

## LITHIFIED AND UNLITHIFIED MG-CALCITE PRECIPITATES IN TROPICAL REEF ENVIRONMENTS

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**ABSTRACT:** Push cores from the branching-coral framework of lagoonal reefs in Belize and Panama indicate that the **micritic** Mg-calcite in the unlithified mud matrix is similar in composition to the well documented submarine lithified **micritic** crusts and **infillings** found in open reef framework. The sediment matrix of the lagoonal framework contains significant concentrations of 12 to 13 mole %  $\text{MgCO}_3$  calcite that shows **almost** no signs of skeletal origins, as indicated by a fairly consistent mineralogy and independent distribution patterns in sand-, silt-, and clay-size fractions. Its sedimentological and mineralogical similarity to cemented **micritic** crusts and infillings suggests that the precipitation of **micritic** Mg-calcite is widespread in tropical-reef waters and becomes lithified when precipitated in open frameworks but remains unlithified when trapped in impermeable lagoonal muddy sediments.

### INTRODUCTION

Until the 1960s, Mg-calcite lithification in coral-reef frameworks was a little-recognized phenomenon. Following the discovery of extensive submarine lithification in modern coral-reef environments, mainly by micritic Mg-calcite (Macintyre 1967; Ginsburg et al. 1967; Macintyre et al. 1968), the Bermuda conference on "carbonate cements" focused attention on submarine lithification (Bricker et al. 1969), and this topic promptly became the subject of increasing research. Ensuing studies documented the widespread occurrence of submarine cementation in coral reefs, in locations such as Jamaica (Land and Goreau 1970; Land and Moore 1980), Bermuda (Ginsburg et al. 1971a; Ginsburg et al. 1971b; Shinn 1971; Ginsburg and Schroeder 1973; Schroeder 1972a, 1972b; Schroeder and Zankl 1974; Focke and Gebelein 1978), the Red Sea (Friedman et al. 1974; Gvirtzman and Friedman 1977; Brachert and Dullo 1991), Belize (James et al. 1976; Shinn et al. 1982; Macintyre 1984), Panama (Macintyre and Glynn 1976; Macintyre 1977, 1983), Australia's Great Barrier Reef (Marshall and Davies 1981; Marshall 1983, 1986), Antigua (Macintyre et al. 1985), Florida (Lighty 1985), and Tahiti (Montaggioni and Camoin 1993).

For the most part, these occurrences of submarine lithification by Mg-calcite were found in the fore reef, in areas of high wave energy and slow reef accumulation. In Belize, for example, the phenomenon was observed only on the seaward margins of the barrier and atoll reefs and not in lagoons with low wave energy (James et al. 1976). Similarly, the exposed outer reefs of the Great Barrier Reef of Australia were found to contain considerably more submarine lithified deposits than the innermost protected reefs (Marshall 1986). Mg-calcite crusts and infilled rims of corals were also reported to be a common feature in high-wave-energy reef facies in a fringing reef off the Caribbean coast of Panama, where a very dense Mg-calcite matrix had formed in the more slowly accumulating pavement facies (Macintyre 1977). Some of the most spectacular Mg-calcite lithified deposits occur in Bermuda cup reefs

located in areas of high wave energy (Ginsburg et al. 1971a; Ginsburg and Schroeder 1973; Shinn 1971). By contrast, there has been only one report of extensive lithified deposits forming in quiet water: on projections formed by serpulid worms on the ceiling of a cave in the back-reef lagoon of Belize (Macintyre 1984).

Interestingly, <sup>lithified</sup> Mg-calcite deposits at the bases of skeletal cavities or on the upper surfaces of corals commonly form geopetal textures. Pavement limestones lack this geopetal characteristic (Macintyre and Marshall 1988) because they are formed when a hiatus in reef accumulation allows a section of the reef to be multicyclically bored and infilled with micritic Mg-calcite. This can result in most of the skeletal structure being replaced by the Mg-calcite.

Many Mg-calcite lithified deposits have a marked peloidal appearance, with "repeated nucleation around centers of growth" (Macintyre 1985, p. 115). Peloidal precipitates in skeletal cavities also tend to have geopetal textures. These peloids exhibit different stages of precipitation, with an inner core of anhedral micrite surrounded by an outer rim of euhedral crystals (Macintyre et al. 1968; Shinn 1969; Land and Goreau 1970; Alexandersson 1972; Macintyre 1977).

These geopetal characteristics and dominantly micritic texture have given rise to some confusion over the terminology applied to Mg-calcite lithified precipitates. A central question is whether such deposits should be called cements or matrices. Clearly, most of these precipitates nucleate in reef-framework cavities and settle to eventually become lithified deposits, in somewhat the same way that snow settling on the ground hardens into sheets of ice. To help clarify the issue, Reid et al. (1990) suggested that all micritic precipitates in subsurface cavities, both rim attachments and matrix infillings, be referred to as "internal micrite precipitates" (p. 164).

Owing to the lack of submarine lithification in low-wave-energy environments, many researchers have assumed that Mg-calcite is not precipitated in such settings and hence have focused primarily on Mg-calcite deposits cementing outer reef frameworks. Our study of lagoon

