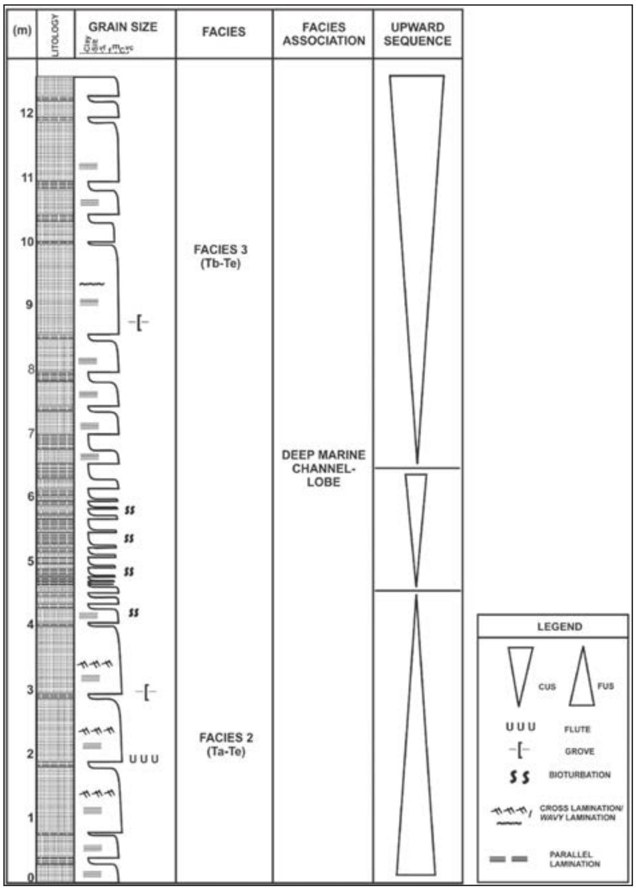

Figure 9: A vertical lithological section showing part of the Crocker Formation from the Paal area, Locality L4. The outcrop shows numerous fining and coarsening upward sequences that is also present in Facies 2 and 3.

abundance of shale was due to the sufficient concentration and times the mud suspended. The thickening-upward sequence was due to the overflow of sediment from the main channel, especially the abundance of the mud. Some bioturbation occurred in beds, showing that the environment had a good oxygen supply and was deposited by low-density turbidity currents (Callow *et al.*, 2012). The proper T_d-T_e Bouma sequence abundantly showed that current reversal occurred in the dominant mud environment during sediment overflow. Additionally, this facies can be interpreted as levee deposits.

Facies 5 (F5: The T_c-T_e Beds)

Description

Facies 5 comprises interbedded sandstone and shale with thick to thin sandstone beds (Figure 11 (a) and (b)). However, some outcrops displayed the amalgamated bedding of this facies (Figure 12 (a)). The exposed bedding was about 41 meters thick and showed a thickening-upward sequence. Bouma sequences differ from those in Facies 2 in that T_a and T_b units were obscured or did not exist and the T_c units were irregularly distributed, sometimes in a bed, sometimes singly (Figure 12 (b)), followed by T_d and T_e units. Additionally, this facies has several pre-deposition structures like flute casts, grooves, and other erosional structures, which are tremendously important in the determination of paleocurrent directions (Figure 12 (c)). Other structures, for example, dewatering structures also exist in some bedding (Figure 12 (d)). The biogenic structure was less exposed in this facies.

Interpretation

Interbedded sandstone-shale in a continuous sequence can reasonably infer that the effective rate of sedimentation

Figure 10: (a) The outcrop typically shows a harmonic series of distinct bedding sequence of Facies 4. The material is rich with thick shale and thin sandstone. (b) and (c) A typical package of coarsening upward sequence (CUS) represents the Facies 4.

Figure 11: (a) and (b) The outcrops of Facies 5 which consist of thin to medium bedding sequences. It is revealed distinctively that the outcrop displays coarsening upward sequences.

is slow. The repetitive sandstone and shale in a sandstone sequence can explain the deposition that occurs in a low-density turbidite current (Lowe, 1982). The absence of the T_a unit was believed to be due to erosion during early deposition or perhaps due to a limited source of sediment supply from braided channels. The thickening-upward sequence typically suggests that the sediment discharge led to overload and further flows to an outer-fan lobe. Erosional structures were naturally formed by eddy current action at the bottom of beds.

