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Quantitative Microfacies Study of Miocene Carbonate, Central Luconia, Sarawak

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Abstract

A thorough qualitative and quantitative interpretation has been made on carbonate sediments from Central Luconia, using microfacies study paired with published geological reports. In this study, the relationship between depositional environments and diagenetic alteration of EX Field, located in the southwest of Central Luconia Province, offshore Sarawak were investigated using core description and microfacies study. Seven facies (F1-F7) were identified from EX-2 and EX-3 wells based on the lithology, texture, fossil assemblages and depositional environment. Each of the facies has been diagenetically altered extensively by micritization, cementation, neomorphism, dolomitization, compaction, and fracturing. Carbonate typically has calcite, dolomite and occasionally other mineral such as pyrite and clay especially those that formed in high sea level/ transgressive unit. The presence of clay mineral during deposition has influenced the diagenetic alteration of the EX Field. A geochemical and stable isotope analysis would provide more information on the pore fluid.

Keywords: *Facies; Porosity; Lagoon; Thin section.*

1. Introduction

Cenozoic carbonates are one of the primary targets for petroleum exploration in the South East Asia region [1-3]. Massive hydrocarbon production was coming from the Miocene carbonate in which more than 200 carbonate build- ups have been mapped out [4]. Due to the increase in the importance of oil and gas recovery and the growing realization that the Luconia carbonate reservoirs are more heterogeneous than assumed in the past, it is important to understand the facies distribution, which directly controls the reservoir properties. With more than 40 TSCF of gas initially in place and over 30 TSCF ultimate recovery, the Central Luconia represents about 40% of the total non-associated gas reserves in Malaysia [5].

Eight major stratigraphy cycles, from Oligocene to Holocene, are regionally distinguished in Central Luconia [1]. Each cycle is bounded by thin transgressive unit at the base [6]. Late Eocene Cycles I and II are dominated by non-marine to marine clastic. The Late Early Miocene Cycle III contains abundant marine shales with thin layers of sandstones and limestones [5]. There are thicker packages of limestones at the top layer of Cycle III in the form of lenses. Cycle IV is dominated by the extensive blankets of limestone bank deposits up to 300-meter-thick in the structurally elevated areas [5]. The carbonate sediments stack-up during this cycle classically were referred to as the Megabank stage [7].

During the Middle to early Late Miocene, the entire shelf was an open marine and Cycle V started to develop. The development of Cycle V was referred to as the pinnacle stage [8-9]. The pinnacle stage is characterized by a thick vertical carbonate deposition, which reaches up to 500 m but the areal extent was reduced [9]. Episodic, small shallow water lagoons may occur during the pinnacle stage [10]. Skeletal component rich carbonates continued to develop in structurally elevated areas producing individual buildups up to 20 km in length and 1.5 km thick [10]. Uplift and erosion were reported at the end of Cycle V. This study attempts to investigate the relation between the depositional environment and diagenetic alteration using well logs, core description and microfacies analysis from EX-2 and EX-3 well of Cycle V. Well understood depositional environment and diagenesis alterations of the carbonate platforms will dictate the reservoir facies delineation and modeling to predict the carbonate reservoir in the subsurface.

2. Geological setting

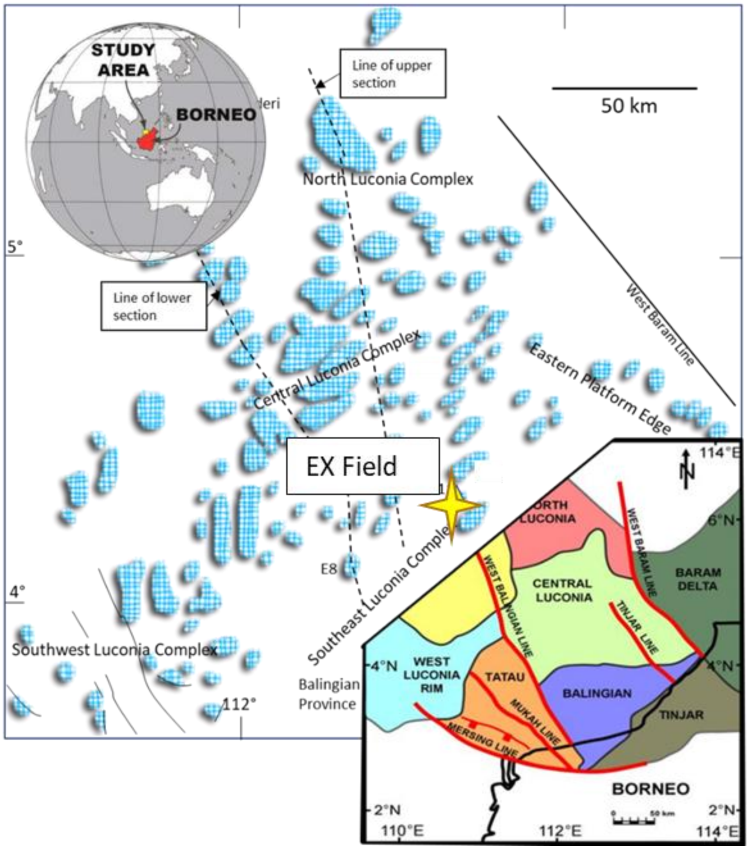


Figure 1. EX Field located in southwestern region of Central Luconia, offshore of Borneo *(Modified from [12])*

Central Luconia is located about 100 to 300 km from the present coastline of Sarawak and covers an area of 45 000 km2 [11]. It is part of the seven geological provinces in offshore of Sarawak. The Central Luconia Province is bounded by North Luconia Province in northern area, Balingian Province in southern area, West Baram line in the eastern area, and West Balingian Line in western area (Fig. 1). The size of carbonate platform in Central Luconia ranged from a couple of km^2 up to more than 200 km2 [11].

