Offshore Carbonate Facies Characterization and Reservoir Quality of Miocene Rocks, Central Luconia, Offshore Sarawak, Malaysia

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Abstract: Carbonate rocks are important hydrocarbon reservoirs around the globe and in Southeast Asia particularly, the Central Luconia province. Understanding the internal characteristics, distribution, geometry and lateral extent of these rocks are essential parts for the exploration and production success. This study provides a unique and detailed work on carbonate reservoir facies including qualitative and quantitative analysis of photomicrographs and reservoir quality considering microporosity. Stratigraphically, these carbonates are known as Cycle IV and V and are represented by eight major type of facies. The analysed carbonate facies are: coated grain packstone (F-1) (av. Ø = 3%, av. Kh = 0.5 mD) (av = Average; Ø = total porosity, and Kh = permeability), massive coral lime grainstone (F-2) (av. Ø = 14.7%, av. Kh = 6 mD), oncolite grain-dominated packstone (F-3) (av. Ø = 10%, av. Kh = 4 mD), skeletal lime/dolo packstone (F-4) (av. Ø = 15%, av. Kh = 4.6 mD), coral (platy) lime mud dominated packstone (F-5) (av. Ø = 4%, av. Kh = 0.5 mD), coral (branching) lime dominated pack-grainstone (F-6) (av. Ø = 15%, av. Kh = 1 mD), cross-bedded skeletal lime packstone (F-7) (av. Ø = 20%, av. Kh = 2 mD), and bioturbated carbonate mudstone/chalk (F-8) (av. Ø = 8%, av. Kh = 0.8 mD). Thin sections study revealed that red algae, foraminifera, corals are the dominant fossil components with a minor admixture of echinoderms, bivalve, bryozoans, and green algae skeletal fragments. The microporosity value were quantified using digital image analysis software. All the parameters, e.g., facies characterization, petrography, porosity-permeability value, and microporosity value were utilized for obtaining a reliable reservoir quality. Another major achievement of this research is the improvement of the correlation coefficient (R²) value considering the presence of microporosity than total porosity in carbonate rocks. The value of correlation coefficient R² has increased from 0.51 to 0.82.

Key words: Carbonate facies, petrography, grain types, porosity-permeability, reservoir quality, microporosity.

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1 Introduction

The Central Luconia platforms have been studied intensively, in terms of their geology, stratigraphy and reservoir aspects (Doust 1981, Epting 1980, Epting 1989, Ali and Abolins 1999, Vahrenkamp 1998, Vahrenkamp et al. 2004, Madon 1999, Madon, Kim and Wong 2013, Koša 2015). According to Wee and Liew (1988) the exploration of gas fields in Central Luconia began in 1982, leading to an increase of production rate in the Sarawak region of Malaysia, where 60 of the 200 mapped platforms were explored and drilled. These carbonate rocks are economically significant and are believed to hold initial reserves of 65 trillion cubic feet of gas in place with minor contribution of oil reserves (Abdullah et al. 2012, Khazali, Osman and Abdullah 2013). According to Epting (1980), carbonate production in Central Luconia was mainly controlled by the growth of corals and coralline red algae. The same calcified organisms were responsible for the carbonate production in many contemporary and ancient carbonate platforms (Checconi et al. 2007, Ghosh and Sarkar 2013).

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The development of shallow marine carbonates in Central Luconia reached its apex between Middle to late Miocene time (Ting, Chung and Al Jaaidi 2010). The eustatic sea-level, basinal and clastic sediment supply from the Baram delta in northwest (NW) Borneo has influenced the development of carbonate build-ups (Epting 1989, Zampetti et al. 2004, Menier et al. 2014).