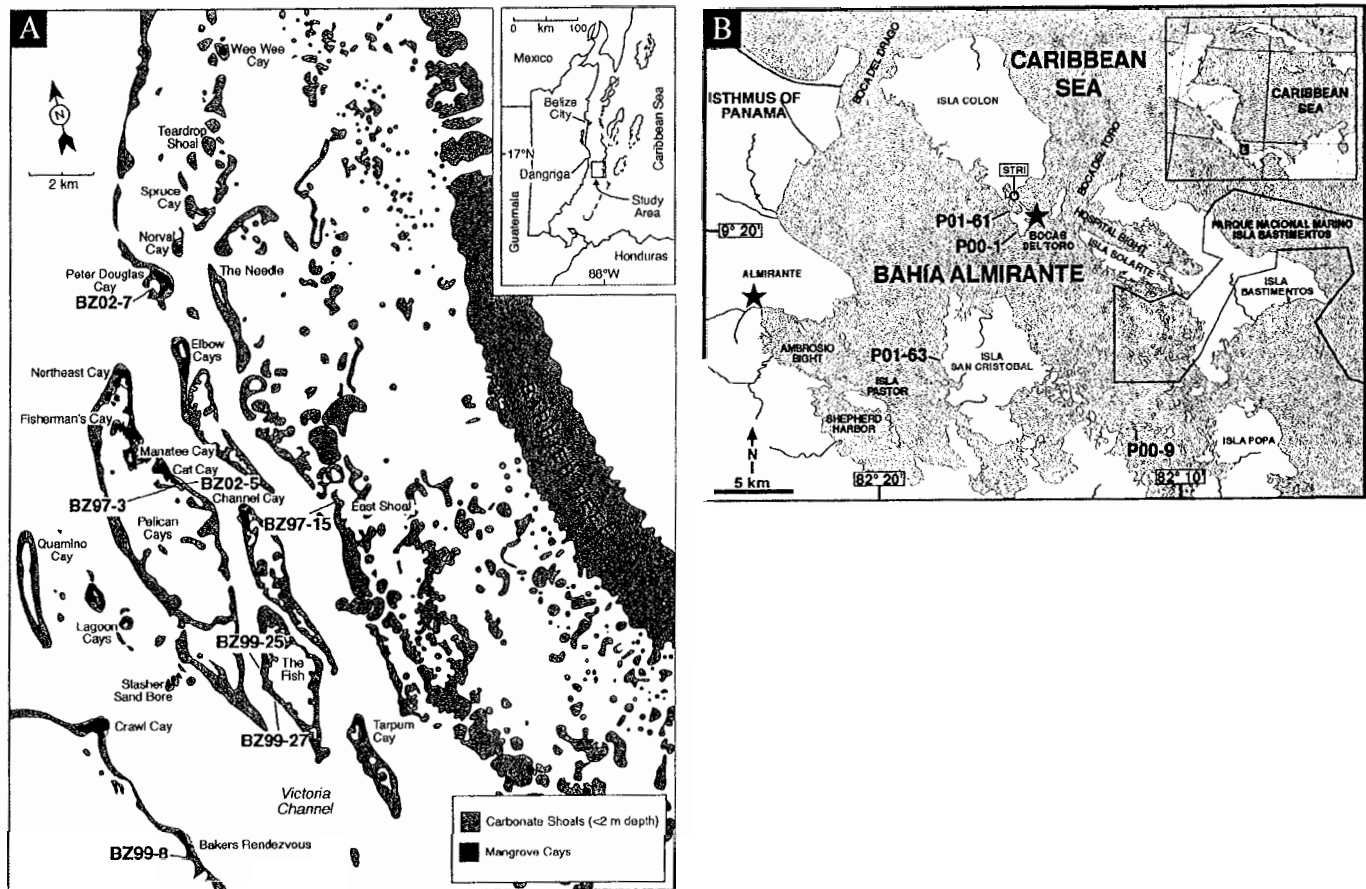


FIG. 1.—Index maps of research sites showing the locations of cores sampled in this study. A) The rhomboid shoals of the central lagoon, Belize Barrier Reef. B) Almirante Bay, Caribbean coast of Panama

reefs in Belize and Panama suggests otherwise. When we examined several of the numerous cores documenting the history of the branching framework of these reefs over the past 3,000 to 4,000 years (Aronson et al. 1998; Aronson et al. 2002; Aronson et al. 2004) we discovered that micritic Mg-calcite is precipitating in lagoonal tropical-reef environments. The difference is that in lagoonal environments, it remains an unlithified mud.

#### METHODS

Push-core tubes measuring 4 to 5 m in length and 7.6 cm in diameter were used to collect cores from the lagoonal rhomboid shoals of the Belizean Barrier Reef and the fringing reefs of Almirante Bay, a coastal lagoon in northwestern Panama (Fig. 1). Core tubes were made of aluminum with teeth cut into the leading edge. With the aid of adjustable handles, we first pushed the tubes into the branching framework (dominantly *Acropora cervicornis* in Belize and branching *Porites* in Panama) (Fig. 2) and then used a sliding hammer weight over the top of the tube to penetrate the substrate further. After the tubes were driven into the sea floor 3 to 4 m, we took measurements and tightly capped the top of the tube. Upon recovering the full core tube, we also capped the base. Field measurements indicated that little or no core material was lost during extraction (see Dardeau et al. 2000).

After extruding the cores in the laboratory, we collected sediment-matrix samples from several cores. Continuous sediment samples were



FIG. 2.—Collecting an open-barrel push core in Belize lagoon reef. Note pipe-weight with handle on aluminum core tube.

collected at 5- or 10-cm intervals in four of the cores from Panama and one from Belize. In addition, samples were collected from similar depths in five cores from Belize. The mud-size fraction of these sediment samples was obtained by washing them through a 63- $\mu$ m sieve. The carbonate mineralogy was carried out by standard X-ray diffraction techniques (Goldsmith and Graf 1958; Milliman 1974) using a Scintag X-ray diffractometer with Cu K $\alpha$  radiation, a Peltier detector, and zero-background mounting plates. The percentage of aragonite and Mg-calcite in each mud sample was determined by peak-area analyses in reference to a standard curve for aragonite concentrations (Boardman 1976). The amount of carbonate present in each sample was determined by weight loss after treatment with 10% hydrochloric acid.

Five representative sediment-matrix samples from increasing depths in a core from Belize and one from Panama were separated into clay-size (< 4  $\mu$ m) and silt-size (4–63  $\mu$ m) fractions by settling and decantation (Folk 1961). Small samples of each size fraction were mounted and gold-plated on aluminum stubs and examined with a Leica 440 scanning electron microscope. The carbonate mineralogy of the remaining silt- and clay-size fractions, along with the sand-size fractions, was analyzed by X-ray diffraction. Thin sections were prepared from the sand samples in these two cores and their composition were determined with 200 point counts at spacing intervals of 2 mm along transects. In addition, EDS (Energy Dispersive Spectrometer) spectra were acquired from a clay-size sample using a JEOL JSM-840A scanning electron microscope.

In this study we are investigating the major origin of the Mg-calcite in the mud matrix that occurs in mostly branching coral framework in the lagoons of Belize and Panama. This soft muddy matrix varies in

TABLE 1.—Mineralogical analyses of carbonate in Belize lagoonal mud samples from various depths in five cores.

