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A comparative study of modern carbonate mud in reefs and carbonate platforms: Mostly biogenic, some precipitated

Eberhard Gischler [a,*], Sarah Dietrich [a], Daniel Harris [b], Jody M. Webster [b], Robert N. Ginsburg [c]

[a] *Institut für Geowissenschaften, J.W. Goethe-Universität, Altenhöferallee 1, 60438 Frankfurt am Main, Germany*
[b] *University of Sydney, School of Geosciences, Sydney, NSW 2006, Australia*
[c] *Comparative Sedimentology Laboratory, University of Miami, RSMAS-MGG, 4600 Rickenbacker Causeway, Miami, FL 33149, USA*

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ABSTRACT

Carbonate mud from reefs and carbonate platforms in six locations of the Atlantic, Indian, and Pacific Oceans (Belize, Bahamas, Florida, the Maldives, French Polynesia, Great Barrier Reef) was systematically and quantitatively analyzed with regard to texture, composition, mineralogy, and geochemistry. Mud composition shows considerable variability, however, the data supports the contention that these muds are largely derived from the breakdown of skeletal grains and codiacean algae. Only mud from the Bahamas and northern Belize, areas which are characterized by common whitings, is interpreted to be mainly inorganically precipitated. Three grain-size fractions (63–20 μm, 20–4 μm, <4 μm) from twelve samples of mud were investigated by scanning electron microscopy (SEM) to identify grains, X-ray diffraction to measure relative abundances of carbonate minerals, atomic absorption spectroscopy (AAS) to determine strontium concentration, and mass spectrometry in order to measure stable-isotope ratios of carbon and oxygen. The coarser grain-size fractions 63–20 and 20–4 μm are dominated by skeletal fragments with the exception of the Bahaman samples that are composed of peloids. The grain-size fraction <4 μm is characterized by the occurrence of small aragonite needles, nanograins, and coccoliths. Coccoliths are common in deeper lagoonal settings of the open ocean settings (Maldives, French Polynesia). The geochemistry of the <4 μm fraction indicates algal and skeletal origins for most of the samples because strontium concentrations range between 2000–8000 ppm and the δ^{13}C values are not as high as in non-skeletal grains. The Bahaman samples, however, exhibit the highest aragonite contents and strontium concentrations, suggesting physico-chemical precipitation. The northern Belize and Great Barrier Reef samples show the highest magnesium calcite values and, accordingly, produced the lowest aragonite and strontium measurements. The high-magnesium calcite portion of the northern Belize mud is either precipitated or due to abundant micritized skeletal grains (e.g., foraminifera): more studies are needed to verify the origin. In the case of the Great Barrier Reef sample, coralline algae appear to be the source of abundant high-magnesium calcite. This study emphasizes that from a global perspective, modern muds in reefs and carbonate platforms exhibit different compositions but are in many cases biologically derived. Even though the composition of modern carbonate muds varies among the six locations investigated, they may serve as analogs for the formation of muds in Cenozoic and Mesozoic reefs and carbonate platforms. Limitations of the interpretation of carbonate-mud origin include the difficulty of identifying, quantifying, and analyzing small grains, the ease with which small grains and crystals are diagenetically altered to microsparitic limestone, and the fact that several modern producers of carbonate mud did not exist in the geological past.

1. Introduction

The origin of mud in reefs and on carbonate platforms is a major problem for carbonate sedimentologists. Many ancient limestones are fine-grained, i.e., micritic (grain sizes <4 μm), microsparitic (grain sizes approx. 5–15 μm) (Folk, 1959), or qualify as mudstone and wackestone (Dunham, 1962). However, their origins are difficult to determine because of textural modifications during diagenesis such as neomorphism producing microspar (Hathaway and Robertson, 1961; Steinen, 1978, 1982) or partial dissolution and the development of chalky texture (Saller and Moore, 1989). Only a few studies have found evidence for aragonite needle muds as precursors of microspar in Pleistocene (Lasemi and Sandberg, 1984), Miocene (Turpin et al., 2011), and Silurian limestones (Munnecke et al., 1997).

