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FACIES AND SANDSTONE CHARACTERISTICS OF THE KUDAT FORMATION, SABAH, MALAYSIA

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ABSTRACT

The Kudat Formation, formed the major rock unit of Kudat Peninsula in the northern tip of Borneo Island, is made up of interbedded sandstone and mudstone with fossiliferous limestone lenses. Lithostratigraphically, it is divided into Tajau Member and Sikuati Member. The Tajau Member differs from the Sikuati Member by the thicker coarsening upward sequence and the presence of limestone lenses. Field mapping and petrographic analysis were utilized to study the facies and sandstone characteristics. The formation as a potential reservoir is largely dependent on the original sandstone composition, which was influenced by deposition in a shallow marine setting and local sourcing activity. The succession of the sequence is composed of a major shoreface deposits during the late Early Miocene. The measured sections are predominantly composed of interbedded sandstone and mudstone usually show sedimentary structures which are indicative of wave and tidal processes, such as swaley, hummocky, trough and planar cross stratifications. The sequence grades up-section into facies packages of increasing tidal energy and terminate with the deposition within the upper regime shoreline settings. The selected Tajau sandstones in this study are texturally and mineralogically mature quartz arenites with good sorting. However, the presence of unstable lithic grains and feldspars during diagenetic processes contributed to the reduction of porosity, giving irregular porosity, due to deformation by compaction, and susceptibility to chemical alteration of labile minerals. Reservoir quality was also influenced by the subsequent diagenesis of the sandstones, which was driven by increase overburden pressure and could be culminated by increase temperature during the proceeding depth. Lithic fragments, feldspars and authigenic cements were altered to form diagenetic mineral suites, which tend to occlude porosity; however, dissolution and chemical reactions of some of these grains also enhanced secondary porosity development. Most observed porosity in the sandstone sequence is secondary, developed from dissolution of both carbonate cement and unstable framework grains. Mean porosity suggested a weak decreasing trend with depth of burial. However, detailed examination of several localities revealed that porosity development was strongly influenced by local factors. Thus, sandstones of the Kudat Formation are generally fair reservoir characteristics, due to the presence of unstable framework grains, early carbonate cementation and authigenic/diagenetic mineral suites.

1. INTRODUCTION

This study was conducted at the tip of Borneo, Sabah State of Malaysia (Figure 1). Excellent geological map was established by the Department of Mineral and Geosciences of Malaysia showing the rock units of the area [1]. The Kudat Formation, clastic sequence, is the major rock unit of the area. The purpose of studying the facies and sandstone characteristics is to investigate the rock unit and reservoir properties of changing facies in the early Miocene depositional sequence of the Kudat Formation. Understanding the properties of sandstones is essential in the exploration of hydrocarbon potential from the subsurface sedimentary strata as these properties strongly influenced their reservoir qualities. This rock unit is exposed in the study area and was deposited within sedimentary environments ranging from marginal coastal areas which was affected by waves and tidal processes to shallow submarine region.

2. GEOLOGIC SETTING

The geology of the area is part of the fragmented pre-Tertiary ophiolites and the Tertiary sedimentary sequence of north Sabah (Figure 1). The oldest rock association of Kudat Peninsula is classified as the Chert-Spilite Formation of Early Cretaceous age. The complexly deformed and fragmented pre-Tertiary ophiolites cropped out at the area formed part of the Tertiary tectonic belt from Palawan Island to the Sulu Islands of the Philippines Archipelago curving through Sabah from Kudat Peninsula to Darvel Bay area [2]. This arc borders the deformed sedimentary basins, dominantly Paleogene deep marine clastics, forming the backbone of a large mountain belt extending along west Sabah. The deformed late Eocene to Oligocene sedimentary basins extends northward forming the major sequence of Kudat Peninsula. The late Early Miocene sequence of the area at the northern part of the Peninsula is made up of the Tajau Member and the Sikuati Member of the Kudat Formation.

3. MATERIALS AND METHODS

Facies analysis was undertaken at the study site of Kudat Peninsula, Sabah (Figure 2). Field descriptions containing information regarding sedimentary structures, grain type and size were made for the individual units within the section. This information was used for the interpretation of the separate facies in terms of process and depositional sub-environments. This data collection created an opportunity to create four sedimentary logs from across the section, allowing for the identification of changes in facies and therefore depositional environments through space and time [3]. Rock samples were collected and labeled with code, an arrow indicating the "way up" was marked and nicely packed. Thin sections were prepared by cutting and grinding to a standard of 30 μm thickness. Compositional percentages of sample were based on 200-point modal analysis. Samples were prepared for SEM analysis by removing small freshly fractured rock fragment. Samples were analyzed using a HITACHI 3000S scanning electron microscope (SEM) and all necessary studies were carried out at the laboratory of Universiti Malaysia Sabah. XRD analysis was carried out for clay fraction ≤2 μm by using Phillip X'Pert PRO PW3040/60 Diffractometer (XRD MPD) type [4]. Initial disaggregation was conducted under distilled water in an agate mortar. The sample was then transferred to a suitable beaker together with a dispersing agent to prevent flocculation. Standing the beaker in an ultrasonic bath for 30 min facilitated liberation of the clay component. The 2 μm fraction was removed from suspension by centrifuge and the remaining clay was decanted off and transferred to a glass slide.

