MICRITIZED SKELETAL GRAINS IN NORTHERN BELIZE LAGOON: A MAJOR SOURCE OF MG-CALCITE MUD[1]

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ABSTRACT: Lime mud in northern Belize lagoon is composed predominantly of silt-size cryptocrystalline grains and clay-size clumps, both of which consist of anhedral, equant crystals less than 0.5 μm in size. This mud is 70–90% Mg-calcite containing 9–10 mole % $MgCO_3$. Detailed petrographic, morphologic and mineralogic analyses suggest that the cryptocrystalline grains are micritized skeletal grains and that the mud formed by abrasion and bioerosion of these altered grains. Micritization of skeletal grains occurred primarily by recrystallization of original skeletal carbonate (laths, prisms and blades of Mg-calcite, aragonite and calcite) to equant crystals of micritic Mg-calcite, with additional alteration by micritic infilling of microborings and skeletal cavities. Because of differences between crystal morphologies and mineralogies of original skeletal components and their micritized counterparts, mud produced by diminution of micritized grains is distinct from that produced by skeletal breakdown. The abundance of cryptocrystalline grains in the Bahamas and other shallow carbonate environments suggests that micritized grains are potentially an important source of lime mud that has not previously been identified.

INTRODUCTION

Carbonate mud is a major constituent of limestone in the fossil record, yet its origin, in large part, remains an enigma. Three potential sources of mud are generally recognized: 1) physiochemical or biochemical precipitation (Drew 1914; Cloud 1962; Wells and Illing 1964; Friedman 1965; Shinn et al. 1989); 2) post mortem disintegration of calcareous algae (Lowenstam 1955; Lowenstam and Epstein 1957; Stockman et al. 1967; Neumann and Land 1975; Land 1970; Patriquin 1972; and Nelsen and Ginsburg 1986); and 3) physical or biological abrasion of skeletal material (Folk and Robles 1964; Swinchatt 1965; Matthews 1966; Stieglitz 1972).

Aragonitic mud on the Bahama Banks has long been of interest to geologists as a possible analog for ancient mud deposits. As a result of numerous studies in the Bahamas, the term "lime mud" has become synonymous with "aragonite needles" in the minds of many geologists (see Blatt et al. 1980, p. 460). Mg-calcite, however, is a major component of mud in many modern marine environments, including south Florida and Belize (Taft and Harbaugh 1964; Enos 1977; Tennet 1982; Matthews 1966; Pusey 1975).

The present study examines the source of Mg-calcite mud in northern Belize lagoon. Detailed petrographic, morphologic and mineralogic analyses of this sediment offer new insights into processes of mud formation.

BACKGROUND AND SETTING

The Belize shelf was the focus of an integrated research program by Purdy and his students at Rice University in the 1960s. The results of these studies, many of which are published in Wantland and Pusey (1975), form the basis of subsequent research in the area.

A fringing and barrier reef complex 250 km long is developed at the edge of the Belize shelf; it is the longest continuous barrier formation in the western Atlantic (Smith 1971). A lagoon 20–40 km wide lies between the barrier reef and the mainland. North of Belize City, the lagoon is muddy and less than 6 m deep; to the south, the lagoon widens and deepens to 50 m (Purdy et al. 1975). Patch reefs are developed in the more open southern lagoon.

Geological and biological characteristics of the northern Belize shelf were described by Pusey (1975) and Purdy et al. (1975). These authors subdivided the area into an outer platform between the reef tract and a discontinuous line of cays, and an inner shelf lagoon that grades into Chetumal Bay north of Bulkhead shoal (Figs. 1 and 2). Pusey suggested that Bulkhead shoal is a bay mouth bar being formed as water flowing out of Chetumal Bay loses velocity and deposits sediment upon reaching the lagoon.

Water characteristics of the northern Belize shelf were measured by Pusey (1975) in July and August, 1961–62. Salinities ranged from 20–30 ppt in Chetumal Bay west of Ambergris Cay to 25–35 ppt in the inner lagoon and 35–36 ppt on the outer platform. Pusey speculated that Chetumal Bay becomes hypersaline in the dry winter
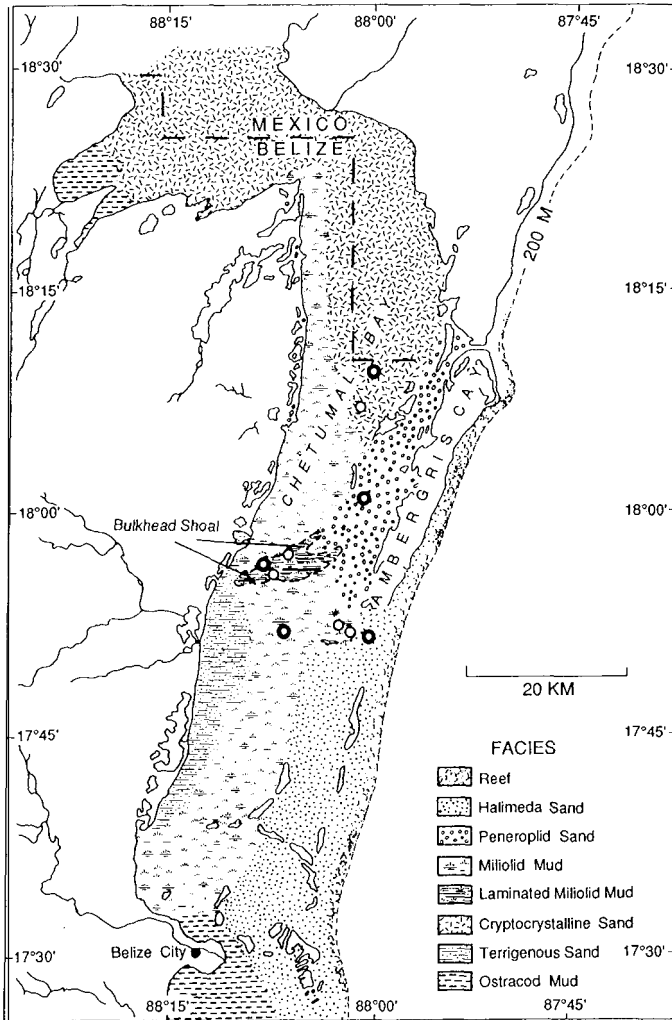
FIG. 2.—Bulkhead mud-shoal complex, which comprises the laminated miliolid-mud facies. A) Oblique aerial photograph looking northeast across the large mud-bank complex (BMS) cut by tidal channels and stretching across the mouth of Chetumal Bay (CB). The coast of the mainland can be seen in the upper left (M). B) Bottom photograph showing a sparse seagrass (Thalassia *testudinum*) cover and scattered growth of a red alga (Laurencia intricata) on disorganized ripples of sandy mud.

months. Surface water temperatures in the summers of 1961 and 1962 were 29°C near the reef and 30°C in the lagoon and bay, with daily warming of 2°C. Bottom temperatures were < 1°C cooler than surface temperatures. Shelf waters were supersaturated with respect to aragonite.

