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Research Article
Sedimentology and Reservoir Geometry of the Miocene Carbonate Deposits in Central Luconia, Offshore, Sarawak, Malaysia

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Abstract
Background: Carbonate buildups in Central Luconia are proven prolific hydrocarbon reservoirs, represented by thick limestone deposits with a minor proportion of dolomitic limestone. The limestone diversity attracted the considerable attention of oil and gas companies and geologists from all over the world. However, owing to many changes in lithology, facies characteristics and reservoir prediction of this formation, industry players still face challenges to identify and corroborate the lithology, facies and reservoir occurrence. **Objective:** To have better understanding on the reservoir quality and to increase hydrocarbon production, the current study aims to identify the lithofacies, depositional environment and diagenetic process which influence the reservoir rock. **Methodology:** Core description was conducted, core plugs were collected and thin sections of these core plugs were prepared. **Results:** The Central Luconia carbonates are divided into 8 facies. Based on the sedimentary structure, texture, components and fossils contents, 5 facies are identified in well A and B, namely: (1) Coated grain packstone, (2) Coral massive (m) lime grainstone, (3) Oncolite lime grain packstone, (4) Skeletal lime packstone and (5) Coral platy (p) lime mud packstone. Facies 4 is the dominant facies types in well A and B. Biota includes red algae, coral, foraminifera, echinoderm, sponge, green algae, bryozoans and bivalve. Visible porosity is from poor to very good. It varies in different facies with common open moulds and small vugs. However, low (Facies 1 and 5) to moderate (Facies 2, 3 and 5) permeability valves suggests that matrix porosity provides only limited interconnection between the large moldic pores. Many pores appear to form an early leaching of foraminifera and corals in facies 2 and 4. **Conclusion:** Deposition environment is interpreted to be lagoonal condition for these facies based on the features of the biotic assemblage. Lithofacies indicate a good quality reservoir, but diagenesis plays an important role in creating and destroying porosity. The main diagenetic processes affecting the reservoir quality are compaction including stylolite and cementation of calcite and dolomite. Whereas the dissolution is the main diagenetic processes in improving porosity and mechanical compaction enhancing permeability by forming small fractures.

Key words: Central Luconia, facies, depositional event, diagenetic event, reservoir properties,

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Central Luconia is the major gas contributor, containing 60% of the Malaysian gas reserves (Fig. 1). Central Luconia extends for some 240×240 km and is covered by the South China sea, which is 20-80 m deep[1]. The first offshore gas field in Central Luconia was developed[2] in 1982. Many research literature have been published on Central Luconia platofrm coverting geology, stratigraphy and reservoir aspects[3-11]. More than 200 carbonate platforms have been systematically mapped and out of those 60 have been drilled so far in the area of Sarawak, Malaysia (Fig. 1). These carbonates are massive gas producers, containing 65 trillion cubic feet of gas in place with minor contribution of oil reserve[12,13]. The corals and coralline red algae are the chief contributors for the growth of these carbonate platforms in Central Luconia[4]. According to Checconi *et al.*[14] and Ghosh and Sarkar[15], the carbonate production in many other modern carbonate platforms was also controlled by coralline red algae. Despite numerious publications, a proper documentation of facies scheme, depositional event, diagenetic events and reservoir properties is still missing.

The current study aimed to understand the sedimentological and reservoir properties (porosity, permeability and grain density) of carbonate reservoir of middle miocene age, offhsore, Sarawak, Malaysia. The main objectives of this study are (1) To determine the facies characterization, (2) To analyze the different diagenetic procceses and their events, (3) To highlight the different reservoir properties of different types of carbonate rocks and (4) To develop a relationship between the facies characterization, diagenesis and reservoir properties.

Central Luconia is distinguished from adjacent tectonic domains based on relatively shallow burial and structural simplicity. The province is flanked by deep basins on the West, North and East sides (Fig. 2). A prominent lineament, the West Baram line, separates Central Luconia from the Baram Delta. The Western part of the Baram Delta, located in Sarawak, is known informally as the West Baram Delta (WBD). In the South is the compressed Balingian province (Fig. 2)[5,7,16,17]. Because of extensional forces Central Luconia is divided into a number of localized extensional half grabens and grabens, which trend SSW-NNE, whereas compressional structures mostly trend WSW-ENE directions (Fig. 3).

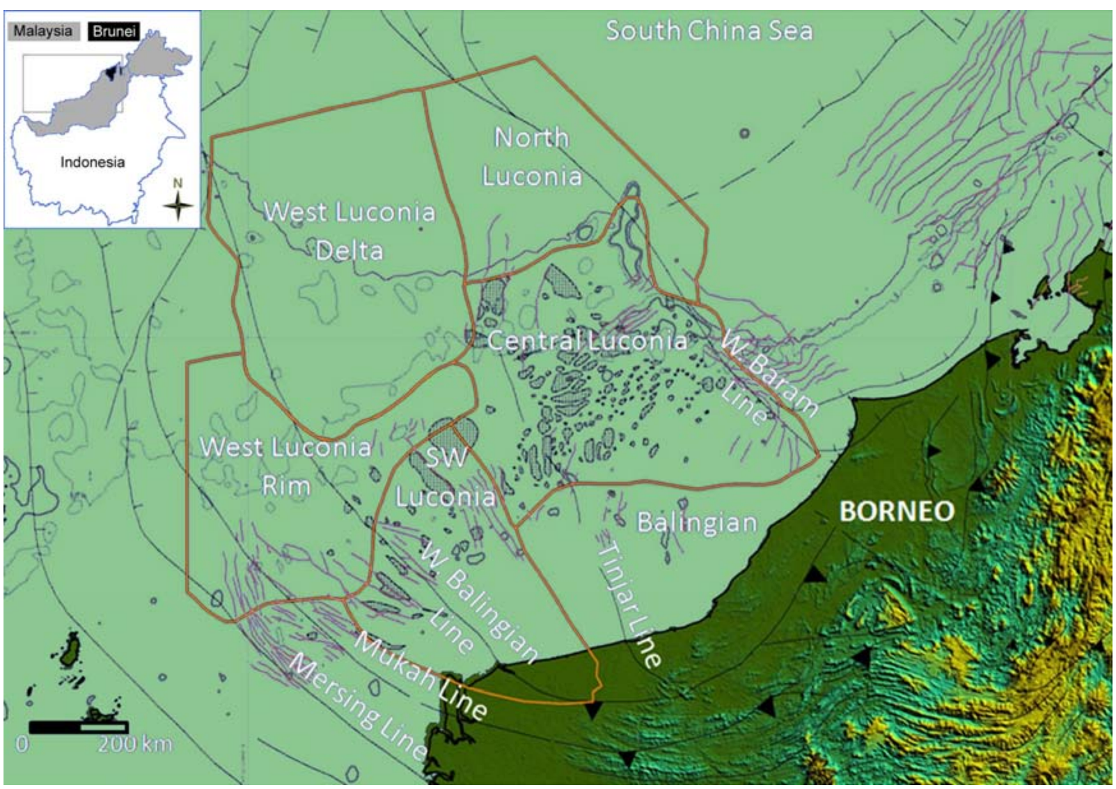

Fig. 1: Geological sectors differentiated in the Luconia province, offshore Sarawak, East Malaysia. The isolated carbonate platforms scattered mostly throughout Central Luconia