Core	Depth in Core (m)	% Carbonate in mud	% Mg-calcite in mud	Mole % MgCO <sub>3</sub>
Bakers Rendevous BZ99-8	1.3	84.3	24	12.3
Pelican Patch Reef BZ97-15	0.9	91.9	27	12.5
Cat Cay BZ97-3	1.05	94.5	28	12.6
The Fish BZ99-25	1.7	94.6	28	12.1
The Fish BZ99-27	0.9	93.7	22	12.3
Average and Standard Deviation		91.8 $\pm$ 4.3	25.8 $\pm$ 2.7	12.4 $\pm$ 0.2

composition from sandy mud to muddy sand. No distinct horizons of clean sand or silt were encountered.

We use the term "precipitate" to describe physicochemical precipitation of micrite (1–4  $\mu$ m) and minimicrite (< 1  $\mu$ m) carbonate in the water column above the substrate or in the upper surface of the substrate.

## RESULTS

The mineralogic composition of the lagoon muds in cores from Belize and Almirante Bay, Panama, is strikingly consistent, as illustrated by two representative cores (Fig. 3). Most notably, the average percent carbonate

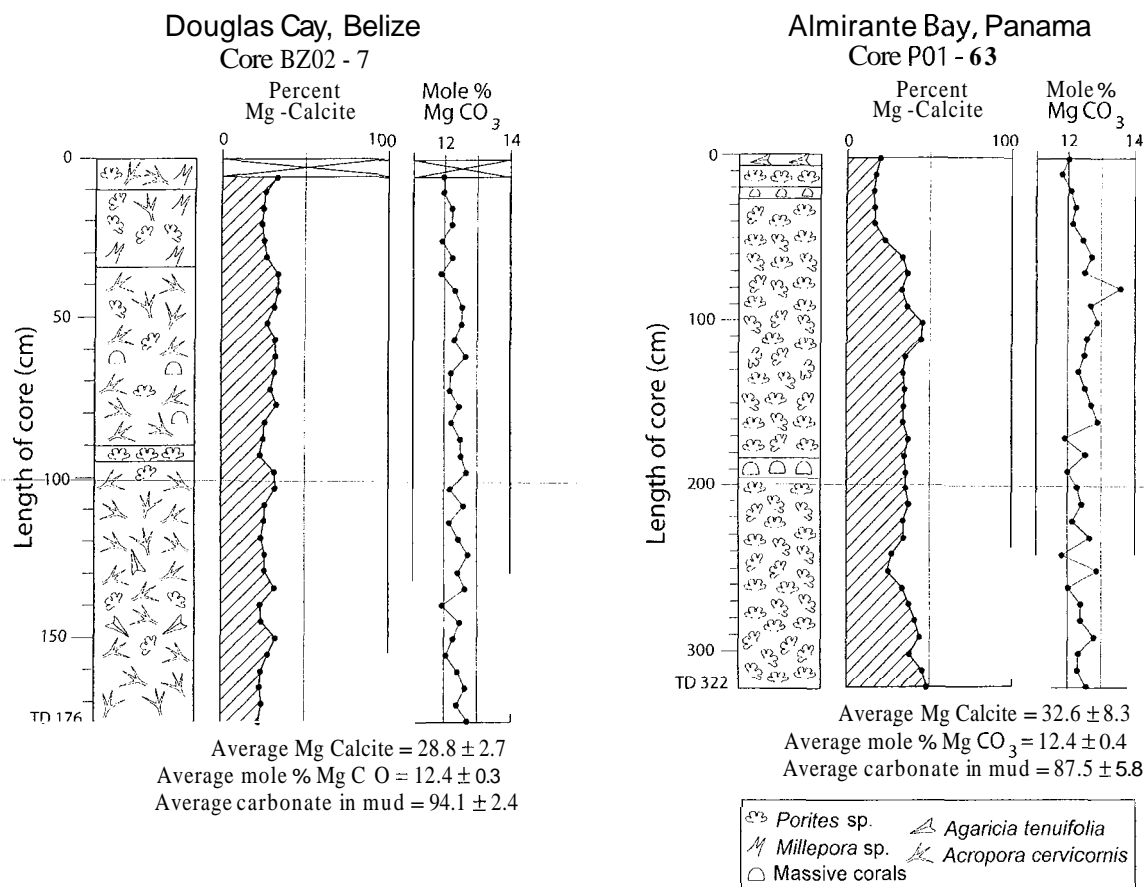


FIG. 3.—Graphic illustration of the carbonate mineralogy of mud fractions collected in cores from Belize (central shelf lagoon) and Panama (Almirante Bay).

TABLE 2.—Average values for mineralogical analyses of carbonate in Almirante Bay, Panama mud samples collected from the total length of three cores. Errors are standard deviations.

Core	Length of each core (cm)	Intervals sampled (cm)	% Carbonate in mud	% Mg-calcite in mud	Mole % $\text{MgCO}_3$
P00-1	134	5	83.2 $\pm$ 4	19.9 $\pm$ 5.8	12.4 $\pm$ 0.6
P00-9	290	10	93.3 $\pm$ 2.2	13.9 $\pm$ 6.3	12.1 $\pm$ 0.6
POI-61	300	10	77.0 $\pm$ 6.6	30.6 $\pm$ 5.7	12.8 $\pm$ 0.3

(Belize 94.1  $\pm$  2.4 SD; Panama 87.5  $\pm$  5.8 SD), % Mg-calcite (Belize 28.8  $\pm$  2.7 SD; Panama 32.6  $\pm$  8.3 SD), and mole %  $\text{MgCO}_3$  in the calcite (Belize 12.4  $\pm$  0.3 SD; Panama 12.4  $\pm$  0.4 SD) show no significant difference. There is only minor variation with increasing depth, as is evident in the minor standard deviations obtained in each analysis.

Analyses of individual samples from five cores from Belize further demonstrate the compositional consistency of these lagoonal muds (Table 1). The average percent carbonate (91.8  $\pm$  4.3 SD) is only slightly less than that of Belize core BZ02-7 from Douglas Cay. (Fig. 3). The % Mg-calcite (25.8  $\pm$  2.7 SD) is also slightly less, while the mole %  $\text{MgCO}_3$  of the calcite (12.4  $\pm$  0.2 SD) is almost identical. The analyses of continuous intervals in three other cores from Panama (Table 2) exhibit a little more variation, with the average percent carbonate in the muds ranging from 93.3  $\pm$  2.2 SD to 77.0  $\pm$  6.6 SD, the % Mg-calcite ranging from 13.9  $\pm$  6.3 SD to 30.6  $\pm$  5.7 SD, and the mole %  $\text{MgCO}_3$  from 12.1  $\pm$  0.6 SD to 12.8  $\pm$  0.3 SD.

