Malaysian Journal of Microscopy Vol.8 (2012) pg. 11-16

A MICROSCOPIC ANALYSIS OF RECENT LITHIFIED LIMESTONES FROM PRESENT- DAY PLATFORMS, EAST OF SABAH, MALAYSIA

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A detailed petrographic study, XRD and SEM analysis of the beachrock, submarine hardgrounds and exposed reef limestones from a number of present-day carbonate platforms in the Celebes Sea, east of Sabah, Malaysia, aims at determining the diagenetic history and the origin of the cements that have lithified carbonate sediments. The texture of the beachrocks from Sibuan and Maiga Islands is consistently a coarse-grained, skeletal-dominated and moderately sorted grainstone. Micritic envelopes formed after deposition, then cemented by fibrous aragonite, forming needle-like crystals. This clear dominance of aragonite cements implies cementation in marine waters. The texture, composition and diagenesis of a submarine hardground in northern Maiga Island are similar to the beachrock. One specific feature found is the common presence of borings by Lithophaga sp. after cementation. The walls of the borings are clearly erosional and are devoid of cement. The exposed reef limestone of Selakan and Sebangkat Islands is classified as textures of packstone and boundstone. The diagenetic alteration starts with the formation of a micritic envelope, followed by dissolution of aragonite. Replacement and recrystallization took place after dissolution into blocky calcite spar and large monocrystalline calcite, suggesting subaerially diagenesis by freshwater-vadose environment in reefs.

Keywords: Beachrock, Hardground, Raised reef, Diagenesis.

INTRODUCTION

Carbonate sediments deposited on platforms are commonly subject to early diagenesis, mainly cementation and dissolution, either during or shortly after deposition or during periods of subaerial exposure. The process of early submarine cementation occurs in beachrock, hardgrounds, shallow subsurface cemented layers, lithified reef and cemented fore-reef or upper slope deposits [1] and is a widespread process in several modern carbonate depositional environment and fossil reefs [2]. Early cementation allows good preservation of many microfabrics, although it may decrease initial porosity. Furthermore, by creating a rigid framework that resist to the compaction, the process may also help the preservation of porosity that particularly occur in porous skeletal or oolitic limestones at windward-margin marine environments [3].

Cemented horizons are found on present-day carbonate platforms and islands of the Celebes Sea, east of Sabah, Malaysia and are the subject of this paper. Beach rock occurs on islands, where beach sediments are rapidly cemented through the precipitation of carbonate cements in the intertidal zone [4]; hardgrounds, where the submarine sediment surfaces became lithified before a subsequent sediment layer was deposited, occur both on shallow-water shelves and on deeper, off-shelf slopes and basins [2], and are found on Maiga Bank and lithified reefs that make up the islands of Selakan and Sebangkat, rich in corals and now elevated by about 3 to 5 meters above their original position may indicate sea level change and/or local tectonic uplift [5].

Combined field and detailed petrographic study of these cemented facies and horizons provide new constrains on the diagenesis and origin of the cements that lithified carbonate sediments.

The purpose of this study is to: (1) classify the carbonate rocks, (2) document submarine cementation of the Holocene lithified limestones of the present-day carbonates platforms, east of Sabah, (3) analyse the diagenetic history of the facies found on the platforms, and (4) interpret the depositional environment of the lithified limestones.

Study area

Located at Tun Sakaran Marine Park, east of Sabah, a number of present-day carbonate platforms (Fig. 1), seem to have been affected by relative sea level fluctuations in the recent past. Study areas consist of two islands that made up by coral reefs and have raised on Selakan Bank, Selakan and

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Sebangkat; beachrocks line discontinuously the eastern coasts of Sibuan and Maiga Islands and shallow submarine hardgrounds underlie the recent sediments in the lagoon of Maiga Bank. These recent isolated carbonate platforms of the Celebes Sea are thought to have developed on the fault blocks or on Late Tertiary volcanoes [6] and faced the dominant northeast trade winds where coral reefs develop along the windward margin [5]. There was probably a continuous magmatic arc from Semporna peninsula to Dent peninsula throughout the Sulu arc [7], possibly the product of north-directed subduction of the Celebes Sea [8].

Sebangkat and neighbouring Selakan, Islands both about 1 km in diameter, are elevated above present-day sea level and have been exposed to meteoric influence for some time. Located in the southern part of Selakan Bank, these two islands are referred to as raised limestone platforms [6]. Selakan Island consists of a core of volcanic rocks at the northern end, may be part of the 'Bodgaya Volcano' found on the neighbouring Gaya Bank [9] and is partly surrounded by Pleistocene or Holocene lithified coral reefs. These ancient coral reefs can also be seen in Sebangkat Island.

