Porosity Modification, A Key To The Carbonate Diagenetic Environments. Case Study: Reefal Limestone, Marah Formation, Miau Baru, East Borneo, Indonesia

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Abstract. Through the Eocene-Oligocene transition, localised carbonate shoal formed the northern part of Kutai basin. Miau Baru is a small village located in Kongbeng sub-district, East Kutai, NE Borneo which has a relatively narrow area with complex geological features. This relatively thick the carbonate successions of Marah Formation previously have less attention from diagenetic perspective. To achieve the objective in this diagenetic study of the reefal limestone of Priabonian-Rupelian Marah Formation, limestone samples were collected and sectioned. A total of 35 samples were selected, 25 from Goa Indah section and 10 from Kongbeng section. This paper compiles current knowledge on the sedimentology aspects of this Kongbeng complex region and includes the first attempt to synthesise petrographic data onto carbonate diagenetic environment and history in Miau Baru Area. Detailed identification of porosity modification helped to reconstruct carbonate diagenetic environment and its application in expecting a petroleum reservoir for the region, thereby highlighting areas where further geological research is required.

Keywords: Carbonate, Limestone, Diagenesis, Porosity, Marah Formation, Borneo.

1. Introduction

A set of parameters of depositional environment can affect the diagenetic process in carbonate deposit such as Micritization, compaction dissolution, cementation, recrystallization and dolomitization. Pore water chemistry and tectonic history through the geological time of the sedimentary basin can modify the original mineralogy and depositional texture of limestone component. For example, for some aragonitic corals, the original mineralogy can be easily altered to more resistance form such as calcite or dolomite. Different diagenetic process from specific environment also characterized by different diagenetic products This interaction of these controlling parameters makes successful modelling of the role of diagenesis on distribution and evolution history of the quality of the carbonate deposits. this rock. Petrographic observations are essential for the proper understanding of the origin and timing of porosity development or retention in carbonate reservoir rocks [1].

2. Geological Setting

Borneo is located on the eastern part of Sundaland in SE Asia, the cratonic part consist of Tertiary sediment record [2]. Kutai basin in Borneo is the deepest and the largest Tertiary basin in Indonesia which bounded by Mangkalihat High in the northern part; Adang–Paternosfer Fault in the southern part; Kuching High in the western part of the Kalimantan Central Ranges; and Straits of Makassar in the eastern part [3]. Due to the basement rifting during late Paleocene-Middle Eocene to Oligocene, Kutai basin has experience subsidence, became open marine depositional setting and favorable for the carbonate platform to develop [3,4]. In Eocene, the deposition of Beriun sands as product of the mechanism of basin sagging, resulting in the deposition of marine shales of the Atan Formation and carbonates of Kedango Formation [4]. Transgression phase during Eocene to Oligocene also favorable for carbonate platform development [5].

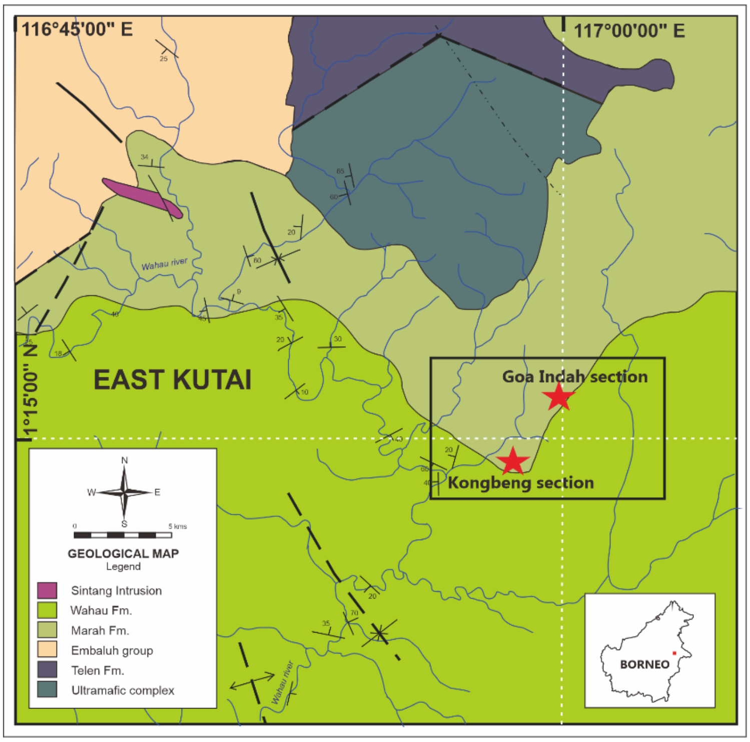


Figure 1. Geological map of the study area. Red stars point locations of study (modified from [6,7])

3. Materials and methods

A detail measured stratigraphic sections were conducted at Goa Indah section (01°15’00.4” N-117°00’10.0” E) and Kongbeng section (01°14’04.0” N-116°59’29.0” E) (see Table 1). A total of 35 limestone samples were obtained through the sections. In this present study, 25 samples were sectioned from Goa Indah section and 10 samples from Kongbeng section. Petrography was the method to achieve the objectives in present study. Under a polarizing microscope, thin sections (3 x 4 cm) are investigated and photographed to identify the diagenesis traits. Modal analyses of the limestone component by counting 300 points were conducted. Petrographic observation and description of carbonate successions following the nomenclature of Dunham (1962) and Embry & Klovan (1971) were identified under normal or polarized light. All thin sections are stored in the Geological and Survey Laboratory, Mulawarman University.

Table 1. GPS plotting coordinates and outcrop observations of the studied sections at Miau Baru Area.

GPS coordinates	Location/ Section	Field observations	Sample taken
01°15’00.4”N-117°00’10.0”E	Goa Indah section	Wacke/packstone to rudstone facies, fresh, white to light buff, silt to clay-grained lime mud, well-cemented, hard, shows good bedding plane. Coral framestone consists of tabulate and scleractinian corals as it main components. Vugs, potholes and cavern are common. Cave morphology is 5-10 meters in height and 12 m wide. Show intensive karstification with stalactite.	25 samples taken: 1B, 2A, 3B, 7A, 5LP2B, 9, 12, 14B, 15, 19, 21, 24B, 28, 29, 30, 40B, 42, 44A—C, 48, 52, 56, 60, 64.
01°14’04.0”N-116°59’29.0”E	Kongbeng section	Wacke/packstone to rudstone facies, fresh, brown to yellowish buff, silt to clay-grained lime mud, well-cemented, hard, and massive. Rounded clasts. Scleractinian coral framestone is common. Spotted distribution.	10 samples taken: 10A—B, 11A—B, 34A, 34C, 35A—B, 36A—B