The northern shelf is mantled with 2 to 6 m of Holocene sediment that overlies Pleistocene limestone, which is exposed on and around many of the cays (Pusey 1975). The sediments are reported to be greater than 80% carbonate, with 70–80% of the insoluble residue in the < 2 μm size fraction being montmorillonite, and the remaining 20–30%, illite plus kaolinite (Scott 1975). An abundance of mucus-like slime is present in muds from the inner lagoon (Pusey 1964, 1975; Scott 1975; and Bloch and Cunningham 1986); total organic carbon in the mud shoals ranges up to 2% (Bloch and Cunningham 1986).
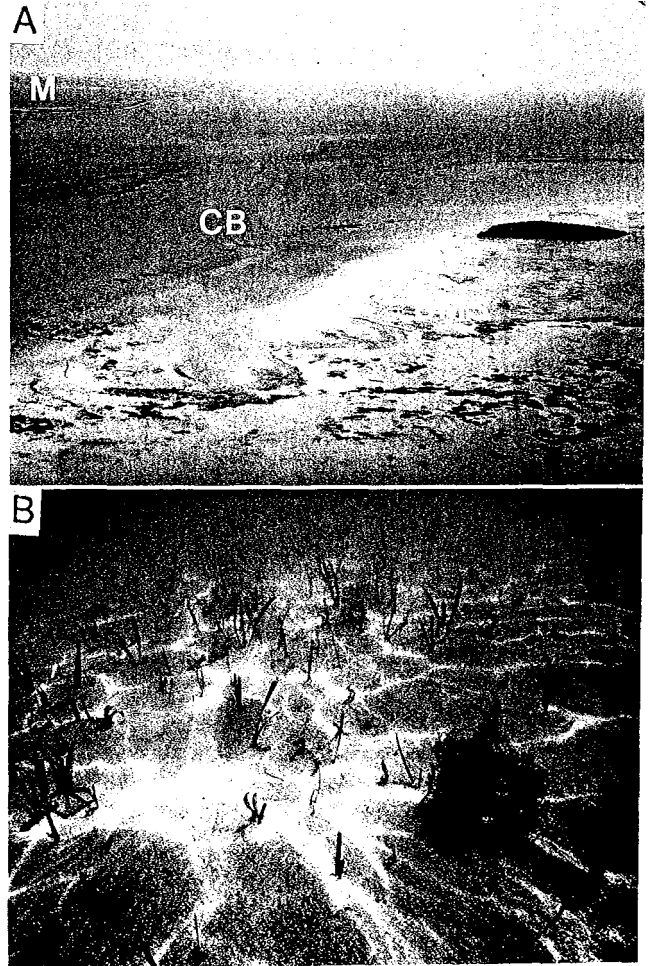
Six major carbonate facies on the northern shelf were identified and described by Pusey (1975): reef and *Hal*-imeda-sand facies on the outer platform, peneroplid-sand, miliolid-mud, laminated miliolid-mud and cryptocrystalline-sand facies in the inner lagoon and Chetumal Bay (Fig. 1). In addition, terrigenous-sand and ostracod-mud facies are present nearshore. Pusey described these facies in great detail, treating each sediment type and the sedimentary processes within each facies as separate entities. As a result of this detailed treatment, his discussion on the origin of the muds is somewhat confusing. Pusey concluded that the muds formed by abrasion of sand-size constituents, with algal crusts forming low Mg-calcite mud in Chetumal Bay, altered foraminifera forming dominantly high Mg-calcite mud in the inner lagoon and skeletal grains such as *Halimeda* and coral forming dominantly aragonitic mud on the outer platform.

METHODS

Field Investigation

In November 1987, we collected surface samples from 10 sites on the northern Belize shelf (Fig. 1). The sites were selected to obtain representative samples from 5 of Pusey's sediment facies: the cryptocrystalline-sand facies, peneroplid-sand facies, laminated miliolid-mud facies, miliolid-mud facies and *Halimeda-sand* facies. Additional muddy surface samples were collected from the southern Belize shelf from 1) a backreef submarine cave near Columbus Cay, 2) shallow water near the mangrove island of Twin Cays and 3) the deep forereef (30 m depth) off Carrie Bow Cay (see Macintyre et al. 1982). Triplicate sediment samples and bottom photographs were taken in each of these locations by free diving, except in the cave and forereef where SCUBA diving was necessary.

Sedimentologic Analyses

Samples were soaked in 5% sodium hypochlorite for 24 hours to remove dissolvable organics. Subsequently, the sediment was separated into four size fractions: a sand fraction (> 63 mm), obtained by wet sieving, and three mud fractions, coarse silt ($20–63$ μm), fine silt ($4–20$ pm) and clay (< 4 μm), separated by settling and decantation. Thin sections were made of the sand fractions. The mud fractions were filtered onto 0.4 μm nucleopore filter paper, mounted on aluminum stubs, gold plated and examined with a Hitachi S-570 scanning electron microscope. In addition, hand-picked sand-size skeletal grains in various states of alteration were fractured and mounted on stubs for SEM examination. Carbonate contents of the mud fraction (< 63 μm) of uncloroxed samples were determined using a modified version of the gasometric apparatus described by Jones and Kaiteris (1983).

Mineralogic Analyses

Mineralogies were determined by powder x-ray diffraction (XRD), using a computer-automated Scintag diffractometer outfitted with a solid-state intrinsic-Ge detector. The data were collected with Cu Kα radiation over the range 20–80° 2θ at a scan rate of 1°/min. In general, powdered samples were packed into aluminum cavity mounts for data collection, but for small samples, powder mixed with acetone was smeared onto a low-background quartz plate. Data were analyzed using the Rietveld refinement method to determine unit-cell parameters and weight fractions for each carbonate phase and mole % $MgCO_3$ in calcite. In this study, calcite with > 4 mole % $MgCO_3$ is referred to as Mg-calcite.

The Rietveld refinement method and its applications were reviewed by Post and Bish (1989). In this procedure, a computer program uses known crystal structures to calculate an ideal composite powder diffraction pattern. This calculated pattern is compared on a point-by-point basis to the observed pattern and then using a least squares procedure, unit-cell parameters, scale factors, background and peak-shape coefficients are varied to achieve the best match between the observed and calculated powder diffraction patterns. A correction factor is also refined that accounts for most of the systematic errors caused by sample displacement and diffractometer misalignment.

The advantage of applying the Rietveld method to the study of carbonates is that, from a single data set and subsequent refinement, it is quickly and easily possible to obtain for each carbonate phase: 1) a quantitative analysis (see Bish and Howard 1988; Bish and Post 1988; Snyder and Bish 1989), and 2) accurate unit-cell parameters and interplanar spacings, which, for calcite, can be used with published determinative curves (e.g., Goldsmith and Graf 1958; Goldsmith et al. 1961; Bischoff et al. 1983) to assess mole % $MgCO_3$. It is not necessary to mix an internal standard with each sample or to prepare calibration plots for quantitative analysis. A more detailed discussion of the application of the Rietveld method to the study of carbonate sediments is in preparation and will be presented elsewhere.

Quantitative analysis of carbonate sediments of known composition using the Rietveld refinement method suggests that relative proportions of carbonate minerals can be determined with an accuracy of ±3%. In the present study, mole % $MgCO_3$ in calcite was determined using $d(211)$ spacings derived from Rietveld refinement with the determinative curves constructed by Goldsmith and Graf (1958). Duplicate and triplicate analyses suggest that this procedure has a precision of ±1 mole %. The accuracy of mole % values is uncertain because of errors associated with the determinative curves for biogenic carbonates (see Mackenzie et al. 1983). Despite uncertainties in the accuracy of absolute values of mole % $MgCO_3$, we assume that relative values and observed trends are valid.

