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FACIES ANALYSIS AND PALAEODEPOSITIONAL ENVIRONMENT OF THE TANJONG FORMATION IN THE KALABAKAN AREA, SOUTHEAST SABAH

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ABSTRACT

An integrated approach is adopted to study the sedimentary deposits of the well-exposed Early to Middle Miocene Tanjong Formation in the Southeastern part of Sabah. The integrated sedimentological and palynological data will provide a better insight into the depositional architecture of the area. This work presents the first detailed sedimentological facies analysis of the Tanjong Formation within the Kalabakan area. The integration of facies analysis, ichnological and palynological data provide a better evaluation of the organic matter (OM) origin and the reconstruction of the palaeodepositional model. An extensive outcrop-based sedimentological facies analysis was performed on eight (8) well-exposed outcrops with studied stratigraphic sections. Seven facies associations are classified in the Tanjong Formation from twelve lithofacies elements which have been interpreted from the fluvial-deltaic to shallow marine environment: FA1 - Floodplain facies association; FA2 – Fluvial channel facies association; FA3 - Coastal swamps facies association; FA4 – Tidal flat facies association; FA5 – Delta front facies association; FA6 – Mouth bar facies association; FA7 - Upper shoreface facies association. The palynomorphs of the studied coal samples yielded abundant mangrove and freshwater types of pollen assemblage, while the analysed mudstone samples suggest deposition within a lower coastal plain setting with proximity to the marine environment. The presence of Florschuetzia levipoli (Sonneratia caseolaris) and Florschuetzia trilobata suggest an age not older than the Early Miocene and/or younger. The reconstructed palaeodepositional environment model is essential in improving the predictability of the petroleum system mechanisms and the hydrocarbon potential for conventional petroleum exploration.

Keywords: *Sedimentology, facies association, fluvial-deltaic, shallow marine, geochemical, palynology*

INTRODUCTION

Sabah is a Malaysian province located in the northern part of Borneo (Figure 1). In southern Sabah, sandstone or mudstone makes up the majority of the exposed rocks, whereby the former commonly contains quartz arenites while the latter is often thinly bedded and grey or black, despite brighter coloured units occurring in place. Different sedimentary structures are indicative of varying environments, such as continental (coals) to shallow marine (cross-bedded sandstones) to deeper marine (turbidites). Numerous rock units have relatively weak fossil assemblages, offering minimal biostratigraphic data from macrofossils or foraminiferal organisms [1]. The Early Miocene to the Early Pliocene of the Neogene sedimentary successions exposed in Southeast Sabah includes the oldest Kalabakan Formation, followed by the Tanjong Formation, Kapilit Formation, and the youngest Simenggaris Formation. The overlying sediments of the Kapilit Formation and the Simenggaris Formation were thought to be separated by an unconformity [2]. Following the occurrence of uplifting between 22 and 16 Ma (Lower to Middle Miocene) corresponding with the deep regional unconformity (DRU) is the presence of the Early Miocene unconformity between the Kuamut Formation and its melange with the overlying Tanjong Formation. Before the unconformity, Sabah was characterised by deep water with prevalent turbiditic sedimentation followed by shallow water [3].

Numerous studies have been conducted on the geology of Sabah; however, this study will focus on the sedimentary or stratigraphic successions and their correlation to the environment where the onshore Tanjong Formation was deposited in Southeast Sabah. The Kapilit Formation is on top of the Tanjong Formation, which dates from the Lower to the Middle Miocene. The Tanjong Formation was first described as a thick sequence of sandstones, mudstones, and siltstones with limestone and lenses of conglomerate [2]. A coarse-grained sandstone, conglomerate, carbonaceous mudstone, and coal seams (Unit II) are deposited on top of a lower mudstone and siltstone sequence (Unit I), forming a coarsening-upward mega sequence of the Tanjong Formation [3]. Studies on facies analysis concerning the Tanjong Formation's depositional environment have not been well investigated, and data on sedimentology, stratigraphy and the identification of fossils are still sparse. Thus, this study aims to assess the sedimentology and depositional environment of the study area through in-depth facies analysis and facies association studies with the determination of the deposition process involved. The specific objectives of this study are to (i) document the lithofacies' characteristics and facies successions of the Tanjong Formation, (ii) recognise the depositional environment of the facies associations of the formation, and (iii) produce a paleodepositional model for the Tanjong Formation of the Kalabakan area. The acquired findings will help explain variations in sedimentary characteristics essential for the different depositional environments.

GEOLOGY AND TECTONIC SETTING

The Northern part of Borneo, Sabah, had a complex geological history. It is located between the Sulu Sea on the North-East, the Celebes Sea on the South-East, and the South China Sea on the West. Five well-defined tectonostratigraphic provinces are discernible in Sabah (Figure 1), which include: (i) an ophiolite complex, which is considered to form the basement to the sedimentary succession of Sabah [4], (ii) the Rajang-Crocker accretionary prism, an arcuate belt made up of deformed deep-marine, Eocene-Oligocene strata [5]-[7], (iii) broken formations and melanges that exhibit characteristics of tectonic, sedimentary, and diapiric origin and are believed to have formed in a series of related events in the Early to Middle Miocene [8], (iv) Neogene sedimentary rocks, which are primarily shallow marine to fluvial-deltaic facies deformed into sub-circular to elliptical, fault-bounded areas that are known as the "circular basins" of Sabah [6],[9], (v) The Semporna-Sulu Arc, a region andesitic to the dacitic volcanic activity of Miocene to Quaternary age in the Dent and Semporna peninsulas. The study area is situated within the recognised tectonostratigraphic province of Neogene sedimentary rocks. The deep marine Oligocene Labang Formation is the initial formation in the central Sabah circular basins, specifically on the western sides of the basins. In the Miocene paralic environment, low-energy Tanjong Formation deposits evolved towards the depocenter [2]. As evidenced by the presence of carbonaceous material in the sandstone, fossil Textualaria, and coal seams, at least a portion of the Tanjong Formation was deposited in shallow water, partially in brackish and estuarine conditions [2]. In the southern and eastern parts of the Sabah Basin, the Tanjong Formation dates from the Early to Middle Miocene [2],[10]-[11]. Numerous researchers have used palynological and nanofossil analyses to determine the Early to Middle Miocene age of the Tanjong Formation [3],[9].

The several hypothesised tectonic theories, each of which implied a distinct interpretation mechanism, have led to ongoing debates over the general geology of Sabah [3],[12]-[14]. Some suggested that Pre-Neogene uplift and tectonic deformation in the Proto-South induced fore-arc region China Sea block drifting to the NW Borneo and SW Philippines [12]-[13]. The Top Crocker Unconformity (TCU) was produced as a result of the event that is causing the formation of melanges and deposition of new sediments [13],[15]-[16]. The thrust mountain from Borneo to Palawan was elevated during the Early

Miocene Sabah-Cagayan Arc formation (Sabah Orogeny). Since most of eastern Sabah was still below sea level at the time, it resembled shallow marine environments that rested on deformed deep-water rocks in the basin. Then, at around 21 Ma, the SE Sulu Sea opened [17] as a result of the NW Celebes Sea subduction's "roll-back," creates the Dent-Semporna Arc in southeast Sabah [13]. At the back-arc basin, extensional subsidence is generated. Clastic sediments associated with the Tanjong and Kapilit Formation, unconformably deposited in shallow-deltaic settings upon the Kalabakan and pre-Neogene deep sediments, were continuously supplied by the uplift in Central Borneo to the NE up to the Sulu Sea. East Kalimantan's extensional basin was likewise created by the rifting of the Sulu Sea [18]-[19], which

