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Sedimentological Analysis of Thin-Bedded Sequence of Eastern Part of West Crocker Formation, Northwest Sabah, Malaysia

(Analisis Sedimentologi Jujukan Selang Lapis Nipis di Bahagian Timur Formasi Crocker Barat, Barat Laut Sabah, Malaysia)

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Abstract

It has been suggested that the eastern part of the West Crocker Formation is the slope to the inner fan of a deep-water system. Detailed sedimentological examination of eight outcrops of this formation in this study identified four types of facies: interbedded sandstone and mudstone facies (F1), chaotic facies (F2), and mudstone facies (F3). The immature textures and deformations with rolled-over sandstone block deposits occur as infers due to the presence of an angle of loose sediments, while the repeated thinly bedded sandstones and mudstones were recognized as levee-channel complexes. The overbank was identified as thick mudstone deposits. The sandstone deposits are synonymous with strong energy carried by the head of the turbidity current, while the fine to very fine sediment grains are typical of sediments that are carried by the body and tail of turbidity current and may deposited far away from the first deposition of sand. All the characteristics presence in the environment of slope are to the inner fan of a deep-water system with deformed structures. This deformed slope is believed to be part of a late Eocene accretionary complex formed during the Sabah orogeny.

Keywords: Crocker Formation; deep-water; mass transport deposits; Paleogene

Abstrak

Bahagian timur Formasi Crocker Barat merupakan cerun hingga kipas dalam sistem pengendapan laut dalam. Penilaian sedimentologi secara terperinci ke atas lapan lokaliti singkapan batuan telah mengelaskan kawasan kajian kepada tiga jenis fasies iaitu: fasies selang lapis batu pasir dan batu lumpur (F1), fasies terkacau (F2) dan fasies batu lumpur (F3). Tekstur yang tidak matang dan canggaan yang tinggi dengan kehadiran blok-blok batu pasir di dalamnya terbentuk disebabkan kehadiran satah cerun pada enapan sedimen yang longgar, manakala selang lapis batu pasir dan batu lumpur yang terbentuk di dalam singkapan kawasan tetambak. Kehadiran lumpur tebal pula dikenal pasti sebagai singkapan yang terbentuk di kawasan dataran lembangan. Pengendapan sedimen bersaiz pasir adalah sinonim diangkut melalui tenaga yang kuat di bahagian kepala arus keruh, manakala butiran sedimen berbutir halus boleh diangkut melalui badan dan ekor dalam arus keruh dienapkan di kawasan yang lebih jauh daripada pengendapan batu pasir. Kesemua ciri yang ditunjukkan pada singkapan yang dikaji membuktikan kawasan kajian merupakan kawasan cerun hingga kipas dalam di dalam sekitaran pengendapan laut dalam yang tercangga. Cerun yang tercangga ini dipercayai sebahagian daripada kompleks akresi berusia lewat Eosen terbentuk semasa Orogeni Sabah.

Kata kunci: Enapan angkutan jisim; Formasi Crocker; laut dalam; Paleogen

Introduction

The Crocker Formation forms part of a subduction-accretion complex on the margin of the South China Sea beneath the north Borneo-Luzon arc. The subduction of this complex initiated the deposition of the Rajang-Embaluh Group accretionary complex, the result of continuing tectonic activity, which was uplifted, folded, and eroded to create a major unconformity 36 Ma during the Late Eocene (Hall 2002, 2001, 1996; Honza, John & Banda 2000; Hutchison, Hall & Blundell 1996; Hutchison 2004; Tongkul 1991). Northeastern to southwestern (NE-SW) ongoing outboard subduction and compression of the accretionary complex formed a new uplifted Rajang-Embaluh Group (Hall 2002; Hazebroek & Tan 1993; Tongkul 1991; Wang et al. 2016). This new complex comprises the Crocker Formation, which has been interpreted as sand-dominated facies (Zakaria et al. 2013).

During early Miocene rifting, the eastern part of Sabah was supplied with shallow marine sediments. This increase in sediment caused the collision of the Reed Bank terrane with the new Rajang-Embaluh Group, triggering the uplifting of the Crocker Formation. During the Middle Miocene, northwest Borneo was uplifted by the ongoing subduction of the margin of the South China Sea. This ongoing subduction caused the deformation, folding, imbrication, and NE-SW thrusting of the Crocker Formation bedded sediments (Hall 2013; Leong 1999; Tongkul 2015, 1995, 1991).

