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PETROGRAPHIC INVESTIGATIONS AND RESERVOIR POTENTIAL OF SHALLOW MARINE SANDSTONE: A CASE STUDY FROM NYALAU FORMATION, SARAWAK BASIN, MALAYSIA

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ABSTRACT

Reservoir potential and heterogeneity are critical important factors for exploring shallow marine sandstone reservoirs. Shallow marine sandstones are crucial hydrocarbon bearing reservoirs around the globe and in Southeast Asia. The integrated analysis consisting of petrographic characteristics and reservoir properties for Nyalau Formation from Bintulu area have been discussed in this case study. The field observations, helium porosimetry on core plugs, thin sections study and petrographic approach provides insight into the factors responsible for variations in porosity and permeability in shallow marine sandstone. The results indicate that Nyalau Formation is comprised of five different facies well exposed in Bintulu area, Sarawak basin, Malaysia. The identified facies based on sedimentary structures and lithology are, trough cross-bedded sandstone, laminated sandstone, bioturbated sandstone and massive sandstone facies. It is analyzed that total clay content, grain size, grain shape and grain sorting impact the reservoir in different ways. The trough cross-bedded and massive sandstone facies have low clay content and medium grained, subrounded and well sorted having porosity around 20-25 % and permeability 15-20 millidarcies. The laminated and heterolithic sandstone facies are fine grained, poor to moderately sorted, high clay amount and subangular are comprised of low porosity (8-12 %) and low permeability (0.5-2 millidarcies). The bioturbated sandstone facies is highly disturbed due to burrow activity and having very low porosity (5 %) and low permeability (0.5-1 millidarcies). By integrating these parameters, it is concluded that trough cross bedded and massive sandstone facies have best reservoir quality among all facies of Nyalau Formation.

Keywords: petrography, reservoir potential, sandstone, porosity, permeability, clay content.

1. INTRODUCTION

The reservoir properties and petrographic parameters mainly dependent on depositional setting of any rock. Shallow marine sandstones are build up within the depositional setup which occurs between the landward influence of marine processes and seaward influence of fluvial processes (Wright et al., 1978; Boyd et al., 1992; Reading *et al*., 1996; Harris *et al.*, 2003; Siddiqui *et al.*, 2016). There is a significant amount of hydrocarbons that are explored through shallow marine sandstone deposits (Molenaar *et al.*, 1988; Howell *et al*., 2008). This case study is related to petrography and reservoir potential of shallow marine Nyalau Formation, well exposed in Bintulu area, Sarawak basin, Malaysia. This study involved detailed petrographic investigations and impact of different petrographic parameters on reservoir properties in Nyalau Formation.

The Early Miocene Nyalau Formation is dominated by shallow marine, coastal and intertidal facies. The Nyalau Formation (Early Miocene) is equivalent to its hydrocarbon producing offshore cycles I and II in Sarawak basin (Liechti et al., 1960; Madon *et al.,* 2013; Rahman *et al*., 2014; Iqbal *et al*., 2016). The detailed study related to sedimentology and depositional setting of Nyalau Formation has been carried out by previous scholars, mainly in Bintulu area (Liechti *et al*., 1960; Madon *et al.*, 2007; Jia *et al.*, 2009; Rahman *et al.*, 2014; Siddiqui *et al*., 2015). The previous study was based on traditional field studies on sedimentology and depositional environments in Sarawak region to evaluate the reservoir. Moreover, in previous the reservoir properties are determined through thin sections and mercury injection techniques only. The main objective of this study is to characterize the Nyalau Formation through thin sections analysis, field observations, petrographic analysis and core analysis (helium porosimetry). An attempt has been made to integrate all the findings to identify the best reservoir quality facies of Nyalau Formation. The trough cross bedded sandstone and massive sandstone facies are considered as best facies as compare to laminated sandstone, heterolithic sandstone and bioturbated sandstone facies of Nyalau Formation. By establishing the relationships of petrographic investigations and reservoir quality of all facies, it is found that there is some heterogeneity in Nyalau Formation. After identifying the best quality reservoir facies of Nyalau Formation through this study, an analogous approach can be adopted for its equivalent offshore cycles in subsurface.

