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Soft-Sediment Structures in Mud-Dominated Turbidites of Pedawan Formation (Upper Jurassic - Cretaceous) along Jambusan-Semadang Road, Siburan, Sarawak, Malaysia

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Abstract

Three (3) outcrops belonging to the Pedawan Formation found along Jambusan-Semadang Road in the Siburan area are characterized by well-developed soft-sediment deformation structures (SSDS). SSSD is formed due to instability, which possibly results from factors like rapid sedimentation, overloading, or earthquake. The SSDS in Siburan, in the form of folded and faulted structures, were recorded within thick sequences of mud-dominated turbidites of the Pedawan Formation (Jurassic – Cretaceous age). These SSDS are grouped into five (5) different types, which are 1) mud-dominated slumped structures, 2) folded and overturned sandstone beds, 3) contorted argillaceous mudstone beds, 4) sandstone boulder, and 5) envelope structure. The small-scale SSDS (<1 m), like localized slumps and envelope structure, are interpreted to have formed due to overloading and rapid deposition. The large SSDS (> 1 m), such as detached sandstone blocks, internal faulting, and folds, are attributed to movements related to earthquakes.

Keywords: *Turbidite; Soft-sediment deformation structures; Slump; Pedawan Formation; Kuching zone; Sarawak.*

1. Introduction

Soft sediment deformation structures (SSDS) involve the deformation of unconsolidated sediment either during or after deposition but before lithification [1-3]. According to Olabode (2016), SSDS is formed due to a drastic decrease in shear resistance in water-saturated and unconsolidated sediments [4]. These structures are related to liquefaction and fluidization processes, which can develop in ancient and modern sedimentary environments [4]. Liquefaction and fluidization disturb the primary stratification and grains as the result of increased pore fluid pressure [1,5].

According to Bhattacharya *et al.*, liquefaction is common in coarse silt to fine sand [5]. In detail, liquefaction takes place when grain weight is briefly shifted to the pore fluid, through the collapse of loose grains or via an increase in pore-fluid pressure [2]. This process creates a structure that distorts the existing stratification. Meanwhile, fluidization occurs when the upward shear of a fluid that moves through a pore opposes the grain weight, leading to reduced strength of the sediment [2]. Through the combination of both liquefaction and fluidization, new stratification may develop, such as; convolute lamination, load structures, pillar structures, water-escape structures, and deformed cross-bedding [2].

For a deformation to occur, a triggering mechanism must be available to stimulate the deformation process. Triggering agents may be large or small in scale, and these include earthquake shocks, tsunami, volcanic activities, groundwater fluctuations, pounding waves during storms, meteorite impacts, sub-aqueous mass movement, shear stress along with the sediment-water interface, rapid sedimentation, overloading, and upward movement of pore water/gas [2,5].

Therefore, the soft-sediment deformation structures should be investigated by incorporating all other geological information that is present so that the best diagnostic outcomes can be obtained [3].

The main focus of this paper is the outcrops of the Pedawan Formation, located in the Kuching Zone. The Pedawan Formation ranges in age from Jurassic to Cretaceous and has been interpreted to be deposited in a subsiding marine setting which deepened in Late Cretaceous [6]. Azhar reported the occurrences of mass-flow deposits in Batu Kitang-Siniawan (located north of Siburan) [7]. He proposed that the mass flow deposits and the turbidites near the margin of the Pedawan basin irregularly collapsed and deposited the sediment into the deeper part of the basin.

The three (3) outcrops identified along the Jambusan-Semadang road are marked by mud-dominated turbidites sequences. Within these outcrops, well-exposed soft-sediment deformational structures (SSDS) were documented. SSDS like slumps is known to be the result of mass transport processes, which are due to the failure, dislodgement, and downslope movement of sediment under the influence of gravity [8]. The well-developed deformational structures might also be formed as a consequence of instability originating from strong external factors like earthquakes [9]. These SSDS units may represent periods of rapid sedimentation that take place subaqueously due to instability of the sedimentary succession [10].

This paper investigates the soft-sediment deformational structures and the processes that created them in relation to the sedimentology and stratigraphy of the Pedawan Formation in Siburan. The possible triggering mechanism is also evaluated.

The study area is located in the south-central of Kuching Zone. The outcrops are located along Jambusan-Semadang road, Siburan area of Kuching Zone, within longitude of 110°10’ E to 110°20’ E and latitude of 1°15’ N to 1°25’ N as shown in Figure 1.