The Crocker Formation comprises Early Paleogene sandstone, siltstone, and mudstone sediments (Hall & Nicholas 2002; Hutchison 2005; Jamil et al. 2021; Lambiase et al. 2008; Leong 1999; Liechti et al. 1960; Zakaria et al. 2013), including sand-dominated debris flow deposits and heterolithic siltstones and mudstones. These show complete and incomplete Bouma sequences, reflecting the architecture of inner, middle, and outer fans deposited in a deep-water depositional environment (Jackson et al. 2009; Zakaria et al. 2013). The deep-water depositional environment is dominated by high to low turbidity currents, mass transport deposits, and debrite and co-genetic debrite deposits (Jackson et al. 2009; Jamil et al. 2021; Tongkul 2015; Zakaria et al. 2013).

This is a detailed sedimentological analysis of eight outcrops located along the Pan Borneo Highway that is part of the Eastern Crocker Formation. This study focused primarily on the geometries and architectural elements of the deep-water sand-dominated fan systems of the Crocker Formation. The sediments in the outcrops are predominantly thin-bedded with chaotic textures, implying tectonic activity. This publication attempts to analyze this area utilizing the thin-bedded sequences as research materials since no such detailed mapping and evaluation has been done and published, other than Tongkul 2015. The characteristics are summarized in terms of Bouma (1962) and Lowe (1976) standard facies sequences. The ambiguities in the interpretation have been highlighted, however it must be acknowledged that precise differentiation is not always achievable on the basis of sedimentary characteristics alone (Stow & Smillie 2020). The regional scale of association and small-scale sedimentary facies observation are the scale approaches to distinction for the study area.

METHODS

The extensive geological fieldwork included detailed outcrop descriptions, log sketches, and sampling at eight localities in the eastern part of the West Crocker Formation along the Pan Borneo Highway, Sabah (Figure 1(A), 1(B)). The outcrops were extensively logged and documented using the sedimentological parameters of lithology, grain size, thickness and sedimentary structures. The conventional facies sequences for the deep water depositional environment of Bouma (1962) and Lowe (1976) as well as fan systems based on Walker (1978) are used in the investigation of the outcrop. Many contemporary scholars have utilized Walker's (1978) fan model as a reference because it is well-liked. However, due to geological changes and the localized sedimentation process, each deep water turbidite characterization is likely to have different variances. Otherwise, Pickering et al. (1986) served as the foundation for the facies association, and Ghosh and Lowe (1993) provided a comprehensive systemic framework for comprehending architectural hierarchies. The framework creates a whole architecture that may be applied to virtually all depositional situations.

FIELD OBSERVATION

Eight outcrops (L1–L8) (Figure 1(B)) distributed along the Kinarut to Kawang Road on the Pan Borneo Highway were examined (Figure 1(B)). The L1 to L5 outcrops comprise equal bedding of interbedded sandstones and mudstones (Figure 2). These outcrops also contain various-sized sandstone blocks ranging from 10 cm to 50 cm. Outcrops L5 to L8 comprise sandstones, interbedded sandstones and mudstones, and mudstones (Figures 3 & 4). The outcrops in these four locations also underwent slumping.

FACIES ANALYSIS

Interbedded sandstone and mudstone facies (F1)

Description The interbedded sandstone and mudstone facies (F1) have either a 1:1 to >1:1 ratio of sand to mud, depending on the thickness and dominant sediment.

