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Porosity, Permeability and Pore Throat Size Distribution of Nyalau Formation, Bintulu Area, Sarawak Basin, Malaysia

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ABSTRACT

Nyalau Formation is a shallow marine sandstone of Oligocene-Middle Miocene age which is well exposed around the Bintulu area, Sarawak. Understanding the reservoir properties which mainly include porosity, permeability and pore throat distribution is important for reservoirs to characterize them for successful exploration. In previous, porosity and permeability of Nyalau Formation was measured by imaging techniques like thin sections and there no work on effect of pore throat diameter on porosity and permeability for Nyalau Formation. This study presents the above mentioned properties of Nyalau Formation, which is proven reservoir in its equivalent cycles in offshore. In this paper, five facies of Nyalau Formation have been identified on the basis of lithology. Porosity and Permeability measurements were carried out by using Helium Porosimetry on core plugs and Mercury Injection Capillary Pressure (MICP) on rock chips, while pore throat size distribution was observed by MICP method only. The identified facies are Cross-bedded sandstone, laminated sandstone, Silty Mudstone, Bioturbated Mudstone and Clayey sandstone. By integrating all of these factors, it is concluded that pore throat size has strong effect on permeability while porosity is effected by pore structure in each facies. It is also investigated that Nyalau Formation has variable reservoir properties for each facies due to its lithology.
KEYWORDS: Nyalau Formation, Porosity, Permeability, Pore Throat Size Distribution.

INTRODUCTION

The porosity and permeability are the most important properties of any reservoir to evaluate it, beside these, the pore throat size distribution play an important role in enhancing or decreasing the porosity and permeability. This research is based on reservoir properties of Nyalau Formation from Bintulu, Sarawak. Nyalau Formation is Oligocene to Middle Miocene, shallow marine sandstone having tidal influence [1]. This formation covers the whole part of Bintulu area and it consists of massive sandstone intervals, laminated clays, coal bearing mudstone and cross bedded sandstones [2-3]. The extensive variety of vertical facies successions and sedimentary environments are found in outcrops of this formation and in its equivalent offshore cycles II and III, which is covered by detailed study of prior authors in Bintulu area [4-6]. Nyalau Formation has its equivalent offshore cycles II and III in offshore Sarawak [7].

The previous work was based on sedimentology, structural and stratigraphic approach on the basis of field studies. The porosity and permeability has been measured by only imaging techniques like point count method on thin sections and there is no relation of pore throat size and porosity-permeability has been shown in previous work. The main objective of this study is to evaluate the Nyalau Formation on the basis of porosity and permeability measurements in different facies, and effect of pore throat size on porosity and permeability is also an important part of this study. An attempt was made to identify Nyalau Formation in different five facies on the basis of lithology in this study. The response of lithology on porosity and permeability was measured to know the effect of lithology on each facies properties. Moreover, the variation of pore throat size distribution in different facies is also shown in this study and an attempt is carried out to connect its effect on porosity and permeability.

Geological Background

The Sarawak Basin of NW Borneo is tectonically linked with rifting and sea floor spreading in the South China Sea marginal basin and the southern margin of the Oligocene to Recent South China Sea basin is formed due to it [8]. The Sarawak Basin is a result of closure and uplift of a Late Cretaceous to Eocene proto-South China Sea or Rajang Sea [9]. On the basis of subsidence history and structural style, some authors have interpreted it as a strike slip basin [10]. The Sarawak basin is underlain by about 12 km of Tertiary siliciclastic and carbonate sediments [11]. The Central Sarawak basin occupies the northwestern part of Borneo, which lies

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at the intersection point of three major plates, Eurasian plate in north, Indo-Australian plate in south and Philippines plate in east. In early tertiary times, the accretion of terranes and creation of marginal basins occurred due to the relative movement of these three plates in a complex pattern. Central Sarawak represents part of an accreted terrane, which is lying adjacent to an extended continental margin towards north.