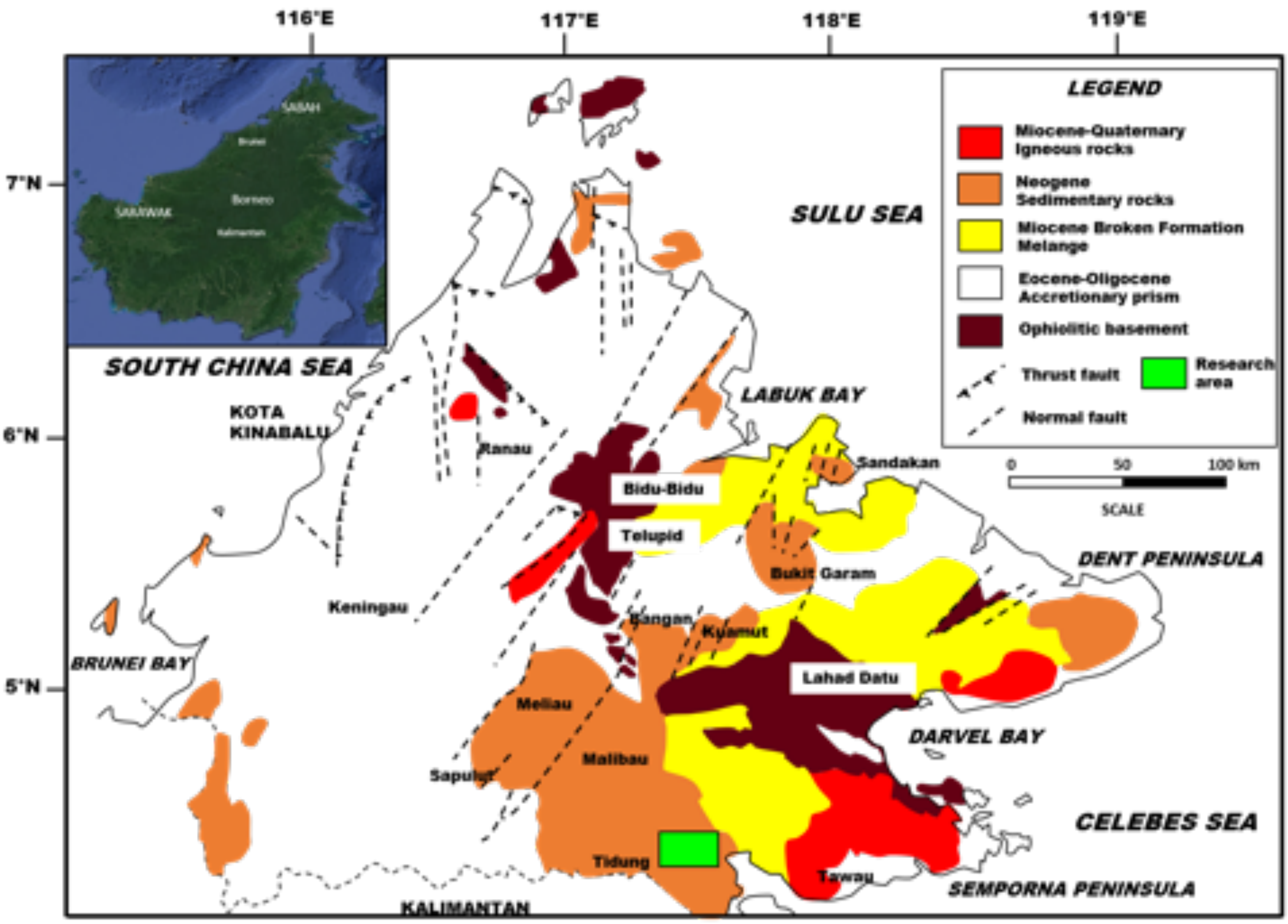

Figure 1 Outline of the main geological units in Sabah [1],[20]-[21]

the basin formation previously had been influenced by the rifting of the Makassar Strait.

The deposition of the Kalabakan, Tanjong, and Kapilit Formations in the Southeast Sabah basin, often referred to as the Circular basin, was impacted by the compression-to-extension-to-subsidence in the Early to Late Miocene. More muddy facies succession was visible towards the northeast, which indicates deltaic progradation to the shallow marine system. There was also a period of relative tectonic quiescence during the late Middle Miocene [15] since the Tanjong Formation displayed an absence of syn-sedimentary structure [3]. The eastern subsidence (12–13 Ma) left reefal facies overlain by deep marine clastic, and the onset of thick sedimentation over the Tanjong, Kapilit, and Sandakan sediments delta-plain led to a high burial thermal maturity [14]. Prior to another "roll-back" episode, all Miocene sediments in Southeast Sabah were deposited in a single shallow basin. Additionally, the deformation of regional strike-slip in the recent outcrop pattern is thought to have been induced by the emergence of transpressional tectonics and basin inversion in the Pliocene period.

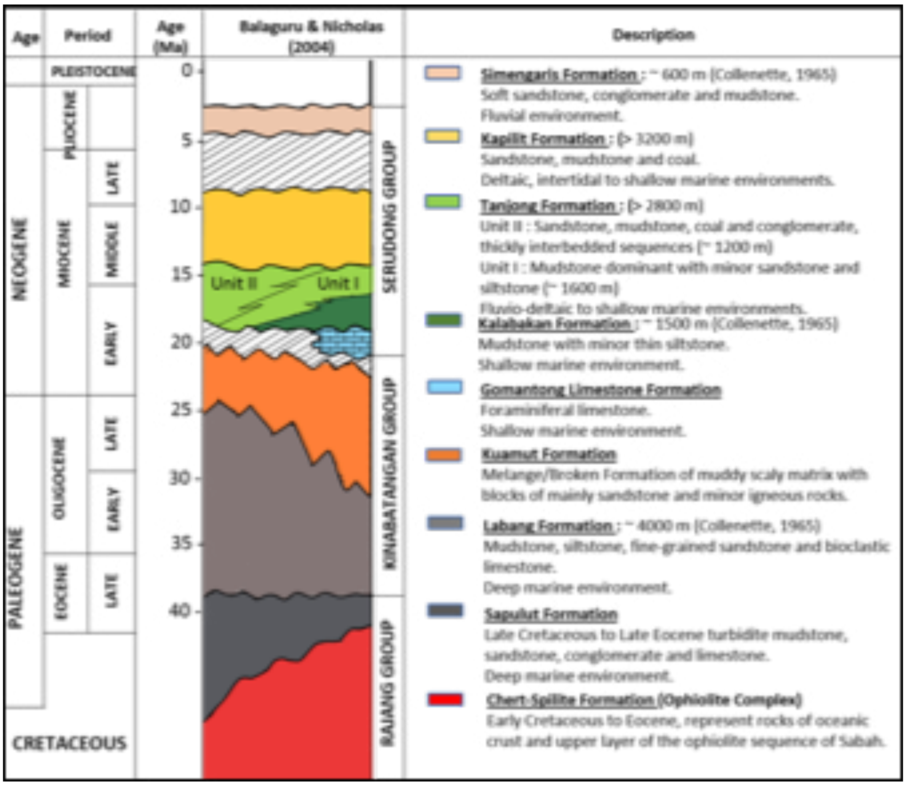

Figure 2 The modified stratigraphy of the southern Sabah study area [3]

STUDY AREA

The study area is located in the Southern to Southeastern Sabah (Figures 2 and 3). There are many extensive and relatively new outcrops of the Tanjong Formation within the Kalabakan area, mainly along the Kalabakan–Sapulut road. Eight (8) well-exposed and complete sections were identified and selected for a detailed sedimentological study with a total distance of approximately 50 km. Precise correlation of the studied sections is impossible due to the complex deformation, vegetation, and lateral facies variations. Sedimentary logging was done based on lithological composition, geometry, sedimentary and biogenic structures of eight (8) vertical field sections (designated as TJ01, TJ02, TJ03, TJ04, TJ05, TJ06, TJ07, and TJ08) totalling up to about 340 meters in measured section. Facies assemblages and their correlatable depositional features of the exposures were also studied to understand better the processes and fluvial sedimentations of the study area. Most outcrops represent the upper part (Unit II; TJ01, TJ02, TJ03, TJ04, and TJ05) of the Tanjong Formation, with three sections probably representing the lower part (Unit I; TJ06, TJ07, and TJ08).

The overall lithologies or facies observed in the outcrops of the Tanjong Formation are dominant in sandstones and mudstones. In outcrops TJ01, TJ02, TJ03, TJ04, and TJ05, sandstone-dominated facies are observed with minor shales and coal seams. In outcrops TJ06, TJ07, and TJ08, mudstone facies predominate with interbedded sandstone and mudstone facies. The thickest bed is a massive, ungraded medium-grained sandstone bed with 13.6 m in thickness found in TJ05. Meanwhile, the thinnest is the thin laminated mudstone layer around 0.02 to 0.05 m in thickness. The sedimentary succession for TJ01 and TJ02 are quite similar in that both outcrops are composed of thick and massive sandstone beds, mudstone, and intercalated shale. Meanwhile, the sedimentary succession of outcrops TJ03, TJ04, and TJ05 displayed similarity in the lithology presence of thick sandstone beds, mudstone, carbonaceous shales, and minor coal seams followed by interbedding of mudstone and sandstone observed in outcrops TJ07 and TJ08. The presence of coal seams within the studied outcrop indicates the upper unit II Tanjong Formation. Heterolithic bedding with mud drapes is commonly found within most outcrops made up of a mix proportion of sandstone and mudstone, indicative of a tidally influenced environment.

Furthermore, scattered coal lenses and thin lamination of carbonaceous materials can also be observed in most outcrops, indicating a high organic matter content. The dominant strike/dip reading is measured in the TJ05 thick sandstone bed, which gave a reading of 048˚/062˚ in the SW dip direction. Palynological analysis of coal and mudstone samples from two of the studied sections (TJ05 and TJ06) indicate an Early Miocene to the younger age of the Tanjong Formation, based on the occurrence of Florschuetzia trilobata and Florschuetzia levipoli. The sections are up to 92m in stratigraphic thickness and provide the first opportunity for a detailed facies analysis representative of the upper and lower part of the Tanjong Formation. The depositional environment of the formation varied from fluvial, deltaic, and transitional into the shallow marine based on the analysed facies association.