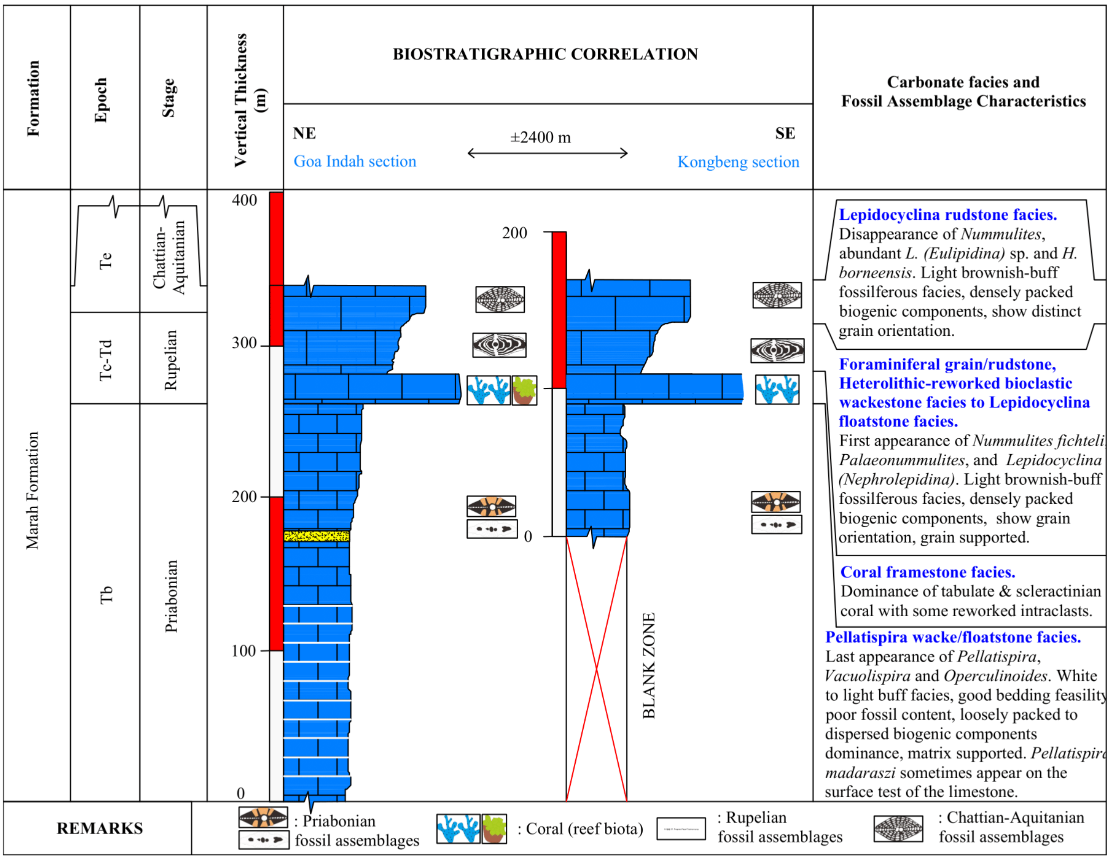


Figure 2. Simplified stratigraphic correlation based on fossil content of the Priabonian-Aquitanian reefal limestone of Marah Formation at study area.

4. Results

4.1. Petrography of the limestone

Based on petrography observation, the limestone in Miau baru area are generally pure limestone. Based on modal composition analyses of thin section from two sections in present study area, modal composition of limestone diagenesis is simplified into allochems, micrite/mud, peloid, equant inter-/intragranular calcite cement, channel/fractured-filled blocky-equant calcite, dolomite cement, replacive dolomite, inter-/intragranular porosity and moldic porosity. Diagenetic process in present study includes Micritization, dissolution, cementation, dolomitization, and recrystallization. The We summarized the modal composition from both section on Table 1.

Table 2. Summary of limestone modal composition of present study

Modal composition/ outcrop sample	Goa Indah section		Kongbeng section	
	Range (%)	Average (%)	Range (%)	Average (%)
Allochems & Bioclast	0-64	22,9	0-74	32,3
Biomicrite/Mud	0-83	43,6	1-81	39,6
Peloid	0-39	2,8	0-18	3,9
Equant intergranular calcite cement	0-24	3,5	0-7	1,6
Equant intragranular calcite cement	1-67	9,4	0-24	7,4
Channel/fractured-filled blocky-equant calcite	0-6	0,7	0-5	1,3
Dolomite cement	0-100	4,0	0-48	5,1
Replacive dolomite	0-11	0,3	0	0,0
Intergranular porosity	0-10	2,9	0-11	1,8
Intragranular porosity	0-28	6,3	0-17	5,8
Moldic/Fenestral porosity	0-9	1,4	0-4	1,1

Table 3. Description of the main facies and diagenesis type from Marah Formation of present study at Miau Baru Area.

Facies Code	Occurences	Microfacies features	Depositional Environment	Diagenetic summary
Lepidocyclina rudstone facies	11B, 40B	Coarsely grained microfacies, densely packed fossil content, component supported, showing fossil imbrication, intact fossil is common.	Platform margin environment; upper slope/fore-reef (FZ4)	Brittle fracture and suture of grains showing mechanical compaction are common. Minor cementation and micritization.
Foraminiferal grain/rudstone facies	7A, 19, 29, 34A, 36B, 44B, 48	Fine to medium-grained facies, grain supported, broken fossils are common, bioclasts are worn and fragmented, reef-derived biota as it main component	Platform margin environment; upper slope/fore-reef (FZ4)	Stylolite and dissolution seam are common, showing sutured between grains (low to high relief). Blocky equant calcite filled the foraminiferal chambers and its non-pervasive. Cementation is common.
Lepidocyclina floatstone facies	10A, 15, 28, 30, 35A	Poor fossil content, dispersed, fragmented, sometimes exhibit fossils orientation.	Low energy, shallow platform deposit. Open marine with restricted circulation (FZ7).	Show some brittle fracture. Dominantly micritization. Sometimes coral/sponge skeleton has underwent complete dissolution of its originally aragonitic structure and neomorphically replaced by granular mosaic to equant calcite. Blocky equant calcite filled the foraminiferal chambers and its non-pervasive.
Coral framestone facies	12, 21, 44A	Moderately-preserved coral, some of these elements are highly crystallized.	Platform margin reef (FZ5)	Coral replaced and infilled by neomorphic calcite. Dolomitization is very common. Micritization.
Heterolithic-reworked bioclastic wackestone facies	11A, 14B, 34C	Mud-rich facies, wackestone texture. No fossil orientation detected.	Shallow water, partly restrictive lagoon (FZ7).	Wackestone matrix is partly dolomitized. Some coral fragment already neomorphosed. Vuggy porosity.
Pellatispira wacke/floatstone	1B, 2A, 3B, 5LP2B, 9, 10B, 24B, 35B, 36A, 42, 44C, 52, 56, 60, 64	Fine-grained facies, wackestone to floatstone matrix texture is common. rounded clasts, intact fossils are common, loosely packed, micrite envelopes of different sizes on most of main skeletal grain.	Low energy, shallow platform deposit. Shallow water, partly restrictive lagoon (FZ7).	Dominantly micritization, clay-rich matrix, few grain-to-grain contacts. Blocky equant calcite filled the foraminiferal chambers and its non-pervasive. Channel/fractured-filled blocky-equant calcite. Stylolite is less common. Minor dissolution.