The Sarawak Basin is considered as most important hydrocarbon producing basin of Southeast Asia region. The Southeast Asia is geologically complex region and its complexity with regard to its evolution has prompted by many authors and they yielded many models [12-13]. The Sarawak Basin is consisting of onshore and near coastal region, the West Baram Line (115° E, East of Miri) separating it from the Sabah Basin [14]. The Sarawak basin prolongs towards East Natuna Basin in Indonesia in westwards. The basement rock of pre-Oligocene age are exposed in between Miri and Sibu and further extends towards inboard belt of Sabah Basin as shown in Figure 1 [15]. The Tatau Mersing Line which acts as boundary between Sibu and Miri zones exhibits the main unconformity between Belaga, Mulu and Kelantan Formations of Rajang Group and overlying Eocene to Recent sediments of the Miri zone. There is unconformity in between Middle-Late Miocene age in Sabah and Late Eocene age in Sarawak Basin [16-17].

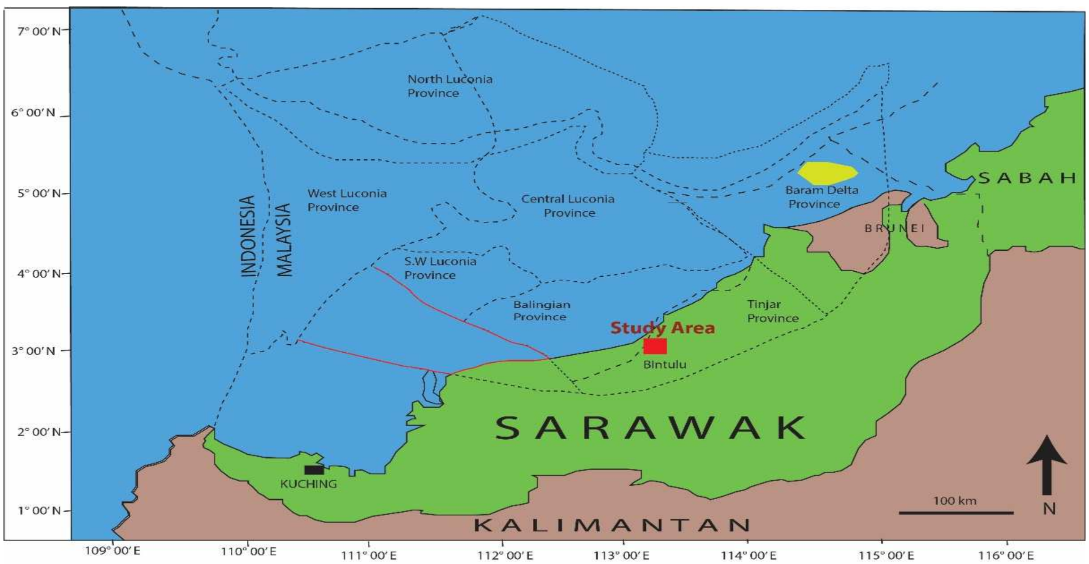


Figure 1: Structural distribution of Sarawak Basin modified after [7]

In Balingian province, the Nyalau Formation is exposed which is equivalent to its offshore cycles II and III of Early Miocene age as shown in Figure 2. It comprises thick succession of coastal plain deposits [18]. The onshore geology of the southern part of Balingian province is dominated by Nyalau Formation. During the closure of Rajang Sea and the Sarawak orogeny during Late Eocene, the peripheral foreland basin fill (Sarawak basin) is formed and Balingian province is a part of it [20]. This foreland basin fill includes the Nyalau Formation and unconformably. The foreland basin fill including the Nyalau Formation, unconformably superimpose strongly deformed deep water deposits of Rajang Fold Thrust Belt accretionary complex [21].

