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Wave-tide depositional setting on the Middle to Late Miocene outcrops in Miri, Sarawak and Brunei Darussalam, Northwest Borneo

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Abstract: The Northwest Borneo basin has recently garnered significant attention from researchers across various fields, with a primary focus on both onshore and offshore geology. The Miri, Lambir, and Belait Formations are the principal study areas, with specific emphasis on aspects related to oil and gas. In this study, sedimentological analysis has identified two predominant groups of lithofacies: wave-generated lithofacies and tide-generated lithofacies. The wave-generated lithofacies include occurrences of lithofacies such as planar, swaley, and hummocky cross-stratified sandstone, primarily associated with wave-dominated shoreline deposits. These have been grouped into five lithofacies associations (LA): foreshore (LA 1), lower shoreface (LA 2), middle shoreface (LA 3), upper shoreface (LA 4), and upper offshore (LA 5). On the other hand, tide-generated lithofacies are represented by numerous heterolithic structures and herringbone cross-stratified formations, further categorized into lagoon (LA 6), tidal sandbar sandstone (LA 7), tidal to sub-tidal sand flat (LA 8), and sub-tidal mud flat (LA 9). The percentage of wave-tide activity suggests that both events are nearly equivalent, with the outcrop predominantly displaying either wave or tide deposits based on the observed sedimentary structures. The paleocurrent analysis suggests that the regional paleocurrent direction was either northeast or southwest. Consequently, the siliciclastic detritus was sourced from the Rajang Group. Tidal activity is believed to have occurred during mean sea level and is preserved in the wave sediment. Therefore, the study suggests that the deposition within the study areas occurred within the range of the outer part of the estuary (i.e., open-mouth area) to a shallow sandy sea.

Keywords: Miri Formation, Lambir Formation, Belait Formation, lithofacies analysis, estuary

INTRODUCTION

Northwest Borneo comprises North Sarawak, Brunei Darussalam, and the western area of Sabah. During the Miocene age, these regions were partly covered by shallow marine sediment (coastal deposits) (Leong, 1999; Madon, 1999; Wannier *et al*., 2011), displaying dominant facies characteristics associated with marine environments, including lagoonal facies, foreshore, and shoreface facies (Rahman & Tahir, 2019). Abundant sedimentary structures, particularly the swaley-hummocky cross-bedded sequences, confirm the shallow marine environment of documented outcrops in the study area (Rahman & Tahir, 2017; Collins *et al.*, 2017). Tidal sedimentary features are also evident in the study area (Rahman & Tahir, 2017; Roslim *et al*., 2020) and are distributed as major or minor lithofacies in Northwest Borneo (Collins *et al*., 2014; Rahman & Tahir, 2019), collectively presented as heterolithic lithofacies. Noteworthy structures like flaser, wavy, and lenticular bedding, recorded in various scales and geometries, suggest the interplay of wave and tidal regimes at different water depths and current intensities.

The study focuses on two main areas, North Sarawak and Brunei Darussalam (Figure 1 (A)), actively investigated by researchers from diverse fields for hydrocarbon exploration purposes (Madon, 1997; Wannier *et al*., 2011; Jong *et al*., 2017). Previous reports on the formal lithostratigraphic units, namely the Miri, Lambir, and Belait Formations, interpreted them as fluvial to deltaic environments (Rijks, 1981; Balaguru & Lukie, 2012; Collins *et al*., 2020). However, observations reveal widespread distribution of shallow marine sediments along the coastal area from Miri to Brunei Darussalam, with hummocky-swaley cross-bedding being a common sedimentary structure (Rahman & Tahir, 2018; 2019). Intermittent layers with tidal sedimentary structures are also present in wave-dominated regimes.

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Wave-tide deposits are prevalent throughout the bedding sequence, with the Miri and Belait Formations predominantly exhibiting wave-dominated lithofacies and various heterolithic bedding. The Lambir Formation, on the other hand, is primarily composed of tide-generated lithofacies and some wave-generated lithofacies. In this study, lithofacies descriptions are detailed based on locality (i.e., measured outcrops) rather than formation, as the lithofacies share equivalent appearances, distributions, and exposure locations. This approach aids in better understanding the relationship between lithofacies and depositional settings, contributing to the elucidation of lithofacies, the interpretation of lithofacies associations, and sedimentary environments. Furthermore, the study aims to establish a depositional environment model as the final result of lithofacies analysis.

GEOLOGICAL SETTING

The Northwest Borneo basin surrounded by three active plates, namely the Indian-Australian Plate, the Eurasian Plate and the Philippine Sea Plate. Various researchers, including Hamilton (1979), Hall & Nichols (2002), Hutchison (2005), and Hall (2013), have previously highlighted the complex and debated geological history of Borneo. According to Hall (2013), the uplift of the Borneo land resulted from the collision of the Luconia microcontinental block, originating from the north, with the West Borneo Basement, part of Sundaland in the south. The Early Miocene (20-15 Ma) witnessed deep marine sediment erosion and intense tectonic events, leading to the leveling of mountains in Sarawak. Subsequently, sediment distribution covered northern Sarawak as shallow marine deposits toward the southwest. The Middle Miocene phase played a crucial role in the region's stratigraphical-structural evolution, marked by the Deep Regional Unconformity or Middle Miocene Unconformity. This event occurred as the Luconia Block drifted and collided with the crust of central Borneo. The emergence of the Rajang Mountains during the Middle to Late Miocene resulted in the formation of sand-rich deltas (Baram and Champion delta) and embayment, representing a shallow marine environment associated with the Lambir and Miri Formations. Liechti *et al*. (1960) described the Lambir, Tukau, and Miri Formations as sand-rich sediments grading laterally into one another (Figure 1 (B)). The Lambir Formation exhibits an alternation of sandstone and shale with a distinctive calcareous admixture, including limestone and calcareous shale. Hui & Leman (1994) conducted a study on the Lambir Formation in Ulu Bok Syncline, recognizing lithology units consisting of interbedded sandstone and shale with minimal mudstone and siltstone. Facies analysis of the Miri Formation by Tan *et al*. (1999), Hutchison (2005), and Teoh & Rahman (2009) revealed various sedimentary facies, including trough cross-bedding, herringbone cross-bedding, hummocky-swaley cross-stratified, flaser-wavy bedding, lenticular bedding, planar stratified, and parallel laminated sandstone. Liechti *et al*. (1960) concluded that these sediments were deposited in the littoral to the inner neritic shallow marine environment based on marine microfauna and lithological characteristics. Hutchison (2005) interpreted the Miri Formation as a result of sedimentation in a tide-dominated estuary.

STRATIGRAPHY

Belait Formation

According to Hutchison (2005), the Belait Formation in Brunei Darussalam consists mainly of interlayered thick-bedded sandstones and clays. Similarly, Curiale *et al*. (2000) mention that the Belait Formation consists predominantly of sandstone successions with interbedded shales and coals. It spans from the Early to Late Miocene and comprises the entire Champion Delta deposition system in Brunei. The type locality of the Belait Formation is situated along the Belait-Berakas flanks in Brunei and Limbang in Sarawak (Liechti *et al*., 1960). Hutchison (2005) stated that the outcrop of the Belait Formation reaches a total thickness of 11,200 m on the east flank of the Belait Syncline, 6,300 m on the central flank, and 6,000 m on the west flank, while the thickness of the Belait Anticline ranges from 4,500 m to 5,700 m. Stratigraphically, the lower part of the formation overlies and is time-equivalent with the Setap Formation (Liechti *et al*., 1960; Chung, 1982; Sandal, 1996). The upper part of the formation is laterally time-equivalent with and transitional into the Miri and Lambir Formations (Chung, 1982; Sandal, 1996) (Figure 2). In the Belait Syncline, the Seria Formation conformably overlies the Belait Formation (Liechti *et al*., 1960). According to Hutchison (2005), the fluvial Belait Formation transitions into transgressive shallow marine sequences represented by coarsening-upward offshore shales and shoreface sandstones. The time-stratigraphic position of the Belait Formation, according to Liechti *et al*. (1960), indicates that the formation is dated to Tf1 based on pelagic foraminifera. He postulated that the whole area of the Belait Formation belongs to Tf due to the occurrence of F*losculinella botangensis, Ammobaculites I*, and *Haplophragmoides II* in the Labu Syncline and Limbang Syncline. According to Sandal (1996), these formations range from the Middle to Late Miocene. However, Simmons *et al*. (1999) dated a few samples from the Belait, Lambir, and Miri Formations within the age of the Middle Miocene. Meanwhile, Hutchison (2005) stated that in addition to mudstone, the limestone of Pulau Burong also yields valuable foraminifera and belongs to Tf1 (Middle Miocene), and he subsequently proposed the formations as Middle to Late Miocene.

Lambir Formation

The general aspect of the Lambir Formation, according to the distribution of rock units, is an alternation of sandstone and shale similar to the Belait Formation, but with a distinctive calcareous admixture (limestone,

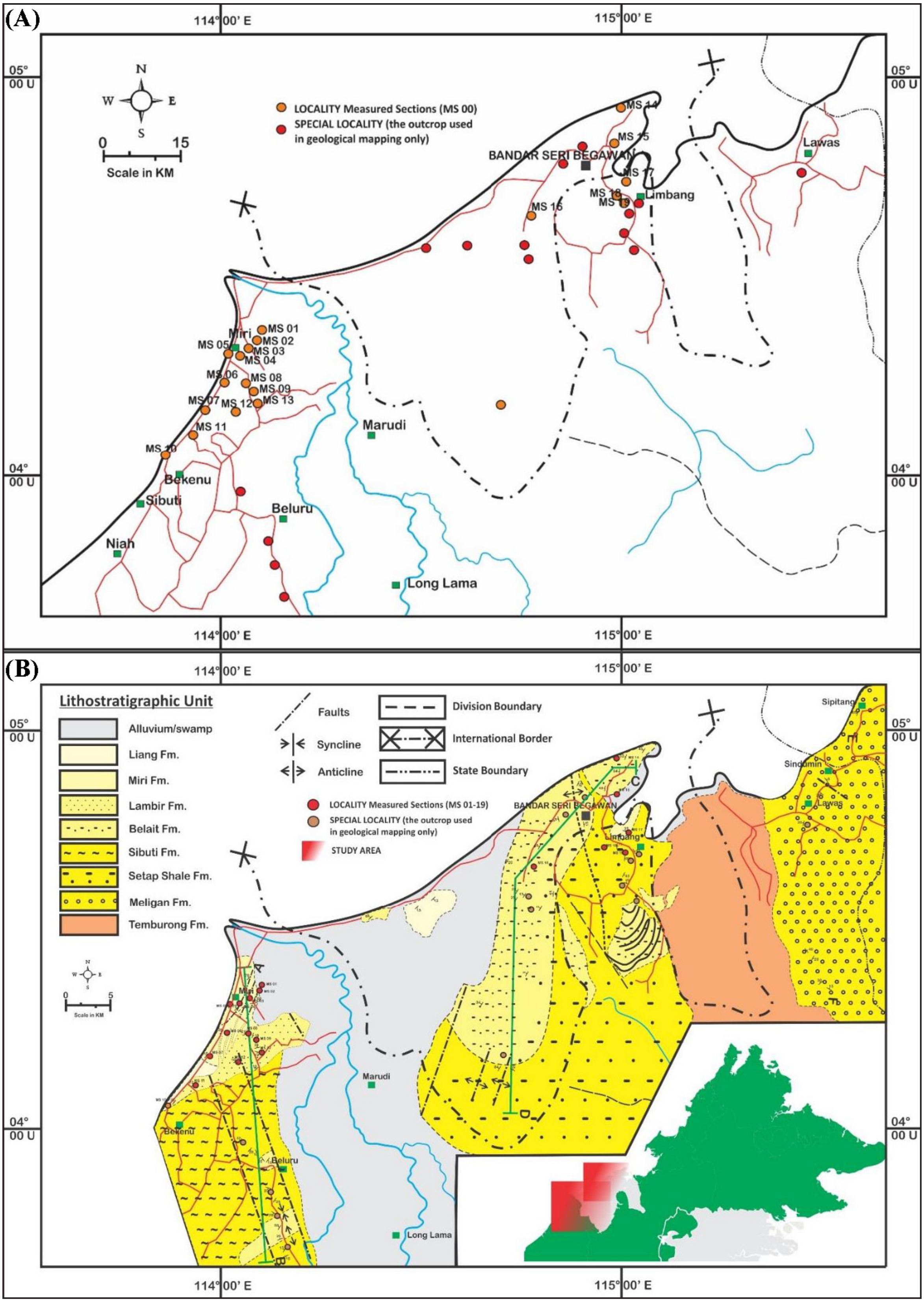

Figure 1: (A) The distribution of sampling locations in the study area. (B) The study area encompasses the entire region of Northwest Borneo, highlighting detailed geological aspects and lithostratigraphic units. The data are primarily derived from field studies and some adaptations from previous researchers, including James (1984), Banda & Honza (1997) and Hutchison (2005).

calcareous shale), which may be locally absent. Liechti *et al*. (1960) explain that the lithofacies of the Lambir Formation comprise calcareous and non-calcareous units. A study by Hui & Leman (1994) on the Lambir Formation in the Ulu Bok Syncline recognized some lithological units in the Lambir Formation, which consist of interbedded sandstone and shale with a little mudstone and siltstone. According to Banda & Honza (1997), this formation consists of sandstone interbedded with shale, being mainly sandy rather than muddy. Hutchison (2005) stated that the rock units of the Lambir Formation are composed of thick-bedded sandstones overlying medium dark-grey mudstone and calcareous mudstone (Sibuti or Setap Shale Formation). Based on Liechti *et al*. (1960), the type locality of the Lambir Formation is at the Lambir Hills in Sarawak and the Bakong Valley in Brunei. However, as outcrops are rather poor, it is suggested that the succession in the comparatively undisturbed block between the headwaters of Sungai Muchok (Sungai Sintulang), Sungai Tansau, and the coast be used. According to Liechti *et al*. (1960), the rock-stratigraphic position at the basal boundary of the Lambir Formation shows a gradual, slightly diachronous transition from the argillaceous Sibuti to the predominantly arenaceous Lambir Formation (Figure 2). The top boundary, observable only in the Lambir Hills, is a rapid transition, with the arenaceous uppermost part of the Lambir Formation contrasting with the softer, more argillaceous overlying Miri Formation. In the Pasir wells, subsurface evidence shows that the Lambir Formation still intergrades and interfingers with the Belait Formation. According to Kessler & Jong (2015), the Mid-Late Miocene deltaic sediments, called the Lambir Formation, unconformably overlie the Upper Setap Shale. According to Wilford (1961), the Lambir Formation is the time-stratigraphical equivalent of the Belait and Tukau Formations and strongly resembles the basal arenaceous parts of the Belait Formation lithologically. The Lambir Formation rests on the Sibuti or Setap Shale Formation, with the boundary being transitional through a gradual upward increase in sand content.

