SEPM Society for Sedimentary Geology

4111 S Darlington
Suite 100
Tulsa, Oklahoma 74135
USA

Phone: 918-610-3361
Fax: 918-621-1685
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ORIGIN AND ACCUMULATION OF LIME MUD IN OOID TIDAL CHANNELS, BAHAMAS[1]

MARK R. BOARDMAN
Department of Geology
Miami University
Oxford, Ohio 45056
AND
CINDY CARNEY
Department of Geological Sciences
Wright State University
Dayton, Ohio 45435

ABSTRACT: Mud layers have been found within the ooid sands of Joulters Cays and Lee Stocking Island, Bahamas. A 1.3-m vibracore extracted from 4 m water depth in the Lee Stocking tidal channel contains a lower unit of dark brown muddy sand (skeletal rich) overlain by two layers of ooid sands intercalated with two layers of creamy, white mud. The two upper mud layers are aragonite-rich, sometimes pelleted, and contain very few skeletal grains. The contacts between the ooid sands and mud layers are commonly sharp, but some contacts show evidence of burrowing and mud clast formation. A mud layer with similar textural, mineralogic and petrographic characteristics was recovered from a 16-cm core from a tidal channel on Joulters Cays, Bahamas. This mud layer was also enclosed within ooid sands.

Mud in the Lee Stocking ooid tidal channel is apparently of two origins. Mud in the lower unit of the core contains a more equal distribution of aragonite and calcite (≈50% each) and abundant skeletal grains of normal marine origin, indicating that the lower unit is lagoonal. Mud that is interlayered with ooid sands in the same core is dominated by aragonite (≈80%) and contains little sand-sized material, suggesting that it is not a typical lagoon mud. SEM examination also confirms that this mud is quite different from the lagoonal mud found at the base of the core.

C-14 dating of the mud from the lagoonal unit shows that this sediment was deposited in water depths of 2 to 3 m approximately 5000 years ago when sea level was 3 m lower than present. C-14 dating coupled with knowledge of Holocene sea level indicates that both the ooid sands and the mud layers were also deposited as subtidal sediments. The mechanism by which the mud layers are accumulated with ooid sands is problematic. Suspension by storms and transport to tidal channels is one possibility; however, evaluation of the data suggests an alternative explanation. The post-lagoon history of deposition of the tidal channel may include nearly continuous restriction during which mud layers were deposited. The restriction was possibly caused by the formation and maintenance of ooid sand barriers. Ooid sand deposition and burial of these layers may have accompanied barrier destruction.

INTRODUCTION

Ooid sand accumulation has long been recognized as a diagnostic criterion of high-energy, continually agitated environments, while lime mud accumulations are diagnostic of quiet-water environments. This understanding is rightfully entrenched in the major classification schemes of carbonate rocks and sediments (Dunham 1962; Folk 1962; Embry and Klovan 1971).

Mixtures of lime mud with ooids and other well-rounded, well-sorted sand grains are found in both modern sediments and ancient limestones and form oolitic wackestones and packstones. One logical explanation is that the oolitic sand grains were transported to the site of mud accumulation by storms (Newell et al. 1960; Hine 1977; Harris 1979; Halley et al. 1983). Another is that significant changes in environments occurred over relatively short times (Harris 1979). Subsequent mixing such as by bioturbation homogenizes the sediment.

The accumulation of pure lime mud layers and lenses with well-sorted ooid sands is problematic, however, because these two sediments represent mutually exclusive environments of deposition. Lime mud in the form of clasts found with otherwise pure ooids has been interpreted as intraclasts derived from a nearby muddy environment such as a tidal flat (Smosna 1984). Mud lenses and layers have been found in Cambrian and Jurassic oolites (figure 5 in Chow and James 1987; type B and figure 3 in Strasser 1988) and the Pleistocene Miami Oolite (Lasemi and Sandberg 1984; Lasemi et al. 1990). These occurrences of mud with ooids have not been fully explained, perhaps because models of deposition arising from modern and ancient analogs of mud accumulation (Irwin 1965; James 1984; Read 1985) are inadequate to embrace this association.

The recent description of mud layers and mud chips being exposed and excavated accompanying the migration of ooid sand waves in the modern ooid sand shoals north of Lee Stocking Island, Bahamas (Kendall and Dill 1987; Dill and Steinen 1988; Dill et al. 1989) and the report of a mud layer in a tidal channel from Joulters Cays (Shinn et al. 1989, p. 159) are notable because they provide a modern example of the accumulation of mud and mud chips in ooid sand shoals. In both locations, it is thought that storms transport mud from the lagoon to the tidal channel. Once in the tidal channel, accumulation is by "a mechanism not yet identified that causes the mud to form aggregates" permitting the mud to settle in this high-energy environment (Dill et al. 1989). How the mud is able to remain in the tidal channels where migrating sand waves are found is unknown.