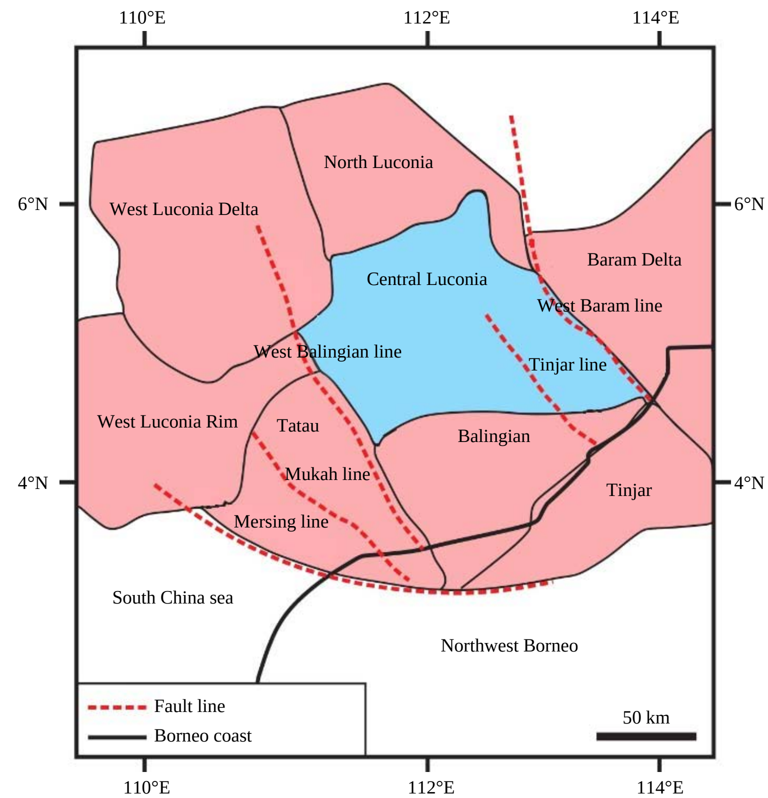

Fig. 2: Structure map of Central Luconia carbonate platform offshore Sarawak, Malaysia. Source: Janjuhah *et al.*[62]

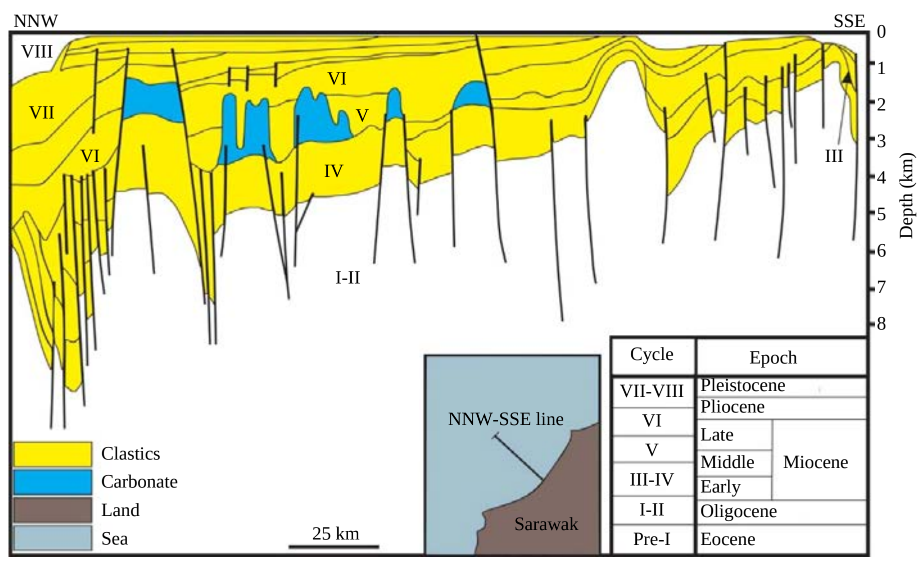

Fig. 3: Offshore Sarawak's structural sketch showing the boundaries of Central Luconia-a sector with numerous isolated carbonate platforms-in the Luconia province. Source: Janjuhah *et al.*[62]

In Central Luconia most of the sediments are dominated by prograding clinoforms, which form the basis for subdivision of the stratigraphy into 8 regressive cycles that are separated by major transgressions[3,7]. These cycles range in age from eocene to present. During cycle I time (Fig. 3), deep-water argillaceous and shallow marine siliciclastic successions were deposited in an early synrift graben-filling sedimentation process. This was followed by a late phase of synrift sedimentation through cycles II and III during the opening of the South China sea. Continuous subsidence and formation of half-grabens resulted in widespread middle to upper Miocene carbonate deposition during cycles IV and V (Fig. 3). This was eventually stopped by the influx of siliciclastic sediments derived from the uplifted Rajang fold-thrust belt during cycle V and VIII[10]. According to Epting[5] all four of these events occurred in a specific pattern in space and time in the Miocene carbonate platforms of Central Luconia.

MATERIALS AND METHODS

To achieve the goal of this study the cores were initially described manually onto the description sheet known as well A and B representing cycle IV (Middle miocene) and cycle V (Late miocene) carbonates. A total of 688 ft (210 m) of cores were logged from well A and B. Emphasis at this stage is placed on description of various sedimentological features such as depositional textures, nature of skeletal and non-skeletal grains, stylolites and matrix (Fig. 4, 5). The grain size profile in well A (Fig. 4) and well B (Fig. 5) represents the dominant size of the main skeletal components (algae, foraminifera, coral and echinoderm fragments). Carbonate depositional texture in both wells (Fig. 4, 5) is based on the classification of Dunham[18]. These thin sections from both wells (Well A and B) were also examined at 1 ft spacing and described for the quantitative distribution of grain, matrix, cement and visible porosity (Fig. 4, 5). Reservoir properties were established on the basis of standard core plugs measurement. Core plugs were measured under overburden pressures at 1800 psi.

RESULTS AND DISCUSSION

The facies scheme used for well A and B cores is the scheme introduced by Janjuhah. The scheme classifies rocks on the basis of depositional texture and wireline log response. In well A and B only five facies of Janjuhah are recognized, namely: (1) Coated grain packstone, (2) Coral massive (m) lime grainstone, (3) Oncolite lime grain packstone, (4) Skeletal lime packstone and (5) Coral platy (p) lime mud packstone. Based on the core plug matrix density measurement, well A and B are composed of 90% of limestone with 10% of dolomitic limestone (Fig. 6). Among these five facies, facies 4 is the dominant facies types in well A and B covering 45% of the cored intervals followed by facies 1 (25%), facies 5 (15%), facies 2 (10%) and facies 3 (5%), respectively (Table 1). Quantitative observation of petrographic observation revealed that grain is dominant, covering 35% of the total area and matrix is the second contributor with 30% followed by cement 30% and visible porosity 5% (Table 1, Fig. 4, 5). Qualitative observation revealed 8 dominant components in well A and B in Central Luconia, offshore, Sarawak, Malaysia (Fig. 7). These grains are dominated by red algae 35%, foraminifera 20%, coral 20%, green algae 10%, sponge 5%, echinoderm 5%, bivalve, bryozoans are <5%. These dominant components cover 35% of the grain area (Table 1, Fig. 7). Mouldic (Fig. 8a), intraparticle (Fig. 8a), interparticle (Fig. 8d), vuggy (Fig. 8c) and fracture (Fig. 8b) are the five dominant porosity types observed in well A and B (Fig. 8) based on Choquette and Pray[19]. Mouldic porosity is the most dominant porosity types covering an area of 50% (Table 1) and highly observed in facies 2, 3 and 4, vuggy porosity is the second dominant porosity types in well A and B covering 20% of the total interval, then intraparticle porosity 15%, interparticle porosity 10% and fracture porosity <5%. All of this semi-quantitative observation of porosity types is the further subdivision of 5% of the visible porosity (Table 1, Fig. 4, 5).

Facies 1: The facies 1 consists of well-connected packstone (floatstone) textures (Fig. 4, 5, Table 2). It's composed of algae, corals and diverse assemblage of skeletal debris with minor constituent of echinoderm and bivalve. The size of the grains in this facies varies from fine to medium gravel. Most of the allochems are moderately to poorly sorted grains[20]. The visible porosity in this facies is very little apart from isolated vugs. Stylolites are dominantly present. Facies 1 indicates marine condition based on the fossils assemblage. Facies 1 indicates high energy environment based on the presence of oncolite together with the roundness of most of the allochems. Alshuaibi *et al.*[21] highlighted that the high rolling frequency is the cause of algae coating which supports the initial interpretation of high energy. The porosity in this facies ranges from 0.1-8% and an average permeability is 1 mD (Fig. 9). This is a poor reservoir facies with low porosity and permeability. It seems that this type of limestone transforms right after deposition and additionally diagenesis modify the rock[22-24].

