Petroleum and Coal

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Sedimentology and Facies Analysis of the Pedawan Formation along Borneo Heights road, Siburan Area, Kuching, Sarawak, Malaysia

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Received March 22, 2021; Accepted April 28, 2021

Abstract

Several outcrops of Pedawan Formation (Jurassic – Cretaceous age) found along the Borneo Heights road in the Siburan area were evaluated. Detailed facies analysis of four (4) outcrops were undertaken, and seven (7) lithofacies were identified. These are, i) S1: Massive, ungraded medium-grained sandstone, ii) S2: Graded, coarse to fine-grained sandstone (turbidite sequence, Ta-Tb), iii) S3: Thick, medium to fine-grained sandstone with mudstone interbeds, iv) S4: Thick, laminated medium to fine-grained sandstone with floating mud clasts, v) S5: Massive slumping structure of medium-grained sandstones with thin mudstone layers, vi) M1: Massive, laminated thin mudstone with medium to fine sandstone interbeds, and lastly, vii) M2: Thick mudstone with thin, fine to medium-grained sandstone interbeds. The lithofacies are grouped into five facies associations, which are; i) FA1: Slope – cohesive flow deposits and slump structure, ii) FA2: Canyon floor filled with high to low-density debrites and turbidites, iii) FA3: Distributary turbidite channel, iv) FA4: Lobe fringe – fine to medium-grained sandstone with thick mudstone, and v) FA5: Thin mudstone and sandstone interbed of the basinal plain. The overall depositional environment is interpreted to be the slope to the fan lobe area of the deep marine setting. Based on a paleontological analysis, six (6) species of microfossils are determined and mostly deposited in benthic marine depositional environments.

Keywords: *Sedimentology; Mudstone; Lithofacies; Deep marine; Turbidites; Pedawan Formation; Fan lobe.*

1. Introduction

Sarawak is situated in northwestern Borneo and has been separated into three tectonostratigraphic zones: the Kuching Zone, Sibu Zone, and Miri Zone. The summarized stratigraphic column of the three zones can be referred from Figure 1. The Jurassic – Cretaceous Kuching Zone is located in the western part of Sarawak. Shwaner Mountains bound this zone at the south, and it is separated in the north from Sibu Zone by the Lupar Line. Madon [1] has reported that Kuching Zone contains Carboniferous limestones in the central area, and the Jurassic overlies it to Cretaceous siliciclastic sediments [1]. These rocks are unconformably mixed overlain by terrestrial and marine sedimentary rocks of Late Cretaceous to Middle Miocene siliciclastic rocks. The Pedawan Formation in Kuching Zone ranges from Jurassic to Cretaceous in age, and it overlies conformably on the Bau Limestone [2]. It is made up of a thick sequence of predominantly argillaceous rocks, mostly black shales with rare sandstone and radiolarite beds [2].

The Pedawan Formation in the Siburan area has not been studied in detail in sedimentology, stratigraphy, and biostratigraphy. Thus, this paper will present the detailed facies analysis of the Pedawan Formation in Siburan. There are four (4) outcrops of Pedawan Formation studied, with the following objectives: (1) to analyse the sedimentological and paleontological characteristics of the different facies of Pedawan Formation in the study area, (2) to evaluate the facies associations and the possible depositional environment.

The study area for the Pedawan Formation is located within the Borneo Heights - Siburan area of Kuching Zone, from the longitude of 110 º15’ E to 110 º25’ E and from the latitude of 1 º10’ N to 1 º25’ N as seen in Figure 2.

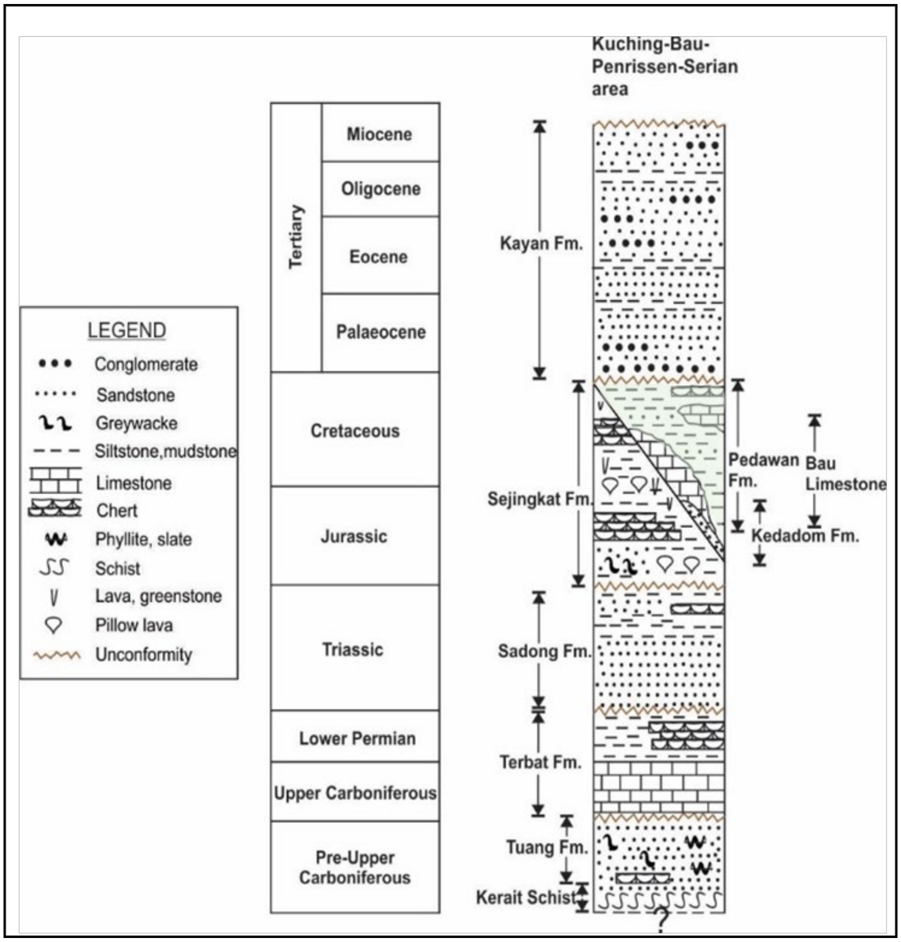

Figure 1. Stratigraphic column of Kuching-Bau-Penrissen-Serian area. Pedawan Formation is dated from Jurassic to Cretaceous age in range (after Ting, [2])