FACIES ASSOCIATIONS

Based on the facies analysis discussed above, three facies associations could be identified, namely, channel-levee, channel-lobe, and distal lobe associations (Figure 13). The two-channel development here is mainly deposited in two various processes, where both channels showed distinct characteristics, including geometry, lithology, and sedimentary structures (i.e. Bouma divisions). Most of them formed a fining-upward trend. In the field, these channelised sandstones can be grouped into two specific classifications based on the variable of the sandstone units, namely Type A1 and Type A2. These classifications will adequately discuss the facies associations below.

Deep Marine Channel-Lobe Association (Type A1)

Description

The Channel-Lobe Association (A1) mainly consists of Facies 1, Facies 2, and Facies 3, while another term is referred to as channelised lobe in the turbidite system. The

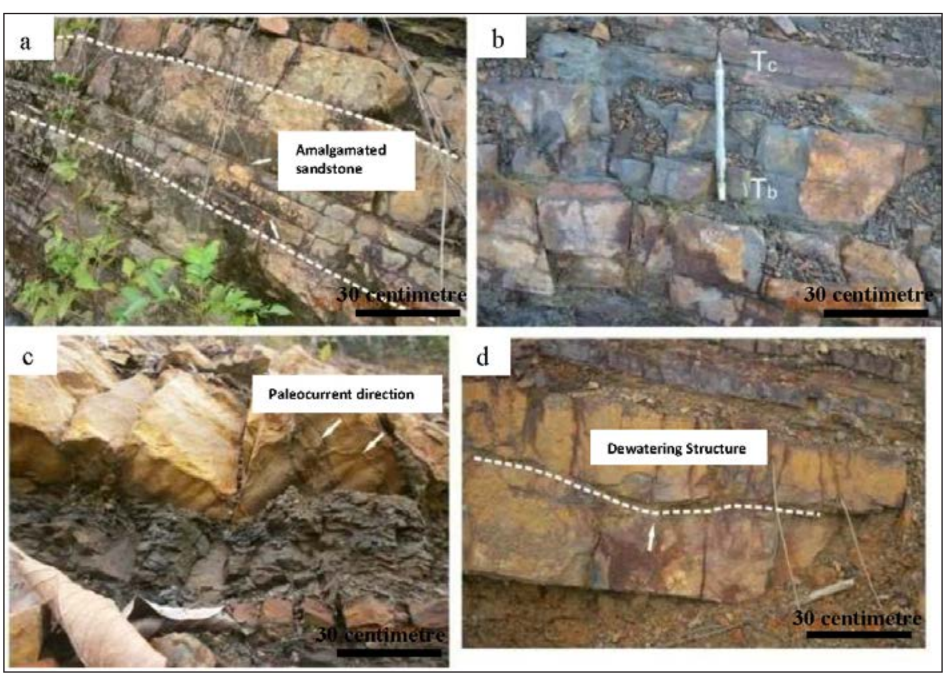

Figure 12: (a) An amalgamated bed is appropriately displayed in Facies 5 with a medium scale bedding. (b) The bedding of an outcrop in Facies 5 exhibits the T_b and T_c division units of Bouma sequence. (c) The flute cast and its paleocurrent direction. (d) The dewatering structure naturally occurs on the sandstone bedding of Facies 5.