Several researchers emphasized that understanding the distribution and quantification of microporosity are especially important when dealing with carbonates (Baechle et al. 2008, Cantrell and Hagerty 1999, Janjuhah et al. 2017d, Daigle 2014). According to Baechle et al. (2008), Kaczmarek, Fullmer and Hasiuk (2015), Fournier and Borgomano (2009) the cored measured porosity which is known as total porosity does not entirely contribute to fluid flow due to the pore geometry which represents dissimilar pore throats that cause a negative impact on fluid flow. These researchers also stated that carbonate reservoir models mainly depend on different pore types, such as mouldic and vuggy porosity but the porosity present within the matrix is underestimated and this uncertainty has a high impact on the reservoir assessment. Also, the subdivision of pores into macropores and micropores would help to study the abundance and occurrence of microporosity in Central Luconia. Anselmetti, Luthi and Eberli (1998), Ruzyla and Jezek (1987), Yanguas and Dravis (1985), Milliken and Curtis (2016), Cantrell and Hagerty (1999) emphasized that the quantification of pore types in blue epoxy resin impregnated thin section is an effective tool to detect the microporosity zones. Sedimentological studies (facies, petrography, and reservoir quality) were conducted on Miocene carbonate rocks (Cycle IV and Cycle V) from the Central Luconia province, offshore Sarawak, Malaysia (Figure. 1). The main objectives of this study are: (1) to investigate and determine the facies characterization; (2) to examine the petrographic images qualitatively and quantitatively; (3) to diagnose the reservoir quality of the eight facies, (4) to distinguish the effect of microporosity on reservoir quality of different facies.

2 Geological Setting

2.1 Tectonic framework

The study area is located about 170 km offshore north of Bintulu, Sarawak (Figure. 1). The region is geologically known as Central Luconia province, is distinguished from adjacent tectonic domains by its relatively shallow occurrence and structural simplicity (Figure. 2). The province is flanked by deep basins on the west (West Luconia Delta), to the north (North Luconia Basin), and to the east (Baram Delta) borders. A
prominent lineament, the West Baram Line, separates Central Luconia from the Baram Delta. To the south the compressed Balingian Province (Figure 2) (Doust 1981, Haq, Hardenbol and Vail 1987, Mat-Zin and Swarbrick 1997, Hutchison 2004, Cullen 2010). Due to extensional forces, Central Luconia is divided into a number of local extensional half grabens and grabens, which trend in SSW-NNE, whereas compressional structures mostly trend in WSW-ENE directions.

![Structural map of Central Luconia Carbonate Platform Offshore Sarawak, Malaysia. Adopted from, Janjuah et al. (2017a)](image)

**2.2 Stratigraphy**

The Central Luconia has undergone various episodes of sedimentation. During the early stage of petroleum exploration in Central Luconia, a number of local stratigraphic units was established to describe the stratigraphy of this province. The Tertiary formations were defined using paleontological methods because of the absence of distinctive lithological characteristics. Ho (1978) used a wireline log and well data to subdivide the Late Eocene to Pleistocene sequence into eight major cycles, separated by major flooding surfaces.

In Central Luconia, most of the sediments are dominated by prograding clinoforms, which served for a subdivision of entire sequence into eight regressive cycles separated by major transgressions (Epting 1989). These cycles range from the Eocene to the Present. The Cycle I includes deep-water argillaceous and shallow marine siliciclastic successions filling an early synrift graben (Figure 3). This was followed by a late phase of synrift sedimentation through the Cycles II and III during the opening of the South China Sea. Continuous subsidence and formation of half-grabens resulted in widespread carbonate deposition during the middle to late Miocene Cycles IV and V (Figure 3).
This phenomenon was eventually stopped by the influx of siliciclastic sediments derived from the uplifted Rajang Fold-thrust Belt during Cycle V and VIII (Madon 1999). In general, the resulting carbonate platforms become thinner (<500 m) towards the southern part of Central Luconia, and on the northern side, they became thicker, up to 3000 m (Doust 1981, Hutchison 2004).