4.2. Micritization

Micritization is a lime mud formation process which is commonly present in limestone [8]. Microbial Micritization is a process whereby bioclast are altered by endolithic algae, fungi and bacteria, and sometimes the skeletal grains are bored around the peripheral side and filled with fine sediment or spar [9]. Based on the shape and the chamber arrangements, the type of micritized original skeletal fragment can be identified, which are empty or most commonly filed with calcite cement [10]. Micritization varies from partially to extensively micritized both in Goa Indah and Kongbeng section (see Figure 3).

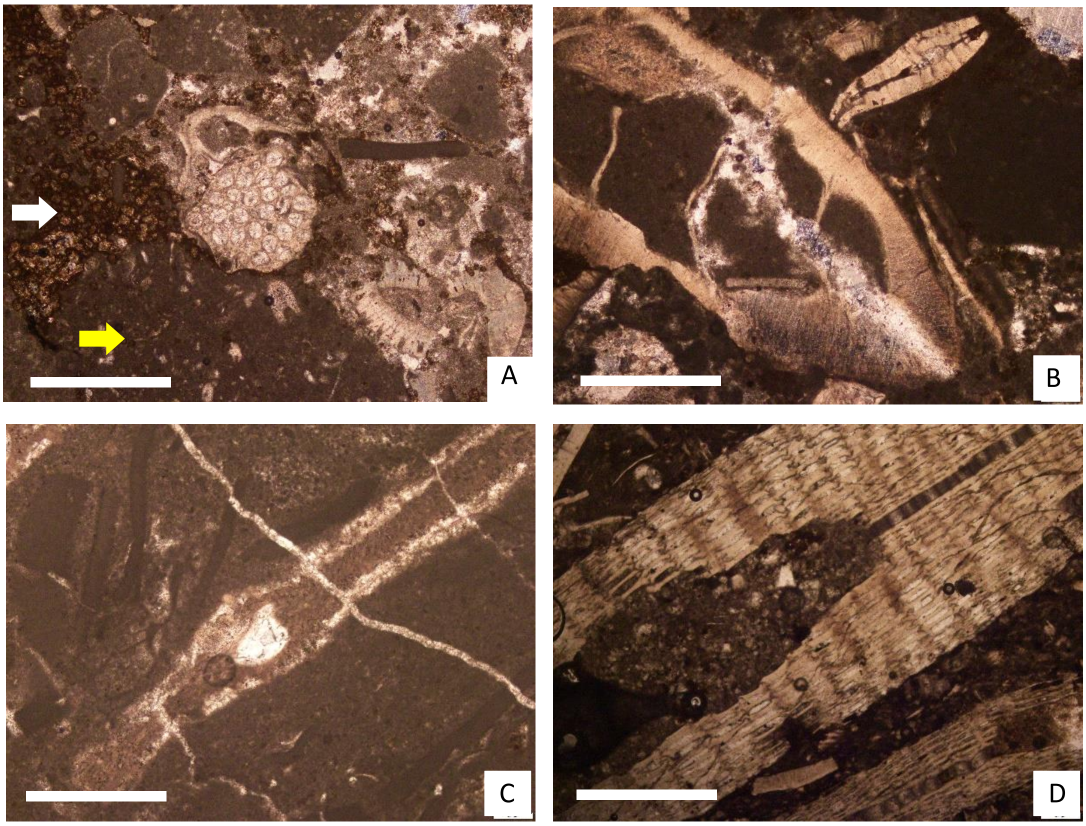


Figure 3. Photomicrograph representative of Micritization identified from petrographic thin sections in present study, A—B Kongbeng section; C—D Goa Indah section. (A) Partial microbial Micritization of limestone consist of dark biomicrite (yellow arrow). Notice the partial dolomitization of the limestone (white arrow), sample 34C; (B) Micritization and partially cementation on the chamber of gastropod, sample 34C; (C) Extensive micritization in Pellatispira floatstone, sample 5LP2B; (D) Micritization in Lepidocyclina, probably caused by boring organism, sample 40B. Scale bar = 1 mm.

4.3. Mechanical compaction

Mechanical compaction is a mechanical diagenetic process, triggered by the increasing overburden of sediments during burial [11]. Mechanical compaction during burial-stage diagenesis has led to interpenetration of adjacent grains and thus has modified their shapes [1]. Concavo-convex contact, sutured margins between carbonate grains, brittle deformation of carbonate grains, and late stage of stylolitization are kind of mechanical compaction took over limestone in Marah Formation at Miau Baru Area (see Figure 4).