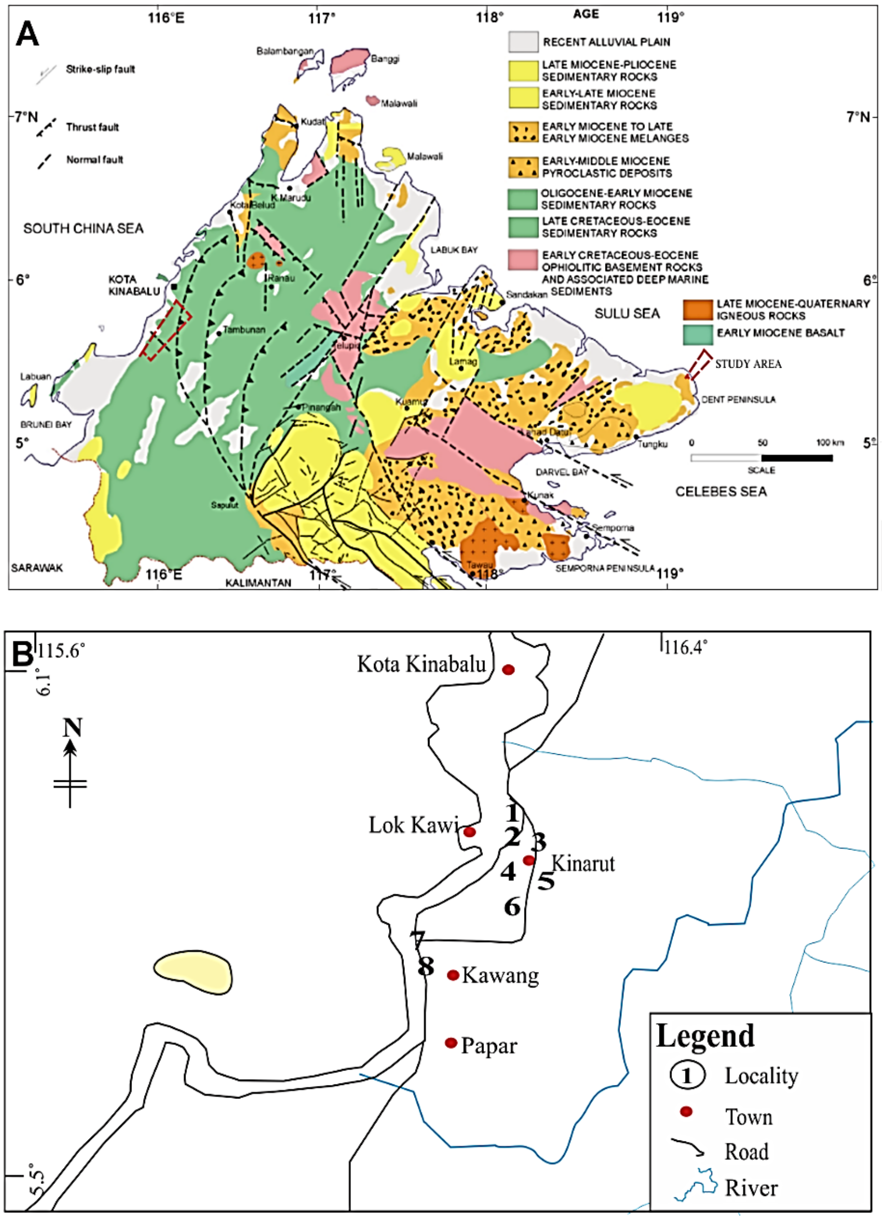

FIGURE 1. A) Location of the study area within the geological distribution of Sabah, and B) Location of the outcrops, L1 to L5 is the localities along the Pan Borneo Highway, L6 is the locality with coordinate N05.70637°/E116.01195°, and L7 with the coordinate of N05.76613°/E116.02694°

Where the proportions of sandstone and mudstone are equal, the beds range from 0.1 cm to 0.7 cm thick. Where the mudstone is dominant, the mudstone bedding is around 0.6 cm to 1.0 cm thick, while the sandstone bedding is around 0.2 cm to 0.4 cm thick. Where the sandstone is dominant, the sandstone bedding is around 0.5 cm to 1.1 cm thick, while the mudstone bedding is around 0.3 cm to 0.7 cm thick. Most beds show visible irregular upper and lower contacts with common sedimentary structures found with wavy and parallel laminations. However, no trace fossils have been found in this facies 1 (F1).

FIGURE 2. Characteristic examples of lithofacies encountered in the study area; A) Visual of sandstone blocks in red dashed in the beds shows sandstone blocks embedded in chaotic facies in L1, B) Interbedded sandstone and mudstone with slumping structures at L3, and C) Interbedded sandstone and mudstone facies at L4

