Comparison of origin and mineralogy between clay fractions of lime muds recovered from the Arabian Gulf lagoons and from the Taketomi Island intertidal flats

Satoshi Yamamoto* and Kazukiyo Oshima**

Lime muds and similar kinds of carbonate sediments obtained from the Arabian Gulf regions and from Taketomi Island were isolated into clay and silt fractions and their carbonate mineralogy was investigated by X-ray diffraction (XRD). Two types of lime muds were recognized in the Arabian Gulf lagoons. Aragonite rich lime muds were found in the lagoon near Abu Dhabi. In this mud the concentration of aragonite increases in the clay fraction than the silt fraction. On the other hand, high-Mg calcite (HMC) rich lime muds were found in the lagoon in the Mubarraz shoal. In this mud the concentration of HMC always increases in the clay fraction than the silt fraction. At offshore area of the Arabian Gulf, the lime mud supplied from the coastal lagoons is diluted by low-Mg calcite (LMC) coccolith ooze. In the Taketomi Island samples, it is already known that the underlying coral reef limestones contain numerous patches of lime clay in which HMC is enriched and the HMC lime clay may be supplied to the overlying lime mud by erosion. Similarly, in the Mubarraz shoal lagoon the HMC enriched clay fractions of the lime mud may be supplied from the lime clay enclosures contained in the surrounding coral reefs.

Key words : Arabian Gulf, aragonite, HMC, lime clay, lime mud, Taketomi Island

INTRODUCTION

Lime mud is a mixture of carbonate silt and carbonate clay. Carbonate silt is composed of skeletal fragments of various calcareous organisms, and aragonite needles or cement materials derived from Halimeda and corals. The carbonate silt may be further fragmented into carbonate clay; however, the carbonate clay may contain carbonates of various other origins, including inorganic precipitation. The inorganic aragonite needle which is only observed in the Caribbean Sea (MacIntyre and Reid, 1992; Milli-

man et al., 1993) is clay-size carbonates and suspected to be composed of high-Sr aragonite (HSA) (Milliman, 1974). Whether the clay-size inorganic aragonite needles are precipitating in the Arabian Gulf region or not is not well understood. Kendall and Skipwith (1969) and Purser and Evans (1973) have suggested that non-skeletal aragonite is precipitating inorganically or as blue-green algae in Khor al Bazam and other lagoonal environments along the coastal areas of the Arabian Peninsula.

For a particular sample of lime mud, the separation of the samples into clay and silt fractions and comparison of mineralogy of these fractions may be important. Particularly, origin of clay fractions of the lime mud may be the most important. In this study, lime mud samples were compared between various types of lagoons in the Arabian Gulf and the Taketomi Island inter-

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* Laboratory of Oceanography Faculty of Science, University of the Ryukyus, Nishihara, Okinawa 903-0129 Japan

** Registered Consulting Engineer, 4-9, Toshima 7-chome, Kita-ku, Tokyo 114-0003 Japan

tidal flat, by separating these samples into clay and silt fractions.

SAMPLES

Figure 1 shows the geography and topography of the southeastern part of the Arabian Gulf. Two samples were obtained from the lagoon near Abu Dhabi (Fig. 2) and four samples from the lagoonal area of the Mubarraz shoal (Fig. 3) and as reference study two samples from offshore channel and one sample of algal mat (Am-1) were obtained (Fig. 2). The detail lithology and distribution of modern carbonate sediments in this area were described by Oshima (1988, 1989).

Two lime mud samples from Taketomi Island, Okinawa, Japan (Figs. 4 and 5) were compared with the Mubarraz shoal lime muds, since four samples on the Mubarraz shoal lagoon show sim-

ilar mineralogical composition in silt-clay fraction with the lime muds overlying on intertidal limestone in Taketomi Island. In Taketomi Island, the lime sandy mud covers thinly (about a few cm) the intertidal limestone. The limestone is framestone of *Acropora* or biosparite/biomicrorite limestone (Yamamoto and Tsuboi, 1999). The limestone also contains numerous patches of lime clay (actually comprised of about 80% clay and about 20% silt, by smear slide observation). This kind of sediment is termed as clay in this study.

The clay fraction of the lime mud overlying the limestone may originate from the lime clay patches by erosion (Yamamoto and Tsuboi, 1999).