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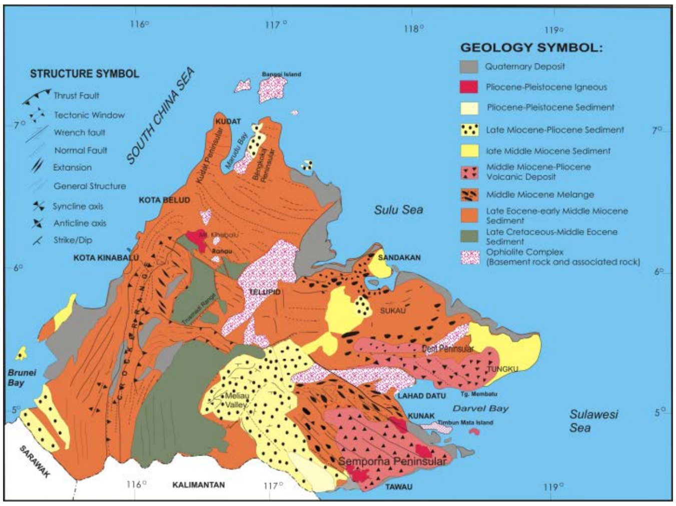
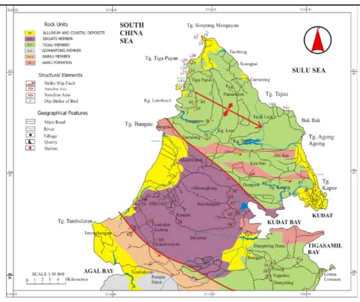


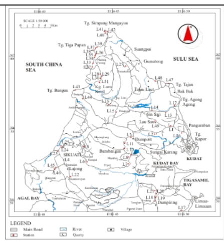
Figure 1: Geological Map of Sabah showing the location of the study area in Kudat.

4. GEOLOGY AND STRATIGRAPHY

The oldest rock unit exposed in the study area is the Early Cretaceous ophiolite sequence which was fragmented into mélange as the Wariu Formation, followed by the Late Eocene Crocker Formation (not exposed in the study area), and the Kudat Formation representing the late Early to early Middle Miocene sequence (Figure 2 and Figure 3). The fragmented ophiolite (Wariu Formation) is mainly exposed along the Kudat Fault Zone, consisting of serpentinite, spilite and chert. The Kudat Formation which is unconformably overlying the Late Eocene Crocker Formation can be divided into two members, namely: the Tajau Member and the Sikuati Member. The Tajau Member is well exposed in Tajau, the northern part of the area while the Sikuati Member occupying the southern part where Sikuati is located. The sandstone is medium to coarse grained with moderately fractured and jointed [5]. This thick sandstone unit is generally good sorting with good porosity and fair permeability. The carbonate facies are rich in benthic as well as planktonic foraminifera and occasionally thinly bedded with calcareous shale. The carbonates are tightly cemented giving low permeability and porosity.



Geological Map of Kudat area



Map showing the sampling stations

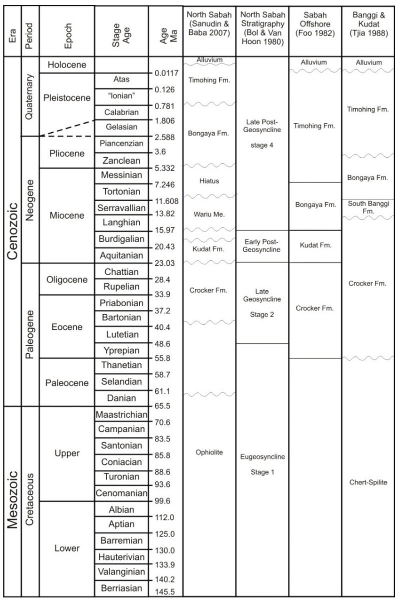


Figure 3: Stratigraphy of Kudat Peninsula

5. FACIES CHARACTERISTICS

The facies are represented by well-sorted, fine to coarse grained sandstone. The coarse sandy deposits are characterized by hummocky cross-stratification and swaley cross stratification. These hummocky and swaley cross-stratified sand beds have the following features:

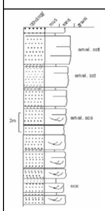
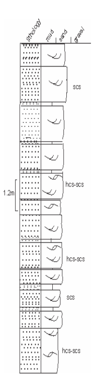
a) Amalgamated and low angle planar cross-stratified coarse-grained sandstone
b) Hummocky-swaley cross-stratified fine to coarse grained sandstone
c) Rare hummocky cross-stratified fine-grained sandstone-siltstone

The above characteristics of the sandstone beds, therefore, are interpreted to have formed within the shore face of a shelf environment [6].

The facies analysis of the rock unit is described as follows (Table 1 and Figure 4):

A. Facies Fs: Planar Cross-Bedded Sandstones
B. Facies Ft: Trough Cross-stratified Sandstones
C. Facies Fhs: Hummocky – Swaley Cross-stratified Sandstones
D. Facies Fsm: Association of Interbedded of Thin Sandstones and Mudstone

Table 1: Facies characteristics of the Kudat Formation

Litholog	Fasies	Characteristics	Interpretation
	Fs	Geometrically, these facies consist of thick planar cross-bedded sandstone generally observed at the eastern part of the area (Figure 4A). Bedding contacts with thin mudstone is commonly sharp and occasional abundant clay pebbles in a random orientation. These facies are gradational with other facies. Physical and biogenic sedimentary structures are typically rare. Planar cross beddings are common with coarse to medium-grained sandstones comprise the uppermost marines and sandstones unit equivalent to foreshore facies succession.	This facies characteristic is commonly associated above eroded surfaces of channelized facies. The existence of planar cross-bedding usually represents seaward-inclined or swash zone deposits. The abundance of organic clay pebbles in this sandstone layer testifies to a high energy storm deposits. Foreshore deposits of Facies Fs represent the highest energy of the shoreline succession.
	Ft	Excellent exposure is occupying the entire tip of Borneo with sandstone thickness more than 2.0m (Figure 4B). Lithologic ally, these facies consists of coarse grained sandstone with occasional pebbly sandstones, yellowish brown to yellowish very coarse-grained sandstones, interbedded with mudstone. Well-sorted sandstone layers with disorganized orientation of pebbles and are intercalated with trough cross-stratified sand package of very coarse-grained sandstone. Most of the finer sandstone strata exhibits lenticular or sheet like geometry in between troughs. Internal sedimentary structures include cross lamination and parallel lamination. In term of sedimentary structures, the lower part is dominated by unidirectional small to large scale ripple. This unit also typically consists of traction-structured deposits with low angle trough cross stratification deformed by soft sediment deformation and sometimes they form cosets up to 2.5m thick with amalgamated packages. The trough cross-stratification is closely related with swaley cross stratification and is typified by predominantly heterolithic lithology, characterized by a combination of a thin to thick-bedded and fine to coarse-grained sandstones.	This Facies is characterized by large trough cross bedding can be interpreted as being formed by series of high energy tidal currents forming migrating sandbar. Swaley cross stratification occurs within these facies is known to occur in the present shore-line complex, especially in the sandy deposit of modern shoreface in the west coast of Sabah. Most of the swaley structures found in these facies are emphasized by amalgamated coarse-grained sandstones. In general, the sandstone dominated lithology with high energy formed sedimentary structures suggests an upper shoreface depositional environment. This depositional environment reflects frequent changes between storm and fair-weather conditions. Therefore, the occurrence of swaley cross-bedding provides an indicator that these facies was formed under conditions of relatively high energy sediment input with active reworking due to occasional storm activities.