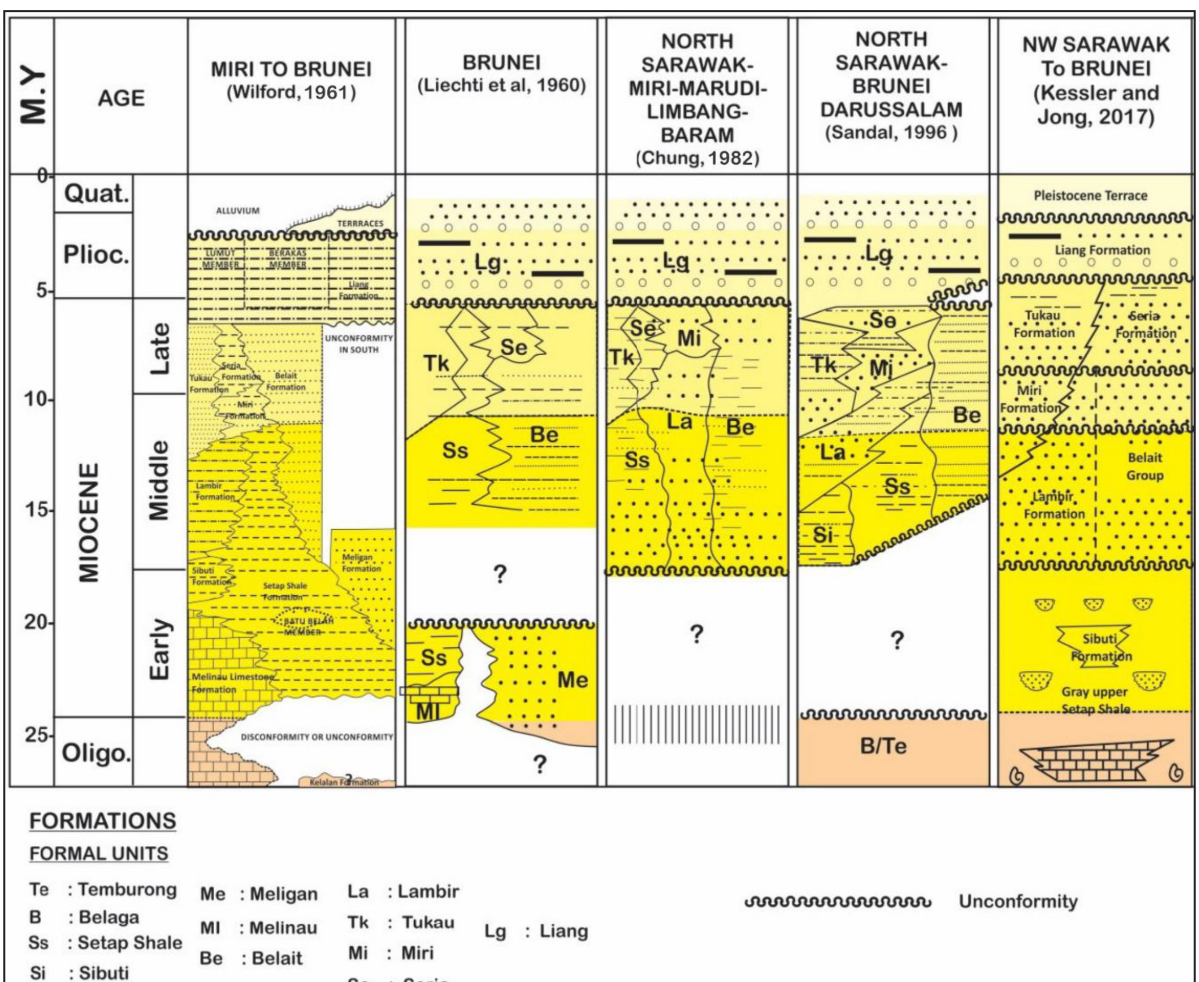

Figure 2: Lithostratigraphic chart of North Sarawak to Brunei Darussalam, adapted and modified from various authors (Liechti *et al*., 1960; Wilford, 1961; Chung, 1982; Sandal, 1996; Kessler & Jong, 2017).

Miri Formation

The Miri Formation was established by Liechti *et al*. (1960), with the type locality found in the Miri Anticline and Miri-Seria subsurface. This formation is a predominantly arenaceous succession with a lithology similar to, but more marine than, the Belait Formation. In the Miri field, according to Liechti *et al*. (1960), this formation is divided into the Lower and Upper Miri Formation. The Lower Miri consists mainly of sandstone and shales, which are distinctly separated. Meanwhile, the Upper Miri is more arenaceous, with the alternation of sandstone and shales occurring more rapidly and less regularly. Wilford (1961) also stated that in the Belait Anticline, the Miri Formation consists of shale and sandstone, overlain by clay that merges laterally into the clay of the upper part of the Belait Formation. According to Banda & Honza (1997), the rock unit consists of an alternation of thick sandstone and siltstone intercalated with a little shale. Meanwhile, Hutchison (2005) states that the Miri Formation is predominantly arenaceous, with clay and shale. His explanations are similar to those of Liechti *et al*. (1960), indicating that this formation is divided into two lithologic units: Upper and Lower. The maximum thickness is over 6,000 feet in the Seria Field and ranges from 1,000 to 4,000 feet in the Miri Field. The rock stratigraphic position between the Miri Formation and others was observed in a few sections. In the Seria and Miri subsurface, the basal boundary with the underlying Setap Shale is a gradual transition from an arenaceous to a predominantly argillaceous succession (Chung, 1982) (Figure 2). Hutchison (2005) also stated that the base of the formation is a gradual transition from the argillaceous Setap Shale to the sandy Miri Formation. The top boundary of the Miri Formation is identified through an electrical marker (subsurface evidence) and is overlain by the more arenaceous lithology characteristic of the Seria Formation. Some paleontological analyses carried out on rocks of the Miri Formation have yielded index microfossils. Researchers like Tan *et al*. (1999) and Hutchison (2005) postulated that the formation dates from the Middle to Upper Miocene due to the range of the Loxostoma 1 zone, Nonion 3, Bolivinita zone, and Triloculina 18. Meanwhile, Banda & Honza (1997) concluded that the Miri Formation is younger than the Globorotalia (T.) peripheronda Zone (N.9), which is equivalent to mid-Miocene and younger.

METHODOLOGY

Nineteen sections were measured in the field across the Miri to Brunei Darussalam areas (Figure 1 (A)). The outcrop sections were vertically logged, and most exhibited similar rock units, including sandstone, interbedded sandstone with mudstone, and heterolithic rock. These sections will be digitized and marked up using CorelDRAW graphic software. A significant number of outcrops were measured to ensure comprehensive data collection for wave-tide depositional setting distribution. Lithofacies analysis distinguished sedimentary structures, lithology, trace fossils, fossils, and stratigraphic contacts to assess the sedimentary sequence and environments. These lithofacies were then grouped into lithofacies associations to diagnose the depositional setting. Paleocurrent analysis data were presented in rose diagrams using Rose.Net software version 0.10, with a class size of 30°, and partly presented in the sedlog. The percentage of tide-wave influence was calculated directly from the lithofacies in the sedlog. The data were derived from the thickness of each bedding, considering the entire thickness, and the percentage values illustrated the dominant exposure of sedimentary deposits. Ultimately, a depositional model was constructed.

RESULT AND DISCUSSION

Outcrop of the Miri Formation

The Miri Formation was proposed by Leichti *et al*. (1960), with the type locality in the Miri Anticline. The outcrops from this formation are denoted as MS01 to MS06 (Figure 4). Field observations indicate that most outcrops of the Miri Formation can be divided into three rock unit divisions: 1) predominantly arenaceous succession, 2) interbedded sandstone-mudstone unit, and 3) heterolithic rock (Figure 3 (A)). The lower part of the sequence is dominated by arenaceous shoreline deposits, while the upper part is dominated by heterolithic tidal deposits. The sandstone beds are well sorted, with grains ranging from rounded to well-rounded and fine to medium size. Some beds show coarse grains in certain localities, such as MS02 and MS03, but these are poorly exposed. Certain sandstone beds have a coarsening upward sequence and sharp contacts with other beds. The heterolithic rock contains varying percentages of sand and mud. Lenticular, wavy, and flaser beddings are most common in the Miri Formation. For example, in measured section 04, lenticular bedding consists of thick mud with 90% silty sand or 90% mud and 10% sand. Flaser-wavy bedding typically contains 50% sand and 50% mud, although wavy bedding does not always appear. The flaser bedding is fine to medium-grained with moderate sorting. It transitions gradually towards the upper part of the bedding sequence and does not contact herringbone bedding. Identifying the boundary of the Miri Formation with other formal lithostratigraphic units in the field is challenging, except where unconformity boundaries are exposed, such as the Pliocene Liang Formation at the Luak area (MS06). The inclined bedding of the Seria Formation, as described by Wannier *et al*. (2011), unconformably underlies the Miri Formation. However, the indistinct boundary between the Miri and Seria Formations on the surface and subsurface has led to the denial of this claim. Both formations are time-equivalent and share nearly identical lithologic properties. Atkinson *et al*. (1986) described storm sand in the Seria area (Brunei Darussalam) with variable thickness, displaying a regression shoreline trend similar to that observed in the Miri area.

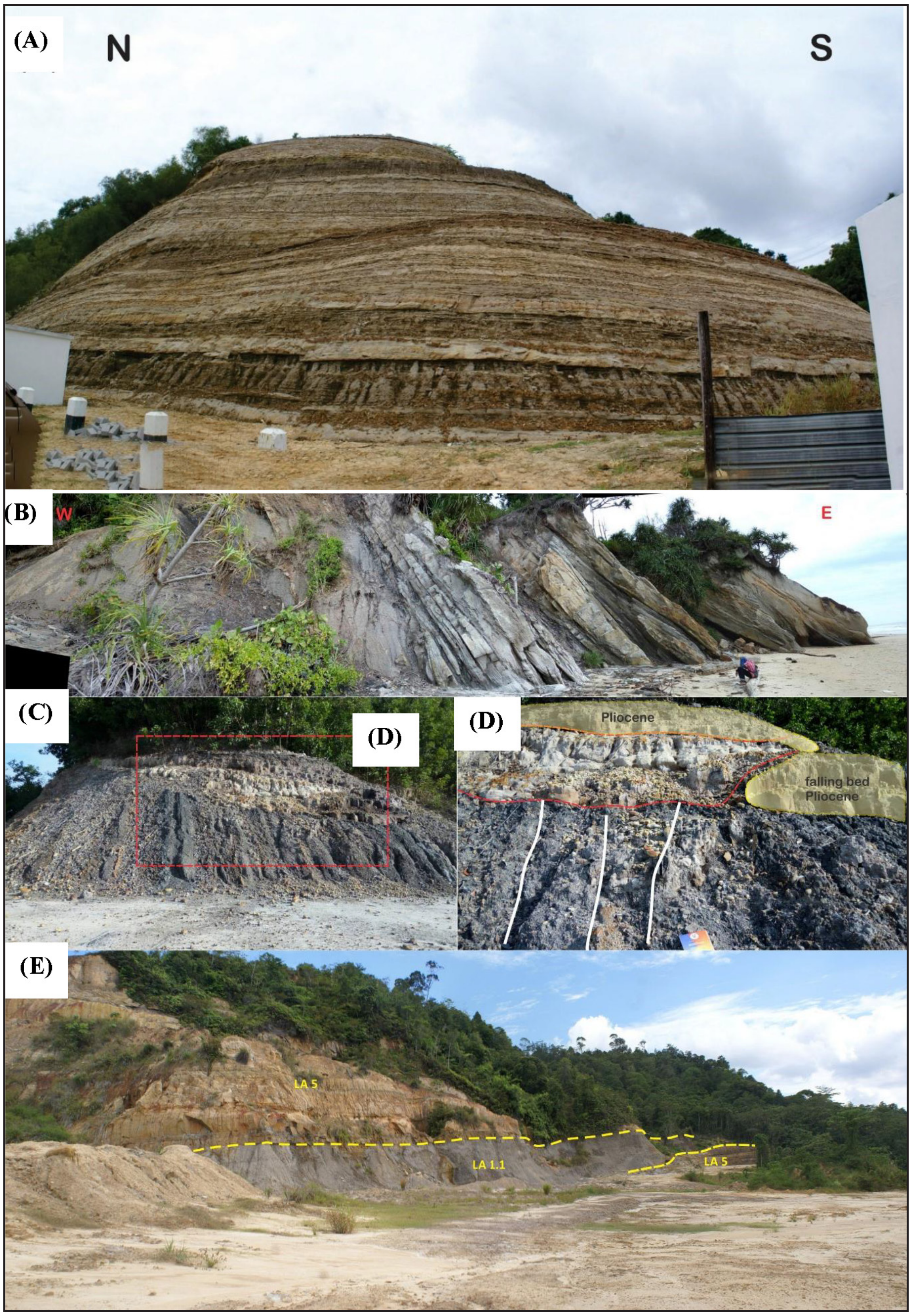

Figure 3: (A) Outcrop of the Miri Formation in Miri, Sarawak. **(B)** Outcrop of the Belait Formation in Brunei Darussalam. **(C)** Outcrop of the Belait Formation showing angular unconformity with the Setap Shale Formation. **(D)** Enlargement of (C). **(E)** Outcrop of the Lambir Formation.

Outcrop of the Lambir Formation

The Lambir Formation is characterized by a white, thick, and amalgamated arenaceous succession of sandstone beds. Other rock units are displayed as interbedded sandstone and mudstone. A recent study also identified heterolithic bedding as part of the Lambir Formation. The formation is well exposed south of the Miri area, specifically traceable from Sg. Nakat (MS08) to Lambir Hill (MS13) and the surrounding area. The outcrops from this formation are denoted as MS07 to MS13 (Figure 5). Thick sandstone beds are widely distributed from the west to Tusan Beach (MS10) and Beraya (MS07). Thick mudstone beds are also exposed in certain outcrops within the Lambir Hill territory, containing coal lenses, plant remnants, leaf fossils, and intense Ophiomorpha burrows (Figure 3 (E)). The cyclic sequence of mudstone bedding is observable at Lambir Hill. In the study areas, the Lambir Formation is believed to interfinger with the Miri Formation, as no boundary was found and both formations share similar lithological and lithofacies characteristics. However, the geometry of the Miri Formation is flat, whereas the Lambir Formation is slightly inclined. Both formations feature thicker sandstone beds in the upper part of the bedding sequence, indicating a regression phase. The Lambir Formation produces well-