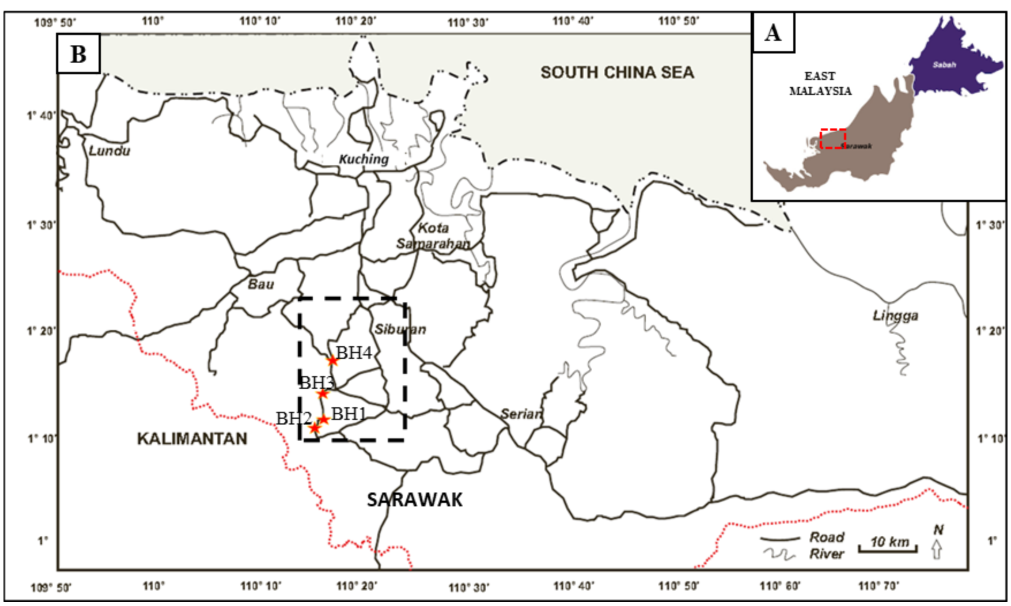

Figure 2. A) Location map of the study area in Kuching, Sarawak. B) Four outcrops are well exposed along Borneo Heights road

2. Geological background

2.1. The Kuching Zone

Kuching Zone includes several sedimentary basins of Late Cretaceous to Late Eocene age. The western side of Kuching Zone is composed of Paleozoic to Mesozoic rocks that are parts of the Sundaland margin [3]. It is believed that in Cretaceous, there was a magmatic arc in Shwaner Mountains and a forearc basin at the north, whereby the Pedawan Formation and Selangkai Formations were deposited [3]. The oldest rocks in west Sarawak have been identified to be phyllite, schist and metagreywacke of Tuang Formation and schist of Kerait Schist in Serian [4]. These rocks are older than Carboniferous and they are considered to have marine origin. They are overlain by Upper Carboniferous-Lower Permian Terbat Formation, Triassic Sadong Formation, Jurassic-Cretaceous Serabang, Sejingkat, Sebangan Formations, Upper Jurassic Kedadom Formation, Upper Jurassic-Lower Cretaceous Bau Limestone, Upper Jurassic-Upper Cretaceous Pedawan Sandstone, and followed by Lower Tertiary Kayan Sandstone, Silantek and Plateau Formation.

2.2. The Pedawan Formation

Pedawan Formation has been dated as Upper Jurassic to Cretaceous and contains thick argillaceous rocks of black shales with some sandstone beds. The age was based on its intertonguing relationship with the Upper Jurrasic portion of the Bau Limestone (as highlighted in Figure 1). The early Cretaceous age is based on its interbedding feature with the Early Cretaceous portion of the Bau Limestone and the presence of *Orbitolina lenticularis* [2]. It overlies conformably on the Bau Limestone Formation with gradational contact [5].

Pedawan Formation is moderately to steeply dipping marine shale and mudstone, with carbonaceous materials and sandstone beds [5]. The facies succession indicate that the depositional setting changed quickly from shallow to deep water environment and turbiditic sequences are significant in some outcrops of Kuching Zone.

Hutchison [5] proposed three divisions of Pedawan Formation - the upper, middle and lower parts. The Lower Division is understood to be poor in fossils. This portion contains long-ranging foraminifera which are poorly preserved in the shales, but better preserved in radiolarite. This condition indicates that the particular region is of the same age as Bau Limestone Formation. The Middle Division is highlighted by the presence of *Orbitolina lenticularis* and possible presence of pollen somewhere above the contact with Bau Limestone Formation. This area has been dated to be Lower Cretaceous. The Upper Division can be separated into three floral zones [5]. These are i) *Caytonipollenites* zone – discovered only in the Lundu-Kayan area and according to the presence of *Caytonipollenites pallidus,* the age is pre-Turonian, ii) *Cicatricosisporites* zone–the age is Albian–Cenomanian, based on the existence of planktonic foraminifera in the Penrissen area, and the last zone is iii) *Araucariacites* zone–based on Hutchison [5], the top contains planktonic foraminifera of Turonian to Upper Santonian age and the overall age range is Cenomanian to Senonian.

A major angular unconformity known as Pedawan Unconformity separates the Upper Cretaceous turbidites of Pedawan Formation from the Upper Cretaceous to Paleocene conglomerates of Kayan Sandstone [3]. This indicates a major tectonic event prior to the sedimentation of Kayan Sandstone in which there was an alteration from deep marine to terrestrial-marine environment in Kuching Zone during Late Cretaceous [3].

3. Methodology

3.1. Geological fieldwork

A fieldwork to Kuching, Sarawak was conducted from 26th August 2018 till 13th September 2018. The outcrop survey was carried out along Borneo Heights road in Siburan. Sedimentological logging and facies analysis were carried out on four (4) well exposed outcrops, in which the rocks were described in term of; lithological composition, texture, colour, bedding, contact, presence of fossil and other sedimentary structures. Systematic rock sampling was also performed.

3.2. Facies analysis

Selley stated that a sedimentary facies is any restricted area of a specific stratigraphic unit with characters significantly different from other parts of the unit [6]. A series of facies of geologically significant relationships with the depositional environment are known as facies sequences or specifically as facies successions. A facies association involves a concept that contain particularly significant depositional elements that are characteristics of a specific depositional environment [7].

3.3. Paleontological study

Paleontology can be defined as the study of ancient life on Earth by discovering and analysing the plant and animal fossils. For this study, foraminifera were used as they are one of the most abundant microfossils and can be found rather easily in marine environments since they have existed since the Cambrian [8].

There were ten (10) rock samples taken and they are mudstones and fine-grained sandstones. The rock samples are processed for micro-paleontological analysis based on Biostratex micropaleontology standard procedure [9]. The identified foraminifera were classified into three major groups; planktonic, arenaceous benthonic and calcareous benthonic.

4. Results and discussion

The four (4) outcrops of Pedawan Formation along Borneo Heights road in Siburan are referred to as BH1, BH2, BH3, and BH4 respectively. Figure 3 shows the photographs of the outcrops (BH1, BH2, BH3, and BH4) and the sedimentological logs produced for each of the outcrops are presented in Figure 7 and 8. There are seven (7) lithofacies and five (5) facies associations recognized at the four outcrops.

