Sedimentary architecture and depositional environment of Kudat Formation, Sabah, Malaysia

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Abstract. Kudat Formation originated from deep marine environment. Three lithofacies association of deep marine turbidity channel was discovered in three Members of the Kudat Formation in Kudat Peninsula, Sabah, Malaysia. Turbidite and deep marine architecture elements was described based on detailed sedimentological studies. Four architecture elements were identified based on each facies association and their lithology properties and character: inner external levee that was formed by turbidity flows spill out from their confinement of channel belt; Lobes sheet that was formed during downslope debris flows associated with levee; Channel fill which sediments deposited from high to low density currents with different value of sediment concentration; and overbank terrace which was formed by rapid suspension sedimentation. The depositional environment of Kudat Formation is shelf to deep marine fan.

Keywords: turbidite system, deep marine, facies association, architectural elements, Kudat Formation, Sabah

1. Introduction
Turbidite sediments in deep marine environment are common in most part of the world (e.g. Gulf of Mexico, Mississippi Fan, etc.). Turbidite deposits are form by density currents composed of water and suspended sediments. Documentation and study of sedimentation processes and deposition that occur in deep water turbidites are important due to prolific hosts for oil and gas resource [1]. In deep marine deposition study geoscientist often use seismic data, but due to deep water complexity of deposition seismic data alone are mostly insufficient. The outcrops study is required to identify the architectural elements, which control the reservoir or source rock physical and geochemical properties. During the last decade many authors had worked on detailed sedimentological architectural elements, e.g., [2-16]. In terms of hydrocarbon exploration and field development study, Kudat Peninsula is located Northwest Sabah (Figure 1) near to offshore oil and gas fields and became noteworthy. This area also had some natural oil seepages occurrence [17].
This paper attempts to explain the sedimentological characteristics and facies architecture which represent the key elements for the identification of depositional environment of Kudat Formation which is located near to the oil and gas production field.

2. Geological Setting

Sabah region is tectonically active and complex. The region is surrounded by three seas (South China Sea, Celebs Sea, Sulu Sea) and is affected by tectonic activity of these seas [18]. The study area is located in the Northwest part of Sabah (Figure 2). Field work was carried out to study the rock formation of the Sikuati Member in which the oil seepage was found in Kampung Minyak. Kudat Formation and Crocker Formation covered almost entirely the North part of Sabah. The Kudat Formation age between Lower to Middle Miocene and It has three members: Tajau, Sikuati and Gomantong [19]. Tongkul [20, 21] interpreted during Middle Eocene to Middle Oligocene a basin was formed in the area due to south-eastward subduction of the South China Sea under the western part of the Celebes Sea. The Kudat Formation was deposited in central part of this basin as deep to shallow marine deposition.

![Figure 1](image_url): A) The location map of study area (Kudat Peninsula). B) Stratigraphic framework of Kudat Formation [18, 22, 23].

The Kudat Formation can be divided into three lithological units: the first one is lower sandy unit that consist of sandstone and mudstone with the sandstone predominating. Middle Muddy Unit comprises
sandstone and mudstone with the mudstone dominance and the third one is upper sandy unit include sandstone and mudstone [24]. The lower sandy unit was deposited in the northern part of the Kudat Peninsula and coincides with the Tajau Member. The middle muddy unit which is known as the Sikuati Member covered the middle part of Kudat Peninsula where Kampung Minyak is located. The last unit occurred in the southern part of Kudat Peninsula and coincides with Gomantong Member [19].

3. Methods
Forty-eight outcrops were investigated from the North to South part of Kudat Peninsula and stratigraphic sections of Kudat Formation were logged and described (Figure 2). Sedimentary units are defined collectively by physical and biogenic properties, lithology, texture and sedimentary structures. Logging of the lithology and sedimentology properties were used to provide vertical and lateral variation in texture (grain size, sorting and roundedness), lithological, physical and biogenic sedimentary structures, fossil content, bed thickness, and nature of bedding contact. The vertical logging was used as the basis for the interpretation of facies distributions, geometries and depositional environments at scales from the individual architectural element to the complete slope–turbidite and debris systems. The lithofacies transition patterns were used to interpret the paleoenvironment of deposition following the method of Pemberton and Mayll [4, 25]. In addition, there is a difficulty to find proper outcrop in terms of size due to high vegetation density in Malaysia.

Figure 2: General Geology of the Kudat Peninsula (Modified from Tongkul, 2006)

4. Facies Association and Depositional Environment Interpretations
The Kudat formation in total was subdivided into three members. The Lower Sandy Member including one facies association, the Middle Muddy Member consists three facies association and the last member, The Upper Sandy is subdivided into two facies association.

4.1. The Lower Sandy Member (Tajau)
This member located at northern part of Kudat Peninsula and its strata is about ~ 409 m along ~ 54.2 Km2. In the field work investigation strata of the Lower Sandy Member Nine Outcrops (Figure 3) were
measured in detail and one associated facies (LSFA1) were identified (Figure 4). Field based lithological description analysis was used to characterize each facies (Table 1).