The texture and composition of modern shallow-water carbonate mud has been studied in a number of localities, the most prominent of which are located in the tropical western Atlantic; different grain-sizes <63 μm were analyzed (Table 1). Based on these studies, there are three basic hypotheses explaining the origin of such mud. (1) Small

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[*] Corresponding author.
E-mail address: gischler@em.uni-frankfurt.de (E. Gischler).

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Table 1
Summary of studies of origins of carbonate muds in reefs and on carbonate platforms. n.i. = no information.

Author(s)	Area	Findings; evidence; number of mud sediment samples in parentheses	
(1) Origin: codiacean algae			
Lowenstam and Epstein (1957)	Bahamas	$\delta^{18}O$ of mud similar to $\delta^{18}O$ of codiacean algae but different from non-skeletal grain $\delta^{18}O$	(9)
McKee et al. (1959)	Kapingamarangi Atoll	Optical data indicates algal and other biogenic sources of mud	(~30)
Neumann and Land (1975)	Bahamas	Budget calculation indicates codiacean algae sufficient to account for existing masses of mud	(26)
Stockman et al. (1967)	Florida	Budget calculation suggests algae (*Penicillus*) sufficient to account for existing masses of mud	(40)
Bosence et al. (1985), Bosence (1995)	Florida	Geochemical (Sr) evidence that muds originate from codiaceans and epibionts on seagrass	(~40)
Macintyre and Reid (1995)	Florida	*Halimeda*; small aragonite needles alter to nanograins; large needles diagenetic (SEM)	(–)
Andrews et al. (1997)	Florida	Five fractions <63 µm investigated geochemically (Sr, Mg, Fe, Mn, $\delta^{18}O$, $\delta^{13}C$), mineralogically and compared to similar data from algal carbonate	(25)
Scholle and Kling (1972)	Belize	skeletal grains identified in SEM observations of <20 µm size fraction	(25)
(2) Origin: biogenic/skeletal			
Thorp (1936)	Pearl & Hermes, Hawaii	Optical data suggests derivation of mud from skeletal grains	(20)
Matthews (1966)	Belize	Skeletal grains identified in optical observations of 65–20 µm size fraction; mineralogical data	(70)
Reid et al. (1992)	Belize	Micritized skeletal grains form fine fraction (thin-section and SEM observations)	(10)
Gischler and Zingeler (2002)	Belize	SEM, mineralogical, geochemical (Sr, $\delta^{18}O$, $\delta^{13}C$) analyses of mud and algal carbonate	(37)
Hay et al. (1970)	Bahamas	Systematical SEM observations of skeletal grains in mud size fraction	(n.i.)
Stieglitz (1972, 1973)	Bahamas	Skeletal particles identified in SEM observations of mud	(n.i.)
Perry et al. (2011), Salter et al. (2012)	Bahamas	High-magnesium calcite precipitates (<2 µm) form in fish gut (SEM)	(–)
Nelsen and Ginsburg (1986)	Florida	Significant amounts of mud from serpulid and red algal epibionts on seagrass *Thalassia*	(58)
Macintyre and Reid (1998)	Florida	SEM of foraminifer *Archaias angulatus* show that test composed of short needles; alteration to nanograins	(–)
Ellis and Milliman (1985)	Red Sea	Fine suspended carbonate grains in waters biogenic; not precipitated (SEM)	(–)
Piller and Müllegger (in press)	Red Sea	Shell and test detritus form mud in sediment samples (SEM)	(15)
Weber and Woodhead (1972)	Kiribati	Needles in lagoonal muds stem from coadiceans and fine skeletal detritus (SEM)	(n.i.)
Adjas et al. (1990)	French Polynesia	Lagoonal muds from fragmented shells and skeletons (SEM)	(61)
Debenay et al. (1999)	French Polynesia, New Caledonia	Disintegrated foraminiferal tests source of needles and nanograins of high and low magnesium calcite (SEM)	(5)
(3) Origin: precipitation			
Black (1933)	Bahamas	Aragonite in mud inorganically precipitated in water column from hypersaline, supersaturated waters (chemical and hydrographical data)	(n.i.)
Cloud (1962)	Bahamas	75% mud inorgan. precipitated; 20% mud algal origin, 5% detrital origin (SEM, hydrol. data)	(~50)
Morse et al. (1984, 2003)	Bahamas	Sediment and porewater geochemistry indicate that dissolution due to organic matter oxidation dominates in bottom sediment	(~40)
Shinn et al. (1989)	Bahamas	Significant differences in $\delta^{18}O$ and $\delta^{13}C$ of codiacean algae and whitings	(30)
Robbins and Blackwelder (1992)	Bahamas	Cyanobacterial picoplankton and cellular matter trigger carbonate precipitation in whitings	(–)
Robbins et al. (1996, 1997)	Bahamas	Mud in whitings precipitated in water column in association with cyanobacteria	(–)
Macintyre and Reid (1992)	Bahamas	SEM of sediment, *Halimeda* show that algal needles are different from those in muds	(n.i.)
Milliman et al. (1993)	Bahamas	Sr contents in muds much higher as compared to those in algal needles (Sr, mineralogy)	(~50)
Broecker and Takahashi (1966), Broecker et al. (2000)	Bahamas	Radiogenic ^{14}C values in bottom muds similar to aragonite in whitings, but dissimilar to those in waters	(3)
Purdy and Gischler (2003)	Northern Belize, Carpentaria Gulf	Observations of whitings (outside of Great Bahama Bank) could be evidence for carbonate precipitation in the water column	(–)
Macintyre and Aronson (2006)	Belize, Panama	High-magnesium calcite-rich mud in southern Belize and Bahia Almirante, Panama, composed of unlithified precipitates (SEM, mineralogy)	(10)