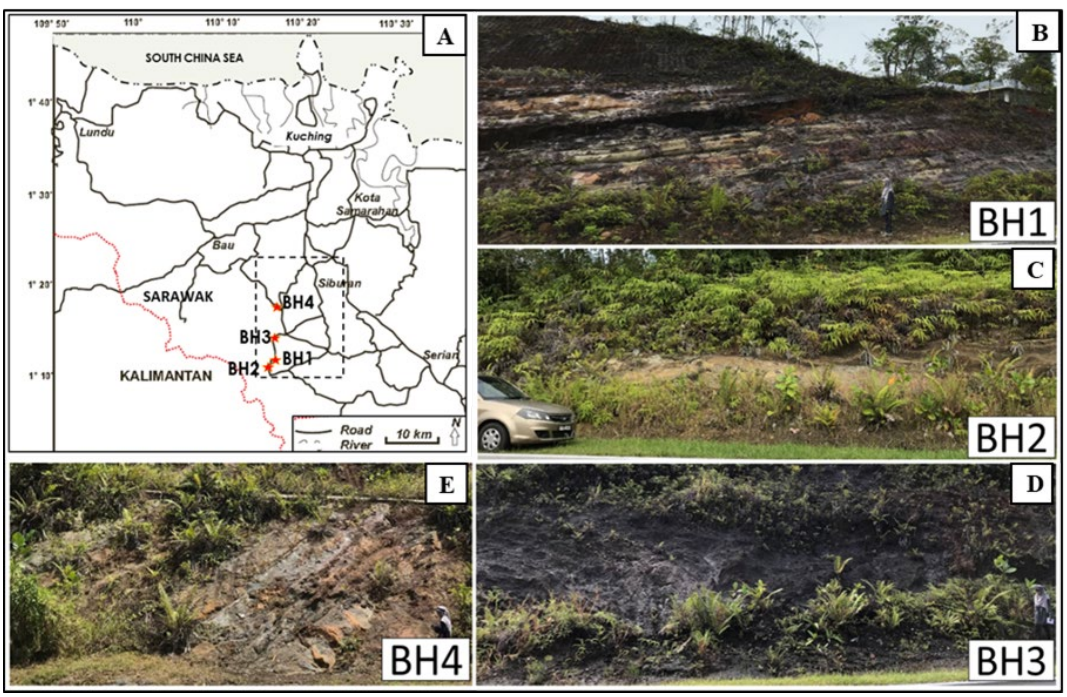

Figure 3. A) Location of the outcrops along Borneo Heights road. B) Field photograph of BH1 indicate that it is dominant with thick sandstone beds. C) Field photograph of BH2 shows that this outcrop is also made up of thick sandstone beds with some mudstone interbeds. D) The outcrop in BH3 is predominant with thin argillaceous interbeds of mudstone and sandstone. E) The outcrop in BH4 is made up of thick mudstone with some sandstone interbeds and it is slightly weathered

4.1. Lithofacies identification

Sedimentological logs generated are useful to understand the facies occurring at the outcrops. There are seven (7) lithological facies determined based on the lithology, sedimentary structures, and fossils available in the outcrops. The detailed photographs of the lithofacies are shown in Figure 4.

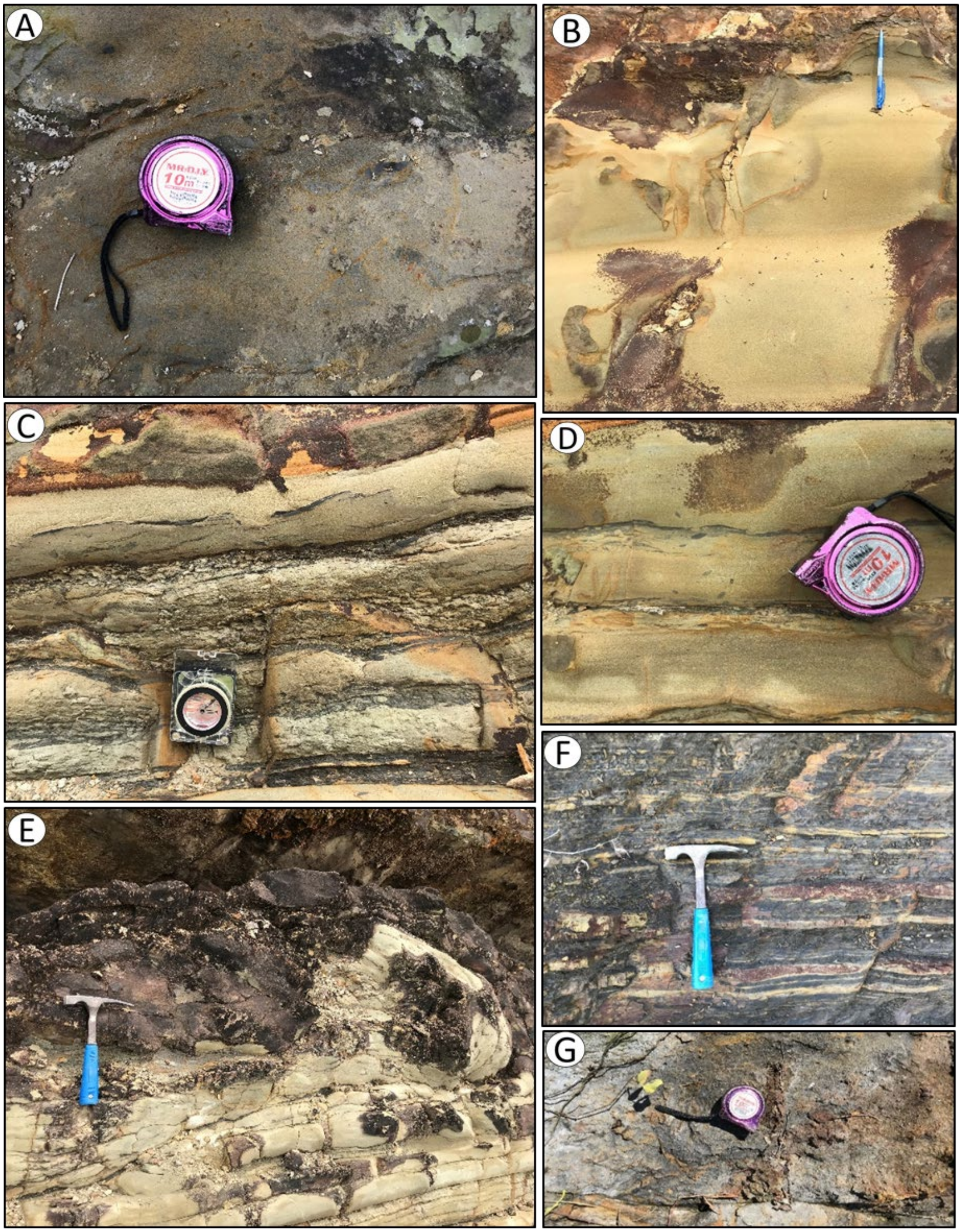

Figure 4. The sedimentary lithofacies. A) S1: Massive, ungraded medium grained sandstone. B) S2: Graded, coarse to fine grained sandstone (turbidite sequence, Ta-Tb). C) S3: Thick, medium to fine grained sandstone with mudstone interbeds. D) S4: Thick, laminated medium to fine grained sandstone with floating mud clasts. E) S5: Massive slumping structure of medium grained sandstones with thin mudstone layers. F) M1: Massive, laminated thin mudstone with medium to fine sandstone interbeds. G) M2: Thick mudstone, interbedded with fine to medium grained sandstone

i) S1: Massive, ungraded medium grained sandstone (Figure 4A)

The S1 sandstone bed (1 – 3.5 m) is thick and ungraded. It is light grey or light brown in colour. There are some laminations and mud clasts observed along the lamination. The base is sharp and irregular. The sandstone bed occurs on top of, and is overlain by, thin mudstone beds. The thickest S1 bed is approximately 3.5 m in thickness.

The massive sandstone structure may indicate grain flow deposits. The sandstone grains were deposited rapidly through grain-supported, high density flow. The water acts as the lubricant to transport the sand grains, and it creates a cohesive force between the grains in which they are transported in a form of suspension. This grain supported flow is then deposited as a massive sandstone bed.

ii) S2: Graded, coarse-to-fine grained sandstone (turbidite sequence, Ta-Tb) (Figure 4B)

The sandstone bed is fining upwards, from coarse to fine grained. This bed displays a part of Bouma's turbiditic sequence – Ta to Tb. Ta section is represented by massive or graded bedding and it indicates deposition from suspension. Tb section displays horizontal (parallel) and ripple laminations in which they are the results from traction or combined traction and suspension processes [10].