2. GEOLOGICAL SETTINGS

The important phenomenon behind tectonic evolution of Northwest Borneo Trough include subduction of the oceanic crust of the proto-South China Sea underneath the Sundaland during Middle Eocene age (Hall *et al.*, 2004; Simons *et al*., 2012). Due to entrance of thin continental crust in the subduction zone, the subduction

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increased during Early Miocene age (Hutchison, 2004; Hutchison, 2005; King *et al*., 2010). The Sarawak Basin is considered as the most important basin in terms of presence of hydrocarbons in complex region of Southeast Asia. There are various models presented by different previous scholars regarding complex evolution of this region (Holloway *et al*., 1982; Lee *et al*., 1995; Hall *et al*., 2004). Bintulu is situated in the NW Sarawak and geologically it is included in the Miri Zone (Figure 1 a & b). This zone is underlined by crustal terrains (Hutchison, 1996). All the area of Bintulu is covered by Nyalau formation (Oligocene-Miocene) and it is extended from the Tatau horst to the Niah River occupying most of the area between the northern margin of the Belaga Formation and the coast. The Nyalau Formation conformably rests on the Buan Formation and unconformably on the Belaga Formation (Liechti *et al.*, 1960). The Nyalau Formation has been deposited in a coastal deltaic environment; The Nyalau Formation is considered as the major transgression over the Eocene land mass. It is a succession of fine grained calcareous often argillaceous sands alternating with all gradation to clay and shales. It is sandy towards west and becomes more muddy eastwards where it is known as the Setap Shales (Liechti et al., 1960).

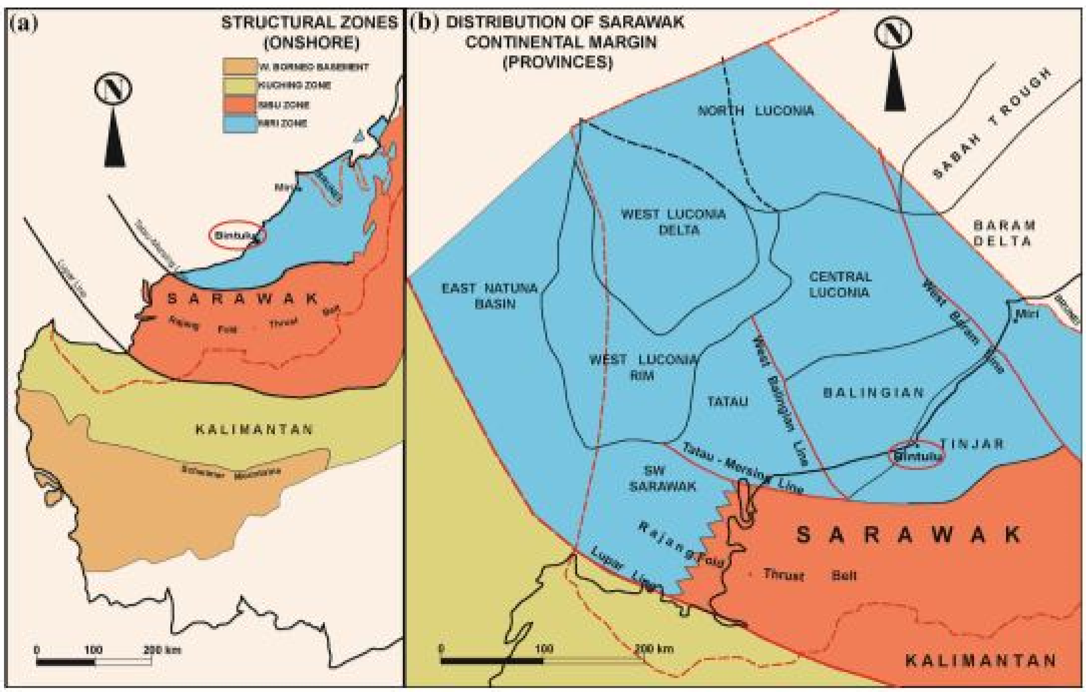

Figure-1. (a) Structural subdivision of Sarawak Basin. (b) Tectonically divided provinces of Sarawak Basin. Small red circle illustrating the study area (modified from (Mazlan et al., 1999; Siddiqui et al., 2016).

The Lower Miocene Nyalau Formation rocks are exposed along the shoreline and coastal areas in Bintulu, Sarawak (Figure-1b). The exposed section around Bintulu town comprises massive sandstones intervals, laminated clays, and brakish-shales and lignite. The hummockey cross-stratified sandstones, flaser wavy to lenticular bedded facies, herringbone cross bedded facies and tabular to low angle cross bedded facies are common facies in the area. These features indicate wave and tidal influence, within a shallow-marine setting (K. M. Leong, 2000). As shown in Figure-2, This formation, and its hydrocarbon-bearing offshore equivalents (Cycles II and III) which belongs to west balingian province which is comprised of a thick succession of Lower Miocene clastic in the Balingian Province of central Sarawak (Madon et al., 2001). It is estimated to be 1000–2000 m thick in the Bintulu area and it consists of coal-bearing mudstones, alternating heterolithic beds, and cross-bedded sandstones (Almond et al., 1990).