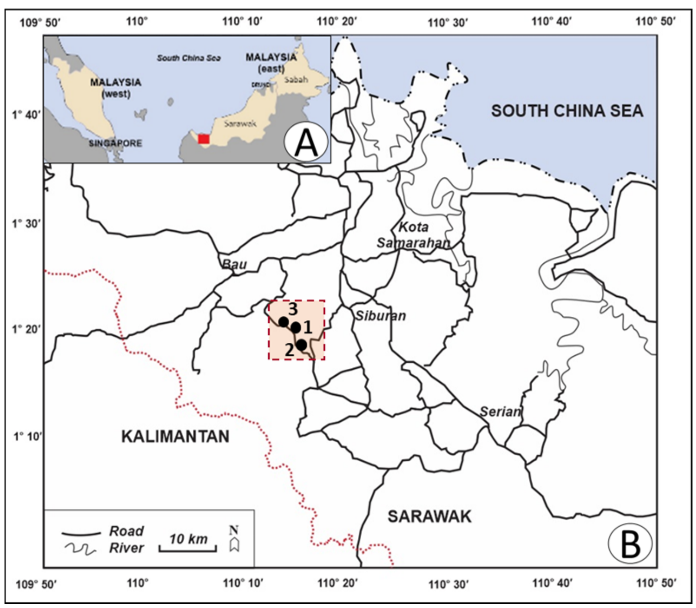


Figure 1. A) The location of study area in Kuching area, Sarawak. B) The three (3) outcrops (indicated by red box) are located along Jambusan-Semadang road in Siburan area, in Kuching, Sarawak

2. Geological background

Borneo Island is a tectonically complex island that lies in the central part of South East Asia. The region is underlain by rocks that were formed through arc-continent collision, continent-continent collision, and subduction-accretion processes resulting from the active convergence events of Indian-Australian, Pacific, and Philippine Sea plates [11-12].

Sarawak is located on the northwestern side of Borneo and has been divided into three tectonostratigraphic zones; these are the Kuching Zone (Upper Carboniferous – Middle Miocene), Sibu Zone (Late Cretaceous – Eocene), and Miri Zone (Paleogene to recent) [13]. The geological complexity of the Sarawak zones decreases from south to north and from west to east [13]. The Miri Zone is separated from Sibu Zone by an unconformity line known as the

Tatau-Mersing Line, which is partly composed of ophiolitic rock. The Sibu Zone comprises the Rajang Group, which were folded and metamorphosed turbidites with radiolarian chert, spilite, and dolerite [13]. According to Hutchison, the Rajang Group basin had been compressed into a fold-thrust belt in the Early Miocene due to the movement of the Miri Zone microcontinent towards the Sulawesi volcanic arc in the SE direction [14]. There are several main faults that have sustained their activity into Quaternary time, and they partitioned the Rajang Group into terrains of opposing strike trend [14].

Kuching Zone is the oldest zone in Sarawak, and it is composed of fossiliferous Carboniferous limestones, Permo-Triassic granites, Triassic marine shales, ammonite-bearing Jurassic sediments, and Cretaceous melanges [13]. The oldest rock in this zone is metamorphosed rocks of the Upper Carboniferous Kerait Schist and Tuang Formation [15].

The location of the outcrops evaluated in this paper belongs to the Jurassic-Cretaceous Pedawan Formation, which is located in Kuching Zone [6]. The age of the Pedawan Formation was estimated to range from Late Jurassic to Cretaceous. The Pedawan Formation consists of thick argillaceous rocks, black shales, and some rare sandstone and radiolarite beds. It overlies conformably on Bau Limestone [16] and, in turn, is overlain unconformably by Kayan sandstone [17]. The Upper Cretaceous turbidites of Pedawan Formation is separated from Upper Cretaceous to Paleocene conglomerates of the Kayan Sandstone by a major angular unconformity, informally referred to as Pedawan Unconformity [17]. The unconformity indicates that in Late Cretaceous, there was a significant period of tectonic uplift, transforming the environment from deep marine to terrestrial depositional setting in Kuching Zone [17]. The unconformity also demonstrates that the uplift and recycling of the Pedawan Formation began in the latest Cretaceous [17].

3. Outcrop description and soft-sediment deformation structures (SSDS)

3.1 Outcrop 1

Outcrop 1 (Figure 2) shows a well-exposed sequence of thin-bedded turbidites with a well-developed 2.5 m thick deformed interval. The outcrop comprises a basal, 1.3 m thick laminated mudstone overlain by 10 m thick fining-upward, interbedding of thin mudstone and sandstone. The sandstone beds are medium-to-fine grained, display parallel-to-convolute laminations, and the individual Sandstone and mudstone bed thicknesses range from 0.05 to 0.1 m. The sequence is overlain by a 2.5 m thick, fine-grained, localised sand-dominated deformed unit. The top part of the succession is marked by 14.0 m sand-rich interbeds of sandstone mudstone; the thickest sandstone bed here measures 0.5 m thick.

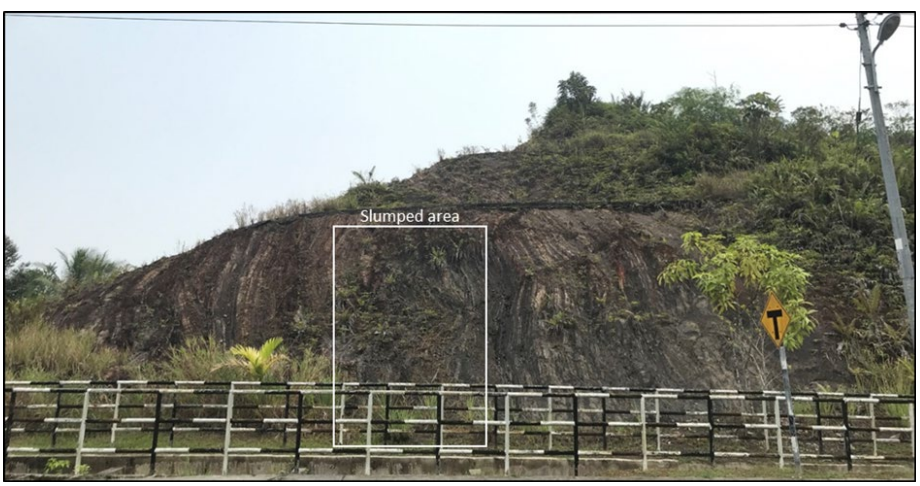


Figure 2. Outcrop #1 depicts thinly bedded sandstone and mudstone interbeds with an apparent interval of slump structures (~2.5 m thick) at the middle part