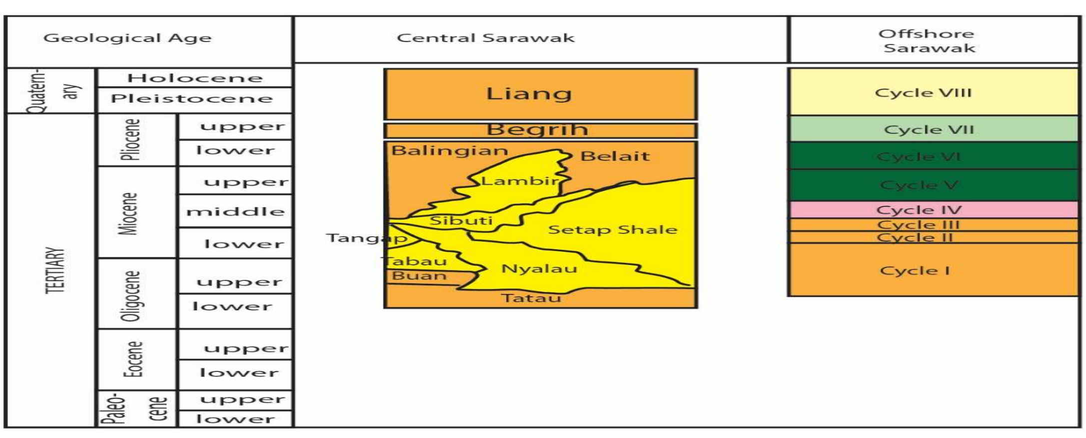


Figure 2: Offshore cycles equivalent to Nyalau Formation (modified from [19])

The Biban Sandstone Member of Nyalau Formation occurs as the oldest rocks of Sarawak Bintulu area, its age is Oligocene to Middle Miocene [22] and it consists of sandstone and subordinate shale. It was deposited under shallow marine conditions, but the presence of coal seams suggests that coastal swamp or deltaic conditions also developed locally all times [23]. The lithology of Nyalau Formation in the area consists of soft to hard, thin-thick bedded, very fine to medium grained sandstone with mud and sandy shale alternations.

METHODOLOGY

A detailed field work was carried out on Nyalau Formation for identification of facies on the basis of lithology and collecting the rock samples for laboratory analysis from Bintulu area. The collection of samples from representative facies of different Nyalau Formation's outcrops was done in different ways according to requirements of laboratory work. The cores of 1.5" diameter and 3" length were plugged from the outcrop for Helium porosimetry to measure the porosity and permeability. Similarly, for Mercury Injection Capillary Pressure (MICP) method the small cubic chips were prepared from different facies. The four main outcrops were covered for identification of facies and collection of samples around the Bintulu Airport area for this study. Total twenty representative samples were selected for MICP and ten core plugs were selected for helium porosimetry measurements.

To achieve the objectives, Helium porosimetry was used to measure the porosity and permeability on core plugs and MICP was mainly used for determination of pore throat size distribution as discussed below:

Helium Porosimetry

The porosity and permeability was measured on dry and clean core plugs by helium porosimetry. This technique follows the Boyl's law for gas expansion. The helium porosimetry measure the grain volume V_g of the sample, Vs is the volume of empty sample container before the sample inserted. V_r known as reference volume which is filled by helium and its pressure P_r has been recorded. The expanded gas from the reference volume to the sample container and then the resulting pressure PX has been calculated. The grain volume Vg is found by applying following formula:

$$P_1V_1 = P_2V_2 \text{ or } P_rV_r = PX(V_r + V_s - V_g \quad (1)$$

Mercury Injection Capillary Pressure (MICP)