4.1.1. LSFA1: Thick and medium bedded sandstone and mudstone (LSFA1)
Description: This facies association includes five facies and comprises interbedded different sandstone facies (A, B, C and E) and mudstone (D) (Figure 4). Bed sets of facies association range from ~10 cm to ~ 5 m thick. Bed bases are commonly flat to undulating contacts with shallow scours up.
Facies A generally is observed at the base of strata and includes three sections and comprises thin and medium bedded pebbly sandstone. The sections consist of aggregation of pebbles (AP), two or three sets of sandstone and siltstone laminations (SL) and non-aggregation pebbly sandstone (NAP) (Figure 5A). The pebbles roundness ranges from angular to sub-angular and their size ranges between 2 to 6 mm. Bed sets of facies range from <80 cm to ~ 190 cm thick. Bed bases are flat to erosional with very shallow scours. Sandstones beds are generally light grey in colour.
In some beds the structures are commonly deformed and showed dewatering structures such as dish structures in non-aggregation pebbly sandstone (Figure 5B). In some outcrops at the base of pebbly sandstone, even rare the coal pebble and mud drops are present. In one outcrop hummocky cross like in different scale occurred in pebbly sandstone (Figure 5C). Other common sedimentary structures in this facies are convolute structure (Figure 5D) and loading. Facies B and C commonly over lied on pebbly sandstone (facies A). Facies B (iron trace sandstone) consists non-continue iron trace lamination of coarse to medium size sand. The thickness of beds ranges between 80 to 200 cm. Beds based are commonly erosional with shallow scours. Sandstone are generally light grey, and the sands are rounded and well sorted. Weathering structures such as honeycomb are abundant in this facies (Figure 5E), especially near to the coast.

![Figure 3](image)

**Figure 3:** Outcrops location of the Lower Sandy Member

Lamination sandstone (facies C) comprises very coarse to coarse sandstone units of undulated to straight laminations. This facies syndepositionally deformed and consist dewatering structures. The thickness of planner lamination varies between 1 to ~ 7 cm.
**Table 1: Facies description of Lower Sandy Member**

| Name                          | Description                                                                                                                                                                                                 |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Pebbly sand (Facies A)        | Including three sections and comprises thin and medium bedded pebbly sandstone. The sections consist of aggregation of pebbles (AP), two or three sets of sandstone and siltstone laminations (SL) and non-aggregation pebbly sandstone (NAP) |
| Iron trace sandstone (Facies B)| Consisting non-continue iron trace lamination of coarse to medium size sand.                                                                                                                                   |
| Lamination sandstone (Facies C)| Comprising very coarse to coarse sandstone units of undulated to straight laminations. This facies syndepositionally deformed and consists dewatering structures.                                               |
| Mudstone (Facies D)           | Mudstone beds including carbonaceous laminations and thickness of beds range from 10 to 28 cm. This facies.                                                                                                    |
| Structureless sandstone (Facies E) | Comprising very coarse to coarse graded structureless sandstone. The sands grain are well rounded and well sorted.                                                                                                |

The sand grains are sub rounded to rounded and moderate sorted. The beds based are commonly undulating with shallow scours up and the sandstone beds have a distinctly light grey. In a small number of beds, coal pebbles although uncommon, occurred. In some location a single or few sets of thin overlying small-scale cross sets (Figure 5F) (as single 3-6 cm thick) occurred at the top of lamination sandstone. The present of flame (Figure 5G) and load structures are most common in strata of this facies. In one outcrop the hummocky cross like and convolute structure are presented. In one outcrop the hummocky cross like and convolute structure are present in this facies. In some outcrops some stone balls (Figure 5H) or their trace are presented and showed that they influenced the flow directions. These stone balls are generally present in sandstones facies and their size range from 5 cm to 70 cm. Generally, the mudstone bedding (facies D) is overlain abruptly the facies B, C and E. Its thickness ranges from 10 to 28 cm. This facies includes carbonaceous laminations. The planner stratified structures are commonly syndepositionally deformed and faulted. At the top of strata the structureless sandstone (facies E) was deposited.
Figure 4: A) Sediment log of the Lower Sandy Member of the Kudat Formation. B) Part of facies strata of the Lower Sandy Member

These sandstones comprised very coarse to coarse graded structureless sandstone. The sands grains are well rounded and well sorted. This facies beds are being up to 1-5 m thick. The sandstone beds are light grey to white in colour. Beds based are commonly flat. This facies in some outcrop is absent. In addition, the order of facies in some location changed and one or two facies may be absent.

Interpretation: This facies association is interpreted as deposition of concentrated density flows with erosional ability, such as high density sand-rich currents [26]. The present of convolute and flame structure which indicated as soft sediment deformation, shows the high deposition rates. The occurrence of dewatering structures in this facies also indicates that rapid deposition of sand and a short recurrence interval between depositional events [7, 27] Mud drop (mud clasts) in facies association particularly
Figure 5. A) The Pebbly sandstone consist of three section which are aggregation of pebbles (AP), two or three sets of sandstone and siltstone laminations (SL) and non-aggregation pebbly (NAP) sandstone. B) Dish structures (shown by arrows) in non-aggregation pebbly sandstone. C) Hummocky cross like in different scale in pebbly sandstone. D) Convolute structure (shown by arrows) in pebbly sandstone. E) Honeycomb (weathering structures) in Iron trace sandstone. F) Small-scale cross sets (shown by arrows) in facies C. G) Flame structure (shown by arrows) in facies C. H) Stone balls in different scale are presented in the Lower Sandy Member. These stone balls generally were arranged in a line along strike direction.