SSDS: In outcrop 1, the deformed section is minor and localised at the middle part of the outcrop. As seen in Figure 2, the steeply dipping interbeds of sandstone and mudstone seem to be disrupted at the central part of the outcrop by wavy and folded slump structures (Figure 6A). The slumped unit also includes a minor overturned fold which is abruptly disconnected and bounded by messy, argillaceous layers of sandstone and mudstone (Figure 6B). There is also a 0.3 m thick, coarse-grained sandstone bed with a sharp base present within the slump interval. This condition may represent the involvement of high density flow which transported the coarse-grained deposits prior to slumping.

3.2. Outcrop 2

Outcrop 2 (Figure 3) is dominated by muddy heterolytic interbeds of mudstone and thin and thickly bedded sandstones forming several fining-upward successions. The thin sandstone beds are 0.05 to 0.1 m thick, while the thicker sandstone beds are 0.2 to 0.4 m thick. The mudstone bed ranges from 0.07 to 0.8 m in thickness. The whole outcrop shows a slightly concave-upwards pattern forming a slightly deformed, synclinal structure.

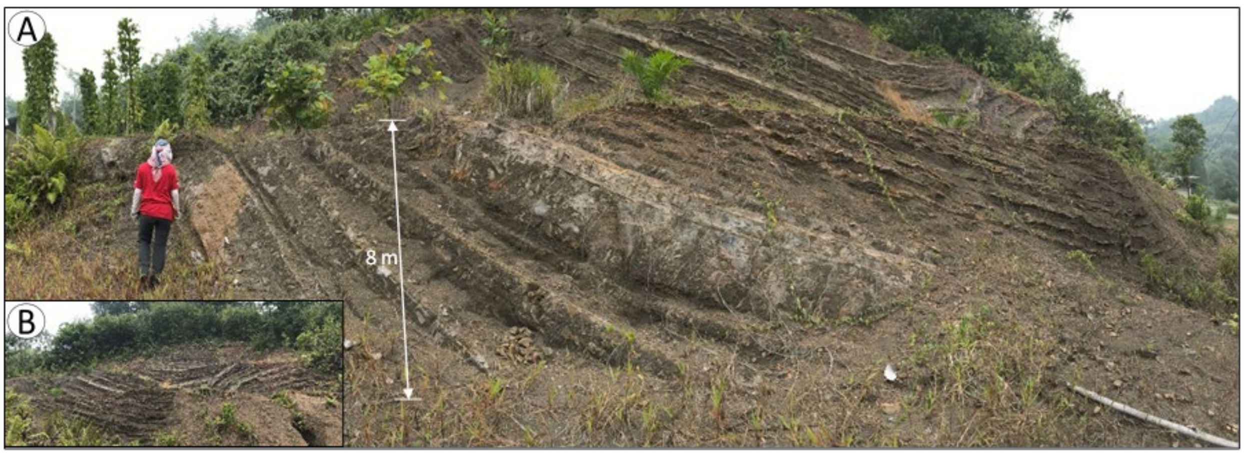


Figure 3. A) Outcrop #2 is composed of turbiditic interbeds of sandstone and mudstone. B) The frontal view of Outcrop 2 shows slightly concave upwards pattern of the interbeds

SSDS: Unlike outcrops 1 and 3, the mild slump structure in outcrop 2 can only be identified in the outcrop scale (Figure 6C). The synclinal deformation is observed to disturb the thinly-bedded turbidites. The gentle fold structure is also associated with some microfaults that probably formed during the period of deformation.