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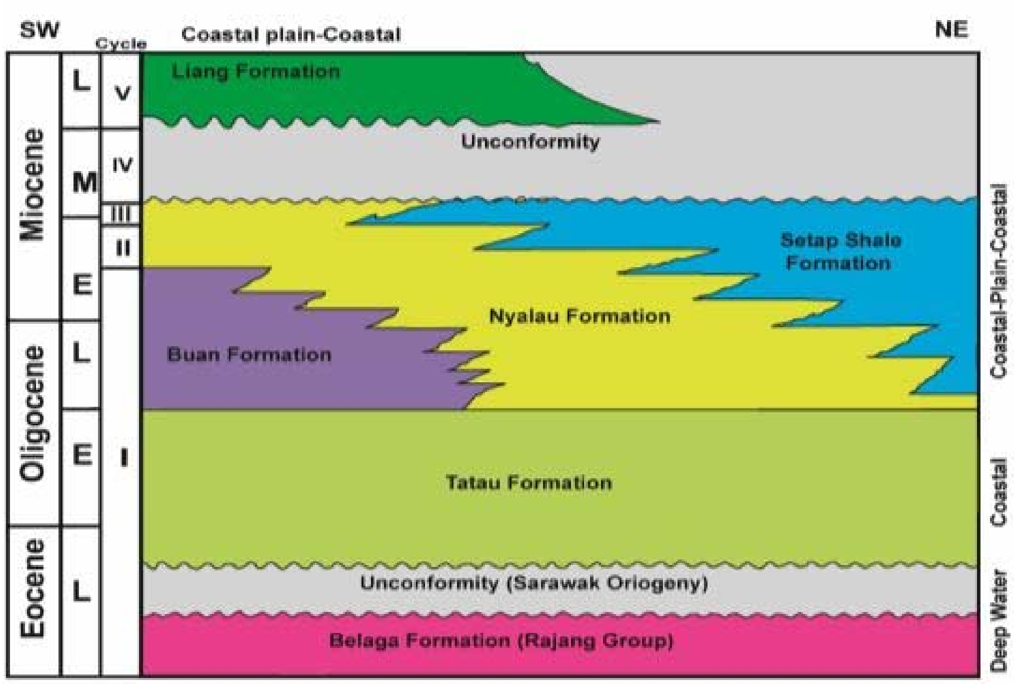

Figure-2. Stratigraphic distribution of different Formations in Sarawak Basin including Nyalau Formation (modified from Hassan *et al*., 2013).

3. MATERIALS AND METHODS

A detailed field work of Bintulu area in Sarawak Basin, Malaysia has been carried out to identify different facies and collect samples from five outcrops of Nyalau Formation. Five different facies have been recognized during field observations and rock samples including core plugs of dimension (1" diameter and 3" length) were plugged through coring machine from outcrop. After collecting samples the laboratory analysis were carried out.

Forty blue dyed, glass covered thin sections were prepared for representative samples of each facies from Core laboratories, Malaysia and Hydrocarbon Development Institute of Petroleum (HDIP), Pakistan. The thin sections were observed under Polarized Microscope in South East Asia Carbonate Research Laboratories, Universiti Teknologi PETRONAS, Malaysia. After getting thin section images through Microscope, 350 point counting was applied to quantify different constituents of sandstone and porosity by using JMicroVision software.

After petrographic observations on thin sections, the porosity and permeability were measured through helium porosimeter instrument from Core Analysis Laboratory, Universiti Teknologi PETRONAS, Malaysia. The helium porosimeter technique was applied on core plugs of specific dimensions to find out the effective porosity and permeability. At the end, all the results of analysis and field observations were integrated to approach the reservoir quality of Nyalau Formation.

4. RESULTS AND DISCUSSIONS

4.1 Facies Description

The Nyalau Formation has been divided into five different facies during field investigations based on sedimentary structures and lithology, as describe below:

4.1.1 Trough cross-bedded sandstone (TCBS)

The trough cross-bedded sandstone facies is differentiated as greyish white, medium grained, moderately sorted, friable sandstone (Figure-3A). The observed sedimentary features include trough cross stratification, thin wavy laminae and mud partings. The blackish carbonaceous materials are also observed in this facies. Sparsely bioturbation is also observed in trough cross bedded sandstone facies. Its upper and lower contacts are gradational. This sandstone facies is formed in the result of small shallow tidal channel fill, which occurs in the form of fine to medium grained sand and deposited due to three dimensional flow (Collins *et al.*, 1981, Siddiqui *et al*, 2015).