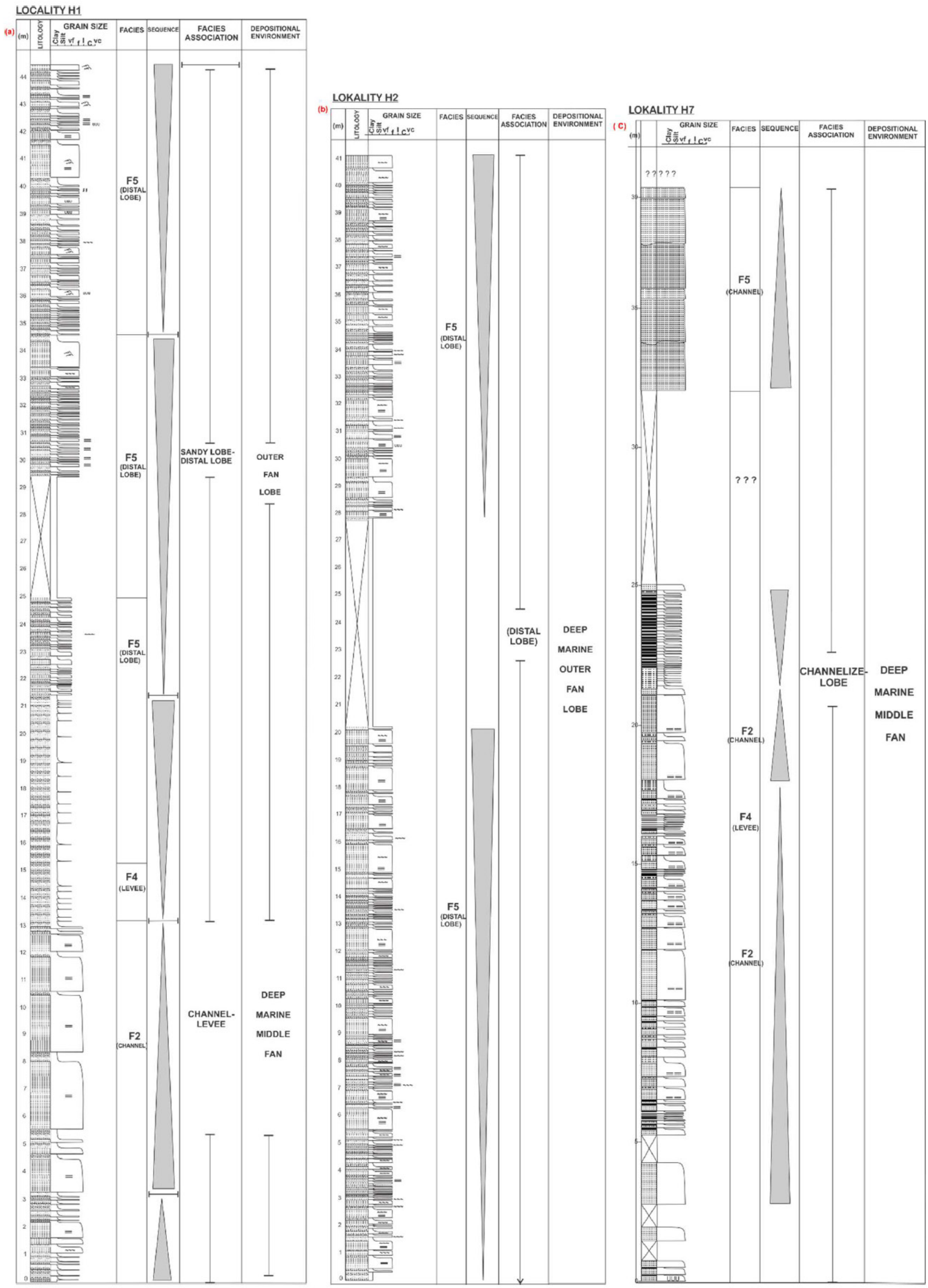

Figure 13: Some complete vertical sedimentary log showing combination of all facies and facies associations in the study area.

Type A1 channel consists of amalgamated thick-bedded sandstone and interbedded thick sandstone with shale. In the research area, this facies association is represented by a channel passing upwards into a lobe without naturally creating levee. The lobe geometry prominently displayed an upward-thickening sequence up to 50 to 80 centimeters thick. At the same time, the channel represents a fining-upward sequence—an individual bed in channels and lobes showing stacked sharp base boundaries in between.

Interpretation

Heavy flow sedimentation in an active channel will instantly transport the sediment out from its possible source then burst to form a lobe, which represents the thickening-upward sequence as observed. A stacked sharp-based boundary showed that the sediment reacted in eddy condition and low-density current. The high-density current flow carried the sediment rapidly to the outer fan and deposited it in a short distribution scale without intentionally creating levee along the channel. In other words, this refers to the progradation of sediment through multiple active channels deposited without levee. This process happens numerously in a braided channel where the sediment consists of dominantly sand.