METHOD

The samples were sieved and coarse fractions

Fig. 1 Index map for the southeastern parts of the Arabian Gulf. Bathymetric contours are in fathom. Modified from Kassler (1973).

Fig. 2 Sampling sites in lagoon near Abu Dhabi, at offshore channels, and at coast line. Sampling sites in the Mubarraz shoal lagoon are shown in Fig. 3. Modified from Kassler (1973).

(sand and gravel fractions) were removed. The remaining mud fractions were suspended in water. No dispersion detergent was used. Using the difference of settling velocity, supernatant clay fractions and settled silt fractions were separated (Fig. 6). The settled silt fractions were dried and powdered for the X-ray diffraction analysis (XRD). The supernatant clay fractions were further settled, and the clay suspending water volumes were gradually decreased by removing surficial clean waters. The water volumes were decreased until the clay suspending waters were filled in a small evaporating dish and the clay suspending waters in the dish were evaporated into dryness using heating lamp. The dried clay fractions were also powdered for XRD. The XRD mineralogy was determined and compared between the clay and silt fractions.

RESULTS

Figure 7 shows an example of XRD. Most of peaks are carbonate minerals, such as high-Mg calcite (HMC), low-Mg calcite (LMC), and aragonite. Some samples contain quartz, clay minerals, and other minerals (Tables 1 and 2). The carbonate contents and the concentrations of combustible organic matter (COM) (Tables 1 and 2) were determined for unseparated bulk fractions, after grinding the bulk samples into powder, by ignition loss analysis. The residual materials excluding carbonates and COM are quartz, silica minerals, silica, clay minerals, and other minerals. The quartz in these carbonates may be contained as authigenic quartz crystals, not as detrital quartz grains.

The concentrations of HMC, LMC, and aragonite in carbonates were calculated on the basis

Fig. 3 Sampling sites in Mubarraz shoal (modified from Oshima, 1989).

Explanation of legend: 1; Mubarraz Island. 2; Intertidal clean (mud-free) coarse sand. 3; Subtidal clean coarse sand. 4; Patch reefs surrounding of Mubarraz shoal. 5; Lagoon muddy sediment. 6; Outer limit of Mubarraz shoal.

of peak areas of the primary peaks and compared between silt and clay fractions of the lime mud (Tables 1 and 2).

In terms of carbonate mineralogical compositions of silt and clay fractions, carbonate muddy sediments in the Arabian Gulf can be categorized into three types. The first type is muds from the Mubarraz shoal lagoon. In these muds, major carbonate minerals are characterized by HMC, and the concentrations of HMC are always higher in the clay fractions than the silt fractions.

The second type is muds from the lagoon near Abu Dhabi. In these samples, major carbonate

minerals are aragonite, and the concentrations of aragonite are always higher in the clay fractions than the silt fractions.

The third type is muds from the offshore channels. In these muds, the LMC concentrations are significantly increased for the clay fractions than the silt fractions. These increased LMC in the clay fraction can be accounted by the mixing of coccolith ooze supplied from the Gulf and open sea waters. The smear slide observation of these samples also confirms the presence of coccoliths in the clay fractions of these mud samples.

HMC is known to reprecipitate as aragonite (possibly as low-Sr aragonite) (Winland, 1969; Alexandersson, 1972); therefore, the weathering and fining processes of HMC may increase the concentration of aragonite in the clay fraction. Aragonite and HMC are known to alter to LMC by weathering and fining processes (Land, 1967). The increase of the HMC concentration in the clay fraction can not be explained by mineralogical changes by fining process in carbonate minerals. The only mechanism to increase the HMC concentration in the clay fraction is that the clay-size HMC must be supplied.

In the case of the Taketomi Island samples (Table 2), it is known that the clay fractions of the lime mud originate from the lime clay contained in the underlying limestone as enclosures (Yamamoto and Tsuboi, 1999). In other words, the lime clay contained in the limestone is enriched with HMC and supplied to the clay fraction of lime mud, increasing the HMC contents in clay fraction (Table 2).

Algal mat sample (Am-1) was obtained at the onshore side of algal mat, just transitional zone between algal mat and coastal sabkha. Although thin black algal layer covered the surface, the sediment underneath the alga was the same type deposited at the supratidal zone. The algal mat (Am-1) occurs as gravel size aggregates of calcareous clay containing organic matter. The algal mat sample was studied for a comparison and silt and clay fractions were also

Fig. 4 Sampling sites (Kondo Beach area, shown by asterisk (*)) in Taketomi Island, southern part of the Ryukyu Islands.