4.1.2 Laminated sandstone (LS)

The laminated sandstone is fine grained, yellowish grey, moderately sorted, hard and having clay laminations. Its thickness is around 2.5-3 m and identified sedimentary structures include extensive flaser and wavy bedding (Figure 3B). The wavy bedding is locally marked by uninterrupted thin (1-2 cm) muddy layers and some are discontinuous. This facies has uniform bedding of sand and mud and its weathering style is controlled by lithology. The wavy and flaser bedding is usually formed

ARPN Journal of Engineering and Applied Sciences

in tidal flat sediment where there is a fluctuation of sediments supply during deposition.

4.1.3 Heterolithic sandstone (HS)

This facies is characterized as fine grained, greyish white, poorly sorted sandstone. This facies is categorized as sand with interbedded clay having flaser bedding in sand layers. There is variation in thickness of sandstone layers around 2-8 cm with alteration of 1-2 cm thick clay and its overall thickness is about 1.5-2 m. The sandstone layers are usually continuous while clay has poor continuity. The sandstone also contains of internal cross laminations and ripple structures with carbonaceous drapes and mud traces (Figure-3C). The sparsely bioturbation is found in muddy portion and mud preserve the internal laminations. The top and bottom parts of this facies are gradational.

4.1.4 Bioturbated sandstone (BS)

This sandstone facies is composed of fine grained, whitish grey, poorly sorted sand having thickness of 1.5-2 m. No clear sedimentary structure has been identified in this facies. However, it is highly bioturbated (Figure-3D) having ophiomorpha with bioturbation index (BI: 4-5). There is no indication of tidal or wave process depositional style in this formation due to reworking of sediments in the result of bioturbation activity. The ophiomorpha presence suggest the shallow marine setting above fair weather wave base (Siddiqui *et al,* 2015).

4.1.5 Massive sandstone (MS)

The massive sandstone facies is comprised of yellowish white, medium grained, well sorted, hard sandstone (Figure-3E). The thick sand beds with some clay layers are the main characteristics of this facies. There is no sedmienatry feature or bioturbation indication has been found in this facies. Its thickness is 1.5 to 2 m and its upper and lower contacts are sharp.