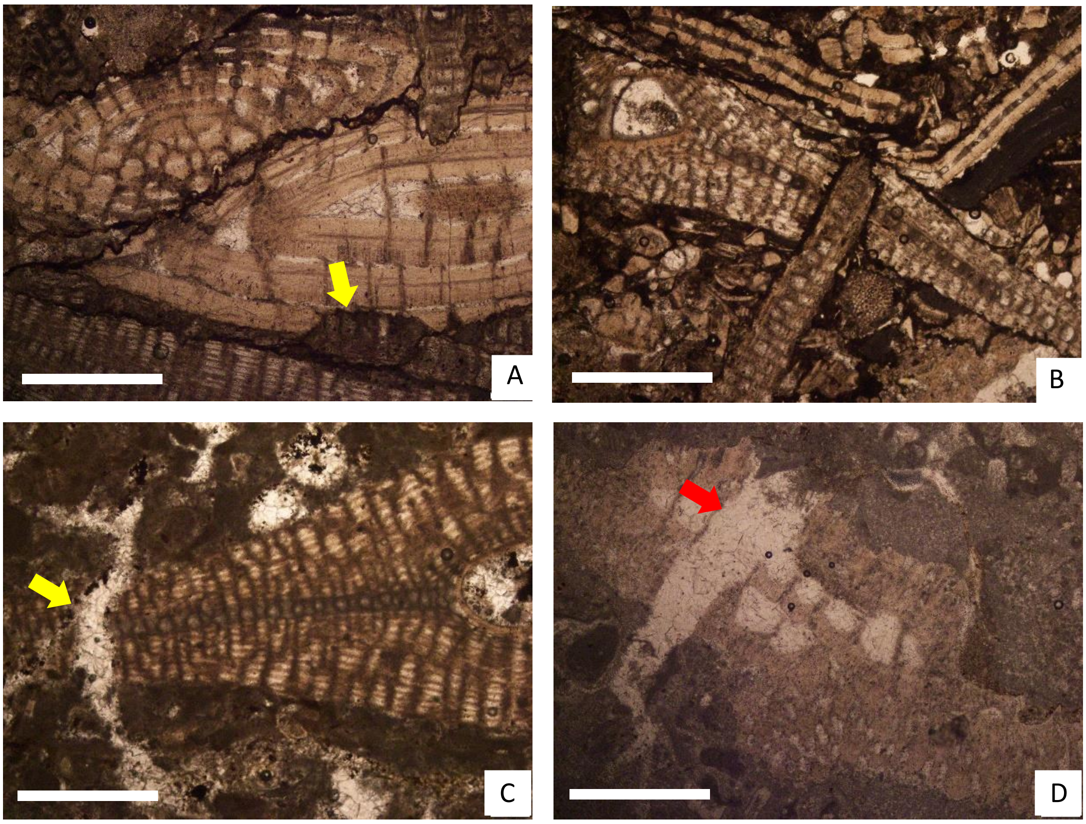


Figure 4. Photomicrograph representative of mechanical compaction process identified from petrographic thin sections in Kongbeng section. (A) stylolitization (high-relief sutured margins) between nummulite tests, show concavo-convex contact between limestone component (yellow arrow) in foraminiferal grain/rudstone facies, sample 29; (B) Perpendicular '*cross-cutting*' component as a mechanical compaction evidence between two grains of lepidocyclinid test in Lepidocyclina grain/rudstone facies, exhibits a fitted fabric, sample 48; (C) cementation took over brittle fractures of grain compaction, may lead to burial diagenetic process, sample 15; (D) Late-stage stylolite on *Pellatispira madaraszi* test, probably caused by burial diagenetic process, cementation can be influenced also by pressure solution, sample 64. Scale bar = 1 mm.

4.4. Dissolution

Limestone in Marah Formation has undergone some dissolution process through the geological time. This dissolution process formed cave morphology and some potholes and vugs as imprint on the outcrop and thin section. The caves scale up to 6–10 meters high in average and potholes range from 3-20 cm on the outcrop surface. The cave morphology only occurs in Goa Indah section (Figure 5A), whilst potholes and vugs identified from both sections (Figure 5B-D). Based on photomicrograph observation, some vugs occur as interparticle, intraparticle, and moldic porosity (Figure 5E-F).

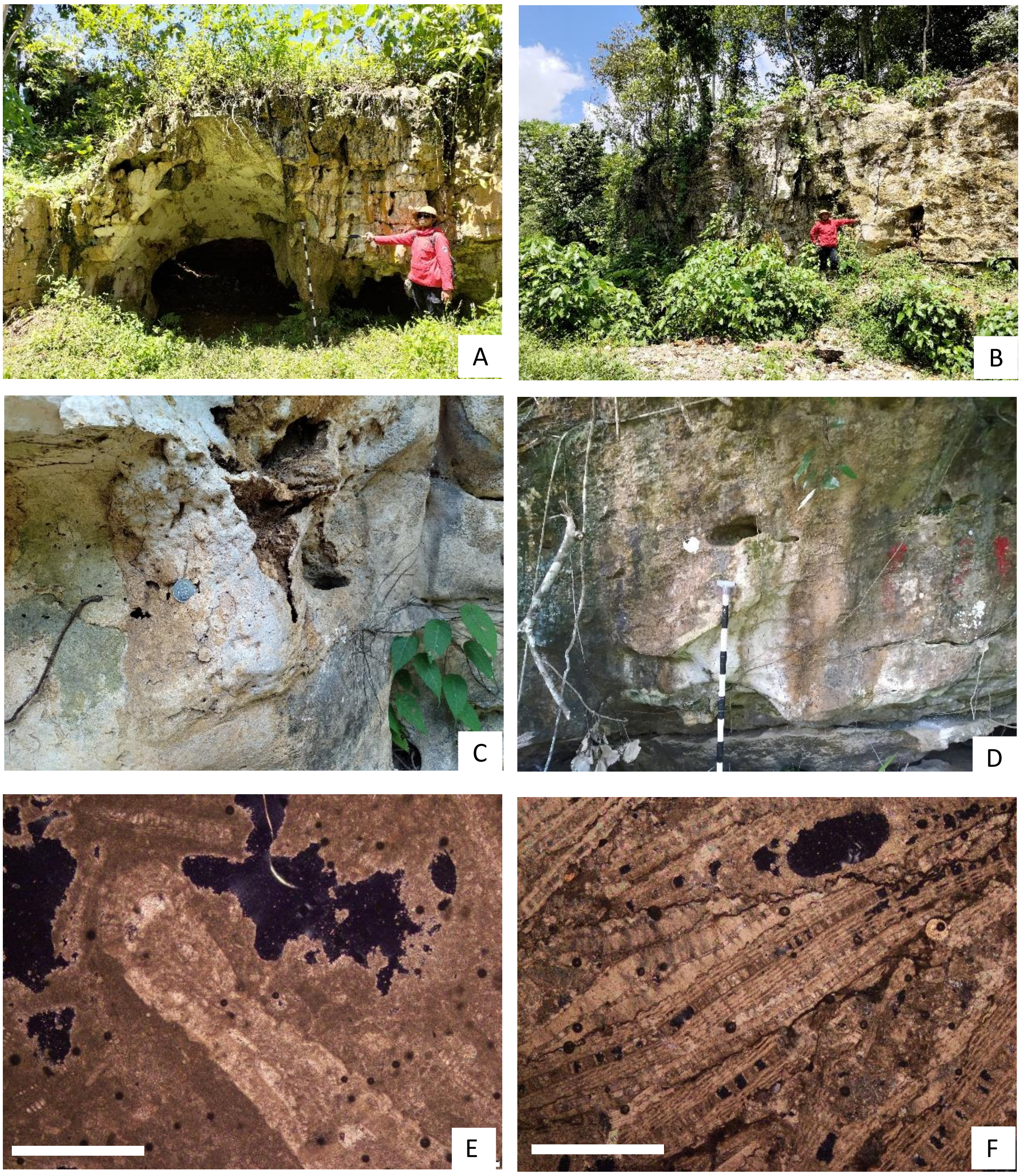


Figure 5. Photographs and photomicrographs representative of dissolution process identified from outcrop observations and petrographic thin sections in present study. (A) Cave morphology in STA 2, Goa Indah section; (B—C) Outcrop situation in STA3, Goa Indah section. Notice the potholes as dissolution evidence; (D) Outcrop situation in STA 34, Kongbeng section; (E) Photomicrographs of Pellatispira floatstone. Note the vuggy porosity as medium mesopore dissolution evidence, sample 3B; (F) Dissolution and leaching took over intragranular porosity on the proloculus and lateral chamber of Lepidocyclina in Lepidocyclina rudstone facies, sample 40B. Scale bar = 1 mm.