3.3. Outcrop 3

Outcrop 3 (Figure 4) is a 47 m thick succession dominated by a variety of deformed intervals. The whole succession can be divided into seven (7) distinct units. Unit I, the basal unit, is composed of a 9 m thick, mud-dominated deformed interval with thin layers of sandstone at the lower part and mud at the upper part (sandstone thickness – 0.01-0.03 m). This unit becomes arenaceous at the upper part, whereby it is composed of more fine-grained sandstone interbeds. The sandstone layers are visible and have a thin-to-medium thickness (0.03-0.05 m). Unit II is marked by 3.4 m thick classical turbidite interbeds of sandstone and mudstone (sandstone thickness – 0.03-0.1 m, mudstone thickness – 0.02-0.08 m). The following unit, unit III, is a 3.6 m thick sand-rich crumpled unit (0.05-0.15 m thick sandstone layers with 0.03-0.1 m thick mudstone interbeds). Unit IV consists of a 5.5 m thick turbidite sequence, which contains partial Bouma graded beds and thin interbeds of sandstone and mudstone (sandstone and mudstone thickness – 0.03-0.08 m). The thick graded bed appears as a block, and it is amalgamated with the overlying interbeds. Unit V displays a 6 m thick, mud-dominated, argillaceous interval with thin fine sandstone layers (0.03-0.08 m) and some pebbles. Overlying this, a 2.2 m thin and thick-bedded classical turbidites (sandstone thickness – 0.03-1 m, mudstone thickness – 0.03-0.05 m), and a 7 m thick, sand-rich rotated unit of fine-to-medium grained sandstone interbeds with some micro faults (sandstone thickness – 0.1-0.3 m) form unit VI. The uppermost part, unit VII, comprises 10.4 m turbidites of 0.05 to 0.15 m graded partial Bouma sandstone beds with 0.03 to 0.08 m mudstone interbeds.

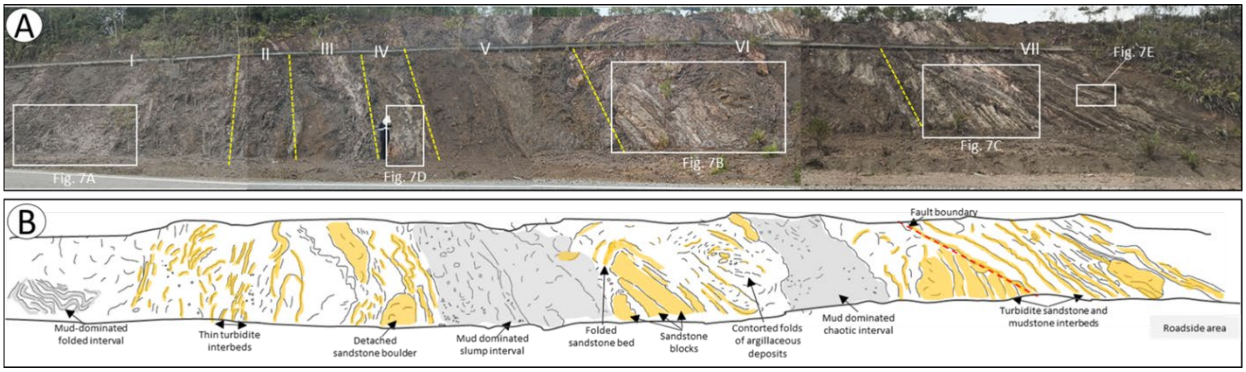


Figure 4. Photomosaic of outcrop #3 displays a combination of sand-rich and mud-rich chaotic slump units and turbidite intervals, with some presence of thick sandstone beds. A) This massive outcrop has been divided into seven (7) sub-units as shown, and the lateral extent of this outcrop is approximately 50 m. B) Some details of the deformed structures are indicated in the line drawings

SSDS: The extensive outcrop 3 is characterized by chaotic deformed intervals and heterolithic turbidite sequences and marked with the presence of some thick sandstone blocks. Figure 4B displays the line drawings of the SSDS found in outcrop 3. The bottom part of the outcrop displays a mud-dominated slump folds unit (Figure 7A). This unit may be previously deposited as thinly bedded turbidites but later developed into a synclinal slump. There is also a sand-dominated slump unit that is observed to be mixed with mud-dominated contorted folds on the right side (Figure 7B). Thick sandstone beds are amalgamated and bounded with overturned and chaotic slump of argillaceous Sandstone (Fig 7B). The slump is arenaceous at the bottom but gradually becomes argillaceous and develops as a contorted rotational fold. A major internal fault line is also identified within outcrop 3. In Figure 7C, the notable line is observed to cut across and separate the vertical, thickly bedded sandstones from the slightly tilted and slumped sandstone beds.

Other distinctive structures identified within the slump intervals include a boulder of sandstone. In Figure 7D, 1 m thick sandstone boulder is amalgamated with turbidite beds. The boulder is located near the sand-dominated slump unit and is seen to be surrounded by some slump remains.

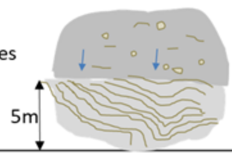
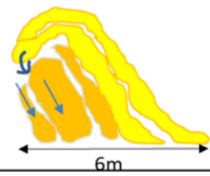
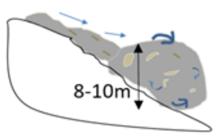
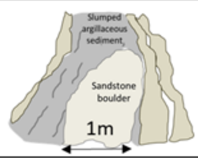
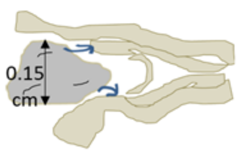
Another SSDS found is a unique soft-sediment structure introduced by Byun *et al.* (2019) as the envelope structure []. In outcrop 3, a fine-grained, rounded sandstone clast (0.15 m diameter) is embedded in mudstone and covered between thin layers of Sandstone (Figure 7E).

The sedimentological logs in Figure 5 summarize the main features documented at the three outcrops described above.