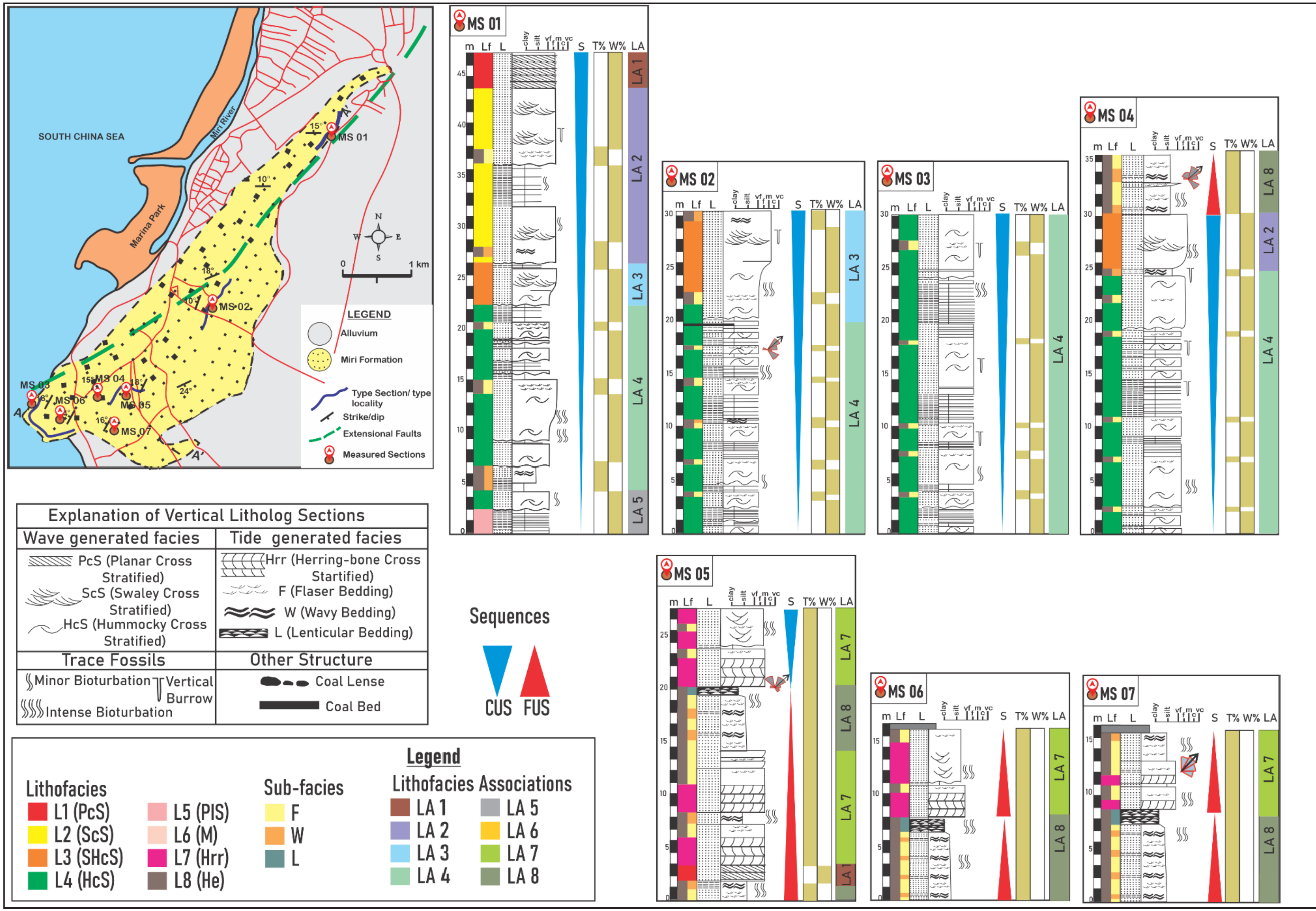

Figure 4: Sedimentary logs display lithofacies, lithofacies associations, paleocurrent directions, wave-tide intensities, and sequences from selected measured sections of the Miri Formation. An explanation of the sedimentary lithofacies symbols and abbreviations used is also provided in the lower right corner of the figure.

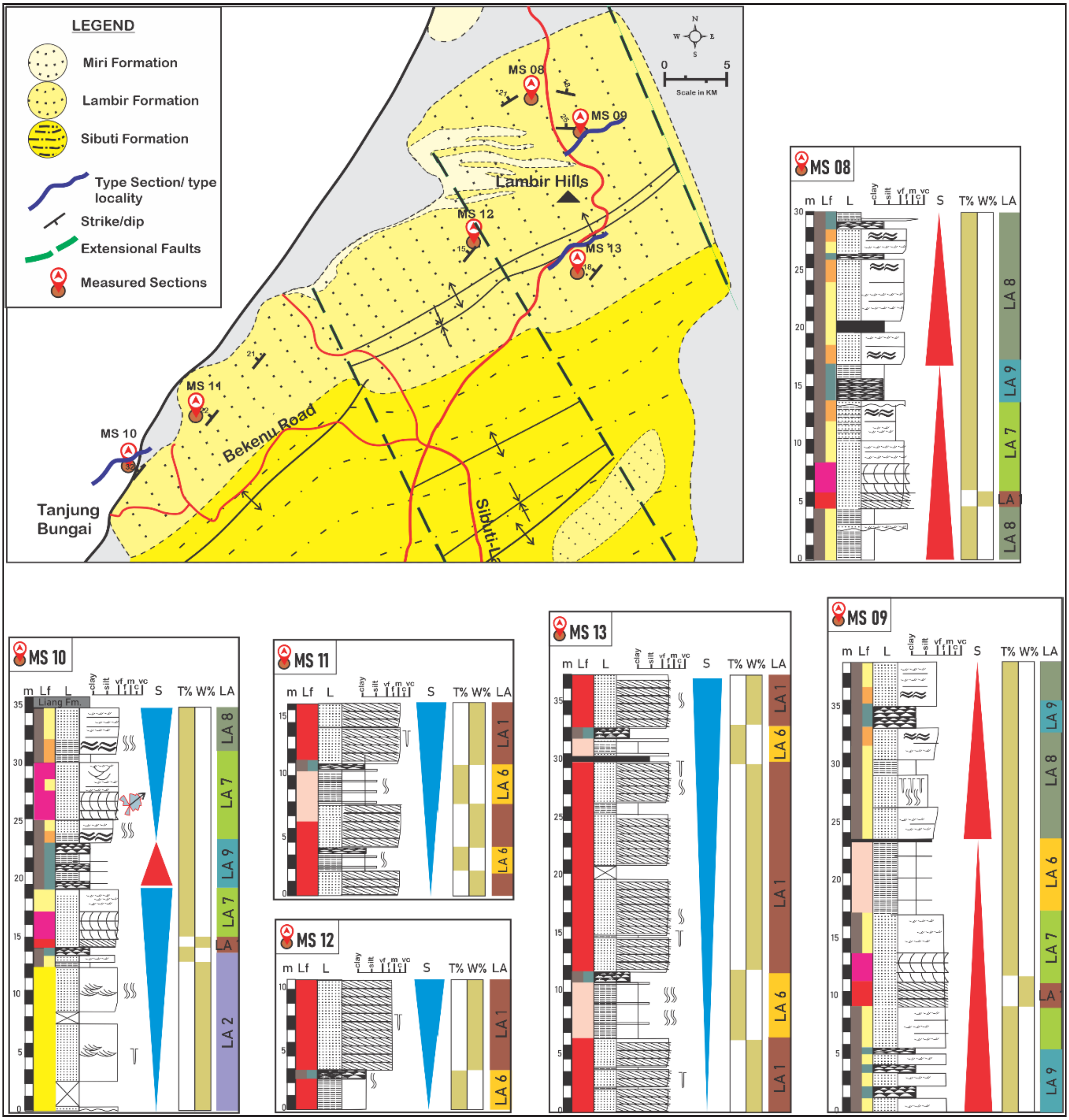

Figure 5: Sedimentary logs display lithofacies, lithofacies associations, paleocurrent directions, wave-tide intensities, and sequences from selected measured sections of the Lambir Formation.

sorted arenaceous sandstone beds. Evidence of co-set planar and cross-bedded sandstone shows systematic alignment of clasts through the winnowing process. Small granule grains are also exposed near the Sg. Nakat area, appearing unsorted and embedded in bioturbated sandstone. Heterolithic rocks are also dominant within the Lambir Formation, with major exposures found at Sg. Nakat. These heterolithic units either exist as distinct rock bodies or are partly embedded within sandstone units. The best exposures of flaser-lenticular bedding can be seen at the Sg. Nakat outcrop and along the Tusan-Bekenu Road. Coal is abundant, forming either as seams within sandstone beds or interbedded with mudstone or heterolithic mud. Some outcrops also contain amber and siderite concretions.

Outcrop of the Belait Formation

The Belait Formation in the study area is characterized by an arenaceous wave-dominated sandstone bed and an

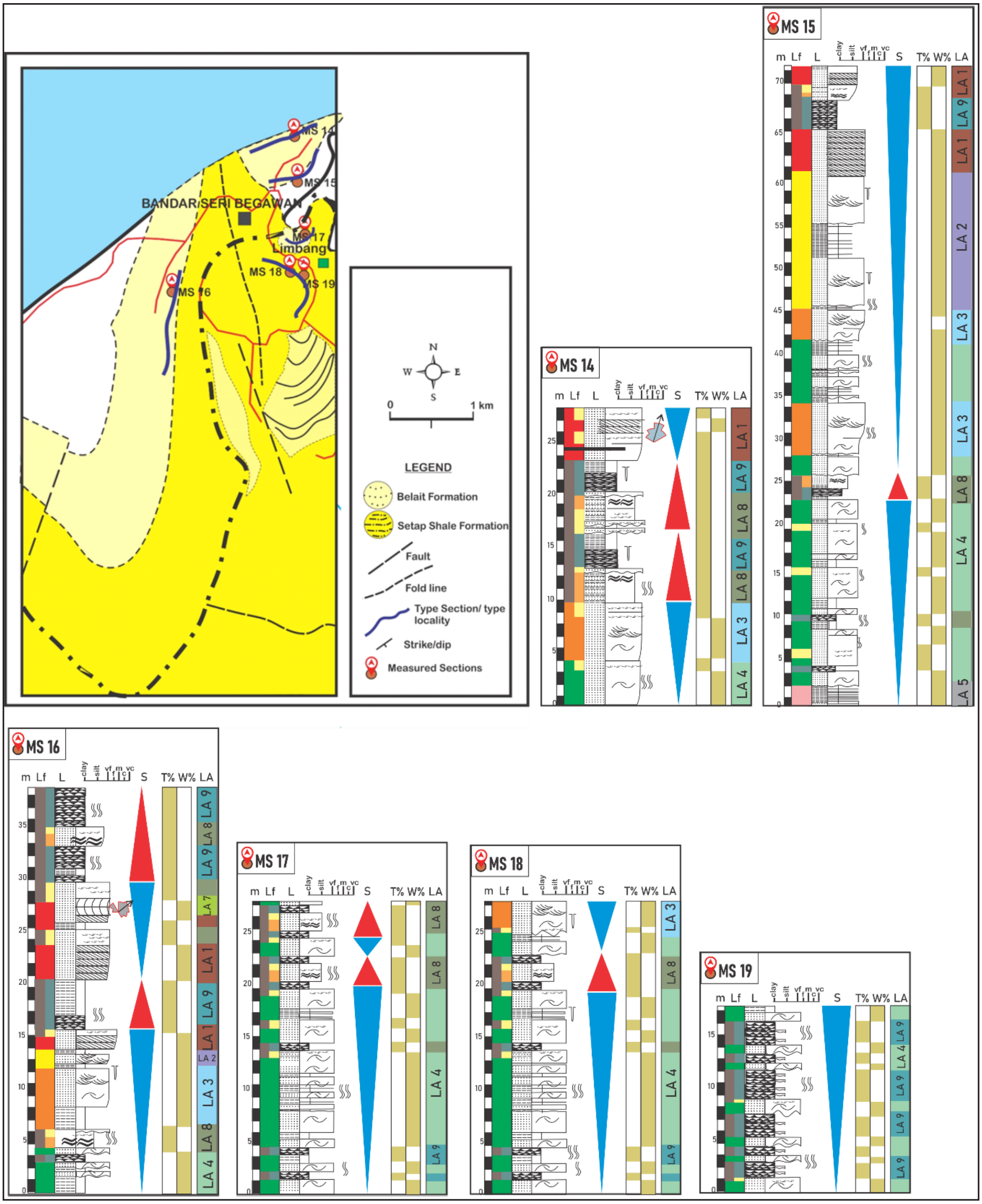

Figure 6: Sedimentary logs display lithofacies, lithofacies associations, paleocurrent directions, wave-tide intensities, and sequences from selected measured sections of the Belait Formation.

argillaceous heterolithic bed. The Belait Formation is primarily distributed in northern Brunei Darussalam and parts of northeast Limbang. Based on field observations, six outcrops (MS14, MS15, MS16, MS17, MS18, and MS19) were chosen as the best examples (Figure 6). This formation is similar to other Miocene formations, such as the Miri and Lambir Formations. According to Liechti *et al*. (1960), the Miri Formation was part of the Belait Formation, and the same applies to the Lambir Formation (Chung, 1982; Sandal, 1996). However, the Belait Formation may be older than previously thought (Liechti *et al*., 1960). Most rock units represented by the Belait Formation are quite similar to those of the Miri and Lambir Formations. The arenaceous succession is the most common, characterized by thick and amalgamated sandstone beds. The unit is also identified by buff sandstone, grey, or shaly mudstone. Most units can be differentiated by their sand-to-mud ratio. The sandstone units generally have a fine to medium grain size. The heterolithic unit is also present in the formation and largely consists of flaser, wavy, and lenticular bedding. This unit is closely related to other formations, such as the Miri Formation and the Lambir Formation. In the study areas, various sandstone beddings, such as inclined bedding, are commonly observed in the Belait Formation (Figure 3 (B)). Angular unconformity is shown between the Belait and Setap Shale Formation underlain by the Liang Formation (Figure 3 (D)). This formation also covers the area of the Jerudung Anticline and parts of northern Limbang. Observations indicate that the Belait Formation experienced intense progressive sedimentation. The thickest sediments were formed due to the uplift of sediment in the Late Eocene (Belaga Formation), which caused intense erosion and resulted in a thick progradation sequence of clastic Late Miocene sediment (Belait Formation).

Lithofacies analysis

Based on the lithofacies analysis described in various outcrops within the Miri Formation and equivalent strata in the Lambir and Belait Formations, the study identified two major lithofacies, grouped into wave storm-generated lithofacies and tide-generated lithofacies (Table 1). The conditions are detailed in the lithofacies sections, where specific sedimentary structures form due to the landward movement of high progressive storm waves, leading to an intense deposition process that increases wave orbital motion, resulting in the deposition of large sediments. Meanwhile, tide-generated lithofacies are present in every part of the formations, either partially or entirely covered. These lithofacies typically exist in the middle or top section, with the middle section showing alternating sandstone beds.

Lithofacies association

According to the lithofacies analysis, they can be grouped into nine major lithofacies associations namely foreshore lithofacies association (LA 1), upper shoreface lithofacies association (LA 2), middle shoreface lithofacies association (LA 3), lower shoreface lithofacies association (LA 4), offshore lithofacies association (LA 5), lagoon lithofacies association (LA 6), tidal sand bar sandstone lithofacies association (LA 7), tidal to sub-tidal sand flat lithofacies association (LA 8) and sub-tidal mud flat lithofacies association (LA 9) (Figure 4, 5 and 6).