Facies 2: Facies 2 is predominantly composed of packstone-grainstone (rudstone) textures (Fig. 4, 5, Table 2). It is dominated by massive coral and coral debris along with diverse assemblage of skeletal components, minor platy corals debris and branching coral debris as well (Table 1). The grain size in facies 2 is very coarse to granule in size with poorly sorted grains[20]. In facies 2 the visual observation from core and petrographic observation revealed that intense leaching turned many grains into large intraskeletal pores like mouldic porosity (Fig. 8a) and created fine microscopic intercrystalline

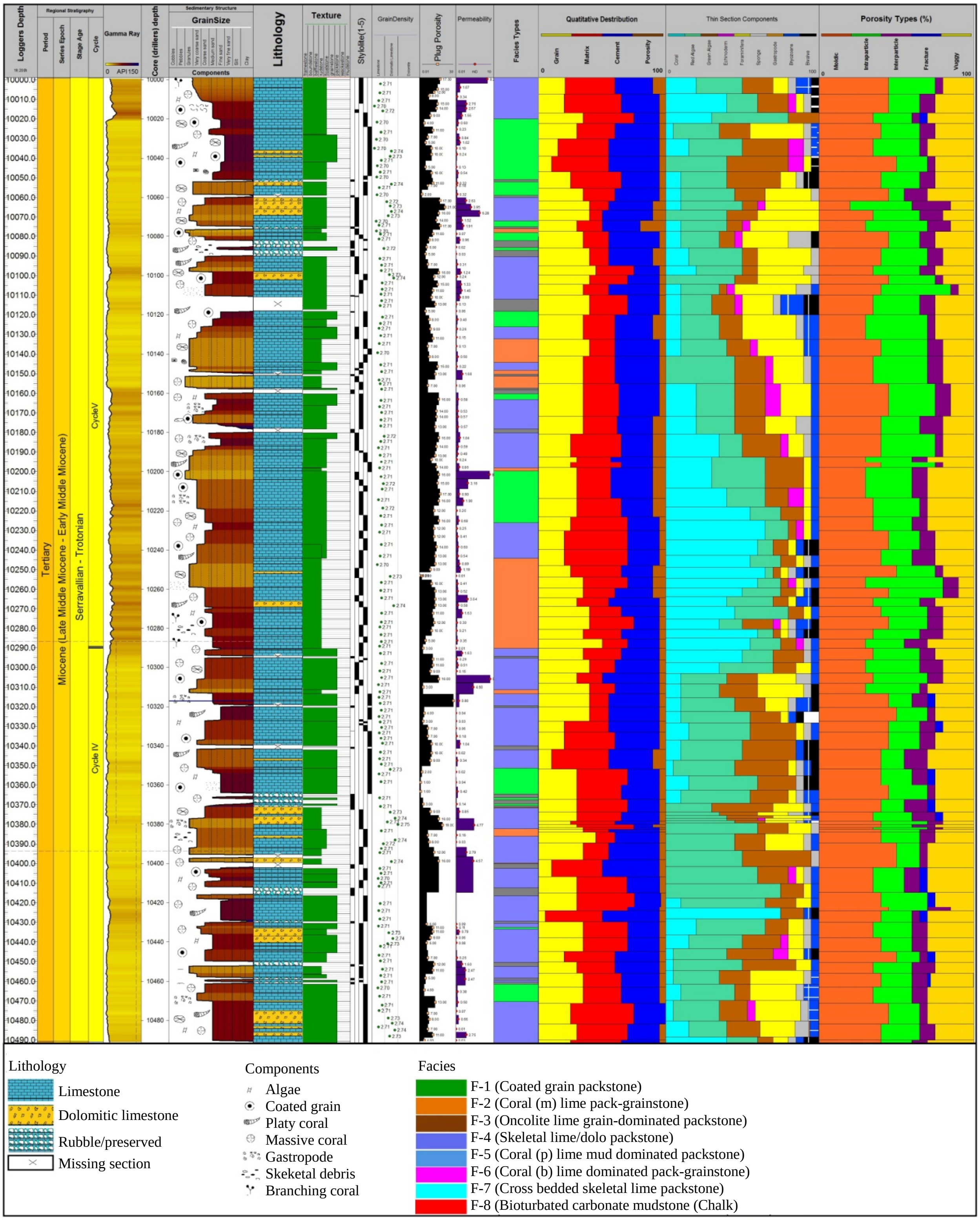

Fig. 4: Sedimentological log showing qualitative and quantitative description of well A in Central Luconia, offshore Sarawak, Malaysia

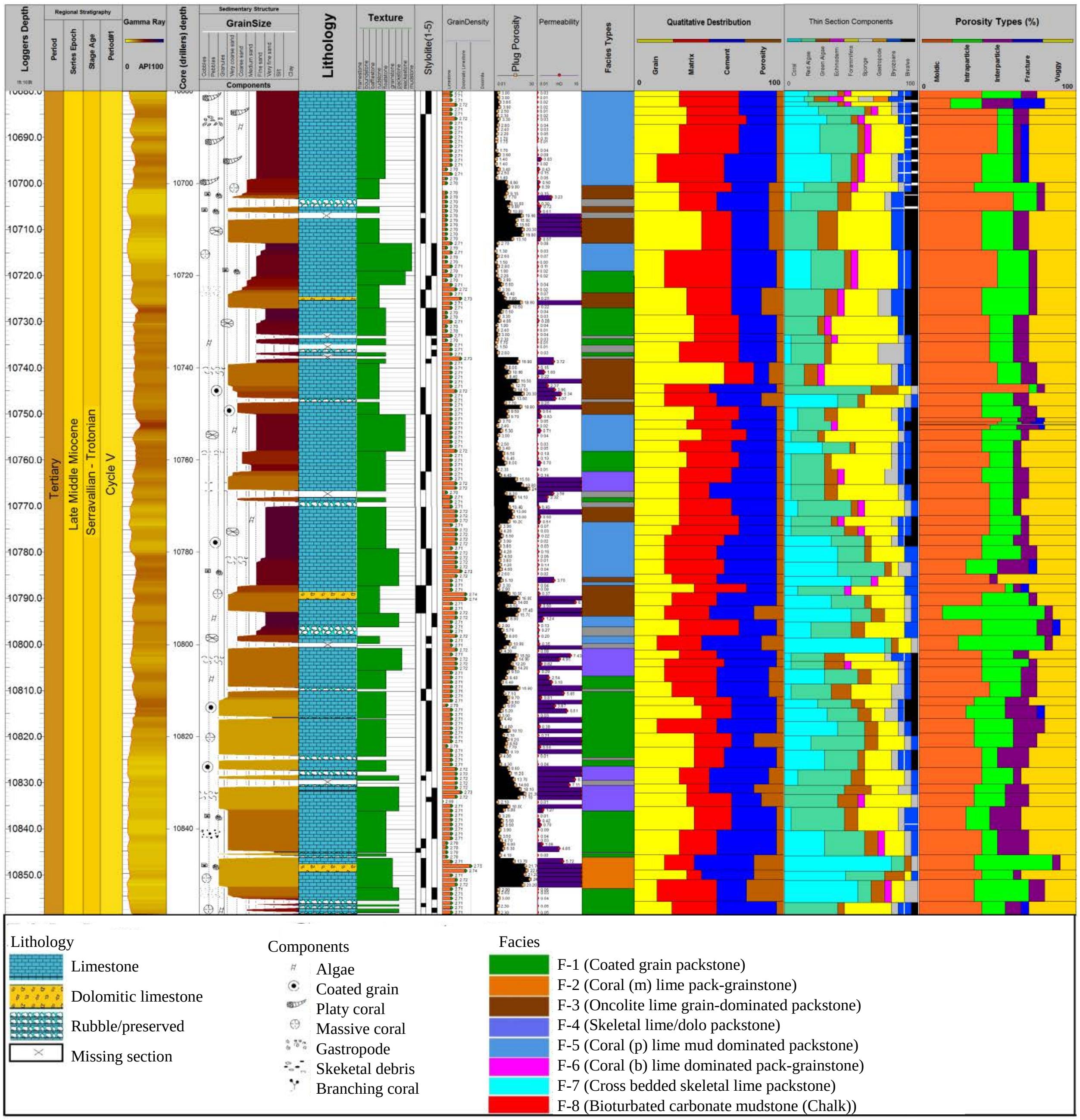

Fig. 5: Sedimentological log showing qualitative and quantitative description of well B in Central Luconia, offshore Sarawak, Malaysia

pores in the muddy matrix[20]. Facies 2 indicates marine condition based on the fossils assemblage. It reflects low energy environment as it can be explained by the size of grains and asymmetrical oncolite coating[25]. Facies 2 is interpreted as lagoonal deposits. This is the best reservoir facies type having the highest average of porosity (7-25%) and permeability up to 10 mD over other facies types in well A and B (Fig. 4, 5, 9).