The MICP method is considered as the ideal method for determination of pore throat size distribution from micron scale to nano scale [24]. This method works on the theory of gas adsorption, this technique is actually based on a phenomenon that mercury acts as non-wetting liquid with solids. Under a pressure range of up to 200 psi the mercury penetrates in the solid samples pores and the pore volume distribution is found as a function of its radius. The mercury pressure and pore throat radius acts as inversely proportional, for smaller pores the mercury pressure is high and vice versa [25]. The relation between pore size and given pressure is described as:

$$P_r = -2y\cos\theta \quad (2)$$

where r = pore radius; y = mercury surface tension; θ = contact angle; p = absolute applied pressure. Winland's regression illustrates the relation between porosity, permeability and pore throat radius as below [26]:

$$\log_r = 0.732 + 0.588\log_k - 0.864\log_\emptyset \quad (3)$$

where, r is pore throat radius, k is air permeability and Ø is porosity. According to Winland's theory, porosity and permeability increases as square of pore radius [26]. The ranges for pore throat size is defined as Macro, Meso and Micro as shown in Table 1 [25].

Table 1: Pore size ranges for each pore type, modified after [25]

Pore Type	Pore Size (Micrometer)	Pore Size (nm)
Macro	2-10	2000-10000
Meso	0.5-2.0	500-2000
Micro	0.1-0.5	100-500

RESULTS AND DISCUSSION

Field Investigations

A total thirty of samples and core plugs were collected from different facies of different outcrops during field work of Bintulu area. The photo of representative facies is shown in Figure 3.

Cross Bedded Sandstone (CBS)

The cross bedded sandstone consists of mainly hummocky cross stratification, it is medium to fine grained sandstone as shown in Figure 3(a). The arithmetic average porosity value obtained by both methods for this facies is 15.6% and permeability is 28 md as shown in Table 1. On the basis of pore throat size distribution as shown in Figure 4(a) its pore diameter is approximate 8000-10000 nm, so it is considered as macro pores the ranges for pore sizes and it is bi to tri-modal.

Laminated Sandstone (LS)

The laminated sandstone is found in the form of lamination of clay in between the sandstone as shown in Figure 3(b), it is fine grained sandstone. The arithmetic average porosity value for this facies is 16.1 % and arithmetic average permeability is calculated as 26.8 md as shown in Table 1. The pore throat size distribution which is shown in Figure 4(b) suggested that it is macro pore and uni-modal because its pore diameter is about 6000 nm which is equal to 6 microns.

(a) (b) (c) (d) (e)

Figure 3: Photographs of different facies of Nyalau Formation (a) Cross bedded sandstone (b) Laminated Sandstone (c) Silty Mudstone (d) Bioturbated Silty Mudstone (e) Clayey Sandstone(Scale: 30 cm Hammer).

Silty Mudstone (SM)