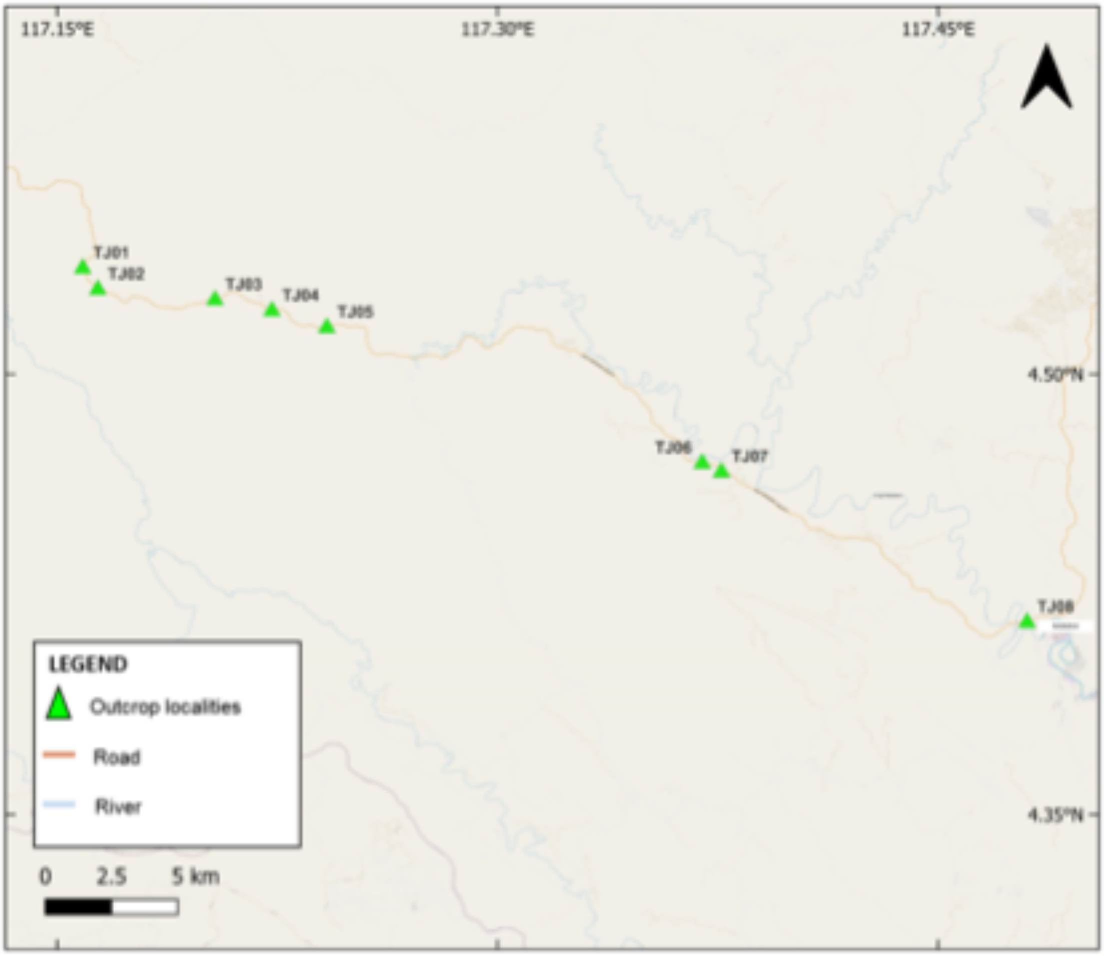

Figure 3 Map of the study area and outcrops location

SAMPLING AND METHODS

Sedimentary Facies Analysis

Well-preserved exposures of the Early to Middle Miocene succession along the Kalabakan-Sapulut road provided a good opportunity for sedimentological facies analysis. Eight (8) stratigraphic sections measuring a total of 340m are evaluated and recorded through bed-by-bed sedimentological logging (Figure 6). During the sampling, lateral and vertical lithological changes within the outcrops were considered. Contamination and weathered surfaces were avoided to accurately represent fresh rock samples of the coal and mudstone in the Tanjong Formation. Facies defined based on lithology, texture, sedimentary and biogenic structures, paleocurrent directions, and the type and degree of bioturbation were used to categorise the analysed facies from the sedimentary succession. The process that governed the transport and deposition of the examined sedimentary succession was then interpreted further [22]-[24]. The classification of facies analysis in terms of individual lithofacies used a three-letter facies code system in which the first capital letter denotes the predominant grain size, while the second and third lowercase letters denote the texture or sedimentary structures of the facies, respectively (Tables 1 and 2). Although a previous study by Miall [25] employed a similar technique, this study designates heterolithic facies with the letter "H." A hand lens and grain size comparator cards were used to determine grain size and sorting visually. Seven samples from the fine fractions are subjected to palynological analysis. The resulting information from the palynological analysis is integrated with the physical characteristics of the sedimentary facies, observed biogenic structures, or trace fossils together with the results from the organic geochemical analyses in the identification and interpretation of their depositional environment.

Palynology Analysis

For palynology analysis, considerable attention was given to the organic matter-rich sediments as it usually contains well-preserved fossil palynomorphs. The outcrops in the Tanjong Formation were thoroughly sampled for fresh present-day carbonaceous mudstones and coals. Palynological analysis was performed on seven carefully selected samples covering different outcrop localities, focusing on the mangrove facies (Figure 6). The processing of samples followed a standard palynological approach developed by [26]-[27], with some modifications to improve the recovery of the palynomorphs. The rock samples were rigorously cleaned with water to verify that all contaminants were removed. Next, Nitric acid (HNO3), hydrofluoric acid (HF), and hydrochloric acid (HCl) was used to treat the samples, followed by a 10% solution of potassium hydroxide (KOH). The slides were prepared in polyvinyl alcohol, and Canada balsam was used for mounting. The prepared slides from the successfully productive samples were examined for qualitative and quantitative evaluation using a Leica diaplan incident light microscope. Each slide contained at least 100–200 counts of recorded palynomorphs.

RESULTS

Facies Analysis

Twelve facies are recognised from the studied outcrops (Table 1). Generally, the studied sedimentary sections

NO.	CODE	LITHOFACIES	Descriptions	Trace fossil	Interpretation
1.	Sm	Massive tabular sandstone	Structureless and massive tabular medium-coarse grained sandstone with sporadic pebbles. The sandstone varies from light brown to grey color with a sharp bed contact. Presence of laminated carbonaceous materials, coal lenses, and mud drapes can be observed within the beds. Hummocky cross-stratification occurs in one of the outcrop.	Possible Skolithos, Orphiomorpha	Massive sandstone is characterised by an absence of internal stratification, are indicative of rapid deceleration and abrupt arrest of high-density turbidity currents (Bouma, 1962; Lowe, 1982; Mutti, 1992).
2.	Sp/St	Planar/trough cross-bedded sandstone	Planar and trough cross-bedded fine-medium grained sandstone varies from light brown to grey color. The bed contact differs from sharp to gradational. Presence of discontinuous carbonaceous laminations, coal lenses and stringers, and mud drapes are observed.	Possible Orphiomorpha	The planar/trough cross-bedded sandstone is supported by a high energy and unidirectional currents.This facies is interpreted as channel fill from sinuous crested dunes migrating under fluvial and tidal channel conditions.
3.	Sh	Horizontal/parallel laminated sandstone	Horizontal and parallel laminated of fine-medium grained sandstone with varying light brown to grey color. The bed contact with other facies ranges from sharp to gradational. Sedimentary structures of laminated carbonaceous materials, coal lenses, mud drapes and rip-up clasts are observed within the sandstone bed.	Possible Orphiomorpha	This facies is interpreted as upper flow regime, high energy plane bed conditions formed during flood conditions. This is supported by the presence of primary current lineations which are pervasive throughout the beds. Planar lamination can also be formed via the repeated collapse of laminar-sheared layers at the base of a high-concentration flow as the rates of sediment deposition decreases (Sumner et al., 2008).
4.	Shcs	Hummocky cross-stratification	Medium-grained hummocky cross stratified light brown color sandstone with gradational contact. This facies can only be found inthe younger section of outcrop T05.	Absent	This amalgamated beds displaying hummocky cross-stratification represents proximal storm beds and record high-energy oscillatory and combined flows during storms (Buatois & Mangano 2003).
5.	SFi	Interbedded sandstone with mudstone/shale	Thin to thickly interbedding of fine to medium grained sandstone with mudstone or shale vary from light brown to dark grey color. Horizontal and parallel laminated sandstone is observed occasionally. In addition, laminated carbonaceous materials, coal lenses and mud drapes can be observed in most of the outcrops. It displayed a sharp upper and lower contact.	Possible Orphiomorpha	Deposition during alternating high/low energy settings with mud deposition during slack water periods. The alternating sandstone and mudstone interbedded with presence of mud drapes suggest a tidal influenced environment (Yoshida et al., 2004).
6.	Sfs	Interbedded flaser beds with sandstone	Thin interbedding of fine grained flaser bed with medium-grained sandstone bed in varying light brown to grey color. The flaser and sandstone beds have a gradational contact.	Absent	Periodic, alternating high and low energy deposition (tidal and/or seasonal) intervals of current or wave flow regularly interspersed with slack water periods.
7.	Sfl	Interbedded flaser beds with lenticular beds	Thin interbeds of heterolithic flaser and lenticular beds with gradational contact and is observed to be vary from light brown to dark grey color.	Absent	
8.	Hf	Flaser heterolithic bedding	Fine-medium grained sandstone interlayered with mudstone whereby the proportion of sandstone is higher than mudstone. The flaser bed sandstone is light brown in color while the interlayered mudstone is grey. It shows a gradational upper and lower contact. There are presence of carbonaceous laminations, coal lenses and mud drapes within the bed.	Absent	Periodic, alternating high and low energy deposition (tidal and/or seasonal) intervals of current or wave flow regularly interspersed with slack water periods. Low energy current flow and mud deposition from suspension.
9.	Hl	Lenticular heterolithic bedding	High proportion of light to dark grey mudstone interlayered with fine-medium grained sandstone lenses or laminae. The facies displayed a gradational upper and lower contact. Presence of carbonaceous laminations, coal lenses, mud drapes and rip-up clasts are observed regularly within the facies.	Possible Orphiomorpha, Echinoderm & Gastropod	
10.	Fm	Dominant mudstone/shale	Structureless, dark grey to black shale or mudstone of sharp contact with common carbonaceous laminations, coal lenses and stringers, mud drapes and iron concretionary strata observed within the facies.	Absent	Low energy current flow with mud suspension deposition. Rapid deposition through flocculation in area of high suspended sediment concentration (i.e., fluid muds).
11.	Cs	Coaly shale	Sharp contact of black colored coaly shale that is a mixture of shale and coal mineral composition dominated by higher shale composition. Coal lenses can be observed within the coaly shale.	Absent	In situ accumulation of plant material in swamps, Marshes, mangroves and coastal mires, flood plain (depending upon the related facies).
12.	C	Coal	Composed of dull to shiny black coal with prominently sharp contact. Coals are highly fractured and contains undifferentiated plant residue.	Absent	In situ or peat accumulation of plant material in swamps, Marshes, mangroves and coastal mires, flood plain (depending upon the related facies). Elevated water table with minimum current flow.