Deep Marine Channel-Levee Association (Type A2)

Description

Deep marine channel-levee associations comprised Facies 2 and Facies 4. About 15 strata showing channelised features were naturally found in the study area. This facies association precisely consists of non-amalgamated sandstone called Type A2, where it was characterised as rhythmic interbedded thick to thin sandstone with shale. The Type A2 channel is also well-known as the depositional lobe because the draining out of the sediment laden of the potential source subsequently created a normal lobe. A lateral gradation may occur from Type A2 to the Type A1 channel according to some exposures in locality H7 (Figure 14). It was shown that the considerable thickness of the sandstone decreases from Type A2 to the Type A1 channel.

Interpretation

The fining-upward sequence prominently displaying rhythmic interbedded sandstone-shale indicated deep-marine channel deposition. The thicker bed in the lower part of the fining-upward sequence indicated that the sedimentation was deposited into two different conditions influenced by the bottom current and high accumulation of the sediment. The channel experienced transition due to the shift of the sediment during the sea-level change. Flowing water laden with the sediment as well as rapid deposition can form a thicker bed. However, due to interaction with sea-level changes, the sediment will pass laterally with an abundance amount of sand, creating amalgamated sandstone bedding.

Distal Lobe Association

Description

This facies association is dominated by Facies 5 in the Crocker Formation by which individual beds showed sharp boundaries between sandstone and shale with specified thicknesses ranging from 1 centimeter to 15 centimeters (middle to thin in size). This facies association illustrated rhythmic bedding with a thickening-upward sequence. In the study area, it has abundantly shown limited exposure and was merely exposed in localities H1 and H7 (Figure 1). Some migrating lobes also appeared intermittent within the same sequence and showed a fining-upward trend. This migrating lobe is a finished section of bedding exposed in a distal lobe.

Interpretation

Progradation and migration of sedimentation from the main lobe (middle fan) to the outer lobe (outer fan) will carry the sediment in a low-density turbidity current, low oxidation process, and low suspension reaction condition (Callow *et al.*, 2012). In the Crocker Formation, this facies association displayed a short range of sequences between ordinary lobes (normal lobe). Some bed thicknesses were middle to thin in size due to the low velocity of sedimentation in a distal setting. This facies association also displayed a short range of sequences between lobes, while the distal lobes are of limited distribution. The lobe could sometimes burst out while carrying reworked sand and mud upon moving and subsequently creating a migrating lobe (Mutti, 1999).

PALEOCURRENT ANALYSIS

Paleocurrent analysis was properly conducted for several measured sections in the study area. All paleocurrent data were taken from various sedimentary structures that typically appeared on every sandstone bedding. Sedimentary structures in measured outcrops were barely visible due to poor preservation and heavy tectonics. This evidence has led to difficulties in gathering palaeocurrent data; however, a few potential exposures revealed flutes and grooves structures in Facies 2 and Facies 3, while some paleocurrent measurements could also be made. About 20 strike data were retrieved from the study area, and some of them showed similar direction patterns in terms of apparent magnitude within the possible range of 0°-90° and 180°-270°.

All of the data were presented in rose diagrams using Rose.Net software version 0.10 with a class size of 30°. A rose diagram is easy to analyse due to the dominant strike data accumulation. Based on the possible results from the rose diagrams, the paleocurrent direction was successfully interpreted to be in NE directions (i.e. mean vector) on the area according to the dominant data plotted in that direction. This suggests that the sediment from the study area was transported and deposited in the NE direction (Figure 15).