Lithofacies association 1 (LA 1): Foreshore

Description

LA 1 consists of lithofacies 1, lithofacies 7, and lithofacies 8. In the Miri area, LA 1 is specifically located at MS01, MS02, MS10, MS11, and MS13. In Brunei Darussalam, it is exposed at MS15 and MS16. The individual bed thickness ranges from 30 cm to 2 m. Typically, the top section of the bed is thicker than the bottom bed of the sequence, with a more dominant development of amalgamated beds. LA 1 is vertically overlain by LA 6 in a sharp contact and directly attached to LA 2. LA 1 is predominantly composed of a planar cross-stratified sandstone bed (Figure 7 (A)). The recorded measurement of cross-stratification is about 25 cm in diameter, and the paleoflow direction is unimodal towards the east. Most cross-stratifications exhibit a high-angle stratification, exceeding 15°. In specific areas like MS01, MS02, MS10, and MS11, LA 1 is associated with LA 7. Mud drape is common here, without a reactivation surface. Additionally, a heterolithic structure (i.e., flaser-tidally structure) is exposed in a series of sandstone beds. A moderate to less bioturbation occurred in LA 1, either medium or with a simple burrow system (Figure 7 (C)). It is mostly documented as a simple system due to fewer trace fossil species observed in the sandstone bed. The bioturbation indices (BI) ranged from 1 to 2 and increased to 3 while approaching the lower bed. Some species have been identified during the study and yielded major groups like *Ophiomorpha* sp., *Thalassinoides* sp., and *Skolithos* sp. The burrows of *Ophiomorpha* sp. have vertical and horizontal arrangements and a simple burrow system. *Thalassinoides* sp. has a medium size with a vertical body and is normally abundant at the upper bed contact with mud. *Skolithos* sp., with a small size body, is attached to compact sandstone and is not too abundant. In this study area, it is basically aligned as a vertical body.

Interpretation

LA 1 is primarily influenced by a storm wave event. The presence of a thick and amalgamated sandstone bed is depicted as the rapid movement of sediment during the deposition phase (Prave *et al*., 1996; Abieda *et al*., 2005). The sediment supply is sufficient to create a substantial geometry of a sandstone bed by extending the sedimentation process. A strong wave current will remove any small particles to be deposited in the proximal part, resulting in a clean, coarse, and well-sorted grain size without mud (Dumas *et al*., 2005). As noted by Hart & Plint (1995), if the wave energy is robust, sandy, and gravelly materials will be progressively reworked on the foreshore, abrading clasts of all sizes to a high degree of roundness and effectively sorting sediment into different sizes. The planar cross-stratification in LA 1 is a result of the wave-generated system in the foreshore part of the sedimentary environment (Hunter *et al*., 1979; Arnott, 1992; Rahman & Tahir, 2018). A mixture of sand and mud in the heterolithic layer occurs due to the variation in current

Table 1: Simplified lithofacies analysis classification for the Middle to Late Miocene sedimentary sequence in the Miri to Brunei Darussalam area. The identified lithostratigraphic units include the Mi Fm (Miri Formation), Lm Fm (Lambir Formation), and Be Fm (Belait Formation), respectively.

Lithofacies name/ symbol	Mesured sections/ (lithostratigraphic unit)	Dominant lithology	Percentage wave/tide deposit, %	Palaeontology (Fauna, flora/ Ichnofauna)	Description	Process interpretation
Wave-Storm Generated Lithofacies						
Lithofacies 1 (L1): Planar Cross-Stratified Sandstone (PcS)	Mi Fm: MS02, MS 01 Lm Fm: MS10, MS11, MS13 Be Fm: MS15, MS16 and MS18	Sandstone	Wave > tide	*Ophiomorpha* sp., *Thalassinoides* sp., and *Skolithos* sp. Bioturbation index, BI: 1-3	- A thick, amalgamated, and stacked planar cross-bed. - A series of planar cross-sets with horizontal stratification. - A uniform grain is present.	- A high wave regime occurs in the upper part of the beach profile. - A high-energy current will wash out any clay input during a storm wave event. - The current carries a quantity of similar materials (e.g., sand) with a uniform energy supply.
Lithofacies 2 (L2): Swaley Cross-Stratified Sandstone (ScS)	Mi Fm: MS01, MS02, MS04 Lm Fm: MS10, MS13 Be Fm: MS15, MS17	Sandstone	Wave > tide	*Ophiomorpha* sp. and *Thalassinoides* sp. Bioturbation index, BI: 3-4	- Thicker sandstone with amalgamated bedding. - High-angle cross-stratification was formed. - Coarsening upward grain size, from fine to medium.	- High-energy currents with a few depositional sequences. - Large bedforms were preserved during the migration of wave ripples. - An increase in flow velocity occurred over the time of deposition.
Lithofacies 3 (L3): Swaley-Hummocky Cross-Stratified Sandstone (SHcS)	Mi Fm: MS01, MS02, MS04 Lm Fm: MS14 Be Fm: MS15, MS16	Sandstone (Ss) and mudstone (M) Ratio: Ss:M 2:1	Wave > tide	*Ophiomorpha* sp. and *Thalassinoides* sp. Bioturbation index, BI: 3-4	- The swaley and hummocky cross-stratification alternates within a single sequence.	- The maximum oscillatory wave orbital velocity acts on the bottom sediment and ultimately creates a mold.
Lithofacies 4 (L4): Hummocky Cross-Stratified Sandstone (HcS)	Mi Fm: MS02 Lm Fm: MS14 Be Fm: MS15, MS17	Sandstone (Ss) and mudstone (M) Ratio: Ss:M 2:1 or 1:1	Wave > tide	Bivalves, mollusc *Ophiomorpha* sp. and *Thalassinoides* sp. Bioturbation index, BI: 5	- Various patterns of sandstone bedding include scour-resembling swale beds, contorted beds, disconnected beds, and non-homogeneous beds. - There are non-homogeneous stratifications, disconnected beds, and hummocky cross-beds.	- The variables in bedforms are related to size, symmetry, wave orbital velocity, unidirectional current velocity, and the availability of sand in the lower beach profile during storm activity. - These variables accumulate after repeated storm reworking in a high-energy setting.

Table 1: Continued.

Lithofacies 5 (L5): Parallel Laminated Siltstone (PlS)	Mi Fm: MS01 Be Fm: MS15	Siltstone (St) and mudstone (M) Ratio: St:M 1:2	Storm wave base	*Ophiomorpha* sp. and *Thalassinoides* sp. Bioturbation index, BI: 1-3	- Discontinuous micro-hummocky structures (thin-bedded sandstone) and parallel lamination. - Thick mud interbedded with siltstone beds.	- Deceleration of wave currents in the inner offshore area. - This condition is still influenced by wave and storm events.
Tide Generated Lithofacies						
Lithofacies 6 (L6): Thick Laminated Mud (M)	Lm Fm: MS08, MS09, MS10, MS12 Be Fm: MS16, MS17	Mudstone, partly silt	Less influenced by wave, influence by tide	Bivalve, leaf imprint *Ophiomorpha* sp. and *Thalassinoides* sp. Bioturbation index, BI: 1-3 some achieved 4	- The predominance of mudstone over sandstone. - The parallel-laminated sandstone or siltstone bed.	- Less influenced by wave- or storm-generated systems. - Turbulent currents occur in slack water deposits.
Lithofacies 7 (L7): Herringbone Cross Stratified Sandstone Bed (Hrr)	Mi Fm: MS02, Lm Fm: MS10 Be Fm: MS14, MS15	Sandstone	Tide > wave	*Ophiomorpha* sp., *Thalassinoides* sp., and *Palaeophycus* sp. Bioturbation index, BI: 2-3	- Thick-bedded sandstone. - Exposure of planar cross-stratification, herringbone cross-stratification, and trough cross-stratification.	- High energy in tidal currents. - The ebb and flood currents may follow different directions at different times.
Lithofacies 8 (L8): Heterolithic Flaser Bedding (F)		% Siltstone > % mudstone	Tide dominated	*Ophiomorpha* sp., *Palaeophycus* sp., *Skolithos* sp., and *Thalassinoides* sp Bioturbation index, BI: 1-2	- Predominantly covered by flaser bedding. - Alternating with shoreface lithofacies (HcS and ScS).	- Slow motion and low energy of tidal current activity during variations in tidal settings. - Incorporation of sedimentation in the shoreface area during mean low tide.
Wavy Bedding (w)	Mi Fm: MS06, MS07 Lm Fm: MS08, MS09, MS10 Be Fm: MS14, MS15, MS19	% Siltstone = % mudstone	Tide dominated		- Thin sand and mud units with a ratio of about 1:1 in thickness. - Lenticular mud drapes with an undulating surface.	The equal thickness of the exposed silt and mud is primarily related to turbulent tidal flow. - The undulating surface is due to natural erosion that occurred during current movement in two directions.
lenticular bedding (L)		% Siltstone < % mudstone	Tide dominated	*Skolithos* sp. Bioturbation index, BI:1	- Thick-bedded laminated mud with a thin siltstone bed. - The thin silt horizontal streak occurred.	- The suspension process occurs with an abundance of silt and clay during the slack-water period. - Turbulent flow occurs within the slack-water period.

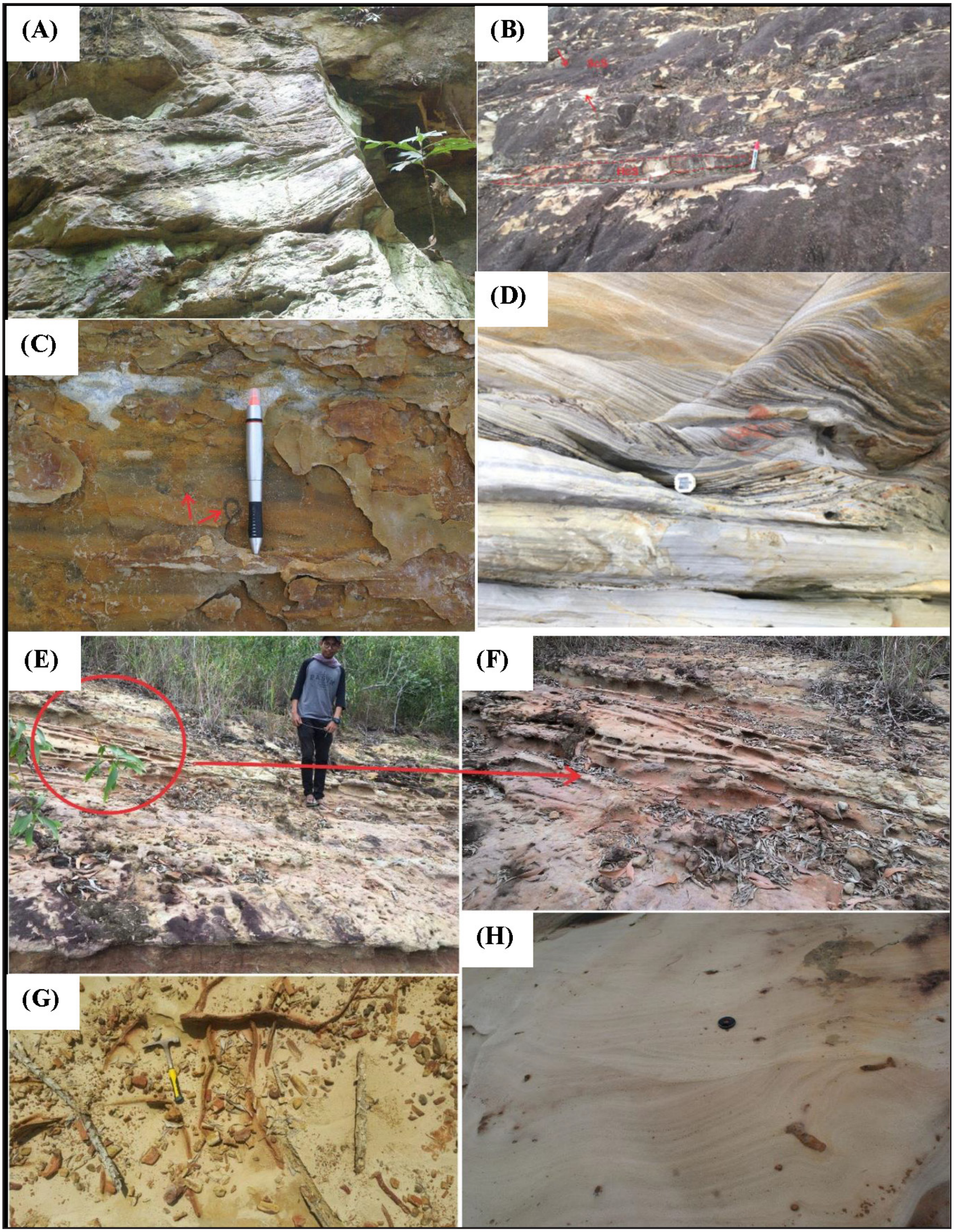

Figure 7: (A) The planar cross-stratification (PcS) exhibits an inclined pattern rather than a tabular pattern. **(B)** The alternation of scour cross-stratification (ScS) and hummocky cross-stratification (HcS) occurs in a single bedding at MS05. **(C)** Less bioturbation occurs in the sandstone bed. **(D)** The alternation of scour cross-stratification (ScS) and hummocky cross-stratification (HcS) occurs in a single bedding at MS14. **(E)** A co-set of high- to low-angle cross-bedding. **(F)** An enlargement of ScS with a high angle of cross-stratification. **(G)** *Thalassinoides* sp. exposed on the sandstone bed. **(H)** ScS with several sets of angles and good sorting of grain size.

or wave activity and sediment supply because of varying current strength and wave power (Reineck & Wunderlich, 1968; Nichols, 2009). The moderate to low bioturbation in this LA is attributed to the slow growth of organisms in a high wave-dominated area. The vertical burrow shape is primarily related to the foreshore environment for organism survival during a storm event. According to Seilacher (2007), *Ophiomorpha* sp. and *Skolithos* sp. are believed to have moved up and down in the sediment with the changing water level of the foreshore. The burrow with a simple system is thought to be preserved in the disturbance area where the organism living rate is low (Norzita & Lambiase, 2014). Furthermore, the increased activity of organisms towards the top of the bed is due to the deceleration of wave energy. Based on the evidence described above, LA 1 is deposited in the foreshore environment.

Lithofacies association 2 (LA 2): Upper shoreface

Description

LA 2 comprises a thick cross-stratified sandstone bed, uniform in a variety of grain sizes ranging from fine to medium, and well-sorted grain orientation. The best exposure of LA 2 is at MS01, MS09, MS10, and MS15. LA 2 generally consists of lithofacies 2 in which individual bedding shows a co-set of high- to low-angle cross-bedding (Figure 7 (E) and (F)). LA 2 is well-distributed across the Miri region to the Brunei Darussalam area. Essentially, LA 2 has a relationship with LA 1 and LA 3 in terms of the vertical section. LA 2 is erosively underlain by LA 1 and overlain by LA 3 in a sharp contact. In the vertical section at MS01, LA 2 showed a gradual transition from fine and medium to coarse grain of LA 1 sandstone. The boundary between LA 2 and LA 1 is obscured within MS04 but can be identified through the pattern of the cross-bedded structure. At MS10, the swaley cross-stratification (ScS) showed a harmonic banding pattern with linear convex lamination, expanding in different sizes towards the bottom of the sandstone bed (Figure 7 (H)). At MS09, a small-scale cross-bedded sandstone appeared as the swale in the middle part of the bedding. The relationship between other facies can be seen in the alternation of hummocky cross-stratification, which is related to LA 3 with a swale bedding. Moderately medium to large burrows of trace fossils like *Ophiomorpha* sp. and *Thalassinoides* sp. are common on the sandstone bed (Figure 7 (G)). According to the bioturbation indices (BI), the value is 3 and approaches 4 towards the lower part of the bed. Vertical burrows are quite intense within the sandstone bed compared to horizontal burrows, which are limited.