3 Material and Methods
Facies composition and carbonate reservoir quality were evaluated by detailed core description and laboratory analysis during which a total of 1610 ft of the core was described representing Cycle IV and V carbonates (Figure. 4). For the laboratory measurements, a total of 820 samples were collected to prepare thin sections and to measure the porosity and permeability.
3.1 Core description

Various sedimentological features such as depositional texture, nature of skeletal and non-skeletal grains, lithology, as well as diagenetic features including leaching, stylolites, and visual porosity were manually plotted at the 1:40 scale onto the core description sheet subdivided into five cores named here wells A-E (Figure 4).

3.2 Petrography

820 thin sections were prepared for the detailed petrographic study, 80% of the thin sections were prepared at Sarawak Shell Sdn, Bhd, and the rest 20% was prepared at the thin section lab, University Technology PETRONAS. These thin sections were impregnated with blue epoxy resin and then studied both under reflected and transmitted light microscopy as well as under a polarized light microscope Olympus BX 51 with DP-27 attached camera at SEACaRL, University Technology PETRONAS. Half of the thin sections were partially treated with an acid solution containing red Alizarin S and potassium ferricyanide stains. For the quantitative analysis of thin sections in terms of grains, matrix, cement and visible porosity, a point counting software J. Microvision was used based on 700 counts per section.
3.3 Quantification of microporosity
For the quantification of microporosity, petrographic images (32 images of each thin section) were subsequently subjected to point counting and digital image analysis (DIA) to determine the amount of visible porosity (macroporosity). Using the DIA software, a threshold value was set out to estimate the amount of macroporosity from petrographic images (Figure. 5). False colour images were produced using DIA to obtain the distribution of macropores (the pores with diameter greater than 10 μm in size) in each sample. The microporosity is then calculated as the difference between the observed porosity in DIA and the measured core plug porosity.

3.4 Porosity-permeability analysis
The core measurements under the overburden pressure of 1800-2000 psi were conducted to obtain the total porosity and permeability values by injecting helium gas, using a porosity-permeability instrument of Vinci Technologies. The cores were washed before porosity-permeability measurements to clean the fluid which is present in the pores by toluene fumes in a centrifugal extractor. After the washing/cleaning, these cores were placed in the oven for 1 day at the temperature of 100 °C. Weight, length, diameter and bulk volume of the cores were calculated individually and were covered with a transparent tape to avoid grain loss. After cleaning, these plugs proceeded for the porosity and permeability measurement. Due to the high density of carbonate samples, the measurements were operated using 1800-2000 psi pressure to get accurate values. The results of this analysis were also correlated with the petrographic observation.

4 Result and Discussion
4.1 Facies analysis
Based on the core analysis, the Miocene (Cycle IV and V) carbonates of Central Luconia were subdivided into eight major facies, namely: coated grain packstone (F-1), massive coral lime grainstone (F-2), oncolute lime grain-dominated packstone (F-3), skeletal lime/dolo packstone (F-4), coral (platy) lime mud dominated packstone (F-5), coral (branching) lime dominated pack-grainstone (F-6), cross-bedded skeletal lime packstone (F-7), and bioturbated carbonate mudstone (Chalk F-8) (Figure 4; Table 1). A detailed description of each lithofacies is given below.