Facies 3: The facies 3 comprises predominantly packstone (rudstone) texture (Fig. 5, Table 2). More than 70% of this facies is dominated by the diverse rhodolite/oncolite assemblage, with other contribution of skeletal debris including foraminifera, red algae, massive corals, minor bivalve and echinoderms (Table 2). The grain size varies from medium to gravel[20]. The grains are moderately to poorly sorted. It indicates marine condition based on the

Table 1: Showing summary of quantitative data set gathered from core and thin section description from well A and B

Regional stratigraphy				Gamma ray	Grain size		Lithology	Texture		Facies	Quantitative description	Components	Porosity types
Period	Series epoch	Stage	Cycle	10-20 API	Medium sand to granule	Clay (0%)	Limestone (90%)	Packstone	50%	Facies-1 (25%)	Grain (35%)	Coral (20%)	Moldic (50%)
						Silt (0%)						Red algae (30%)	
						Very fine (5%)							
						Fine sand (5%)		Grainstone	15%	Facies-2 (25%)	Matrix (30%)	Green algae (10%)	Intraparticle (15%)
						Medium sand (20%)						Echinoderm (<5)	
						Coarse sand (35%)							
Tertiary	Miocene (Late miocene to early middle miocene)	Serravallian-trotonian	Cycle IV-V			V. Coarse sand (20%)	Dolomitic limestone (10%)	Floatstone	20	Facies-4 (50%)	Cement (30%)	Foraminifera (20%)	Interparticle (10%)
						Granule (15%)						Sponge (5%)	
						Pebbles (0%)		Rudstone	15%		Visible porosity (5%)	Bryozoan (<5)	Fracture (<5)
						Cobbles (0%)						Bivalve (<5%)	Vuggy (20%)

Table 2: Facies scheme of Central Luconia based on cores from 8 wells, offshore Sarawak, Malaysia

Lithofacies	Description
FA-1 coated grain packstone	Texture: Packstone (floatstone) Mineralogy: Limestone Components: Algae >50%, oncolite algae <40%, corals <30%, separate vugs, skeletal debris (angular-subangular), forams, echinoderms, gastropods and leaching Grain size/sorting: Fine-medium gravel/moderately-poor
FA-2 coral (m) lime pack-grainstone	Texture: Packstone-grainstone (rudstone) Mineralogy: Limestone Components: Corals (m) >50% (up to 8 cm in diameter), platy coral up to 20%, branching corals (15%), solitary coral <5%, algae, disconnected vugs, oncolite algae, skeletal grains (angular-subangular), gastropods, bivalves and echinoid spines Grain size/sorting: Very coarse-granule/moderately-poor
FA-3 oncolite lime grain-dominated packstone	Texture: Packstone (rudstone) Mineralogy: Limestone Components: Oncolite algae >70% (diameter 2-6 cm), stylolite, corals >30%, separate vugs, algae, gastropods, bivalves, echinoid spines, skeletal grains (angular-subangular) and leaching Grain size/sorting: Medium-gravel/moderately-poor
FA-4 skeletal lime/dolo packstone	Texture: Packstone (floatstone-rudstone) Mineralogy: Limestone-dolomitic limestone Components: Skeletal debris >60% (angular-subangular), bivalves, isolated gastropods, corals (m) <20%, coral (p) <15% and leaching Grain size/sorting: Fine-coarse grain/moderately-well sorted
FA-5 coral (p) lime mud dominated packstone	Texture: Packstone (floatstone) Mineralogy: Limestone Components: Rich platy corals >70%, solitary coral up to 15%, algae, small fractures, disconnected small vugs, skeletal debris (angular-subangular), gastropod, forams and echinoid spines Grain size/sorting: Fine-coarse/poor
FA-6 coral (B) lime dominated pack-grainstone	Texture: Packstone-grainstone (floatstone) Mineralogy: Limestone-dolomitic limestone Components: Branching coral 50 and 20% red algae, 15% forams, 5% massive coral, 5% bivalve, 5% other skeletal debris (angular-subangular) Grain size/sorting: Very coarse-granule/poor
FA-7 cross bedded skeletal lime packstone	Texture: Packstone (floatstone) Mineralogy: Dolomitic limestone to limestone Structures: Graded bedding Components: Forams 65%, red algae 10%, coral fragments 10%, bivalve 5%, echinoderms 5%, other skeletal debris 5% Grain size/sorting: Very coarse-pebble/poorly-moderately sorted
FA-8 bioturbated carbonate mud stone (Chalk)	Texture: Wackstone-packstone Mineralogy: Dolomitic limestone Structures: Bioturbation Components: Burrowing and bioturbation 60%, forams 10%, coral debris 10%, red algae 5% Grain size/sorting: Very fine-coarse/moderately-well sorted

Source: Janjuhah *et al.*[62]

fossils assemblage and their composition. According to Cook *et al.*[26], Myrow and Landing[27] and Pomar[28] the oncolite facies happens relatively in shallow water in a near shore situation close to the basement area. Shallow open marine deposits are featured with the abundance of algal balls (oncolite/rhodolites) and some corals which suggests that deposition occurs under medium to occasionally high energy condition, possibly with some current movement[29-32]. This is moderately good reservoir facies with porosity ranges from 6-20% and permeability is 0.1-10 mD (Fig. 4, 9).

Facies 4: Facies 4 comprises carbonates with grain-supported textures (Fig. 4, 5), (predominantly packstone-floatstone), muddy matrix and macroscopically visible moulds or pores. Based on the grain density facies 4 is composed of limestone to dolomite, but the percent of limestone is more than dolomite (Fig. 6). The average thickness of this facies is from a few centimeter to up to 2 m (Fig. 4, 5). The skeletal debris are the dominant component followed by bivalve, corals (m) etc. (Table 2, Fig. 4, 5). The average grain size of these components are from fine-coarse granule with angular to subangular in shape[20]. These grains are moderately to well-sorted. Porosity in this facies ranges from 0.1-22%, whereas, the permeability is up to 10 mD (Fig. 9) with the grain density ranging from 2.7-2.75, respectively (Fig. 6). Mouldic porosity is the dominant porosity types in facies 4 (Fig. 8a). This main porosity type appears to be of secondary origin and its attributed to leaching of skeletal grain which is clearly observed during core description, in particle of leaching of calcareous algae and corals. This