were formed by high density currents that erosion the previously deposited and after deformed the mud clasts, deposited in new sediments bed [7, 28-31]. Planner lamination form during high sediment-fallout and/or near-bed sediment concentration and generally the flows are fast and the sediment concentration is high [32]. The thin small scale cross-stratified which overlying indicated as deposition from lower energy current such as dilute tail part of flows [33].
The load structure form when dens sediments deposited over less-denser sediments which is liquefied and create Rayleigh-Taylor instability. The presence of these dewatering and loading structures in sediments beds interpreted as rapid deposition and a short recurrence interval between depositional events. Dewatering structure indicated, insufficient time for the underlying bed to dewater before deposition of the overlying bed [7, 27]. The occurrence of hummocky cross-like also indicates this facies association deposited by density flow (frictional) not tempestites currents. Hummocky cross-stratification commonly formed in tempestites but small scale of hummocky that named hummocky cross-like [34] indicated to form in frictional flows [35]. In addition the occurrence of thick structureless sandstone at the top of strata also consistent with other evidence this facies association formed by long duration frictional flows [26, 36]. The present of dewatering structure also support this interpretation [26, 36, 37].

4.2. The Middle Muddy Member (Sikuati)
The Sikuati Member crops out in central part of Kudat peninsula. Most of data discussed here were collected from the 26 outcrops along main road and coast line (Figure 6). Total ~142 Meter in the area of ~66.4 km² was measured in detail. The Sikuati Member of Kudat Formation was subdivided into nine facies (Table 2) and three facies association, with several to tens of meters thick of sediments according to their sedimentary properties. Thin- and medium-beded sandstone and mudstone (MMFA1), fine sandstone commonly with planar-laminated carbonaceous and siltstone (MMFA2) and fine to coarse-grained thick basal, overlain by a thinner succession fine-grained sandstone bedding with shale or mudstone (MMFA3). In conjunction with the broad lithologic tract, the facies could be described by stacking arrangement and geometry of the beds (two-dimensional), grain size, internal stratification structure and architecture, sandstone richness, degree of amalgamation and thickness.

![Figure 6: Outcrops location of the Middle Muddy Member](image)

4.2.1. MMFA1: Thin- and medium-beded sandstone and mudstone
Description: This facies association includes three facies (Figure 7) A, B and C, beginning with thin- and medium-beded sandstone and mudstone (in some outcrops bedded with shale) (Facies A). The bed sets of facies association range from <10 cm to ~60 cm thick. The base of this facies consists of beds that are commonly flat and mostly sharp, but undulating contacts with shallow scour sedimentary structure.
Table 2: Facies description of Middle Muddy Member

| Name | Description |
|------|-------------|
| Thin and medium bedded sandstone and mudstone (Facies A) | Thin and medium bedded sandstone and mudstone. Bed sets of facies association range from <10 cm to ~ 160 cm thick. |
| Cross-bedding Sandstone (Facies B) | Comprising only a single set of cross-bedding at the top of beds that over lain on the planar-laminated carbonaceous and mudstone. |
| Structureless sandstone (facies C) | Fine to very-fine structureless sandstone |
| Planar-laminated sandstone (facies D) | Fine sandstone commonly with planar-laminated carbonaceous and siltstone. The planar-stratified structures are commonly syndepositionally deformed and faulted. |
| Shale (Facies E) | In some outcrops strata, vegetation took place from shale beds. |
| White coarse sandstone (Facies F) | Comprising white and coarser sandstone and in his facies the beds become thinner. |
| Fine to coarse-grained sandstone (facies G) | Thick fine to coarse-grained sandstone |
| Thin sandstone and mudstone bedding (Facies H) | Comprising thin fine-grained sandstone bedding with shale or mud |
| Mud drop sandstone (Facies I) | Sandstone beds comprised mud drop structures (even rare). Mud rip up structures are up to several centimeters long |
Sandstones are generally dark grey to light grey in colour, with several intervals up to several meters thick are conspicuously white stained. Slumps deposits (Figure 8A) are common in this facies association. Some sandstone beds (Facies B) typically comprise only a single set of cross-bedding at the top of beds. This cross-bedding overlain gradationally on planar-laminated carbonaceous and mudstone. Both planar- and cross-stratified structures are commonly deformed. Diffusely planar laminated units cap virtually most of the sandstone beds, and consist of dark carbonaceous siltstone (Figure 8B) (red colour was also observed). The thickness of planar laminated varies not only between beds, but also laterally within a single bed. The thickness of the bed varies from < 1 cm to ~ 5 cm. The third facies, facies C, is typically structure-less fine to very-fine sandstone. Thicker intervals of this facies association from few meters to tens of meters and are easily identified in the field. Although rare, some trace fossil in white sandstone have been observed at the base of some strata (Figure 8C1 & C2).

Interpretation: This facies association is characteristic of the turbidite deposition in deep marine. The shallow basal scours of the succession suggest that flow was less concentrated and/or had less energetic turbulence.