aragonite needles (usually <5 µm long, <1 µm diameter) and nanograins (<1 µm) derived from the disintegration of "codiacean" algae (families Udoteaceae; Halimedaceae) such as *Penicillus* and *Halimeda* (Loreau, 1982) create so-called aragonite needle mud. (2) Biologic and/or physical breakdown to very fine particles derived from mollusk shells, foraminiferal tests, coral and coralline algal skeletons, tunicate spicules, as well as coccolithophorids and pteropods in open ocean settings, may produce abundant mud in reefal lagoons (Matthews, 1966; Scholle and Kling, 1972; Gischler and Zingeler, 2002; and references therein). (3) The precipitation of aragonite in the water column, either biologically induced, physico-chemically, or as a combination of both has been repeatedly investigated on Great Bahama Bank west of Andros Island (Robbins et al., 1996, 1997; and references therein). Whitings, suspensions of fine carbonate particles, are regarded as impressive manifestations of carbonate precipitation in the water column (Shinn et al., 1989; Robbins et al., 1996, 1997), but have also been explained by sediment resuspension by fish (Broecker and Takahashi, 1966; Morse et al., 1984, 2003; Broecker et al., 2000) and turbulent-flow (Boss and Neumann, 1993).

In addition, grain alteration appears to be very common in tropical shallow-marine settings (Reid and Macintyre, 1998), and potentially changes size and shape of small particles in carbonate mud. Micritization, triggered by microboring and subsequent carbonate precipitation in microcavities of modern carbonate grains, was documented by Purdy (1963a, 1968) and Reid and Macintyre (2000). Subsequent grain disintegration may produce mud composed of cryptrocrystalline grains (Reid et al., 1992). Furthermore, crystal alteration processes may turn needle-shaped crystals to nanograins (<1 µm) in the alga *Halimeda* and the foraminifer *Archaias* (Macintyre and Reid, 1995, 1998; Reid and Macintyre, 1998). These processes start very early, when these organisms are still living (Macintyre and Reid, 1995).

In summary, the origin of Holocene lime muds is both controversial and dissimilar in different areas. Studies are usually focussed on one region, and few are from the Indian and Pacific Oceans. Also, methodologies used were different and the studies usually focussed on only one or two aspects such as, e.g., grain composition and mineralogy, or grain composition and geochemistry. With one exception (Gischler and Zingeler, 2002), abundances of identified grains were not quantified. As a consequence, comparisons among studies are in many cases impossible. Therefore, we used a comparative approach and quantitatively investigated the origin of carbonate mud in samples from barrier reef, atolls, and carbonate platforms in six locations in the Atlantic, Indian, and Pacific Oceans by optical (SEM), mineralogical (XRD), and geochemical (strontium concentration; stable isotopes of carbon and oxygen) means.