Central Luconia is highly affected by the opening of South China Sea [5]. During Late Cretaceous to Eocene, Luconia continental block is rifted from South China towards the Borneo Block [12]. The proto South China Sea or also known as Rajang Sea is subducted under the Borneo continental block [12]. During Late Eocene to Early Oligocene age, a complete closure of the proto south China Sea caused the collision between the Luconia microcontinental block with the Borneo Block producing the Rajang Mountain [12]. Recent study based on seismic lines proved that the Central Luconia experienced extension during Middle Miocene and followed by compressional period for most of Middle to Late Miocene. The extensional event during Middle Miocene time is supported through age dating of the tilted syn-rift carbonate at the base of half- graben [13]. The entire Sarawak Basin was affected by NW-SE trending right lateral fault movement, which created the faulted blocks with same trending [14]. Central Luconia has been rotated in a counter-clockwise direction and bounded by dextral-wrench movement along West Balingian line, Mukah Line, Igan-Oya line and others [14]. Central Luconia was a depressional region bounded by uplifted regions created basin edges in south, southwest and southeast during the extension and isostatic readjustment episode. The basin near to the uplifted area, the eastern side, was filled with clastic, while for the rifted western margin part was characterized by extensive carbonate development [14]. According to Epting [1], the overall carbonate growth in Central Luconia was influenced by four major processes: (i) the rate of carbonate producing organism, (ii) subsidence rate, (iii) relative sea level fluctuation, (iv) influx of terrigenous material from onshore of Borneo.

Based on 87Sr/86Sr data [4], Luconia platform growth correlates with a period of sea level highstand during Middle Miocene correspond to the Supercycle TB2 and cycles 2.3- 2.6 on the global sea level curve [15]. The deeper carbonate interval has been dated using Sr isotopes to about 18 Ma and the demise of Luconia platforms coincides with a major eustatic sea level drop at the end of Middle Miocene (boundary TB2-TB3) and the onset of Borneo tectonism [4].

The EX Field is located in the southwest of Central Luconia, 80 km north of Bintulu town. The present top carbonate depth is 1500 m deep with gas column of 520 m [9]. The age of the EX field ranges from Middle Miocene until Late Miocene [1], which implies for over 5 Ma years of deposition [9]. EX Field was first discovered in 1971 with a wildcat well named EX-1, followed by two vertical appraisal wells named as EX-2 and EX-3 [7]. No core was preserved in well EX-1, while there are 292 m and 286 m length cores from EX-2 and EX-3 wells, respectively. The architecture of the platform can be subdivided into two, "Megabank" structure with thickness of approximately 170 m and pinnacles structure with thickness 340 m and was divided by a thick deep marine deposits [9] (Fig. 2). Beneath Cycle IV and Cycle V carbonate lies a thick succession of mixed carbonates and siliciclastic of Cycle III.

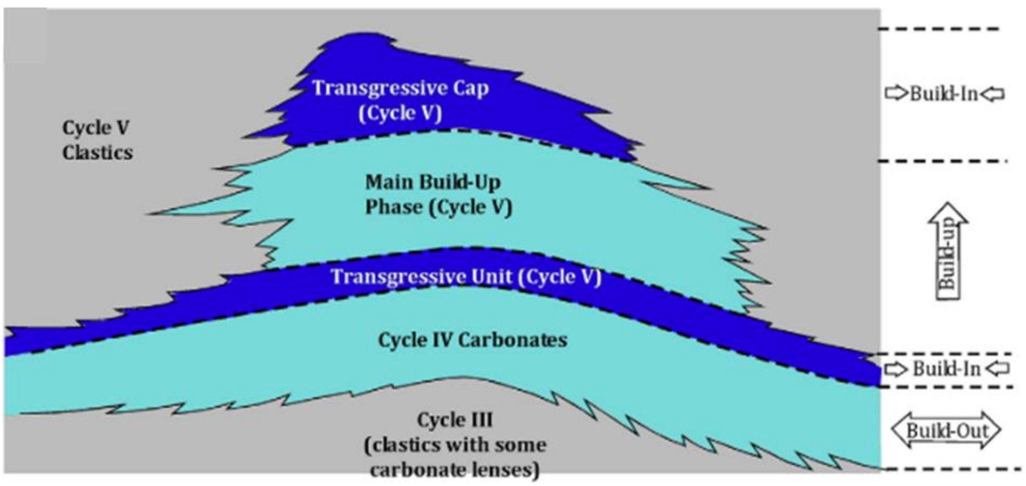


Figure 2 The architecture of EX Field showing the Megabank and pinnacle structure (after [7])

3. Methodology

3.1. Facies analysis

Core description has been used to identify the lithology, texture and skeletal assemblages. The length of core for EX-2 is 292 m and EX-3 is 286 m. 124 thin sections from EX-2 and 68 thin sections from EX-3 were used for microfacies study. The thin sections are impregnated with blue epoxy dye to ease the porosity recognition. The thin section study helps to gain more information on texture, benthic foraminifera assemblages and porosity. Carbonate depositional texture has been described based on Dunham's Classification [16] and Klovan [17].

3.2. Lithofacies association

The facies were grouped into 5 facies association, in accordance to their depositional environment which are forereef, reefoid, reefoid- backreef, backreef- lagoon and lagoon environment. These facies associations were based on lithology, texture, fossil assemblages and depositional environment.

4. Results

4.1. Facies and Facies Association of EX Field

Generally, EX Field is characterized by thick limestone from top to bottom, with dolomitic interval in the middle. The most common carbonate skeletal components in EX Field are red algae, planktonic foraminifera, bivalve, brachiopod, bryozoan, massive corals, echinoid and benthic foraminifera (*Amphitesgina* sp., *Operculina* sp., *Sorites* sp., *Cycloclypeus* sp., *Lepidocyclina* sp., *Miogypsina* sp., *Miogypsinoides* sp., miliolids and uniserial foraminifera). The range of porosity is from 5% to 25%.