RESULTS

The results below are based on field observations and analyses of samples collected for the present study. For additional description of depositional environments and sediments on the northern shelf, the reader is referred to Pusey (1964, 1975).

Site Descriptions

Sample sites in the inner lagoon were characterized by bare sediment bottoms with sparse grass cover. The cryptocrystalline and peneroplid facies supported limited growth of *Thalassia testudinum* on flat sandy surfaces; in addition, scattered patches of the red alga *Laurencia intricata* were present in the peneroplid facies. In the miliolid-mud and laminated miliolid-mud facies, we observed sparse populations of *Thalassia testudinum*, *Laurencia intricata* and *Syringodium filforme* (Fig. 2B). Sediments in the laminated miliolid-mud facies were commonly rippled, whereas those in the miliolid mud facies were generally smooth, with small pits indicative of infaunal burrowing. A flocculent veneer of algal scum was present at the sediment surface in the cryptocrystalline, peneroplid and miliolid facies.

Bottom communities at sample sites in the *Halimeda*

FIG. 4,—Sand-size fraction from the laminated miliolid-mud facies showing a marked increase in the alteration of peneroplid foraminifera with a decrease in grain size (note sequence indicated by arrows). Petrographic thin section, plane-polarized light.
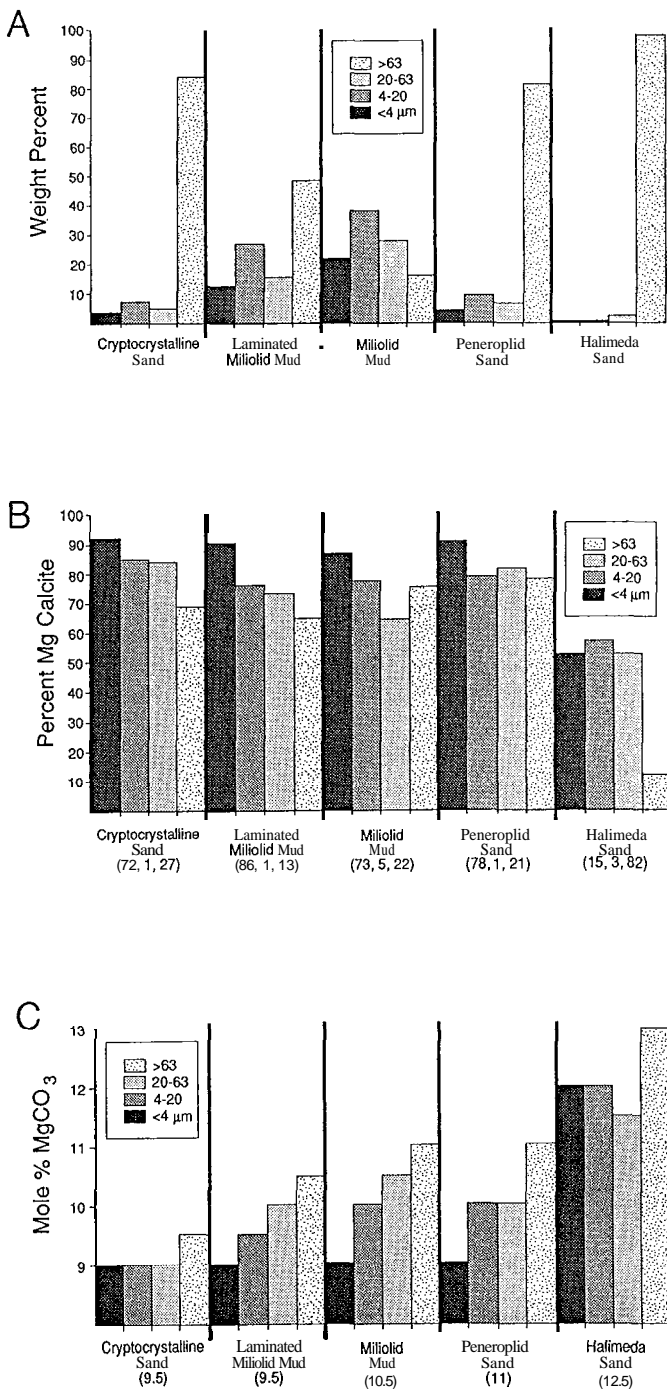

FIG. 3.—Histograms showing results of analyses of four size fractions of samples from the cryptocrystalline-sand, laminated miliolid-mud, miliolid-mud, peneroplid-sand and *Halimeda*-sand facies: **A)** weight % sediment, B)% Mg-calcite, and **C)** mole % MgCO₃. Numbers in brackets below the facies names are values for the bulk sediment; (in B they correspond to % Mg-calcite, calcite and aragonite). Sample locations are indicated on Figure 1.

facies on the outer platform reflect a more open marine environment. These sites were characterized by meadows of *Thalassia testudinum,* a variety of algae including *Penicillus capitus, Rhipocephalus phoenix, Halimeda incras-*

sata and *Laurencia intricata,* and numerous mounds of the burrowing shrimp *Callianassa.*

Sample Descriptions

Size and mineralogic analyses of five samples, one from each of the cryptocrystalline, peneroplid, laminated miliolid-mud, miliolid-mud and *Halimeda* facies, are presented in Figure 3A–C. For bulk samples and for the various size fractions of each sample, Figure 3 shows 1) weight % sediment, 2)% Mg-calcite and 3) mole % MgCO₃.