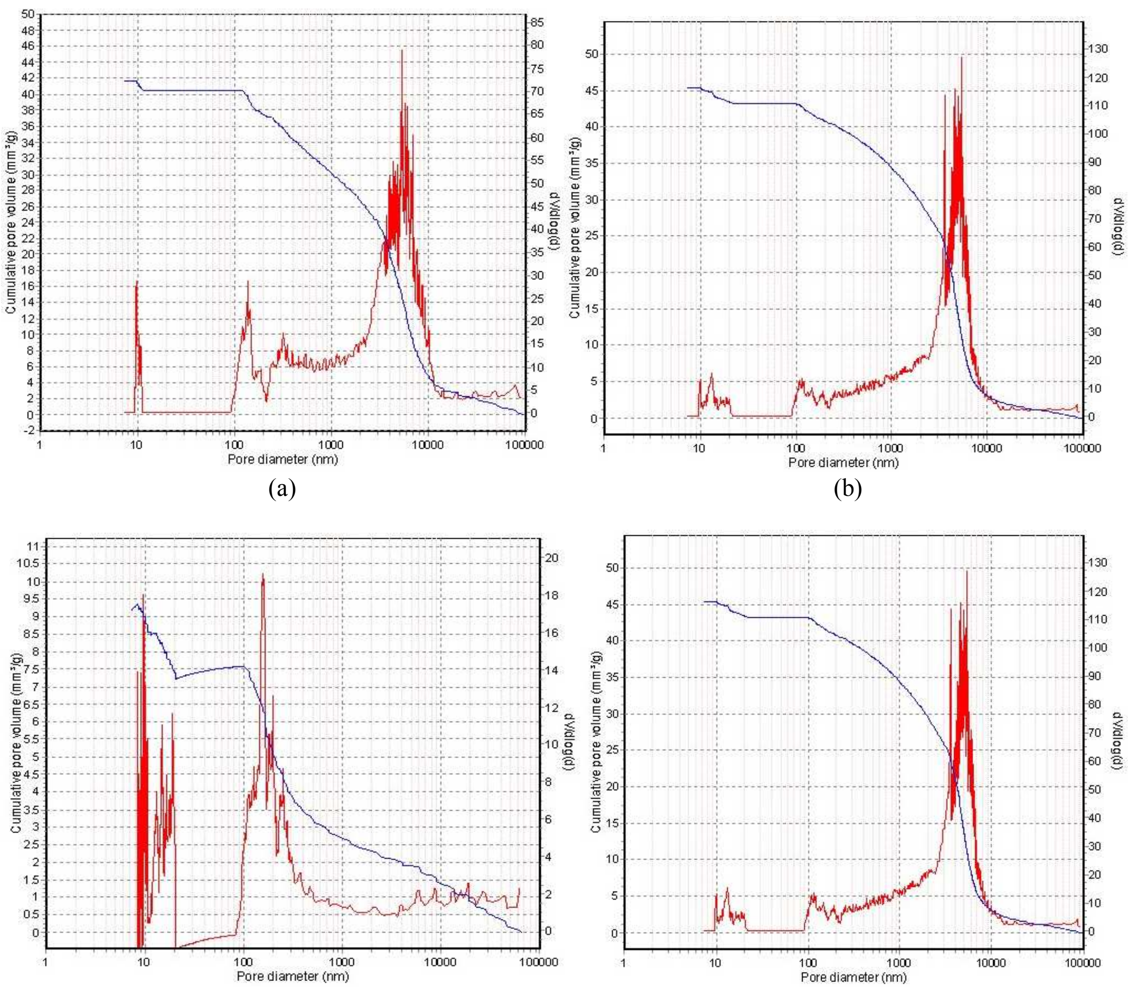
The silty mudstone facies is around 1.5 m thick as shown in Figure 3(c). The arithmetic average porosity and permeability value for Silty Mudstone facies is 4 % and 0.318 md respectively as shown in Table 1. Its porosity and permeability is very low as compare to other facies due to its unique pore size distribution as shown in Figure 4(c). Its pore diameter is 20 to 200 nm so it is micro pore and bi-modal pore throats.

Bioturbated Silty Mudstone (BSM)

The bioturbation has been found in this facies as shown in Figure 3(d). The bioturbated mudstone facies has arithmetic average value of porosity as 3.5 % and permeability as 0.085md as shown in Table 1. Its porosity and permeability is very low due to bioturbation effect. But, its permeability is very low as compare to porosity and it was expected that it may have microporosity. So, it is confirmed by pore throat size distribution due to it has pore diameter as 10 nm and it is uni-modal as shown in Figure 4(d).