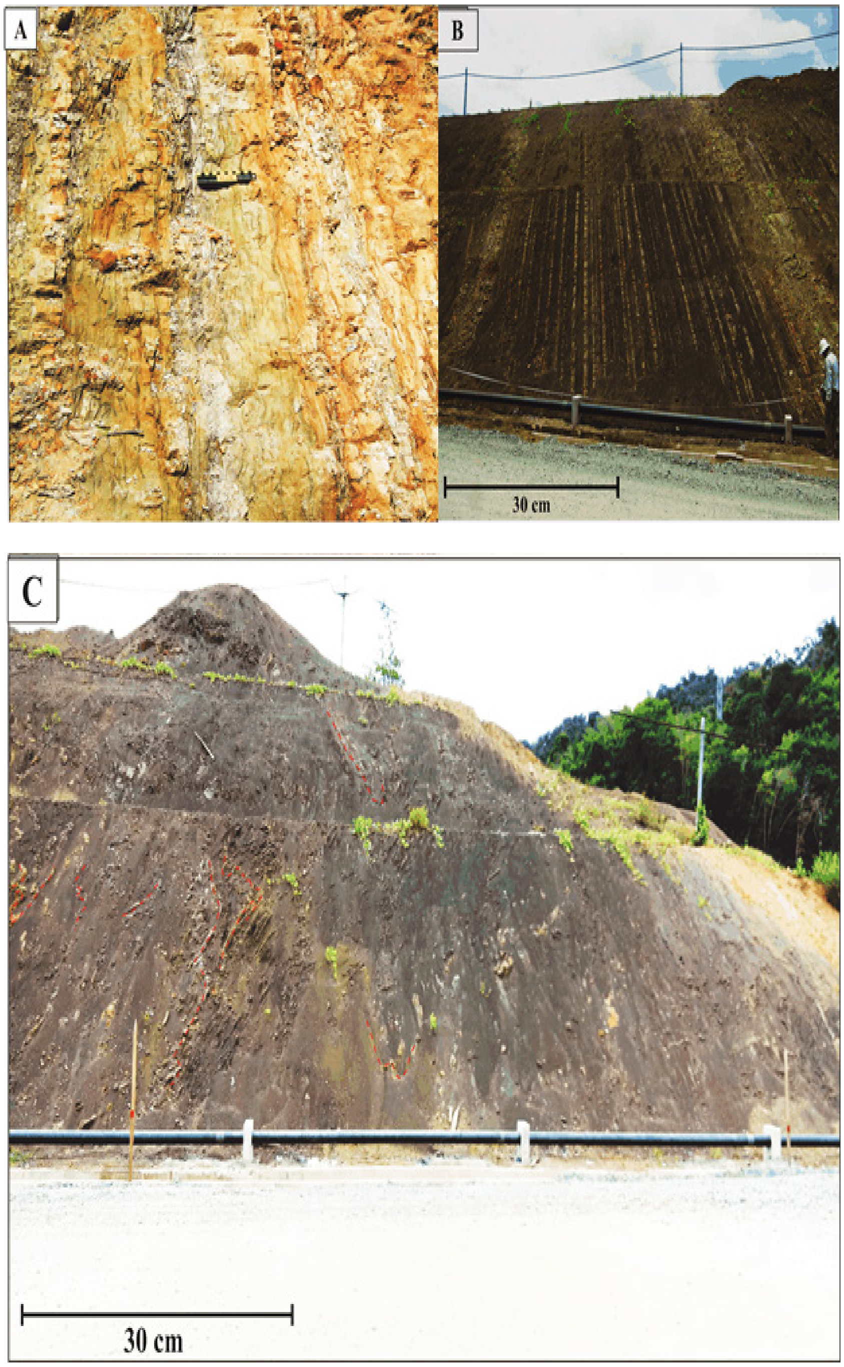

FIGURE 3. Examples of sedimentary bedding in the study area. A) Close-up view of interbedded sandstone and mudstone with some chaotic beds in L2, B) Thinly interbedded sandstone and mudstone facies at L6, and C) Thinly interbedded sandstone and mudstone with slumping and chaotic structures in L6

