Diagenetic history of late Oligocene-early Miocene carbonates in East Sabah, Malaysia

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Abstract. Limestones are particularly susceptible to drastic early diagenesis modifications, mainly cementation and dissolution. During the early Miocene, a major tectonic deformation has caused a widespread of uplift in Sabah. This has resulted change in depositional environment from deep to shallow marine, which favours the deposition of Gomantong Limestone. This study aims to investigate the diagenetic history of Gomantong Limestone in East Sabah. Thorough understanding of the diagenetic processes may provide data to unravel the tectonic activities which affected the reservoir quality of the carbonates. Combining the data from comprehensive petrographic analysis, and Scanning Electron Microscopy (SEM) of 30 samples, two main cements type were identified. These are microcrystalline cement and Mg-calcite cement of granular and blocky mosaics which are dominantly seen in all samples. The sequence of diagenesis events are determined as (1) micritization; (2) grain scale compaction; (3) cementation (pore-filling); (4) mechanical compaction and cementation infilling fractures and (5) chemical compaction. These diagenetic events are interpreted as reflection of changes in diagenetic environment from shallow marine to deep burial. The massive cementation in the Gomantong Limestone has resulted into a poor reservoir quality.

1. Introduction
Tertiary carbonates in Southeast Asia are extensive and diverse particularly on the east side of Borneo. These carbonate deposits are among the major hydrocarbon exploration targets, including drilling that has been carried out in the Sulu Sea in offshore eastern part of Sabah [1]. Through an unpublished seismic data, Gomantong Limestone may have an extension in the offshore where it forms isolated limestone mounds occurring along the boundary between Labang Formation and Tanjong Formation [2].

Diagenetic processes in carbonates can either create or destruct porosity and permeability. Hence, it is also important to note the influences of diagenetic process on the reservoir quality of Gomantong Limestone as diagenesis holds a major control in determining the economical values of the reservoir rocks. However, due to the lack of exposure in the past, little study has been done on the onshore carbonate deposits in Sukau, East Sabah, Malaysia. The outcrops are now being exposed due to rapid plantation development and quarrying activities (Figure 1).

This paper documents the diagenetic features and processes that have affected carbonates of the Gomantong Limestone in Sukau, east of Sabah, Malaysia. The occurrence and distribution of the diagenetic features may provide further information and understanding of limestone mounds that may
have extended to the offshore Sabah Basin. This study was based on field observations and petrographic studies of ten outcrops and samples from identified locations across 50 km road of Sukau. Around 20 rock samples were collected from different sampling locations (Figure 1). Petrographic analyses are based on examination of 20 thin sections impregnated with blue-dyed epoxy. Petrographic examination of the samples was performed using a polarizing microscope and selected samples were examined with a scanning electron microscope for further information on the cements.

2. Geological Setting

Gomantong Limestone is a shallow water coralline limestone formed in the late Oligocene-early Miocene period when there was a sudden change of shallowing of environment, due to uplift event. The outcrops are located at the northern part of the lower Kinabatangan River in Sukau, east of Sabah and can be dated back to early Miocene where there was period of progressive tectonic deformation in the fore-arc region during the subduction and widespread mélange development in Sabah. There are series of isolated exposures of limestone forming the East-West trending belt of steep-sided hill stretching from the Lahad Datu Road (close to the Kinabatangan River) to the east of Sukau. Bands of limestone outcrops can be found extending approximately 15km in a North-South direction. Some of these limestones can be accessed by the Sukau Road. It is argued that the limestone of Gomantong may extend to the offshore, forming isolated limestone mounds occurring along the boundary between Labang Formation and overlying Tanjong Formation (Figure 2) [2].

The formation of Gomantong Limestone occurred during the same period as the Ayer melanges [3]. This can be seen in the Gomantong Caves, where the Gomantong Limestone reaches approximately 300m in thickness. This cave suggested that the Gomantong Limestone apparently overlies the Oligocene Labang Formation unconformably. A detailed study on Gomantong Limestone suggested the possibility of simultaneous deposition (Figure 2) of both clastic (Labang and Kulapis Formations) [4] and carbonate rocks (Gomantong Formations) during Oligocene to Miocene period [2]. Evidence can be seen in one of the outcrops which contains well cemented Labang clast up to 25cm in diameter which in turn suggested an unconformable contact. On the contrary, the limestone is interbedded with several thin, grey-green fissile, clastic mudstone beds which also contain Labang Formation clast [4]. Several other outcrop were found to have small clastic clast or fine-grained clastic material within the limestone deposits. However, these assumptions still remained as assumption which required further study on the lithostratigraphy of the area.