Fig. 5 Sampling sites in Kondoi Beach, Taketomi Island.

Explanation of legend : 1; Terrestrial vegetation line. 2; High tide line. 3; Low tide line. 4; Edge of coral reefs. 5; Small terrace of limestone, including beachrocks. 6; Intertidal limestone area.

isolated from this sample by the same procedure described previously.

The Am-1 is characterized by high organic matter content and rather low carbonate content (Table 3). Carbonate mineralogy in the algal mat shows the presence of siderite in the clay fraction. The amounts of LMC and siderite in the clay fraction are nearly equal to the amount of LMC in the silt fraction, and the aragonite content increases in the clay fraction than the silt fraction. The formation of clay-size siderite may be occurred by the reaction between the clay-size detrital LMC and organic matter or clay minerals. Very small amounts of dolomite were found in the algal mat and other samples (AU-5 and AU-6) in the coastal areas along the Arabian Peninsula (Table 1). This may be influenced by evaporitic conditions in the sabkha environment (Kendall and Skipwith, 1969; Evans et al., 1973). But, no gypsum was found in the samples analyzed in this study.

DISCUSSIONS

Although the fining processes of HMC may increase the concentration of aragonite in the clay fraction due to diagenesis, the most probable reason why the concentration of aragonite is increased in the clay fraction than the silt fraction may be precipitation of clay-size aragonite and supply of clay-size aragonite to the lime mud deposition. Kendall and Skipwith (1969) and Purser and Evans (1973) suggested that nonskeletal clay-size aragonite is precipitating inorganically or as blue-green algae in the lagoons along the Arabian Peninsula. Evans et al. (1973) suggested that the lagoons near Abu Dhabi show high-salinity sabkha conditions and dolomite and aragonite can be precipitated in this sabkha environment.

On the other hand, clay-size HMC may be formed and fill the enclosures contained in coral reef limestone and these clay-size HMC may be supplied to the lime mud in the Mubarrasz shoal lagoon, like Taketomi Island. It is expected that

Separation methods of silt and clay fractions from lime mud

Fig. 6 Flow chart of separation methods.

the lagoonal lime mud in the Mubarraz shoal is supplied from surrounding coral reefs. The coral reefs may contain numerous patches (enclosures) of lime clay enriched with HMC.

Two types and two kinds of origins can be suggested for the genesis of clay fractions of lime mud in the coral reef environments of the world. The one type of lime clay may be the inorganic aragonite needle which is usually observed in the Caribbean Sea (MacIntyre and

Reid, 1992 ; Milliman et al., 1993). The mineralogy of the inorganic aragonite needle is not well understood on the basis of isolation of them from the bulk lime mud. However, Milliman (1974) suspected that the aragonite needles (including the inorganic aragonite needle) in the Great Bahama Bank are composed of high-Sr aragonite (HSA), mineralogically. The inorganic aragonite needle is suspected to precipitate in the basin water column as whittings (Shinn et al.,

Fig. 7 Representative XRD diffractogram of ST-3 (clay fraction).
 Notation of peaks : HMC ; high-Mg calcite. LMC ; low-Mg calcite. A ; aragonite. Q ; quartz.

Table 1 Mineralogical Composition of Arabian Gulf Lime Mud.

	Sample No.		Fraction Aragonite (%)	HMC (%)	LMC (%)	Total (%)	
Mubarratz shoal lagoon (Mud)	ST-1	Silt	25.3	51.5	23.2	100.0	COM=4.02% CaCO ₃ =91.1 % Quartz
		Clay	13.0	54.5	32.5	100.0	
	ST-3	Silt	17.0	52.8	30.0	100.0	COM=3.38% CaCO ₃ =92.6% Quartz, Clay M.(?)
		Clay	13.3	57.7	29.0	100.0	
	ST-7	Silt	25.3	64.1	10.6	100.0	COM=4.40% CaCO ₃ =91.8% Quartz
		Clay	9.1	73.4	17.5	100.0	
	ST-8	Silt	28.3	59.4	12.4	100.1	COM=3.78% CaCO ₃ =92.0%
		Clay	23.8	68.8	7.4	100.0	
Lagoon near Abu Dhabi (Muddy sand)	AU-5	Silt	56.6	25.2	18.3	100.1	COM=4.66% CaCO ₃ =80.6% Quartz, Dol.(?)
		Clay	68.9	21.1	10.0	100.0	
	AU-6	Silt	53.8	32.3	13.9	100.0	COM=2.76% CaCO ₃ =84.1% Quartz, Dol.
		Clay	55.3	29.1	15.6	100.0	
Offshore area (Mud)	MS-1	Silt	29.7	44.7	25.6	100.0	COM=3.47% CaCO ₃ =91.3% Quartz
		Clay	28.2	36.8	35.0	100.0	
	MS-2	Silt	23.1	45.0	31.9	100.0	COM=3.98% CaCO ₃ =89.7% Quartz
		Clay	24.9	28.3	46.8	100.0	