Ta division is determined to be the result of high-density turbidity current, which indicates the plastic flows. The Tb section is related to bottom current that involves some traction [10]. The whole process of the bed formation include the sediments are transported in turbulent flow and then proceed as suspension. From suspension, the sediments drop and deposited as a well-defined bed. The sediments are consequently transported as bed load under the moving suspension [10].

iii) S3: Thick, medium to fine grained sandstone with mudstone interbeds (Figure 4C)

The thick sandstone bed is laminated. There are several mud clasts found floating on top and along laminations. Mud linings or layers are also observed, they might be the formed due to several mud clasts being lithified together. The sandstone bed is well sorted. There are interbeds of thin and thick mudstones in between the sandstones. Some mudstones have laminations. They are ranging from 0.03 to 0.2 m in thickness.

This sandstone bed may have been deposited as sediments spread out from a slope into a channel structure. The turbidity current decreases and causes rapid deposition of medium to fine grained sand sediments. The transport of suspended sediments also include the mud, which was later deposited as a layer or as the floating mud clasts.

iv) S4: Thick, laminated medium-to-fine grained sandstone with floating mud clasts (Figure 4D)

The sandstones are parallel laminated and have no obvious grading. It is characterized by mud clasts horizons at the middle and upper parts. Some mud linings are also observed in this bed. Facies S4 in general shows good sorting. The thickness of individual bed range from 0.3 to 1.3 m.

This massive sandstone facies represents high density flow that transports the medium and fine-grained sand, along with some mud clasts. The density flow consequently reduces and as a result the floating mud clasts are deposited at the middle and top of bed. There is also some small scale flame structures along the thin mud and sand lamination, which is useful for identification of younging direction of the outcrop.

v) S5: Deformed beds of medium grained sandstones with thin mudstone layers (Figure 4E)

A 2 m thick succession sandstone bed displays soft sediment features at outcrop BH1. The thick slump is measured to be 2 m in thickness. The sandstone beds are medium grained and light brown in colour. This massive structure also contains some inter-layering of mudstones which have approximate thickness of 0.01 to 0.02 m. Some sandstone beds indicate fining upward pattern.

In this formation, the sandstone interbedded with mudstone layers displayed a well-preserved, localized slump (as seen in Figure 4E). This soft sediment deformation structure is also known as a drag structure, resulting from the dragging of unconsolidated sediments [11]. There was a deformational process that affected the sandstone and mudstone interbeds. So, the soft interbeds are interrupted and deformed into slump structure.

vi) M1: Massive, laminated thin mudstone interbedded with medium-to-fine sandstone interbeds (Figure 4F)

The mudstone beds are dark grey in colour, and display parallel and wavy laminations. The mudstone are 0.02 to 0.2 m in thickness. At BH3, a thick mudstone bed is interbedded with thin sandstone beds. The thickness of sandstone beds range from 0.02 to 0.3 m in thickness. The sandstone beds are light brown and some of them are parallel laminated. The stratigraphic contact between the mudstones and sandstones is gradational. A rhythmic repeating sequence has been identified at the upper part of BH3 outcrop. The sequence contains fining upward interbeds of mudstone and thin sandstone which overlies a thick sandstone unit. As a whole, the composite thickness at the interbedded unit is around 0.5 to 1.5 m.

The rhythmic interbedding of M1 suggest a sub-environments located far from the slope area. As a result of decreasing energy, the sedimentary sequences display thin and flattened interbedding of mudstone and sandstone. The current flow is very low and thus it can only transports and deposits mud and fine grained sandstone.

vii) M2: Thick mudstone with thin, fine-to-medium grained sandstone interbeds (Figure 4G)

A thick laminated mudstone unit was recorded at BH4. The thickness ranges from 0.1 m to 0.5 m. The mudstone is interbedded with thin sandstone layers (0.02 - 0.08 m thick). It also contains some mud clasts. The interbedded sandstone show fining upwards trends.

The thick mudstone bed in deep marine setting indicates that the energy flow that transported the sediments was low. The mud is deposited in a pelagic environment whereby there is very low to no energy flow. Thus, the mud sediments are deposited through suspension fall-out mechanism that formed the thick mudstone bed.

4.2. Facies association

The facies identified at the outcrops in Borneo Heights area may be grouped into five (5) environmentally distinct facies associations. The description of the facies associations are summarized in Table 1.

Table 1. Summary of facies association (FA1 – FA5) and their characterization

Facies Association (FA)		Lithofacies	Description	Interpretation
FA1	Slope - cohesive flow deposits and slump structure	S1, S2, S4, S5, M1	Massive sandstone with laminations, mud clasts, mud layers or with no structures. The base is erosional or sharp. Fining upwards sandstone (turbidite). Slump structure is available.	High density flow preserves no structures. Liquefied grain flow deposits non-graded bed. Some structures are present due to the decreasing energy flow (eg: fining upward sandstone bed). Slump is formed by gravity flow that deformed the soft sediments. Turbidite sequence indicates that the density flow has become turbulent at the basin floor.
FA2	Canyon floor filled with high to low density debrites and turbidites	S1, S2, S3, S4, M1, M2	Massive and thick sandstone beds. Fining upwards sandstone (turbidite). Parallel and wavy lamination, and mud clasts.	High density turbidity current transports the sediments as they reach the basin floor. Liquefied flow results in deposition of thick sandstone beds. Laminated sandstone beds indicate traction mechanism during high turbidity current.
FA3	Distributary turbidite channel	S2, S3, S4, M1	Fining upwards sandstone and thin mud layer. Thick, medium-fine sandstone beds and thin mudstone interbeds. Laminations and some mud clasts are observed.	Turbidity current becomes lower and sediments start to be transported and deposited by traction mechanism. Finer mud sediments are transported in suspension and deposited by falling out as the energy decreases.
FA4	Lobe fringe - fine to medium grained sandstone with thick mudstone	M1, M2, S3, S4	Dominant laminated mudstone with fine sandstone interbeds. Presence of a thick sandstone bed within a set of interbeds. Thickness of one set: 0.5-2.5 m. Mud linings present.	Low turbidity current produced well stratified sandstone and mudstone beds. Low energy leads to more mudstone beds being deposited through the suspension fall-out mechanism and they became well laminated.
FA5	Thin mudstone and sandstone interbeds of basinal plain	M1, M2, S3	Thin, laminated mudstone interbedded with fine-medium grained sandstone beds. Thickness of one set of interbeds: 1-3 m. Thin mudstone and sandstone interbeds are alternately overlain by a thick sandstone bed.	Low density turbidity current deposited mud by suspension fall-out mechanism. It can be a pelagic sedimentation if biogenic materials like pollen or spores are present in the rock.

The five (5) facies associations are explained below.

i) FA1: Submarine slope – cohesive flow deposits and slump structure

Description: Lithofacies grouped within this facies association are the S1, S2, S4, S5, and M2 facies. FA1 facies can be distinguished by the presence of a thick sandstone beds with slumps (Figure 5D), laminations, and mud clasts. The thickest sandstone bed recorded is around 3 m (in outcrop BH3), which might have resulted from the liquefied or grain flow. Within a grain flow, the grains movement are supported by the cohesive forces between them [10].