Beachrocks are cemented layers of beach sediment, gently dipping in a seaward direction (5° to 20°) in the foreshore zone, dominantly orientated in a southwest-northeast direction. These slabs were locally undercut and fractured to form what appears as a regular "pavement". One of the beach rock layers consists of a storm deposit and contains large coral fragments and shells of the giant clam Tridacna. The uppermost layer of the beach rock contains near-spherical to elongate voids referred to as keystone vugs or birdseyes structures [10] that suggest deposition in the intertidal zone.

An extensive hardground covers a large part of the internal lagoon of Maiga Bank. This hardground is covered by a few centimeters of loose sediments. It currently lies in the intertidal zone and is commonly exposed at low tide. The surface is always uneven, extensively bored, among others by *Lithophaga* sp., and its thickness is irregular, probably comprised between 20 and 50 cm. The color ranges from white to brownish yellow.

MATERIALS AND METHODS

Thin sections of impregnated blue-dyed epoxy samples of elevated reef rock, hardgrounds, and beachrocks were made from 52 core plugs at PETRONAS Research Sdn. Bhd. (PRSB), Bangi. A conventional microscopy is used to examine these thin sections in order to identify the textural features and framework composition, porosity types and determine the cements in order to understand the diagenesis processes that they underwent during lithification and paleoenvironments. Additional investigations included X-ray diffraction (XRD) to confirm the composition of the cements, and Scanning electron microscope (SEM) analysis that allows the identification of crystal morphology and mineralogy, and provide key information on depositional and diagenetic products and processes.

RESULTS AND DISCUSSIONS

Composition, Texture and Cements of Beachrock and Hardground

Texturally, the beach rocks and hardground of Sibuan and Maiga Islands are grainstones [11], coarse-grained and moderately sorted. The grains are rounded to subrounded and consist of calcium carbonate skeletal fragments of bivalves, gastropods, corals, echinoderms, benthic foraminifera, coralline red algae and calcareous green algae.

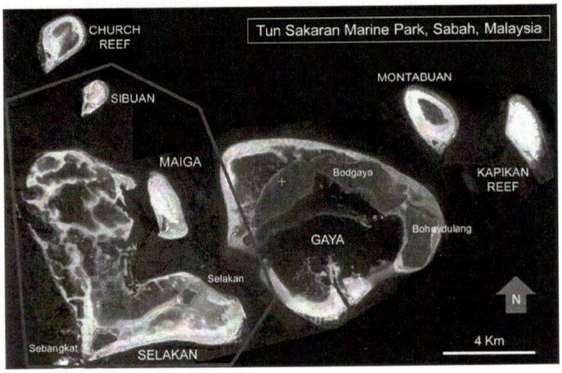

Fig. 1. Satellite image (courtesy Pierson et. al) of location map [5].

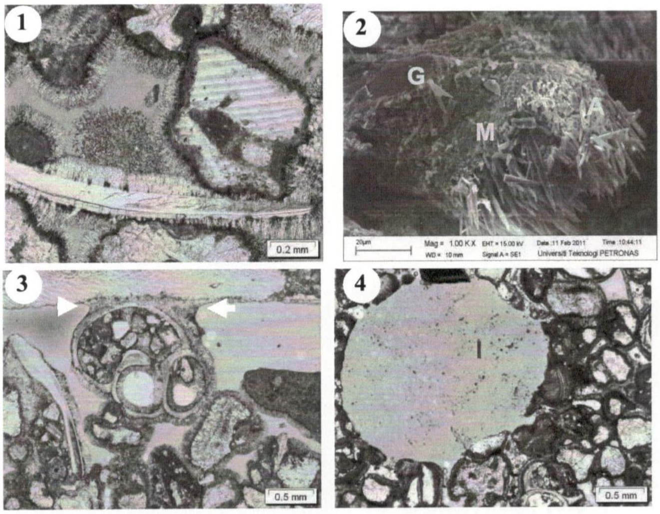

Fig. 2. Characteristic marine cements. (1) An irregular micritic layer (light brown) lines the grains and is followed by a thin micritic envelope (dark brown). Rims of isopachous fibrous aragonite cement grew over the micritic envelope and filled interparticle porosity. Blue color is porosity. Plane polarized light. (2) SEM view of (1). G - grain; M - micrite cement; A - aragonite needle cement. (3) Meniscus cement (arrows) in the beachrock of Sibuan Island. Cement precipitated as aragonite in the marine vadose zone. Isopachous aragonite cement filled intraparticle (I) pore space of gastropod shell. Plane polarized light. (4) Boring by a specialized mollusk (Lithophaga). The mollusk eroded the grains, creating a perfect circular void. Borings are a common feature of hardgrounds, Maiga Island. Plane polarized light.