Interpretation

Well-sorted, a variety of grain sizes from fine to medium-grained sandstone, along with the presence of the ScS sandstone bed, serve as good indicators of the upper shoreface environment (Arnott, 1992; Abieda *et al*., 2005, Rahman & Tahir, 2018; Tahir *et al.*, 2018). LA 2 is generally interpreted as a storm wave event due to the occurrence of the ScS structure. Thick-bedded sandstone with well-sorted grain sizes indicates a high regime of transported current during deposition (Collins *et al*., 2020). The regime strength on LA 2 is slower than LA 1, where the regime is much stronger. This difference is attributed to the transfer of energy from LA 1 to LA 2, causing the current to move sediment on the upper shoreface. Evidence of high regime current is observed on the erosional bed at the upper part of the bedding sequence, explaining why LA 1 is underlain erosively by LA 2. The presence of a high-angle trough cross-bed and a ScS sandstone bed indicates a high-energy storm occurred during deposition. This is consistent with the progressive landward movement of waves (Swift *et al*., 1991) and their tendency to be asymmetric (Clifton, 1976). Various scales of ScS sandstone beds show that changes in current intensity in the upper shoreface environment lead to the formation of several swale structures. Moderately abundant trace fossils with simple burrow systems characterize the upper shoreface environment sandstones (Norzita & Lambiase, 2014). Another indicator is the presence of large to medium trace fossils like *Ophiomorpha* sp. and *Thalassinoides* sp., signifying that larger animals are indicative of a favorable environment. Based on the evidence discussed above, LA 2 is interpreted to have been deposited in the upper shoreface environment.

Lithofacies association 3 (LA 3): Middle shoreface

Description

LA 3 consists of lithofacies 2 and lithofacies 3 in a single bedding. The best exposures of this LA 3 are at MS02, MS04, MS05, and MS14. These areas exhibit good exposure of a series of alternating swaley-hummocky sequences, either in small or large scales. The thickness of the respective bed can reach approximately 80 cm vertically. Naturally, the HcS sandstone bed is overlain by the ScS sandstone bed in one bedding sequence (Figure 7 (B) and (C)). The swaley cross-stratification features a sandstone-dominated interval with a low-scoured surface consisting of moderately well to well-sorted fine to medium grain sizes. Meanwhile, the hummocky cross-stratification is overlain by the swaley cross-stratification, which is less amalgamated and interbedded with mud. In some sections of the study area, such as MS02 and MS04, the ScS is thicker than the HcS, ranging from 50 cm to 1 m. The swaley cross-stratification exhibits a medium-scale stratification with an angle less than 10°, while the hummocky cross-stratification shows a small angle of stratification, less than 5°. Most beds display a coarsening-upward sequence, with a heterolithic bed occurring at the lower and upper parts of the sandstone bedding. LA 3 is documented as a simple burrow system with the exposure of major vertical burrows and fewer horizontal burrows. Moderate to high bioturbation of *Ophiomorpha* sp. and *Thalassinoides* sp. can be observed in every bed of LA 3. The bioturbation indices record intensity values of 3 to 4; however, the value is 5 when approaching the top bed of LA 2.

Interpretation

The presence of swaley and hummocky cross-stratification in one bed is due to the combined flow conditions after storm-wave deposition, which directs high current in a reverse way to the bottom of the sediment, thus creating a mold (Dumas & Arnot, 2006). According to Vakarelov *et al*. (2012), swaley cross-stratification in a hummocky environment indicates a high-energy process and high-frequency episodic deposition. As suggested by Swift *et al*. (1991), this deposition environment is dominated by the incorporation of oscillatory and unidirectional current during a storm event in the midway between the upper and lower shoreface. The sedimentary facies show that the ScS sandstone bed forms first, followed by the HcS sandstone bed during normal deposition in the middle shoreface. The ScS is thicker than the HcS because a large amount of sediment is supplied during a storm event, and the process ends within the upper shoreface interval (LA 2). A variety of grain sizes, ranging from fine to medium intervals, and moderate to well-sorted results from high-energy to lower-energy events during deposition in the middle to lower shoreface (Rahman & Tahir, 2018). A heterolithic bed occurred in a few parts of this LA, suggesting that it may belong to the tidal influence in the subtidal area. The existence of the HcS overlain by the ScS indicates that the environment is influenced by fair-weather wave, whereas the settlement of sand and mud becomes uncertain. This is supported by Arnott (1992) and Dumas & Arnort (2006) where swaley cross-stratification is formed between fair-weather wave base and storm wave base above the hummocky cross-stratification but below the foreshore sub-environment. The variation in grain sizes of sandstone with the existence of swaley cross-stratification in an outcrop is a good indicator for the middle shoreface (LA 3) until the upper shoreface (LA 2) (Mellere *et al*., 2005). A moderate to high bioturbation rate with the abundance of *Ophiomorpha* sp. and *Thalassinoides* sp. and complex burrow systems characterize the middle to lower shoreface sandstones (Norzita & Lambiase, 2014).

Lithofacies association 4 (LA 4): Lower shoreface

Description

LA 4 consists of lithofacies 4 where it varies upon its exposure in Northwest Borneo based on the facies characteristics. This LA 4 composed of an interbedded HcS sandstone bed with a mudstone bed (Figure 8 (C)). Major exposure of this LA 4 is at MS 03, MS 14 and MS 17 respectively. At the MS10, the HcS facies consists of thick cross-bedded sandstone with moderately sorted grain size without showing a coarsening-upward sequence, where its individual bed ranged from 10 to 30 cm thick. At the MS09, the lithofacies displayed medium cross-bedded interbedded with mud. The HcS is typically scoured at the base whereas the upper part has undulating lamination with the exposure of a sand pit, less amalgamated, and a sharp contact with the overlying heterolithic mud (Figure 8 (B)). The bedding is mostly a non-irregular bottom line with a non-homogenous bedding sequence. The relationship between other LA like LA 5 can be seen at the MS03, which is located at the lower part of the outcrop. Other structures that exist within LA 4 include a low to high angle cross-stratification, a parallel-laminated sandstone bed, a ripple cross-stratification, a deformed structure, and a heterolithic bedding. A small exposure of heterolithic mud can be observed as mud laminae but mostly consists of coal lenses. The bioturbation is quite intense in every single bed of sandstone, mostly various kinds of Ophiomorpha burrows (Figure 8 (D)). The burrow system is basically complex with an average bioturbation index (BI of 5). Some macro-fossils like shells, molluscs, and bivalves can also be observed in certain part of the sandstone and the mudstone but are partly dissolved (Figure 8 (A)).

Interpretation

The interbedded sandstone with a mudstone indicates a lateral variation due to the decrease of wave energy in a lower shoreface environment Arnott (1992). According to Dott & Bourgeois (1982), a hummocky bed is formed due to the combination of a scour and depositional operation within a brief span of time. A hummocky cross-bed is also a result from storm wave and occurs in the transition zone of fair-weather wave base and storm wave base. The boundary between the sandstone- and mudstone-dominated portions of the succession is sharp and scoured, and it is interpreted as the boundary between the major subaqueous sandstone set above storm wave base (Vakarelov *et al.*, 2012; Rahman & Tahir, 2017). The moderately well-sorted grain fabric is due to the mixture of sediment during fair current activity. Undulating hummocky lamination is produced either by storm wave base or hurricane storm flow (Hamblin & Walker, 1979). However, Southard *et al*. (1990) suggested that the undulating lamination could be yielded by oscillatory flow. The heterolithic bed occurred in the hummocky cross-bed indicates that the deposition is influenced by tides (Dumas & Arnort, 2006; Collins *et al*., 2020). Some macro-fossils like mud crabs, shells, and gastropod within the sandstone and mudstone beds indicate a transition from brackish water to marine environments (Nesbitt, 1995; Buatois *et al.*, 2005). The exposure of bioturbation like *Ophiomorpha* sp. and *Thalassinoides* sp. with a complex burrow system is characterised as a lower shoreface sandstone (Norzita & Lambiase, 2014).

Lithofacies association 5 (LA 5): Upper offshore

Description

LA 5 consists of Lithofacies 5, which is predominantly laminated mud and a thin-bedded siltstone and minor

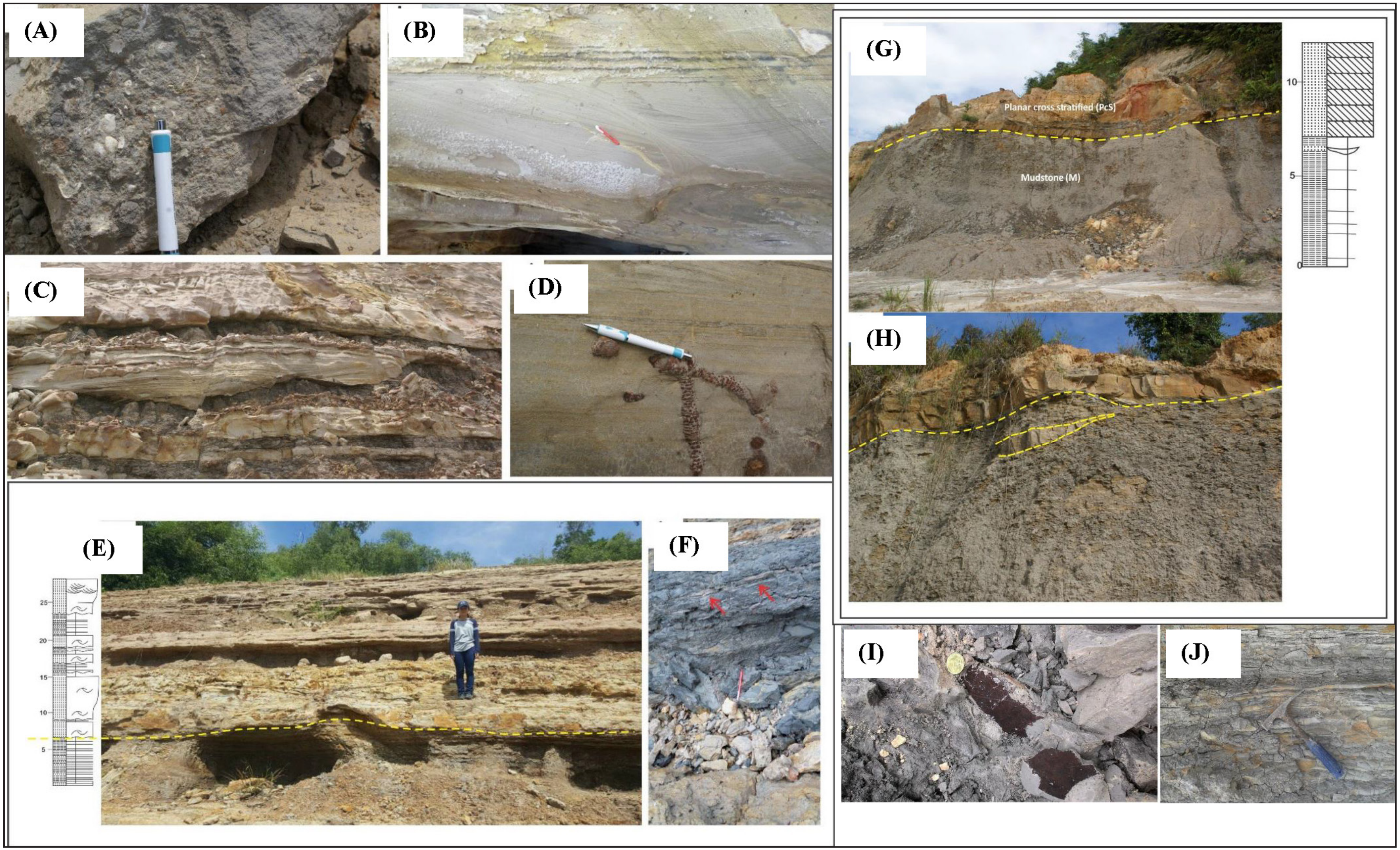

Figure 8: **(A)** Some macrofossils, such as shells, can be observed in certain parts of the sandstone, but they are partly dissolved. **(B)** The angle of stratification that exists in hummocky cross-stratification (HcS). **(C)** Photo showing interbedded hummocky cross-stratified sandstone beds with mudstone. **(D)** Some *Ophiomorpha* sp. lie on the sandstone bed. **(E)** Showcasing the boundary between LA 4 and LA 5, with an erosional base at the bottom representing the storm wave base (indicated by a yellow dotted line), and displaying vertically matched lithology on the left-hand side. **(F)** Figure illustrating thin-bedded sandstone displaying micro-hummocky structures in a thick mud layer (LA 5). **(G)** Photo showing that LA 6 has a sharp contact with LA 1, with a vertical lithology section on the right-hand side. **(H)** Sandstone lenses embedded within thick mudstone. **(I)** Photo showing a leaf imprint within the mudstone bed. **(J)** Photo showing wave-rippled bedded sandstone exposed within a parallel-laminated mudstone bed.

lithofacies 4. The laminated mud ranged from mm to cm thick and consists of a HcS minor thin sandstone bed. The recorded average thickness of LA 5 in study area is about 1 m. The parallel siltstone bed exists as a fine siltstone layer that consists of horizontal parallel lamination and well-preserved ripples. The transition from LA 5 to LA 4 is generally harder to find in Northwest Borneo due to intense weathering process and less exposure of this condition. However, the exposure of this condition at the MS01 is good evidence to show the transition occurred between LA 5 and LA 4. The evidence showed that the boundary between LA 5 and LA 4 is marked by changes in the sedimentary bedding and an erosional base at the upper part of the siltstone bed (Figure 8 (E)). Micro-hummocky can also be observed within LA 5 (Figure 8 (F)). It ranged from 0.2 to 0.3 cm and interbedded with a siltstone bed. It is exposed only at the upper part of the sandstone bed. The HcS bed from LA 4 at MS 01 overlain by structureless coarse grain sediment. From the observation, LA 4 is terminated within the laminated mud of LA 5. LA 5 displayed a weak-to-moderate burrow system and low-intensity bioturbation. However, the bioturbation recorded in LA 5 is moderate in the siltstone and laminated mud. In a siltstone bed, the exposure of *Ophiomorpha* sp. and *Thalassinoides* sp. are rare within the laminated mud.

Interpretation

LA 5 indicated decreased depositional energy and depositional rate according to the fine siltstone and predominant mud record. The slow movement of sediment flow aligns the particles in a similar pattern to produce a laminated bed (Dalrymple, 2010; La Croix *et al.*, 2019). The small-scale hummocky lenses and parallel lamination represent a continuous reworking by current (Khan *et al*., 2017). Storm wave base usually happens between the lower shoreface and offshore, which is marked by the distinguishable sedimentary structure and an erosional bed. According to Seilacher (2007), a weaker burrow system and laminated mud graded into the fine siltstone in the heterolithic-dominated intervals showed that the laminated mud is not deposited in a slow deposition event but typically accumulated in the increase of energy conditions in turbulence, tidal energy, and occasionally wave power. In relation to that consideration, this facies association is deposited at the upper part of the offshore setting (Vakarelov *et al*., 2012).