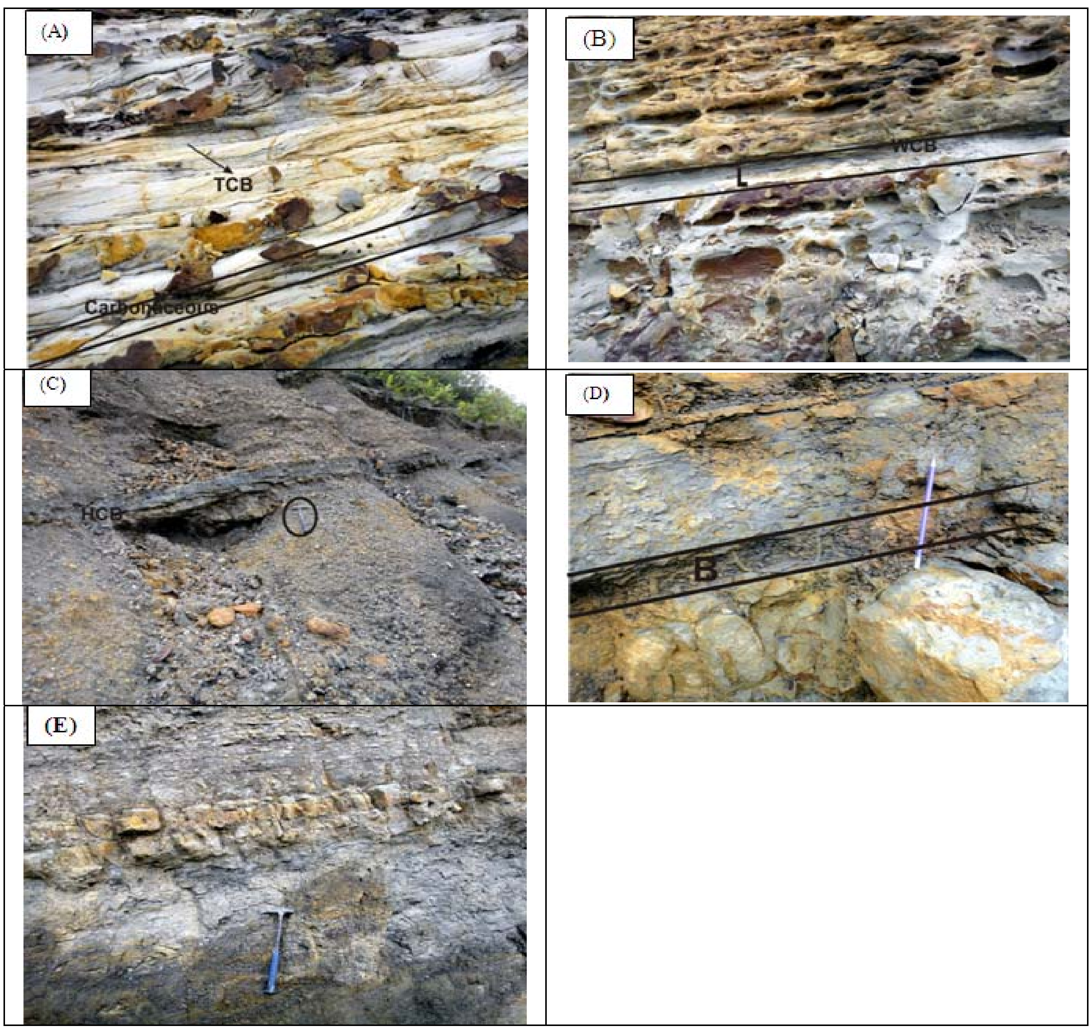

Figure-3. Photographs of different facies of Nyalau Formation: (A) trough cross-bedded (TCB) sandstone (B) laminated (L) sandstone with wavy cross bedding (WCB), (C) heterolithic sandstone (HCB), bioturbated (B) sandstone, (E) massive sandstone. (scale: 30 cm hammer).

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4.2 Petrographic Investigations

As summarized in Table-1, the petrographic analysis of five facies of sandstone by 350 point counting suggest that the facies are consisting of fine to medium grained, poorly to moderately sorted.

The TCBS facies has shown that it has 80-85 % mono and polycrystalline quartz with 5-10 % clay and 8-10 % other amount of feldspar and conductive minerals (Figure-4A). Based on this observation, this facies is considered as quartzarinite. The blue epoxy in thin sections show the porosity presence in this facies. So it has good porosity ranging from 20-22 %. Due to presence of some clay its permeability is affected and it has intragranular interconnected porosity.

The LS facies is composed of 70-75 % monocrystalline quartz, 5 % feldspar and 20-25% clay with low porosity due to clay laminations (Figure-4B). Due to clay blocking effect in this facies, the interconnected porosity is very low. The sorting of grains is also affected in thin sections due to clay distribution. This facies has porosity ranging from 8-10 %.