Porosity is high (~35%), mostly intergranular, with some intragranular porosity in coral fragments and gastropods. Secondary porosity, in the form of borings, created by boring organisms such as pelecypods *Lithopaga* sp.are common in the hardground and are also found in parts of the beach rock. The walls of the borings are clearly erosional and are devoid of hardground cements (Fig. 2.4). Boring traces suggest that the beach rocks and hardgrounds lie or used to lie at or close to the sediment or water interface [2].

SEM, optical microscopy and XRD results from cemented samples from Sibuan and Maiga Island reveal more about the nature of the cements. The most common cements in the beachrock and hardground are: 1) micritic cement and 2) fibrous aragonite cement.

Micritic cement

The grains in the beachrock from both islands are consistently surrounded by a coating of micritic cement rim, probably aragonite. The micritic rim is irregular (Fig. 2.1) and probably consists of a zone of early alteration of the grains (light brown) and an outer zone of cement (dark brown). Micrite also filled the intraskeletal pores spaces particularly in coral fragments and gastropod chambers (Fig. 2.3).

Fibrous aragonite

The grainstone texture is dominantly cemented by needle-like aragonite crystals that developed over the micritic cement rims. This early submarine cement is clear and generally fibrous, under plane polarized light. Individual crystals of fibrous aragonite vary in length. Fibrous cements occur as rims of equal thickness (isopachous) around the grains, within both interparticle and intraparticle pore spaces (Fig. 2.1, 2.3). In some cases, the fibrous needles are occasionally longer in intraparticle pore spaces than around the grains and partially fill this pore type. The aragonitic cement may locally take on a "meniscus" shape (Fig. 2.3). This type of cement is interpreted to be marine [2, 3, 4].

Composition, Texture and Cements of Raised Reef

Packstone and boundstone [11] are the dominant textures of the exposed reef limestones from Sebangkat and Selakan Islands. The reefs

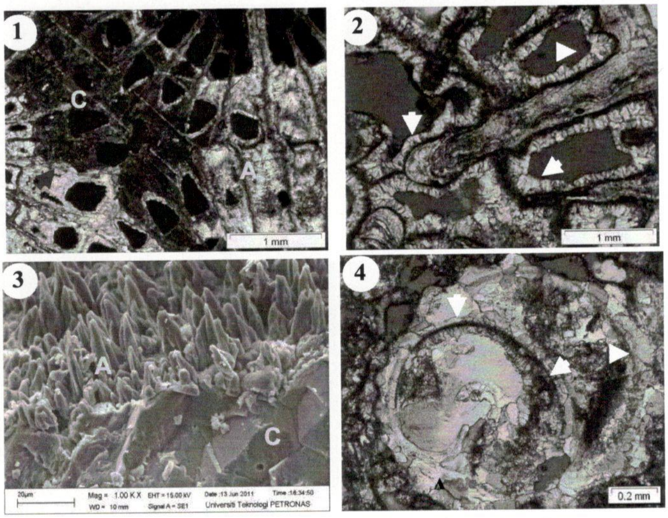

Fig. 3. Cement features from exposed reefs. (1) Two generations of carbonate cement in reef. Fascicle aragonite precursor (A) represents the original coral skeleton. It was locally replaced by later calcite monocrystals (C) that display a single direction of extinction and are typical of neomorphism of aragonite by calcite. The boundary between two different monocrystals is sharp (yellow arrow). Black is porosity. Crossed polars. (2) Isopachous and equant calcite cements (arrows) fringing the interseptal pore of coral skeleton. It lines the organic-rich coral wall initially covered by a micritic envelope (dark line). Blue is porosity. Plane polarized light. (3) Detail morphology of fibrous aragonite and blocky calcite crystals in SEM image. The aragonite crystals show signs of corrosion by freshwater. (4) The early micritic envelope marking the former shell is preserved in a thin dark line (arrows). A = gastropod now composed of blocky calcite spar. Plane polarized light.

are rich in skeletal components such as fragments of corals, bivalves, gastropods, echinoderm, benthic foraminifera, coralline red algae, and calcareous green algae.

Porosity is about 10-20% and includes both interparticle and intraparticle. Interparticle and intraparticle pore spaces are generally filled by meteoric cements and internal sediments.

A variety of morphologies of cements has been identified from the exposed reefs limestones including: 1) microcrystalline cement, 2) fibrous cement, 3) equant calcite cement, 4) blocky calcite cement and (5) large replacement calcite crystals.

Microcrystalline cement

Microcrystalline cement, commonly referred to as the micritic envelope, is the most abundant cement lining the bioclasts (Fig. 3.2, 3.4). Micritic envelopes line the coral cavity in boundstone and packstone (Fig. 3.1, 3.2). This type of cement occurs both in intra- or interparticle pores. Microcrystalline cement is marine pheratic precipitates [12].