4. Discussion

Based on the detailed facies analysis described above, five (5) different types of SSDS were identified at the outcrops in Siburan. These are i) Mud-dominated slump structures with sand-stone interbeds; ii) Folded and overturned sandstone beds; iii) Contorted mudstone beds; iv) Broken sandstone boulder, and v) Envelope structure. Table 1 summarizes the analysis of the soft-sediment deformation structures. A detailed description follows.

Table 1. Summary of SSDS analysed in three (3) outcrops of Pedawan Formation in Siburan

SSDS and associated structures	Deformational Processes	Triggering Agents
1) Mud-dominated slumped structures with sandstone interbeds. 	**Post-depositional dewatering or compaction** due to rapid depositing overlying sediments (Olabode, 2016; Moretti & Sabato, 2007) cause the interbeds to be deformed into folds. Outcrop: 2 & 3	Rapid deposition
2) Folded and overturned sandstone beds 	**Sliding** and sedimentary **dragging** in liquefied state. Sufficient drag force exerted on the grains causes them to move and drag the overlying beds - folded and overturned (Valente et al., 2014). Outcrop: 1 & 3	Earthquake
3) Contorted argillaceous mudstone beds 	The soft mudstone interbeds were collapsed and transported in a turbidity flow. The plastic layers in the head part of unlithified slumped body is folded and distorted by the **rotational movement of turbidity current** (Byun et al. 2019). Outcrop: 1 & 3	Earthquake
4) Sandstone boulder 	Might be a **rock fall**, which was transported and deposited over the soft sediment (slump). The sandstone body is **preserved in the unlithified slump** area. Outcrop: 3	Earthquake
5) Incomplete envelope structure 	The downslope moving sandstone clast exerted **bulldozer-like effect** on the fine-grained sandstone and mudstone layers (Stow et al., 1986). An incomplete envelope structure is formed - sandstone clast (0.15 m in diameter) is embedded in between the interbeds. Outcrop: 3	Overloading

4.1. Mud dominated slump structures with sandstone interbeds

Mud-dominated deformed structures with sandstone interbed were documented at outcrops 1 (Figure 6A) and 3 (Figure 7A).

Prior to the development of the slump, the mud-dominated turbidites might have been deposited by the suspension fall-out mechanism and were well interbedded [18]. While they are still unconsolidated, the mud particles in these intervals probably underwent post-depositional dewatering or compaction caused by **rapid deposition** of overlying sediments [4,19]. The strong force from the overlying sediments caused the parallel layers of the interbeds to be deformed into slightly folded structures and distorted the existing stratification in the beds. This process also created parallel shear within the beds since horizontal shear stress was acting in the sediment while it was deformed [1].

4.2. Folded and overturned sandstone beds

Tilted and folded sandstones were recorded at outcrops 1 (Figure 6B) and 3 (Figure 7B). These beds were in a liquefied state during the deformation, and liquefaction can result in the collapse of the grain framework in a bed, which leads to fluidisation [20]. Fluidisation occurred within the beds as there was sufficient drag force exerted on the grains. This process caused the underlying beds to move (slide) and dragged along the overlying sandstone layer. Gradually, the overlying sandstone becomes folded and overturned. At outcrop 1 (Figure 6B), the structure is particularly localized, but it experienced a similar event that involved the dragging of the soft sedimentary layer. The sliding and dragging of the sediment can be triggered by a large-scale event such as an earthquake.