Table 1: Facies scheme of Central Luconia based on cores from 8 wells, Offshore Sarawak, Malaysia.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>FA-1</strong> Coated Grain Packstone</td>
<td>Texture: packstone (floatstone)&lt;br&gt;Mineralogy: limestone&lt;br&gt;Components: algae &gt;50%, oncolute algae &lt;40%, corals &lt;30%, separate vugs, skeletal debris (angular – subangular), forams, echinoderms, gastropods, leaching&lt;br&gt;Grain size/sorting: fine-medium gravel/moderately - poor</td>
</tr>
<tr>
<td><strong>FA-2</strong> Coral (m) Lime Pack-Grainstone</td>
<td>Texture: packstone- grainstone (rudstone)&lt;br&gt;Mineralogy: limestone&lt;br&gt;Components: corals (m) &gt;50% (up to 8cm in diameter), platy coral up to 20%, branching corals (15%), solitary coral &lt;5%, algae, disconnected vugs, oncolute algae, skeletal grains (angular-subangular), gastropods, bivalves, echinoid spines&lt;br&gt;Grain size/sorting: very coarse-granule/moderately – poor</td>
</tr>
<tr>
<td><strong>FA-3</strong> Oncolite Lime Grain-dominated Packstone</td>
<td>Texture: packstone (rudstone)&lt;br&gt;Mineralogy: limestone&lt;br&gt;Components: oncolute algae &gt;70% (diameter 2 to 6cm), stylolite, corals &gt;30%, separate vugs, algae, gastropods, bivalves, echinoid spines, skeletal grains (angular-subangular), leaching&lt;br&gt;Grain size/sorting: medium-gravel/ moderately - poor</td>
</tr>
<tr>
<td><strong>FA-4</strong> Skeletal Lime/dolo Packstone</td>
<td>Texture: packstone (floatstone-rudstone)&lt;br&gt;Mineralogy: limestone – dolomitic limestone&lt;br&gt;Components: skeletal debris &gt;60% (angular-subangular), bivalves, isolated gastropods, corals (m) &lt;20%, Coral (p) &lt;15%, leaching&lt;br&gt;Grain size/sorting: fine-coarse grain/ moderately – well sorted</td>
</tr>
<tr>
<td><strong>FA-5</strong> Coral (p) Lime Mud dominated Packstone</td>
<td>Texture: packstone (floatstone)&lt;br&gt;Mineralogy: limestone&lt;br&gt;Components: rich platy corals &gt;70%, solitary coral up to 15%, algae, small fractures, disconnected small vugs, skeletal debris (angular-subangular), gastropod, forams, echinoid spines&lt;br&gt;Grain size/sorting: fine-coarse/poor</td>
</tr>
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</table>
4.1.1 Facies-1: coated grain packstone

Facies 1 displays a packstone (floatstone) texture (Figure. 4, 6a; Table-1). It contains a diverse skeletal assemblage, mainly dominated by calcified algal and coral skeletal fragments and oncolites. Minor constituents include foraminiferal tests, echinoderm plates, bivalve and gastropod shells. The grains in Facies 1 are poorly to moderately sorted. Grain size varies from fine to medium gravel. The fossil composition together with a high degree of disarticulation, fragmentation, and rounding of the grains, as well as the presence of oncolites indicate a high energy environment. Complete coating of oncolites by algal sheaths suggests a high frequency of rolling of these structures which further supports the suggestion that the facies formed under high energy conditions (Alshuaibi, Duane and Mahmoud 2012). The occurrence of packstone is attributed to infiltration of carbonate mud through the sediment following a change to lower energy conditions (Gawthorpe and Gutteridge 2009).
4.1.2 Facies-2: coated (m) lime pack-grainstone

Facies 2 displays a packstone-grainstone (rudstone) texture (Figure 4, 6b; Table 1). It contains diverse skeletal assemblage, mainly dominated by fragments of massive corals and calcified algae as well as by platy and branching coral debris. Minor constituents include solitary coral skeletons, gastropod, bivalve shells, and echinoid spines. Grains in Facies 2 are poorly to moderately sorted. Grain size varies from coarse to granule. The diversity of fossil assemblage indicates fully marine conditions while coarse grain size and asymmetrical oncolitic coating can reflect a low energy depositional environment (Gawthorpe and Gutteridge 2009). Facies 2 is interpreted as lagoonal deposits.

4.1.3 Facies-3: oncolite lime grain-dominated packstone

Facies 3 displays a packstone (rudstone) texture (Figure 4, 6c; Table 1). 70% of this facies is represented by abundant rhodolite/oncolite assemblage dominated by skeletal debris of massive corals, calcified algae, and foraminifera. Minor constituents are represented by bivalve shells and echinoids spines. The grains in Facies 3 are poorly to moderately sorted. Grain size varies from fine to medium gravel. The fossil composition indicates a shallow marine depositional environment. According to Cook, Shergold and Cook (2005), the oncolite facies are formed in relatively shallow nearshore waters. While the abundance of algal balls (oncolite/rhodolites) and of some corals suggests a deposition under medium to occasionally high energy conditions under an influence of sea currents.