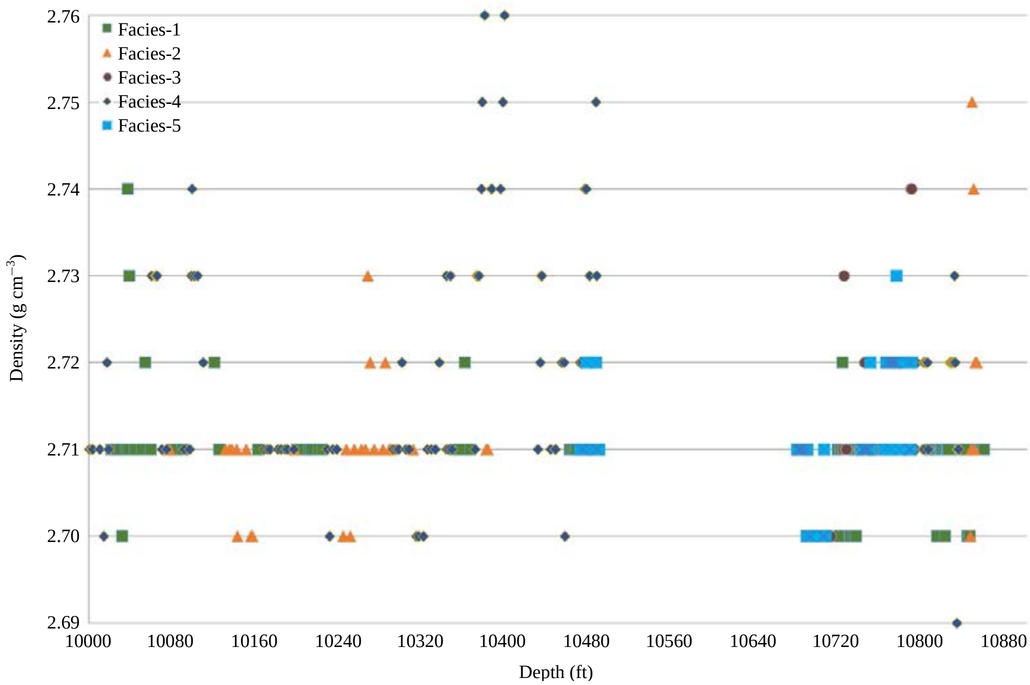

Fig. 6: Cross plot between depth and density present in the reservoir interval of well A and B. The occurrence of density represents the increase in the rate of dolomitization with increasing the depth

process created well connected, enlarged intergranular pores and skeletal moldic porosity.

Facies 5: Facies 5 comprises lime wackstone-packstone textures (Fig. 5). The platy corals are the dominant contributor of this facies along with foraminifera debris 10%, corals and red algae <5% (Table 2). This facies is also characterized by the presence of clay seams and pressure solution features, including horsetail structures with fine to coarse grain carbonate sediments. The grains are poorly sorted. This facies reflects deeper to shallow open marine environment based on the presence of high platy corals, small benthic foraminifera and algae with minor constituent of bryozoans and bivalve[31,32]. The presence of dirty carbonate (argillaceous mud), small benthic foraminifera and no any subaerial exposure are the evidence which reflects deeper, low energy environment[31,33]. The porosity in this facies ranges 1-8% with permeability of <1 mD (Fig. 9). It reflects poor reservoir quality with low porosity and permeability value.

Diagenetic processes

Micritization: In the process of micritization the bioclasts are altered by the attack of bacteria, fungi and endolithic algae leading to form micritic envelops around the bioclasts in the quitter water on the sea floor or just below[34,35]. The first diagenetic processes are micritization and its characteristics of shallow marine environment[33-39]. The micrite envelop is observed in well A and B and is widespread in some of the bioclasts usually echinoderm debris margins are effected by the action of micrite, the holes are filled with micrites which lead to form micrite envelop (Fig. 10a). In well A and B the action of endolithic algae is very intensive, the most of the skeletal grains are completely micritized (Fig. 10b).

Cementation: Calcite (Fig. 10c) and dolomite (Fig. 8d) cements were formed in the studied area in well A and B. These cements are reducing different types of porosity especially vuggy porosity types. On certain occasion the calcite cement is followed by stylolite. The core and thin section observation reveals that the calcite cement mostly fills the fractures and vugs. Whereas the dolomite mostly fills the vuggy pores, towards the center of the pores the crystal size of dolomites is larger and it gets smaller towards the margins as per accommodation spaces.

Neomorphism: The neomorphism mostly effected the grain internal structure as well as the matrix background and it is considered one of the major diagenetic processes[34,40]. As a result of this process, aragonatic allochems such as echinoderms (Fig. 10d) and some other shell fragments are

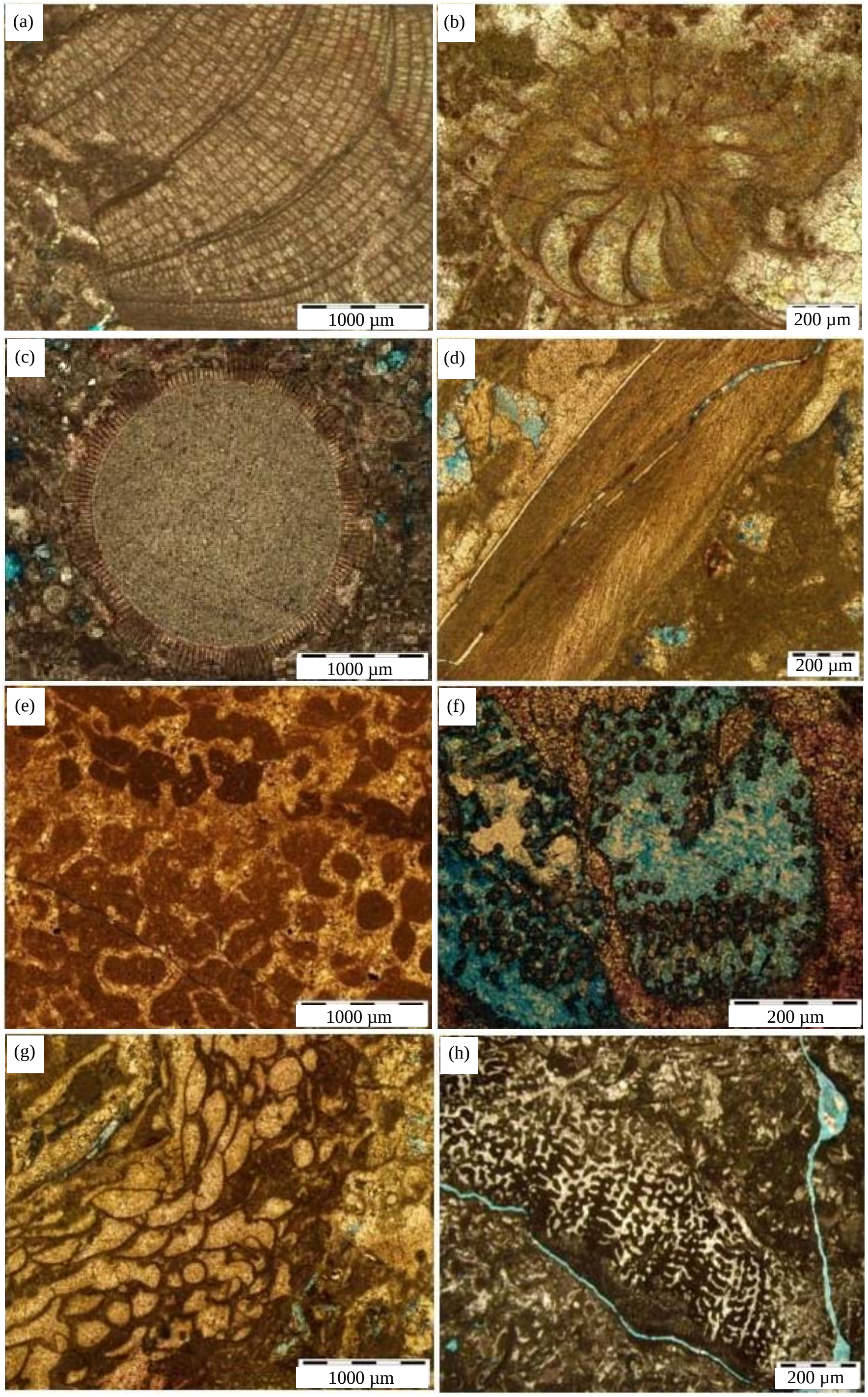

Fig. 7(a-h): Petrographic observations of 8 important components, (a) Red algae: Microstructure is due to micritization and early clacification, (b) Micritization of test walls saves from late stage dissolution. Only the mud filled in the chambers are dissolved and recrystallized, (c) HMC nature of echinoderm plates leads to neomorphism, (d) Bivalves, representing multilayer, the brownish color reflecting organic reniments 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 substained part of the total sediments, (g) Bryzones: Forming large and branching masses, showing regular boxlike arrangement of their zooceia and (h) Sponge: Only the margine of the sponge are selectively micritized. 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