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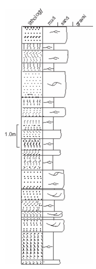
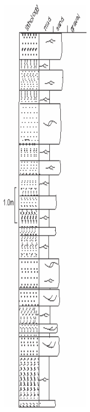
	Fhs	The upper section of this facies is grading towards Facies Ft. Geometrically, bedding pattern exhibits lenticular geometry of mudstone beds either thin sheet or tabular geometry of sandstone beds with erosion base (Figure 4C). Interbedded layers of sandstone and mudstone are in various proportions, where sometime show rythmites or thinly interlayered bedding, lack of sedimentary structures, wavy, flaser to lenticular bedded, and sharp contact with mud layers. Laminated sandstones with gentle discordance are predominant, particularly emphasized by carbonaceous materials and ripple cross-bedding. Facies Fhs hosts an assemblage of sedimentary structures indicative of a lower energy environment consisting of smaller trough and tabular cross-stratification, hummocky cross-stratification, swaley cross-stratification, wave and current ripple bedding. Local association of swaley and hummocky cross-stratifications is common. The lower bounding surface of a hummocky unit is sharp and is commonly an erosional and is overlain by sets of bedding rich in cross-lamination representing the waning stages of storms.	It is suggested that hummocky cross bedding was formed by surges of varied directions of wave current. Overall facies Fhs with sedimentary structures such as hummocky and swaley cross stratification, ripple bedding, and laminated sands indicate higher energy, suggest a middle to lower shoreface depositional environment. The swaley cross stratified sandstone of Facies Fhs form in the settings where the deposition and preservation of mudstone are deduced, which is thought to be part of the middle shoreface. It is estimated that in the middle shoreface, ripple bedding is probably destroyed during new phases of sedimentation since most of the bedding show rare ripple cross-lamination.
	Fsm	These facies represent the lower most sequence in the measured sections with varying thicknesses and is widely distributed throughout the entire southern part of study area classified the Sikuati Member (Figure 4D). It is locally gradational where these facies are underlain by Facies Fhs. It is typified by sandstones-mudstone unit consisting of interbedded of grayish brown clay stones (5 cm to 40 cm), siltstones (5 cm to 30 cm), and rarely exposed grayish shales (1cm to 15cm). The mudstone lithology of this facies is interbedded with thin to thick-bedded sandstone (15 cm to 100cm). The sandstones, clay stones and siltstones intervals of Facies sm are commonly shows wavy bedding exhibiting small scale hummocky cross bedding in the absence of swaley cross bedded. Sandstones are characterized by mature, moderate to well-sorted, medium light grey or medium yellowish or reddish brown, and very fine to fine-grained. The predominant sedimentary structures are current ripple and parallel laminae mostly emphasized by carbonaceous materials and lignite bands, mainly in the sandstone beds. Mud drapes are found in sandstone interbeds which laterally exhibit continuous or discontinuous layers, with varying degree of thickness. Small-scale hummocky and trough cross-stratification can be observed in thin sandstone beds. In several localities, trough and hummocky cross-stratification was emphasized by clay laminae or coal clasts tabulating in sandstones layers, but their distribution is limited.	The interbedded nature of the sandstone and mudstone in Facies sm indicates its deposition took place under fluctuating energy levels, and also reflects alternating conditions from periods of fair weather to storm events as mentioned by previous workers. Mudstone or clay layers on the other hands are deposited during periods of slack water and just before and after the slack water conditions, when there is still a weak current flowing. Thus, the fissile, dark brownish nature of mudstone represents this facies with the slowest deposition within the sedimentation process of the unit. The deepening period of coastal basin during deposition of Facies Fsm resulted in sediments that are more homogeneous and absent of bioturbation at the upper part, where the sediments were mostly deposited below the fair-weather wave base. The presence of flaser, wavy, and lenticular laminations, mud drapes, and convolute bedding with overall coarsening upward suggests a shoaling upward sequence deposited by dominantly distal lower shoreface to inner shelf.

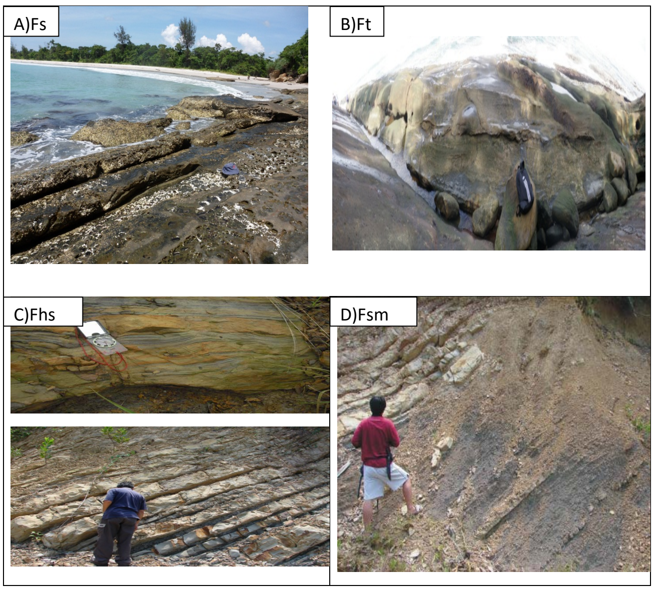


Figure 4: Field outcrops representing facies distribution of the study area; A. Facies Fs: Planar Cross-Bedded Sandstones, B. Facies Ft: Trough Cross-stratified Sandstones, C. Facies Fhs: Hummocky-Swaley Cross-stratified Sandstone and D. Facies Fsm: Association of Interbedded of Thin Sandstones and Mudstone.