4.1.4 Facies-4: skeletal lime/dolo packstone
Facies 4 displays a packstone (floatstone-rudstone) texture (Figure. 4, 6d; Table-1). It contains a diverse skeletal assemblage, mainly dominated by platy coral debris and massive coral fragments. Minor constituents include calcified algae, bivalve, and rare gastropod shells and foraminiferal tests. The grains in Facies 4 are moderately to well-sorted. The grain size varies from fine to coarse-grained.

The diverse fossil assemblage again indicates fully marine conditions. The grain size and subangular to subrounded grain shape of abundant skeletal fragments points to decrease in energy of the environment, probably, due to rapid sea level rise while gastropod, bivalves, green calcareous algae and small foraminifera are typical for lower energy conditions of a restricted lagoon (Karami-Movahed, Aleali and Ghazanfari 2016, Shabafrooz et al. 2015).

4.1.5 Facies-5: coral (p) lime mud dominated packstone

Facies 5 displays a dense wackstone-packstone texture (Figure. 4, 6c; Table-1). It is composed of rich platy coral fragments, with minor remains of solitary corals, gastropods, foraminifera, red calcified algae, and echinoderms. Grain size varies from very fine to coarse-grained and grains are moderately to well sorted. The Facies 5 interval is characterised by tight limestone. The presence of abundant platy corals, foraminifera, calcified algae with a minor contribution of bryozoan, bivalve and some massive coral debris suggests a deeper to open marine environment low energy environment which is evidence also by the presence of the small benthic foraminifera and argillaceous mud. No subaerial exposure features have been recognised in the cores within this facies.

4.1.6 Facies-6: coral (b) lime dominated pack-grainstone

Facies 6 displays a packstone-grainstone (floatstone) texture (Figure. 4, 6f; Table-1). Here the fossil assemblage mostly consists of delicate branching coral fragments including some in situ colonies (branches are 0.5-2.0 cm in diameter) in the packstone matrix. Grains are poorly sorted and vary in size from very coarse to granular. The presence of the corals indicates the normal marine conditions. Miall (2016) ascribed this type of facies to the colonization stage of the reef development. In turn, Blomeier and Reijmer (1999) noted that such coral bioclasts in slope sediments are derived from platform margin. Thus, this facies can represent forereef depositional setting.

4.1.7 Facies-7: cross-bedded skeletal lime packstone

Facies 7 is characterized by packstone (floatstone) texture ((Figure. 4, 6g; Table-1).The fossils here are mostly represented by foraminifera, with a minor constitution of fragments of red calcified algae, coral, bivalves, and echinoderms. Grain size in this facies ranges from fine to coarse, and most of the allochems are moderately sorted. The observed porosity is moderate with a high percentage of isolated vugs. Stylolites and cross-bedding are common and are particularly restricted to this facies. According to Hamblin (1969), cross-bedding occurs only in units composed of ooids, pellets and huge skeletal debris. The cross-bedded, skeletal lime packstone facies represents high variation in grain size. Bioturbation is locally abundant, obliterating the cross bedding. This facies type is the result of transportation of bioclasts and there accumulation in small submarine banks, usually in the less protected area of the carbonate platform. Braga et al. (2012), Macintyre et al. (1987) indicated that in a present-day Brazil shelf, the skeletal sand of a narrow back reef belt runs parallel to the barrier reef, in which sand is transported from the reef especially during a high storm. However, the skeletal sands, in this case, were not considered as a back reef setting.