4.5. Cementation

Cementation comprises processes leading to the mineral precipitation through the pores and requires the supersaturation of pore fluids [9,11]. It affects reservoir quality and provide essential information to the condition encountered during diagenetic process of Paleogene limestones. Cementation is oftenly 'killed' the pore quantity and quality. Cementation is commonly seen grey to white in colour under the microscope. Cementation can occur on micritic matrix between carbonate grains and reduce the interparticle porosity as the result of diagenetic process (Figure 6A). This fine calcite cement also filling the ostracod test which is well-preserved (Figure 6B). Cementation may vary based on the original mineralogy of the organism. Geopetal fabric may form in an echinoid plate as present on Figure 6C.

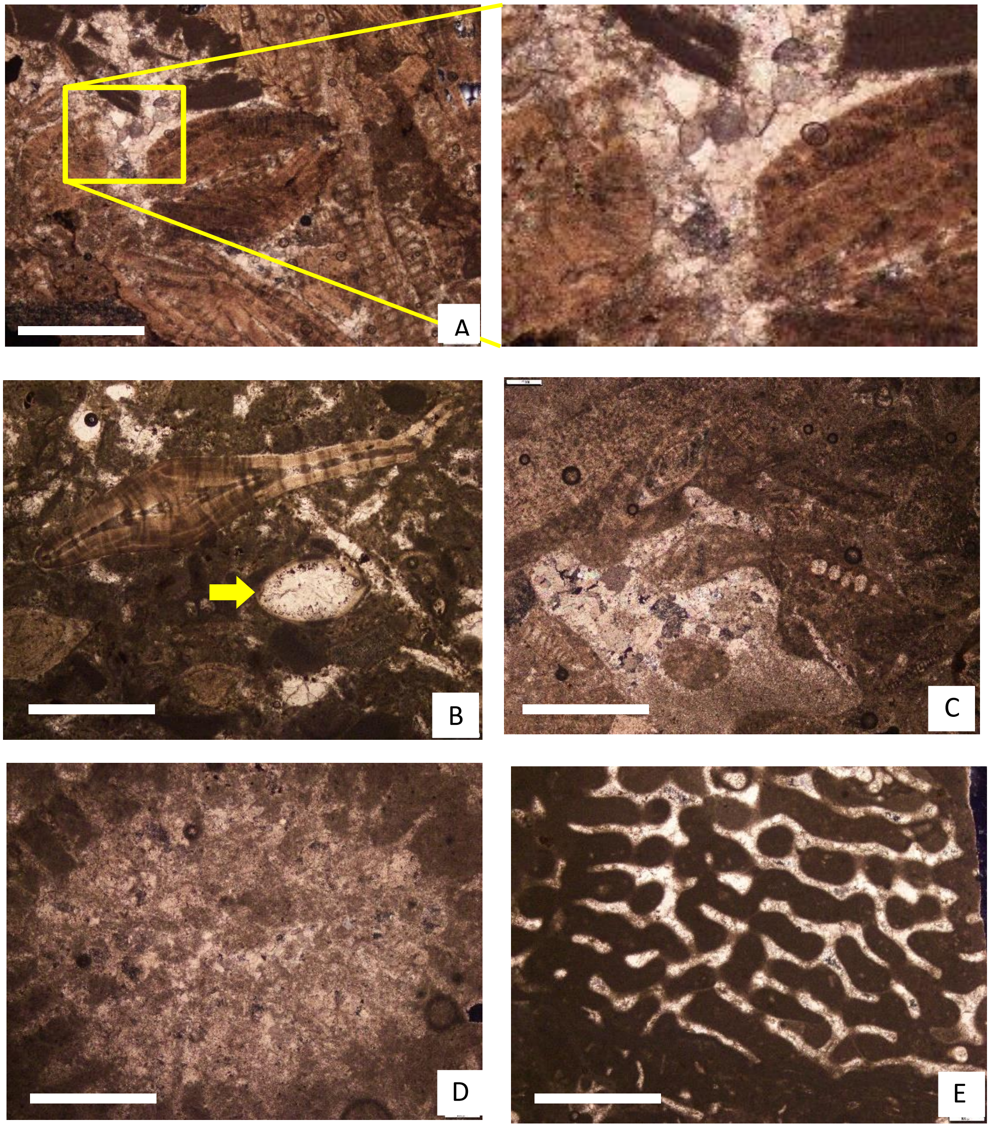


Figure 6. Optical photomicrograph representative of petrographic thin sections from Goa Indah sections. (A) Calcite cementation of micrite, sample 44B. (B) Development of sparite on ostracod test, sample 15. (C) Geopetal fabric on Echinoid plate, sample 36A. (D) Neomorphism on coral framestone, sample 21. (E) Well-preserved internal coral structure cementated by fine calcite cement, sample 34C. Scale bar = 1 mm.

4.6. Recrystallization

Recrystallization is a process by which carbonate grain or crystal transforming from fine to coarser crystal. This recrystallization process can change the composition of skeletal materials from aragonite to blocky calcite. Neomorphism as a process of recrystallization and replacement with possible change in mineralogy [12]. The original aragonitic internal coral structure is completely obliterated due to dissolution process and subsequently infilled by finer calcite cement (Figure 6D). Some non-obliterative texture of coral microstructures identified in (Figure 6E). The most soluble carbonate polymorphs are magnesium and aragonite [13]. In Miau Baru Area, the recrystallization takes over the vein zone. The equant crystal sizes of calcite increasing toward pore centers. This may characterized a burial diagenetic stage, more stable low-Mg calcite [1].