[S – sandstone, F – Fines (silt-clay), m – massive/mudstone, p – planar cross-bedded, t – trough cross-bedded, h – horizontally laminated, hcs – hummocky cross-stratified, i – interbedded, H – heterolithic, f – flaser, l – lenticular]

Table 1 Summary of lithofacies of the study area are composed of siliciclastic rocks associated with thin coal seams. Massive tabular sandstone facies are prevalent in all the studied sections, with observed carbonaceous laminations, coal lenses and mud drapes. A localised hummocky cross-stratification structure of 1 m thick can be observed in one outcrop. Sandstone with parallel laminated and cross-bedded structure form up to 8.5 m thick intervals. Additionally, heterogeneous units of thin, interlayered sandstone and mudstone known as heterolithics (flaser or lenticular) bedding are the most common facies (Facies Hf, Hl). Structureless and carbonaceous mudstone facies are also commonly recognised, together with the presence of shale facies and thin coal seams. Facies description and interpretation are discussed in order of abundance importance to the environmental interpretation (Table 1).

Facies Association

Seven main facies associations were classified (Table 2) based on the sedimentary features identified from the sedimentological logging of eight outcrops found along the Kalabakan- Sapulut road, which is integrated with the identification of discrete lithofacies from the facies analysis and the observed trace fossils. These facies includes sub-environments of the fluvial, deltaic and shallow marine environment. The following details shall explain the characteristics and processes of each facies association (FA). Twelve lithofacies are grouped accordingly into seven facies associations; FA1, FA2, FA3, FA4, FA5, FA6 and FA7. These associations are grouped largely based on the energy of the deposits where FA1, FA3 and FA4 are slow energy deposits with different flow regimes, while FA2, FA5, FA6 and FA7 are higher energy deposits with the presence of coarse to medium-grained massive sandstone bed.

FA1: Floodplain facies association

Sedimentology: This facies association consists of mostly medium to coarse-grained lithofacies (Sm, Sp/St, Sh) with interbedding facies (SFi), mudstone (Fm) and capped by either coaly shale (Cs) (Figure 5C) or coal facies (C) where it varies from thin to thick-bedded. Flaser and lenticular heterolithic beds (Figures 4G and 4H) are also classified under FA1, as observed in outcrop TJ03, TJ04, and TJ05. The FA1 comprises heterolithic and muddy facies capped by thin coal facies, which is observed at the lower section of outcrop TJ05 (Figure 5D). The thinly to thickly bedded sandstone is characterised by massive and structureless sandstone, small-scale planar cross lamination and parallel lamination with the presence of carbonaceous laminations, coal lenses and mud drapes (Figures 5G and 5H). The lenticular of the muddy heterolithic bed exhibits rip-up clasts, whereas the black mudstone facies exhibits coal lenses. The muddy facies are differentiated by the number of carbonaceous materials, their hardness, and their lamination pattern.

Ichnology: Bioturbation is absent to sparse with localised patches of Ophiomorpha trace fossil as observed in the lenticular bed of outcrops TJ04 and vertical trace fossil of Skolithos, which were observed within thin mudstone units from outcrops TJ07 and TJ08. A mold cast of gastropod and echinoderm can be observed in the lenticular bedding from outcrop TJ03.

Interpretation: The thin coal seam and carbonaceous mudstone are signs of soil development in a vegetated floodplain [28]. The presence of sandstone facies stipulates energy fluctuations during deposition. The interbedded cross-stratified sandstone and heterolithic bedding are believed to represent crevasse splay deposits, where sediment was deposited across floodplains after surpassing the main channel [28]. The source and supply of fresh water with some marine incursions is typically supported by mud deposition from suspension along vast floodplains or interdistributary channel embayments. The fining upwards succession pattern of this facies association suggests predominantly fine-grained sediments. The deposited fine-grained sediments settled out of suspension from the floodwaters and were then carried into the flood basin resulting in a broad, low-relief floodplain of a swamp or shallow lake. Most floodplain deposits are made up of thinly interbedded sandstone and mudstone (SFi) with paleosols which may contain evidence of surface processes due to the presence of organic materials and undifferentiated plant material within the mudstone facies. The small diameter Skolithos trace fossils are thought to be the result of the overbank avulsion of the passively infilled tracks from the coarser deposits emplaced in the floodplain environment, while the rare localised Ophiomorpha is indicative of a transitional zone from floodplain to the tidally influenced environment. The observed Skolithos trace fossil is possibly classified under the Scoyenia or continental equivalent of the Glossifungites ichnofacies. The presence of echinoderm and gastropod mold casts in the lenticular bed of the older section outcrop TJ03 suggests an initial phase of tidal flats.zed Ophiomorpha indicates a transitional zone from the floodplain to the tidally influenced environment. The observed Skolithos trace fossil is possibly classified under the Scoyenia or continental equivalent of the Glossifungites ichnofacies. The presence of echinoderm and gastropod mold casts in the lenticular bed of the older section outcrop TJ03 suggests an initial phase of tidal flats.

FA2: Fluvial-dominated channel facies association

Sedimentology: The facies association is represented by either an erosive base of conglomerate or trough cross-stratified sandstone. The most prevalent facies in fluvial channel sandstones is the trough cross-bedded sandstone (St) (Figure 4C). Along with the coarse to medium-grained size of massive tabular sandstone (Figure 4A), horizontally laminated sandstone (Figure 4D) was also observed. The coarse-grained basal sandstone was overlain by either interbedded sandstone and mudstone that was capped by mudstone or shale facies forming a fining upward succession pattern. Additionally, the lamination of carbonaceous material is observed in the massive sandstone bed. Most fining upward sequences are capped by very thin mudstone or shale facies. The fluvial-dominated channel or fluvial channel fill facies association can be observed in the vertical succession of outcrop TJ01, and minor occurrence can be observed in the lower or older section of outcrop TJ05 (Figure 6).

Ichnology: The bioturbation is absent to sparse, with the minor occurrence of the Ophiomorpha trace fossil being observed within the trough cross-bedded sandstone in outcrop TJ01.

Interpretation: Freshwater rivers provide the source for fluvial-dominated channel-fill bodies. The cross-stratified sandstones imply transport and deposition by high-energy unidirectional currents, either in the form of fluid flows or sediment gravity flows, which is restricted to fluvial channel [22],[29]-[32]. The fining and thinning upward trends of the deposits correspond to the river point bars assumed in a fluvial or tide-influenced meandering channel [33]. The trough cross-stratification disclosed the migration of the three-dimensional dunes in the fluvial deposits [29],[32],[34]-[36]. Typically, localised monotaxic assemblages of Ophiomorpha are prevalent in the distributary channels, or fluvial channel fills deposits.

FA3: Coastal swamps and marshes facies association

Sedimentology: The coastal swamps and marshes facies association is recognised at outcrops TJ03 and TJ05, with a presence of coal facies (Figure 6). The FA3 consists of carbonaceous or organic-rich mudstone, shale, coaly shale and thin (5 cm) to very thick (2 m) coal seams (C). This facies association forms 1-4 m thick mud-dominated successions, commonly capped by thin coal, which usually overlies floodplain and tidal flat facies associations (FA 1 and FA 4). The mudstone facies in FA3 exhibit a dark to very dark grey colour, representing a possible high amount of organic matter. The negligible amounts of sand and silt-size particles distinguish these coastal swamps and marshes. At outcrop TJ03, FA3 can be observed in the upper or younger section with coal and mudstone facies. At outcrop TJ05, the FA3 consists of coaly shale capped by 90 cm thick coal facies showing upward fining succession (Figure 5D). Coal clasts or lenses and lamination of carbonaceous materials were observed within the coaly shale facies in outcrop TJ05. Possible in-situ iron concretionary strata were also observed within the mud-dominated facies in outcrop TJ05.

Ichnology: Bioturbation is absent and too intense. Intense bioturbation is commonly observed in the form of general mottling of beds by indistinct trace fossils, which has disrupted the primary sedimentary structures.

Interpretation: The predominance of fine-grained facies indicates a low-energy environment, with deposition mainly through suspension fallout or low-energy currents. Coal and associated carbonaceous facies result from the accumulated plant material and organic matter under stable conditions. The coal bed is thought to have formed in a supratidal environment due to waterlogged conditions and reduced water originating from a vegetation marsh or swamp [37]. The dark-coloured carbonaceous mudstone and related thin coal seams were formed by the accumulation of plant debris and organic detritus in anoxic swamps, probably in fresh and brackish water [38]. The low bioturbation level supports the low-oxygen conditions in the coastal swamp environment. The presence of mangroves results in a highly effective environment for trapping and accumulating thick mud-dominated successions.