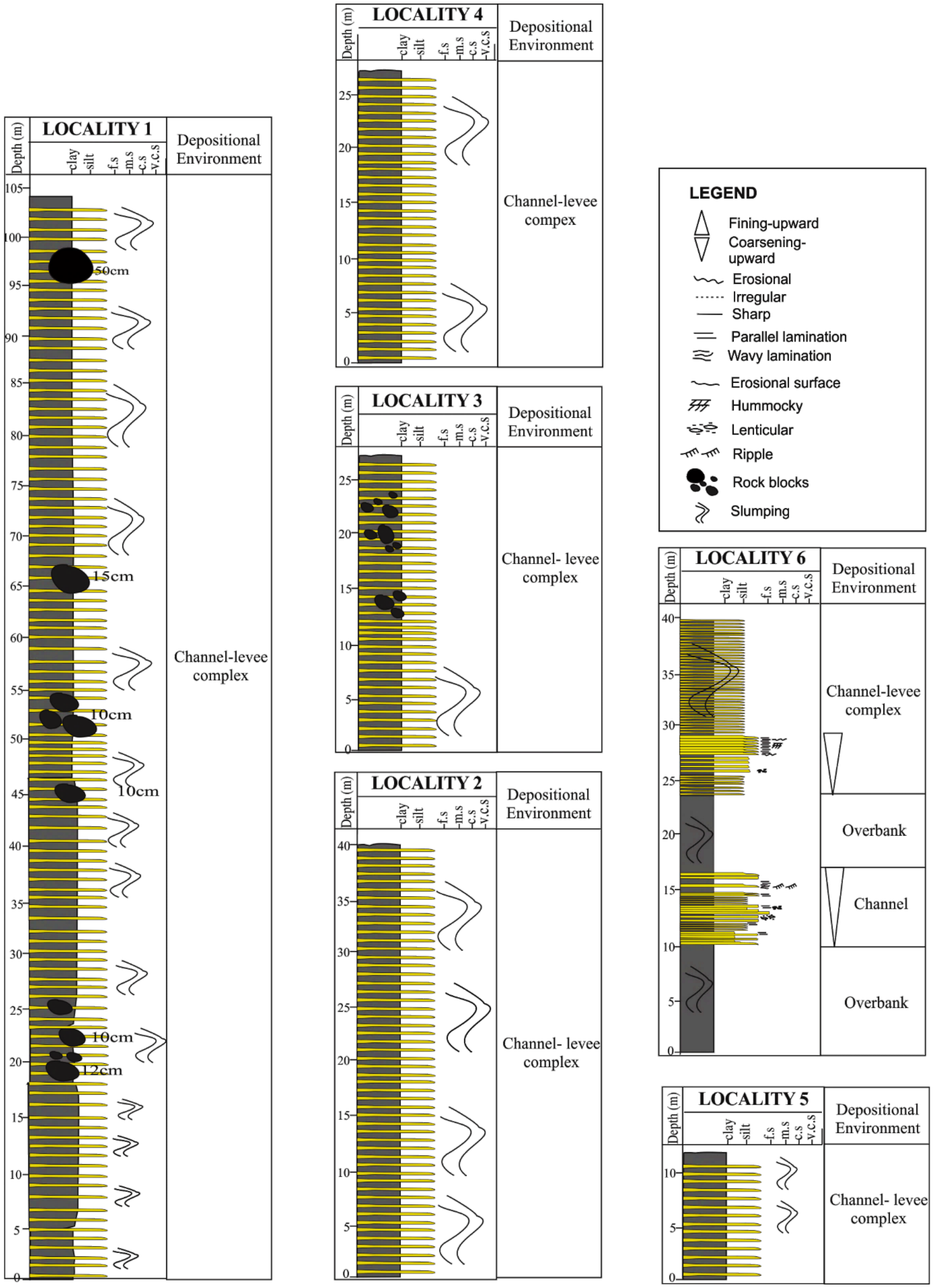

FIGURE 4. Sedimentary log of L1 to L6, east region of northwest Crocker Formation

Interpretation Interbedding occurs due to the couplet deposition of sandstone and mudstone during transition processes (Basilici & Vidal 2018) or modification of current energy and velocity during the deposition process (Prothero & Schwab 2004), possibly from low-density turbidity currents or debris flow. This type of facies also be formed as products of contourite and tidal processes. Contourites usually show deposits mixed between sandstone and mudstone, resulting from the movement of currents under the flow (Rebesco et al. 2014) below the storm wave base.

Based on observations of outcrops in the field, no reverse-graded facies overlapped with normal-graded facies, which indicates that the existing sediments are the result of contourite deposition. The presence of sedimentary structures such as planar cross stratification, hummocky and high bioturbation index that normally formed as a result of tidal currents are not found in the layers. Meanwhile, a comparison of these facies with the Bouma sequence (1962) shows the division of this interbedded sediment fall into T_d and T_e sections. With the presence of parallel lamination structures also found in the layers of mudstone, siltstone and sandstone in this facies interval, it clearly proves that the deposition of sediments took place in the lower flow regime which is the turbidite current with low density (Leeder 1999). Sediment is transported by means of beds load of sandstone layers, but in lower turbidite currents because the sandstone formed is thinner and finer-grained (Mulder & Alexander 2001). Wavy lamination structures are interpreted to be formed by currents moving in an oscillatory direction (Chaudhuri 2005).

Chaotic facies (F2)
Description These facies have very similar characteristics to F1 (interbedded sandstone and mudstone) but consist of boulders of varying sizes up to several meters (10 cm to 50 cm) (Figure 2(A)). It shows immature textures and is poorly sorted with heterogeneous grain sizes from coarse sand to silt and mud. The boulders are mostly rounded, but can sometimes be angular. These facies are characterized by a very chaotic organization and the absence of any stratification (Figure 2(B), Figure 3(C)). They also show disordered material with contorted, slumped, and disharmonious folds (Figure 3(C)).