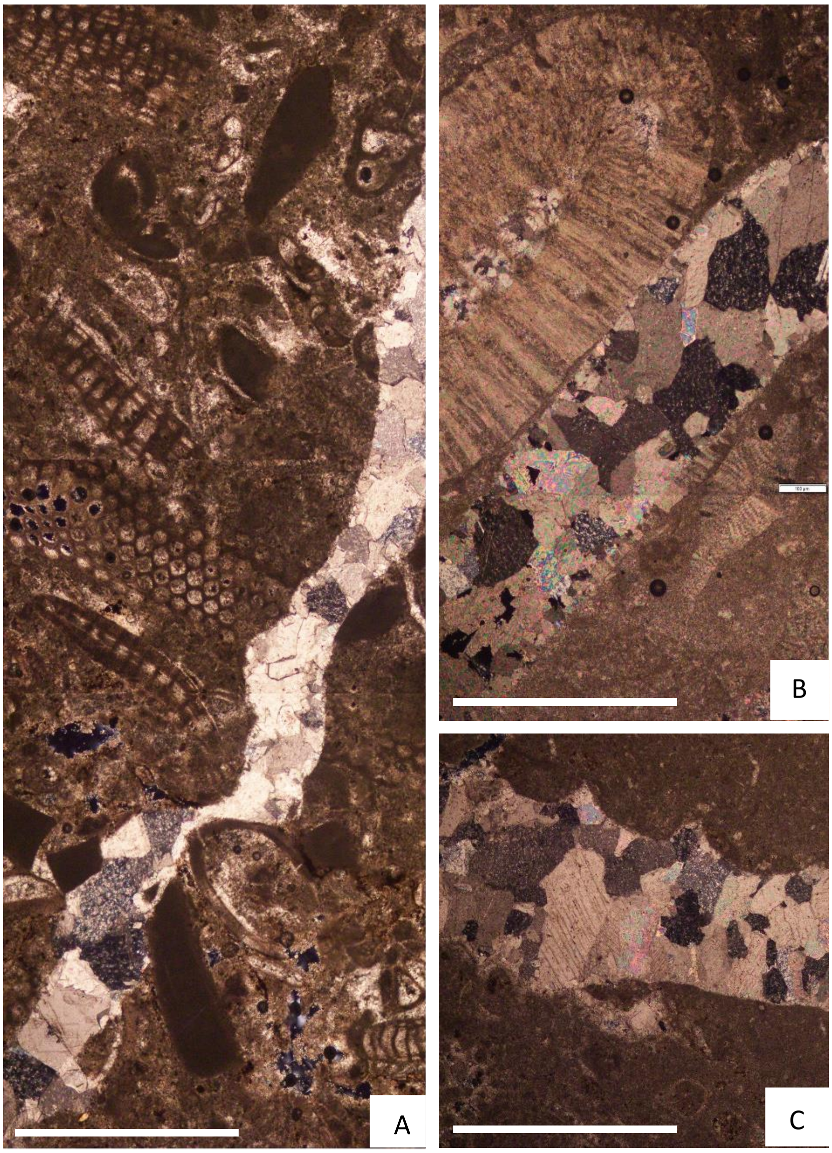


Figure 7. Optical photomicrograph representative of recrystallization in Miau Baru limestone. (A) Channel porosity filled with coarse and drusy calcite, sample 10A. (B) Intercrystalline pores in the recrystallization calcite along the vein; note the presence of coarser calcite crystal towards the pore center. (C) Syntaxial calcite overgrowth develop on sponge fragments. Scale bar = 1 mm.

4.7. Dolomitization

Dolomitization is a process by which the calcitic cement recrystallized into dolomite [13]. Limestone in Miau Baru area is partially underwent dolomitization process. Figure 4.7.A show some textural fabric of dolomite replacement. Irregular fabric, nonlinear, and the subhedral crystal boundaries. Figure 4.7.B exhibit coarse dolomite replacement in an intramicrite. Large areas of limestone matrix were preferentially replaced with dolomite. The dolomite crystals are forming planar subhedral fabric.

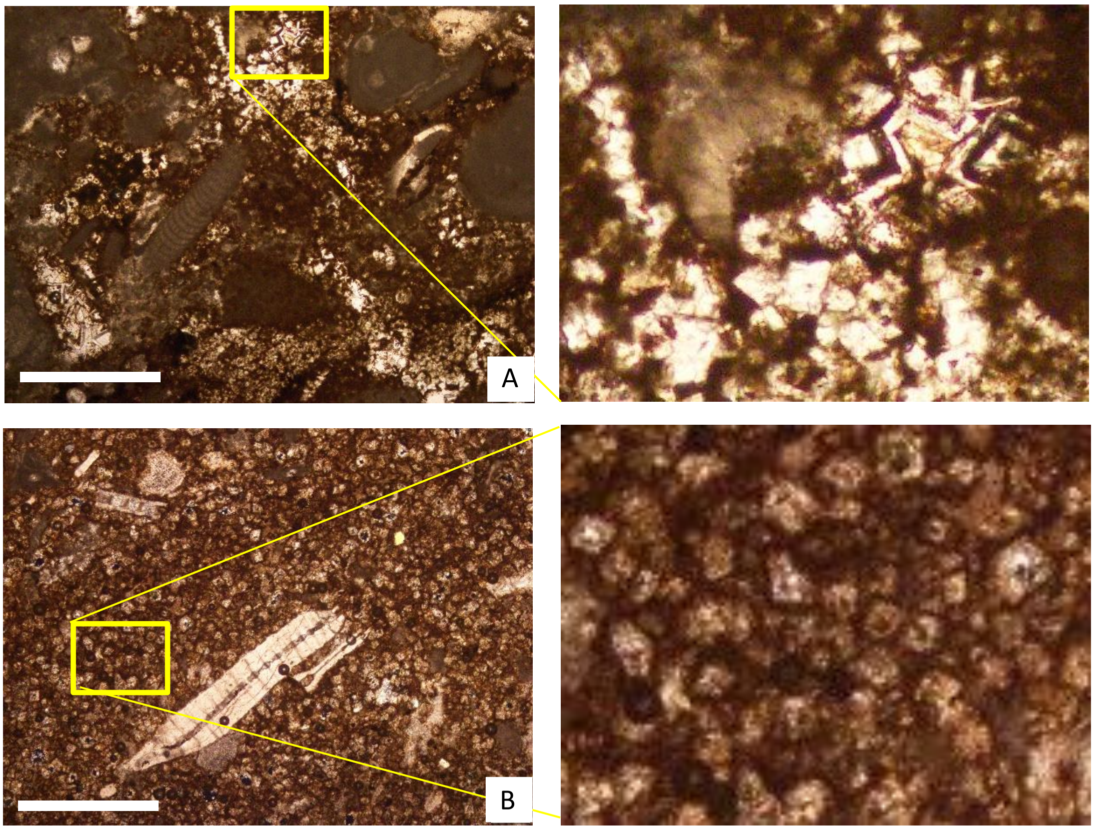
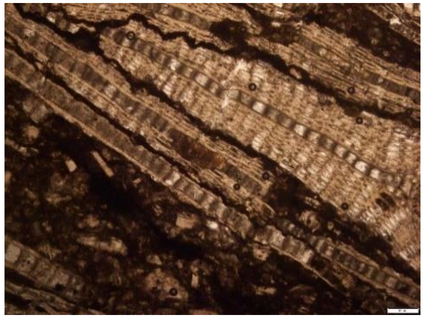
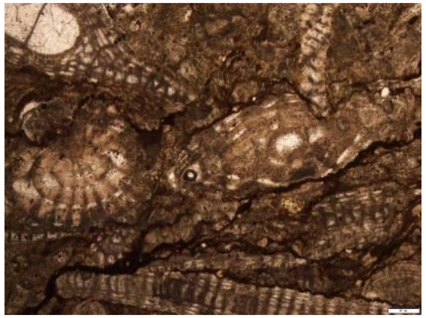
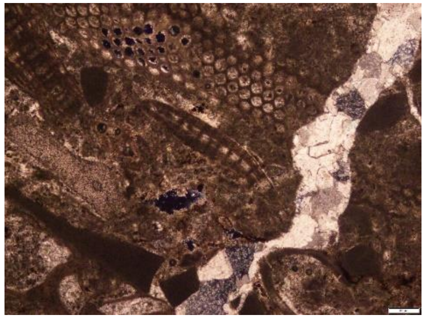
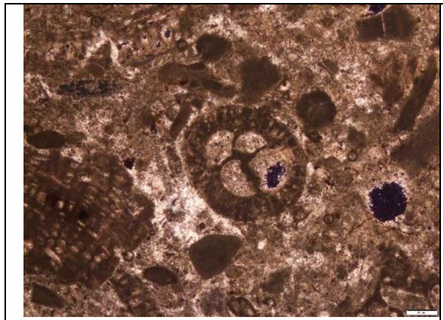
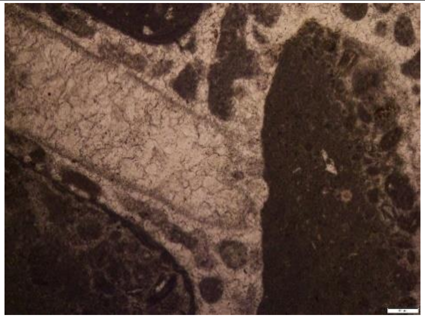