Four main lithology were distinguished in the EX Field: limestone, dolomite, argillaceous limestone, dololime and shale (Fig. 3). The largest fraction of the core consists lithologically thick carbonate succession in both EX-2 and EX-3 wells. The carbonate section consists mainly of limestone and dolomite, with a small portion of dololime. The limestone is composed of massive, structureless bed and well cemented, with minor rubble section. The top of both EX-2 and EX-3 were covered by a shaly interval. The same shaly interval was found in the middle of the section. The shaly interval is interpreted as a transgressive unit for the field, which marked the rise of sea level during the time of deposition. And This transgressive unit marked the division of Cycle IV and Cycle V carbonate succession (Fig. 2).

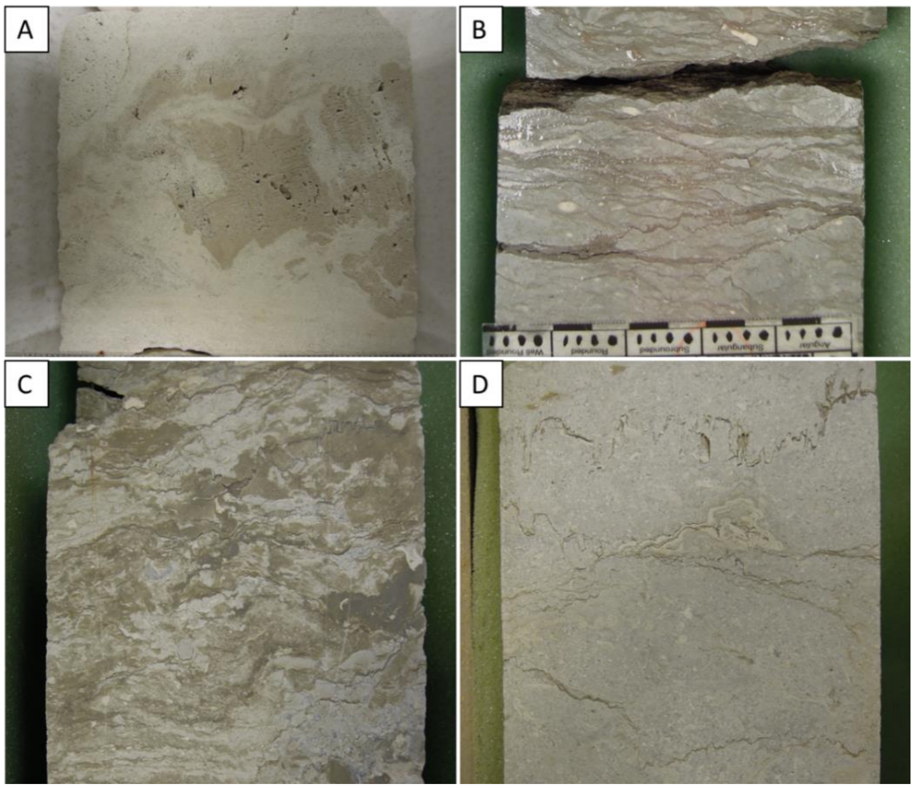


Figure 3. Different type of lithology in EX Field, [A] Dololime; [B] Argillaceous Limestone; [C] Dolostone; [D] Limestone

There are seven facies division from microfacies study on well EX-2 and EX-3 (Fig. 4), namely, F1: Foraminiferal- Red Algal Packstone; F2: Dolomitic Red Algal Wackestone- Floatstone; F3: Coral Framestone; F4: Red Algal-Bioskeletal Grainstone- Rudstone; F5: Red Algal Wackestone- Packstone; F6: Cycloclypeus- Lepidocyclinid Rudstone; and F7: Coral- Red Algal Rudstone. Each of the different facies has been interpreted based on its skeletal and benthic foraminifera assemblages (Fig. 5).

F1 (Foraminiferal- Red Algal Packstone) is dominantly limestone and dololime, characterized by packstone, with rare floatstone and grainstone. 17 thin sections from EX-2 and 18 thin sections from EX-3 are grouped into F1 facies. Common components found are red algae, benthic foraminifera (*Sorites* sp., *Austrotrillina* sp., *Lepidocyclina* sp., miliolid), echinoid, bivalve, brachiopod and fragment of massive coral. Planktonic foraminifera, gastropod, bryozoan, benthic foraminifera (*Cyccloclypeus* sp. and *Amphitesgina* sp.) are uncommon. The depositional environment is interpreted as lagoon.