FA4: Tidal flat facies association

Sedimentology: The FA4 exhibits a fining upwards succession of medium to coarse-grained sandstones, flaser and interbedded sandstone and mudstone, capped by carbonaceous shale and mudstone. The heterolithic flaser to lenticular bedding is observed with varying sizes and lateral extension of sandstone lenses and mud drapes. The flaser bedding contains mud drapes, coal lenses, and carbonaceous laminations. The FA4 is a commonly recurring facies association encountered at all outcrops TJ01, TJ02, TJ03, TJ04, TJ05, TJ06, TJ07 and TJ08. This facies association encompasses various facies, from sandstone-dominated facies to mud-dominated facies and an intermediate variant of heterolithic bedding and interbedding sandstone and mudstone facies. Typically, FA4 displays an overall fining-upward succession of heterolithics from flaser to lenticular bedding. The flaser sandstone heterolithic facies (Figure 4G), with thicknesses ranging from 1 to 7 m, is gradationally overlain by the lenticular muddy heterolithic facies (Figure 4H), which predominate toward the top of fining-upward successions. The muddy heterolithics facies include mud drapes observed at outcrop TJ04 and coal lenses in the bottom section of outcrop TJ03 and the top section of outcrop TJ05.

Ichnology: Bioturbation level is sparse to moderate. The muddy lenticular heterolithic facies has a relatively low diversity of Ophiomorpha trace fossils which can only be observed in outcrop TJ03, while the minor Skolithos trace fossil can be observed in the mudstone facies of outcrop TJ06 (Figure 5F). The Ophiomorpha trace fossils have a moderate assemblage in the flaser heterolithic facies and massive sandstone facies of outcrop TJ04 and TJ05.

Interpretation: The typical vertical succession dominated by flaser to lenticular heterolithic facies and mud drapes structure (Figure 4G) integrated with the trace fossil assemblage suggests flat tidal deposition. In an intertidal to the subtidal environment, this facies association indicates deposition during alternating high and low energy settings with mud deposition during slack water periods. Sand-mud couplets, rhythmic tidal bundles, and unidirectional deposition with reactivation surfaces are some diagnostic indicators of tidal deposits. Tidal flats have a fining upward succession that records the transition from sand flats to mixed flats and mud flats, possibly in the progradation parasequence [39]-[40]. As observed in outcrop TJ03, reverse grading can also take place in retrogradation sequences, generating a coarsening upwards sequence from mud flats to sand flats.

Nevertheless, the stratigraphic position of FA4 and its relationship to other facies associations suggest that mud, mixed, and tidal sand flats were deposited in the upper to lower delta plain. The large diversity in grain size in this facies association also suggests that it was deposited on a wide tidal flat that ranged from a sand flat to a mixed flat to a mud flat [41]. The coal lenses or fragments (Figure 5H) came from the nearby coastal swamps and were transported by waves and currents onto the tidal flat, while the mud drapes were thought to have been deposited at high slack water [42]-[43]. The presence of low Ophiomorpha and Skolithos trace fossils assemblages in mudstones and sandstone indicate that only a small number of organisms could live and create such traces due to the stressed condition [44]. These stressed conditions are typically correlated to high energy during low tide (ebb) and subsequent high tide (flood) operating on the lower delta plain [45]. Low-diversity assemblages of suspension feeders or passive predators Skolithos are frequently found in high-energy zones of tidal flats. Tidal flat facies containing Ophiomorpha may indicate a stressed paleoenvironment where pore-water oxygenation fluctuates with tidal exposure.

FA5: Delta front facies association

Sedimentology: These facies association exhibits coarsening upwards facies succession, composed of basal medium-coarse-grained sandstones, which are mostly massive and tabular, heterolithic bedding, interbeds of sandstone and mudstone and capped by mudstone facies. Carbonaceous laminations and coal lenses are also common in the flaser bed facies (Figure 4G). In situ concretionary iron strata can also be observed within the mudstone facies (Figure 5B). Individual sandstone beds range from 2 to 6m thick, dominated by massive tabular sandstone (Sm), horizontal laminated sandstone (Sh), planar cross-bedded sandstone (Sp) and flaser heterolithic bedding (Hf). In the vertical succession of outcrop TJ01 (Figure 6), a coarsening transition from lenticular, wavy, to flaser bedding is observed. In the flaser heterolithic bedding, ripple structures and some cross-laminae often show evidence for rhythmic mud drapes. Heterolithic intervals commonly show very small-scale fining-upwards or normal grading with gradational contact from fine-grained sandstone to mudstone with possible inverse grading.

Ichnology: Bioturbation is generally absent. The absence of trace fossils implies a freshwater or brackish influence during periods of river flood into the delta-front setting, indicative of lower diversity (stressed conditions) or lower abundance of ichnofauna.

Interpretation: This facies association's deposits imply a substantial supply of coarse-grained sandstones. Massive sandstones may have resulted from intense currents moving toward the toe of the delta front [46]-[47]. Marginal-marine, mid-distal delta-front deposits are characterised by relatively fine-grained heterolithic intervals with a mixture of unidirectional and possibly bi-directional current, wave, and tidal-influenced sedimentary structures [48]. Fluvial discharge variations may result in an irregular coarsening-upward succession with mudstone and sandstone interbedded [48]. Intense wave action may result in the formation of fluid mud within the delta-front environment, resuspending previously deposited mud, which is subsequently re-deposited on top of the storm event bed made by the same storm [49].

FA6: Mouth bar facies association

Sedimentology: This facies association generally overlies the FA5 sediments, forming coarsening-upward sandy successions with thin mudstone as the base. Lamination of carbonaceous materials and mud drapes are observed in the facies of massive sandstone. The sandstone packages, which range in thickness from 2 to 6 m, form a channel-like body and are wedged out laterally (Figure 4A). In outcrop TJ02, the mouth bar facies association is observed as a coarsening succession upward from the lower lenticular bedding to the massive upper sandstone with mud drapes. The dominating of a single massive sandstone bed that exhibits a relative transition to the coarse-grained size towards the top is related to the mouth bar, as observed in outcrop TJ05. A repetitive mouth bar facies association is also observed in outcrop TJ05, which is capped by a coarse-grained sandstone containing laminations of carbonaceous materials at the top section.

Ichnology: Bioturbation is generally absent.

Interpretation: The classified facies of the FA6 deposits suggest sedimentation in a mouth bar environment, where sand is supplied directly by terminal distributary channels. The absence of fine-grained facies must be due to the high and continuous river discharge that drove them farther away from the river's mouth. The FA6 sandstone packages with channel-like and wedging-out lateral bodies are considered mouth bar deposits on a subaqueous delta front with regular subaerial exposure based on the stratigraphic location with other facies associations. Based on the prevalence of current-generated bedforms, a mixture of potentially fluvial and tide-generated facies, coarsening vertical trend upward, and the absence of depleted marine ichnofauna, FA 6 is interpreted as the deposit of a tide-influenced mouth bar. The absence of bioturbation, in general, is consistent with a fluvial-dominated and stressed tide-influenced setting possibly of brackish water.

FA7: Upper shoreface facies association

Sedimentology: Primarily composed of medium-coarse-grained massive tabular sandstones with thin mudstone interbeds. Hummocky cross-stratification (HCS) is observed in the massive tabular medium-grained sandstone, which indicates shoreface deposits (Figure 4E). Carbonaceous laminations can be observed in the massive sandstone facies. The massive sandstone-dominated sediments interval can be seen in the upper shoreface facies association as an upwardly coarsening succession from lenticular mudstone beds (Sm, Shcs, SFi, Hl). The thickness of the dominant massive sandstone bed varies from 1 to 5 m with the presence of hummocky cross-stratification of approximately 1 m thick in outcrop TJ05 (Figure 4E). In outcrop TJ03, interbedding of sandstone and mudstone facies are observed as the basal of the coarsening upwards interval. The predominance of wave-generated facies displayed an overall coarsening upward trend.

Ichnology: Bioturbation is sparse to intense. The most common trace fossil is Ophiomorpha (Figure 5E), with intense assemblages in the massive tabular sandstone and sparse occurrences in the lenticular bed. The horizons with intense bioturbation display general mottling, destroying primary sedimentary structures.

Interpretation: This facies association is a product of shallow marine deposition. Based on the prevalence of wave and storm-generated deposits, high sand content, and more frequent traction current-generated deposits, an upper shoreface depositional environment interpretation for FA7 is made. The presence of HCS indicates storm influence in the upper-lower shoreface settings, which are normally situated above the storm wave base [48]-[50]. Hummocky cross-stratified sandstone indicates the strong influence of storms [51] with waning flow deposition represented by overlying, symmetrical wave ripples [52]-[53]. A thick-bedded sandstone indicates a high-energy winnowing process by transporting current during deposition. The high sand content indicates a more shoreward environment, where fairweather wave action in the shallow waters precluded the deposition of thick suspended mud. The FA7 might represent the prograding, wave- or storm-influenced shoreline in a shallower subtidal shoreface region. The storm-influenced sedimentary structures and Ophiomorpha trace fossils suggest an upper shoreface depositional environment [54]-[55].