The abrupt change from the structure-less sandstone at the base of some beds to the parallel lamination and cross-bedding analogous interpret as Bouma division A, B and C in the classical turbidite [10]. In such case, as the flow continued to decelerate, parallel lamination and a thin layer of small-scale cross-stratification suggests that the flow carries lower sediment concentration and deposits it from lower energy of dilute tail part of the flows [33]. The mudstone beds also analogous to Bouma division D.

**Figure 7:** A) Sediment log of the Middle Muddy Member FA1 of the Kudat Formation. B) Part of facies strata of the Lower Sandy Member FA1.
Figure 8: A) Slump feature is common in FA1. B) Planar carbonaceous lamina (shown by arrows) C1) Trace fossils (shown by arrows) in white and structureless sandstone in FA1. C2) Trace fossil (shown by arrows) in strata of FA1

This facies association is interpreted as the classic thick bedded turbidite that include 10 to 60 cm thick sandstone similar to Bouma division. The presence of slumps within stratified blocks support this interpretation. The slumps suggested the MMFA1 is formed in continental slopes and submarine canyon heads. Slumps formed due to failure of semi-consolidated sediment mass and hydroplastic deformation could occur in most part of the sedimentary system [7, 29, 38].

4.2.2. MMFA2: Fine sandstone with planar-laminated carbonaceous siltstone
Description: The second facies association consist of three facies (Figure 9) comprising fine sandstone (Facies D) commonly with planar-laminated carbonaceous siltstone. The planar-stratified structures are commonly syndepositionally deformed and faulted. The beds are typically ~0.50 to 3 m thick and form bed-sets up to ~45 m thick. The sandstone beds are grey in colour. The bases of the sets are commonly erosional with shallow scours up (Figure 10A) to 3 to 15 cm deep and the bed contacts are typically clear and are easily demarcated.

Small number of beds contain coal pebble (Figure 10B) and bioturbation. Red-brown coloured cement, are also common in a small number of beds. Centimetre-scale dewatering structures are abundant locally (Figure 10D). The cross–bedding are common at the top of sandstone beds (Figure 10C) and distorted cross beds may indicate dewatering or soft- sediment deformation. Mudstone clasts (Figure 10D) vary from absent to abundant and in some cases, make up about 5% to 10% of the total volume in some beds. Mudstone clasts (mud rip up or chaotic mud) vary from small round clasts of several centimetres in diameter to elongated clasts up to ~10 cm thick and occur mostly near and at the bottom of the bed. These mud clasts were originated from upstream due to erosion of previously deposited and are commonly sheared and highly plastically deformed. They indicated shearing within the flow which was sufficient to deform them. In some outcrops strata, vegetation took the place of the shale beds (Facies E), between the sandstone beds. In one of the outcrops at the top of the strata the sandstone grain size became coarser (Facies F), white colour and the beds became thinner (~0.10 – 0.9 m).
Figure 9: A) Sediment log of the Middle Muddy Member FA2 of the Kudat Formation. B) Part of facies strata of the Lower Sandy Member FA2

Interpretation: The MMFA2 is interpreted as deposits of hyper-concentrated flows with erosional ability, such as high-density sand-rich currents. The parallel lamination indicated deep bottom hyper-concentrated flows and traction currents [26, 36]. The cross-stratification part of MMFA2 has similar characteristics to the MMFA1, and this is reflected in a similar interpretation. The occurrence of dewatering structures, deformed parallel and cross stratification in strata of MMFA2 indicates that rapid deposition of sand and a short recurrence interval between depositional events [7, 27] and an insufficient time for the underlying bed to dewater before deposition of the overlying bed. The presence of scours characterized as MMFA2 were deposited from fast-flowing energetic concentrated density flows also centimetres deep scours indicated downward energetic sweeping eddies formed shallower scours [26]. Mudstone clasts in MMFA2 particularly common in the thicker beds and were sourced from erosion of previously deposited. The high-density sand-rich currents deformed and sheared the mud clasts in deposition process [7, 28-31].

4.2.3. MMFA3: Fine to coarse-grained thick basal, overlain by a thinner succession fine-grained sandstone bedding with shale or mudstone

Description: This association include four facies and is made up of a thick basal part (~0.5 to1.5 m) (Figure 11), comprising fine to coarse-grained sandstone (Facies G), overlain abruptly by a thinner succession comprising fine-grained sandstone bedding with shale or mudstone (Facies H) with common
Figure 10. A) Erosional surface with shallow scours up (shown by arrows) of bed base in FA2 B) Coal pebble (shown by arrows) in strata C) Cross stratification (shown by arrows) at top of some beds D) Mud clasts (shown by arrows) in the base of strata FA2

traction sedimentary structures and the beds are ~0.10 to 0.7 m thick. Bed bases are commonly undulating contacts with shallow scours up. The sandstone beds (both, thick and thin) have a distinctly dark grey to grey colour. These beds comprise a unit of planar-laminated carbonaceous and siltstone. The thickness of planar laminated varies between beds and may vary from < 1 cm to ~ 5 cm. The climbing cross-stratified (Figure 12A) sandstone were observed in some beds overlaid by planar laminated carbonaceous, and commonly occurs as single 5-10 cm thick sets. The cross and planar stratified both are commonly syndepositionally dewatering and deformed. At the base of some sandstone beds, mud drop structures (Facies I) (even rare) are present locally. Mud rip up structures are up to several centimetres long. In a small number of beds coal pebble and loading structures (Figure 12B) although uncommon, occurred.