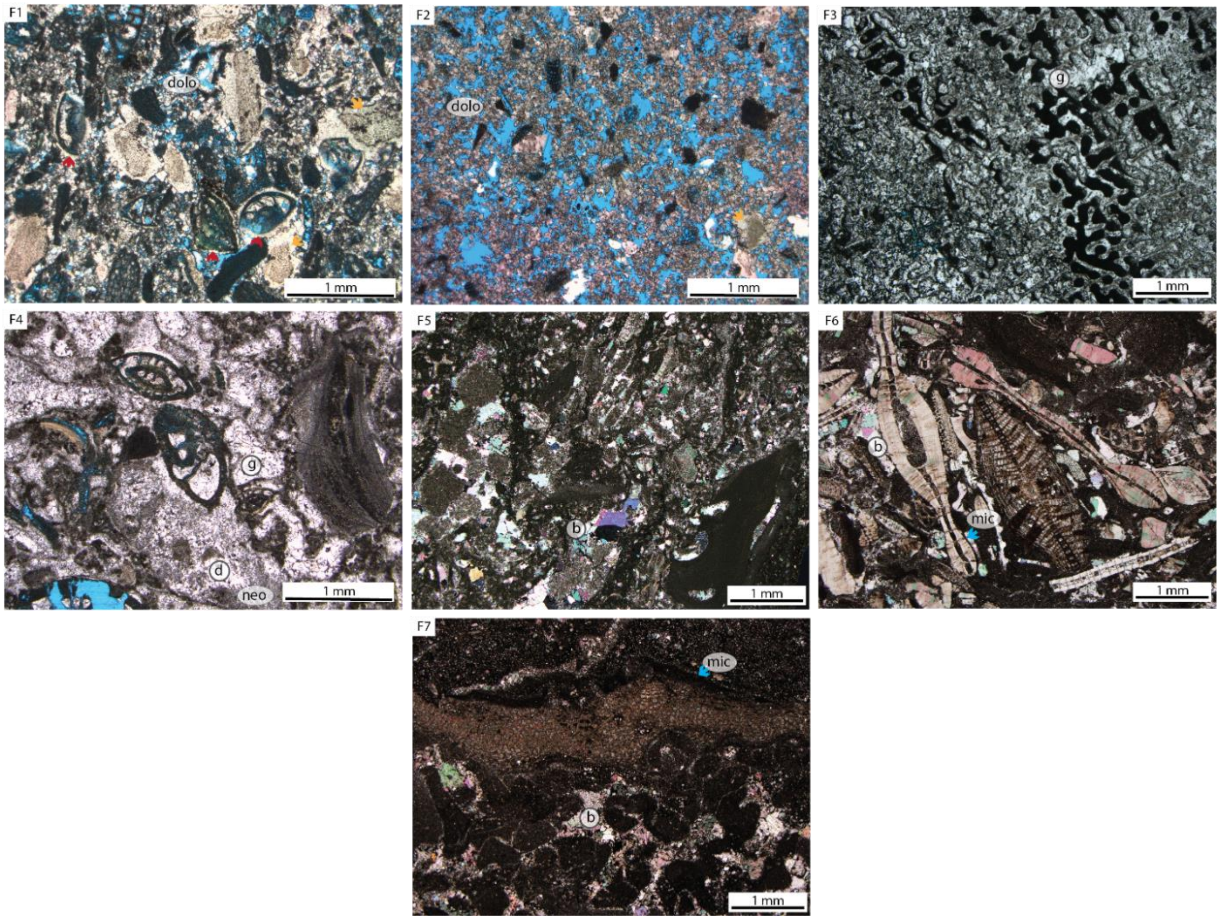


Figure 4. Microfacies of EX Field. F1 shows a dololime facies with packstone texture. It has high number of benthic foraminifera (Operculina sp.), with isopachous rim cement surrounding the grain (red arrow). The overgrowth cement is seen on echinoid plate (orange arrow); F2 shows the dolomitic- mudstone texture of microfacies, where only red algae and echinoid with overgrowth cement (orange arrow) can be seen on the section. This section has high porosity (>20%), contributed by the intercrystalline porosity; F3 shows the massive coral that is heavily crystallize by granular (g) cement; F4 shows a clean rudstone- textured limestone, cemented by granular and drusy, with microspar cement (neomorphism); F5 shows a limestone in wackestone to packstone texture with coarse blocky cement (b) that filled the interparticle space; F6 shows abundance of benthic foraminifera, with no porosity observed. The grains are enveloped by the micritic rim (mic); F7 shows the rudstone texture of coral and encrusting foraminifera

F2 (Dolomitic Red Algal Wackestone- Floatstone) is lithologically of dolomite and dololime, with mudstone and floatstone textures. It consists of mainly red algae with occasional occurrence of echinoid and benthic foraminifera (*Operculina* sp). The presence of dolomite and mainly red algae suggested that the depositional environment for F2 is lagoon. There are 39 thin sections from EX-2 and 19 thin sections from EX-3 are F2 facies.

Facies F3 (Coral Framestone) is only recorded from EX-3 showing massive coral in the thin sections, observed only in two thin sections. The massive coral is mostly crystallized and interpreted as reefoid environment.

F4 (Red Algal-Bioskeletal Grainstone- Rudstone) lithology facies is characterized by grainstone-rudstone texture. 17 thin sections from EX-2 and 7 thin sections of EX-3 are categorized as F4 facies. F4 mainly contain red algae, benthic foraminifera (*Operculina* sp., *Sorites* sp., *Austrotrillina Howchini, Lepidocyclina* sp, miliolid), massive coral fragment and brachiopod. Less common skeletal component found in the F4 are bryozoa, bivalve, biserial foram and encrusting foram. F4 is interpreted as backreef-lagoon depositional environment.

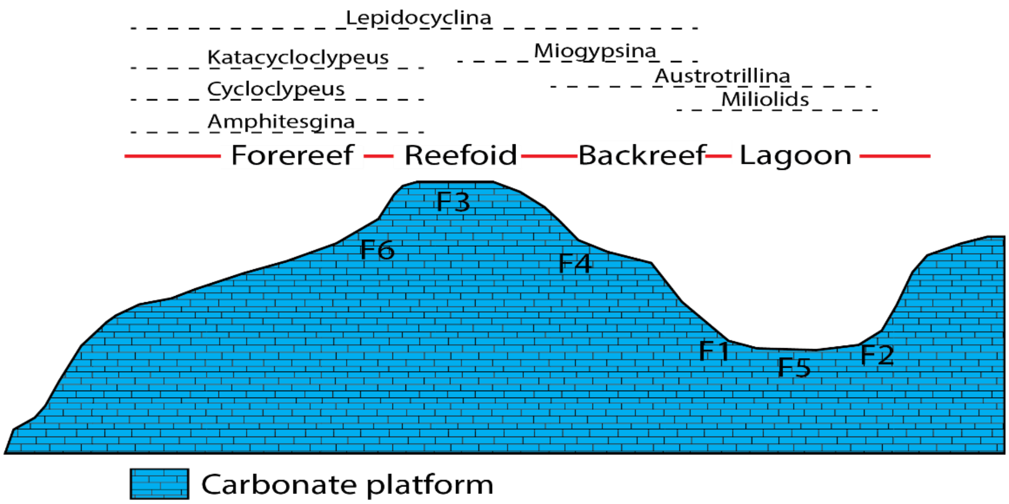


Figure 5 The interpreted facies with its depositional environment for EX Field

F5 (Red Algal Wackestone- Packstone) has limestone and dololime lithology; and it is wackestone textured. It mainly consists of red algae, echinoid, benthic foraminifera (*Sorites* sp., *Operculina* sp., *Lepidocyclina* sp., *Amphitesgina* sp., miliolid), gastropod and skeletal debris. The skeletal present suggesting a lagoon depositional environment for F5 facies. F5 facies is identified on 21 thin sections of EX-2 and 2 thin sections of EX-3.