Fibrous cement

This early submarine cement is clear and generally fibrous, under crossed polarized. Fine fibrous crystals are arranged in radiating bundles (termed fascicles) that grow from the axis of trabeculae in the septa of corals skeleton (Figure 3.1). They are well preserved in some isolated pores of coral skeleton and were not affected by freshwater diagenesis. In connected pores, they are partially to completely dissolved and have been incorporated and maybe recrystallized into blocky calcite spar in the interseptal pore spaces of coral framework. This cement is interpreted to be marine, originally aragonitic, based on analogy with similar recent cement described in other studies [2, 3].

Equant cement

Calcite cements vary in morphology of crystals habits that include encrusting isopachous and equant calcite rims up to 0.5 mm thick. They are well developed mostly along the interseptal pore spaces of corals cements and early geopetal sediments. This type of cement may represent the replacement fabric of a fibrous marine aragonite precursor and is of freshwater vadose and/or phreatic origin [13].

Blocky cement

Fine to medium size of blocky calcite crystals, generally subhedral, are mostly found as replacement of aragonitic coral skeleton, especially where septa are narrow. Such calcite spar cements has been observed also mostly in aragonitic shells (Fig. 3.4) and other skeletal fragments after dissolution. These cements are best developed both in interparticle and intraparticle pore spaces. Meniscal fabric occurs in several parts showing curved fringes of blocky calcite at the grains contact.

Large monocrystalline calcite

Large crystals of calcite are locally observed in coral skeleton, mimicking the shape and texture of the precursor aragonitic skeletal fabric (Fig. 3.1). They form relatively large mono crystals that display extinction in a single direction. The boundary of fibrous aragonite and calcite mosaic is extremely clear, suggesting slow replacement, possibly through neomorphism.

Diagenesis

Early submarine cementation appears to commence with the precipitation of micritic cements as micritic envelopes [15]. The formation of micritic envelopes is thought to be the result of high carbonate concentrations during the commencement of cement precipitation [16]. The initial cementation of micrite in beach sands and reefs framework is possibly controlled by the distribution and metabolic activity of bacteria [17]. Microbially-mediated precipitation of carbonates has been demonstrated in both marine and terrestrial environments [19]. The precipitation of micritic pore-filling cement is common in well-cemented beachrock and reefs resulting from the microbial activity [20] or physicochemical process that caused rapid precipitation [21].

The development of fibrous aragonite takes place after the precipitation of micritic envelopes and is thought to be the result of deceleration of carbonate precipitation due to decreasing ambient carbonate concentration [22]. The clear dominance of these cements implies that the water, from which cements are precipitated, is generally marine [2, 3]. Meniscus fabrics observed in the aragonitic cement indicates that lithification occurred in the vadose zone [14] where precipitation takes place in the presence of two phases, air and water at the intertidal zone and exhibit a curved surface (meniscus) caused by surface tension at the grain contacts [11].

Dissolution of aragonite then occurs in the elevated reefs and is accompanied by the replacement of aragonite by calcite mosaic and by large monocrystals of calcite and by the precipitation of void-filling blocky calcite cement. The original structure of the leached bioclasts is preserved by the stable micritic envelope formed during stabilization in marine pore fluids (Fig. 3.4). Neomorphism is believed to occur also in the reefs as the calcite mosaic formed a large single crystal with one direction of extinction (Fig. 3.1), characteristic of freshwater-phreatic diagenesis [23]. The reefs are now subariselly exposed, possibly due to tectonic uplift and Holocene sea level fluctuations and are consequently subjected to subaerial diagenesis by meteoric freshwater water. Meniscus calcitic cement confirms that diagenesis occurred in a freshwater vadose environment [14].

CONCLUSIONS

Fibrous aragonite cements are mainly found in beachrock, and hardground samples and locally in elevated reef samples. They formed after the formation of micritic envelopes, characteristic of marine water cementation. Freshwater diagenetic features are found in elevated reef limestone and include neomorphism and cementation by calcite. Neomorphism is a partial to complete alteration of metastable aragonite into blocky calcite spar, indicative of diagenesis in a freshwater-vadose environment. Blocky and mosaic calcite are also characteristic of freshwater diagenesis; meniscus cement further indicates precipitation in a freshwater vadose environment.

ACKNOWLEDGEMENTS

This research project, carried out at the South-East Asia Carbonate Research Lab (SEACARL), is financed by STIRF Fund, Universiti Teknologi PETRONAS. The authors wish to thank Sabah Parks for granting them a research permit to work in Tun Sakaran Marine Park and to the staff of Sabah Parks Kota Kinabalu, Semporna, and Bohedulang station for their invaluable help and support during the field visits to Tun Sakaran Marine Park.

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