At the top of strata in two outcrops the thick massive sandstones (Facies D) have been observed interbedded by thin shale beds (~0.1 to 0.2 m). These sandstone beds are being up to about 1-3 m thick and comprised coarse graded structure-less sandstone.

Interpretation: The shallow scours along bed contacts has similar characteristics as strata in FA1, and this is reflected in a similar depositional interpretation.

The planar lamination is interpreted, to be the result of high sediment-fallout and/or near-bed sediment concentration and the flows were faster and/or the sediment concentration high [32]. The thin overlying small-scale cross-stratified indicate deposition of new sediment sourced from the low energy, dilute tail part of flows and flow speeds in the dilute tail part of the current are maintained for periods of time. (analogous to the Bouma Tc division [33]).

The present of dewater and load structures are most common in strata of this facies association. Dewater structures are formed by escaping pore fluids when a significantly high pores water pressure gradient exists. This gradient can be achieved by rapid loading of loosely packed, water-saturated sediment [7] that in turn can create Rayleigh-Taylor instability at the sediment interface, resulting in load structures. The presence of these dewatering and loading structures in sandstone beds characterized rapid deposition of sand and a short recurrence interval between depositional events and an insufficient time for the underlying bed to dewater before deposition of the overlying bed [7, 27].
Figure 11: A) Sediment log of the Middle Muddy Member FA3 of the Kudat Formation. B) Part of facies strata of the Lower Sandy Member FA3

Figure 12: A) Climbing cross stratification in FA3 (shown by arrows). B) Uncommon load structure in some strata of FA3
Mudstone clasts are also common in strata of this facies association. These clasts along bottom part of bed has similar characteristics as FA2. Massive beds are thought to have been deposited from the base of the flow by gradual although rapid aggradation [7].

4.3. The Upper Sandy Member (Gomontong)
The Upper Sandy Member crops out in Southern part of Kudat peninsula. All data were collected from the 13 outcrops along main road and coast line (Figure 13). Total ~500 meter in the area of ~ 81 km2 was measured in detail. Field work strata of the Upper Sandy Member investigation identified two associated facies. Each facies and lithology have been study in detail and lithological description, thin section analysis was used to characterize each facies (Table 3).

![Figure 13: A) Outcrops location of the Upper Sandy Member](image)

4.3.1. USFA1: The upper sandy fine to very fine grain sandstone
Description: The facies association include three facies (Figure 14) and is made up of a facies A, that comprising fine to very fine grain sandstone with undulated carbonaceous laminations. The sandstone beds thickness range from 0.2 to 1.70 m and bed base are undulating with shallow scours up. The undulated carbonaceous laminations thickness varies between beds and also laterally along a single bed and ranges from 2 to 50 mm (Figure 15A). In most of beds some coal pebbles have been observed (Figure 15B). Sandstone beds are dark grey. This facies generally interbedded with mudstone beds which mudstone thickness are 10-25 cm and syndepositionally deformed and faulted. This facies overlain abruptly by structureless sandstone, facies B. This facies comprised fine to medium graded structureless sandstone (in one outcrops, coarse graded sands also have been observed). These sandstone beds are being up to about 0.80-7.70 m thick. This sandstone beds are light grey to dark grey and beds based are commonly flat with no or shallow scours up. At the top of strata, coarse grain sandstone with straight to undulated carbonaceous laminations (Facies C) over lay facie A and B. Facies C consists of medium grain sandstone with straight to undulated carbonaceous laminations. The beds based are commonly undulating. The sand grains are sub rounded to rounded and moderate sorted and the sandstone are distinctly light grey in this facies. The planner lamination thickness ranges from 2 to ~5 cm. The sandstone beds thickness ranges from 0.7 to 1.6 m and interbedded with shale or same facies.
Interpretation: This facies association like the only facies association of Lower Sandy Member interpreted as deposition of concentrated density flows. All sedimentary structure consistent with this interpretation.
Mud drop (mud clasts) in facies association particularly were formed by high density currents that erosion the previously deposited and after deformed the mud clasts, deposited in new sediments bed [7, 28-31]. In addition the planner and undulating lamination in this facies generally formed during high velocity and/or high sediment concentration flows [32].

Table 3: Facies description of Upper Sandy Member

| Name                              | Description                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------|
| Fine to very fine grain sandstone (Facies A) | Fine to very fine grain sandstone with undulated carbonaceous laminations. |
| Fine to medium graded structureless sandstone (Facies B) | Comprising fine to medium graded structureless sandstone. |
| Coarse lamination sandstone (Facies C) | Consisting of medium grain sandstone with straight to undulated carbonaceous laminations. The beds based are commonly undulating. |
| Thin bedded sandstone and mudstone (Facies D) | Comprising thin bedded sandstone and mudstone, which mudstone is dominated. Sandstones are generally structureless. |

4.3.2. USFA2: The upper sandy thin bedded sandstone and mudstone

Description: The second facies association consist two facies. It comprises thin bedded sandstone and mudstone, facies D and in some location facies A (Figure 16). Facies D comprises thin bedded sandstone and mudstone, which mudstone is dominated. Bed sets of facies range from <5 cm to ~ 15 cm thick. Bed bases are commonly undulating to moderately flat. Sand grains of sandstone are fine to very fine in size. Sandstones are generally structureless and light grey to white in colour. This facies is mainly same as facies A in FA1 in Sikuati Member. Thicker interval of this facies is easily identified in the field. Some sandstone beds (facies A) typically comprise fine to very fine grain sandstone with undulated carbonaceous laminations.