Facies Association (FA)	Lithofacies	Description	Bioturbation	Interpretation
FA1 Floodplain	Sm, Sp/St, Sh, SFl, Shs, Hf, Hl, Fm, Cs, C	Medium-coarse grained sandstones which is thinly to thickly bedded underlie the heterolithic and muddy facies that are capped by thin coal facies.	Absent to sparse, presence of Ophiomorpha and Skolithos trace fossils.	The interbedded cross-stratified sandstone and heterolithic bedding are interpreted to be the crevasse splays deposits where sediment surpassed the main channel and was deposited across floodplains (Retallack, 2001).
FA2 Fluvial Channel-fill	Sm, Sp/St, Sh, SFl, Fm	The trough cross-bedded sandstone is observed at the base overlain by either interbedded sandstone and mudstone capped by mudstone facies	Absent to sparse, presence of minor Ophiomorpha trace fossil.	Fining and thinning upward trends in these deposits represents the river point bars that are expected in a fluvial or tide- influenced meandering channel [Thomas et al., 1987].
FA3 Coastal swamps and marshes	Fm, Cs, C	Dark grey shale to black mudstone, coaly shale, with varying amount of organic matter.	Absent to intense	In situ accumulation of plant material in swamps, marshes, mangroves and coastal mires possibly in a fresh and brackish water.
FA4 Tidal flat	Sm, Sp/St, Sh, SFl, Shs, Sfl, Hf, Hl, Fm	Medium-coarse sandstones, flaser and interbedded of sandstone and mudstone, capped by carbonaceous shale and mud.	Sparse to moderate with presence of Ophiomorpha and Skolithos trace fossils.	This facies association is an indicative of a deposition during alternating high/low energy settings with mud deposition during slack water periods within intertidal to subtidal environment.
FA5 Delta front	Sm, Sp/St, Sh, SFl, Hf, Hl, Fm	Composed of basal mudstone facies, heterolithic bedding, interbeds of sandstone and mudstone capped by medium-coarse grained massive sandstones.	Absent	Massive sandstones could have been the product of highly concentrated currents flowing toward the toe of the delta front (Bhattacharya and Walker 1982; Howell et al. 2008; Hampson et al. 2011).
FA6 Mouthbar	Sm, Sh, SFl, Fm	Thin mudstone as the base, followed by thin interbeds of sandstone and mudstone capped by medium-coarse massive sandstone.	Absent	The classified facies of the FA5 deposits suggest sedimentation in a mouth-bar environment, where sand is directly supplied by terminal distributary channels.
FA7 Upper Shoreface	Sm, Sh, Sp/St, Shcs, Sfl, Fm	Primarily composed of medium-coarse grained massive tabular and hummocky cross-stratification sandstones with thin mudstone interbeds.	Sparse to intense with common Ophiomorpha trace fossils.	The presence of HCS within sandstoneintervals reflects storm influence in the upper-lower shoreface settings, typically situated above the storm wave base (Reineck & Singh 1980; Bhattacharya 2010).

Table 2 Summary of facies association (FA1-FA7) with lithofacies of the study area

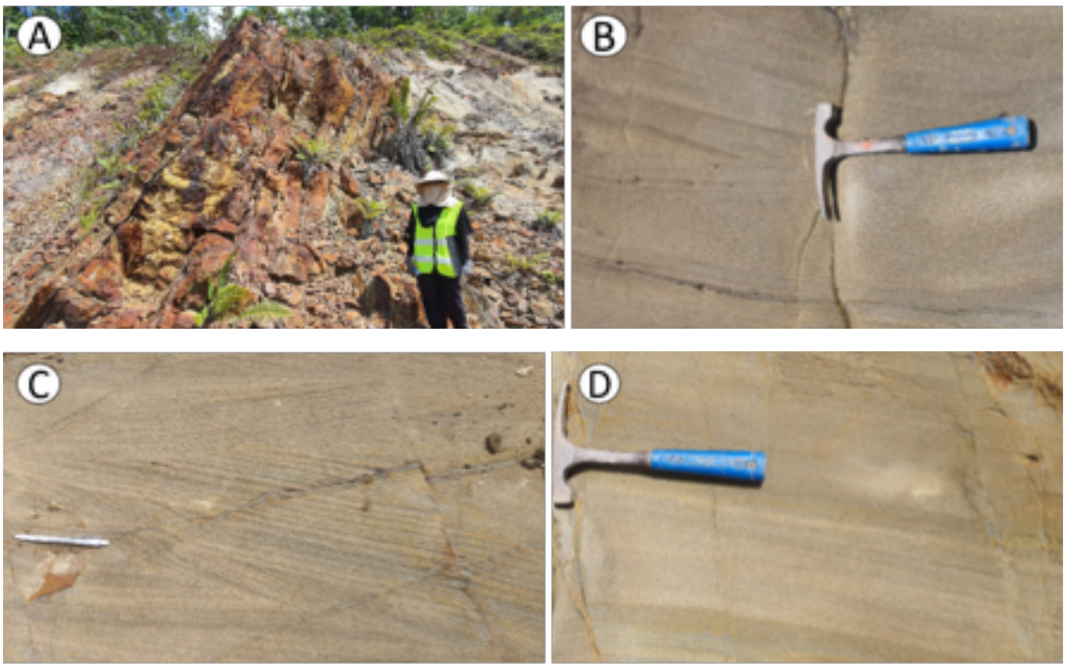

Figure 4 (A) Massive tabular sandstone facies (Sm) found in outcrop TJ03. (B) Planar cross-bedded sandstone was observed in outcrop TJ03 (Sp). (C) Trough cross-bedded sandstone found in outcrop TJ01 (St). (D) Horizontal or parallel laminated sandstone in outcrop TJ01 (Sh). (E) Hummocky-cross stratified sandstone was observed in outcrop TJ05 (Shcs). (F) Interbedded sandstone and mudstone facies were observed in outcrop TJ03 (SFi). (G) Flaser or sandstone dominated heterolithic facies (Hf) in TJ03. (H) Lenticular or muddy heterolithic facies found in outcrop TJ05

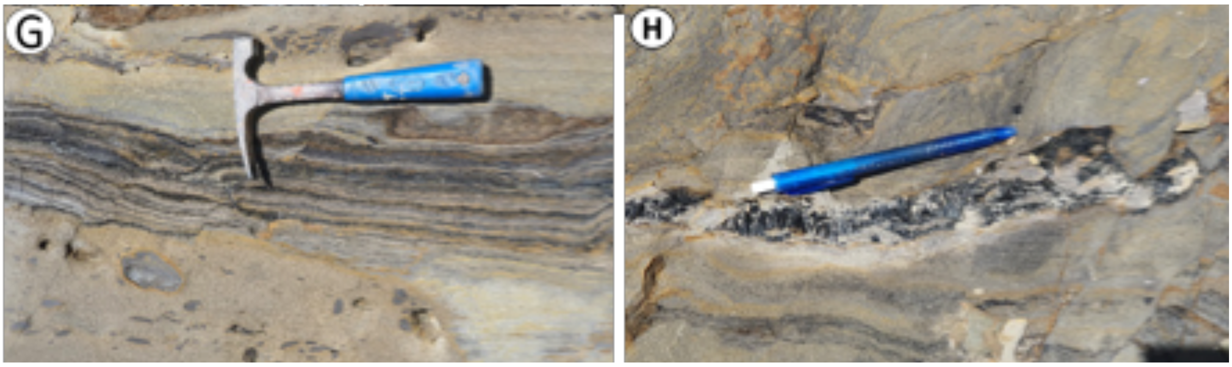

Figure 5 (A) Gradational contact of flaser and lenticular heterolithic bedding. (B) Mudstone-dominated facies with possible iron concretionary strata were observed in outcrop TJ08 (Fm). (C) Coaly shale facies with observed fissility in outcrop TJ05 (Cs). (D) Thick coal seams of 0.9 m thickness were observed in TJ05. (E) Relatively moderate to intense Ophiomorpha trace fossils within the sandstone bed found in outcrop TJ01. (F) Vertical trace fossil of possible Skolithos found in outcrop TJ06. (G) Lamination of carbonaceous material with mud drapes and possible rip-up clasts structure observed in outcrop TJ03. (H) Thick coal lenses within muddy heterolithic facies of outcrop TJ03