Lithofacies association 6 (LA 6): Lagoon

Description

LA 6 consists of Lithofacies M and Lithofacies 8, characterized by thick buff to black mudstone beds, and some exposures of sandstone or siltstone bedding. As discussed in the lithofacies section, LA 6 is most exposed at MS08, MS09, MS10, MS12 in the Miri region, and MS16 and MS17 in Brunei Darussalam. Most mudstone bedding averages about 3 meters thick. LA 6 makes up approximately 10% of all lithofacies associations exposed in the study area and is situated at the top of the LA 1 sequence. LA 1 has a sharp contact with LA 6 at the lower and upper parts of the bed position (Figure 8 (G)). A coal bed is a common mixture within LA 6, with the best exposure at MS09. However, it is displayed as medium to thin-bedded coal (approximately 15 cm to 5 cm). Various materials are also incorporated in LA 6, such as sandstone lenses, coal lens, lignite, root, leaf, and wood fossils (Figure 8 (I) and (H)). One dominant sedimentary structure is a parallel sandstone or siltstone bed. Another structure is a wave-rippled bedded sandstone exposed within sandstone (Figure 5 (J)). The angle of cross-stratification is obscured as the scale is very small. Heterolithic mud normally occurs in the lower bed and alternates with parallel-laminated mud. Bioturbation or burrows vary in a few locations in the study area, depending on the bioturbation index. For example, in the Miri region, a few outcrops of Lambir Hill showed highly intense *Ophiomorpha* sp. exposed in every single mudstone bedding with a complex burrow system (BI ranges from 3 to 4). However, in Brunei Darussalam, the bioturbation index scores range from 1 to 2 intensities and increase upward of the mud bedding. *Ophiomorpha* sp. and *Thalassinoides* sp. are the most common burrows.

Interpretation

A thick-laminated mudstone is a normal phenomenon that happened in low-energy flowing water of a restricted area. The current flows throughout that area and brings together suspended materials, such as silt and clay particles. Low-energy wave ripples occurred in LA 6 is good evidence to describe lagoon deposit because it will not happen in a lower beach profile, which agreed to the finding of Nichols (2009). The wave rippled sandstone exposed due to the wave influence from the wind blowing out the sand into the lagoon (Nichols, 2009) and washover sheet deposit (Reinson, 1992). The exposure of heterolithic mud in the upper mud bedding sequence and graded to silty mud is related to the tidal process during the slack-water period. This tidal effect can be seen on the upper bed because the process is only limited to that area. LA 6 has a relationship with LA 1 in terms of sedimentary progradation process where extra sediment is carried forward into stagnant water before being deposited. Basically, the remnant of fine to medium grains will be deposited together with mud and assisted by wind, which is the reason for the direct contact of LA 6 with LA 1. The evidence of coal lens, lignite, root, leaf, and wood fossil is related to a swamp or lagoon sedimentary environment (Oertel *et al.*, 1989; Nichols, 1989; Reinson, 1992). Intense bioturbation activities describe that the area is oxygen favourable and can sustain living organisms. According to the geometry, sedimentary structure, material, and bioturbation, it is suggested that LA 6 is deposited at a lagoon area.

Lithofacies association 7 (LA 7): Tidal sand bar sandstone (TSB)

Description

LA 7 is characterized as a thick-bedded sandstone with a less amalgamated bed. It comprises lithofacies 7 and lithofacies 8, the latter being a major sedimentary structure within the sandstone bed. LA 7 is occasionally associated with LA 1 and LA 6. However, it is obscured in some places within the study area. The outcrops exposed at MS06, MS08, and MS17 show good exposure of LA 7, with measurements averaging 10 cm to 50 cm in thickness. However, in MS08 and MS17, the exposed sections are on a smaller scale, ranging from 8 to 10 cm in thickness, accompanied by a co-set series of lithofacies 7 (Figure 9 (A), (C), and (D)). Unfortunately,

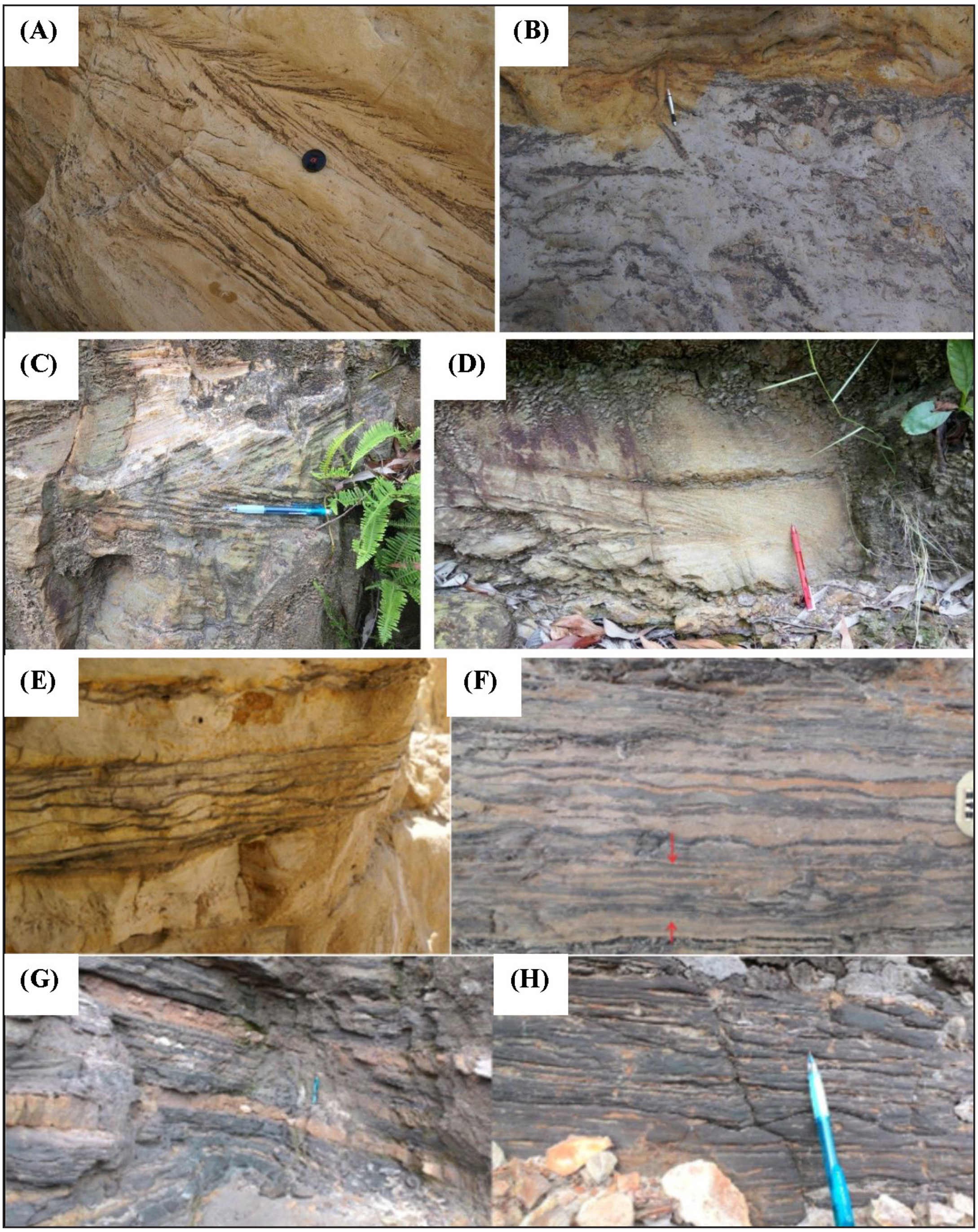

Figure 9: (A) Mud drapes are well preserved within the herringbone cross-stratified sandstone bed. **(B)** Bioturbations such as *Ophiomorpha* sp., *Thalassinoides* sp., and *Paleophycus* sp. are highly diversified and abundant in the tidal bar and have a complex burrow system. **(C)** Herringbone cross-stratification is generally associated with sand dunes and planar cross-stratification. **(D)** Medium herringbone structures are associated with heterolithic mud. **(E)** Displaying flaser structures that resemble micro-hummocky features formed in the sandstone bed interbedded with thin mud. **(F)** Horizontal laminated mud with an equal proportion of sand and mud is overlain by lithofacies F and W in a sequence of beds. **(G)** and **(H)** Displaying thick-bedded laminated mud interbedded with very fine sandstone in a 3:1 ratio.

these sections are hidden by an intensive weathering process and are predominantly covered by a heterolithic unit, making differentiation challenging. Mud drapes are clearly observed between the cross-bedded sets, mostly situated in the lower part of the sandstone bed. This LA is visibly linked with LA 7 in the upper part of the bedding, forming the basis for facies succession. It is essentially associated with LA 7 in terms of facies succession. Bioturbators like *Ophiomorpha* sp., *Thalassinoides* sp., and *Palaeophycus* sp. are highly diversified and more abundant in the tidal bar, showcasing complex burrow systems (Figure 9 (B)).

Interpretation

A thick-bedded sandstone of lithofacies 7 with a less amalgamated bed is developed by a large source of sediment deposited during different tide flows. Initially, the large sediment is carried by the waves in the foreshore and continues its journey through the migration of ripples. The migration of ripples tends to follow different pathways, with the flood tide moving up one side of the estuary and the ebb tide following a different route down the other side (Dalrymple & Choi, 2007). Additionally, the formation of a herringbone cross-bed is attributed to the tendency of the ebb and flood tidal flows to move in different pathways. The flood tide moves upward, and the ebb tide moves downward to the other side. The occurrence of mud drapes serves as typical evidence for a tidally influenced environment (Dalrymple *et al*., 1992). According to Dalrymple *et al*. (1992), mud drapes form within the lamination of a cross-bed due to the deposition of lamina sand on the lee slope during a strong tidal event. Clay materials eventually settle out of suspension when the tidal flow changes direction, resulting in the draping of the subaqueous dune. The high diversity and abundance of organisms are attributed to favorable environmental conditions, shifting substrates, and an overall high presentation potential (Howard & Frey, 1984). Based on the described facies association, it is interpreted that this facies association represents the tidal sandbar.

Lithofacies association 8 (LA 8): Tidal to sub-tidal sand flat

Description

LA 8 consists of sub-lithofacies F and sub-lithofacies W in lithofacies 8. Sub-lithofacies F is characterised by a large amount of sandstone rather than mudstone with the amount of sand is more than mud about 8 to 1. The sub-lithofacies F-W is common in the outcrops around the MS07, MS08, and MS 19. Sub-lithofacies F displays the formation of micro-hummocky in the sandstone bed interbedded with thin mud (Figure 9 (E)). Typically, this structure is irregular in size with an undulating base. According to an outcrop at the MS07, the best exposure of this lithofacies is about 5 m high. Meanwhile, sub-lithofacies W is usually seen as interbedded straight to slightly wavy intercalations of mm to cm thickness of grey to bluish grey mud and a light grey ripple cross-laminated sandy siltstone and a fine sandstone (Figure 9 (F)). Laminated sands are typically ripple-laminated and mud-draped facies, generally irregular in shape and bipolar. Ripple laminations can be seen with a small-scale stratification lies on top of the bedding sequence. They alternate in one sequence with the angle of stratification becomes narrower to the top. This LA is attached to LA 9 in a vertical order. Burrows and soft-sediment deformation structures, generally small-scale fill structures are found in several outcrops. The bioturbations are relatively moderate compared to the tidal sand bar with abundance of *Ophiomorpha* sp., *Palaeophycus* sp., *Skolithos* sp., and *Thalassinoides* sp.

Interpretation

The exposure of flaser and wavy bedding is related to the unidirectional flow of water current due to the decrease in current velocity. This is supported by the statement from Ekwenye & Nichols (2016), which is caused by the migration of unidirectional current in water during the deceleration of high-velocity current. According to Dalrymple & Choi (2007), the abundance of mud drapes within flaser bedding and ripple cross-lamination gives evidence of a tidally influenced environment. Furthermore, Reading (2009) stated that mud drapes are typically one of the most distinctive features of tidal deposits and represent the fluctuation of a tide. A heterolithic bedding like flaser and wavy bedding is basically the natural evidence of a tidal-flat environment (Reineck & Wunderlich, 1968). Sandy-silty alternation indicates that the environment is influenced by the slack-water condition. Finer grains and silt materials are yielded from slowing down tidal current during the tidal flat. The abundance of these materials is believed to have derived from the high progradational rate of sediment during the current action on a sandy flat area. The occurrence of flaser bedding on shoreface lithofacies is normal evidence of a tidal setting where it can occur in every part of a beach profile. The preservation of bioturbation with less appearance of *Ophiomorpha* sp. suggested that the area is deposited in a subtidal sand flat. However, the condition may be influenced by the sandy flat environment as shown by less bioturbation and the alternation of sandy deposit without mud. The moderate bioturbation explained that the velocity of current is slow and there is sufficient food for organisms to grow. Furthermore, the high-energy level with low food supplies will not support a diverse group of organisms (Norzita & Lambiase, 2014). From the information above, this LA can be interpreted as the tidal to subtidal sand flat.

Lithofacies association 9 (LA 9): Sub-tidal mud flat

Description

LA 9 consists of predominantly sub-lithofacies L in lithofacies 8 that comprises a rhythmic to an alternate layer of thin silt with clay. The best outcrop recorded is along the MS07 to the MS10, which achieved approximately 8 m thick.

The LA 9 has grey to bluish grey colour and many colours are dark. LA 9 is lithologically clay to silt with percentage mud is more than sand (Figure 9 (G) and (H)). The lenses internally showed tiny cross-lamination with 2–4 mm solid ripples. The thin coal bed also occurred within the thick mud and mostly covered a large area around the MS10. The evidence of bioturbation is rare to quite low within the heterolithic bed. However, the burrows (Skolithos sp) occurred at several intervals within a few outcrops at the MS09 and the MS10. Soft sediment deformation as well as micro-scale folds and flaws are apparent in several units of the lenticular bedding.

Interpretation

The existence of a lenticular bedding is good evidence of a sub-tidal mud flat. As supported by Nio & Yang (1991), the rhythmic layer of mud is interpreted as a sub-tidal mud flat. The alternation of thin clay layers indicates that the cyclic process occurred during the tidal influence on the inner estuarine sediments (Kuecher *et al*., 1990). The fine grain size indicates slow current movement during deposition. According to Shanmugam *et al*. (2000), the silt layers represent the traction deposition from ebb and flood tides, whereas the clay layers represent the deposition from the suspension during the slack-water period. The burrows are rarely observed in this LA, which is typically related to the low rate of sedimentation or low salinity of water to support burrowing organisms (Norzita & Lambiase, 2014).

Environmental depositionl interpretation

Based on the observation from several sections around Northwest Borneo, this study yielded numerous information in terms of sedimentary structure diagnostic (wave- or tidal-generated sedimentary structures), lithology, and bioturbation data. The results estimated that the environment record is divided into wave-generated and tidal-generated regimes.

Wave dominated lithofacies depositional environment

On the basis of dominant sediment distribution (Walker, 1984), for the rock units, five depositional settings have been identified, namely the offshore, the lower shoreface, the middle shoreface, the upper shoreface, and the foreshore. All of this information suggested that the sediment has been deposited at a shallow-marine environment, specifically at the shoreface depositional environment with the influence of wave and storm events (Figure 10 (A)). According to Clifton (2006), some structures attributed by most workers to storms are the hummocky cross-stratification (HcS). The abundance of hummocky cross-stratification is also a good indicator that sediment has been deposited at the lower shoreface during storms. Basically, the hummocky cross-stratification is indicative of the deposition in the lower shoreface area or generally preserved in areas of weak tidal activity that lies below fair-weather wave base and also indicative of the deposition in the lower part of a wave or storm-dominated shoreface (Walker & Plint, 1992, Johnson & Baldwin, 1996). The variety of grain sizes of sandstone with the existence of swaley cross-stratification (ScS) is a good indicator for the middle shoreface until the upper shoreface. In such a setting, storms would create shallow scours (elliptical to circular in the plan view) filled with flattening-upward laminae conforming to the shape of the swale (Leckie & Walker, 1982) that contributed to the swaley cross-stratification of the rock sequence in the area. Meanwhile, the thick mudstone interbedded with a sandstone suggested a fair-weather period that contributes to the formation of a sand pit somewhere in the middle of the lower shoreface and the middle shoreface. In many examples from the geological record, ScS sand bodies occurred stratigraphically above HcS sandstones and interbedded mudstones (Walker & Plint, 1992). This section of the outcrops is deposited at the shallow-marine environment under the fluctuations of high and low flow of wave-dominated regimes.