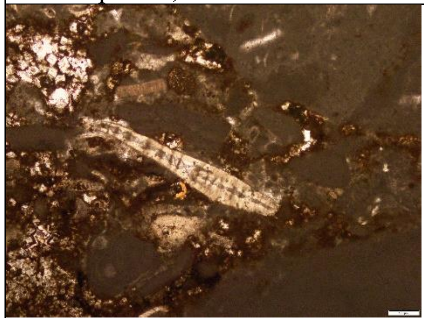
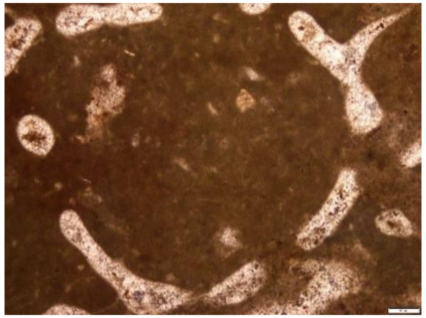
Figure 8. Optical photomicrograph representative of dolomitization evidence from Miau Baru limestones. (A) Replacive dolomite, sample 14B; (B) Planar subhedral dolomite cement, sample 11A.

Table 4. Summary of associated diagenesis evidence and its related diagenetic interpretation observed in thin section in Miau Baru Area

Associated Diagenesis Evidence observed in thin sections	**Facies**	**Modifying Terms**			**Porosity type**	**Type of Diagenesis**	**Diagenetic environment**
		Genetic modifiers	Size modifiers	Abundance modifiers			
 Sample 11B; Kongbeng section	Lepidocyclina rudstone	Fracturing Minor leaching and cementation on Lepidocyclina proloculus and chamber	Small mesopore	Percent porosity (<5%)	Primary intraparticle Primary interparticle	Mesogenesis	Subsurface environment
 Sample 11B; Goa Indah section	Lepidocyclina rudstone	Suture between grains (low relief) Minor cementation	Small mesopore	Percent porosity (<5%)	Primary intraparticle Primary interparticle	Mesogenesis	Subsurface environment

 Sample 29; Goa Indah section	Foraminiferal grain/rudstone	Stylolite Minor cementation and non-pervasive cementation on *N. fichteli* ‘s proloculus and chamber	Small mesopore	Percent porosity (<5%)	Primary intraparticle Primary interparticle Primary fenestral	Mesogenesis	Subsurface environment
 Sample 34A; Kongbeng section	Lepidocyclina grain/rudstone	Stylolite Minor cementation	Small mesopore	Percent porosity (<5%)	Primary intraparticle Primary interparticle Fenestral porosity	Mesogenesis	Subsurface environment
 Sample 10A; Kongbeng section	Lepidocyclina floatstone	Fracturing Blocky-equant calcite cement Disscolution/leaching	Small mesopore	Percent porosity (±5%)	Intraparticle porosity Vuggy porosity Channel porosity Intercrystalline porosity	Telogenesis	Meteoric environment

 Sample 35A; Kongbeng section	Lepidocyclina floatstone	Partial leaching of grains and complete cementation	Small mesopore	Percent porosity (<5%)	Primary intraparticle Moldic porosity	Telogenesis	Meteoric phreatic environment
 Sample 30; Goa Indah section	Bioclastic floatstone	Neomorphosed of originally aragonitic sponge fragment Micritization	Small mesopore	Percent porosity (<5%)	Intraparticle porosity Interparticle porosity	Eogenesis-Mesogenesis	Marine to subsurface environment
 Sample 64; Goa Indah section	Lepidocyclina floatstone	Cementation drusy mosaic of equant sparite Partial grain leaching	Small mesopore	Percent porosity (<5%)	Intreparticle porosity Intercrystalline porosity	Telogenesis	Meteoric environment (Deep meteoric phreatic zone)

 Sample 30; Goa Indah section	Coral framestone	Neomorphosed, originally aragonitic coral Drussy mosaic calcite	Small mesopore	Percent porosity (<5%)	Intercrystalline porosity Interparticle porosity	Mesogenesis	Subsurface environment
 Sample 14B; Goa Indah section	Heterolithic limestone	Partial dolomitization Recrystallizatio n of calcite spar Micritization	Small mesopore	Percent porosity (±5%)	Interparticle porosity Intercrystalline porosity	Eogenesis-Mesogenesis	Marine and meteoric environment (probably mixing zone due to the dolomitization)
 Sample 12; Goa Indah section	Coral framestone	Micritization Neomorphism of originally aragonitic coral skeleton	Small mesopore	Percent porosity (<5%)	Intraparticle porosity Intercrystalline porosity	Eogenesis	Marine environment

5. Diagenetic history and model

Carbonate rocks generally have a more complex pore system because of the wide variety of component's mineralogy and grain shapes. The presence of intragranular, framework, and fenestral porosity in carbonates, and the potential for the development of moldic and highly irregular dissolution-related porosity in carbonates [8]. The key to the development of porosity modification models is the ability to recognize the diagenetic environment in which the porosity modification process appear [14]. In this study, petrographic observation is necessary to place a diagenetic event based on the pore modification. There are three major stage of diagenesis which commonly used for knowing the diagenetic event for sedimentary rock. These are Eogenesis, Mesogenesis and Telogenesis (see Figure 9), [15]).