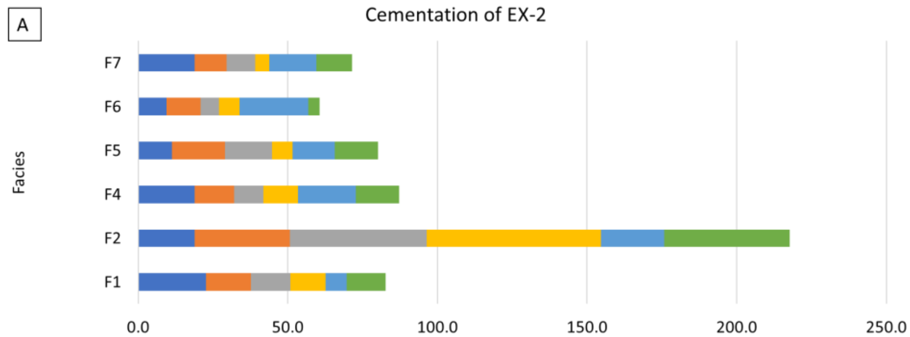
F6 is characterized by heavily diverse benthic foraminifera in rudstone textured limestone. The benthic foraminifera include *Cycloclypeus* sp., *Katacycloclypeus* sp., *Miogypsina* sp., *Lepidocyclina* sp., *Operculina* sp. and *Amphitesgina* sp. Other components include red algae, echninoid, bryozoan and massive coral fragment. The foraminifera suggesting a slightly deep marine/ forereef environment for the facies. There are 13 thin sections from EX-2 and 8 thin sections from EX-3 that are classed into F6 facies.

Lastly, F7 (Coral- Red Algal Rudstone) is limestone in lithology and is identified by its rudstone- packstone texture. It is dominated by coral, red algae, benthic foraminifera (*Operculina* sp., *Amphitesgina* sp., *Sorites* sp., *Textularia* sp. and encrusting foram), planktonic foram and brachiopod. F7 is interpreted as reefoid- backreef depositional environment. F7 facies can be seen in 16 thin sections from EX-2 and 11 thin sections from EX-3.

4.2. Diagenetic alteration on carbonates

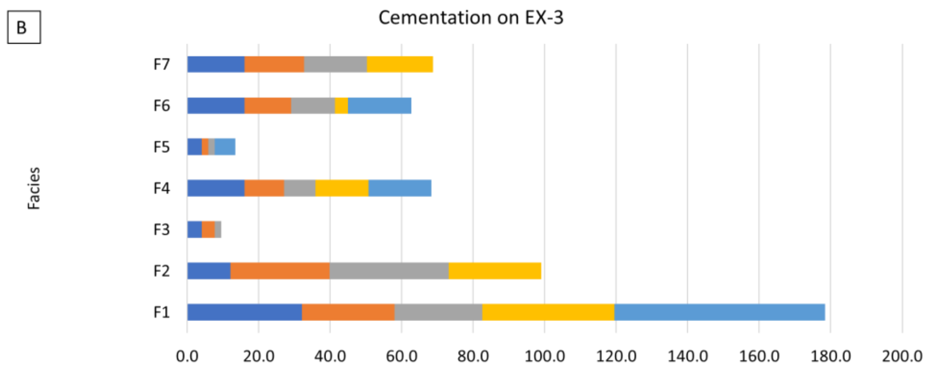
The carbonate sediments from EX field has undergone extensive diagenetic alteration, affecting the porosity evolution. The diagenesis processes include micritization, cementation, dissolution, dolomitization, compaction and fracturing. Micritization is the earliest diagenetic alteration that affected most of the sediments of the EX field. There are 108 thin sections out of 124 from EX-2 and 53 out 68 thin sections from EX-3 field that were affected by micritization. Micritization is recognized by its dark rim that surrounded the grain or skeletal on thin section (Fig. 4: F6; F7).

The cementation diagenetic process reduces porosity within the sediments. The cement morphologies found in EX sediment are fibrous, isopachous/ bladed cement, drusy, blocky, granular and overgrowth (Fig. 4: F1; F2; F4; F5; F6; F7). The cements in the EX are developed in both intraparticle and interparticle pores as well as in fractures. Different generation of cementation can be seen from the microfacies study, ranging from marine, meteoric and burial environment. Bladed/ isopachous cement is fairly distributed among all facies, except its low occurrence in F2 (Fig. 6). Granular and drusy cement is found to be high in F5, and lowest in F2. The difference between granular and drusy is in the size of the cement, where drusy cement have equant to bladed cement that increases in size towards the center. Overgrowth cement is found to be the highest in F1 and the lowest in F5 while blocky cement is highly recorded in F2 facies, and low occurrence in F3 facies.



	F1	F2	F4	F5	F6	F7
Intraparticle	22.6	18.9	18.9	11.3	9.4	18.9
Microporosity	15.0	31.9	13.3	17.7	11.5	10.6
Intercrystalline	13.3	45.8	9.6	15.7	6.0	9.6
Mouldic	11.6	58.1	11.6	7.0	7.0	4.7
Fracture	7.0	21.1	19.3	14.0	22.8	15.8
Vuggy	13.2	42.1	14.5	14.5	3.9	11.8

Percentage (%)



	F1	F2	F3	F4	F5	F6	F7
Bladed/ Isopachous	32.0	12.0	4.0	16.0	4.0	16.0	16.0
Granular	25.9	27.8	3.7	11.1	1.9	13.0	16.7
Blocky	24.6	33.3	1.8	8.8	1.8	12.3	17.5
Overgrowth	37.0	25.9	0.0	14.8	0.0	3.7	18.5
Drusy	58.8	0.0	0.0	17.6	5.9	17.6	0.0

Percentage (%)

Figure 6. Bar chart of different cement morphologies on EX-2 (Chart A) and EX-3 (Chart B). The highest cementation is found from F1 for both well

Mechanical and chemical compaction processes is noted in the carbonate sediments of the EX well. (Fig. 7). Mechanical compaction is identified by the close packing between the grains, which led to concavo- convex contact as well as sutured contact while chemical compaction is recognized by the presence of insoluble seams, such as stylolite and horsetail pressure solution (Fig. 7).