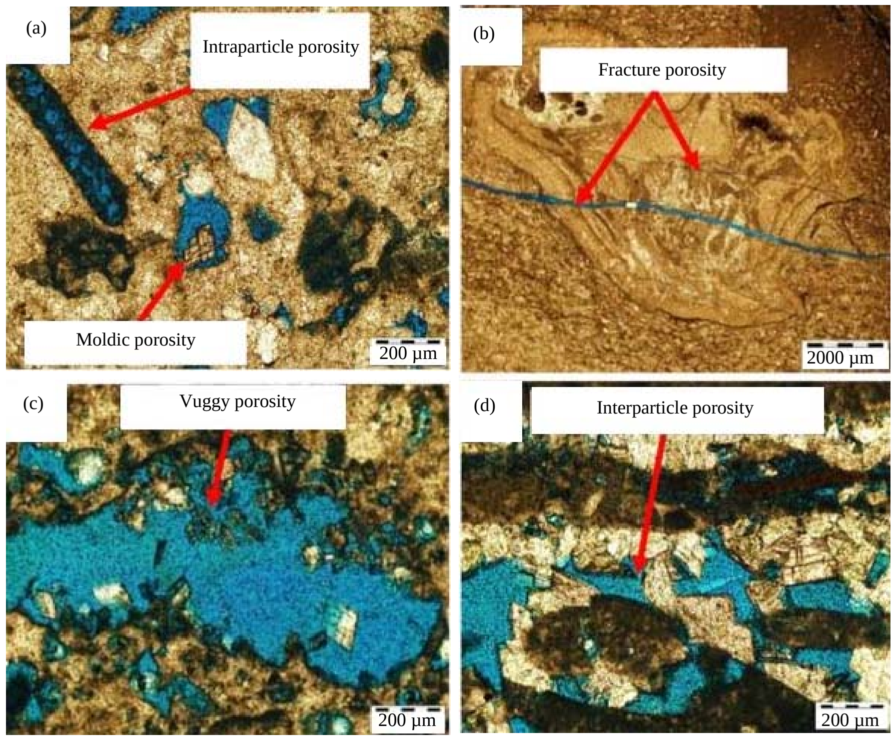

Fig. 8(a-d): Photomicrograph representing different types of porosity, (a) Intraparticle and moldic porosity, (b) Fracture porosity, (c) Vuggy porosity and (d) Interparticle porosity and partial filling of dolomite, dolomite cement filling pore spaces and the rate of dolomitization increase with time in well A and B, offshore Sarawak, Malaysia

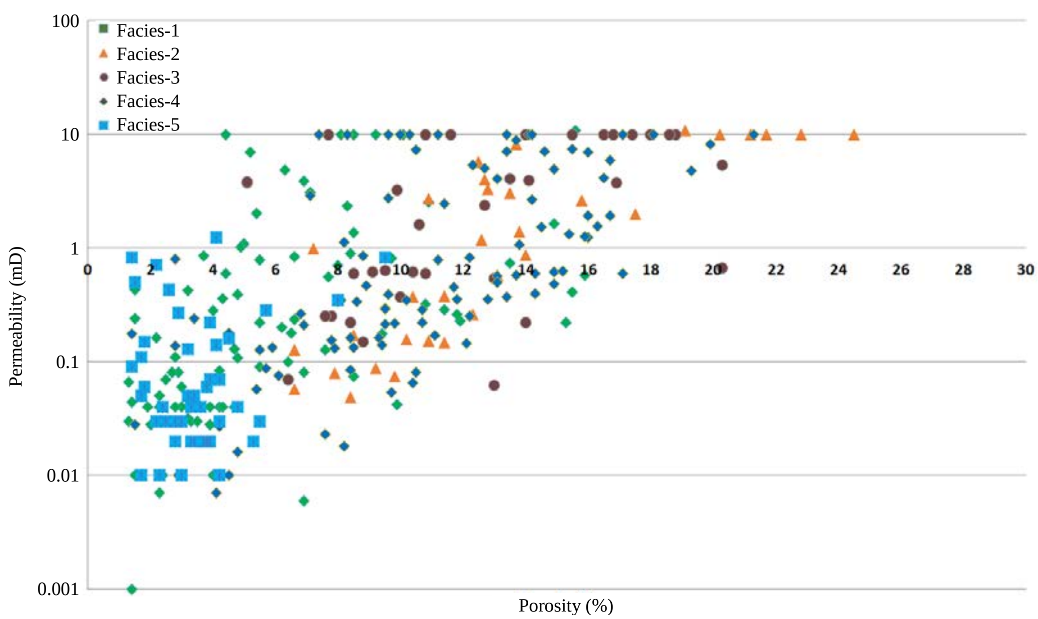

Fig. 9: Cross plot between porosity and permeability. Facies 5 represents minimum permeability of 1 mD, while facies 1-4 permeability is up to 10 mD

replaced with calcite. In the aggradation neomorphism it is found that the huge majority of the microcrystalline calcite samples are recrystallized to sparry calcite with different range of crystal size. The aggradation neomorphism of the skeletal