5.1 Facies Associations

All measured lithologs represent the successions demonstrate the validity of environmental interpretations of the Neogene sedimentary rocks of the Kudat Peninsula by calibrating those litholog for facies sequences. Deduced from the four facies as analyzed above for the interpretation of depositional environment, two facies association (FA) can be concluded that exhibit a distinctive succession. Based on the dominant facies distribution, facies association has identified two depositional sequences. The two different facies association, namely FA1 (storm and wave-dominated middle shoreface to inner-shelf), and FA2 (wave-dominated upper shoreface and foreshore), each consisting of two facies, briefly described in the following paragraphs.

5.1.1 Facies Association 1 (FA 1): Wave-Dominated Upper Shoreface and Foreshore

Facies Association 1 (LA 1) represents beach depositional system and comprises two discrete, recurring facies, labeled as Facies Fs and Ft. Facies Ft formed the base and gradationally overlain by Facies Fs. This facies association generally displays abundance vertical stacked wave and storm generated sedimentary structures with maximum composite thickness of about 330m or more of coarse-grained sandstones alternating with thinly bedded mudstone. The interbedded unit is underlain by hummocky and some swalley cross stratified fine-grained quartz-rich sandstone, and capped by trough cross stratified sandstones of middle shoreface. It is characterized by recurring and regressive units of repeating coarsening upward sequence (CUS). It is interpreted that this facies association represents a shallowing upward succession deposited by fully storm and wave-dominated sedimentation within upper shoreface to foreshore.

5.1.2 Facies Association 2 (LA 2): Storm and Wave-Dominated Middle Shoreface to Inner-Shelf

This facies association is the combination of Fhs and Fsm showing the transition between lower shoreface and inner shelf. Facies Fhs comprises moderate to highly-bioturbated, interbedded of lenticular mudstones and sheet sandstones, exhibiting some ripple cross lamination, medium to very large-scale trough, hummocky, and rare swaley cross stratification. The main bedding type of the middle to lower shoreface is small to medium scale ripple bedding. Sandstones of Facies Fhs make up a majority of the total sediment represents the middle to lower shoreface environment. This lower shoreface depositional environment was subjected to numerous physico-chemical effects, including a strong wave climate, high sedimentation rates with subsequent loading.

Facies Fsm comprises of interbedded thin sandstones and mudstone with various thickness ratio which is considered as distal marine facies, the most widely distributed. Typically, the Facies Fsm are the lower most facies within these successions. Facies Fsm comprises the lowermost unit of LA 2, and it is consistently and repeatedly overlain by Facies Fhs. Collectively, the physical and biogenic sedimentary structures of Facies Association 2 (LA 2) represent lower shoreface to inner shelf deposits.

5.2 Depositional Model

The depositional history of the Kudat Formation was primarily controlled by the Early Miocene post-tectonic framework and fluctuations in the sediment supply. The facies represent shoreface depositional environment, influenced by fluctuations of high and low flow regimes. Under these circumstances recurring and frequent sediment transport took place during periods of storm accompanied with high sediment input. It was intermittently contrasted by periods of low water agitation reflected by the deposition of thick mud. The examination of distribution, composition, association and thickness of each facies helps to evaluate the mechanism to reconstruct the depositional history. In the late Early Miocene sedimentation process in Kudat area, depositional environments encompassing the foreshore to upper shoreface as Facies Association 1(FA1) and lower shoreface to inner-shelf deposits as Facies Association 2(FA2) (Figure 5).

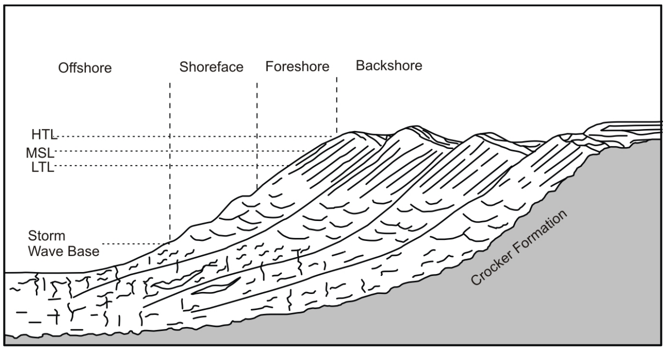


Figure 5: Depositional Model of Kudat Formation (modified from Inden & Moore 1983)

6. SANDSTONE CHARACTERISTICS

Important sandstone characteristics such as porosity, permeability, and diagenetic properties were determined by a combination of depositional and burial effects. It is critical to know the distribution of these properties within a basin to achieve maximum efficiency in reservoir potential for future petroleum exploration potential. For this future potential in the study area, a quantitative work in characterizing and evaluating the reservoir is needed to understand the reservoir characteristics. Besides that, it is also essential to understand the reservoir characteristics and its capacity. The sandstone properties are partly controlled by facies characteristics which in turn are related to depositional processes.