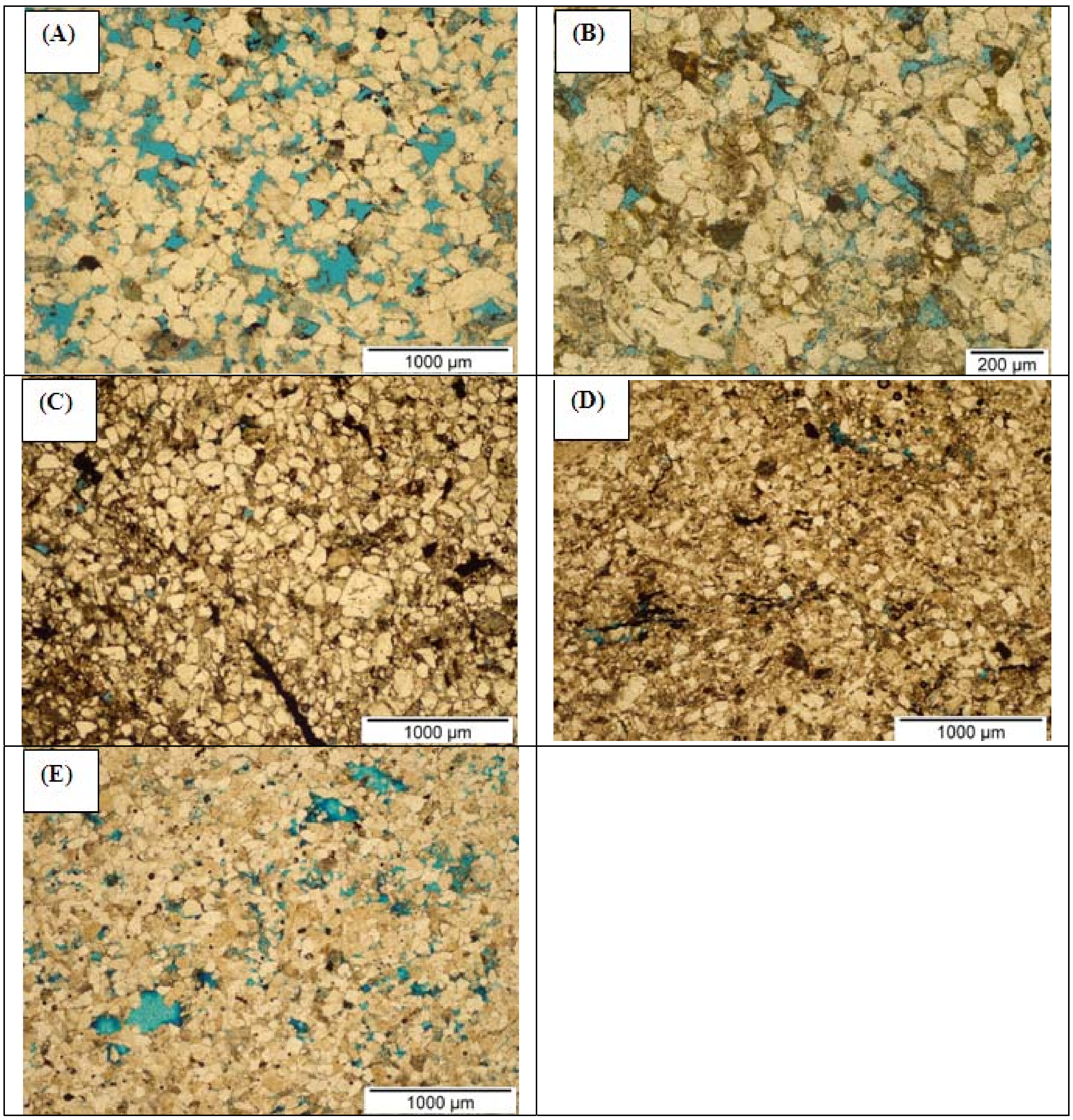

Figure-4. Thin section images showing different constituents of sandstone in different facies: : (A) trough cross-bedded sandstone, (B) laminated sandstone, (C) heterolithic sandstone, bioturbated sandstone, (E) massive sandstone.

The HS facies is characterized as having fractured grains and intrusion of fine grained material in between quartz grains. It is containing of 75-80 % mono and polycrystalline quartz with 20-25 % clay and 3-5 % feldspar (Figure-4C). Due to infiltration of clay in between sand grains its porosity is very low ranging from 5-7 %. The grains are comparatively poorly sorted in heterolithic sandstone facies.

The BS facies is highly effected by bioturbation activity (Figure-4D). This facies has very low porosity and low permeability due to poor interconnection of pores and grains. The bioturbated sandstone facies is very fine grained, poorly sorted, and having 60-65 % quartz and 35-40 % clay. The burrow activity caused intrusion of fine grained material (mostly clay) and lack of preferred grains orientation. Due to these disturbances, the porosity and permeability of this facies is highly effected.

The massive sandstone facies is categorized as having 85-90 % polycrystalline quartz with 10-15 % clay and feldspar (Figure-4E). The quartz grains are moderately sorted and the porosity of this facies is comparatively good in the range of 15 %. The dissolutioning is also observed in this facies so due to that it has secondary porosity. Due to interconnection of pores, it has comparatively good permeability.

4.3 Reservoir potential of Nyalau Formation

The sandstone samples were gathered from the outcrops to understand the reservoir potential of Nyalau Formation. The reservoir potential mainly includes porosity, permeability and clay volume, which is affected by mineralogical composition and sorting of any reservoir (Ali et al., 2010). Moreover, the minerals distribution may be controlled by different diagenetic stages and many model are introduced related to their mutual effect on reservoir (Machel, 1999). The porosity of each facies has been estimated by 350 point counting on thin sections and additionally by applying helium porosimeter on core plugs. Whereas, the permeability is calculated only through helium porosimeter. The clay volume has been discussed in section 4.2 for all facies. The porosity, permeability, grain size and clay volume of all facies has been shown in Table-1.

The TCBS facies having quartz dominantly and comparatively having good sorting is evaluated as having good helium porosity ranging from 18-20 % and helium permeability of around 15-20 millidarcies (Table-1). Due to well oriented grains and roundness, the porosity is good in this facies. While due to sparsely bioturbation and clay infiltration, the permeability is low in trough cross-bedded sandstone facies. The helium porosity of laminated sand stone facies is ranging from 10-12 % and helium permeability is 10-15 millidarcies (Table-1). The texture and clay distribution have marked effect on porosity and permeability of a sandstone reservoir (Worthington, 2000). In this facies, due to high clay volume the porosity is decreased but permeability is relatively good due to laminar clay. The heterolithic sandstone facies has very low helium porosity ranging from 5-10 % and helium permeability is around 0.69 millidarcies (Table-1). These low reservoir properties is due to high influence of clay on sandstone.