To investigate the source of the Mg-calcite in these muds more closely, we separated five samples from core BZ02-5 off Cat Cay, Belize, and five samples from similar depths in core P00-1 from Almirante Bay, Panama, into sand-, silt-, and clay-size fractions. This enabled us to see the carbonate mineralogy relationships in each size fraction. In general, we found Mg-calcite values for the Belize core (Table 3) to be uniform in

each size fraction from the various depths: the average was 13.8% for the silt-size fraction and 9.4% for the sand-size fraction, and jumped to 38.2% in the clay-size fraction (with a maximum of 54%). Similarly, the Panama core (Table 4) showed fairly consistent values in each size fraction from the various depths, again with a marked increase in the clay-size fraction, which averaged 50.2% (reaching a maximum of 58%), while average values were 16.0% for silt and 12.6% for sand.

All silt-size fractions of Belize and Panama samples also appeared fairly similar under the scanning electron microscope. They consisted primarily of microbored coral fragments, clionid sponge chips, and a variety of spicules (Fig. 4). Some differences were apparent in clay-size fractions, however: the Belize photomicrographs contained an abundance of broken and eroded needles (Fig. 5A) whereas those from Panama (Fig. 5B) indicated an abundance of anhedral minimicrite (< 1  $\mu\text{m}$ ). In both cases, the larger platy grains are probably noncarbonate clays.

To check whether Mg-calcite in the mud fractions could have had a skeletal source, we conducted a point-count analysis of thin sections of the sand fractions from the previous samples collected from representative depths in cores from both Belize and Panama (Table 5). Here we found constituent grains well preserved (Fig. 6A, B) with little or no evidence of the micritization characteristic of sand grains in the northern Belize lagoon (Reid et al. 1992). Apparently, sediment in our study areas is rapidly trapped in the branching coral frameworks, with the result that exposure time on the sea floor is too short for alteration to occur. As can be seen in Table 5, corals are the dominant constituent grains in both study areas (they average 62% in Belize and 78% in Panama), with much smaller amounts of echinoids, molluscs, foraminifera, crustose coralline algae, and worm-tube grains. Constituent sand grains of the two areas differed primarily in the abundance of *Halimeda* grains (Fig. 6A), which averaged 23% in Belize and appeared only in trace amounts in the Panama samples (Fig. 6B).

In an effort to identify the Mg-calcite grains in the clay-size fraction, EDS spectra were obtained from grains on a SEM image of a sample from Panama (P00-1, 125–130 cm) containing 54% Mg-calcite (Table 3). As can be seen in Figure 7, the Mg-calcite grains are anhedral and are

TABLE 3.—Mineralogical analyses of the carbonate in the clay-, silt-, and sand-size fractions in samples from core BZ02-07, central shelf lagoon, Belize.

Depth interval in core (cm)	% Clay in mud	% Silt in mud	Mineralogical Composition of Clay			Mineralogical Composition of Silt			Mineralogical Composition of Sand		
			% Aragonite	% Mg calcite	Mole % $\text{MgCO}_3$	% Aragonite	% Mg calcite	Mole % $\text{MgCO}_3$	% Aragonite	% Mg calcite	Mole % $\text{MgCO}_3$
25–30	35.5	64.5	69	31	11.8	86	14	12.1	93	7	13.7
50–55	39.1	60.9	46	54	11.6	86	14	12.0	86	14	11.8
74–80	33.3	66.7	66	34	11.5	87	13	12.6	95	5	13.7
100–105	34.9	65.1	64	36	11.7	86	14	10.7	90	10	12.2
130–134	34.3	65.7	64	36	12.2	86		11.4	89	11	12.5
Average values for percent of Mg-calcite			38.2			13.8			9.4		

TABLE 4.—Mineralogical analyses of the carbonate in the clay-, silt-, and sand fractions of samples from core P00-1, Almirante Bay, Panama.

Depth interval in core (cm)	% Clay in mud	% Silt in mud	Mineralogical Composition of Clay			Mineralogical Composition of Silt			Mineralogical Composition of Sand		
			% Aragonite	% Mg calcite	Mole % $\text{MgCO}_3$	% Aragonite	% Mg calcite	Mole % $\text{MgCO}_3$	% Aragonite	% Mg calcite	Mole % $\text{MgCO}_3$
30–35	27.8	72.2	53	47	13.7	82	18	12.3	84	16	12.7
50–55	41.2	58.8	46	54	12.6	86	14	12.0	93	7	12.8
80–85	47.6	52.4	62	38	13.9	88	12	11.3	91	9	12.7
100–105	26.6	73.4	42	58	12.4	85	15	12.5	86	14	11.8
125–130	41.8	58.2	46	54	13.8	79	21	12.4	83	17	13.7
Average values for percent of Mg-calcite			50.2			16.0			12.6		



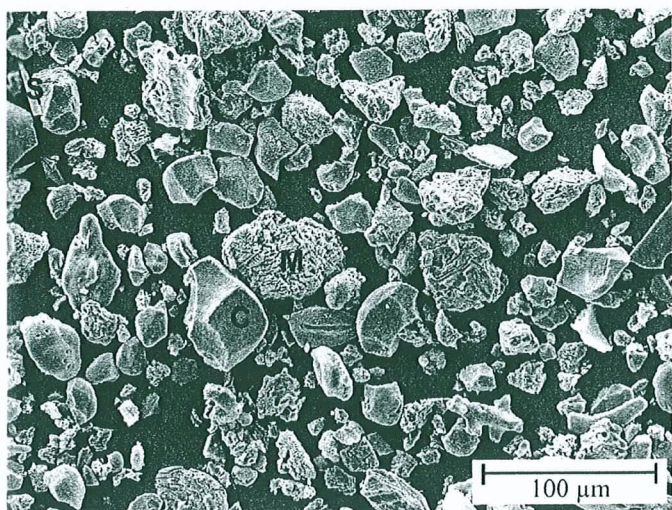


FIG. 4.—SEM photomicrograph of the silt-size fraction from 75-80 cm mud sample, core BZ02-5, Cat Cay, Belize. Note the abundance of micro-bored coral fragments (M), smooth-surface boring-sponge chips (C), and spicule fragments (S).

difficult to distinguish from both aragonite grains and terrestrial clay particles.