6.1 Sandstone Diagenetic Evidences

The most common diagenetic constituents of the Kudat Formation are quartz, chlorite, calcite, kaolinite and illite. XRD data showed the most common clay types in their diffractograms (Figure. 6). Diagenetic constituents are described in the subsequent sections below.

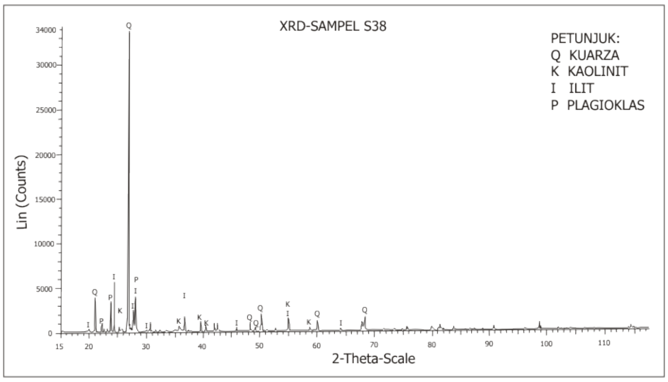


Figure 6: X-ray diffraction analysis shows the different clay types

6.1.1 Silica cement

Silica is generally the most abundant cement in the Tajau sandstone, ranging from 0.5% to 3.5%. Quartz overgrowths consisting of small euhedral crystals are locally developed in primary pores (Figure 7). Microcrystalline (<10 μm) pyramidal quartz overgrowths are also locally developed. Quartz cement is developed in large intergranular pore networks and the pores are often occluded by large quartz overgrowths. Quartz overgrowths enclosed kaolinite and chlorite plates, often interlocking narrow pore throats.

6.1.2 Authigenic chlorite

Chlorite content ranges from 0.5% to 1.5%. Pore-lining chlorites are extensively developed in intergranular networks. It also occurs as rims around detrital grains. Chlorite consists of microcrystalline (<5 μm) plates, aligned in a grain-perpendicular form, occasionally enclosed by quartz overgrowths. Chlorite pore lining fringes are commonly developed upon detrital mixed layer clay substrate. Pore bridging chlorite crystals were also observed in some samples. Chlorite forms very occasionally as replacement of feldspar and lithic grains.

6.1.3 Calcite cement

Calcite occurred as dominant pore occluding cements generally ranges from 0.5% to 7%. In calcite cement dominated samples, pore spaces are completely blocked and porosity–permeability values are quite insignificant. The detrital framework grains appear to float in the calcite cement as poikilotopic in nature (Figure 7). There is also evidence of corrosion by the cementing fluid along the outer margin of the grain.

6.1.4 Authigenic kaolinite

Authigenic kaolinite is locally distributed in primary and secondary voids, limiting (local) connectivity and presenting zones of microporosity (Figure 7). Intergranular pores are locally filled with clusters of vermicular kaolinite, consisting of euhedral, fresh stacks with evidence of illitisation. Blocky habits are also noticed in some samples. In occasional cases, kaolinite phase (partially illitised) locally replaced detrital micaceous mineral.

6.1.5 Authigenic Illite

Authigenic illite cement is developed in most of the samples analyzed (Figure 7). Illite is one of the pore occluding cement generally up to 1.0%. The formation of illite cement in the Tajau sandstone could be to the reaction between K-feldspar and kaolinite in the presence of connate water in the pore spaces at deeper burial. This illitisation process, however, is less responsible for the loss of porosity that affect the sandstone during diagenetic process. Fibrous illite was recorded forming thin lining along pore walls and thin coating around detrital grains.

This sandstone diagenetic study indicates that The Kudat sandstones are characterized by three main stages of authigenic-mineral formation: (i) an early diagenetic-clay coating around detrital grains, (ii) formation of kaolinite at intermediate burial depths, and (iii) growth of pore bridging illite at the final stage of burial.