Table 2 Mineralogical Composition of Taketomi Island Lime Mud.

Sample No.	Fraction	Aragonite (%)	HMC (%)	LMC (%)	Total (%)	
TA-1	Silt	20.0	63.3	16.6	99.9	COM=3.52%
	Clay	14.9	66.3	18.8	100.0	CaCO ₃ =91.9%
TA-2	Silt	16.2	64.3	19.4	99.9	COM=3.08%
	Clay	18.6	66.8	14.6	100.0	CaCO ₃ =91.8% Quartz

Table 3 Carbonate Mineralogical Composition of Algal Mat in Arabian Gulf.

Sample No.	Fraction	Aragonite (%)	HMC (%)	LMC (%)	Siderite (%)	Total (%)	
Am-1	Silt	25.9	17.6	56.6	0.0	100.1	COM=8.35%
	Clay	36.5	13.5	30.1	19.9	100.0	CaCO ₃ =70.9% Quartz, Plagioclase, Clay M., Dol.

1989; Morse and He, 1993); however, there still remain numerous mysteries on the mechanism of precipitation.

The other type of lime clay in the coral reef environments of the world may be the HMC clay derived from patches of lime clay in the coral reef limestone, as suggested in this study. Reid et al. (1992) emphasized the importance of the micrite envelopes in and around carbonate grains for the source of Mg-calcite (HMC) mud in the coral reef environments. The micrite envelopes are originally bored space by organisms. Winland (1968) found large scale envelopes in molluscan shells and reported that such envelopes are filled with clay-size HMC. Yamamoto and Tsuboi (1999) have found that the lime clay enclosures were bored space by organisms and enriched with HMC. The micrite envelopes and lime clay enclosures may be the important source of HMC lime clay in the coral reef environment.

CONCLUSION

Two types of clay fractions are suggested here for the lime muds from lagoons in the Arabian

Gulf region and in coral reef environments of the world. The clay fractions of lime muds from the Mubarras shoal lagoon and from the Taketomi Island intertidal flat are enriched with HMC and it is suggested that HMC lime clay is supplied to the lime mud from somewhere. The probable source area of the lime clay is the underlying or surrounding coral reefs/limestone. In other words, the coral reef limestone contains patches of lime clay, as observed in Taketomi Island. The other type is probably HSA rich lime clay, which may be observed in the Great Bahama Bank area or in the lagoons along the eastern parts of the Arabian Peninsula. The separation of lime clay from lime mud and the carbonate mineralogy of lime clay may become a clue to the genesis of lime clay in the coral reefs.

REFERENCES

- Alexandersson, T., 1972: Intragranular growth of marine aragonite and Mg-calcite: Evidence of precipitation from supersaturated seawater. *Jour. Sed. Petrol.*, **42**, 441-460.
- Evans, G., Murray, J. W., Biggs, H.E.J., Bate, R. and Bush, P. R., 1973: The oceanography, ecology, sedimentology and geomorphology of parts of the Trucial Coast barrier