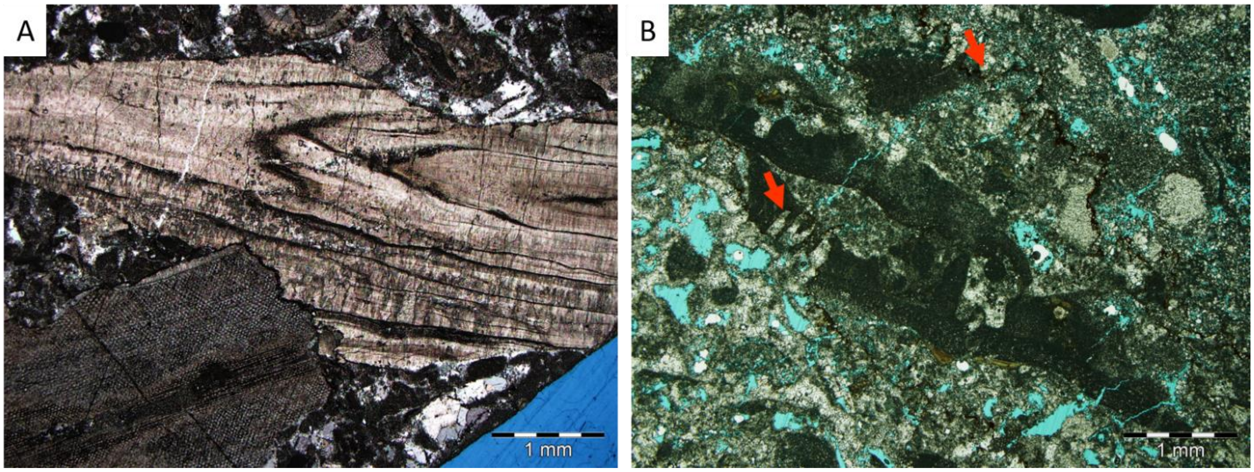
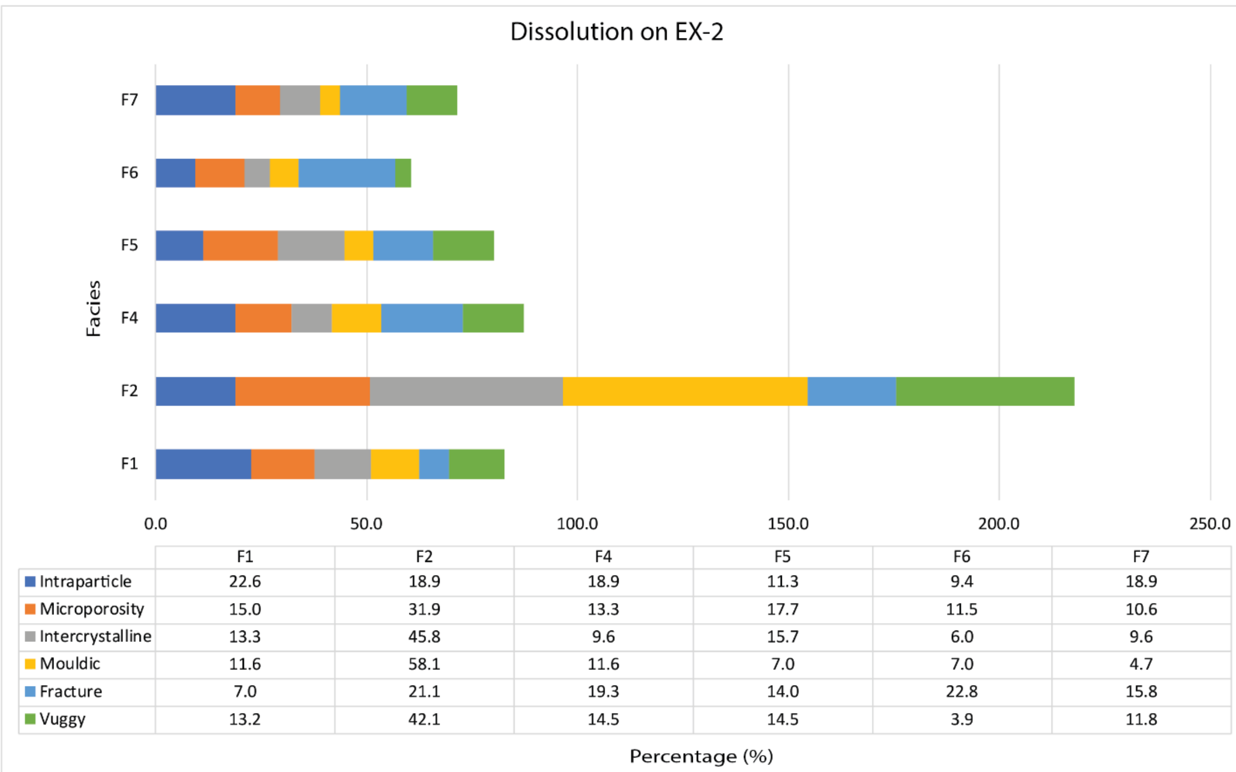


Figure 7 The compaction in EX-3 sediments. [A] mechanical compaction caused a sutured contact between the grain. [B] The chemical compaction caused induced the formation of stylolite (red arrow) with moldic, vuggy and fracture porosity



	F1	F2	F4	F5	F6	F7
Intraparticle	22.6	18.9	18.9	11.3	9.4	18.9
Microporosity	15.0	31.9	13.3	17.7	11.5	10.6
Intercrystalline	13.3	45.8	9.6	15.7	6.0	9.6
Mouldic	11.6	58.1	11.6	7.0	7.0	4.7
Fracture	7.0	21.1	19.3	14.0	22.8	15.8
Vuggy	13.2	42.1	14.5	14.5	3.9	11.8

Figure 8. Bar chart for dissolution on EX-2 sediments in accordance of different facies. Highest porosity is found to be in F2 while the lowest is from F6

Dissolution process played an important role in increasing the reservoir quality in the EX field. Porosities in the EX sediments include intraparticle, mouldic, vuggy, fracture (Fig. 7B), micropore (Fig. 4: F1) and intercrystalline (Fig. 4: F2). The highest porosity is recorded from F2 facies, ranging between 10% to 25%. The mentioned facies has the highest occurrence of microporosity, intercrystalline, vuggy and mouldic porosity (Fig. 8). Meanwhile the lowest porosity is recorded from F6, which is interpreted as transgressive unit in EX Field, suggested by its foraminifera assemblages and as tight unit (Fig. 5D). It is a tight unit, with a very low porosity (<5%).