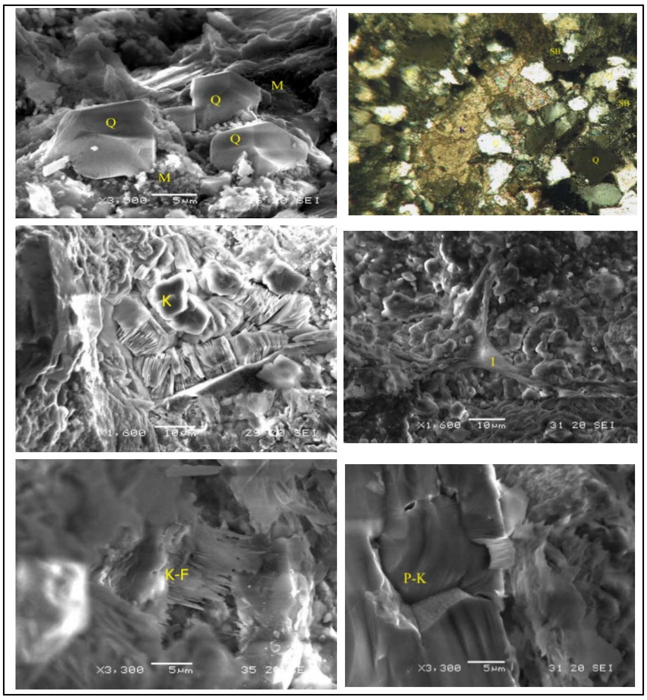


Figure 7: SEM showing cements of quartz(Q) overgrowth, authigenic kaolinite(K), authigenic illite (I) and feldspar (K-F and P-K) and calcite cement.

6.2 Reservoir properties

6.2.1 Porosity

Sandstone porosity in the study area varies from 11% to 13% with an average 12% (Table 3). In case of petrographic analysis, porosity is highest in the well sorted, low matrix environment. Thin section and SEM photomicrographs indicate two pore types are present. These are intergranular and micro pores. Both primary and secondary intergranular pore types are present in most of the samples. In the studied interval, secondary pores are the abundant pore types and are affected by dissolution and formation of authigenic cements.

Secondary intergranular pores are primarily associated with the dissolution of calcite cement and rock fragments. Micro porosity is associated with the presence of authigenic clay minerals. Porosity reduction appears to be depth controlled. Intergranular macro porosity is inversely correlated with cement and authigenic clay. It implies that intergranular macro porosity reduces with increasing cement. With increasing depth, the detrital grain contacts are turned from point to long contact and thus reduce porosity. At greater depths, the volumetric amounts of quartz, calcite and clay cement increases and partially occlude intergranular pore space.

6.2.2 Permeability

Permeability ranges from 4 to 6 mD with an average 5 mD (Table 4). Porosity and horizontal permeability shows very good positive correlation. The general correlation between permeability and porosity indicates that due to compaction and cementation permeability decreases with depth as in the case of porosity. Permeability shows very good inverse correlation with the volume of cement including authigenic clay. Dramatic decrease of permeability also noticed in some samples where the cement volume is very high. Zones with permeability values above the regional trend generally have significant preservation of primary porosity and/or extensive development of secondary porosity. In samples with significant grain and/or cement dissolution, the presence of large, isolated secondary pores give rise to high porosity and somewhat less permeability.

Table 4: Permeability result from the analyzed sandstone

Sample location	Major authigenic cement	Porosity	Permeability
Bak Bak	Kaolinite	16	Good
Bak Bak	Kaolinite	18	Fair
Tg. Mengayau	Kaolinite	20	Good
Tajau	Kaolinite & Illite	18	Fair
Tajau	Kaolinite & Illite	15	Fair
Sikuati	Illite	15	Fair
Sikuati	Illite	10	Fair
Sikuati	Illite	15	Fair

7. DISCUSSION

The Kudat sandstone is represented by well-sorted, fine to coarse grained sandstone deposited in a shoreface environment. The sequence is characterized by hummocky-swaley cross-stratified of a common shoreface deposits and its associate. Early deposited of the facies have largely been affected by the initial phase of physical compaction and this effect progressively accelerated with increasing depth of burial. The grains were squeezed and extruded between rigid sand particles blocking the throats and leaving abundant unconnected pores. The effects of compaction due to overburden pressure were responsible for packing readjustments of the framework grains and ductile deformation. In this study, development of pseudomatrix by crushing of soft lithic grains is a common phenomenon in the Kudat sandstone that may significantly affect the sandstone porosity and permeability, especially where argillaceous clasts are abundant. In few samples, locally developed K-feldspar overgrowths as euhedral crystal on detrital feldspar grains partially stabilize the grain framework and locally arresting grain compaction. The development of secondary porosity as the common diagenetic feature largely depends on the leaching of feldspar as detrital grain and dissolution of calcite as cement suggests the dissolution of stable grains as a mechanism of secondary porosity development. Leaching and dissolution process lead to the formation of kaolinite and quartz overgrowth in the subsequent stages. Quartz overgrowth is one of the important pores occluding cement in the Tajau sandstone. Quartz cement can occur due to intergranular pressure solution derived from grain contacts. The generation of quartz overgrowth cement postdates the kaolinite cement. Kaolinite has been interpreted to be a by-product at the expense of K-feldspar at temperature as a result of the diagenetic advancement. The evidence of transformation of feldspar to kaolinite was also observed in some samples.