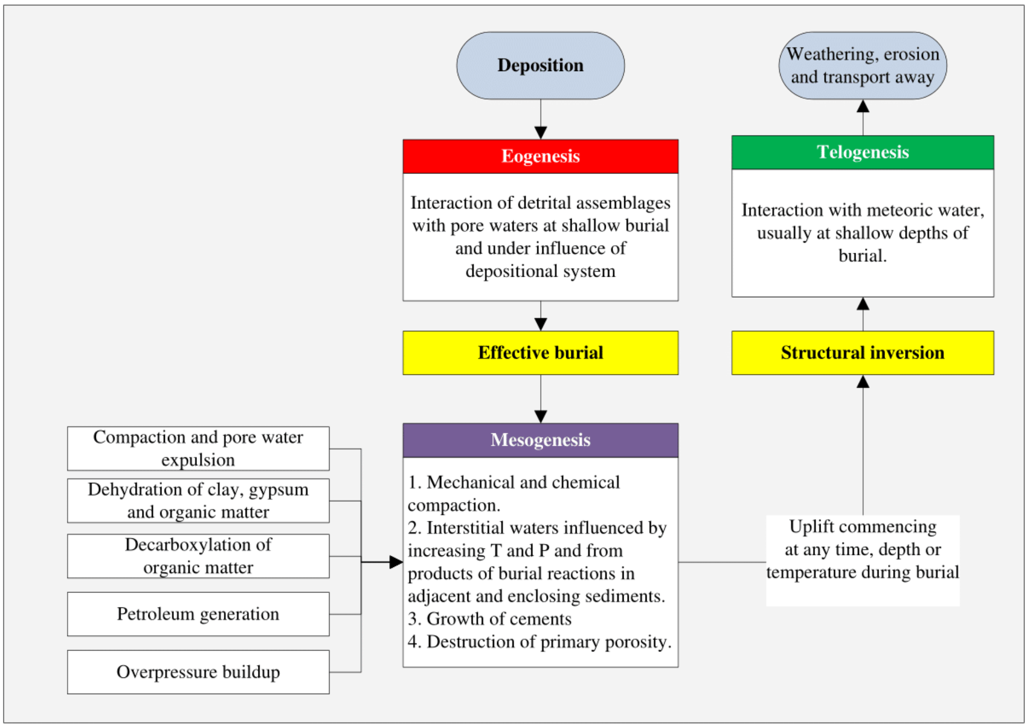


Figure 9. Diagenetic stage illustration (modified from [15])

Reefal limestone of Marah Formation in Miau Baru area has experience long diagenetic history since the deposition from late Eocene until present day (refer to Figure 10). Eogenesis is an early stage of diagenesis (eogenesis) in marine environment setting. This characterized by the replacement of unstable mineralogy with more resistance carbonate mineralogy (Figure 10; 0). The very simple example is the neomorphism in scleractinian coral (Figure 6C). In Miau Baru area, mesogenesis (Figure 10; 1) is responsible for destruction process of primary porosity with cementation and mechanical and chemical compaction (Figure 4A-D; Figure 6). At last, structural inversion during Miocene in Kutai basin resulting uplift of the deposit into shallow depth (Figure 10; 2-3). Telogenetic stage in this study interpreted as deep meteoric phreatic based on the complete cementation and partial leaching also mixing zone dolomitization. The formation of cave morphology, potholes and vugs in outcrop is also an evidence for meteoric vadose stage, although no meniscus cement found in this study.

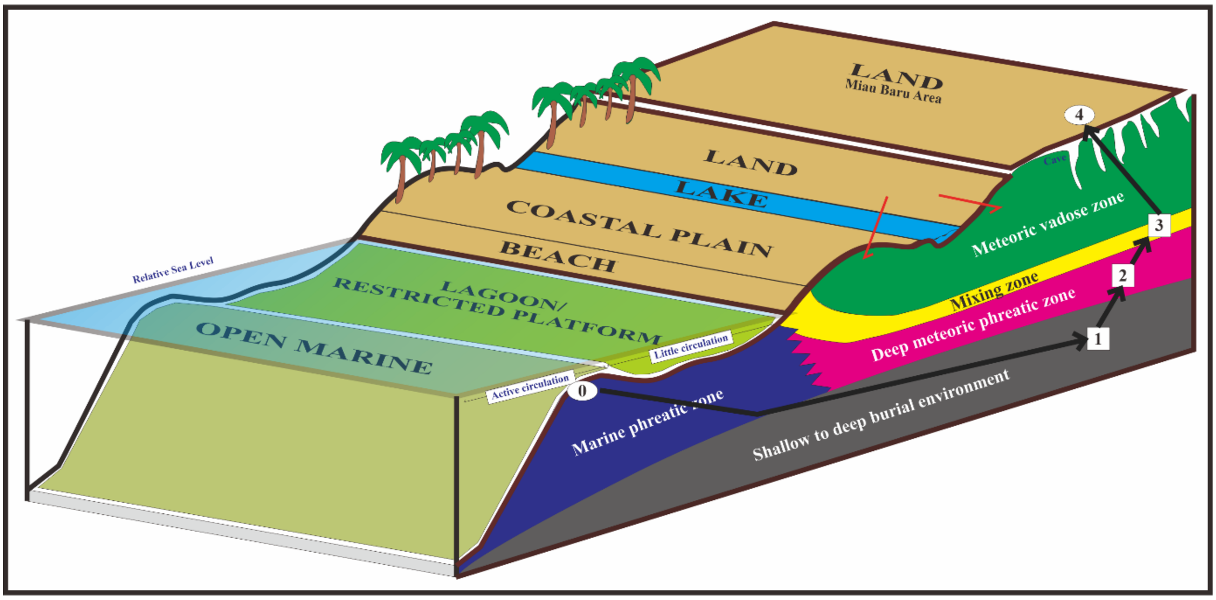


Figure 10. Major diagenetic environments. Arrows and number (0—4)show the interpreted diagenetic environments experienced by reefal limestone in Miau Baru Area (modified from [1,14])

6. Conclusions

Reefal limestone in Marah Formation at Miau Baru area, East Borneo underwent some porosity modifications as follows: micritization, dissolution, mechanical cementation (including stylolitization), dolomitization, and recrystallization (including neomorphism). Reefal limestone of Marah Formation in Miau Baru area has experience long diagenetic history such as eogenesis, mesogenesis, and telogenesis diagenetic stage. The diagenetic environment interpreted as marine phreatic environment, subsurface environment, and meteoric environment. All original aragonitic test of Scleractinian coral either dissolved or recrystallized into calcite in marine phreatic environment. Mechanical and chemical compaction features such as brittle fracture of grains, concavo-convex contacts, sutured contacts between grains and late-stage stylolites as well as common burial-stage cement fabrics such as drusy mosaic of equant spar and syntaxial calcite overgrowth indicate a burial diagenesis environment. Dolomitization and partial leaching interpreted to form in metoric phreatic environment and mixing zone. The tight cementation as well as the small mesopore (±5%) throughout this reefal limestone study can be not so profitable for petroleum accumulation. Further carbonate porosity calculation test is required to acknowledge its reservoir potential in Miau Baru Area.

7. References

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