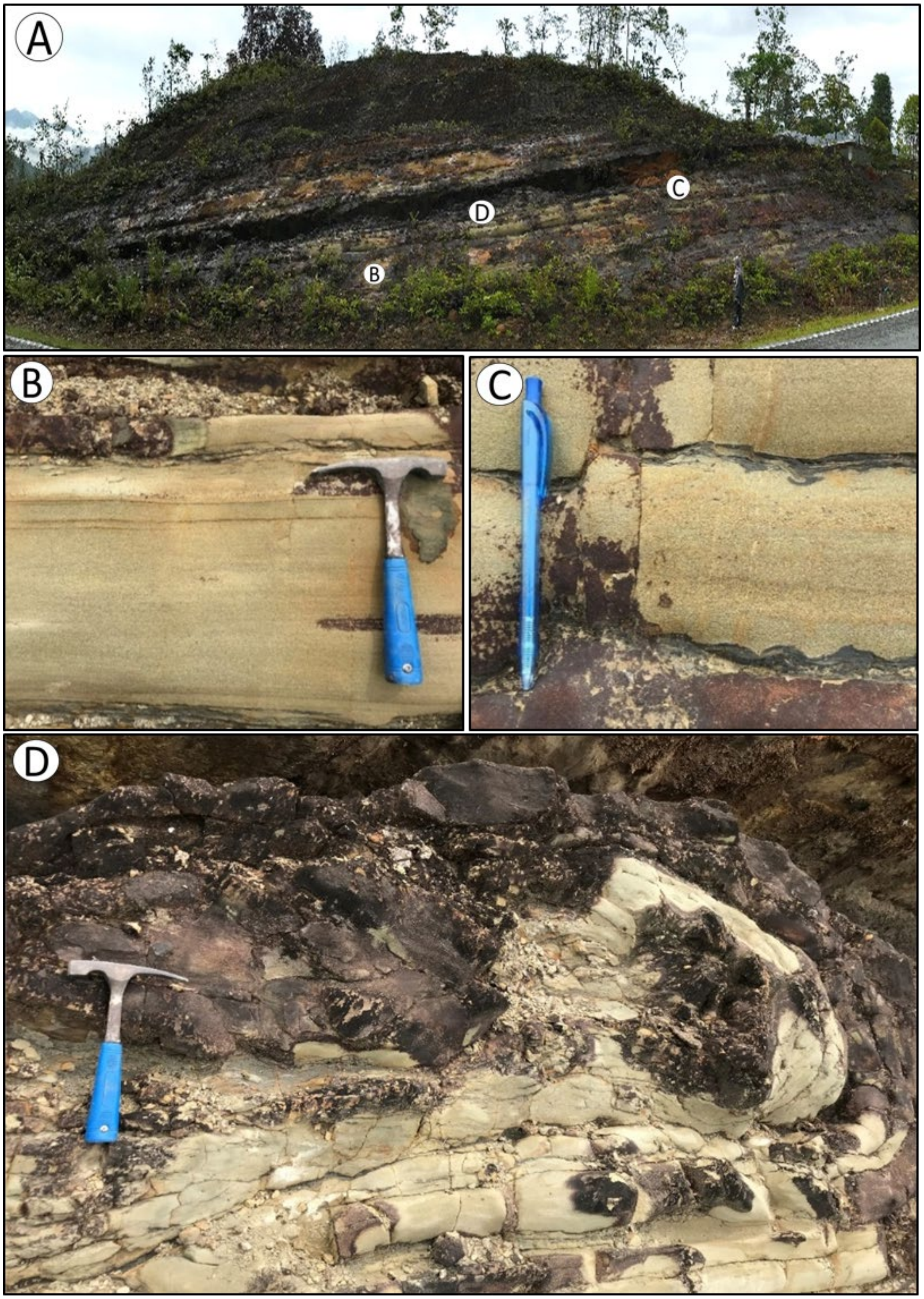

Figure 5. A) Outcrop BH1 shows thick sandstone beds with mudstone interbeds. B) Fine sandstone bed with parallel lamination (FA2). C) Fining upwards sandstone bed with basal-flame structures and mud clasts (FA3). D) Slump structure is recorded with a thickness of ~2 m, and can be found within chaotic beds of FA1. The sedimentary log for outcrop BH1 is shown in Figure 7A

Interpretation: Slump structure is one of the soft sediment deformation structures. The 'soft sediment deformation structures' is a term used to describe the deformations that reflect deformational processes which affected sediments that were not yet lithified [11].These structures are formed by a mechanism that involves the intergranular movement and the cohesive forces. In this study, the slump is interpreted to represent the slope area of deep marine setting. Due to gravity, the sedimentary layer above the soft sandstone interbeds moves downslope and causes the sandstone to be deformed into slumps. Graded beds are deposited by the waning flow, which indicates a gradual decrease in energy or velocity [10]. As energy decreases, the coarser sediments will be deposited first, followed by the finer sediments.

ii) FA2: Canyon floor filled with high to low density debrites and turbidites

Description: Lithofacies included within this facies association are the S1, S2, S3, S4, M1, and M2 facies. FA2 can be recognized by the fining upwards sandstone (Figure 5B) and some thick sandstone beds. Structures observed are parallel and wavy lamination, and mud clasts (debrites) (Figure 5C).

Interpretation: FA2 is interpreted as deposits of the canyon floor, located near the slope area, where sediments are transported by high density turbidity current. The sediments are distributed as they reach the basin floor, and they might be transported through a liquefied flow [10], which results in deposition of some thick, medium-to-fine grained sandstone beds. The current is strong enough to create a channel that starts from the foot of slope. Debrites are also transported in the middle or upper part of the sandstone bed. The combination of turbidity current and liquefied flow results in the deposition of the thick, laminated sandstone beds, alternated by the thin and thick mudstone beds.

iii) FA3: Distributary turbidite channel

Description: Lithofacies grouped within this facies association are the S2, S3, S4, and M1 facies. In FA3, the medium-grained sand gradually fine upwards followed by a thin mud layer. There are also thick, medium and fine-grained sandstone beds and thin mudstone interbeds. Some mud clasts and laminations are observed on the sandstone and mudstone beds. The turbidite sequence, Ta and Tb are observed in the fining upwards sandstone beds (Figure 5C).

Interpretation: The sand and mud sediments are deposited by the traction and suspension mechanism. Moving away from the slope, the channel structure is thinner and smaller. Sediments are fining upwards due to the waning flow whereby the energy and gravity gradually decreases. As a result, the sandstone bed has the massive feature at the bottom and parallel lamination at the top part. Finer sediments like mud are also transported as suspension and consequently deposited by falling out as the energy becomes very low [10]. In deep marine setting, it is understood that mud clasts are commonly transported by the gravity-driven fluid flow, but may involve both laminar and turbulent flows [12].

iv) FA4: Lobe fringe - fine to medium grained sandstone with thick mudstone interbeds

Description: Lithofacies included within this facies association are the M1, M2, S3, and S4 facies. The facies associated for lobe fringe is dominated by thick mud (Figure 4G) with fine to medium grained sandstone interbeds. There is also thinner interbeds of sandstone and mudstone which is fining upwards. Overall, this facies shows fining upwards pattern of small thickness of sandstone and mudstone interbeds, with dominantly thick mudstone bed. A set of the interbeds ranges from 0.5 m to 2.5 m in thickness. There is also some presence of a thick sandstone bed within a set of the interbeds.