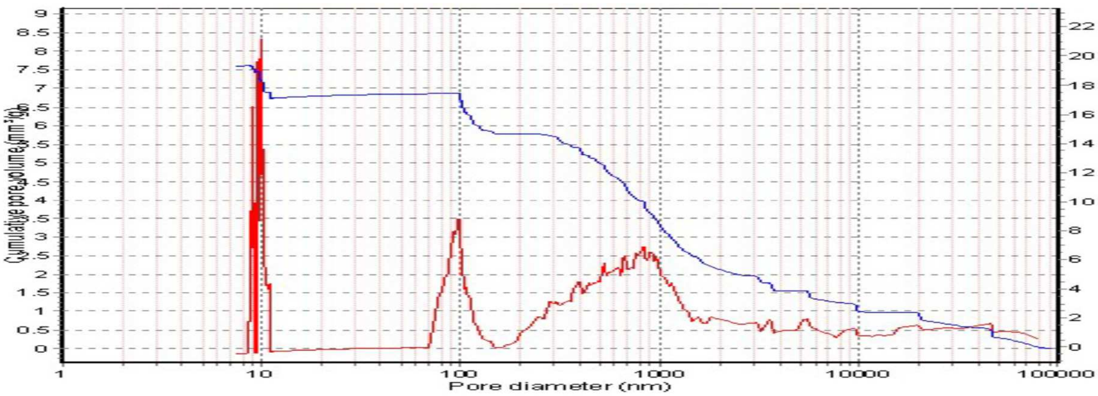
Clayey Sandstone (CS)

This facies is shown in Figure 3(e). The clayey sandstone has arithmetic average porosity of 2.5 % and permeability as 0.6 md as shown in Table 1. On the basis of pore size distribution as shown in Figure 4(e), it is bi to tri-modal and micro to meso pore because its pore size range is 100 to 1000 nm.



(a) (b)

(c) (d)



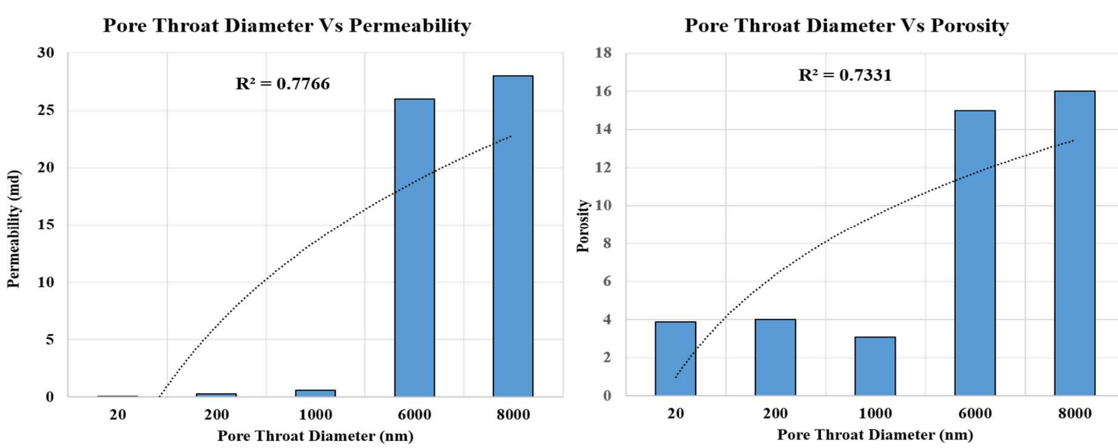
(e)

Figure 4: Pore throat size distributions (a) Cross bedded sandstone facies, (b) Laminated Sandstone facies, (c) Silty Mudstone facies, (d) Bioturbated Silty Mudstone facies, (e) Clayey sandstone facies

Relationship between Porosity, Permeability and Pore Throat Size Distribution

The Nyalau Formation is divided into five main facies on the basis of lithology. Each facies has different porosity and permeability values due to its variable lithology as discussed in each facies. In previous studies, the porosity and permeability for this formation was measured mostly by using point count method in thin sections and there is no relationship shown in between porosity, permeability and pore throat diameter. In this study, porosity and permeability is measured by using two methods; Helium porosimetry and MICP. The porosity measured by helium Porosimetry is considered as benchmark and reliable. As helium porosimetry gives high porosity values because the helium's (He) kinetic diameter is smaller than most reservoir gases, so connected porosity will be interrogated [27].