![Figure 1](image1.png)

**Figure 1.** Geological map showing the overview of limestones distribution in Sukau.
Recent study proposed three hypotheses in explaining the formation of the Gomantong Limestone and mélanges as shown in Figure 3 [5]. The first hypothesis is that the limestone is deposited above the mélange. The second hypothesis is that the limestone was deposited together with the mélanges. The third hypothesis states that the limestone might deposited below the mélange. However, the three hypotheses on the formation of Gomantong Limestone may not be supported by sufficient numbers and variation of rock samples and thus this study will be undertake more precisely and detailed sampling in order to confirm the diagenesis history of Gomantong Limestone Formation.

3. Results and Discussions

The diagenesis of Gomantong Limestone is similar to other Tertiary platforms from neighbouring islands of Borneo such as Tonasa Platform (Sulawesi, Indonesia) [7] which showed limited early diagenesis (marine or meteoric) together with prevalent of dissolution, cementations and compaction that is related to shallow to deeper burial diagenesis [6-8]. The types and morphology of cement are discuss in the subsequent sections (Figure 4A-4F):

3.1 Types and morphology of cements

3.1.1 Microcrystalline cements

Microcrystalline cement formed by micritization that can be seen as light to dark brown rims on the outer part of the allochems. Grain micritization is almost seen in all thin sections but the area of the rim is said to be less than 2-5%. The size of micritic rim is observed dominantly between 20 and 30μm. Micritisation is the first alteration process that occurs at the early stage of diagenesis which affected almost all of the samples. Moreover, it is consider pre-date of other diagenetic features as those features cross-cut the micrite envelopes and also micritic rims surrounding the allochems. The micritic rim found is said to be due to infilling of microborings that formed by endolithic organisms as the micritisation mostly are encroached into the bioclasts. Micritizations are abundant in wackestones-
packstones and also boundstones in platform top. It may due to the reason of high endolithic organism activity in shallow water which are influenced by low to moderate energy.

**Figure 4A.** Thin layer of micritic cement (dark brown, red arrow) line the former *Lepidocyclina* sp. Note crystals of blocky calcite cement occupy the secondary porosity of the forams. Plane polarized light.

**Figure 4B.** Packstone with many *Lepidocyclina* sp. and *Miogypsina* sp. forams which are partly broken. Mechanical burial diagenesis caused grain distortion and cross-cutting of fracture within the grains which then infilled by granular mosaic calcite cements. Plane polarized light.

**Figure 4C.** Grainstone in shallow water platform top with abundant of *Lepidocyclina* sp. forams and minor mud matrix. Note many of grain breakage and minor fractures between grains due to mechanical burial diagenesis of post-depositional alteration. Plane polarized light.

**Figure 4D.** Poikilotopic calcite cements at the left upper part of a thin section from Outcrop 2. Plane polarized light.

**Figure 4E.** Blocky cements infilled within the fractures and in most of the intergranular pores.

**Figure 4F.** SEM image of Figure 4C showing the presence of blocky calcite cements (C).
3.1.2 Crystalline cements

Detailed observations on most of the samples indicate the presence of Mg-calcite cement. The calcite cement are dominantly occupied both inter- and intragranular porosity and secondary fractures by the granular mosaic and blocky mosaic and predominantly by the poikilotopic cements. The blocky calcite cements can be seen as equidimensional crystal up to 200μm and euhehedral. Poikilotopic crystals are larger than 400μm which enclose a number of allochems and this cements are only seen in one thin section from Outcrop 2 (Figure 4D). The cementations are seen to be after grains-related compaction and mostly are blocky mosaics. The diageneric of shallow marine to shallow burial environment is deduced as the granular mosaic and blocky calcite mosaics postdates most of the grains breakage events.

3.2 Diagenetic process and environment

Through petrographic analysis, there are five diagenetic features that can be observed, which consist of micritization, grain scale compaction, cementation, mechanical compaction and chemical compaction (Table 1). These studies reveal that there are three main phases that reflecting the environment of diagenesis that have affected the Gomantong Limestone in Sukau; (1) the presence of micritic envelope shows that the sample has gone through pervasive shallow marine micritization (Figure 4A), followed by (2) moderate burial diagenesis shown by the grain distortion, mechanical grain breakage and closer grain packing due to mechanical compaction and pore-filling cementation by granular calcite cement (Figure 4B, 4C); and (3) moderate - deep burial diagenesis shown by cross-cutting fractures due to compaction followed by cementation of blocky calcite cement and poikilotopic cement (Figure 4D, 4E, 4F), and chemical dissolution that resulted the formation of stylolites.