As suggested by the facies names, sediments from the northern shelf vary in predominant grain type and amount of mud. Samples from the cryptocrystalline-sand facies, the most widespread facies, are muddy sands (approx 20% < 63 μm; Fig. 3A) consisting dominantly of medium-sized (0.5–0.25 mm) cryptocrystalline grains. (Note: "Cryptocrystalline grains" are grains composed dominantly of micrite, following Pusey (1 975). The term "micrite" is used in a general sense for microcrystalline carbonate that is, for the most part, < 4 μm in size and which appears translucent or dense in thin section.) Skeletal grains compose about 40% of the sand-size fraction; barnacle and mollusc fragments are abundant and peneroplid and miliolid foraminifera are common. Skeletal material occurs in all stages of preservation, from fresh to extensively altered cryptocrystalline grains which indicate their origin only by their shape. Details of the
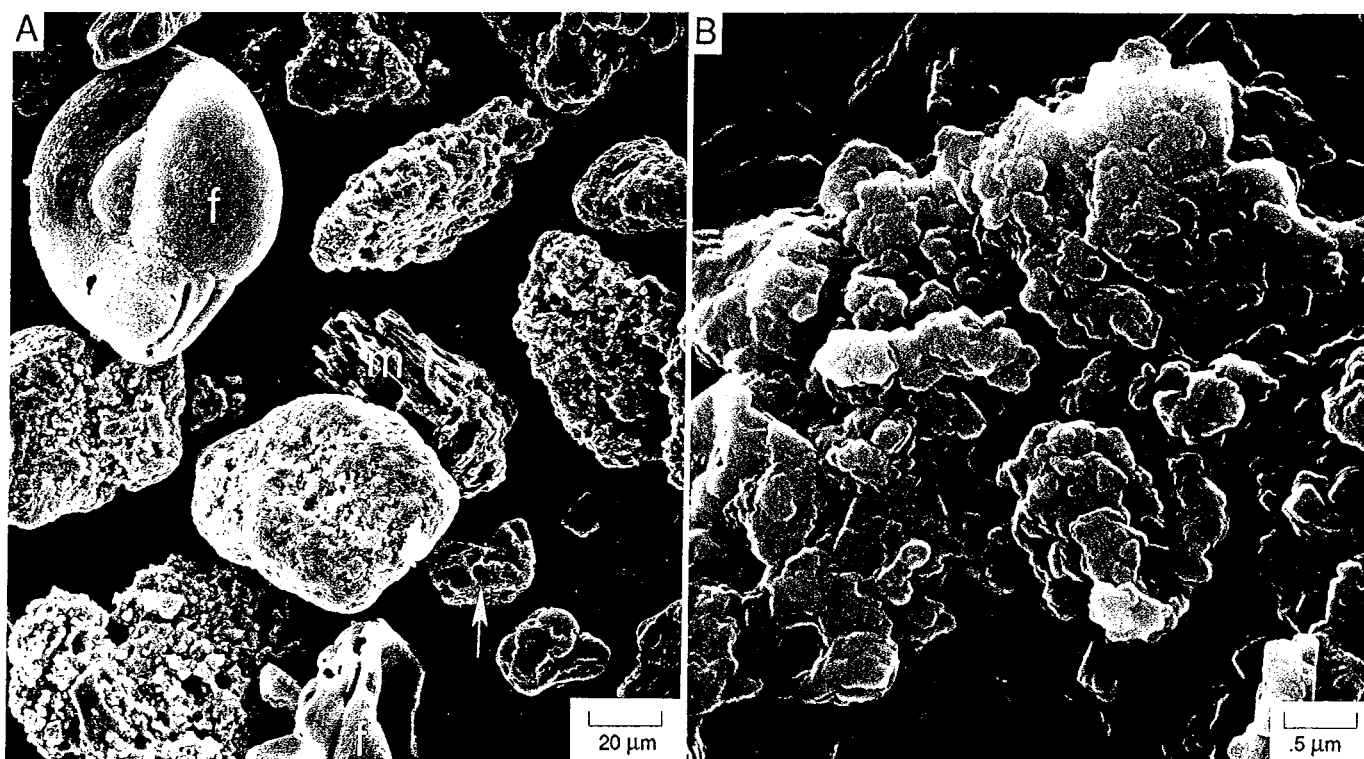
FIG. 5,— A) Scanning electron micrograph of coarse silt from the cryptocrystalline sand facies showing abundant cryptocrystalline grains as well as miliolid foraminifera (whole and fragments; f), and a possible mollusc fragment (m). Note the smooth abraded outer surfaces of some of the cryptocrystalline grains and the open microborings (arrow), which give some of the cryptocrystalline grains a swiss cheese appearance. B) Magnified view showing the anhedral equant crystals composing a cryptocrystalline grain; note that although individual crystals are less than 0.5 μm in size, they are commonly welded together in 1-4 μm-sized clumps.

alteration of skeletal grains are presented in the following section.

Samples from the peneroplid-sand facies, like those from the cryptocrystalline facies, contain about 20% mud (Fig. 3A). Fine to coarse sand-sized peneroplid and miliolid foraminifera and mollusc fragments are the most abundant grain types. The skeletal material occurs as fresh to extremely altered grains. Cryptocrystalline grains are abundant in the fine sand-size range (0.25–0.125 mm), constituting about 30% of the total sand fraction.

The laminated miliolid-mud facies, which composes Bulkhead shoal, consists of laminated sand-rich and mud-rich sediments. Pusey (1975) suggested that the laminations formed during periods of turbulence and winnowing. The sand-size fraction is dominantly very fine to medium (0.063 to 0.5 mm) cryptocrystalline grains, with less common miliolid foraminifera. Scattered coarser grains are mostly peneroplid foraminifera and mollusc fragments, most of which are highly altered. In all three of the above facies, the degree of alteration of skeletal grains tends to increase with a decrease in grain size (Fig. 4).

Miliolid-mud facies samples contain 15 to 20% sand (Fig. 3A), which is mainly very fine (125–63 μm) cryptocrystalline grains. Coarser skeletal grains of miliolid and peneroplid foraminifera and molluscs are generally freshly preserved, showing little evidence of alteration. The

lack of intense alteration is in sharp contrast to the skeletal debris in samples from all of the other facies.

Samples from the Halimeda-sand facies are medium to fine grained (0.5 to 0.125 mm) sand with only a trace of mud (Fig. 3A). They consist of a variety of skeletal debris including Halimeda, coral, molluscs, coralline algae and foraminifera. Most grains are extensively altered, and they are commonly cemented together to form grapestone lumps.

SEM observations show that the silt-size (63-4 pm) fractions of all facies consist predominantly of cryptocrystalline grains, with less abundant skeletal fragments in all stages of alteration (Fig. 5). The cryptocrystalline grains are composed of equant, anhedral crystals less than 0.5 μm in diameter which are commonly welded together in small (1 to 4 μm) clumps (Fig. 5B). The surfaces of some of the cryptocrystalline grains are rough, others are smooth and rounded. Many of the cryptocrystalline grains are riddled with open bore holes, 4 μm in diameter, which give the grains a "swiss cheese" appearance. Skeletal fragments were recognized by shape and ultrastructure (see Stieglitz 1972; Tennet 1982).

Clay-sized (< 4 μm) sediment from the inner lagoon and Chetumal Bay consists predominantly of clumps (1–4 pm) of anhedral, equant crystals (< 0.5 pm) (Fig. 6). Rare skeletal fragments and elongate grains (1 × 0.1 μm) are also present in this clay-size sediment, but rhomb-
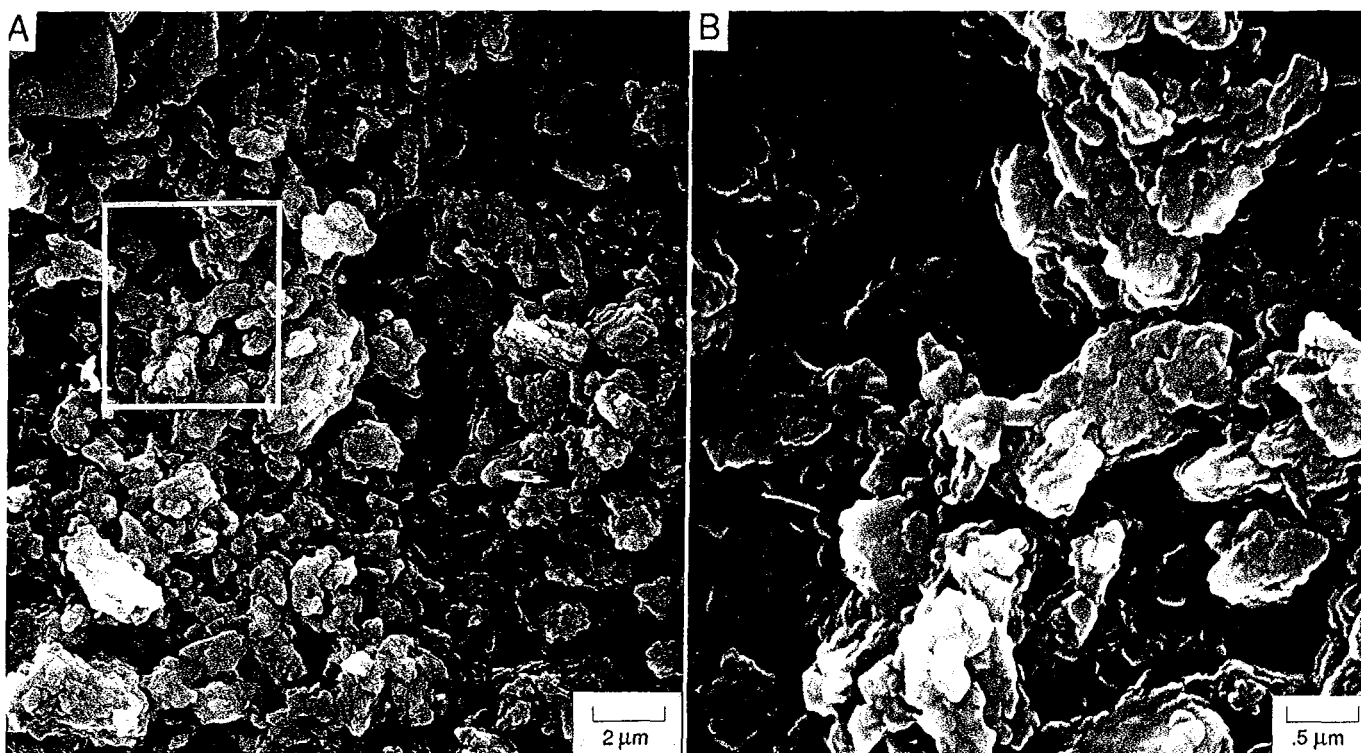
FIG. 6.—Scanning electron micrographs of the clay-size fraction of sediment from the miliolid mud facies. **A)** Sediment is comprised dominantly of 1–4 μm-sized clumps of very small crystals (< 0.5 μm). B) Magnified view showing individual anhedral, equant crystals that comprise the clumps shown in **A.**