Interpretation: This facies association is characteristic of the turbidite (hyperpycnal turbidites) deposition such as FA1 in Sikuati Member. The shallow basal scours of the succession suggest that flows were less concentrated and/or had less energetic turbulence.

The abrupt change from the structureless sandstone at the base of some beds to the parallel lamination and cross-bedding analogous interpret as Bouma division A, B and C in classical turbidite [10]. The flow continued to decelerate parallel lamination and a thin layer of small-scale cross-stratification, that suggested the flow have had lower sediment concentration and deposited from lower energy, dilute tail part of flows [33]. The mud beds also analogous to Bouma division D.
Figure 14. A) Sediment log of the Upper Sandy Member FA1 of Kudat Formation B) Part of facies strata of Upper Sandy Member FA1

Figure 15. A) Carbonaceous laminations in USFA1 is Undulated and showed varies thickness B) Carbonaceous laminations and Coal pebbles in USFA1 (shown by arrows)
This facies association interpreted as the classic thick bedded turbidite that include 10 to 100 cm thick sandstone and tend to be composed of Bouma’s division.

As a final point the presence of slumps with stratified blocks support this interpretation. The occurrence of slumps suggested the FA1 is formed in continental slopes and submarine canyon heads. Slumps formed due to failure of semi-consolidated sediment mass and hydro plastic deformation and it occurred in most part of the sedimentary system. [7, 29, 38].

Figure 16. A) Sediment log of the Upper Sandy Member FA2 of Kudat Formation B) Part of facies strata of Upper Sandy Member FA2

5. Architectural Elements
To characterize architecture elements and litho-stratigraphic framework, detailed sedimentary facies association, depositional architecture and environment context were identified.

In this study area six architectural elements were characterized: channel fill, inner external levee, lobes sheet, overbank terrace

5.1. LSFA1: Channel Fill
The association of irregular, pebbly sandstone, iron trace and lamination sandstone and mudstone, structure-less sandstone in FA1, is interpreted as channel fill (Table 4).
Channel comprised of shallow erosional base filled with pebbly sandstone that representing deposition from low-density currents. The occurrence of mud clast at the base of some beds shows initial fill eroded from the channel bottoms and sides. The presents of lamination sandstone with small scale cross bedding in channel fill also indicated the sediment deposited by low density current approximately at distal part of channel complex [39-41]. In contrast the present of structure-less sandstone shows this facies formed from high density current with high sediment concentration [39-41] and also it indicated the velocity and density of flows were fluctuated. The considerable thickness of structure-less sandstone in some outcrops (up to 5 m) representing these beds deposited by long lived and generally steady flows. Masalimova and his colleagues [41] argue that if no obvious fining upward trends characterized in the sediments beds is because of limited range of grain size.

Table 4: Sedimentary facies and element architecture of LSFA1

| Facies Association | Facies | Lithology | Primary structures | Ichnofacies | Architecture Elements |
|--------------------|--------|-----------|--------------------|-------------|-----------------------|
| Thick and medium bedded sandstone and mudstone (LSFA1) | A      | Thin and medium bedded pebbly sandstone | Laminated carbonaceous coal pebble, mud clasts, dewatering structures, cross-bedding, flame and convolute structure | Non | Channel fill: Sediments deposited from high to low density currents with different value of sediment concentration in channel |
|                   | B      | Iron trace sandstone | Laminated carbonaceous | Non | Non |
|                   | C      | Lamination sandstone | Laminated carbonaceous coal pebble, hummocky like, dewatering structures, cross–bedding, flame and convolute structure | Non | Non |
|                   | D      | Mudstone structureless sandstone | Laminated carbonaceous | Non | Non |

5.2. MMFA1: Inner External Levee

The architectural element A is characterized by regular interval of thin bedded sandstone and shale and/or mudstone in FA1, and interpreted as inner external levee. This element is formed when distal overbank turbidity flows spill out from their confinement of channel belt. The deposition take place outside channel belts and basically has significant lateral bed thickness variation and deformation [42]. The deformation of AEA at inner external levee, architecturally characterized as a result of slumping directed to the channel belt. The thicker sandstone beds (>40 cm) are characterized as crevasse splays when flows cut the levee and deposit sand. In the external levee, thin beds are deposited perpendicular to the channel belt deposition. Further the slope gradient is steeper into the channel belt than the slope dis away from channel. The inner external levees located between outer portion of external and internal levees and they are normally formed during regressive time [42-44] (Table 5).