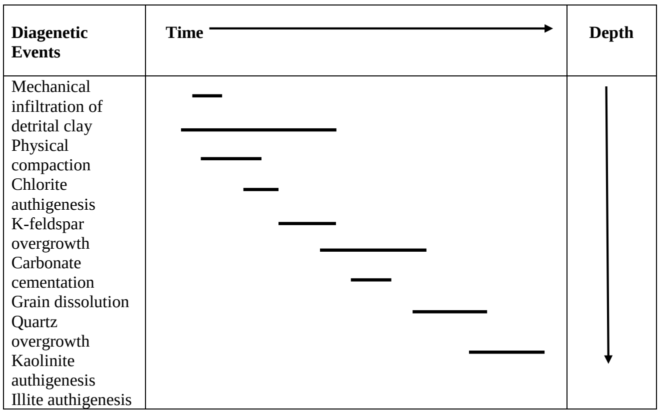


Figure 8: Paragenetic sequence of reservoir sandstone of the Kudat Formation.

The diagenetic phases, as determined from the mutual textural relationship of thin section and SEM examinations are summarized in the Figure 8. Early diagenesis includes clay infiltration, compaction, development of kaolinite and illite followed by feldspar overgrowth, poikilotopic calcite cementation, development of pressure solution.

Reservoir quality is a function of depositional environments and diagenetic processes. Grain size, sorting, grain shape, packing, and mineralogy are controlled by these geological processes. As a result, these rock properties affected the grain-pore relationships and pore–pore throat characteristics. The best quality rocks are characterized by medium to coarse grained grain size, good sorting and massive textures rich in quartz grains.

Diagenesis has significantly controlled the reservoir quality. Compaction, formation of quartz and carbonate cements, development of authigenic clays, dissolution of feldspars and rock fragments are the important processes that affected the porosity and permeability. Grain contact changes from dominantly floating to point and long contact due to progressive burial. In the deeper horizons (reservoir sections), mica and lithic fragments are commonly deformed. Petrographic data indicate that compaction is the important process reducing reservoir quality. Quartz overgrowths cement increases with depth and affected the reservoir porosity and permeability. Quartz overgrowths are important reservoir quality deteriorating mechanism in many deep burial petroleum reservoirs. Quartz cementation is a major cause of porosity loss in many petroleum reservoirs in both moderately to deeply buried sandstone reservoirs [7,8]. Calcite is another cement acts as potential barriers to fluid flow within sand bodies. Locally developed calcite cemented horizons are volumetrically insignificant compared to the reservoir section, the lateral continuity of such horizons is uncertain. However, some samples show calcite cement dissolution to increase the secondary porosity in a later stage. As observed, authigenic kaolinite is also present as pore choking cement and creates permeability barrier. Leaching feldspar and rock fragments increases with depth. In the deeper horizons, almost all the larger pores are the product of leached detrital grains.

8. CONCLUSIONS

The sandy layers of the shoreface environment revealed the grain framework as detrital of the Kudat Sandstones dominated by quartz, feldspar and lithic fragments. Cement component recognized in this study include quartz, kaolinite, calcite, illite and chlorite. Quartz is generally the abundant pore occluding cement in most of the samples. It developed as overgrowth forming small euhedral crystals and locally as large pyramidal crystals in the primary pores. Pressure solution derived from grain contact may be the main contributor of quartz overgrowths. Kaolinite locally developed and accelerated the minor porosity loss due to pore-occlusion. The presence of illite associated with kaolinite flakes either as coatings on detrital grains or surrounds kaolinite flakes on grain surfaces. Illite also observed growing out into pore-filling kaolinite aggregates. Chlorite occurs as pore-lining and pore filling cement. In some cases, chlorite helps to retain porosity by preventing quartz overgrowth. In some samples, pore-occlusion by calcite cement is very much intense.

The initial porosity was decreased by compaction and cementation and then increased by leaching of the feldspar and lithic grains and dissolution of carbonate cement. Reservoir quality was mostly controlled by the pore occluding cements. Porosity, permeability and cement volume exhibit good agreement to each other. Thus, the sandstones of the Kudat Formation are generally fair reservoir potential, due to the long history of diagenetic processes in a deep burial stage.

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