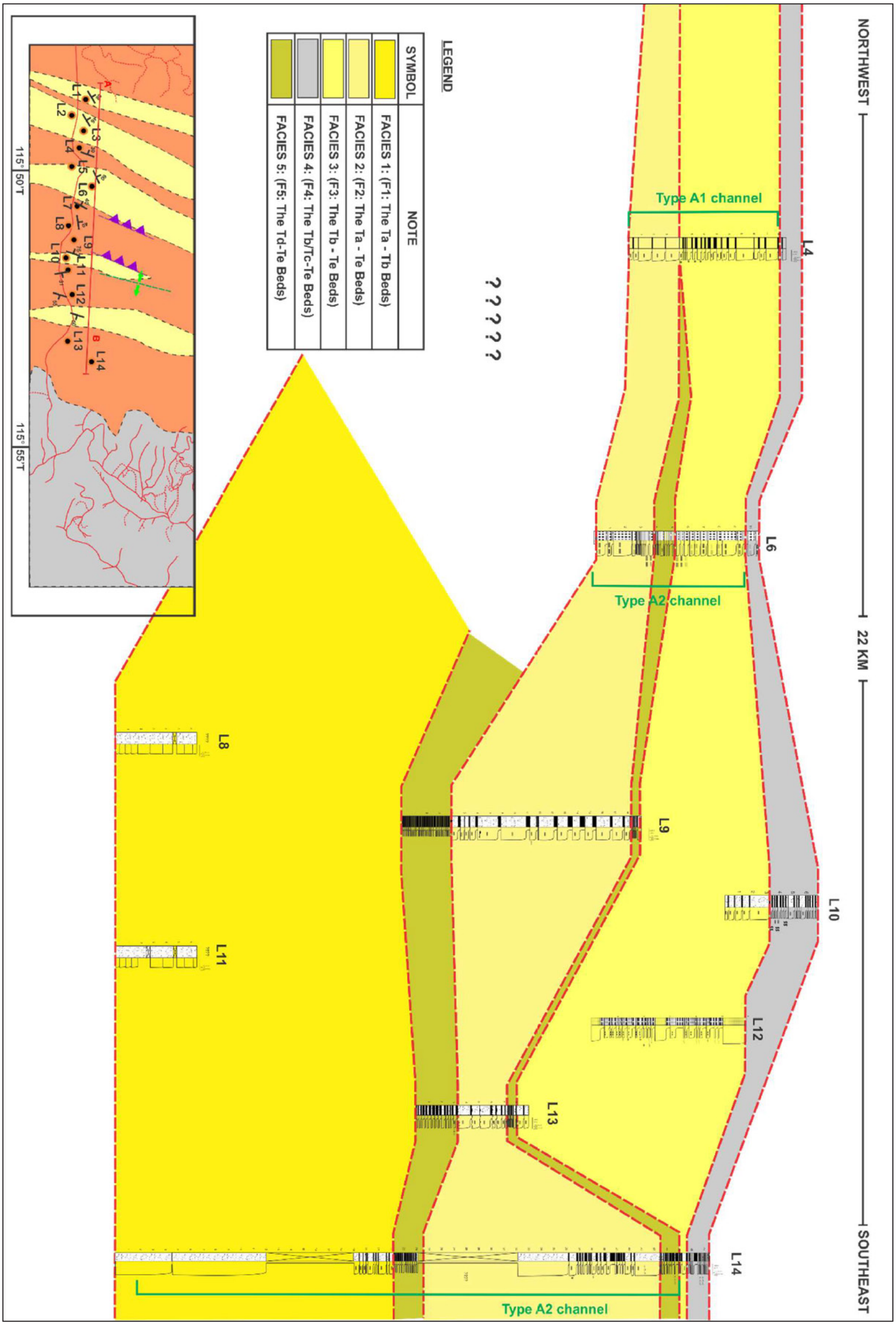

Figure 14: A correlation section of the Paal area properly showing the west-east transect from Locality 1 (L1) to Locality 12 (L12). Some of the localities are not included in the correlation section because the author is only focused on the Crocker Formation's outcrop. The localities available for the correlation are L4, L6, L8, L9, L10, L11, L12, L13, and L14. Other locality i.e. L1, L2, L3, L5, and L7 are related to the Temburong Formation and are not included in the correlation section. However, the Crocker Formation typically interfingers with the Temburong Formation, as shown in Figure 1.

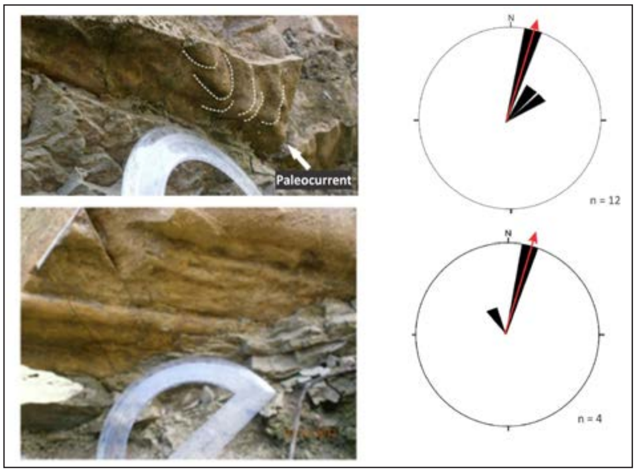

Figure 15: A typical flute and groove cast exposed in Facies 2 of the Crocker Formation. The rose diagram on the right-hand side displays a distinct current direction pattern using data from flute and groove cast.