Interpretation: This facies association reflect a low density turbidity flow which produced the well stratified sandstone and mudstone beds [13]. The lobe fringe area is near to the distal fan and similarly, it has relatively low energy. As a result, there are more mudstone beds deposited through the suspension fall-out mechanism and they are well laminated.

v) FA5: Thin mudstone and sandstone interbeds of basinal plain

Description: Lithofacies grouped within this facies association are the M1, M2, and S3 facies. Basin plain facies association is marked by thin and thick mudstone beds interbedded with fine to medium grained sandstone beds. This facies association shows a composite thickness of 1 to 3 m, respectively for each set. It is dominant at BH3 outcrop, whereby the interbedding of mudstone and sandstone beds are apparent as a whole (Figure 6C and 6E). The FA5 facies associations comprised of the thin mudstone and sandstone interbedding unit, and this unit is overlain by a thick sandstone bed. This succession may indicate the beginning of a new turbidite event.

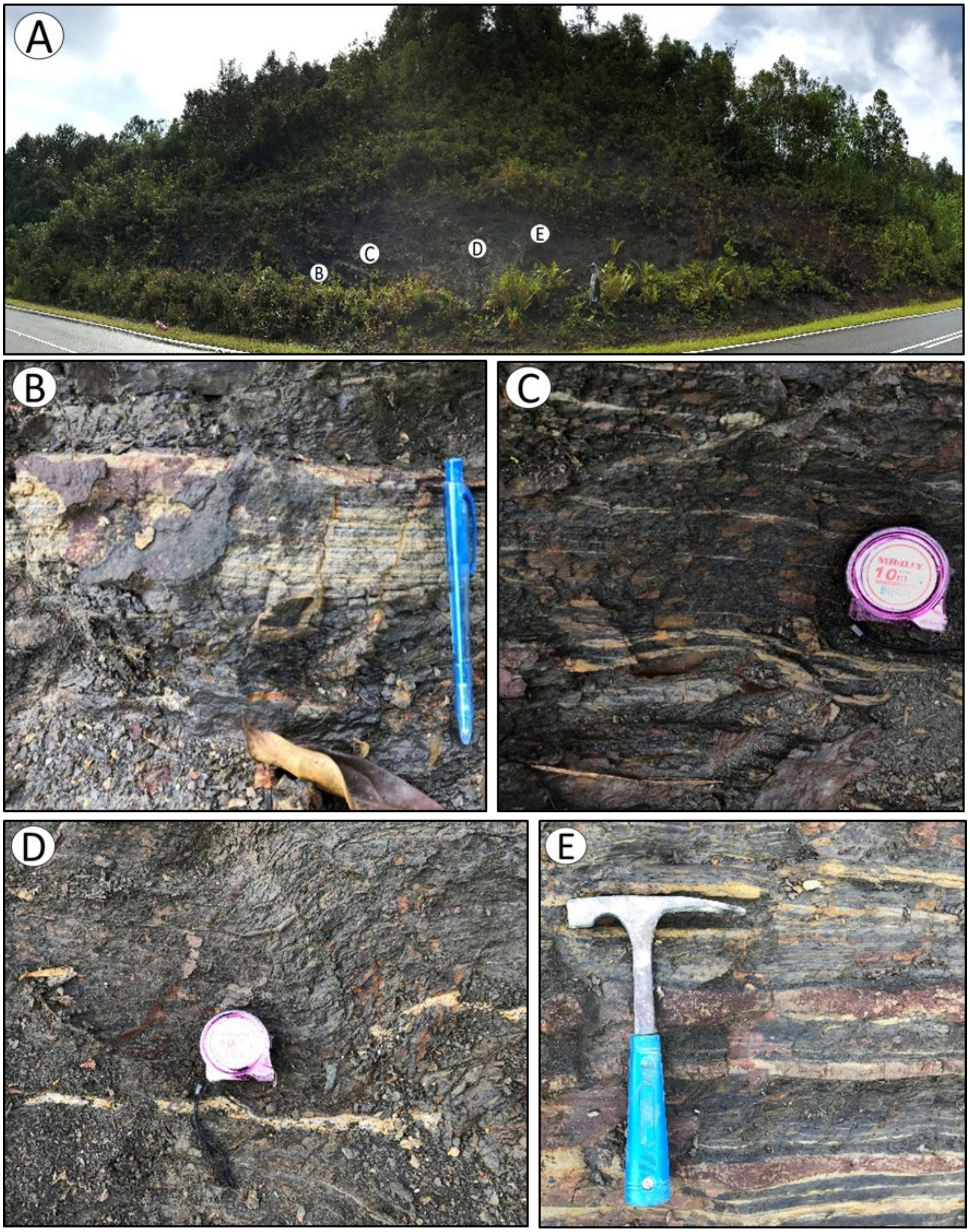

Figure 6. A) Outcrop BH3 massive mudstone beds with some sandstone interbeds, B) Thick, 0.1 m thick laminated sandstone in between mudstone beds (FA4). C) Mudstone bed with wavy laminations, interbedded with thin, medium grained sandstone is common in FA5 facies association. D) Mudstone bed with minor slump event is recorded in this outcrop. E) Thin sandstone and mudstone interbeds at the upper part also indicate the FA5 facies association. The sedimentary log for outcrop BH3 is shown in Figure 8A

Interpretation: Located away from the slope area, basin plain has the lowest turbidity current compared to other facies associations. The mud deposited by suspension fall-out mechanism is thin and well interbedded with the thin sandstone interbeds [10]. The mud dominated sedimentation can be categorized as a pelagic sedimentation if biogenic materials like pollen or spores are present in the rock.