The bioturbated sandstone facies has helium porosity ranging from 8-10 % and helium permeability is ranging from 1.5-3 millidarcies. The burrow activity highly impacts the reservoir quality in shallow marine sandstone reservoirs (Siddiqui *et al*., 2015). The intrusion of fine grained material in between sand particles cause the poor quality of this facies. The presence of ophiomorpha as bioturbation having clay filled burrows is the responsible for declining the reservoir potential and increasing the clay volume in bioturbated sandstone facies. The massive sandstone facies is analyzed as having good helium porosity range from 20-25 % and helium permeability ranging 20-25 millidarcies. In this facies, the influence of clay and other sedimentation disturbance activities are comparatively less than other facies.

Table-1. Average quantity of petrographic constituents and reservoir properties for all facies of Nyalau Formation.

Facies Name	Petrographic Analysis						*Reservoir Properties		
	Q (%)	F (%)	Cl (%)	Sorting	Grain shape	Grain type	He-porosity (%)	He-permeability (md)	Point count porosity (%)
Trough cross-bedded sandstone	82	8	10	Well sorted	Sub-rounded	Medium grained	20	18	21
Laminated Sandstone	70	5	25	Moderately sorted	Sub-angular to sub-rounded	Fine grained	10	12	8
Heterolithic Sandstone	75	3	22	Moderately sorted	Sub-angular to sub-rounded	Fine grained	8	0.5	5
Bioturbated Sandstone	65	-	35	Poorly sorted	Sub-angular	Very fine grained	9	1.5	6.5
Massive Sandstone	90	5	5	Well sorted	Sub-rounded	Medium grained	22	20	16.5

4.4 Relationship between Petrography and Reservoir properties

The reservoir potential of any rock is mainly dependent on diagenesis processes, depositional setting and petrographic characteristics (Zhang *et al*., 2011; Kassab *et al*., 2014; Wang *et al*., 2014). In Nyalau Formation, the reservoir potential is effected by mainly sorting or grains and clay content. The relationship of total clay content with porosity and permeability is shown in Figures 5 & 6, respectively. According to this relationship, the porosity and permeability is decreasing drastically with increasing clay content. The reason behind is due to clay blocking effect on pores spaces in a reservoir (Nabawy *et al*., 2014; Han *et al*., 2015).

*adopted from Iqbal *et al*., 2017 submitted in Journal.

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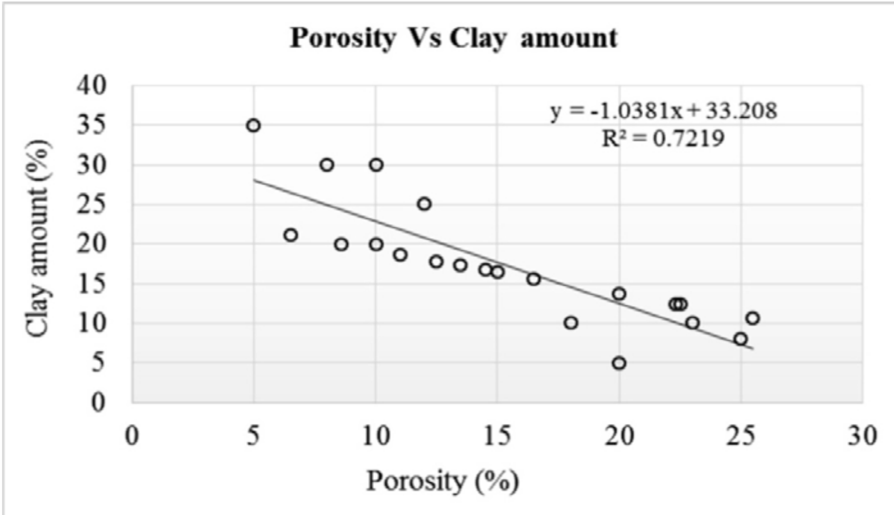

Figure-5. Relationship of porosity with clay amount showing inverse relationship.