The dominant carbonate encrusting organisms on *Thalassia* seagrass blades in both the Belize and Panama lagoons are crustose coralline algae (Fig. 8A). These encrusters are most abundant in waters less than 1 meter deep. Five samples from Belize and six from Panama gave an average value of 11.6 mole %  $\text{MgCO}_3$  with a range of 10.5 to 13.0. Since the range of their mole %  $\text{MgCO}_3$  is within that found in our mud samples, it seemed worthwhile to examine their skeletal structure under the scanning electron microscope. These corallines have a particularly distinctive radiating coralline cellular pattern (Fig. 8B), which was found in only trace amounts in several silt-size SEM photomicrographs.

#### DISCUSSION

Most of the clay-size Mg-calcite in our lagoonal cores has a physico-chemical rather than biological origin. We found an inadequate supply of skeletal Mg-calcite in coarser fractions to produce major quantities of clay-size biological Mg-calcite. Mg-calcite skeletal grains would have to have been present in significant amounts in the coarser fractions to produce clay-size biological Mg-calcite in the quantities that we found in our cores. Instead, the silt- and sand-size fractions in our samples contain minor amounts of Mg-calcite, averaging only 13.8% (Belize, Table 3) and 16% (Panama, Table 4) in the silt-size fractions and 9.4% (Belize) and 12.6% (Panama) for sand. However, the average value of Mg-calcite in our clay-size fractions is 38.2% for Belize (Table 3) and 50.2% for Panama (Table 4).

This conclusion is corroborated by the results of our thin-section analyses (Table 5). Crustose coralline algae and echinoid grains never exceed 10% of the constituent grains. Although Matthews (1966) also noted this enrichment of Mg-calcite in southern Belize lagoonal sediment mud fractions (up to 70%), he discounted precipitation as a possible source while failing to substantiate a skeletal source. It might be argued that the concentrations of Mg-calcite in the clay-size fractions are due to selective dissolution of clay-size aragonite. However, our samples show no evidence of extensive etching of aragonite needles (Fig. 5A). It is therefore evident that a concentration of Mg-calcite in the clay-size fractions, with only minor amounts in the coarser sand- and silt-size fractions of the same samples (Tables 3 and 4) does not indicate a grad-

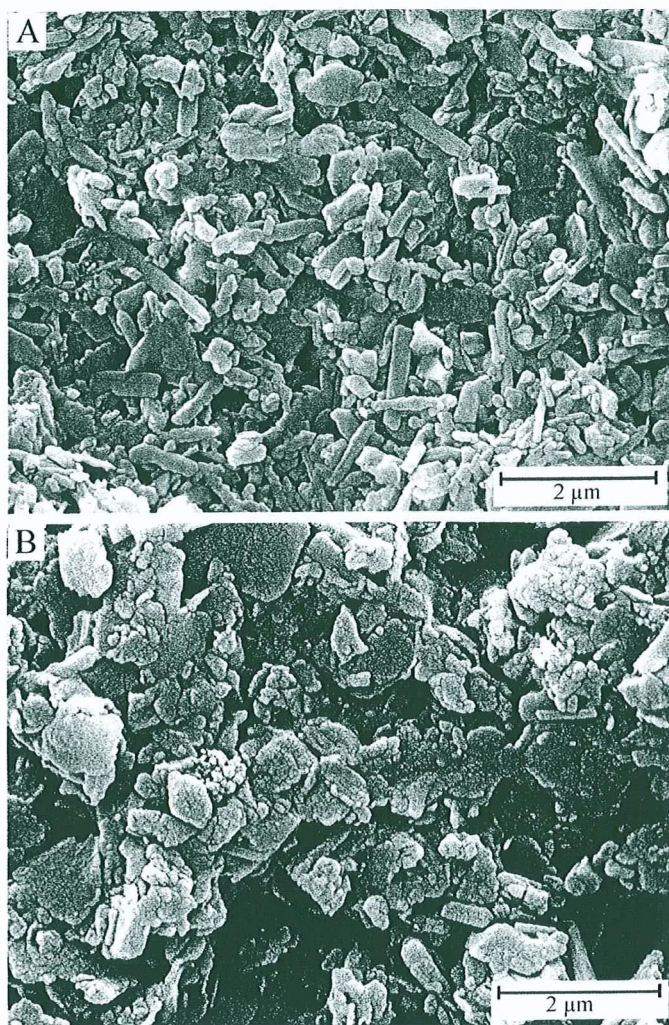


FIG. 5.—SEM photomicrograph illustrating the different texture of clay-size fractions from Belize to Panama. Larger platy grains in both samples represent terrigenous noncarbonate clay particles. A) 75-80 cm, core BZ02-5, Cat Cay, Belize, dominated by broken needles and anhedral minimicrite. B) 80-85 cm, core P00-1, Almirante Bay, Panama, consisting of anhedral minimicrite enclosing platy non-carbonate clay particles.

ual disintegration of skeletal material to provide biological clay-size Mg-calcite.

Additional evidence that argues against a biological source for the clay-size Mg-calcite is the lack of significant variation in the amount of Mg-calcite in the Belize and Panama lagoon muds ( $28.8 \pm 2.7\%$  and  $32.6 \pm 8.3\%$  respectively) in continuous core logs (Fig. 3), as well as the consistent composition ( $12.4 \pm 0.3$  to  $12.4 \pm 0.4$  mole %  $\text{MgCO}_3$ ) in the calcite fractions. As indicated in Tables 1 and 2, the Mg-calcite of muds from both Belize and Panama also have a limited variation in mole %  $\text{MgCO}_3$ ; five samples from different locations in Belize give an average value of  $12.4 \pm 0.2$ ; similarly, samples along the lengths of three cores from Panama range in average value from  $12.1 \pm 0.6$  to  $12.8 \pm 0.3$ . Although detailed study of clay-size fractions from both Belize and Panama (Tables 3 and 4) reveal a wider range of mole %  $\text{MgCO}_3$  (11.5 to 13.9), it is not great enough to suggest a skeletal source for the Mg-calcite. It is not reasonable to expect such consistent values in so many samples to result from a variety of Mg-calcite skeletons when their skeletal composition shows such variation in mole %  $\text{MgCO}_3$  (Milliman 1974).



TABLE 5.—Percent composition of sand-size fraction from Belize and Panama cores.