- island complex, Persian Gulf. *In* Purser, B.H., ed., "The Persian Gulf". Springer-Verlag, Berlin, 233-277.
- Kassler, P., 1973 : The structural and geomorphic evolution of the Persian Gulf. *In* Purser, B.H., ed., "The Persian Gulf". Springer-Verlag, Berlin, 11-32.
- Kendall, C.G.St.C. and Skipwith, P.A. d'E., 1969 : Holocene shallow-water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, Southwest Persian Gulf. *Am. Assoc. Petroleum Geologists Bull.*, **53**, 841-869.
- Land, L.S., 1967 : Diagenesis of skeletal carbonates. *Jour. Sed. Petrol.*, **37**, 914-930.
- MacIntyre, I.G. and Reid, R.P., 1992 : Comment on the origin of aragonite needle mud : a picture is worth a thousand word : *Jour. Sed. Petrol.*, **62**, 1095-1097.
- Milliman, J.D., 1974 : Marine Carbonates. Springer-Verlag, Berlin, 375p.
- Milliman, J.D., Freile, D., Steinen, R.P. and Wilber, R.J., 1993 : Great Bahama Bank aragonitic muds : mostly inorganically precipitated, mostly exported. *Jour. Sed. Petrol.*, **63**, 589-595.
- Morse, J.W. and He, S., 1993 : Influences of T, S, and P_{CO_2} on the pseudo-homogeneous precipitation of $CaCO_3$ from seawater ; implications for whiting formation. *Mar. Chem.*, **41**, 291-297.
- Oshima, K., 1988 : Petroleum geology of carbonate rocks, No. 8, shallow sediments deposited in channel. *Journal of Petroleum Development and Storage*, 88.8, 91-117. (in Japanese)
- Oshima, K., 1989 : Petroleum geology of carbonate rocks, No. 9, shallow sediments deposited in shoals surrounded by reefs. *Journal of Petroleum Development and Storage*, 89.4, 84-115. (in Japanese)
- Purser, B.H. and Evans, G., 1973 : Regional sedimentation along the Trucial Coast, SE Persian Gulf. *In* Purser, B.H., ed., "The Persian Gulf". Springer-Verlag, Berlin, 211-231.
- Reid, R.P., Macintyre, I.G. and Post, J.E., 1992 : Micritized skeletal grains in northern Belize lagoon : a major source of Mg-calcite mud. *Jour. Sed. Petrol.*, **62**, 145-156.
- Shinn, E.A., Steinen, R.P., Lidz, B.H. and Swart, P.K., 1989 : Perspectives : whittings, a sedimentologic dilemma. *Jour. Sed. Petrol.*, **59**, 147-161.
- Winland, H.D., 1968 : The role of high Mg calcite in the preservation of micrite envelopes and textural features of aragonite sediments. *Jour. Sed. Petrol.*, **38**, 1320-1325.
- Winland, H.D., 1969 : Stability of calcium carbonate polymorphs in warm, shallow seawater. *Jour. Sed. Petrol.*, **39**, 1579-1587.
- Yamamoto, S. and Tsuboi, H., 1999 : Lime clay infilling bored space in coral reefs at Taketomi Island, Okinawa, Japan. *Bull. Fac. Sci., Univ. Ryukyus*, **68**, 3-12.

アラビア湾礁湖内及び竹富島潮間帯干潟から採集されるサンゴ礁泥の 粘土部分の鉱物組成と成因における比較

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アラビア湾及び竹富島から採集されたサンゴ礁泥及びこれに類似する炭酸塩堆積物について、これらからシルト分と粘土分を分離し、X線粉末回折法によって炭酸塩鉱物組成を検討した。その結果、二つのタイプのサンゴ礁泥がアラビア湾に分布していることが解った。まず、一つのタイプはアラゴナイト質のサンゴ礁泥で、アブダビ付近の礁湖内に分布している。この泥では、アラゴナイトの含有量は、常に粘土分の方がシルト分比べて高くなる傾向がある。もう一つのタイプは、高マグネシウム方解石（HMC）質のサンゴ礁泥で、ムバラス浅瀬の礁湖内に分布している。この泥では、HMCの含有量は、常に粘土分の方がシルト分比べて高くなる傾向がある。これら両者礁湖の沖合いのアラビア湾では、沿岸の礁湖から供給されるサンゴ礁泥は、湾内のココリス軟泥によって薄められ、低マグネシウム方解石（LMC）の含有量が高くなる。竹富島のサンゴ礁泥では、HMC質のサンゴ礁粘土の封入物が下位のサンゴ礁石灰岩に無数に含まれ、この封入物が浸食され上位のサンゴ礁泥にHMC質の粘土を供給していることが知られている。同じようにムバラス浅瀬礁湖内のサンゴ礁泥でも、周囲のサンゴ礁に含まれるHMC質のサンゴ礁粘土の封入物が浸食されて、HMC質の粘土分を供給しているものと推定される。