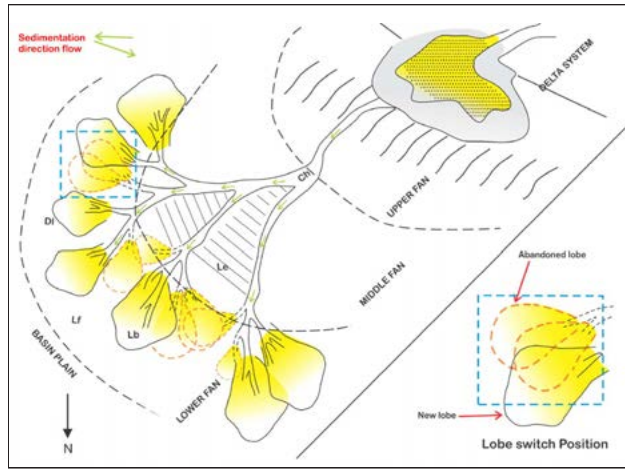

Figure 16: A depositional model of the Late to Middle Miocene Crocker Formation in the study area is revealed. A reliable source of sediment is believed to have derived from the delta system and intentionally brought to the middle and outer fan lobe. The illustration in the small box on the lower right-side indicates lobe abandonment or an inactive lobe that can happen due to low transport efficiency of the sediment.

DEPOSITIONAL MODEL

The ideal combination of individual facies analysed above has resulted in a proper interpretation of a large depositional system with micro-environmental variations in a deep marine basin. Accordingly, Facies 1 was interpreted as deep-marine axial channel deposits, Facies 2 as deep-marine marginal channel and ordinary lobe deposits, Facies 3 as deep-marine levees, and Facies 4 as distal lobes of a submarine turbidite fan. The channel-levee, channel-lobe, and distal lobe association were the results of all of the interpreted facies accumulated within a single fan. Figure 14 shows the model that we propose to illustrate evidence within the middle- to outer-fan turbidite system. The abundance of thicker and amalgamated sandstone beds typically indicated that rapid deposition current naturally occurs in the deep marine channel. Due to the overflow of the sediment, the small size of bedding called levee formed an upward-thickening pattern. The sediment was then transported away from the main channel to the channel mouth and deposited as a thicker bed called a lobe. The lobe may also be coarsening upwards due to the progradation of the sediment.

Abundant channel fill deposits in the Crocker Formation with medium- to fine-grained sandstones suggested that the sediment was derived from a large progradation of a delta. This channel of the Crocker Formation links the delta to the outer-fan lobe. Additionally, the fluxo-turbidite is unlikely to have occurred in the Crocker Formation, thus indicating that the slope was not too steep, and the gravity flow was moderate. The North-East oriented Crocker Formation was accurately calculated from the several structures measured. Two essential aspects can be seen through this orientation: 1) the distribution of turbidite facies and 2) the paleoflow direction, where the reliable sources of the sediment were previously dispersed.

The relationship between the two types of channels is evident from the lateral correlation (i.e. lateral gradation) or transition of the Crocker Formation. The research area was dominated by the Type A2 channel, laterally grading into the Type A1 channel, while Type A2 typically alternates with Facies 4, levees (overbank). The abundance of the Type A2 channel at the field can be suggested as a depositional lobe as it consists of both channels and levees. This depositional lobe has been interpreted as deposited in the inner-fan system. However, the Type A1 channel consists of a distributary channel and mainly ordinary lobe without creating a levee; hence, it is interpreted as deposited in the middle-fan system. Lobe abandonment or inactive lobe can happen due to the low transport efficiency of the sediment that makes a transition from coarse to fine grain size, and subsequently blanket by mud or silt particles (Figure 15). Strata formed by these systems consist of thick, moderately extensive packages of sandy high-density turbidites separated by mud layers that represent the periods of lobe abandonment (Nichols, 2009).

Based on the discussion above, these depositions can be envisaged as part of a large submarine fan of the Crocker Formation, where the palaeoenvironment ranged from the middle- to outer-fan turbidite system (Figure 16).