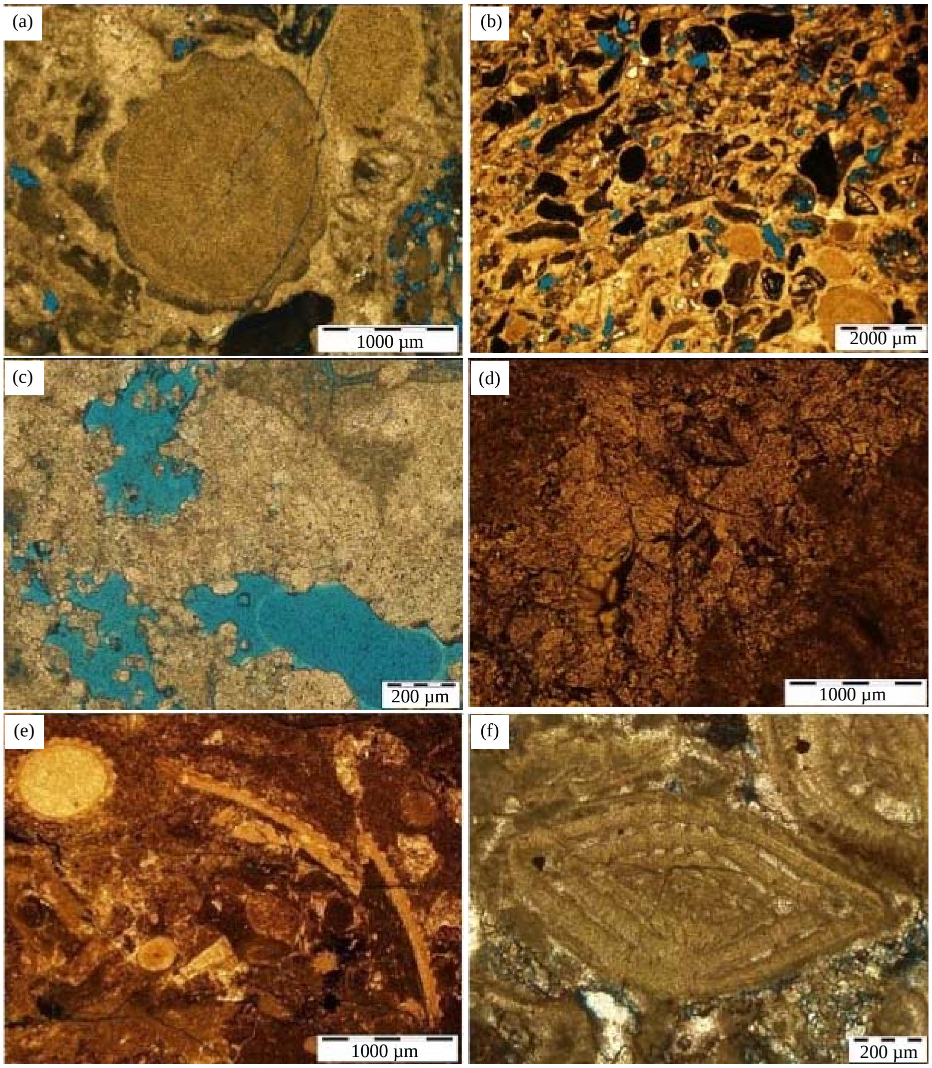

Fig. 10(a-f): (a) Micrite and micrite envelope in limestone, syntaxtial growth cement syntaxtial overgrowth on a piece of echinoderm, (b) The partial to complete micritization of bioclasts in Central Luconia offshore Sarawak, Malaysia, (c) Calcite cement filling up the vugs, (d) Equant spars of marine phreatic zone with frequent enfacial junctions, increase of spar size towards centre of pore. These spars underwent late stage destructive neomorphism, (e) Breackage of bioclasts due to mechanical compaction which caused by overburden pressure or tectonic stress and (f) Micritization was the first diagenesis sequence followed by dissolution of the nummulites forams which was later filled up by equant cement. Subsequently, burial diagenesis is observed where, g-g contact (concanve-convex features of the grain)

particles in all the facies is very common, where these components go through different processes from complete to partial aggradation recrystallization. The process is supported by the presence of high magnesium calcite that probably builds up the shell of the skeletal components to the stable phase under the meteoric condition[41].

Compaction: Compaction in well A and B in Central Luconia, offshore Sarawak is due to mechanical and chemical processes and overburden pressure. Mechanical compaction results in grain fracture and porosity reduction by closer packing[42]. Compaction process depends on different aspects such as overburden, sub-surface temperature, pore pressure and the chemical content of pore-water[43,44]. Physical compaction is caused by sediment overburden, leading to dewatering, breakage and distortion of different grain (Fig. 10d) and concave-convex contact, which results in a decrease in thickness, porosity and permeability. The mechanical

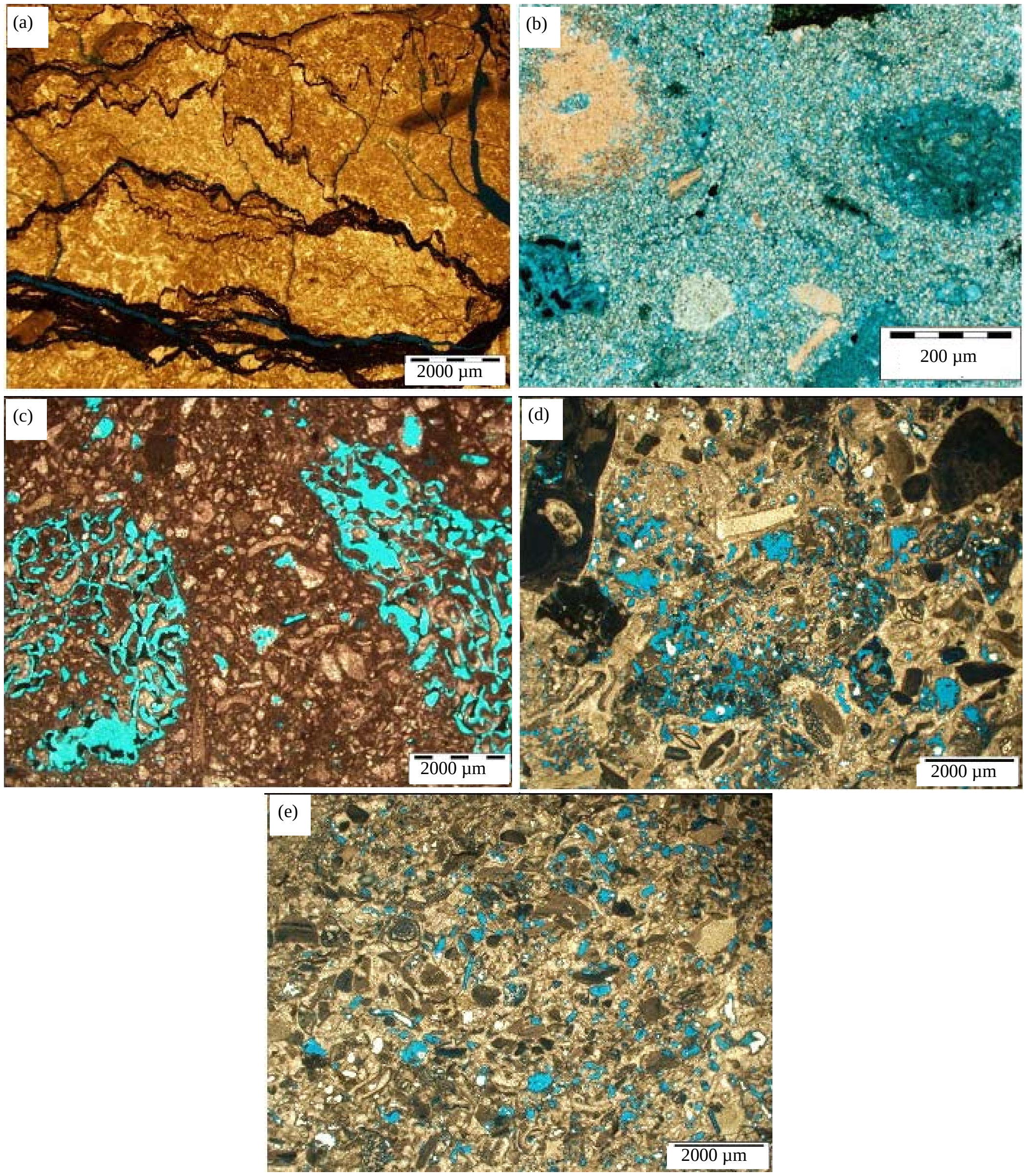

Fig. 11(a-e): (a) Calcified algal mounds with bedding parallel late stage fractures and stylolites filled with organic matter, (b) Large skeletal particles set in sucrosic dolomite matrix (white crystals in matrix). Highly localized manner in which some echinoderm fragments remained calcareous, while other have been mostly replaced by dolomite, red algae have mostly been replaced by dolomite, (c) Facies 2 microscopic view representing hight dissoultion with high rate of micritization, (d) Facies 3 representing various types of completely micritized bioclasts appear in high abundance and high rate of dissolution forming touching and non-touching moulds and (e) Facies 4, unsorted, randomly oriented grains composed of numerous types of bioclasts showing micritization and micrite coatings. Mesogenetic physical and chemical compaction produced realignments of larger bioclasts and moulds. Moldic porosity is frequent

compaction in forms of closer packing of nummulites and algae grains are commonly observed at different depths (Fig. 10e). Stylolites and solution seams are the products of chemical compaction (Fig. 11a). Throughout the cores interval the closer packing of the allochemical grains, fracturing and breakage of the soft shells (algae and bryozoan) are dominant in packstone texture and rare in grainstone texture.

Dissolution: The dissolution is the main diagenetic processes which enhances the reservoir quality by improving the porosity and permeability[23]. The leaching and the solubility of calcium carbonate increases from low magnesium (LMC) to aragonite and High Magnesium Calcite (HMC) which are the major cause of dissolution[23,45]. Mouldic and vuggy porosity is largely generated by the process of dissolution[46,47]. The vuggy porosity which is generated by the process of dissolution of grains, matrix and cement is non-fabric selective in nature[19]. The rate of dissolution is based on the time of sediments exposed to meteoric water. The dissolution resulted in different types of porosity namely, moldic (Fig. 8a), vuggy (Fig. 8c), intraparticle (Fig. 8a) and interparticle (Fig. 8d). Dissolution occurred in all the facies but more intensively in facies 2 and 4, producing secondary porosity as dominated by moldic followed by vuggy, intraparticle and interparticle porosity. The presence of moldic porosity is dominant in all the facies but more intense in F-4.