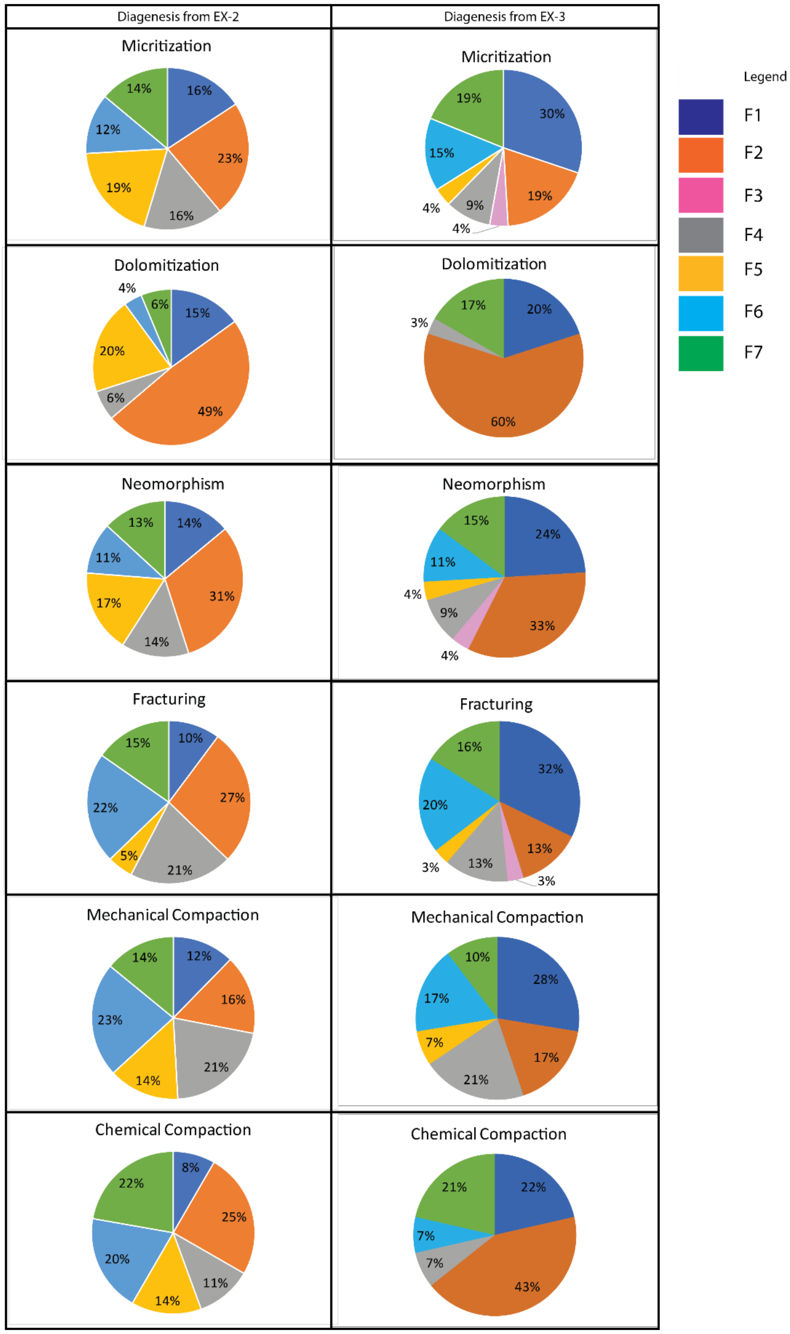


Figure 9. The comparison of diagenesis on difference facies type, from EX-2 and EX-3

Dolomitization is one of the diagenetic processes that occurred in the EX field. Dolomitization is particularly abundant in F2 (Fig. 4: F2). The process has significantly increased the porosity of the field, from intercrystalline porosity. The dolomites in the studied field are found to be both fabric- preserving and fabric destroying dolomites. The dolomite developed in micritic sediments as well as washed sediments. The shape of dolomite crystal found are planar euhedral and subhedral, as well as nonplanar anhedral which is more common in micrite- rich sediments. The planar dolomite (euhedral and subhedral) typically formed in both shallow and deep burial diagenetic zone, where the crystals undergo faceted growth with planar interfaces [18].