Interpretation These facies exhibit the same depositional processes as F1. The deposition of the sediment grains is related to the settling velocity, grain diameter, and kinematic viscosity (Cheng 1997), and the time interval variable controlled the length of the sedimentation process resulting in different thicknesses of the sediments. The chaotic organization and the absence of stratification suggest a significant plastic deformation and transport over at least a small distance, allowing the destruction of the original bedding. Meanwhile, the disorganized material probably implies that tectonic activity occurs during and after the deposition of sediments (Shan et al. 2021).

Mudstone facies (F3)
Description The mudstone facies are exhibited in two tones which are greyish and reddish. Both comprise silt- to mud-sized fine-grained bedded sediments that display parallel lamination without bioturbation. Ranging in thickness from 0.7 m up to >10 m (thin to very thick), the greyish color was found in almost all the sampling localities while the reddish color was found in L7 and L8.

Interpretation Mudstone, fine-grained sediment (0.125 to <0.063 mm), is usually deposited in a pelagic or hemipelagic environment. It also may result from the deposited of tail sediments from turbidity current, commonly transported beyond by suspension processes (Boggs 2001) before being deposited in open, calm marine areas.

The mudstone exhibits a physical difference in terms of its color, caused by the chemogenic process, the chemical alteration of minerals (Pickering et al. 1986; Tucker 2001) to either grayish or reddish. The gray color, is an indicator of more than >1% organic matter, while the reddish, indicates the oxidation of iron in the mud. The presence of parallel and wavy lamination indicates the influence of water movement during the deposition process. Generally, the deposition of F3 was not affected by current energy, and appears to have been deposited in calm, open areas.

FACIES ASSOCIATION

Facies association A: Channel-levee complex
Description Facies association A consists of F1 and some of them are present of F2 (Figures 4 & 5). The channel-levee complex exhibits a continuous layer of thin interbedded sandstone and mudstone. The beds show repeated Bouma T_d to T_e divisions. This depositional area was exposed to continuous couplets of low- and medium-energy transitions, which emplaced thin interbedded sandstones and mudstones.

Interpretation In general, turbidite currents in the channel have the ability to slow down and overflow when numerous and concentrated sediments are present (Bowen, Normark & Piper 1984). These levee deposits have a fining-upward sequence with a variety of amalgamation configurations and sediment thicknesses. The sediment deposition is fine-sized sediment such as silt and mud with thin layers, and this morphology is the result of turbidite currents spilling out of the channel (Kane & Hodgson 2011; Morris et al. 2014). The concentration and flow patterns may cause repeated Bouma T_d to T_e.

Facies association B: Overbank

Description These facies, consisting of mudstone facies (F3) (Figure 4), pelagic sediment that resulted from the falling of suspension-transported very fine sediment. The deposited finest sediments may be from the tail of turbidity currents, spread to various directions, and exhibit a wide range of thicknesses.

Interpretation The development of overbank deposits is concurrent active sediment transport, bypass and deposition of coarser-grained material in a channel. The overbank bedforms are sedimentary structures that are suggestive of initially Froude-supercritical flow conditions and a progressive waning of flow strength and found above an erosion surface (McArthur et al. 2020). A different interpretation of this facies transition may represent autogenic compensational stacking. The assumption that deep-water mudstones are predominantly the deposits of passive rainout along continental edges is challenged by the ubiquity of sediment density flow deposits, especially in positions distal or lateral to the sediment entry point (Boulesteix et al. 2019).

DISCUSSION

This sedimentological analysis showed that the eastern area of the Crocker Formation was predominately deposited by turbidity currents (Figure 5), as has been described in previous studies (Azfar, Abdul Hadi & Mohd Suhaili 2015; Jackson et al. 2009; Jamil et al. 2021; Stauffer 1968; Tongkul 1990; Tracy, Sanudin & Junaidi 2018; Zakaria et al. 2013). Most beds show incomplete Bouma sequences with visible irregular upper and lower contacts. Parallel lamination indicates that sediment deposition took place during the low energy of a low-density turbidity current in T_d division (Bouma 1962; Leeder 1999; Shanmugam 1997; Talling 2014). The area's thinner and finer-grained sandstone beds were probably transported by traction above the bed in low- energy turbidite currents (Bouma 1962; Mulder & Alexander 2001).