Dolomitization: Dolomitization is the most striking diagenetic process for the reservoir rock development[48,49]. Algae, peloid, lime mud and partially foraminifera are dolomitized in well A and B. The presence of most of the dolomite in the studied area is highly dolomitized calcitic dolomites with grain density more or equal to 2.82 (Fig. 6). In lagoon the matrix consists of small, generally euhedral to sub-hedral dolomite crystals and are randomly distributed at different angle (Fig. 8d). The observed dolomites are originated from two different processes at different stages of diagenetic history.

Sucrose dolomite: The local source dolomitization is the responsible source of forming sucrose dolomite from the high coralline red algae content and thus local high Mg/Ca rate of the original sediments (Fig. 11b). These dolomites represent very good reservoir quality[50].

Crystalline dolomite: The distant source of dolomitization at the later stage results in crystalline dolomites (Fig. 8d). The crystalline dolomite indicates poor reservoir quality. The discrete small euhedral dolomite crystals disseminates within the matrix, stylolite or lamination in dolomitic limestone with grain density less than 2.82 might be of authigenic origin. This small scale diagenesis has no to less effect on the reservoir quality.

Depositional event: Facies and selected thin sections of these facies in well A and B indicate that initially isolated algae colonized in individual isolated mounds established firm substrate. Deposition of algae, foraminifera bioclasts dominated lithologies and shallow marine, strenohaline, well-oxygenated and circulated conditions seem dominated. It appears from the microfacies associations that the initial colonizers of soft substratum, i.e., on the carbonate shelf, the sponge and algae attempted repeatedly to grow and form independent reef on a temporal scale, but failed recurrently[31]. It was followed by foraminifera and rich algal bindstone, that trapped sediments. These accreted vertically relatively faster than adjoining regions that might have provided conducive milieu for coral reef development. However, the coral-algae facies and adjoining coral algal rudstone and floatstone facies represent typical coral reef[34]. The encircling reef crest and talus on the windward side respectively form the vertically accreting platform. Further down slope, the reef talus deposits with textural inversion characteristics might have developed[51]. Towards the older section of the interval shallowing of the depositional bathymetry, the development of back reef condition may have started as a result of the introduction of coral reef aggradation[31,52]. This resulted in the decrease of coralline reef components, progressively replaced by algae bindstone and packstone. The four major facies associations/depositional settings, namely coral/algae reef, reef talus, algal mound and carbonate shelf settings were recognized. The carbonate shelf was the dominant depositional setting.

Diagenetic events: Different diagenetic processes and major events are recognized in well A and B. Post-depositional processes can be separated into three stages: Eogenetic, mesogenetic and telogenetic.

Eogenetic: Leaching, calcification, aragonite-calcite, HMC-LMC, slow rate of deposition is indicated by extensive micritization and micrite coating on bioclasts and highly oxygenating environment[53,54]. The corg (organic rich mud) might have been destroyed at depositional stage itself. Depositional extensive coral reef and associated algae facies development depend on syndepositional calcification (aragonite-calcite for coral and HMC-LMC for algae) at the marine phreatic stage, also in an oxygenating environment (i.e., at shallow burial stage). Significant leaching took place, which caused almost all the frame builders to be converted into moldic pores by dissolution. These voids were filled by equant spar calcite cement, which might have destroyed the remaining corg (organic rich mud) and made the sediments less porous.

Mesogenetic: The HMC-LMC, realignment, bedding, fracturing and faulting, dissolution-precipitation, additional molds and vugs creation and equant spar filling, physical and chemical compaction.

Telogenetic: It is physical compaction, fracturing and destructive neomorphism. The deep burial stage was associated with extensive neomorphism, which had converted the bioclasts, matrix and mesogenetic cement spars into regionally varying sized clumsy microspar, sealing all the pores that were present in the rock. However, there were differential compaction effects as reflected by various amount of physical and chemical compaction. Stratigraphically, there are various proportions of syndepositional mud, mesogenetic equant spars, creation and occlusion of moldic and vuggy porosity in bioclast precursors[4].

Reservoir properties: Reservoir potential is generally considered to be fair for hydrocarbon in well A and B, Central Luconia, offshore Sarawak, Malaysia. Visible porosity varies from poor to fair in facies 1 and 5 and is locally good to very good in facies 2, 3 and 4. The porosity and permeability data of various reservoir facies (Fig. 9) also shows that facies 2 (av. Ø = 14.7%, av. Kh = 6 mD), facies 3 (av. Ø = 10%, av. Kh = 4 mD) and facies 4 (av. Ø = 15%, av. Kh = 4.6 mD) have better reservoir qualities: While tight limestone facies 1 (av. Ø = 6%, av. Kh = 1 mD) and facies 5 (av. Ø = 4%, av. Kh = 0.5 mD) are characterized by poor reservoir qualities. In hand-specimen/petrographic observation is found to be mainly secondary porosity, common-grain mould to locally vuggy porosity[19]. Large mouldic pores commonly occur within coral fragments, while smaller mouldic pores appear to have formed from leaching of finely disperse coral, foraminifera and algae debris. However, mouldic porosity does not occur most of the time in corals fragments, many corals have completely cemented by calcite cement (Fig. 7e), representing tight reservoir intervals[19,55]. The presence of intraparticle and interparticle porosity is usually cemented by fine crystalline calcite cement and is therefore rare in grainstone[34,48]. Mouldic pores are dominantly pores types present in well A and B (Table 1). Most mouldic pores are partially cemented by calcite cement or entirely free of calcite cement. The low permeability is strongly linked with the non-touching pores or poorly interconnection due to the small size of matrix intercrystalline pores, also the presence of organic rich mud and pressure solution seams are also responsible for reducing the porosity in these facies, which may constitute a potential barrier to fluid flow[56]. This may help conclude that the facies 2 (Fig. 11c), facies 3 (Fig. 11d) and facies 4 (Fig. 11e) are the potential reservoir facies except for occasional development of non-touching mould and micritization. Micritization is the diagenetic process which affects the reservoir quality in almost all the facies, but in facies 2 the rate of micritization is higher compared to other facies. The micritization destroyed the internal structure of the grains and reduced the porosity[57-59]. According to Taghavi *et al.*[23], the micritization decreases the grain size or reduces the pore throats by filling them which resulted in decreasing porosity. Shakeri and Parham[40] mentioned that micritization reduces porosity very dramatically but when it reaches at certain depth it enhances porosity because of the increasing overburden pressure. The permeability is affected by the process of micritization and compaction which filled up the pore spaces[60,61]. The major diagenetic processes of micritization (Fig. 10b, 11c-e), cementation (Fig. 10c, 11b) and compaction (Fig. 10e, f) resulted in significant destruction of permeability in all the observed facies. However, the lithofacies is the first signature for reservoir quality. Facies 2 and 4 see a wide scatter especially in permeability (Fig. 9), which is related to the pore-types variation in well A and B. This pore variation is related to the percent of leaching and early cementation.

CONCLUSION

The well A and B carbonate buildup platforms are tilted towards the open basin in the northeastern part of Central Luconia. These buildups constitute the deepest carbonate platforms, representing cycle IV and V carbonates. Central Luconia carbonates yielded the following lithofacies types: Coated grain packstone (Facies 1), coral (m) lime grainstone (Facies 2), oncolite lime grain-dominated packstone (Facies 3), skeletal lime packstone (Facies 4) and coral (p) lime mud dominated packstone. The studied well A and B underwent the following diagenetic alterations: Micritization, cementation, recrystallization, silicification and dolomitization. Most of the original aragonitic skeletons of corals either dissolved or recrystallized to calcite. These lithofacies are distinguished by textures, structures, grains (types, sizes and sorting), fossil types and argillaceous content. Each type of lithofacies reflects a specific depositional environment with a certain level of wave energy. The facies and fossil content of corals, bivalves, gastropods, brachiopods and foraminifera indicated an environment ranging from shallow marine to lagoonal deposit. The studied facies in well A and B show distinct differences in terms of reservoir quality. Good reservoir quality is associated with facies 2-4 while poorer reservoir quality is found in facies 1 and 5.

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