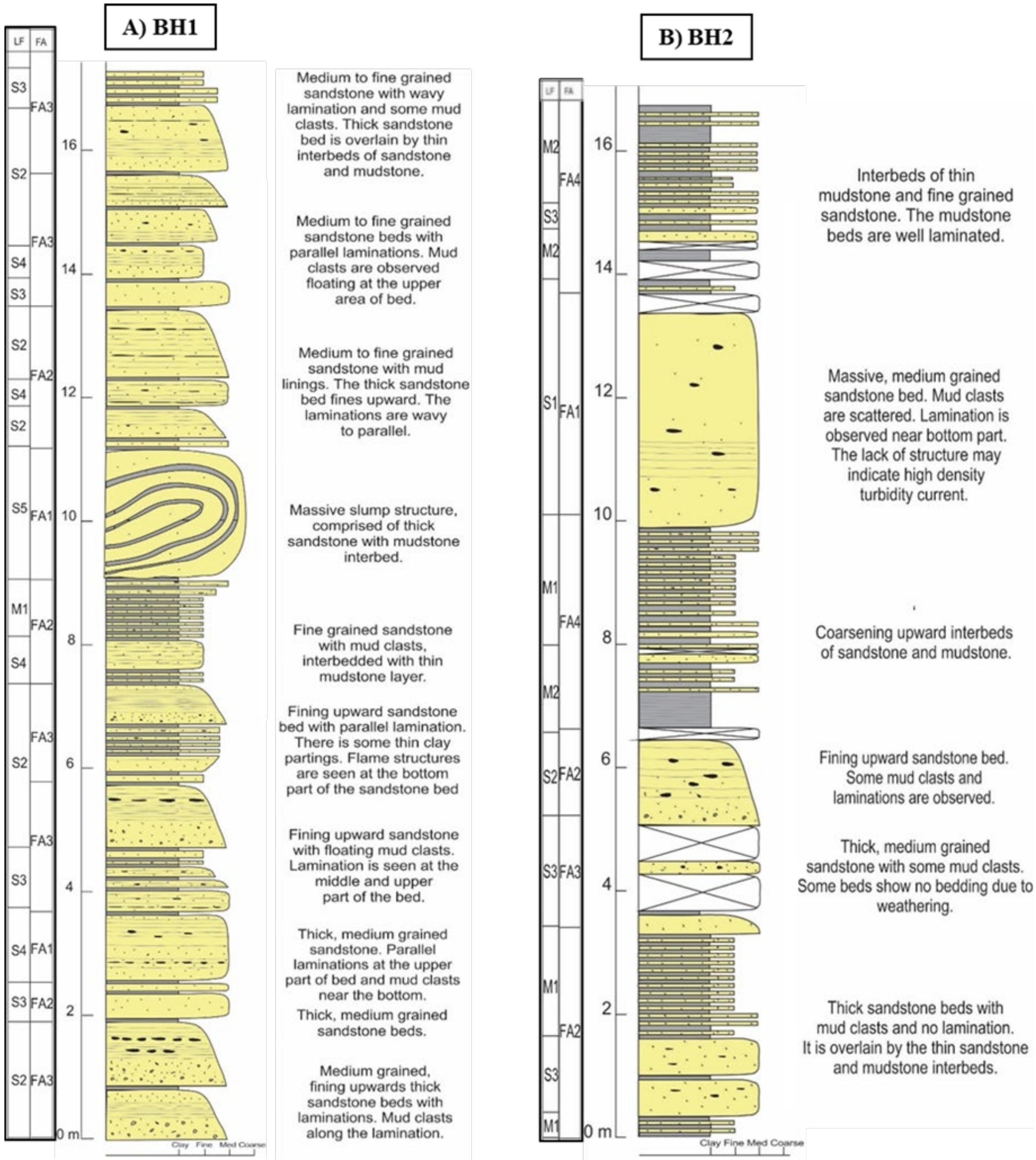

Figure 7. The sedimentary log for outcrops in BH1 and BH2. A) Outcrop BH1 is marked by the presence of thick slump structure and dominant thick sandstone beds with mudstone interbeds. B) Outcrop BH2 is also made up of thick sandstone beds, interbedded with mudstone. The thickest sandstone is measured to be more than 3 m.

[LF – lithofacies, FA – facies associations, S1- massive, ungraded medium grained sandstone, S2 - graded, coarse to fine grained sandstone, S3 - thick, medium to fine grained sandstone with mudstone interbeds, S4 - thick, laminated medium to fine grained sandstone with floating mud clasts, S5 - chaotic beds of medium grained sandstones with thin mudstone layers, M1 - massive, laminated thin mudstone with medium to fine sandstone interbeds, and lastly, M2: thick mudstone with thin, fine to medium grained sandstone interbeds, FA1 – submarine slope, cohesive flow deposits and slump structure, FA2 - canyon floor filled with high to low density debrites and turbidites, FA3 - distributary turbidite channel, and FA4 - lobe fringe, fine to medium grained sandstone with thick mudstone.]

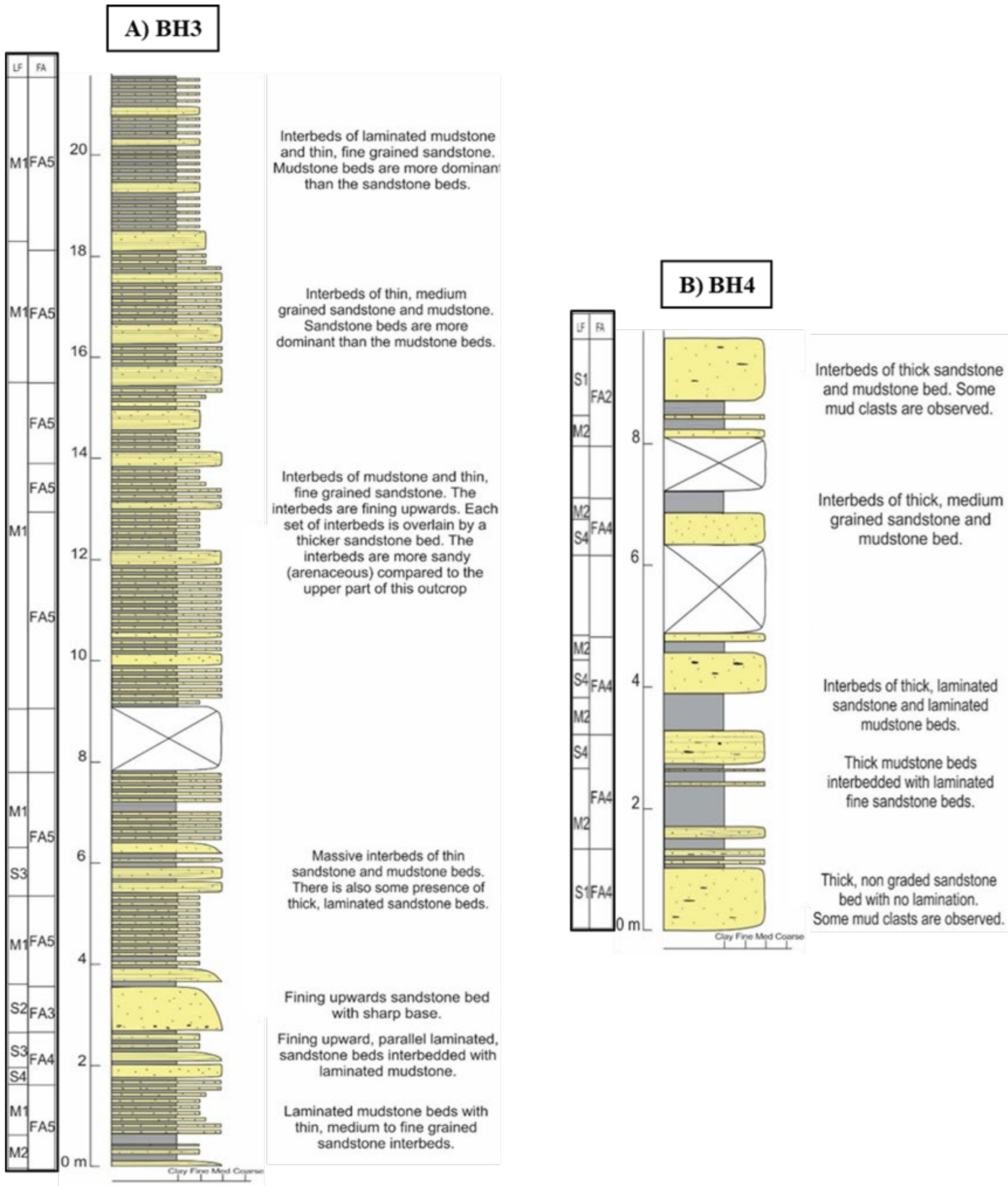

Figure 8. The sedimentary log for outcrops in BH3 and BH4. A) Outcrop BH3 is predominantly made up of interbeds of thin mudstone and sandstone, with minor thicker sandstone. B) Outcrop BH4 is slightly weathered, comprises of thick mudstone and sandstone beds.
[LF – lithofacies, FA – facies associations, S1- massive, ungraded medium grained sandstone, S2 - graded, coarse to fine grained sandstone, S3 - thick, medium to fine grained sandstone with mudstone interbeds, S4 - thick, laminated medium to fine grained sandstone with floating mud clasts, S5 - chaotic beds slumping structure of medium grained sandstones with thin mudstone layers, M1 - massive, laminated thin mudstone with medium to fine sandstone interbeds, and lastly, M2: thick mudstone with thin, fine to medium grained sandstone interbeds, FA1 – submarine slope, cohesive flow deposits and slump structure, FA2 - canyon floor filled with high to low density debrites and turbidites, FA3 - distributary turbidite channel, FA4 - lobe fringe, fine to medium grained sandstone with thick mudstone, and FA5 - thin mudstone and sandstone interbeds of basinal plain.]