CONCLUSIONS

The general conclusions that can be typically derived from this study are:

1) Based on the facies analysis of the Crocker Formation, it is comprised of four facies namely Facies 1 (F1: T_a-T_b beds), Facies 2 (F2: T_a-T_e beds), Facies 3 (F3: T_b-T_e beds), Facies 4 (F4: T_d-T_e beds), and Facies 5 (F5: T_c-T_e

Table 1: Detailed explanation about facies exposed in the Crocker Formation using Bouma sequence division.

Facies Criteria	**Facies 1 (F1: T_a - T_b Beds)**	**Facies 2 (F2: T_a-T_e Beds)**	**Facies 3 (F3: T_b-T_e Beds)**	**Facies 4 (F4: T_d-T_e Beds)**	**Facies 5 (F5: T_c-T_e Beds)**
Geometry	Amalgamated, stacked and thick bedded sandstone.	Fining/thinning upward sequence (FUS). Large scale.	Coarsening/thickening upward sequence (CUS). Large scale	Coarsening/thickening upward sequence (CUS). Small scale.	Coarsening/thickening upward sequence (CUS).
Lithologies	Amalgamated and thick bedded sandstone.	Interbedded sandstone and shale. (Thick to thin bedding)	Interbedded medium sandstone and shale. (Thick to medium bedding)	Interbedded siltstone and thick shale. (Thin bedding)	Interbedded siltstone and thick shale. (Medium to thin bedding)
Sedimentary structures (according to Bouma sequence)	T_a-T_b units - Massive sand to parallel lamination (obscure). Other units were missing.	T_a-T_e units - Graded sands, parallel lamination, cross lamination or ripple lamination, mud lamination and hemipelagic mud.	T_b-T_e units - Parallel lamination (rare), cross lamination or convolute lamination, mud lamination and hemipelagic mud. T_a unit not exist due to the lack of sediments supply.	T_d-T_e units - Mud lamination and hemipelagic mud. Excessive source of sediment supply from the main channel due to the rapid energy of deposition.	T_c-T_e units - Cross lamination (ripples), mud laminae and hemipelagic mud. A rhythmic bedding and abundance of shale indicates that the deposition occur in distal lobe.
Pre-deposition (sedimentary structure)	Channel	Channel, bounce effect, flute and groove.	Bounce effect, flute and groove.	No.	Groove
Trace fossil	Not recorded.	Some species recorded e.g. *cosmohaphe sp.* and *Helminthopsis sp.*	Recorded but limited exposure.	Bioturbation recorded but not too extensive.	Bioturbation recorded but not too extensive.
Micro fossil	Not recorded in any shale exposed.	Some species of planktonic and benthic foraminifera.	Planktonic foraminifera (dominant)	Not recorded	Some species of planktonic
Paleocurrent direction	Bedding measurement trending northwest-southeast.	Flute measurement: northwest.	Flute measurement: northwest.	-	Groove measurement, ripples cross lamination: northwest.
Interpretation	Main channel (A1).	Distributaries channel (A2).	Distal lobe.	Levee.	Distal Lobe

beds). Every distinct unit of proper Bouma sequence prominently displays various patterns of sedimentary structures related to turbidity current activity. Specific data of the Crocker Formation and its facies are listed in Table 1, with some facies associations derived from facies analysis interpreted as channel-lobe facies, channel-levee facies, and distal lobe facies associations.

2) Facies adequately representing deposition in the middle to outer fan turbidite system are characteristic of the Crocker Formation.

ACKNOWLEDGEMENTS

This paper has benefited from discussions with and comments from fellow geologists inside and outside of the Geology Department, Universiti Malaysia Sabah, and Universiti Malaysia Terengganu. We appreciate the constructive feedback received from the respective reviewers that has significantly improved the quality of the manuscript.

AUTHOR CONTRIBUTIONS

MNIAR conceptualized the research, developed the methodology, performed the analysis and prepared the original draft. HJ designed the model and computational framework. MA provided the software, resources and data curation. IAR supervised the research. SHT supervised the research and edited the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

CONFLICT OF INTEREST

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

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Manuscript received 2 May 2019;
Received in revised form 30 October 2020;
Accepted 19 November 2020
Available online 16 November 2021