shaped grains as illustrated by Pusey (1975, fig. 32c) were not observed. The minor clay-size fraction from the *Halimeda* facies contains abundant anhedral equant grains but differs from the inner lagoon clay-size carbonate in having a greater proportion of rod and needle-shaped particles.

X-ray diffraction analyses indicate that bulk samples from the inner lagoon and Chetumal Bay consist of 72–86% Mg-calcite, 13–27% aragonite and less than 5% calcite (Fig. 3B). The composition of these sediments contrasts with the sample from the *Halimeda* facies on the outer platform, which is 82% aragonite, 15% Mg-calcite and 3% calcite. The higher aragonite content in the *Halimeda* facies sediments is comparable to that found in bulk sediment samples from southern Belize, Florida Bay and the Bahamas, which ranged from 55 to 84% aragonite (Table 1).

The distribution of Mg-calcite in the various size fractions of samples from northern Belize shows a trend toward increased amount of Mg-calcite with decreasing size (Fig. 3B). In particular, all samples show a marked increase in % Mg-calcite in the clay-size fraction relative to the sand-size fraction.

Values of mole % $MgCO_3$ (Fig. 3C) show distinct facies variations. Bulk samples show an increase from 9.5 mole % in the cryptocrystalline facies to 9.5–11 mole % in the inner lagoon and 12.5 mole % in the *Halirneda* facies. The size fractions show a trend of decreasing mole %

$MgCO_3$ with smaller grain size. Clay-size Mg-calcite in samples from the inner lagoon and Chetumal Bay contain 9 mole % $MgCO_3$, in contrast to clay-size carbonate from the *Halimeda* facies on the outer platform, with 12 mole % $MgCO_3$.

Alteration of Skeletal Grains

The alteration of skeletal grains was investigated by x-ray diffraction, thin section petrography and SEM. Fresh and altered grains of miliolid and peneroplid foraminifera (Mg-calcite), molluscs (aragonite), *Halimeda* (aragonite) and barnacles (calcite) were hand-picked from the sand-size fractions of sediment samples to document changes in mineralogy and ultrastructure accompanying the alteration process.

X-ray analyses indicate that all types of skeletal grains from the inner lagoon and Chetumal Bay and many grains from the *Halimeda* facies, regardless of original mineralogy, have altered to Mg-calcite. The amount of Mg-calcite in the altered grains varies from only a few percent in lightly altered molluscs to 24% in an assemblage of highly altered molluscs and 79% in a highly altered *Halimeda*. In addition to diagenetic Mg-calcite, x-ray patterns showed that several of the aragonite pelecypods and *Halimeda* grains contained traces of calcite, and many of the altered foraminifera and the altered barnacle fragments contained minor aragonite. In contrast to pervasive

TABLE 1.— *Composition of carbonate muds and reef sand in other locations*

Location	Composition			Mole % MgCO₃ in Mg-Calcite
	% Mg-Calcite	Calcite	Aragonite	
Belize-Southern Shelf				
1. Back-reef, Cave				
Bulk sample	34	2	64	12½
< 4 μm	54	2	44	13
2. Back-reef, Mangrove Is.				
Bulk sample	38	4	58	12
< 4 μm	47	2	51	12
3. Fore-reef Sand Trough				
Bulk sample	27	3	70	13½
< 4 pm	56	5	39	13½
Florida Bay				
Cross Bank				
Bulk sample	40	8	55	13
< 4 μm	35	2	62	12½
Bahamas				
West Andros Is.				
Bulk sample	14	2	84	12

FIG. 7.— Composition of skeletal grains in various states of alteration as determined by x-ray diffraction. *Halimeda* and all of the molluscs identified were originally aragonite; unaltered peneroplids are Mg-calcite, and a fresh barnacle analyzed was 100% calcite.

alteration to Mg-calcite in the inner lagoon, microborings and skeletal cavities of some grains from the Halimeda facies are infilled with acicular aragonite.

A facies pattern is reflected in the values of mole % $MgCO_3$ in the diagenetic Mg-calcite of altered skeletons, which increase from a range of 8.5–11 mole % in the cryptocrystalline facies to a range of 10–12 mole % in the inner lagoon and 12–13 mole % in the Halimeda facies (Fig. 7). The skeletal mineralogy of unaltered peneroplid foraminifera exhibits a similar trend, with values of 9.5 mole % $MgCO_3$ in the cryptocrystalline facies, 10.5–11 mole % in the inner lagoon and 12 mole % in the Halimeda facies (Fig. 7). The increase of mole % $MgCO_3$ in altered skeletal grains from increasingly open marine facies is equivalent to the trend observed in sand-size sediment samples (Fig. 3C).