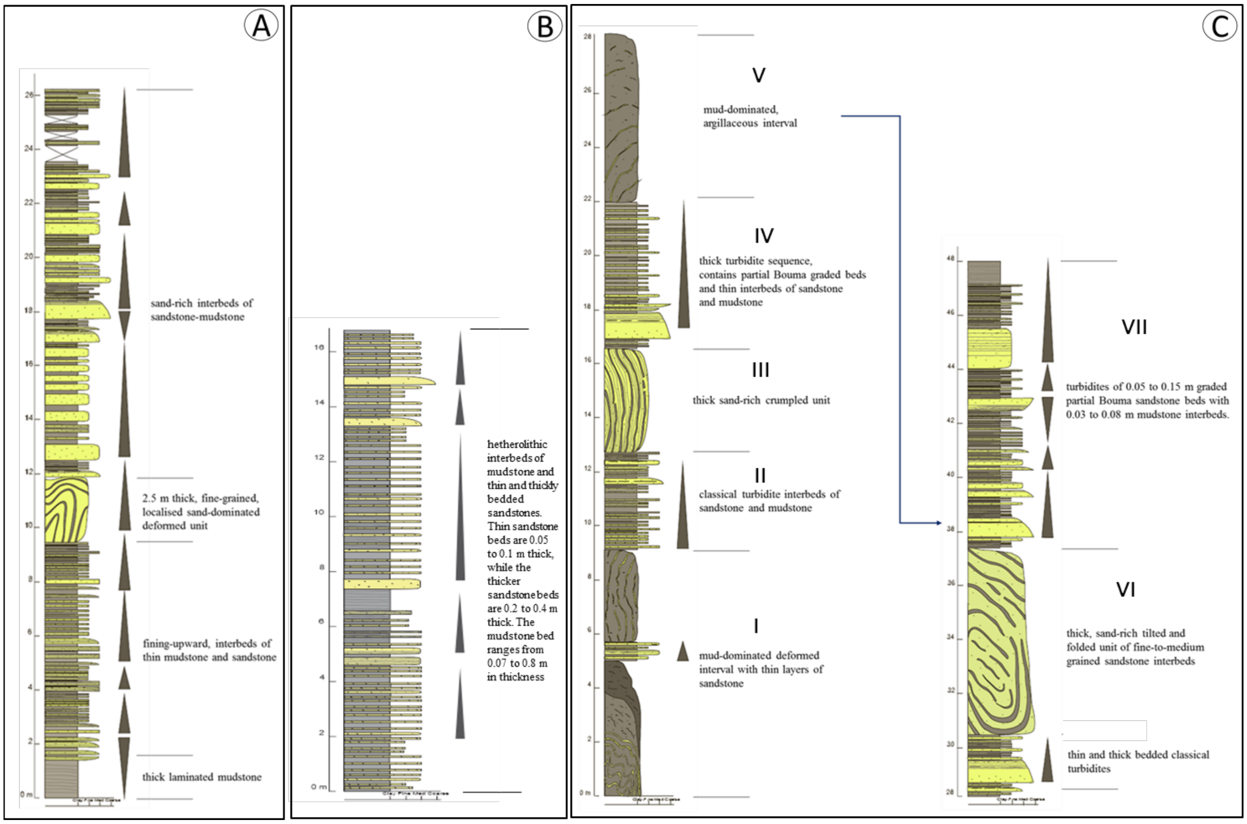


Figure 5. The sedimentological logs of outcrop 1, 2 and 3. A) Outcrop 1 consists of turbidite sequences with thick sandstone beds, and a localised slump unit. B) Outcrop 2 is mainly thinly-bedded turbidite beds, and the overall outcrop displays a synclinal slump structure. C) Outcrop 3 is made up of chaotic slump intervals, alternated with thinly-bedded turbidite beds

4.3. Contorted mudstone beds

The contorted folds on the right side of the deformed Sandstone (Figure 7B) are composed of argillaceous mudstone with several sandstone layers.

The deformation of this part was in a plastic condition. The possible event for this deformation is the collapse of a great mass of mud-dominated interbeds, which can happen due to an **earthquake**. The soft sediment mass is eroded and transported along the slope in a turbidity flow. Based on Byun *et al.*, the plastic layers in the head part of the unlithified slumped body can be easily folded by the rotational movement of turbidity current [10]. The rotational movement of the slump heads eventually led to deformation that distorted the original bedding and preserved the contorted folds.

4.4. Broken sandstone boulder

A 1m thick sandstone boulder is found interbedded with argillaceous slump beds at outcrop 3 (Figure 7D). The large sandstone block could have probably been transported by a high-density flow and deposited over the soft sediment (slump) when the slump was still developing and not fully lithified. Another possible process is a rock fall event, whereby the detached rock boulder was deposited over the unlithified soft sediment. Both high-density flow and rock fall events would have been triggered by a strong force, and especially tectonic events like an **earthquake**.