Location and Depth in Core (cm)	Corals	Echinoids	Mollusks	Foraminifera	Halimeda	Worm Tubes	Crustose Coralline Algae	Unknown	Misc Octocoral Sclerites Bryozoans
Core BZ02-05 Cat Cay, Belize									
25-30	62	7	5	TR	22	TR	1	1	
50-55	61	5	5	1	20	1	2	3	2
75-80	68	6	1	1	21	-	1	1	
100-105	58	3	2	TR	29	2	4	1	1
130-136	59	7	4	-	24	TR	1	2	
AV	62%	6%	3%	TR	23%	TR	2%	2%	TR
Core P00-1 Almirante Bay, Panama									
30-35	70	3	11	1	TR	1	7	6	TR
50-55	90	2	2	-	1	TR	3	1	
80-85	80	8	5	TR	2	-	4	1	
100-105	78	10	2	1	1	1	4	2	
125-130	74	5	6	2	2	2	7	3	TR
AV	78%	6%	5%	TR	1%	TR	6%	3%	

TR=trace amounts.

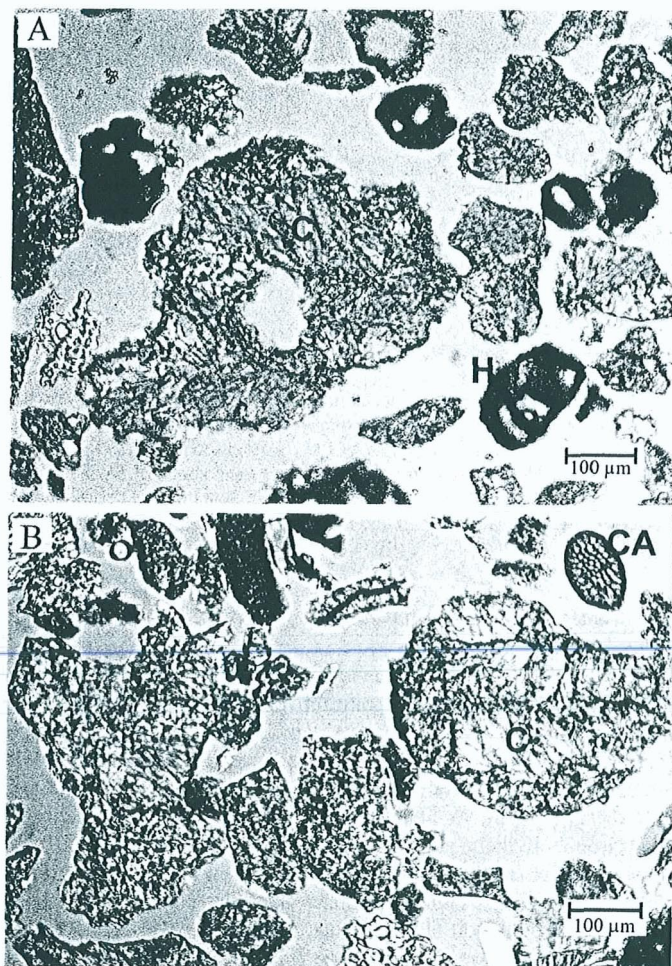


FIG. 6.—Photomicrographs illustrating the well preserved condition of sediment grains in the sand-size fractions. A) Core BZ02-5, 50-55 cm, Cat Cay, Belize; dominantly unaltered coral (C) and Halimeda (H) grains. B) Core P00-1, 30-35 cm, Almirante Bay, Panama; freshly preserved coral (C) with a trace of crustose coralline algae (CA).

One possible skeletal source for Mg-calcite in our muds could be the epiphytic growths on seagrass blades, particularly crustose coralline algae. Crustose coralline epibionts on *Thalassia* blades are considered an important source of Mg-calcite mud in Jamaica (Land 1970), Barbados (Patriquin 1972), and Florida Bay (Nelson and Ginsburg 1986). However, the characteristic cellular structure of the crustose coralline algae that encrust *Thalassia* blades occurs in only trace amounts in the silt-size fractions of our lagoonal muds and is a minor constituent in our sand fractions, which show an average of 2% for Belize and 6% for Panama (Table 5). The mole %  $MgCO_3$  values obtained from these encrusting coralline algae indicate that some of the Mg-calcite in our mud samples could be derived from these encrusting epiphytes. This source of Mg-calcite, however, must be minor because of the significant lack of Mg-calcite in the silt- and sand-size fractions and the remarkable concentration in the clay-size fractions (Tables 3, 4). This and the lack of crustose corallines in SEM and thin sections are not indicative of the breakdown patterns that would suggest that they are an important source of Mg-calcite muds in these lagoons.

Compared to Panama, the lower percentages of Mg-calcite in the Belize clay-size fractions are related to the abundance of *Halimeda* needles in the clay-size fractions, which is a reflection of the larger amounts of *Halimeda* in the sand-size fractions. This indicates that although *Halimeda* is commonly an important source of micritized grains (Irmbull 1988; Reid and Macintyre 1998), particularly in current-swept environments (Macintyre and Reid 1995), it can disintegrate in low-wave-energy and muddy conditions to provide significant amounts of clay-size needles. Indeed the needles in the clay-size fractions from Belize are the same size as original skeletal needles from *Halimeda* (Macintyre and Reid 1995).

Reid et al. (1992) suggested that most of the Mg-calcite muds in the shallow northern Belize lagoon have resulted from the breakdown of Mg-calcite micritized skeletal fragments, because skeletal grains clearly alter to Mg-calcite in this area and the micritic texture of the altered grains is similar to that in the muds. However, they did not rule out the possibility of some direct physicochemical precipitation of minimicritic Mg-calcite. Our study suggests that direct precipitation is probably a more important source of Mg-calcite muds in this area than they suspected. This view is also supported by the presence of whittings in the northern shelf lagoon (Purdy and Gischler 2003). Because skeletal grains are well preserved in the central Belize lagoon and Almirante Bay, Panama, sediments, Mg-