The presence of interbedded sandstone and mudstone is usually formed by the deposition of low-energy currents and pelagic suspensions. Embedded along these facies are the large to small-sized sandstone blocks causing the interbedded to exist in chaotic forms (Figure 4) and some of them are present in the deformed structures (Figure 5). A part of these characteristics, suggests that this environment has been impacted by the company of angle and tectonic movements which caused the sliding of loose sediments into the bedded sediments, or the emplacement of fallen blocks from slopes during debris flows or mass transport events (Carter 1975; Caussot & Meunier 1996; Talling 2014), resulting in the random disruption and consequent settlement of the sediments.

Besides, the presence of immature textures and very poor sorting observed in the outcrops suggest a nearby sediment source and a short transport distance. No trace fossils were found, as these were doubtless damaged or hidden due to slumping and the falling of various-sized blocks after slope failures (Figure 5) resulting from the development of scarps near inner fan slopes (Figure 6). The blocks seen in the outcrops are likely fan-slope sediments that randomly entered the depositional area and greatly disturbed the sedimentary deposits. Normally, the rotational slumps and floating sandstone blocks suggest the deposition of sediments due to gravitationally unstable slope conditions (Fakhruddin 2021; Madon 2010; Shan et al 2021). All the sedimentary characteristics observed in the outcrops were consistent with deposition in a deep-water slope (Figure 6). This area can be interpreted as a low-efficiency system rich in sandstone (Richards, Bowman & Reading 1998), affected by subsidence and block sliding.

The combination of criteria indicates that the slope formed a ductile structure (Elliot & Williams 1988). The composition of clasts is dominated by very fine grain size demonstrating that the lithification process occurred before deformation. The formation of this slope also probably due to the mass transport of <5 m in thick of the sediment (Jackson et al. 2009; Zakaria et al. 2013), was identified as being consistent with the result of slope failure during the formation of the Crocker Formation accretionary belt.