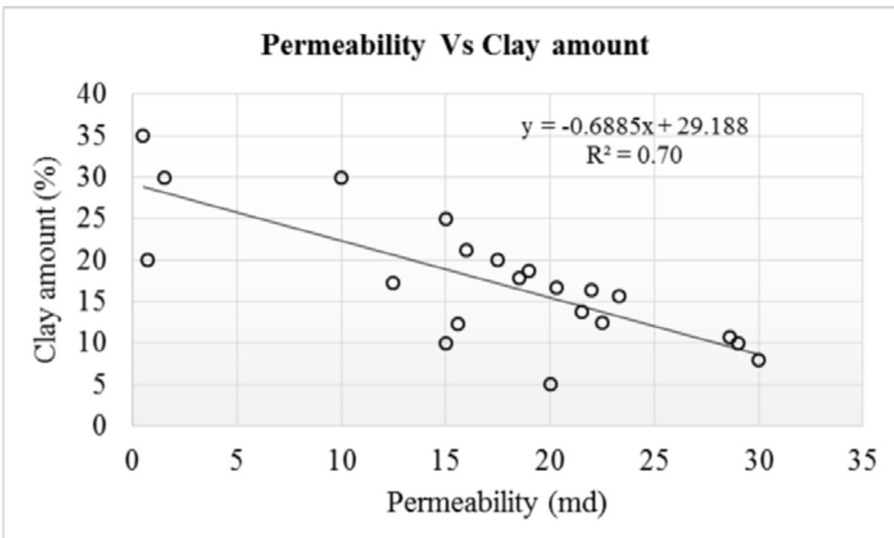

Figure-6. Inverse relation of clay amount with permeability in all facies of Nyalau Formation.

Furthermore, it also depends on the mode of occurrence of clay, more likely towards distribution of clay in a reservoir. Moreover, the sorting, shape of grains and grain size also result the enhancement or reduction in reservoir properties. The fine grained and poorly sorted facies of Nyalau Formation e.g. heterolithic sandstone and bioturbated sandstone facies have low reservoir properties due to poor sorting. The grain size mainly effect the permeability and grain shape impact the porosity of a clastic reservoir. The trough cross bedded sandstone and massive sandstone facies have relatively good grain size and grain shape than other facies, so their reservoir potential is far better. The laminated sandstone facies is fine grained and with high clay content, so its reservoir properties is medium than other facies because its grain shape is sub-angular.

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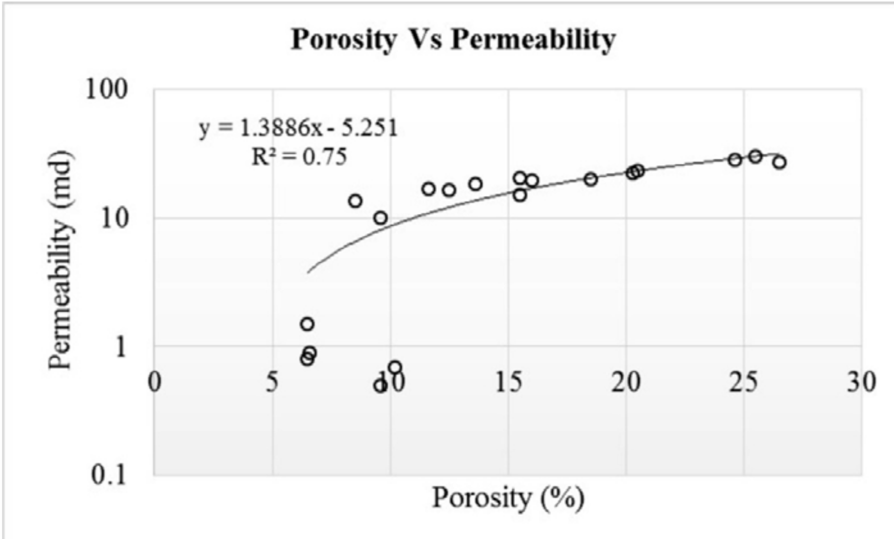

Figure-7. Direct relationship of porosity with permeability.

As mentioned earlier that porosity is determined through different methods, one of them is through thin sections which gives visible porosity and other one is effective porosity through helium porosimeter analysis on core plugs. The porosity-permeability relationship is also shown in Figure-7. The increment in porosity enhances the permeability because with increase in number of pores the interconnectivity will also be increased so permeability increases too.

5. CONCLUSIONS

By integrating field observations and laboratory analysis it is concluded that:

- Shallow marine Nyalau Formation exposed in Bintulu area, Sarawak Basin, Malaysia is consisting of five different sandstone facies; trough cross-bedded sandstone, laminated sandstone, heterolithic sandstone, bioturbated sandstone and massive sandstone facies.
- It is observed that the reservoir potential of Nyalau Formation is mainly controlled by clay content and petrographic features e.g. sorting of grains, grain shape and grain size.
- An inverse relationship is determined between porosity, permeability and total clay content. This inverse relations is explained due to clay blocking effect in sandstone reservoirs.
- A best direct correlation has been observed in between porosity and permeability of all facies.
- It is also concluded that out of five identified facies of Nyalau Formation, two facies (trough cross-bedded sandstone and massive sandstone) are considered as having best reservoir quality with good porosity and permeability ranges and low clay content.

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