The abundance of amalgamated ScS and the existence of planar cross-stratification (PcS) in the sandstone give the best indicator of the upper shoreface to foreshore deposits. The high regime of current subjected to sediment caused a high angle of PcS. Meanwhile, the upper part of this area is abundant with the medium to coarse-grained sandstone, showing the characteristics of the upper shoreface. The sediment typically coarsened towards the upper part of the shoreface, which is the most energetic part of the system (Clifton, 2006). The exposure is either intermittent or obscure and sometimes filled by the tidal deposit. This situation is actually discussed by Selley (1970), according to the low input of sediment from the land during stormy coasts. Otherwise, the exposure of planar cross-stratification at the Lambir Hill interbedded with lagoon mud generally occurred in a high-energy foreshore environment (i.e., the zone of breaking waves and swash zone).

Evidence of tidally dominated deposition

Tidal lithofacies analysis has yielded three lithofacies associations attributing to environmental processes, namely tidal sand bar (LA 7), tidal-sub tidal sand flat (LA 8), and sub-tidal mud flat (LA 9). The tidal process of the Middle-Late Miocene sedimentation in Northwest Borneo has actually been discussed by many researchers (Hassan *et al*., 2013; Norzita & Lambiase, 2014; Collins *et al*., 2014). Some sedimentary structures exist in several sections of Miri (North Sarawak), and Brunei Darussalam areas are related to a tidal environment, such as herringbone cross-bedding, rhythmic mud bedding, micro-lamination mud, mud drapes, reactivation surface, ripple lamination, flaser wavy and lenticular beddings. These structures are formed according to the fluctuation of flood and ebb currents during the tidal range effect. This study determined that the occurrence of herringbone cross-stratified beds in the study area is related to tidal sand bar deposit. It is resulted from a tidal current in different directions for a period of time. This sedimentary structure is only exposed at a few areas in Northwest Borneo like some parts in the Miri area (Locality: MS 06, MS 07, MS 08, MS 09), Brunei Darussalam (Locality: MS 16, MS 17), and the Limbang area (Locality: MS 12, MS 19), which means that only those areas are covered by tidal sandy deposit. A statement quoted by Tovmasjana (2013) that the herringbone structure displayed the diagnostic features of the transition from a tidal to a river environment that happened at the field but there is limited exposure in the study area. Most structures related to fluvial deposit is limited occur at the field. The dominant exposure of a heterolithic bedding like flaser and wavy bedding suggested the deposition in a tidal to sub-tidal sand flat environment where the velocity of current decreases and then creates irregular ripples under bidirectional non-uniform energy. Furthermore, mud drapes occurred within the cross-lamination suggested a tidally-influenced regime and the fluctuation of tide. The evidence of lenticular bedding in the study area is related to the predominance of mud and silty sand. The occurrence of thick mud rather than sand represents sub-tidal mud flat deposition (LA 9). LA 9 is characterised as a slow current movement of particles during the slack-water period. Furthermore, the rhythmic layer of mud indicates a cyclic process occurred during tidal influence on the inner estuarine sediments (Kuecher *et al*., 1990).

Depositional environmental model

A straightforward model of the sedimentary environment was successfully established based on lithofacies data. The primary sediment distribution in the study area generally flows northeast, as indicated by paleocurrent analysis data, but shifts southeast towards the interior of Lawas. Figure 10 illustrates continuous exposure of shoreface sediment from Miri, Brunei Darussalam, and Limbang areas. Shoreface sediment stands out as the main dominant exposure in the study area, overshadowing tidal deposits, except for sedimentary deposition in the Lambir Formation. Tidal-deposited sediment is found between the shoreface and mainland, abundantly present in every shoreline outcrop, either lying at the upper part or between shoreline deposits. Numerous heterolithic rocks within the shoreline deposit provide evidence of disturbance by storm activity.

The lagoon (LA 6) appears as a small exposure in the study area because foreshore (LA1) and shoreface sediment (LA 2 -LA 3) are forced landward, reducing the size of the lagoon area. The lagoon may or not be linked to the fluvial system due to the low input of sediment transferred into the lagoon, eventually creating a small pond with marshland. Moreover, there is no evidence of major fluvial environmental deposits observed in the field due to the limited exposure of sedimentary structures belonging to fluvial deposits. For instance, there is no evidence of a stacked conglomerate channel (i.e., fining-upward sequence) and limited exposure of a trough and planar cross-bedding sandstone found in the field. This study notes that the submarine channel previously stated by Wannier *et al*. (2011) belongs to the large hummocky deposits of the Miri Formation and cannot be part of the fluvial deposit. Recent observations in certain parts of the Borneo region, such as the Mengkabong lagoon, the Karambunai lagoon, and the Likas lagoon in Sabah, are examples of modern lagoons without well-developed fluvial systems or poorly developed fluvial systems (Figure 10 (C)).

The vertical cyclic pattern in the transition in tide-generated lithofacies associations and the fining-upward trend in sedimentary packages/stratigraphic units is considered to reflect a retrograding estuarine succession and subtidal to intertidal sandy to muddy flat system, fringing the shoreline deposit (Figure 10 (B)). Based on tidal signatures found throughout the distribution area of the Middle to Late Miocene sedimentary successions and the regional geological trend, deposition occurred in the tide-dominated estuarine system and on adjacent tidal flats. The deposits of the Miri, Lambir, and Belait Formations exhibited various coarse-fine grain size trends at both ends of the so-called estuarine-barrier island system (wave-tidal deposits) due to the cyclicity present in the outcrop, reflecting two sediment sources: estuary and beach. Coarser deposits were typical in the eastern (landward) part of the distribution area, while most fine-grained deposits, including significant mud layers, occurred in the southern part. In contrast to the fluvial-deltaic system, the overall basinward fining grain-size trend was typical, driven by the fluvial sediment source (Dalrymple & Choi, 2007) since fluvial-deltas are defined as progradational sedimentary bodies that shift from the shoreline, where tidal currents rework river-supplied sediments basinward (Willis *et al*., 1999). This evidence illustrates that the estuary-barrier island distributes source from landward to basinward due to the regressive-transgressive trajectory, while the fluvial-delta distributes source basinward. Based on the concrete evidence discussed from wave- to tide-dominated regimes, the environment of deposition is suggested as a shoreline deposit and part of paralic successions ranging from estuary, lagoon, tidal flat, and shoreface environments. However, it may be or detached separately from a fluvial system based on some evidence stated above.

CONCLUSION

In conclusion, the depositional sequence from the Middle to Late Miocene, spanning from Miri to Brunei Darussalam areas, is primarily situated within the estuarine (i.e., open mouth area) to shallow marine (i.e., barrier island system) environments. Although the historical development of a paleo-estuary in North-West Borneo is plausible, the channelized system remained obscure in the field. The estuary-shallow marine environment is emphasized as a primary depositional setting, as many tidal signatures resemble modern-day areas with shoreface deposits in the study regions. The presence of heterolithic assimilating in the

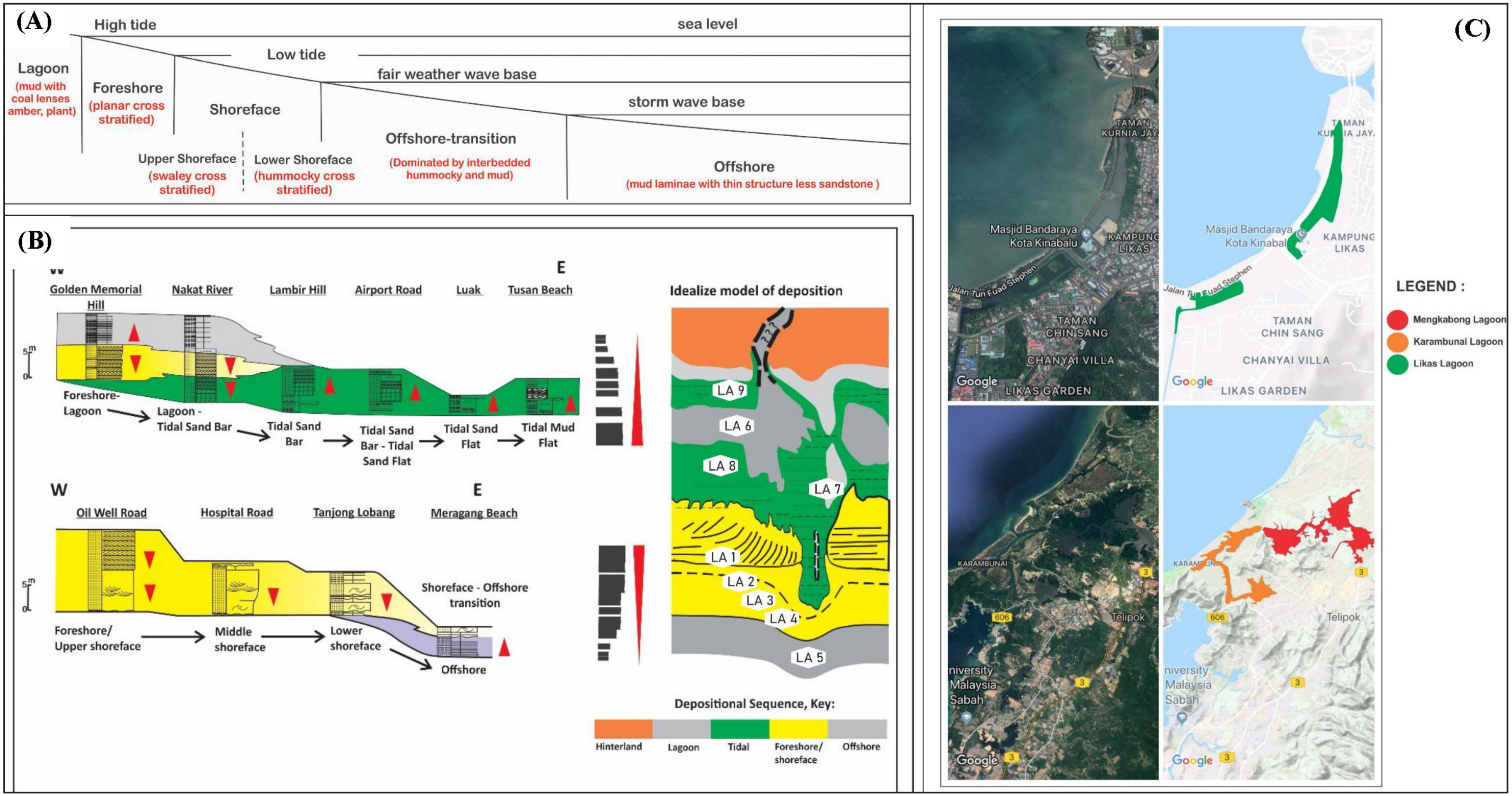

Figure 10: **(A)** An idealized schematic of the simplified beach and shoreface environmental model, adapted and rebuilt from Prothero (1990). **(B)** The transgressive-regressive cycle is delineated from lithofacies associations in the study area. It is accompanied by an idealized model of the sedimentary environment, proposing a depositional sequence ranging from offshore to lagoon areas. The depositional model is modified from Dalrymple *et al*. (1992). Note that the fluvial area is obscured due to limited evidence of sedimentary structures related to fluvial deposits. **(C)** Comparisons of lagoons and estuaries in two different areas around Sabah, Malaysia, using satellite imagery from Google Maps. Both are depicted as disconnected from the main fluvial system. The Mengkabong Lagoon is highlighted in red, the Karambunai Lagoon in orange, and the Likas Lagoon in green.

shoreface deposits in Miri and Lambir Formations indicates the influence of tides at or near the mean sea level or fair-weather wave base. Abrupt changes in sediment transport from the estuary decrease the supply of fluvial deposits, resulting in limited fluvial deposits in the field. Wave actions further contribute to sediment distribution during this process. The suggested source of sediments is from the estuary, influenced by tidal regimes, and reworked sediments are deposited in the paleocoastline (barrier island system). These sediments then move from the paleocoastline to the shoreface and offshore. Numerous heterolithic preserved in the field reveal subtidal sand flat to intertidal mud flat, suggesting the reception of sediments from the estuary before tidal regimes take place. Additionally, the shallow marine environment receives reworked sediment from the estuary, transporting it to the shoreface and offshore settings. The abundance of fine-grain sediments in the outcrop successions indicates multiple transportation events before settling on the beach.

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AUTHORS CONTRIBUTION

MNIAR: conceptualized the research, developed the methodology, performed the analysis, wrote the manuscript.

EHA, DAN, NBB: support and provide idea throughout the research.

JA: provide idea and edited the manuscript.

CONFLICT OF INTEREST

The authors declare that this work has no financial interests or any personal conflict which have or could have influenced the work reported in this article.

REFERENCES

Abieda, H.S., Harith, Z.Z.T. & Abd. Rahman, A.H., 2005. Depositional Controls on Petropysical Properties and Reservoir Characteristics of Middle Miocene Miri Formation Sandstones, Sarawak. Bulletin of the Geological Society of Malaysia, 51, 63-75.

Arnott, R.W.C., 1992. Ripple cross-stratification in swaley cross-stratified sandstones of the Chungo Member, Mount Yamnuska, Alberta. Canadian Journal of Earth Sciences, 29, 1802–1805.

Atkinson, C.D., Goesten, M.J.B.G., Speksneijder, A., & Van Der Vlugt, W., 1986. Storm-generated sandstone in the Miocene Miri Formation, Seria Field, Brunei (NW Borneo). In: Knight, R.J., & McLean, J.R. (Eds.), Shelf Sands and Sandstones, Canadian Society of Petroleum Geologists, 11, 213-240.

Balaguru, A., & Lukie, T., 2012. Tectono-Stratigraphy and Development of the Miocene Delta Systems on an Active Margin of Northwest Borneo, Malaysia. Petroleum Geoscience Conference & Exhibition. 23-24 April 2012, Kuala Lumpur.

Banda, R.M. & Honza, E., 1997. Miocene stratigraphy of northwest Borneo Basin. Bulletin of the Geological Society of Malaysia. 40, 1-11.

Buatois, L.A., Gingras, M.K., Maceachern, J., Ma´ngano, M.G., Zonneveld, G.P., Pemberton, S.G., Netto, R.G., & Martin, A., 2005. Colonization of brackish-water systems through time: Evidence from the trace-fossil record. PALAIOS, 20, 321–347.

Chung, C.S., 1982. Geological Map of Sarawak. The Geological Survey of Malaysia, Kuala Lumpur, Malaysia. 1:500000 scale.