4.1.8 Facies-8: bioturbated carbonate mud (chalk)

Facies 8 displays wackstone-packstone texture (Figure. 4, 6h; Table-1). This lithology is composed mostly of bioturbated carbonate mud yielding abundant planktonic foraminifera and minor debris of corals and red calcified algae. The grain size varies from very fine to coarse. The porosity in this facies is mainly associated with dissolution. Stylolites are present. Due to the abundance of carbonate mud, planktonic and small benthic foraminifera and ostracodes, this facies is interpreted to be deposited towards the open sea, more specifically as off-reef deposits (Pomar et al. 2015, Pomar 2001). In off-reef settings, sediments are intensely burrowed; locally Ophiomorpha, and Thalassinoides are present. The optimum water depth for the carbonate production here is 100 m, below the photic zone.
4.2 Petrography

4.2.1 Grain types

The qualitative observation of thin sections revealed that a restricted number of components constitute the bulk rock volume. These are almost exclusively skeletal components. Ooids are absent, and peloids are uncommon. Predominantly eight skeletal varieties are observed including red calcified algae (Figure 7a), foraminifera (Figure 7b), echinoderms (Figure 7c), bivalves (Figure 7d), corals (Figure 7e), green calcified algae (*Halimeda*) (Figure 7f), bryozoans (Figure 7g), and calcified sponges (Figure 7h).

Fig. 7. Petrographic images of 8 important components, (a) Red algae: Microstructure is due to micritization and early calcification, (b) Micritization of test walls saves from late stage dissolution. Only the mud filled in the chambers are dissolved and recrystallized, (c) HMC nature of echinoderm plates leads to neomorphism, (d) Bivalves, representing multilayer, the brownish color reflecting organic remains and growing bending layer representing calcitic layer, (e) Only the corallite crevices/cavities recognizable by corg rich mud, (f) Green algae: Leached in the limestone in which green algae form a substanied part of the total sediments, (g) Bryzones: Forming large and branching masses, showing regular boxlike arrangement of their zooecia and (h) Sponge: Only the margin of the sponge are selectively micritize, the rest of the sponge was leached and the resulting pores were filled with cement, which is dominantly present in well A and B, Central Luconia offshore Sarawak, Malaysia Adopted from Janjuhah *et al.* (2018a).

Fig. 8. Photomicrographs of representing different porosity types, (a) Intraparticle and moldic porosity, (b) Fracture porosity, (c) Vuggy porosity and...
4.2.2 Pore types

The pore system in Central Luconia is dominated by isolated vugs (Lucia 1995, Lucia 2007). It is attributed to leaching of skeletal allochems leading to a partial or complete destruction of primary rock fabric. Such a selective dissolution was caused by the primary composition of skeletons which consists of either aragonite (corals, green algae, some foraminifera, bivalve, and sponges) or a high-magnesium calcite (red algae, echinoderms, some foraminifera, bivalve, and sponges); both these carbonate mineralologies were highly labile and dissolved soon after burial (Zhuravlev and Wood 2009). The initial observation of the thin section indicates that the mouldic pores are dominated. The process created poorly connected enlarge mouldic porosity. Pore types include mouldic, intraparticle, interparticle, fractured and vuggy porosity (Figure. 8), are observed based on Choquette and Pray (1970). Most of the observed pores are almost exclusively secondary in nature.

4.2.3 Quantitative analysis of thin sections

A detailed petrographic quantitative study revealed that the considered core lithology is composed of 85% of limestone, with 10% of dolomitic limestone and 5% dolostone (Figure. 9a). The core of these wells are mostly composed of coarse-grained carbonate grains that are generally depleted of mud. In terms of texture, packstone account for 50% of the cored rock, and grainstone, floatstone and rudstones constitute other 40% (Figure. 9b). This sectioning allowed us to quantify the grain, matrix, and cement content as well as visible porosity and revealed that carbonate grains cover an area of 33%, followed by 31% of matrix, 29% of cement and 7% of visible porosity (Figure. 9c). The grains and visible porosity is further classified based on the quantitative observation of 8 dominant components and different pore types. The grains are dominated by eight components namely, by red algae (30%), corals (30%), foraminifera (25%) and green algae (10%) while echinoderm, bryozoans, and bivalves account to the remaining 5% (Figure. 9e). Besides, five different pore types are observed in descending order, mouldic porosity is the dominant porosity, covering an area of almost 50%, vuggy porosity (20%) intraparticle porosity (15%), interparticle porosity (10%), and fracture porosity (<5%) (Figure. 8, 9d).
4.3 Petrophysical properties and reservoir quality based on deposition, diagenesis, and microporosity