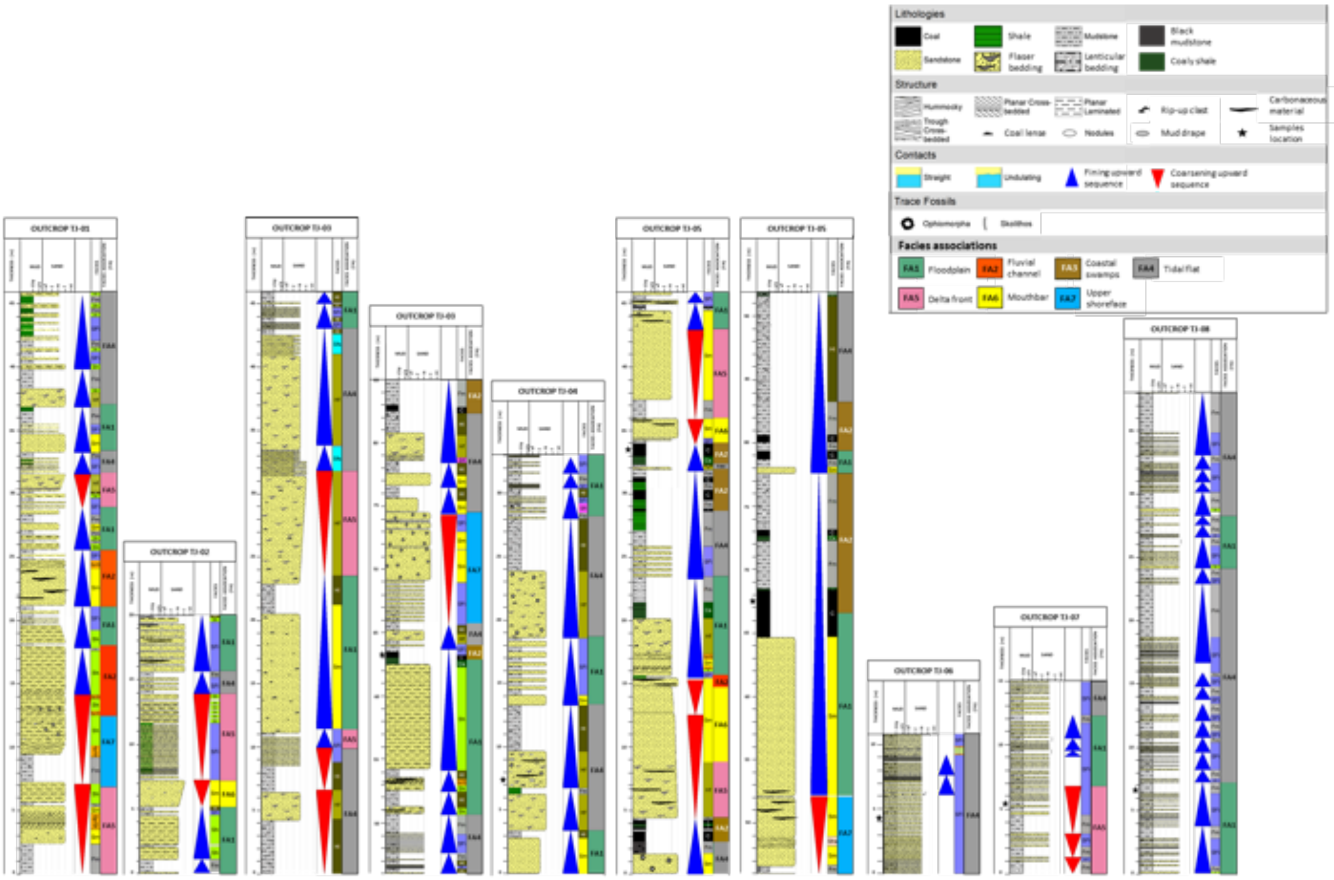

Figure 6 Sedimentary logs showing sedimentology, ichnology, lithofacies, and facies associations in the studied outcrops of the Tanjong Formation

Palynology Analysis

Table 3 provides the vertical frequency distribution of significant taxa in the studied Tanjong Formation coal and mudstone samples. Although only a small number of horizons are moderately rich, palynomorph distribution is typically low in the analysed samples. The recovered palynomorph groupings support truly tropical vegetation by representing marine (aquatic) and continental (terrestrial) elements. Major palynomorphs found in coals from the Tanjong Formation belong to the genera Sapotaceae and Stenochlaena, with frequent but not abundant pteridophytic spore presence in the assemblage. Families Cyatheaceae, Polypodiaceae, and Schizaeaceae, are mostly observed and attributed to the pteridophytic spore. Plants of these families are found in swampy to subaquatic environments. The terrestrial palynofossils in the assemblage strongly suggest a near-shore depositional environment. The studied coal samples in the Tanjong Formation are characterised by very little pollen and spores. Only a few recorded taxa originated from peat swamp and riparian vegetation, such as Arenga, Calamus, Cyrtostachys, Dactylocladus, and Elaeocarpus type, Ilex type and Pandanus, including single grain of rainforest taxa, i.e., Lithocarpus type and grass pollen of Gramineae or Poaceae family. A single grain of Florschuetzia trilobata was identified in the sample TJ-05. Single-grain F. trilobata without supportive marker pollen precludes relative age interpretation for the analysed samples. Overall, the coal samples are overwhelmed by black-dark brown wood organic matter (vitrinite equivalent).

		Mangrove/Back Mangrove										
Sample	Lithology	Acrostichum aureum	Avicennia type	Brownlowia type	Camptostemon	Florschuetzia levipoli	Florschuetzia meridionalis	Florschuetzia trilobata	Florschuetzia type	Nypa	Oncosperma	Rhizophora type
TJ-03	Coal											
TJ-04	Coal											
TJ-05	Coal											
TJ-05	Coal							1				
TJ-06	Mudstone											1
TJ-07	Mudstone		2			1		1				3
TJ-08	Mudstone		1						1			2

		Hinterland																	
Sample	Lithology	Alchornea	Anacolosa	Arenga	Barringtonia	Blumeodendron	Caesalpiniaceae	Calamus type	Calophyllum type	Campnosperma	Casuarina type	Chrysophyllum type	Cyrtostachys	Dactylocladus type	Dipterocarpus	Durio type	Elaeocarpus type	Eugeissona type	Euphorbiaceae
TJ-03	Coal												1						
TJ-04	Coal			1				1						1					
TJ-05	Coal																		
TJ-05	Coal												1	1			1		
TJ-06	Mudstone																		
TJ-07	Mudstone	1			1	1			1		1			2			1		
TJ-08	Mudstone	1					1							1					

		Hinterland																
Sample	Lithology	Ficus	Gonystylus type	Hibiscus	Ilex type	Lithocarpus type	Magnoliaceae	Melanorrhoea type	Myrtaceae	Nenga	Pandanus	Papilionaceae	Pometia	Proteaceae	Rubiaceae	Sapotaceae	Stemonurus	[illegible]
TJ-03	Coal					1												
TJ-04	Coal																	
TJ-05	Coal				1													
TJ-05	Coal										1					1		
TJ-06	Mudstone																	
TJ-07	Mudstone				1				1		1	1			1	2	1	
TJ-08	Mudstone		1				1		1			1	1	1			1	

		Spores								Seasonal/Montane				
Sample	Lithology	Cyathidites sp. (Cyatheaceae)	Stenochlaenidites papuanus	Laevigatosporites sp. (Schizaeaceae)	Lycopodium cernuum	Osmunda	Polypodiisporites sp. (Polypodiaceae)	Pteris type	Verrucatosporites usmensis (Stenochlaena)	Alnus	Picea	Pinus	Podocarpus	Gramineae/Poaceae
TJ-03	Coal			1										1
TJ-04	Coal	1		2			1		2					
TJ-05	Coal													
TJ-05	Coal	1							1					2
TJ-06	Mudstone													
TJ-07	Mudstone													
TJ-08	Mudstone			2						1				1

Table 3 Vertical frequency distribution of important taxa in the studied Tanjong Formation coals and mudstones

The Tanjong Formation mudstone samples record slightly higher pollen and spores than coal samples. The samples record a significant amount of mangrove pollen, although in a very low percentage represented by families Caesalpiniaceae, Magnoliaceae, Papilionaceae, Proteaceae, Rhizophoraceae, Rubiaceae and Sapotaceae. The mangrove assemblage represented by Avicennia, Rhizophora, and Florschuetzia (F. trilobata and F. levipoli) reflects brackish conditions. The hinterland group is characterised by peat swamp and coastal elements such as Alchornea, Barringtonia, Blumeodendron, Calophyllum, Casuarina, Dactylocladus type, Elaeocarpus type, Gonystylus type, Pometia and Stemonurus. The analysed samples also record riparian elements represented by the Myrtaceae family, Pandanus, and Ilex type. The Florschuetzia group pollens (derived from the mangrove genus Sonneratia) identified in the studied samples, such as Florschuetzia levipoli (Sonneratia caseolaris) and Florschuetzia trilobata are important marker species in dating Miocene sediments, especially within Borneo and adjacent areas suggesting an age of not older than Early Miocene and/or younger [56].

DISCUSSION

Palaeodepositional Environment Model

The characteristics of the sedimentary facies analysis and the Tanjong Formation's ichnology indicate a fluvio-deltaic to the shallow marine environment. Based on the sedimentary log succession (Figure 6), the lower, older section of the formation is dominated by fine-grained facies characterising the floodplain, tidal flat and delta front facies associations, while the middle section was observed with a dominance of coal seams indicating a mangrove coastal swamps facies association to the upper, younger section dominated by coarse-grained facies of the fluvial channel fill, mouth bar and upper shoreface facies associations or sub-environments. The facies associations indicate significant river, wave and tide interaction within the depositional system. There are a high proportion of wave and tidal facies associations (FA 3, FA 4, FA 5, FA 6, and FA 7) compared to the less common river process of the fluvial deposits (FA 1 and FA 2).