Petrographic and SEM observations show that alteration of skeletal grains to Mg-calcite has occurred primarily by recrystallization, with additional alteration by precipitation in skeletal cavities and minor infilling of microborings. The overall process is one of micritization. (The term "recrystallization" is used here to indicate changes in crystal texture or changes in mineralogy, following Purdy (1968, p. 186.) "Micritization" is used in the sense of Alexandersson (1972, p. 206) to refer to the alteration of a preexisting fabric to micrite by a decrease or increase in crystal size or by the destruction of an ordered crystal arrangement.) The initial stage in the textural alteration of all types of skeletal grains, regardless of original mineralogy, is the recrystallization of laths and needles (in foraminifera and Halimeda) and prisms and blades (in molluscs and barnacles) to equant crystals of microcrystalline Mg-calcite less than 0.5 μm in size (Fig. 8A, D, E). Microboring by endolithic organisms appears to enhance the process of recrystallization, particularly with respect to the molluscan and barnacle material, which
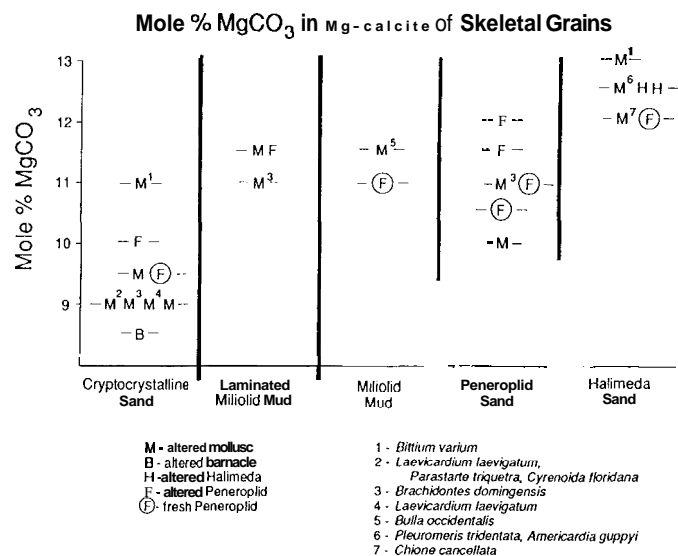
is composed of tightly interlocking crystals. However, skeletons with open structures composed of needles and laths, including both foraminifera and Halimeda, are commonly extensively altered with no evidence of microboring. These observations are in agreement with Pusey (1975, p. 182), who noted that microboring promotes but "is not a prerequisite for recrystallization".

Our observations suggest that formation of micritic rims by multicyclic boring and infilling as documented by Bathurst (1966) and Alexandersson (1972) is only of minor importance in our study area. We generally found open borings surrounded by altered skeletal walls. The only abundant secondary infillings we observed were dentate euhedral crystals of microspar lining skeletal cavities, particularly in foraminifera and Halimeda (Fig. 8F).

Skeletal grains weakened by the micritization process on the northern Belize shelf break down into silt-size and finer material. Abrasion and disintegration of altered grains is illustrated by the smooth outer edges of many of the extensively micritized grains (Fig. 5A) and by the increased abundance of altered grains in the finer size fractions (Fig. 4).

A second stage of recrystallization has followed the size reduction of micritized skeletons in some of the open-needle and lath structures of the foraminifera and Halimeda. During this stage, the finer secondary crystals (< 0.5 pm) coalesce to form coarser crystals (1–10 pm). In the latter stages of this marine recrystallization, patches of sparry mosaic in the skeletal walls interlock with the dentate infilling in the skeletal cavities to form a densely altered grain in which most, if not all, of the original skeletal textures have been destroyed (Fig. 8C, F). The textural changes observed in the skeletons of foraminifera and Halimeda on the northern shelf are similar to the stages of alteration of fossil miliolacean foraminifera doc-
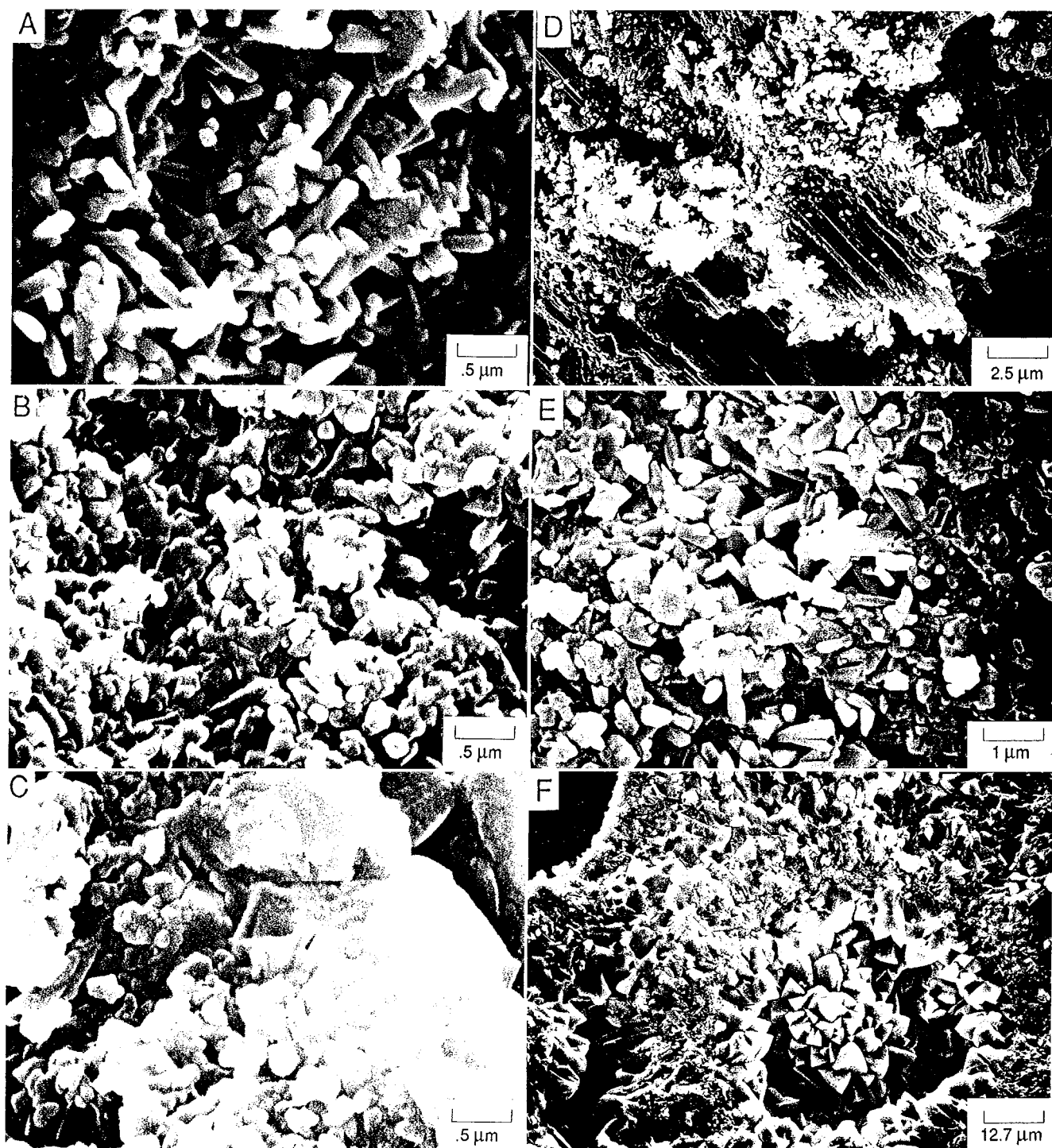
FIG. 8.— Scanning electron micrographs showing fractured surfaces of skeletal grains in various stages of alteration. PENEROPLID FORA-MINIFER: A) Unaltered laths of Mg-calcite, B) laths recrystallized to much finer equant crystals of Mg-calcite (< 0.5 μm in size), C) equant micritic crystals altering to coarser crystals (1–10 μm). MOLLUSC: D) blades of aragonite in a pelecypod shell recrystallized to equant micritic Mg-calcite; note open microborings in lower right. HALIMEDA: E) aragonite needles partly recrystallized to equant Mg-calcite, F)dentate euhedral Mg-calcite lining a utricle (lower right) with coarser Mg-calcite crystals replacing the finer equant micrite in the skeletal framework.

umented by Towe and Hemleben (1976), in which original skeletal laths recrystallized to "equant grains" and then to a "coarser mosaic of microsoar" (p. 339), but in their study of fossil foraminifera no Mg-calcite was observed at any stage.