4.3. Depositional environment

Figure 9 shows the proposed depositional model which accommodates the facies associations of Borneo Heights, from the slope area to distributary channels and basin floor.

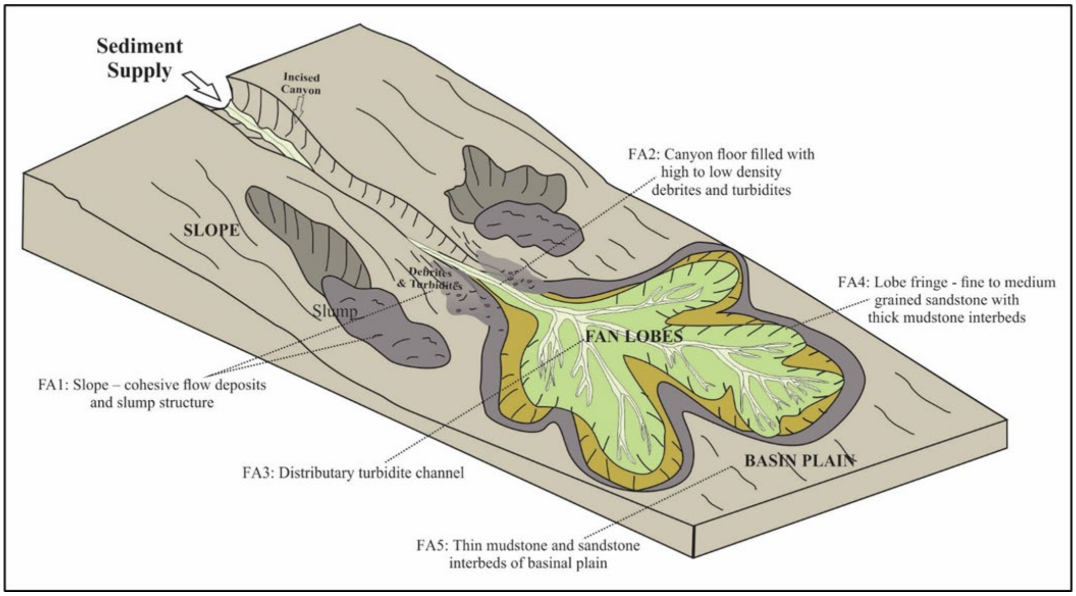

Figure 9. Proposed depositional model for the Pedawan Formation of the Borneo Heights road in Siburan (modified from Meng, *et al.*, [14]). The model proposed the location of deposition of the different facies associations made. The sediment supply originates from the shallower marine area and mostly are transported via the deep marine canyon. Transportation and deposition of sediments are supported by the density and turbidity flows, and later being spread at the basin floor area as the lobes

FA1 is represented by the slope area which involves massive slump structures. This area has high energy, cohesive and turbulent flows. There is also some thick sandstone beds in the FA1. FA2 is dominated by massive and thick sandstone beds and this is indicated by the canyon floor area. Due to high energy flow, debrites and turbidites are transported and deposited within in area. FA3 can be distinguished by the thick, fining upwards sandstone bed. They are determined to be deposited as distributary turbidite channel. The presence of turbidites indicate the decreasing turbidity flow as sediments are transported further from the slope area. FA4, the fringe area, is marked by the low flow energy. The sand are deposited by traction, while mud sediments are deposited by suspension fall-out mechanisms. FA5 is identified as the basin plain and it is located furthest from the slope area. The energy flow is very low for transportation of sediments. This condition resulted in the dominant mud deposition compared to the sand deposition. The suspension fall-out mechanism deposit the laminated fine grained mudstone and sandstone.

4.4. Paleontological evidence

The detailed facies analysis can be enhanced by applying the study of micropaleontology, in which for this research foraminifera was used due to their abundancy and can provide evidence of the relative ages of marine rocks as they have existed since the Cambrian [8].

Table 2 summarize the occurrence of the identified foraminifera in the four outcrops of Siburan area. They are four (4) main groups; the calcareous benthic foraminifera (FOBC), arenaceous benthic foraminifera (FOBA), planktonic foraminifera (FOP), and other microfossils (MM). For this study, there are only FOBC and FOBA found, and only two outcrops yield the foraminifera. A total of six (6) species of foraminifera are identified, two (2) are calcareous and four (4) are arenaceous foraminifera.

Table 2. Microfossils count in four (4) outcrops along Borneo Heights road

Sample Label	FOBC		FOBA				Total
	Cibicides spp.	Heterolepa dutemplei	Arenaceous undifferentiated	Ammobaculites spp.	Bathysiphon spp.	Trochammina spp.	
BH1B							0
BH2D							0
BH3B					2		2
BH4B	1	1	1	1		5	9

Only BH3 and BH4 show the presence of microfossils. Some of the species of foraminifera and other fossils recorded are described as below (based on http://marinespecies.org and http://foraminifera.eu):

i) Cibicides spp.

Phylum: Foraminifera Class: Rotaliata Order: Rotaliida
Family: Cibicididae Genus: Cibicides

ii) Heterolepa dutemplei

Phylum: Foraminifera Class: Rotaliata Order: Rotaliida
Family: Heterolepidae Genus: Heterolepa

iii) Ammobaculites spp.

Phylum: Foraminifera Class: Globothalamea Order: Lituolida
Family: Lituolidae Genus: Ammobaculites

iv) Bathysiphon spp.

Phylum: Foraminifera Class: Monothalamea Order: Astrorhizida
Family: Rhabdamminidae Genus: Bathysiphon

v) Trochammina spp.

Phylum: Foraminifera Class: Globothalamea Order: Lituolida
Family: Trochamminidae Genus: Trochammina

All foraminifera are of benthic origin, with either calcareous or arenacous characteristics. The genus *Ammobaculites* is understood to have covered most of the ecological niches in modern seas [15]. It is also known to be an infaunal deposit feeder and live in brackish to normal marine salinity, in marsh to upper bathyal environments [15]. It is reported by Saja *et al.* that, the almost featureless and tubular *Bathysiphon spp*. lives in bathyal setting of the deep marine environment [16]. The genus *Trochammina* is of both an infaunal and epifaunal deposit and a plant feeder, whereby it is recognized to be tolerant of low oxygen level. Most species of the benthic genus *Cibicides* and *Cibicidoides* are generally believed to dwell in an epibenthic habitat [17].

5. Conclusion

Detailed facies analysis was carried out at four different outcrops along Borneo Heights road, Siburan. This resulted in seven (7) lithofacies identification and five (5) main facies associations. The facies analysis has identified that structures like slumps and thick sandstone beds indicate high density current. Meanwhile, thick mudstone or laminated mudstone and sandstone interbeds indicate an environment of low density and turbidity current. The depositional environment is interpreted to be the slope to fan lobe of deep marine setting.

The palaeontological analysis has determined the presence of some microfossils, which are mostly benthic foraminifera. The foraminifera have supported the interpretation of facies analysis made, whereby the depositional environment of Pedawan Formation in Siburan is possibly the deep marine environment. The benthic marine setting is calm and has much lower energy than the slope area. So, finer sand and mud sediments were deposited in suspension mode and the benthic organisms would be preserved well in this condition.

Acknowledgement

This research has been funded by the Yayasan UTP grant (0153AA-H10). The authors would like to acknowledge the support from the Research and Innovation unit of Universiti Teknologi PETRONAS.

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