The palaeodepositional environment (Figure 7) is marked by a basal fluvial-tidal channelised complex, overlain by tidal sand flat to the mud flat, delta front composed of mudstones and heterolithics facies and thick sandstone facies in the mouth bar and upper shoreface with well-developed coastal swamps. The intertidal flats developed near the basin margin while salt marshes formed further landward [57]. The subtidal expansion of neighbouring mangroves and tidal flats is formed by suspension and lower energy traction deposits, represented by the tidal flat facies association (FA 3). It is also possible that tidal mud flats transitioned into marshes based on the mangrove and back mangrove assemblages found in the coal and underlying horizon. The vertical trend from fluvial-tidal sandstone and heterolithics is consistent with a progradational delta succession, with the coarser-grained heterolithic facies representing parts of the delta plain and delta front. The succession of tidal bars, mouth bars, and fluvial channel fills is interpreted as bar forms deposited within distributary channels. The gradual shallowing of the environment, a feature of a prograding delta, is viewed as being represented by the upward vertical change from the upper shoreface into the delta front and floodplain, fluvial channel, tidal bar and mouth bar deposits and capped by mud overbank and coals of the coastal swamps. It can be observed from the sedimentary log succession that outcrop TJ05 displayed complete facies associations (FA1, FA2, FA3, FA4, FA5, FA6 and FA7) with the facies transition from a sandstone-dominated fluvial channel fill, delta front, mouth bar and localised upper shoreface indicated by the hummocky cross-stratification to the mudstone dominated with heterolithic bedding floodplain and tidal flat capped by coastal swamps/mangroves. The palaeodepositional model (Figure 7) has been generated supported by the classified sedimentological or facies analysis observed in ichnological and palynological analysis on the Early to Middle Miocene Tanjong Formation in the Kalabakan area, Southeast Sabah.

Palynological analysis of four coals and three mudstone samples indicate a variation from mangrove to coastal

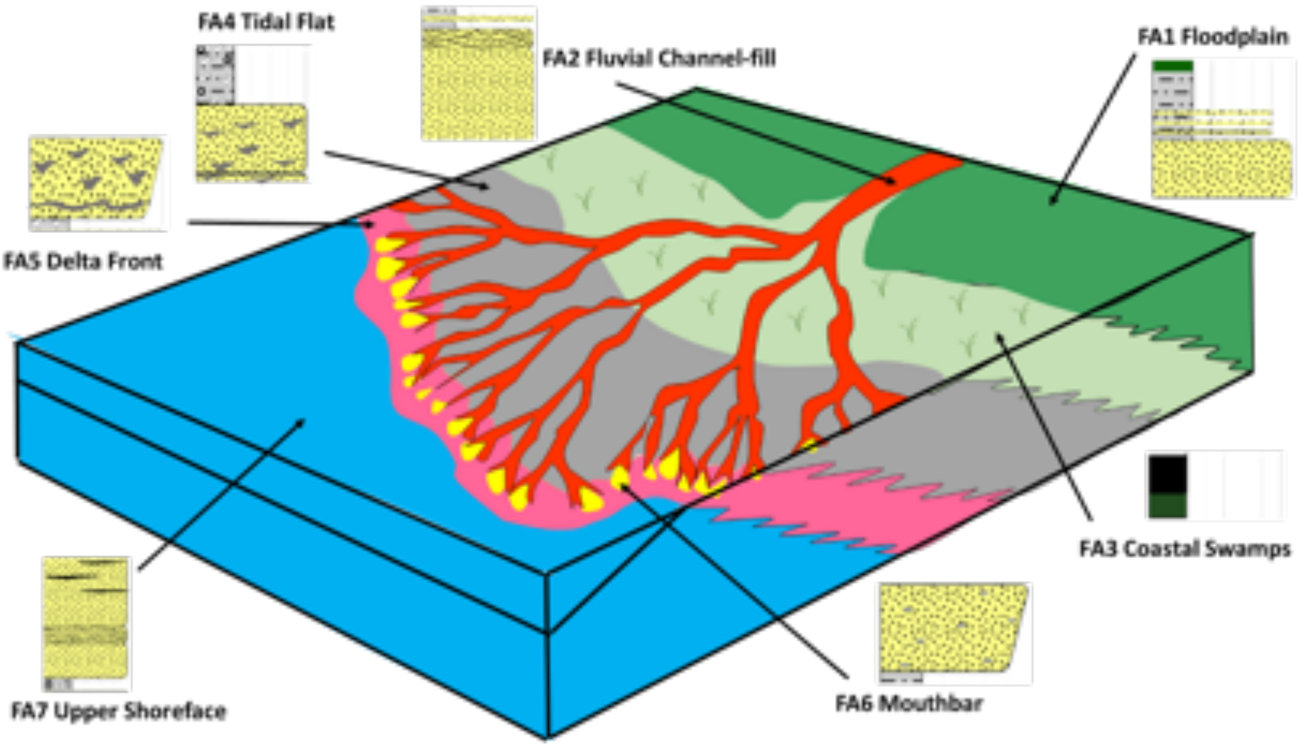

Figure 7 Palaeodepositional model for the studied Tanjong Formation

freshwater or peat swamp environment (Table 3). Precise stratigraphic positions of the samples were marked in a log (Figure 6). An abundance of mangrove palynomorphs, including species from the genera Florschuetzia and Rhizophora, are found in organic-rich paralic mudstones with accompanying coals in the Oligocene-Miocene Gulf of Thailand, which covers the Malay Basin [58]- [59]. The presence of a comparatively high concentration of the Rhizophoraceae family in the palynoassemblage suggests mangrove-mixed source vegetation. Only a few taxa are recorded in the coal samples, which originated from peat swamp and riparian vegetation represented as freshwater palynomorphs such as Arenga type, Calamus type, Cyrtostachys, Dactylocladus type, Elaeocarpus type, Ilex type and Pandanus including single grains of rainforest taxa, i.e., Lithocarpus type and grass pollen of Gramineae or Poaceae family. The pollen assemblages in the examined samples indicate that the coal was developed beyond the tidal-limited zone in freshwater or peat-swamp environments. The mudstone samples are characterised by peat swamp and coastal elements such as Alchornea, Barringtonia, Blumeodendron, Calophyllum type, Casuarina type, Dactylocladus type, Elaeocarpus type, Gonystylus type, Pometia and Stemonurus as well as the riparian elements of Pandanus and Ilex type suggesting deposition within a lower coastal plain setting with proximity to the marine environment. The documented palynomorphs of families Cyatheaceae, Polypodiaceae, Schizaeaceae and Caesalpiniaceae, Magnoliaceae, Papilionaceae, Proteaceae, Rhizophoraceae, Rubiaceae, Sapotaceae of the coal and mudstone samples, respectively, indicate proximity to the terrestrial source area (fluvio-deltaic systems) associated to the lower energy oxygenated environments including single grain of rainforest taxa, i.e., Lithocarpus type and grass pollen of Gramineae or Poaceae family. The pollen assemblages in the examined samples indicate that the coal was developed beyond the tidal-limited zone in freshwater or peat swamp environments. The mudstone samples are characterised by peat swamp and coastal elements such as Alchornea, Barringtonia, Blumeodendron, Calophyllum type, Casuarina type, Dactylocladus type, Elaeocarpus type, Gonystylus type, Pometia and Stemonurus as well as the riparian elements of Pandanus and Ilex type suggesting deposition within a lower coastal plain setting with proximity to the marine environment. The documented palynomorphs of families Cyatheaceae, Polypodiaceae, Schizaeaceae and Caesalpiniaceae, Magnoliaceae, Papilionaceae, Proteaceae, Rhizophoraceae, Rubiaceae, Sapotaceae of the coal and mudstone samples, respectively, indicate proximity to the terrestrial source area (fluvio-deltaic systems) associated with the lower energy oxygenated environments [60]-[61].

CONCLUSION

This study includes sedimentary facies analysis of the onshore Tanjong Formation outcrops integrated with the validated palynology analysis of sedimentary facies (coal and mudstones). The study unravelled the following findings about sedimentology and the paleodepositional environment or conditions during sedimentation, which the generated palaeodepositional environment model represents. Detailed facies analysis work carried out at eight well-exposed outcrops along Kalabakan to Sapulut road in Southeast Sabah has resulted in twelve lithofacies identification which is; (i) Massive tabular sandstone (Sm), (ii) Planar/trough cross-bedded sandstone (Sp/St), (iii) Horizontal/parallel laminated sandstone (Sh),(iv) Hummocky cross-stratified sandstone (Shcs), (v) Interbedded sandstone with mudstone/shale (SFi), (vi) Interbedded flaser beds with sandstone (Sfs), (vii) Interbedded flaser beds with lenticular beds (Sfl), (viii) Flaser heterolithic bedding (Hf), (ix) Lenticular heterolithic bedding (Hl), (x) Dominant mudstone/shale (Fm), (xi) Coaly shale (Cs), and (xii) Coal (C). From the lithofacies description, facies association of the study area shows a range of (four) sub-depositional environments: from FA1-floodplain, FA2-fluvial channel-fill, FA3-coastal swamps and marshes, FA4-tidal flat, FA5-delta front, FA6- mouth bar, FA7-upper shoreface and. Based on these facies associations, the overall facies based on an outcrop scale suggests a sub-environment ranging from a transitional fluvial, deltaic, and shallow marine. The identified facies associations were used to construct the complete depositional model for the Miocene deposits of the study area, which is further integrated and validated with the analysed results from the identified palynomorphs. The identified palynomorph assemblages are marked with high incidences of pollen having an affinity with mangrove Avicennia, Florschuetzia, and Rhizhophora in the Tanjong Formation mudstones with indicative freshwater or peat swamp Arenga, Cyrtostachys, Elaeocarpus and Gramineae in the Tanjong Formation coals thus confirmed the associated facies association of the coastal swamps and marshes.

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