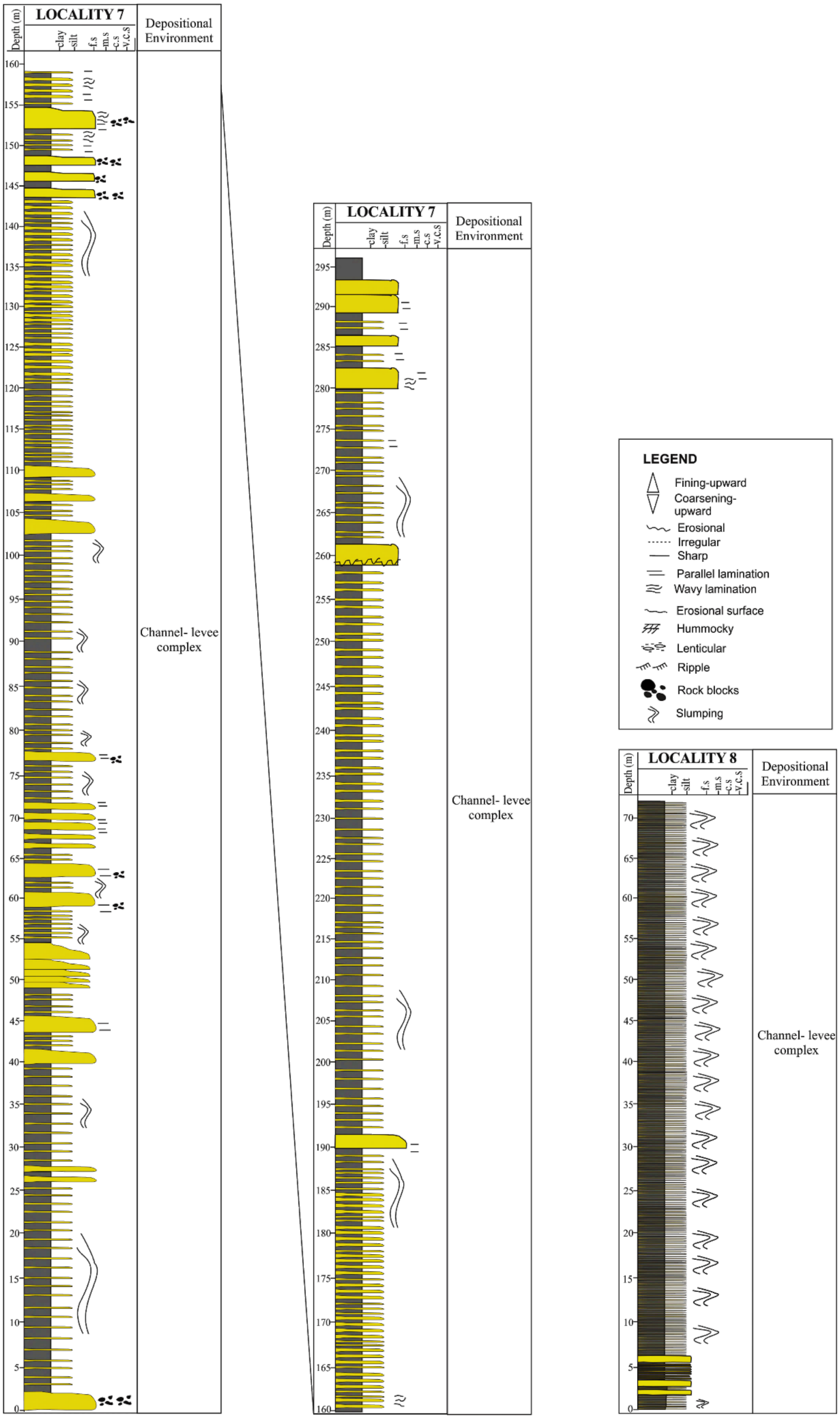

FIGURE 5. Sedimentary log of L7 to L8, east region of northwest Crocker Formation

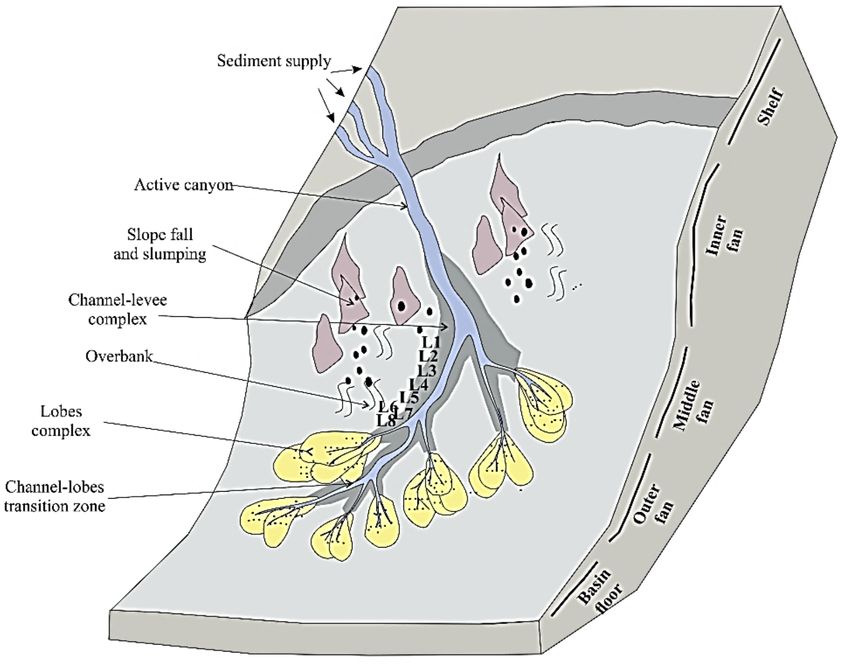

FIGURE 6. Schematic depositional environment of the study area. L1 to L8 are basically deposited near the slope with the sub-depositional environment of the channel-levee complex. L6 shows some characteristics of the overbank present by thick sedimentation of mudstone facies. Most of the area was deformed due to tectonic activity and there also present of sedimentary blocks also fell near the interbedded sandstone and mudstone deposits

Conclusion

The depositional environment was recorded as deep water in the eastern portion of the West Crocker Formation. The three facies that make up the sedimentological study are (i) the interbedded sandstone and mudstone facies (F1), (ii) the chaotic facies (F2), and (iii) the mudstone facies (F3). Then, the facies were divided into two facies associations, namely, overbank and channel-levee complex (facies association B). The channel-levee complex, which consists of F1 and F2, was created in a layer of mudstone and sandstone that is interbedded thinly, with repeated T_d to T_e Bouma division. The overbank deposits, meanwhile, are made up of F3 mudstone that has a wide range of thicknesses. The examination of the outcropping eastern Crocker Formation indicated that the sediments were deposited as slope failures that occurred during the formation of the Crocker Formation accretionary belt, possibly beginning in the Late Eocene. This appears similar to previously reported indeterminate, giant mass transport deposits in the Kawang area by Tongkul (2015). Future investigations might benefit from focusing on new tectonic evaluations and mass deposit traces in the Crocker and Temburong Formations in Northwest Sabah, from Labuan Island to Brunei Darussalam.

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