5.3. MMFA2: Lobes Sheet

The architectural element B is characterized by consisting of interbedded fine massive thick sandstone (up to 3m), it interbedding with shale and it is characteristic of lobes deposition. The individual lobe is showing more tabular or sheet like than lensoid and/or lobate particularly in the large lobes and mature channel system [7].
Table 5: Sedimentary facies and element architecture of MMFA1

| Facies Association | Facies | Lithology | Primary structures | Ichnofacies | Architecture Elements |
|--------------------|--------|-----------|--------------------|-------------|-----------------------|
| Thin- and medium- | A      | Several meters thick, dark grey to light grey sandstone. | Laminated carbonaceous | Non         | Inner external levee: Distal overbank turbidity flows spill out from their confinement of channel belt |
| bedded sandstone and mudstone (MMFA1) | B      | Sandstone with cross-bedding over planar lamination carbonaceous | Cross-bedding and planar-laminated carbonaceous | Non         |                     |
| C                  | Structure-less fine to very-fine sandstone |                     | Trace fossil |             |                     |

This element formed in lob complex, as downslope sandy hyper-concentrated flows develop lob like features. Massive sandstones are inferred to have been deposited by rapid sedimentation from high-density currents. Shallow and broad dishes dewatering structures indicated as result of fast deposition rate and effective weight of the overlying sediments and also fluidization process [7]. This element deposited in fully mature channel system is feeding stacked of lobe complexes associated with levees. The shale clasts found at the base of the bed are the result of high energy erosive rip-up of the underlying shale and indicate high energy erosion [7] (Table 6).

Table 6: Sedimentary facies and element architecture of MMFA2

| Facies Association | Facies | Lithology | Primary structures | Ichnofacies | Architecture Elements |
|--------------------|--------|-----------|--------------------|-------------|-----------------------|
| Fine sandstone commonly with planar-laminated carbonaceous and siltstone (MMFA2) | D      | Grey, fine sandstone with planar-laminated carbonaceous | Laminated carbonaceous coal pebble, dewatering structures, cross – bedding, Mudstone clasts | Trace fossil | Lobes sheet: Deposited in fully mature channel system feeding stacked lobe complexes and associated with levees |
| E                  | Siltstone |                     | Laminated carbonaceous, dewatering structures, cross –bedding | Non |                     |
| F                  | White, coarse and thin bedded sandstone |                     |                     | Non |                     |

5.4. MMFA3: Overbank Terrace

The architectural element C is characterized by the association of irregular, thick-bedded sandstones interbedded with thin sandstones and mudstone of FA3, this is typically an overbank terrace where the deposition of sediments is on a gentle gradient margins of the channel belt. The overbank terrace is formed by rapid suspension sedimentation from collapsing sand rich, high density currents or/and by unconfined sandy flow and also off-axis turbidity currents. This deposition is common on low stand trend and in low and middle stage of channel complex sets [45-47]. In FA3 the occasional of thin sandstone and mudstone beds intervals suggests that the sediments are coming from suspension during low energetic flow. On the other hand, the thick sandstone beds are
interpreted to be coming from higher energy currents or/and unconfined flows resulting in transporting greater material and thicker sandstone beds (Table 7).

5.5. USFA1: Channel Fill
The association of irregular, pebbly sandstone, iron trace and lamination sandstone and mudstone, structure-less sandstone in FA1, is interpreted as channel fill (Table 8). Channel comprised of shallow erosional base filled with pebbly sandstone that representing deposition from low-density currents. The occurrence of mud clast at the base of some beds shows initial fill eroded from the channel bottoms and sides.

The presents of lamination sandstone with small scale cross bedding in channel fill also indicated the sediment deposited by low density current approximately at distal part of channel complex [39-41]. In contrast the present of structure-less sandstone shows this facies formed from high density current with high sediment concentration [39-41] and also it indicated the velocity and density of flows were fluctuated. The considerable thickness of structure-less sandstone in some outcrops (up to 5 m) representing these beds deposited by long lived and generally steady flows.

That was argued if no obvious fining upward trends characterized in the sediments beds is because of limited range of grain size [41].

| Facies Association | Facies | Lithology | Primary structures | Ichnofacies | Architecture Elements |
|--------------------|--------|-----------|--------------------|-------------|-----------------------|
| Fine to coarse-grained thick basal, overlain by a thinner succession fine-grained sandstone bedding with shale or mud (MMFA3) | FG | Fine to coarse-grained sandstone | Planar-laminated carbonaceous and siltstone, climbing cross-stratified, coal pebble and loading structures | Non | Overbank terrace: Forms by rapid suspension sedimentation from collapsing sand rich, high density currents or/and by unconfined sandy turbidity flow |
| FH | Fine-grained sandstone bedding with shale or mud | Planar-laminated carbonaceous and siltstone, climbing cross-stratified, coal pebble | Non |
| FI | Sandstone beds with mud drop structures | Mud drop | Non |
| FD | Thick massive sandstones interbedded by thin shale beds | Non |

5.6. USFA2: Lob Complex
The intervals of two facies association of Upper Sandy Member interpreted as lob complex (Table 9). This lob complex consists of very fine grain sandstone with undulated carbonaceous laminations, fine to medium graded structureless sandstone, medium grain sandstone with straight to undulated carbonaceous laminations and thin bedded sandstone and mudstone, which mudstone is dominated.
In terms of rapid collapsing high density current (turbidite) in distal lob the structureless sandstone were deposited. In proximal lobes deposits generally, dune like structure is observed in contrast of distal lobes which planner lamination and or thin cross lamination structure is dominated. During high density currents, when the flows were steady the dune like and bed load transport occurred. Further downslope, when current decline and flow collapse accelerated, structureless beds formed [7, 39-41]. Masalimova [41] argue that coarser structureless sands form by high suspended-sediment fallout in more proximal lobe.