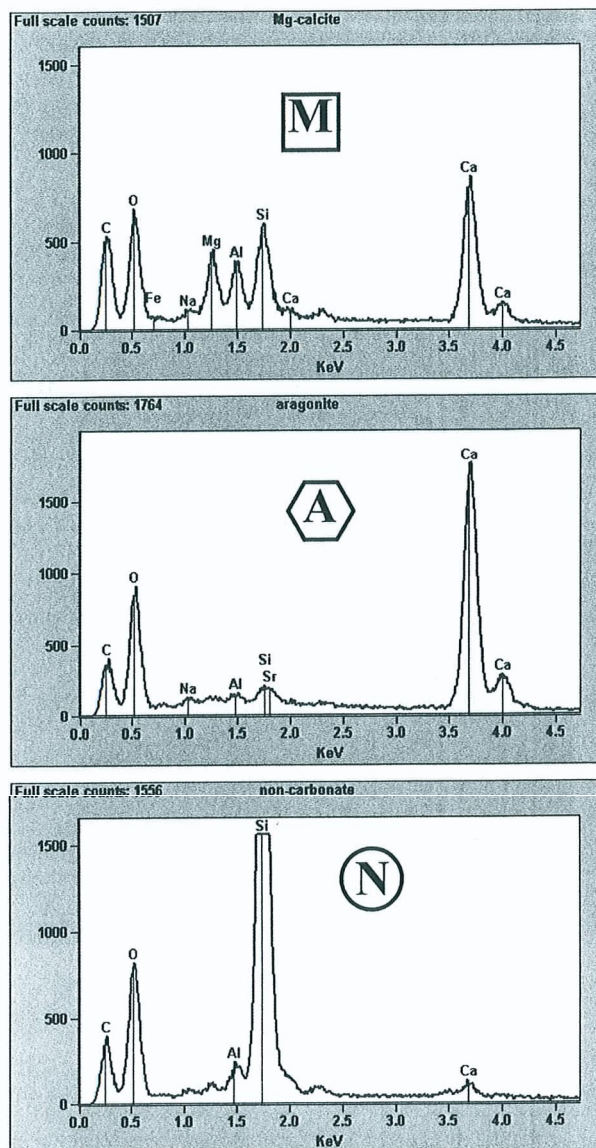


FIG. 7.—Secondary electron image of clay-size fraction of Panama sample P-00-1 (125–130 cm). EDS spectra allow identification of Mg-calcite (M), aragonite (A), and noncarbonate grains (N), which are impossible to differentiate visually. Note difficulty of isolating grains of this size range.

calcite in the mud fractions cannot be attributed to the detrition of diagenetically altered Mg-calcite grains.

When we compared the amount of Mg-calcite and the mole %  $\text{MgCO}_3$  content of our samples with those reported by Reid et al. (1992), we found little difference: the clay-size fractions of their southern Belizean shelf sediments—in the deeper fore reef 56% with a mole %  $\text{MgCO}_3$  of 13.5; in the lagoonal mangrove islands 47% with a mole %  $\text{MgCO}_3$  of 12; and 54% with a mole %  $\text{MgCO}_3$  of 13 in a back-reef cave. In addition Reid et al. (1992) also reported that a clay-size fraction from Cross Bank, Florida, contained 35% Mg-calcite with a mole %  $\text{MgCO}_3$  of 12.5 along with a bulk mud sample from off West Andros Island consisting of 14% of 12 mole %  $\text{MgCO}_3$ . It therefore appears that Mg-calcite precipitation occurs throughout tropical-reef environments but when deposited in sediments, it does not become lithified.

Lagoonal surface sediments of three Belizean offshore atolls reportedly have as much as 40% "high magnesium calcite" (Gischler and Zingeler 2002, p. 1062) in their silt-size and clay-size fractions. The abundance of "micritic grains" (p. 1065) in their clay-size fractions is identical to the Mg-

calcite anhedral micritic found in our cores. Hence, the source of this material could be precipitated Mg-calcite rather than the suggested algal aragonite for many of these grains. These similar amounts of Mg-calcite in atoll surface sediments may provide further evidence of the widespread precipitation of Mg-calcite muds in reef environments. At the same time, our analyses indicate that the lagoonal muds of the rhomboid shoals of Belize and Almirante Bay, Panama, are predominantly aragonite and that the decreasing amounts of aragonite in the sand-, silt-, and clay-size fractions (Tables 2 and 3) does suggest a skeletal source in this instance. We therefore agree with Matthews (1966) and Gischler and Zingeler (2002) that the aragonite fractions in our lagoonal muds are derived from the breakdown of aragonite skeletal material.

Mg-calcite precipitates tend to be overlooked in lagoonal settings because submarine lithification is rare in these areas. Nonetheless, micritic Mg-calcite appears to precipitate in or near the sea-floor surface in all tropical-reef environments during normal water conditions, settling in intergranular or reef-framework space. In the open reef framework or borings or cavities in surfaces exposed to open water for long periods of



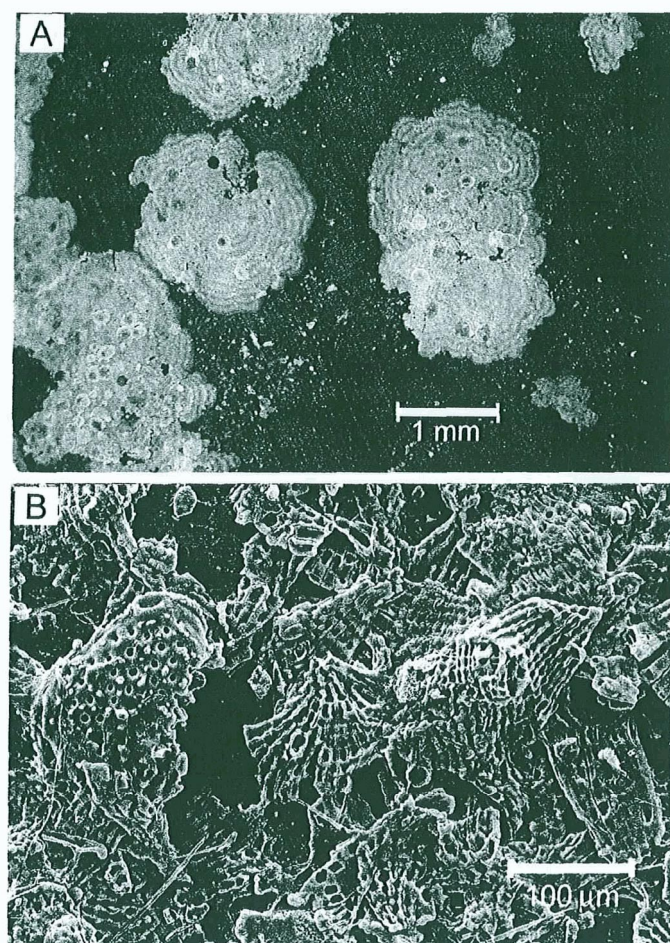


FIG. 8.—Crustose coralline algae (*Porolithon fragilis*) that encrust *Thalassia* seagrass blades, Almirante Bay, Panama. A) Detail of crustose coralline patches on *Thalassia* blade. B) SEM photomicrograph of this coralline algae showing very distinctive cellular pattern.