4.3.1 Facies and petrography

The porosity and permeability measurement and petrographic analysis of the eight facies revealed that the visible porosity varies from poor to fair in facies 1, 5 and 8 while it is locally good to very good in facies 2, 3, 4, 6 and 7. Considering total porosity, the hydrocarbon reservoir potential is suggested to be generally thought-out to be fair for the middle to upper Miocene (Cycles IV and V) carbonates of the Central Luconia, Offshore Sarawak, Malaysia. The porosity-permeability values of numerous reservoir facies also expresses that the facies-2 (av. Ø = 14.7%, av. Kh = 6 mD), facies 3 (av. Ø = 10%, av. Kh = 4 mD), facies 4 (av. Ø = 15%, av. Kh = 9 mD), facies 6 (av. Ø = 15%, av. Kh = 1 mD) and facies 7 (av. Ø = 20%, av. Kh = 3 mD) exhibits better reservoir qualities (Figure. 10). On the contrary, the facies 1 (av. Ø = 6%, av. Kh = 1 mD), facies 5 (av. Ø = 4%, av. Kh = 0.5 mD) and facies 8 (av. Ø = 8%, av. Kh = 0.8 mD) are thought to be dense limestone characterizing by a poorer reservoir quality. In hand-specimen/petrographic observation revealed that large mouldic pores commonly occur within coral fragments, while smaller mouldic pores appear to be formed from leaching of finely dispersed coral, foraminiferal and algal debris. It is also observed that most of the porosity present in the corals are completely cemented by calcite cement (Figure. 7e), representing tight reservoir intervals. Janjuhah, Salim and Ghosh (2017b) also documented that calcite cement filled the void spaces in Central Luconia carbonate rocks. As has
been shown, mouldic pores are the dominant pore types. Diagenesis also play an important role in controlling the reservoir quality (Janjuhah et al. 2017c, Janjuhah et al. 2017b). Janjuhah et al. (2017b), Janjuhah et al. (2017c), Janjuhah et al. (2017a) stated that mouldic pores which are present in Central Luconia are isolated in nature. The presence of low permeability value in different facies is strongly related to the non-touching pore system or poorly interconnection due to the small size of matrix intercrystalline pores as well as the presence of organic rich mud and pressure solution seams. These phenomenon may constitute a potential barrier to fluid flow (Janjuhah et al. 2017b), it is worth saying that the micritization is the major diagenetic process which effect the reservoir quality because it destroys the internal structure of the grains and reduced the porosity. The porosity in carbonate rocks are usually reduced by the micritization which decreases the pore throat radius or grain size by filling them with micrite (Taghavi, Mørk and Emadi 2006). The same phenomenon is also mentioned by Shakeri and Parham (2014), Janjuhah et al. (2017c), who stated that micritization and compaction severely reduced porosity in carbonate rocks.