DISCUSSION

Origin of Cryptocrystalline Grains

Petrographic, morphologic and mineralogic evidence suggests that cryptocrystalline grains, the most abundant

grain type on the northern Belize shelf, are micritized skeletal grains. Documentation of the transition from fresh skeletons to cryptocrystalline carbonate, as shown in Figure 8, shows that the diagenetic carbonate of the altered skeletons is composed predominantly of very small anhedral, equant crystals (< 0.5 μm) which are identical to the carbonate that forms the cryptocrystalline grains (Fig. 5). X-ray diffraction analyses indicate that the mineralogy of the altered skeletons and sand-size fractions of sediment, which are composed largely of cryptocrystalline grains, shows similar facies variations: altered skeletons show an increase in mole % $MgCO_3$ from 8.5–11 mole % in the cryptocrystalline facies to 10–12 mole % in the inner lagoon and 12–13 mole % in the *Halimeda* facies; sand-size fractions increase from 9.5 mole % in the cryptocrystalline facies to 10.5–11 mole % in the inner lagoon and 13 mole % in the *Halirneda* facies. The abundance of skeletons in all stages of alteration throughout the northern Belize shelf (including the cryptocrystalline-sand facies, in which Pusey reported a paucity of skeletal grains) indicates an adequate source of skeletal material. Pusey (1975) suggested that the cryptocrystalline grains in the cryptocrystalline facies originated as low Mg-calcite algal crusts from the mouth of the Rio Hondo River. Low Mg-calcite crusts, however, are probably of little importance as a source of cryptocrystalline grains in our samples, where all size fractions contained at least 9 mole % $MgCO_3$. Indeed, Pusey's own data (p. 231–233) show that, except in the upper reaches of Chetumal Bay, calcite in sediment from the cryptocrystalline facies contains 7–9 mole % $MgCO_3$.

Micritization of skeletal grains, as observed in northern Belize, is also an important diagenetic process in other shallow marine environments, including the Bahamas, Persian Gulf and Florida Bay (Purdy 1963, 1968; Bathurst 1966; Winland 1968, 1969; Kendall and Skipwith 1969; Trumbull 1988; and others). In contrast to alteration to Mg-calcite on the northern Belize shelf, grains in the Bahamas and Persian Gulf alter to aragonite (Purdy 1963; Bathurst 1966; Kendall and Skipwith 1969; Trumbull 1988). This difference in mineralogies is illustrated by the alteration of peneroplid foraminifera: in the Persian Gulf, the chambers of these foraminifera are filled with acicular aragonite and the test is replaced by microcrystalline aragonite (Kendall and Skipwith 1969, p. 849), whereas in the inner shelf of northern Belize, dentate Mg-calcite fills the skeletal chambers and the lath microtexture of the tests is replaced by equant microcrystalline Mg-calcite. A radiocarbon age of 450 ± 105 yr for sediment from northern Belize lagoon consisting largely of altered peneroplids (Pusey 1975, p. 180) suggests that micritization is actively occurring in the lagoon and that the altered grains are not relict.

More than one mechanism for micritization has been proposed. For example, Bathurst (1966, 1975) suggested that micritization occurred primarily by repeated boring by algae and fungi and infilling of the microborings with microcrystalline precipitates. Other authors (e.g., Purdy 1968; Pusey 1975; Winland 1969; and Kendall and Skipwith 1969) observed by thin section petrography that the

distribution of cryptocrystalline carbonate in altered grains was not suggestive of replacement by boring and infilling, and instead proposed that micritization occurred as a result of recrystallization. Our study is, to our knowledge, the first to document the recrystallization process in modern sediments using the scanning electron microscope.

The most important diagenetic process in shallow, normal marine environments is generally considered to be precipitation (Moore 1989; Bathurst 1975). It has been suggested that carbonate skeletons composed of aragonite and Mg-calcite are stable with respect to the depositional water and that as long as skeletons remain in the marine environment, degradation processes are minimal (see, for example, Brand and Morrison 1987). However, our study indicates that carbonate grains are not stable in the northern Belize lagoon and suggests that recrystallization may be an important diagenetic process in shallow tropical marine carbonate sediments. Determination of the process responsible for recrystallization in the northern Belize lagoon is beyond the scope of this study but will be the subject of future geochemical investigations.

The relative stabilities of carbonate minerals with respect to one another and the general stability of carbonate minerals in shallow water are not well known (Milliman 1974). Influence of water chemistry on the amount of magnesium incorporated in calcite on the northern Belize shelf is suggested by the systematic increase of mole % $MgCO_3$ with increasingly open marine conditions, as seen in sand-size sediments, altered skeletal grains and fresh foraminiferal skeletons from Chetumal Bay, the inner lagoon and outer platform. Pusey's data (1975) extend this trend, showing a continuing decrease in mole % $MgCO_3$ northward in Chetumal Bay, with low Mg-calcite in the upper reaches of the Bay. Specific factors responsible for controlling the distribution of $MgCO_3$ in calcite are uncertain, but Mg/Ca ratios in the surrounding waters may be important (Mucci and Morse 1983; Walter 1986).

Pervasive alteration of skeletal grains to Mg-calcite on the northern Belize shelf provides a counterpart to the Bahamas, where grains are altering to aragonite. Various factors have been suggested to affect precipitation of aragonite versus calcite in the marine environment, including substrate mineralogy (Purdy 1968; Alexandersson 1972; Walter 1986), carbonate ion concentration (Given and Wilkinson 1985), temperature (Burton and Walter 1987), and relative concentrations of sulphate and phosphate (Walter 1986). Northern Belize and the Bahamas would provide natural laboratories for the study of sedimentologic and geochemical processes involved in the contrasting styles of diagenesis.

Origin of Mud

Theories regarding the origin of lime mud in northern Belize lagoon must account for three factors: 1) the anhedral, equant shape of crystals comprising the majority of silt-size grains and the clay-size fraction; 2) the general increase in amount of Mg-calcite with decreasing grain size in all facies (Fig. 3B); and 3) variations in mole % $MgCO_3$ in the size fractions of each facies (Fig. **3C).**

The presence of foraminiferal and molluscan fragments in the various size fractions of all facies on the northern shelf is evidence that sand-size skeletons are breaking down to mud-size fragments. However, the anhedral equant morphology of crystals constituting the bulk of the mud fraction in the lagoon and Chetumal Bay contrasts with the original lath and prism-shaped crystals composing most of the skeletal grains. The predominance of cryptocrystalline grains in these mud fractions, together with the similarity in ultrastructure of the cryptocrystalline carbonate with micritized skeletal material, suggests that altered skeletal grains are the major source of the mud. Differences in mole % $MgCO_3$ in altered skeletal grains from the lagoon (10–12 mole %; Fig. 7) and mud fractions from the equivalent facies (9–10.5 mole %; Fig. 3C) suggest that much of the lagoonal mud may have been derived from altered skeletal grains in the cryptocrystalline facies, as discussed later in this section.