Clifton, H.E., 1976. Wave-formed sedimentary structures - A conceptual model. In: Davis, R.A., Jr., & Ethington, R.L. (Eds.), Beach and Nearshore Sedimentation. Society for Sedimentary Geology (SEPM) Special Publication, 24, 126–148.

Clifton, H.E., 2006. A re-examination of facies models for clastic shorelines. In: H.W. Posamentier & R.G. Walker (Eds.), Facies Model Revisited. SEPM Spec., 84, 293-337.

Collins, D.S., Allison, P.A., Johnson, H.D., Avdis, A., Hill, J. & Piggot, M., 2014. Integrating Tidal Modeling and Facies Analysis for the Miocene, Northwest Borneo, South China Sea. AAPG Annual Convention and Exhibition.

Collins, D.S., Johnson, H.D., Allison, P.A., Guilpain, P. & Damit,A.R., 2017. Coupled 'storm-flood' depositional model: Application to the Miocene-Modern Baram Delta Province, north-west Borneo. Sedimentology, 64, 12031235.

Collins, D.S., Johnson, H.D., & Baldwins, C.T., 2020. Architecture and preservation in the fluvial to marine transition zone of a mixed-process humid-tropical delta: Middle Miocene Lambir Formation, Baram Delta Province, north-west Borneo. Sedimentology, 67, 1-46.

Curiale, J., Morelos, J., Lambiase, J. & Mueller, W., 2000. Brunei Darussalam characteristics of selected petroleums and source rocks. Organic Geochemistry, 31, 1475-1493.

Dalrymple, R.W., 2010. Interpreting Sedimentary Successions: Facies, Facies Analysis and Facies Models. In: James, N.P. & Dalrymple, R.W. (Eds.), Facies Models 4. Geological Association of Canada, St. John's, Newfoundland and Labrador, Canada. 586 p.

Dalrymple, R.W. & Choi, K.S., 2007. Morphologic and facies trends through the fluvial–marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation. Earth Sci. Rev., 81, 135–174.

Dalrymple, R.W., Zaitlin, B.A. & Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology, 62, 1130-1146.

Dott, R.J., & Bourgeois, J., 1982. Hummocky stratification: Significance of its variable bedding sequences. Geological Society of America Bulletin, 93, 663–680.

Dumas, S. & Arnot, R.W.C., 2006. Origin of hummocky and swaley cross-stratification - The controlling influence of unidirectional current strength and aggradation rate. Geological Society of America, 34(12), 1073-1076.

Dumas, S., Arnott, R.W.C. & Southard, J.B., 2005. Experiments on oscillatory-flow and combined-flow bed forms: implications for interpreting parts of the shallow marine sedimentary record.

J. Sed. Res., 75, 501–513.

Ekwenye, O.C. & Nichols G., 2016. Depositional facies and ichnology of a tidally influenced coastal plain deposit: the Ogwashi Formation, Niger Delta Basin. Arab J. Geosci., 9, article number 700.

Hall, R., 2013. Contraction and extension in northern Borneo driven by subduction rollback. Journal of Asian Earth Sciences, 76, 399-411.

Hall, R., & Nichols, G., 2002. Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis. In: Jones, S.J., & Frostick, L. (Eds.), Sediment Flux to Basins: Causes, Controls and Consequences. Geological Society of London, 191, 5-22.

Hamblin, A.P., & Walker, R.G., 1979. Storm-dominated shallow marine deposits: the Fernie-Kootenay (Jurassic) transition, southern Rocky Mountains. Can. J. Earth Sci., 16, 1673-1690.

Hamilton, W., 1979. Tectonics of the Indonesian region (U.S. Geological Survey Professional Paper). United States Government Printing Office, Washington. 345 p.

Hart, B.S. & Plint, A.G., 1995. Gravelly shoreface and beachface deposits. Special Publication of the International Association of Sedimentologists, 22, 75-99.

Hassan, M.H.A., Johnson, H.D., Allison, P.A. & Abdullah, W.H. 2013. Sedimentology and stratigraphic development of the upper Nyalau Formation (Early Miocene), Sarawak, Malaysia: A mixed wave- and tide-influenced coastal system. Journal of Asian Earth Sciences, 76, 301-311.

Howard, J.D., & Frey, R.W., 1984. Characteristic trace fossils in nearshore to offshore sequences, Upper Cretaceous of east-central Utah. Canadian Journal of Earth Sciences, 21, 200-219.

Hui, L.C., & Leman, M.S., 1994. The occurrence of Lambir Formation in Ulu Bok Syncline, North Sarawak. Bulletin of the Geological Society of Malaysia, 35, 1-5.

Hunter, R.E., Cliton, E., & Phillips, R.L., 1979. Depositional processes, sedimentary structures, and predicted vertical sequences in barred nearshore systems, Southern Oregon coast. J. Sedi. Petro., 49(3), 0711-0726.

Hutchison, C.S., 2005. Geology of North West Borneo, Sarawak, Brunei and Sabah. Elsevier, Amsterdam. 444 p.

James, D.M.D., 1984. The Geology and Hydrocarbon Resources of Negara Brunei Darussalam. Muzium Brunei, Bandar Seri Begawan. 169 p.

Johnson, H.D. & Baldwin, C.T., 1996. Shallow Clastic Seas. In: H.G. Reading (Ed.), Sedimentary environments: Processes, facies, and stratigraphy. Blackwell Science, Oxford. 689 p.

Jong, J., Idris, H.A.M., Barber, P., Kessler, F.L., Tran, T.Q. & Uchimura, R., 2017. Exploration history and petroleum systems of the onshore Baram Delta, Northern Sarawak, Malaysia. Bulletin of the Geological Society of Malaysia, 63, 117-143.

Kessler, F.L. & Jong, J., 2015. Northwest Sarawak: a complete geologic profile from the Lower Miocene to the Pliocene covering the Upper Setap Shale, Lambir and Tukau Formations. Warta Geologi, 41(3-4), 45-51.

Kessler, F.L. & Jong, J., 2017. The roles and implications of several prominent unconformities in Neogene sediments of the greater Miri area, NW Sarawak. Warta Geologi, 43(4), 1-8.

Khan, A., Aslam, M. & Rahman, E., 2017. Wave-dominated Shoreline Sediments in Early Cretaceous Surajdeval Formation, Saurashtra Basin, Gujarat Western India. International Journal of New Technology and Research (IJNTR), 3(2), 74-78.

Kuecher, G.J., Woodland, B.G & Broadhurst, F.M., 1990. Evidence of deposition from individual tides and of tidal cycles from the Francis Creek Shale (host rock to the Mazon Creek biota), Westphalian D (Pennsylvanian), northeastern Illinois. Sedimentary Geology, 68, 211–221.

La Croix, A., He, J., Wang, J., & Underschultz, J., 2019. Facies prediction from well logs in the Precipice Sandstone and Evergreen Formation in the Surat Basin; The University of Queensland Surat Deep Aquifer Appraisal Project – Supplementary Detailed Report. The University of Queensland.

Leckie, D.A. & Walker, R.G., 1982. Storm- and tide-dominated shorelines in cretaceous Moosebar-lower gates interval; outcrop equivalents of Deep Basin gas trap in Western Canada. AAPG Bul., 66, 138-215.

Leong, K.M., 1999. Geological setting of Sabah. In: Leong, K.M. (Ed.), The Petroleum Geology and Resources of Malaysia. PETRONAS, Kuala Lumpur. 665 pg.

Liechti, P., Roe, F.W., & Haile, N.S., 1960. The Geology of Sarawak, Brunei, and the Western part of North Borneo. Geological Surv. Dept., British Territories in Borneo, Kuching, Sarawak. 360 p.

Madon, M., 1997. Sedimentological aspects of the Temburong and Belait Formations, Labuan (offshore west Sabah, Malaysia). Bulletin of the Geological Society of Malaysia, 41, 61-84.

Madon, M., 1999. Geological Setting of Sarawak. In: Leong, K.M. (Ed.), The Petroleum Geology and Resources of Malaysia. PETRONAS, Kuala Lumpur, 273-290.

Mellere, D., Zecchin, M. & Perale, C., 2005. Stratigraphy and sedimentology of fault-controlled backstepping shorefaces, Middle Pliocene of Crotone basin, southern Italy. Sediment. Geol., 176, 281-303.

Nesbitt, E.A., 1995. Paleoecological analysis of molluscan assemblages from the Middle Eocene Cowlitz Formation, southwestern Washington. J. Paleont., 69(6), 1060-1073.

Nichols, G., 2009. Sedimentology and Stratigraphy. Wiley-Blackwell, West Sussex. 419 p.

Nichols, M.M., 1989. Relative sea-level rise in lagoons. Marine Geology, 88, 201-219.

Nio, S.D. & Yang, C.S., 1991. Diagnostic attributes of clastic tidal deposits: a review. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin & R.A. Rahmani (Eds.), Clastic Tidal Sedimentology. Can. Soc. Petrol. Geol. Mem., 16, 3–28.

Norzita, M.F. & Lambiase, J.L., 2014. Ichnology of shallow marine clastic facies in the Belait Formation, Brunei Darussalam. Bulletin of the Geological Society of Malaysia, 60, 55 – 63.

Oertel, G.F., G.T.F. Wong, & J.D. Conway, 1989. Sediment accumulation at a fringe marsh during transgression, Oyster, Virginia. Estuaries, 12, 18-26.

Prave, A.R., Duke, W.L., & Slattery, W., 1996. A depositional model for storm-and tide-influenced prograding siliciclastic shoreline from the Middle Devonian of the central Appalachian foreland basin, USA. Sedimentology, 43, 611-629.

Prothero, D.R., 1990. Interpreting the stratigraphic record. W.H. Freeman, New York. 410 p.

Rahman, M.N.I.A., & Tahir, S., 2017. Wave dominated shoreline deposits in the Late Miocene sedimentary sequence in the Miri Formation North Sarawak, Malaysia. Geological Behaviour (GBR), 1(2), 14-19.

Rahman, M.N.I.A., & Tahir, S., 2018. Measured Section for the Possible Stratotype of the Miri Formation, at Miri Hill, North Sarawak, Malaysia. Geological Behaviour (GBR), 2(2), 10-16.

Rahman, M.N.I.A., & Tahir, S., 2019. Middle Miocene Wave Influenced Tidal Dominate Lambir Formation, Miri, Sarawak: Case study in Tusan Beach and Lambir Hill. Geological

Behaviour (GBR), 3(1), 20-27.

Reading, H.G., 2009. Sedimentary environment: process, facies and stratigraphy. Wiley-Blackwell, Malden, Oxford. 704 p.

Reineck, H.E. & Wunderlich, R., 1968. Classification and origin of flaser and lenticular bedding, Sedimentology, 11, 99-104.

Reinson, G.E., 1992. Transgressive barrier island and estuarine systems. In: Walker, R.G. & James, N.P. (Eds.), Facies Models - Response to Sea Level Change. Geological Association of Canada Publications, Canada. 409 p.

Rijks, E.J.H., 1981. Baram Delta geology and hydrocarbon occurrence. Bulletin of the Geological Society of Malaysia, 14, 1-18.

Roslim, A., Antonino Briguglio, A., Kocsis, L., Rahman, F.A., Bahrein, I.F., Goeting, S., & Razak, H., 2020. Palaeoenvironmental interpretation of Late Miocene outcrops (Miri and Seria formations) along Jalan Tutong in Brunei Darussalam. Bulletin of the Geological Society of Malaysia, 70, 39 - 56.

Sandal, T., 1996. The geology and hydrocarbon resources of Negara Brunei Darussalam. Brunei Shell Petroleum Co. Sdn. Bhd. Brunei Museum, Brunei. 243 p.

Seilacher, A., 2007. Trace fossil analysis. Springer-Verlag, Berlin, Heidelberg, New York. 226 p.

Selley, R.C., 1970. Studies of sequence in sediments using a simple mathematical device. Quarterly Journal of the Geological Society of London, 125, 557-581.

Shanmugan, G., Poffenberger, M. & Toro Alava, J., 2000. Tide-dominated estuarine facies in the Hollin and Napo (“T” and “U”) formations (Cretaceous), Sacha field, Oriente basin, Ecuador. AAPG Bulletin, 84(5), 652-682.

Simmons, M.D., Bidgood, M.D., Brenac, P., Crevello, P.D., Lambiase, J.J. & Morley, C.K., 1999. Microfossil assemblages as proxies for precise paleoenvironmental determination - an example from Miocene sediments of northwest Borneo. In: Jones, R.W., & Simmons, M.D. (Eds.), Biostratigraphy in Production and Development Geology. Geological Society, London, Special Publication, 152, 219–241.

Southard, J.B., Lambie, J.M., Federico, D.C., Pile, H.T., & Weidman, C.R., 1990. Experiments on bed configurations in fine sands under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification. Journal of Sedimentary Petrology, 60, 1–17.

Swift, D.J.P., Oertel, G., Tillman, R., & Thorne, J., 1991. Shelf sand and sandstone bodies; geometry, facies and sequence stratigraphy. International Association of Sedimentologists, Oxford, UK. 532 p.

Tahir, S., Musta, B., Asis, J., & Hanis, F., 2018. Wave and Tide Influence in Neogene Paralic Hydrocarbon Potential Reservoirs in Sabah. ASM Science Journal, 11(2), 278-292.

Tan, D.N.K., Abd. Rahman, A.H., Anuar, A., Bait, B. & Tho, C.K., 1999. West Baram Delta. In: Leong, K.M. (Ed.), The Petroleum Geology and Resources of Malaysia, PETRONAS, Kuala Lumpur, 291-342.

Teoh, Y.J., & Rahman, A.H.A., 2009. Comparative analysis of facies and reservoir characteristics of Miri Formation (Miri) and Nyalau Formation (Bintulu), Sarawak. Bulletin of the Geological Society of Malaysia, 55, 39–45.

Tovmasjana K., 2013. Depositional environment of the tidally-dominated transgressive succession: Rzekne and Pärnu regional stages, Baltic Devonian basin. PhD thesis, University of Latvia, Riga, Latvia. 145 p.

Vakarelov, B.K., Ainsworth, R.B. & MacEachern, J.A., 2012. Recognition of wave-dominated, tide-influenced shoreline systems in the rock record: Variations from a microtidal shoreline model. Sedimentary Geology, 279, 23-41.

Walker, R.G., 1984. Shelf and Shallow Marine Sands. In: R.G. Walker (Ed.), Facies Models 2nd ed. Geoscience Canada, Canada. 317 p.

Walker, R.G. & Plint, A.G., 1992. Wave- and storm-dominated shallow marine systems. In: R.G. Walker & N.P. James (Eds.), Facies Models: Response to Sea-Level Change. Geol. Assoc. Can., Canada. 407 p.

Wannier, M., Lesslar, P., Lee, C., Raven, H., Sorkhabi, R. & Ibrahim, A., 2011. Geological excursions around Miri, Sarawak. EcoMedia, Miri. 279 p.

Wilford, C.E., 1961. The Geology and Mineral Resources of Brunei and Adjacent Parts of Sarawak with descriptions of Seria and Miri Oilfelds. British Borneo Geol. Survey Memoir 10, Geological Survey, Borneo Region, Malaysia. 319 p.

Willis, B.J., Bhattacharya, J.P., Gabel S.L., & White, C.D., 1999. Architecture of a tide-influenced delta in the Frontier Formation of central Wyoming, USA. Sedimentology, 46, 667–688.

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