Secondly, it gives effective porosity because it is applied on dried core plugs so clay bound water is dried out and the pores which were filled with clay bound water now due to dry it is filled with helium and their porosity is added in the results. Therefore, this method is more effective than point counting because it is applied on core plugs so the helium intrude in each pore and gives good porosity, permeability values. The porosity and permeability is also measured by MICP but this technique is standard for characterization of pore structure. The porosity measured by MICP is less than helium porosity because it is limited to accessible pores. Pore throat diameter is measured by this method and its relationship with porosity and permeability has been also taken into account. Normally, it is considered that pore throat has no relation with porosity but it is also fact that porous media with uniform structure has higher porosity than non-uniform structure [28]. For this study, the relationship among these properties has been shown in Figure 5. In Figure 5(a), the relationship of pore throat diameter and permeability has been shown. According to Swanson's theory, the permeability varies as square of pore throat size. So, for Nyalau Formation the pore throat diameter also effects on its permeability, the permeability increases as pore throat diameter has increased as shown in Figure 5(a).



(a) (b)

Figure 5: Relationships between (a) pore throat diameter and permeability and (b) pore throat diameter and porosity

As pore throat diameter varies in each facies due to its lithology permeability also varies. Similarly, as discussed above, the porosity also affected by pore throat diameter indirectly. Hence, cross bedded sandstone and laminated sandstone facies has high porosity because its pore structure is uniform as shown in Figure 4(a). The blue curve which depicts that the pore structure is uniform, so its porosity is high than other facies which have non uniform pore structure. As shown in Figure 5(b), the relationship between pore throat diameter and porosity is uniform and direct which due to mainly pore structure. According to pore throat size ranges, the cross bedded sandstone facies has meso to macro pores, laminated sandtone, silty mudstone and clayey sandstone facies has meso pores and bioturbated silty mudstone facies has micro pores which may be due to bioturbation effect. Among all facies, there is variable ranges of porosity and permeability which is due to pore throat diameter and lithology. Overall, the Nyalau Formation has effected by lithology and pore structures.

Table 2: Integration of all gathered results for showing average porosity and permeability values of available samples

Facies Type		Cross Bedded Sandstone	Laminated Sandstone	Silty Mudstone	BioturbatedSilty Mudstone	Clayey Sandstone
Porosity (%)	He	18.3	20.1	3.9	4.1	3.1
	MICP	12.94	12.3	4.1	3.14	2.01
Permeability (md)	He	29	32.1	0.315	0.15	0.9
	MICP	27	20	0.32	0.02	0.3
Pore Throat Diameter (nm)		8000-10000	6000	20-200	10	100-1000
Pore Type		Meso to Macro	Meso	Meso	Micro	Meso
Pore Distribution		bi to tri-modal	Uni-modal	bi-modal	uni-modal	bi to tri-modal
Capillary Pressure Curve		Uniform	Uniform	Non-Uniform	Non-Uniform	Uniform
Reservoir Quality		Good	Good	Poor	Poor	Poor

CONCLUSION

This research helped us to conclude that pore throat diameter effects on permeability and pore structure effect on porosity. Nyalau Formation has been identified into five facies on the basis of lithology and in each facies lithology and pore throat size played a major role on porosity and permeability. Cross bedded sandstone and laminated sandstone facies has macro pores sizes and uniform pore structure due to which their porosity-permeability is also good, while other facies has low pore throat size so their permeability is also low and due to non-uniform pore structure their porosity is also low. Helium porosity method is more reliable for porosity-permeability measurements because it gives us effective porosity while MICP is more reliable for pore throat size determination. Moreover, cross bedded sandstone and laminated sandstone facies is considered as good reservoir facies due to its large pore throat size, uniform pore structure, good porosity and permeability ranges and lithology. It is also concluded that pore structure varies with lithology. In future, a detailed work on Nyalau Formation can be done related to effect of different mineralogy in each facies.

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