5. Discussion

5.1. Influence of depositional environment on diagenetic processes

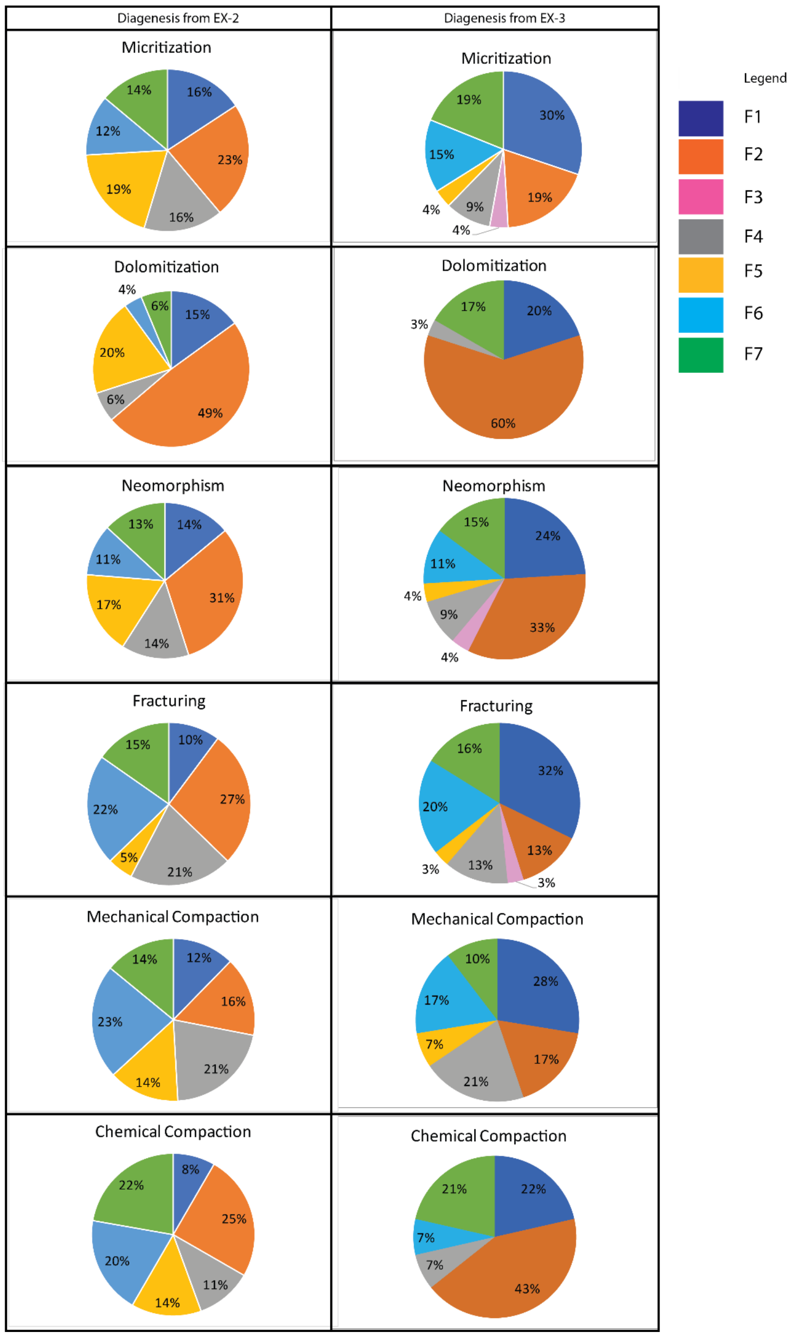


Figure 9 The comparison of diagenesis on difference facies type, from EX-2 and EX-3

Fluid origin and fluid flow in sedimentary basins have a very important influence on various diagenetic alteration processes [19]. The depositional environment is imperative in providing the fluid flow that can promote the diagenesis. The occurrence of each diagenesis on different facies has been plotted in a series of pie chart in Figure 9. Micritization occurred on all facies regardless of its depositional environment.

Based on microfacies studies, most of sediments from lagoonal facies, F1, F2 and F5 were affected by dolomitization (Fig. 9). This suggest that in the lagoonal facies of EX field, the fluid was rich with magnesium ion and the magnesium ion could be originated from minerals that existed in lagoonal area [18,20]. In subsurface environment, aided with sufficient temperature, the pore water can become dolomitizing solution.

Different type of cement morphology has a different distribution on EX sediments. The cement morphology was highly influenced by the fluid flow, mineral saturation and the number of nuclei and the evolution of crystal growth patterns [21]. Factors that control cementation can be: 1) the reprecipitation of the dissolve carbonate phase within sediments and 2) the reprecipitation of dissolve aragonite and calcite from subaerial surface [22]. The bladed or isopachous cement has been associated with marine phreatic environment and considered as early cement or eogenetic cement [19, 21,23], while blocky cement can form in both marine and meteoric phreatic environment [21]. The occurrence of bladed cement is observed in all facies, suggesting its formation may not be affected by any depositional environment factor. Granular cement and drusy cement are seen to be high in mud-supported lagoonal facies. Granular and drusy cement are associated with meteoric phreatic zone [23]. Overgrowth cement has higher occurrence in lagoon environment. The overgrowth cement is typically observed on echinoderms showing a single calcite crystal on each grain, producing a poikilotopic fabric [23].

For dissolution, the highest porosity is found in dolomitic facies (F2), which is mainly contributed by the intercrystalline, mouldic and vuggy porosity. The solubility of a grain increases with increasing percentage of magnesium in a crystal structure[24], which explains the finding in this study.

Compaction diagenetic process typically starts with mechanical compaction, in which sediments were compressed and lithified together during burial. As the overburden increase with time, this led to chemical compaction within the sediments. Compaction has significantly reduced the porosity in the carbonate succession. mechanical compaction is observed in all of the facies but it is significantly high in the backreef- lagoon facies. Chemical compaction was also observed in all facies, with an abundance from lagoonal environment (F1 and F2) and reefoid- backreef environment (F7). The response of compaction varies with the pore fluid geochemistry, temperature, clay content and amount of overgrowth cement at grain contact[25]. The sediments that are rich in clay may have assisted the chemical compaction to occur. This is due to the locally smaller contact area existed in clay rich region which induced a locally greater rate of chemical compaction[25].

6. Conclusion

There are four different sub-depositional environments that have been interpreted for the EX Field, which are lagoon, lagoon- backreef, backreef- reefoid, reefoid and slightly deep marine. Each of the different facies has undergone substantial diagenesis process which led to creation and destruction of porosities. A good reservoir property (what counts as a good reservoir property?) is seemed to be developed in the reefal to lagoonal setting, while the deeper marine facies has very low porosity and has been interpreted as transgressive unit. Most of the skeletal grains were dissolved and cemented in most of the thin section. In the tight zone, the skeletal grains have commonly preserved their original fabric. Presence of clay in the studied platform is believed to have aided the dolomitization and chemical compaction of the sediments, while for the other diagenesis processes, the reasons remained unclear. The linkage between depositional environment and diagenetic environment is still vague for EX field where geochemistry and stable isotope might aid in enhancing the understanding of the pore fluid.

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