time, this micritic material becomes lithified in the form of micritic crusts or dense void-filling micritic deposits. Even under low-wave-energy conditions on the ceiling of an open cave, thick crusts of dense micritic Mg-calcite form on the upper surfaces of serpulid worm-tube projections (Macintyre 1984). Thin sections of these dense cappings in this cave, which also occurs in the southern Belizean lagoon about 30 km north of our rhomboid shoals study site, show a texture identical to the mud matrix in our cores, with the exception that the micritic Mg-calcite is lithified. In mud-rich sediments, however, the micritic Mg-calcite precipitates are isolated from open water and therefore remain unlithified deposits. Perhaps surface biofilms need to be present before mud deposits can become lithified, a condition that occurs only in open and commonly high-wave-energy settings. Further research is needed to explain the lithification of Mg-calcite precipitates that are deposited in settings open to ambient waters.

Although this study was restricted to coral-reef environments, micritic Mg-calcite may well be precipitated in many other shallow tropical waters. For example, unlithified muds of the shallow Persian Gulf sea floor are enriched with Mg-calcite (> 15%; Shinn 1969, p. 133). In that area, "submarine cementation is observed to be most pronounced" in sand-size sediment (p. 122). This is further evidence that lithification of the substrate in shallow tropical environments is related to the ability of water to penetrate the sea floor, whether sediment or reef framework.

This first report of micritic Mg-calcite precipitates in the lagoons of Belize and Panama may have analogs in the fossil record. The most obvious example is the Pleistocene limestone below the mangrove islands of Twin Cays, Belize, just 16 km north of our study site (Macintyre and Toscano 2004). This limestone, which has been subaerially altered to calcite, consists of branching *Porites* in a dense microcrystalline matrix and is an almost identical example of the *Porites* in mud sections that we cored in Panama. Extending even further into the fossil record, there are some similarities, on a grander scale, to the "inorganic production of lime mud" (p. 1293) in a low-energy setting for the formation of thick Late Jurassic lime-mud deposits in Mississippi (Heydari and Wade 2002). Furthermore, there could be some relationship of our lagoonal mud deposits to the numerous occurrences of fossil carbonate mud mounds—for example in Spain in both the Lower Cretaceous (Neuweiler et al. 1999) and the Upper Carboniferous (Porta et al. 2004), the Devonian mud mounds of Belgium (Boulvain 2001), and the Jurassic sponge mounds of Morocco (Neuweiler et al. 2001), to just mention a few recent examples. These carbonate mud mounds have generally been considered to be large deposits of microbial carbonate mud (see Monty 1995; Pratt 1995; and Riding 2000). More recently this microbial origin has been called into question by Neuweiler et al. (2003) on the basis of earlier work on the mud mounds of Spain (Neuweiler et al. 1999). In this latter publication Neuweiler et al. (2003) pointed out that the microbial origin of these mounds has been based on petrographic textures such as fine laminations and peloids, traditionally accepted as indicating microbial activity, with no evidence of the direct role of microorganisms. They suggested that fluorescence spectrometry and rare-earth-element distribution both indicate that the catalyst for automicrite ("in situ precipitated marine microcrystalline calcite," p. 681) precipitation in these mud mounds is marine fulvic compounds and humification under suboxic conditions.

A similar controversy has existed in the study of the origin of internal micritic deposits in modern coral-reef frameworks. Impressed with the laboratory experiments of Towe and Malone (1970), in which they released ammonium carbonate (a by-product of organic decay) in seawater and precipitated both aragonite and Mg-calcite, Macintyre (1984) and Macintyre and Marshall (1988) suggested that a major factor in the precipitation of reefal micritic deposits is the decay of trapped organic debris. Others have suggested that the precipitation of micritic carbonate in coral reefs is related to photosynthesis of reef communities (Friedman et al. 1974; Epstein and Friedman 1982) and microbial sulfate reduction (Pigott and Land 1986). More recently there has been the emphasis of petrographic textures (both laminations and peloids), as in the case of mud mounds, indicating the microbial origin of these micritic deposits (i.e., Chafetz 1986; Brachert and Dullo 1991; Montaggioni and Camoin 1993; Camoin et al. 1999). In the study by Chafetz (1986) he indicated that some peloids contained "fossil bacterial clumps" (p. 812) but later noted that "the great majority of peloids observed in etched samples did not display any evidence of the presence, or former presence of bacteria" (p. 814). A very recent paper by Bosak et al. (2004) clearly demonstrated that peloidal crusts can be formed by "purely abiotic mechanisms" (p. 189). Therefore, better evidence than petrographic textures of fine banding and peloids is needed to identify a direct role of microbes in the precipitation of micritic carbonate.

In this study of lagoonal sediments of Belize and Panama there are two significant factors that suggest physicochemical rather than a skeletal or direct microbial origin for the majority of the micritic Mg-calcite fraction. First, there is the closely associated extensive micritic Mg-calcite precipitates on the ceiling in a lagoonal cave in Belize (Macintyre 1984) that have similar texture and composition to the lagoonal micritic sediments. Secondly, the LIMER 1975 report of very high ammonia levels found in Great Barrier Reef lagoonal sediments resulting from organic decay (LIMER 1976). More work is needed to identify the direct or indirect roles of microbes in the precipitation of micritic Mg-calcite in



oral-reef environments and the reason why this micrite is not lithified when trapped in sediments.

## CONCLUSION

Magnesium calcite with 12–13 mole %  $\text{MgCO}_3$  is a significant fraction of the mud matrix in the branching-coral facies of both the central shelf lagoon of Belize and *Almirante* Bay in Panama. Although calcite precipitation appears to occur in most reef settings, heretofore it had been noticed only in permeable substrate settings, where it becomes lithified in the form of crusts, cements, and dense micritic infillings. Our results demonstrate that micritic Mg-calcite precipitates may also become trapped in an impermeable substrate, in which case they remain as an unlithified mud if isolated from the surrounding ambient waters.

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