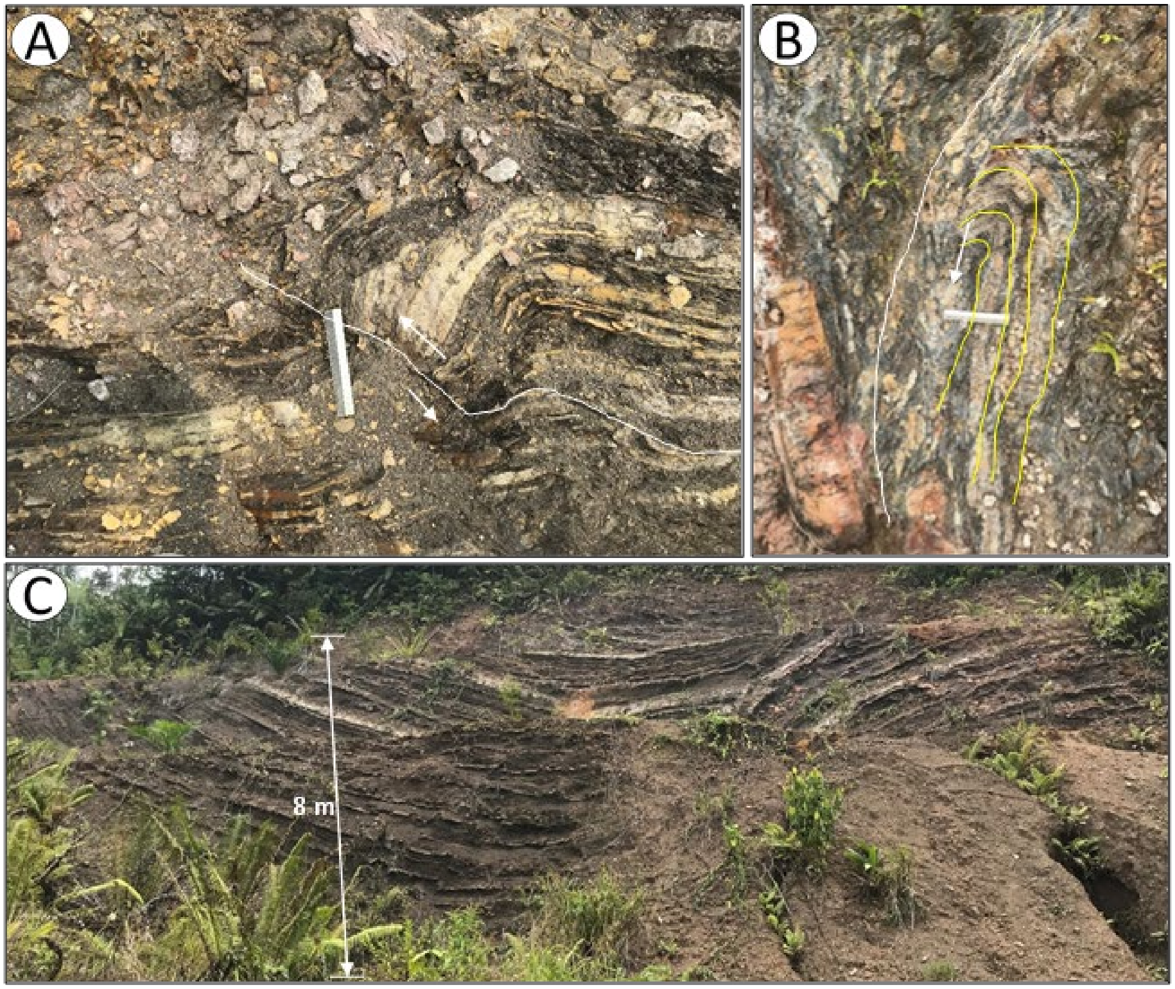


Figure 6. A) 0.2 m thick, wavy and slightly folded interbeds unit is found outcrop 1. This structure is the result of parallel shear that occurred in the bedding. B) Minor overturned fold structure is created due to the deformation of the argillaceous layers in outcrop 1. C) The whole outcrop 2 displays slightly slumped syncline structure (in outcrop scale)

4.5. Envelope Structure

The envelope structure SSDS is composed of coarse-grained sediment that encloses finer-grained sediment and is said to form an envelope-like structure (Figure 7E). Stow *et al.* stated that in the downslope region, compression is common with thrusting and bulldozing of basin-floor sediments [21]. In the particular section of outcrop 3 (Figure 7E), the downslope moving non-cohesive sandstone clast might have exerted a bulldozer-like effect on the fine-grained, cohesive sandstone and mudstone layers [10]. The bulldozing effect resulted from the **over-loading** of denser sediment over a water-saturated, less dense substrate [1,19]. In liquidized state, the denser sandstone clast was able to sink within the less dense thin interbeds due to unstable density gradient [1]. This event preserved the envelope structure of fine-grained sandstone clast (0.15 m in diameter) being embedded in between interbeds of fine-grained sandstone and mudstone.