### 4.3.2 Reservoir quality enhancement based on microporosity

The macroporosity includes all pore types (mouldic, intraparticle, interparticle, vuggy) greater than 10 μm. However, the total porosity which is measured from the core plug and the macroporosity which is quantified from thin sections revealed that this is the microporosity that comprises a significant percentage in Miocene carbonates. (Figure. 11) illustrated clearly a contribution of microporosity by comparing of total porosity vs. permeability cross plot with macroporosity vs. permeability cross plot (Figure. 10, 11). The relationship macroporosity versus permeability cross plot represents a good fit with an increase of R² (coefficient of determination) values as compared with total porosity verse permeability cross plot. The R² increased from 0.51 (total porosity vs. permeability) (Figure. 10) to 0.81 (macroporosity vs permeability) (Figure. 11).
Furthermore, to obtain the contribution of the microporosity with respect to the different facies encountered within wells, a separate cross plot for each facies was built. Among all identified facies, the measured porosity is higher than the macroporosity but when the macroporosity is cross plotted with permeability, it shows a better fit with an increase of the R² values compared to the total porosity versus permeability curve. The Facies-1 coated grain packstone represented a mean total porosity of 10% with R² = 0.51 (Figure. 12a), considering the macroporosity as a function of permeability, the R² increased to 0.67 (Figure. 12b). Facies-2 (Coral (m) lime-dominated pack-grainstone) total porosity versus permeability cross plot resulted a coefficient of determination R² = 0.51 (Figure. 12c). Considering macroporosity than the total porosity vs permeability - an increase in the value of R² which is 0.70 (Figure. 12d). The cross plot of total porosity vs permeability for Facies-3 (Oncolite lime-grain-dominated packstone) gave a correlation coefficient of R² = 0.76 (Figure. 12e). The regression coefficient R² increased up to 0.90 when the permeability value of Facies-3 is plotted with respect to macroporosity (Figure. 12f). Facies-4 (skeletal lime dominated dolo-packstone) revealed a total porosity up to 20%, the average valued of R² in total porosity vs permeability cross plot is 0.59, (Figure. 12g), whereas by considering macroporosity the R² increased up to 0.72 (Figure. 12h). Same phenomena observed in other facies as well. As Facies-5 (Coral (p) lime mud-dominated packstone) where R² increases from 0.66 to 0.81 (Figure. 12i-j), Facies -6 (Coral (b) lime dominated packstone) from 0.61 to 0.78 (Figure. 12k-l), Facies-7 cross-bedded skeletal lime packstone from 0.50 to 0.69, and Facies-8 (Bioturbated carbonate mudstone (Chalk) the coefficient of determination R² increased from 0.44 to 0.67 (Figure. 12 m-p).
4.3.2 Facies distribution

The eight identified facies have been grouped into two classes known as good reservoir facies and poor reservoir facies (Figure. 13). Facies-2, Facies-3, Facies-4, Facies-6, and Facies-7 are ascribed to good reservoir facies, whereas Facies-1, Facies-5, and Facies-8 possess a poor reservoir quality. Figure. 13 provides a correlation of two grouped reservoir facies in five wells within two carbonate platforms (1 and 2). The platform-1 is a deeper platform towards the NE direction of Central Luconia. Where the poor reservoir quality is overlay the good reservoir quality and this is due to the deepening of platforms towards the open sea (Figure. 13). This phenomenon is also supported by the dominant presence platy corals and argillaceous material in Facies-5 in Well-B. While in the platform-2, the good reservoir facies are dominant towards the landward but as the platform extent towards the open sea, the thinker good reservoir quality are interbedded with thinner poorer reservoir facies (Well D and Well E) (Figure. 13).

5 Conclusion

The carbonates in Central Luconia, Offshore Sarawak, Malaysia, consist mainly of limestone with minor constituent of dolomitic limestone and dolomite. A detailed core description revealed that these carbonates consist of eight facies: coated grain packstone (F-1), massive coral lime grainstone (F-2), oncolite lime grain-dominated packstone (F-3), skeletal lime/dolo packstone (F-4), coral (p) lime mud dominated packstone (F-5), coral (b) lime dominated pack-grainstone (F-6), cross-bedded skeletal lime packstone (F-7) and bioturbated carbonate mudstone (Chalk F-8). Foraminifera, red algae, and corals are the main fossils components. The porosity-permeability measurement shows a good porosity but low permeability value at a given total porosity, the presence of high isolated mouldic pores that are observed under the micropores is the main reason to have a high porosity with low permeability. In carbonate rocks, the porosity and permeability value is directly related to the diagenesis, which alter the rock properties. It is also documented that the impact of microporosity cannot be simply neglected, especially when dealing with carbonate reservoirs. The microporosity has an obvious impact on the quality of reservoir. While assessing reservoir properties or reservoir performance, taking macroporosity into consideration can improve the reservoir quality prediction in Central Luconia, Offshore Sarawak, Malaysia.
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References


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