The general increase in amount of Mg-calcite with decrease in grain size in sediments from all facies (Fig. 3B) is interpreted to reflect the alteration of all types of skeletal grains (i.e., grains of calcite, Mg-calcite, and aragonite) to Mg-calcite. In the lagoon and Chetumal Bay, we suggest that degradation of altered grains produces mud that is about 90% Mg-calcite and composed largely of micrite-sized clumps of equant anhedral crystals about 0.5 μm in size. Even in the open-water *Halimeda* facies, where rod-shaped grains (which are probably aragonite) are abundant in the clay-size fraction, Mg-calcite increases from 11% in the sand fraction to 52% in the clay fraction.

The significance of variations in mole % $MgCO_3$ in the size fractions of each facies (in particular, the decrease from values of 10.5 or 11 mole % $MgCO_3$ in sand fractions of the lagoonal facies, to 9 mole % $MgCO_3$ in the clay-size fractions of equivalent facies; Fig. 3C), as well as differences between Mg-calcite compositions of mud and altered sand-size skeletal grains from the lagoon (9–10.5 mole % $MgCO_3$ in mud, Fig. 3C, and 10–12 mole % $MgCO_3$ in altered skeletons, Fig. 7), is uncertain because the differences are small (generally $\leq$ 2 mole %) in comparison with the precision of individual analyses ($\pm$1 mole %). However, the consistency of the observed trends, in many cases substantiated by duplicate or triplicate analyses of sediment samples, suggests that the differences in composition are real. Decreasing values of mole % $MgCO_3$ in the size fractions are unlikely artifacts of x-ray diffraction caused by grain size because clay-size carbonates in the *Halimeda* facies (Fig. 3C) and from both southern Belize and Florida Bay (Table 1) contain 12–13.5 mole % $MgCO_3$. Therefore the consistently low values of 9 mole % $MgCO_3$ in clay-sized fractions of lagoonal muds are interpreted as indications that a major portion of this sediment did not form *in situ* by breakdown of sand-sized grains in the lagoon but rather originated within, and was transported from, the cryptocrystalline facies in Chetumal Bay, where sand-size sediment contains 9.5 mole % $MgCO_3$.

Undoubtedly clay-size material is being formed by breakdown of micritized grains in each of the facies. However, this *in situ* contribution is only recognized in the *Halimeda* facies, where clay-size carbonate is 12 more % $MgCO_3$. In the peneroplid and miliolid facies, we suggest that the local contribution of clay-size material is completely masked by input from the cryptocrystalline facies. The gradual decrease of mole % $MgCO_3$ with decreasing size in silt-size fractions of the peneroplid, miliolid and laminated miliolid facies could reflect contamination by clay due to incomplete size separation or could be a result of transport of silt-size material from the cryptocrystalline facies. Pusey (1975) suggested that a major portion of the sediment in the miliolid facies was transported from the cryptocrystalline and peneroplid facies based on the paucity of altered skeletal grains and abundance of very fine sand-sized cryptocrystalline grains in the miliolid facies.

Fragments of coralline algal epibionts growing on *Thalassia,* reported to be an important source of Mg-calcite mud in Jamaica (Land 1970); Barbados (Patriquin 1972) and Florida Bay (Nelsen and Ginsburg 1986), are considered minor components of mud in northern Belize lagoon for the following reasons: 1) *Thalassia* is not abundant in the inner lagoon and Chetumal Bay; 2) coralline algal epibionts are composed mainly of tiny rod-shaped crystals (approximately 2 μm × 1 μm), but rods or skeletal fragments composed of rods are uncommon in the mud fraction; and 3) coralline algal epibionts contain 12–14 mole % $MgCO_3$ (Tennet 1982; this study), whereas the mud fraction of sediments from the inner lagoon are 9–10.5 mole % $MgCO_3$.

The importance of physiochemical precipitation in forming mud in northern Belize lagoon is not known. Whitings have been observed in the area (Pusey 1975), but their origin remains uncertain (see Shinn et al. 1989, for discussion of whitings in the Bahamas). Pusey (1975, p. 214) suggested that direct physiochemical precipitation of Mg-calcite was unlikely, but that photosynthetic bacteria may have been important in precipitating mud. We have no reasons to discount either physiochemical or bacterially induced precipitation in the northern lagoon, but our data suggest that breakdown of micritized skeletal grains is an adequate source for all of the mud in the area.

Implications

Our study of northern Belize lagoon suggests that, in addition to conventional origins of lime mud (both skeletal, from disintegration or mechanical/biological erosion of original carbonate skeletons, and direct precipitation from the water column), there is another important source: breakdown of micritized skeletal grains. Although micritization and grain diminution are two well established processes, micritized grains have not previously been identified as a potential source for mud that is morphologically and mineralogically distinct from mud produced by skeletal breakdown. For example, Matthews (1966) identified up to 25% cryptocrystalline grains in the silt-size fraction of samples from the southern Belize shelf. With the absence of scanning electron microscopy, he did not, however, recognize recrystallization of grains, and he attempted to identify the source of these cryptocrys-

talline grains by comparing their chemistry to that found in original skeletons.

Recognition of the breakdown of micritized grains as a source of mud could help to resolve some of the controversies over the origins of lime mud. In particular, it offers a possible explanation for the lack of similarity of component mud grains to skeletal crystals (see, for example, Loreau 1982; Steinen et al. 1988). In addition, as micritization of skeletal grains is common in shallow tropical environments, this newly proposed source does not conflict with reports of skeletal production in excess of *in situ* lime mud deposition (e.g., Neumann and Land 1975).

The close association between cryptocrystalline grains and lime muds in such classical "lime mud factories" as the Bahamas (Illing 1954; Newell et al. 1959; Purdy 1963) and Persian Gulf (Kendall and Skipwith 1969; Purser 1973) suggests that lime-mud formation by the breakdown of micritized grains may not be limited to the northern shelf of Belize. Indeed, Illing (1954, p. 27) considered cryptocrystalline grains to be the "fundamental unit in the formation of the vast spreads of calcareous sands that cover the sea bottom on the (Bahama) Bank". We suggest that cryptocrystalline grains may also be a fundamental source of mud on Great Bahama Bank. We further suggest that the difference in compositions between the dominantly Mg-calcite mud of the northern Belize shelf and aragonitic mud in the Bahamas and Persian Gulf could be related to the contrast in chemical alteration of carbonate grains in the two areas: micritization to Mg-calcite in Belize and to aragonite in the Bahamas and Persian Gulf.

In a recent study of the northern Great Bahama Bank, Trumbull (1988) illustrated formation of aragonitic peloids by micritization and abrasion of *Halimeda* plates. His sequence showing a "continuum from large skeletal grains to small pelletoids" (p. 43) not only indicates a micritized skeletal source for peloids but also suggests a potential source of aragonitic mud in this area.

In summary, we propose that micritization and diminution of skeletal grains in shallow tropical seas can provide a major source for lime mud that has not previously been recognized.

CONCLUSIONS

1) Pervasive micritization of aragonite, calcite and Mg-calcite skeletal grains in northern Belize lagoon has formed Mg-calcite cryptocrystalline grains, which are a dominant component of sediment in the area.

2) Micritization in the northern lagoon is mainly the result of recrystallization of skeletal material, but it also occurs by infilling of skeletal cavities and microborings.

3) Abrasion and bioerosion of micritized grains provides the dominant source of Mg-calcite-rich mud that characterizes northern Belize lagoon.

4) Similar processes involving breakdown of micritized skeletal carbonate sand could be an important source

of mud in other areas, including the Bahamas and Persian Gulf.

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