Micritic envelopes appear at an early stage of submarine cementation. The micrite cement is found interbedded with and surrounding calcite crystallites of the allochems, indicating the original structure of the allochems (e.g. forams). The original structure of the leached bioclasts (e.g forams) is preserved by the stable micritic envelope formed during stabilization in marine pore fluids (Figure 4A). The presence of micritic rims is thought to be the result of high carbonate concentrations during the commencement of cement precipitation [9] and possibly controlled by the distribution and metabolic activity of bacteria [10] or physicochemical process that caused rapid precipitation [11].

Diagenetic alteration continues with burial compactional features by the evidence of the grain distortion, mechanical grain breakage and closer grain packing which latter includes the tangential and concavo-convex grain contacts that is prevalent throughout the samples of packstone-grainstone facies (Figure 4B, 4C). However, the degree of closeness between grain packing, grain breakage and the sutured grain contacts are highly variable between samples from different outcrops which might indicate the increased burial compaction relative to lithification and depth. However, there might also influenced by the lithology-influenced. It can be seen that the closer grain contacts leading to pressure dissolution which occur over the shallow marine to moderate burial depth (Table 1) where the depth ranges are lower than those micrite dominated matrix samples. The grain-related compactional features are prevalent in samples which have (1) contain grains or lithologies which are prone to grain breakage (2) strongly affected by burial prior to cementation and lithifications.

Cross-cutting fractures (Figure 4B) were observed more than individual grains (including the grain breakages). The relative timing of fracturing varies with every samples and some samples may have undergone several phases of fracturing. Granular and blocky mosaics are most commonly observed as infilled in all the fractures with crystal size commonly <100μm. The fracturing is mostly related to mechanical compaction which is formed in both shallow and deep burial depth as the diageneric environments. Fractures filled by blocky cements may have burial or tectonic structuration origins depending on their relative timing and later cements fills. In this case, the relative timing is said to be post-date of micritization, grain breakage and cementations processes as it crossect all of the features. Moreover, the filling of the fractures are mostly by blocky cements induced that this mechanical compaction occurred further down the shallow burial depth and may have influenced of meteoric influence after the sediments underwent an uplift.
Stylolites with features of continuum of jagged like to ‘anastomosing’ dissolution seams [8] are observed in certain thin sections. The stylolites are mostly postdate all other diagenetic features. Stylolites observed are mostly bed parallel and also some occur as circum-clast stylolites. The stylolites and dissolution seams can be spotted as dark brown-black color. Stylolites, which is the chemical compaction features, post-date all the other diagenetic features based on the cross-cutting relationships. This features are mostly form in moderate to deep burial environments.

Table 1. Summary of diagenetic features and environment.

| Diagenetic Features | Diagenetic Environment |
|---------------------|------------------------|
|                     | Shallow Marine         | Shallow Marine – Moderate Burial | Moderate – Deep Burial | Meteoric Influence |
| Micritization       |                        |                                   |                        |                    |
| Grain Scale Compaction |                        |                                   |                        |                    |
| Cementation (Inter- & Intragranular Pores) |                        |                                   |                        |                    |
| Fracturing          |                        |                                   |                        |                    |
| Fracture Filling Cements |                        |                                   |                        |                    |
| Stylolites & Dissolution |                        |                                   |                        |                    |

3.3 Reservoir Quality
Diagenesis comprises a wide spectrum of geochemical, physical and biological post deposition events where the original sedimentary mineral assemblages and their interstitial pore waters interact in attempt to reach the textural and thermodynamic equilibrium with their environment [12]. The Gomantong Limestone Formation has low porosity and permeability due to the pervasive cementation. The porosity of the Gomantong Limestone decreases with the increasing depth due to compaction process. However, burial diagenetic settings cause dissolution between bioclasts which can enhance the porosity (Figure 4).

4. Conclusion
In the Gomantong Limestone Formation is well preserved and variation of lithofacies can be observed throughout the ten outcrops identified in Sukau. The diagenetic processes and environment is determined through detailed petrographic analysis and scanning electron microscopy results. The diagenetic processes of the Gomantong Limestone Formation are mostly minimal due to the lack of sub-aerial exposure and restricted to shallow marine and burial diagenetic environment. It is found that there is little variation of cements with dominant granular and blocky cement types. Over 90% of the samples are fractured indicating shallow burial effects. The Gomantong Limestone Formation has very low reservoir potential due to the high cementations. However, a few samples indicating the burial diagenetic settings showed enhancement of reservoir quality where the dissolution processes created pores between bioclasts.
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