Table 8: Sedimentary facies and element architecture of USFA1

| Facies Association | Facies | Lithology | Primary structures | Ichnofacies | Architecture Elements |
|--------------------|-------|-----------|--------------------|-------------|-----------------------|
| FA1: The Upper Sandy fine to very fine grain sandstone (USFA1) | A | Fine to very fine grain sandstone | carbonaceous laminated coal pebble | Non | ArC: Channel fill: Sediments deposited from high to low density currents with different value of sediment concentration in channel |
| | B | Fine to medium graded structureless sandstone | Non | | |
| | C | Coarse lamination sandstone | undulated carbonaceous laminations | Non | |

Table 9: Sedimentary facies and element architecture of USFA

| Facies Association | Facies | Lithology | Primary structures | Ichnofacies | Architecture Elements |
|--------------------|-------|-----------|--------------------|-------------|-----------------------|
| The Upper Sandy thin bedded sandstone and mudstone (USFA2) | D | Fine to coarse-grained sandstone | Planar-laminated carbonaceous and siltstone, climbing cross-stratified, coal pebble and loading structures | Non | Overbank terrace: Forms by rapid suspension sedimentation from collapsing sand rich, high density currents or/and by unconfined sandy turbidity flow |
| | A | Fine-grained sandstone bedding with shale or mud | Planar-laminated carbonaceous and siltstone, climbing cross-stratified, coal pebble | Non | |

6. Discussion and Depositional Environment

During Miocene the region which include the area of this study is undergoing complex tectonic activity (both extensional and compressional stresses) [48] and the presence of mélange deposition in Kudat Peninsula is evidence of this complexity [21, 22, 49, 50]. Besides that, this tectonic activity can be caused of gravity flow, slumping, and other turbulent currents.
It is demonstrated that the Kudat Formation was deposited in Lower Miocene intimately with the Crocker Formation in shallow to deep marine environment [18, 22, 50]. Tongkul [21] believed the Crocker and Kudat Formation are both formed in deep marine environment. However, the Kudat Formation also shows shallow marine properties evidence, and he suggested this formation was deposited in shelf slope. Cronin [9] demonstrates that deep water canyon system has three different characteristic geographic regions and stages, those are erosional area, erosional and depositional area and depositional area in order through shelf slope to sea floor. On the other hand, it suggested that in general the channels form in three phases: erosion and bypass, channel-fill and over-bank deposits, and abandonment. The initial phase makes a typical channel U shape by erosion and bypass processes. In the next phase, due to decreasing in transport energy the channel-fill and over-banks deposits. At the base of the channel in this phase the poorly sorted pebbly sandstones and mudstones are deposited and most of the sandy material continues to by-pass this depression towards the sea basin. With decreasing energy, the sand is deposited within the channel and latter with continued in decreasing energy the suspension sediments are deposited. The last phase occurs when numerous turbidities with suspension of fine-grained sand and mud are dominated [13]. It was argued that this phase can follow Cronin [9] stages where the first phase is characterized by erosional stage, and basal erosion of old sediments. The following phased shows a mixed erosion and deposition stage. During these processes of channel development, the slumping may occur in this stage. The last phase is characterized by deposition with transition between sand and silts followed by mud deposition [13]. A shelf to deep marine turbidite and hyper-concentrated flow depositional system is best described of the depositional scenario for the Sikuati Member. These sediments are interpreted to be formed during the second phase of channel evolution system and mostly deposited in erosion and deposition area of Cronin model. The presence of slumping and hyper-concentrated sediments indicate deposition occurred in the second stage [9, 13].

7. Conclusion
Lithofacies and sedimentary structures have provided useful data for interpret the depositional environments and modelling of the three members of Kudat Formation. The Lower Sandy Member including one facies association (LSFA1) that including five facies. The USMFA1 is thick and medium bedded sandstone and mudstone that interpreted as channel fill deposition. The Lower to Middle Miocene Middle Muddy Member consists of nine sedimentary facies which can be grouped into three facies association: MMFA1 is characterized by thin- and medium-bedded sandstone and mudstone that was deposited as the inner external levee. MMFA2 is typically fine sandstone with planar-laminated carbonaceous siltstone that can be interpreted as lobes sheet. MMFA3 indicated fine to coarse-grained thick sandstone overlain by a thin fine-grained sandstone bedding with shale or mudstone and this association is identified as overbank terrace. The Upper Sandy Member is divided into two facies association with four facies. The UPFA1 is characterized as fine to very fine grain sandstone that interpreted as channel fill. Sediments deposited from high to low density currents with different value of sediment concentration in the channel. The USFA2 including thin bedded sandstone and mudstone and characterized as over bank trace which forms by rapid suspension sedimentation from collapsing sand rich, high density currents or/and by unconfined sandy turbidity flow. In conclusion the Kudat Formation was deposited in shelf to deep marine environment as channel system and fan turbidite depositional system.
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