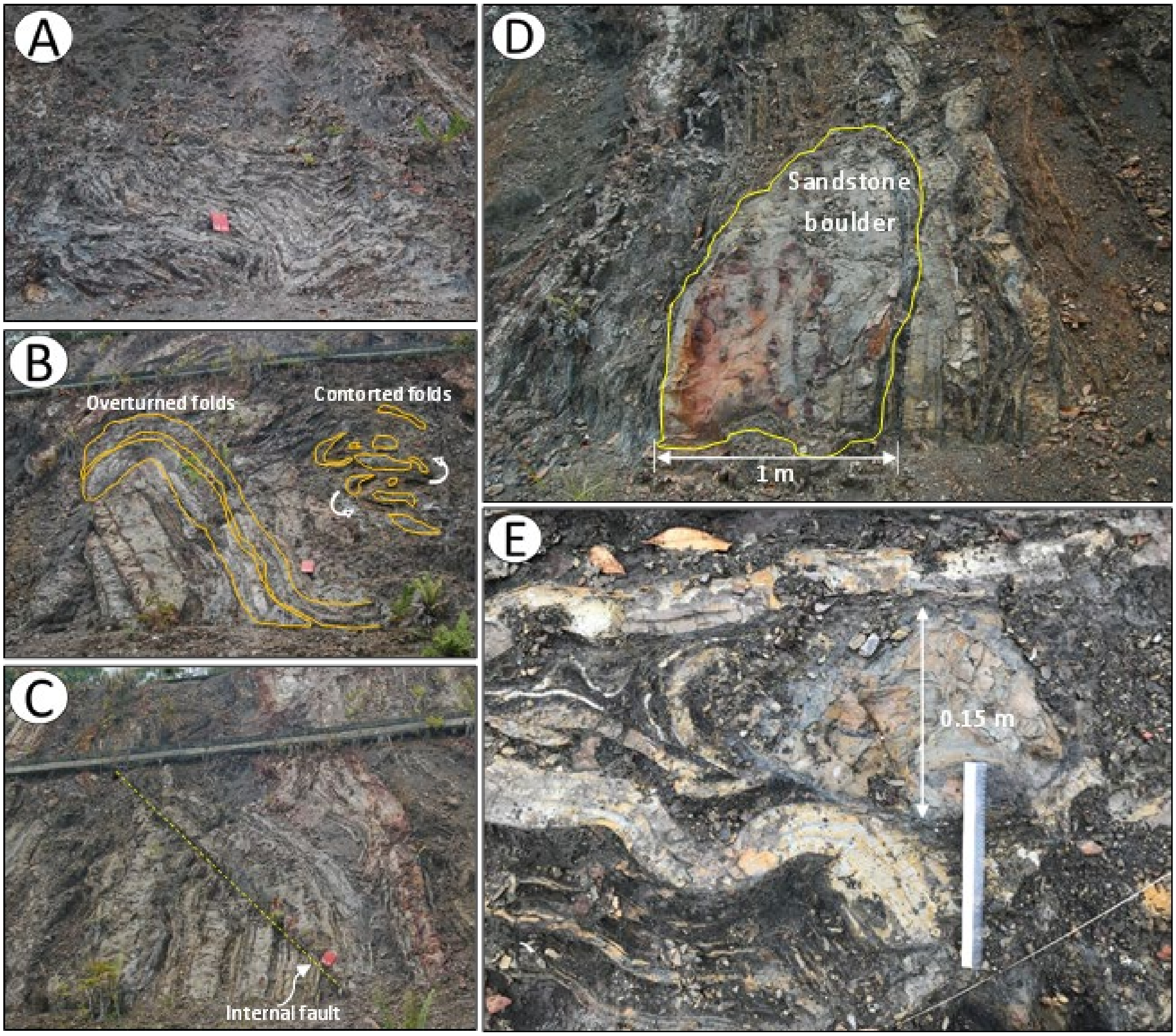


Figure 7. Various slump units at outcrop 3. A) Mud-dominated slumped intervals is identified at the basal part of the outcrop. B) Thick sandstone beds are bounded by overturned folds and contorted mudstone deposits. C) The cross-cutting relationship between the vertical bedding of thick sandstone and the deformed and tilted, muddy sandstone interbeds is created by the internal fault. D) A 1 m thick, detached sandstone boulder is found amalgamated near the slump unit, and it is believed to be transported by the high density turbidity current or fallen from a nearby source. E) A sandstone clast is embedded between mud and thinner sandstone layers which formed an incomplete envelope structure

4.6. Triggering factors

The outcrops of the Pedawan Formation in the Siburan area are composed of thinly-bedded turbidites with thin-to–medium bedded sandstone interbeds, and these indicate that the possible depositional setting would be the marginal or distal fan lobe area. A faulting event in the distal lobe area is often mentioned as a possible cause for slumping [22]. Sudden external force, like an earthquake, creates instability to the deposited beds and initiates the faulting and deformation events [9]. Since they are not fully lithified, the sandstone and mudstone beds become disturbed.

In the deep marine environment, the SSDS are formed mostly due to seismic or seismic-induced processes such as tsunamis [20]. Even though SSDS are common in the tectonically active region (like fore arc basins and back-arc basins), they can also develop in the levees of submarine fan channels [20].

Slump structures are well known to be developed with the presence of steep slopes. However, the three (3) outcrops in Siburan are mud-dominated, which indicates that the deformation might have occurred in the area further from the slope – like a gentler slope region. Thus, the deformation processes of the slumps are possibly seismically induced.

A faulting event occurring at a greater depth can still generate earthquakes that disturb the sedimentary surface layers. The effect of shockwaves from the earthquakes causes changes in the pore-water pressure that lead to the hydroplastic deformation, either slightly or in a chaotic manner [20]. According to Moretti *et al.*, the presence of slumps and slides in a flat area is usually related to palaeoseismicity [19]. The SSDS in the study area, thus, might be the outcomes related to the reconstruction of slump and slide morphologies through liquefaction and lateral spreading of irregularities of the water-sediment interface [19].

For small-scale mechanisms like liquefaction, the triggering mechanism is rapid sedimentation or overloading [19]. The fast deposition of sediment induces an increase in interstitial water pressure in the underlying laminae and disrupts the stable grain arrangement [19,21]. The grain arrangement becomes closer and creates excess pore fluid, which escapes due to excess fluid pressure [19,21]. Fluidization is a result of the upward movement of fluid that supports the grain, and it mostly occurs when there is liquefaction [21]. Fluidization takes place during the dewatering of a liquefied sedimentary layer, which causes the layer to move and develop SSDS. Both mechanism eventually results in irregular deformation of the underlying sediments.

5. Conclusion

Facies analysis conducted at the three (3) outcrops of Pedawan Formation along the Jambusan-Semadang road has resulted in the identification of five (5) types of SSDS. They are 1).mud-dominated slumped structure, 2) folded and overturned sandstone beds, 3) contorted argillaceous mudstone beds, 4) sandstone boulder, and 5) envelope structure. The SSDS is mainly developed through the liquefaction and fluidization of soft sediment.

The triggering factor for the deformation of sediment in this study can range on a small or large scale. The small deformation and localized slump are products of rapid deposition and/or overloading, while the larger-scale deformation results from the instability created by seismic shocks like an earthquake.

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