We report in this paper the presence of stacked mud layers interbedded with ooid sands in the channel north of Lee Stocking Island and provide a detailed description of the mud in these layers as well as the sedimentary sequence. Mud layers in the ooid sand shoal of Lee Stock-

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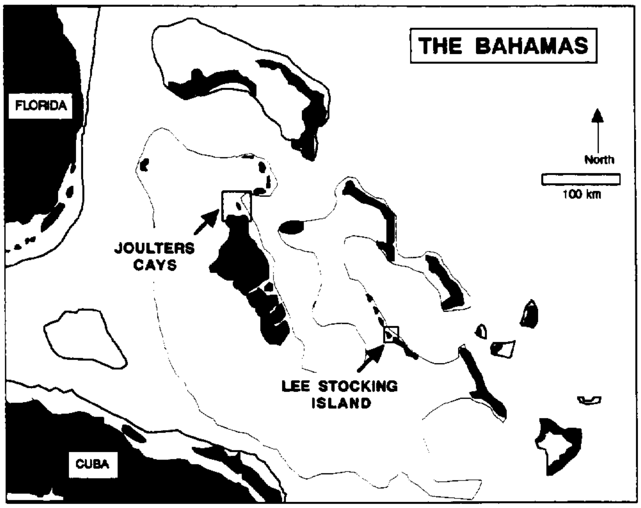

FIG. 1.—Map of the Bahamas. Lee Stocking is a small island 10 km north of Exuma Island. Joulters Cays are the major islands associated with the large ooid sand shoal north of Andros Island.

ing Island are compared to those of tidal channels at Joulters Cays, Bahamas (Fig. 1). We suggest an alternative model of deposition of the mud and of this ooid-mud sequence. Questions arising from these observations include the following. What is the origin of the mud? How was it deposited? What is the sequence of depositional environments leading to the remarkable intercalation of ooid sands and lime mud?

LEE STOCKING TIDAL CHANNEL

The geography, physical conditions and benthic environments of deposition of the tidal channel have been described (Dill et al. 1986; Kendall and Dill 1987; Dill et al. 1989). The inlet is approximately 1 km long, 0.5 km wide and 4 to 8 m deep with tidal currents up to 100 cm/s passing through twice daily. Ooid sands in megaripples occur in a central zone of the inlet and are engulfing giant subtidal stromatolites (approximately 1 to 2 m high and 1 m in diameter). In the troughs of some megaripples, lime mud is exposed and being excavated. Elsewhere in the tidal channel are *Thalassia* meadows, bioclastic sand shoals and a rock surface covered with sponges and soft corals. The islands surrounding the tidal channel are mostly Pleistocene in age, although portions of the islands are comprised of Holocene eolian dunes.

A sediment vibracore was extracted from a trough within the migrating megaripples of ooid sand located in the tidal channel north of Lee Stocking Island, Bahamas (Figs. 2; 3A). At the core site mud chips were strewn on the bottom, and a patch (layer) of mud was cropping out on the floor of the trough (Fig. 3B). The core is 1.3 m in length and contains five discrete units and three distinct facies (Fig. 4). The three facies include 1) a burrow-mottled, bioclastic muddy sand, 2) two medium-grained ooid sand units, and 3) two light tan to white mud layers. Because the core was taken from an ooid megaripple trough, it does not include the present-day ooid sands overlying these core sediments.

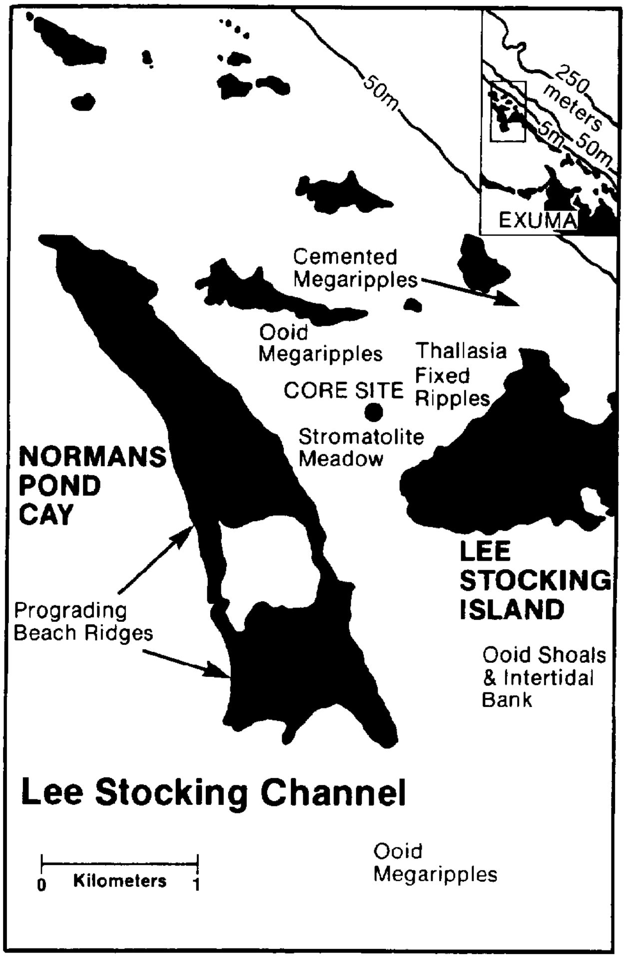

FIG. 2.—A high-energy tidal channel is located northwest of Lee Stocking Island (after Kendall and Dill 1987).

Facies Description

Dark Brown Muddy Sand (63–128 cm Core Depth).—The lowermost 65 cm of the core is a burrow-mottled, dark gray and brown muddy sand (average 44% mud-sized material, i.e., < 63 μm diameter) with burrows up to 2 cm in diameter (Figs. 5; 6A). The sediment is poorly

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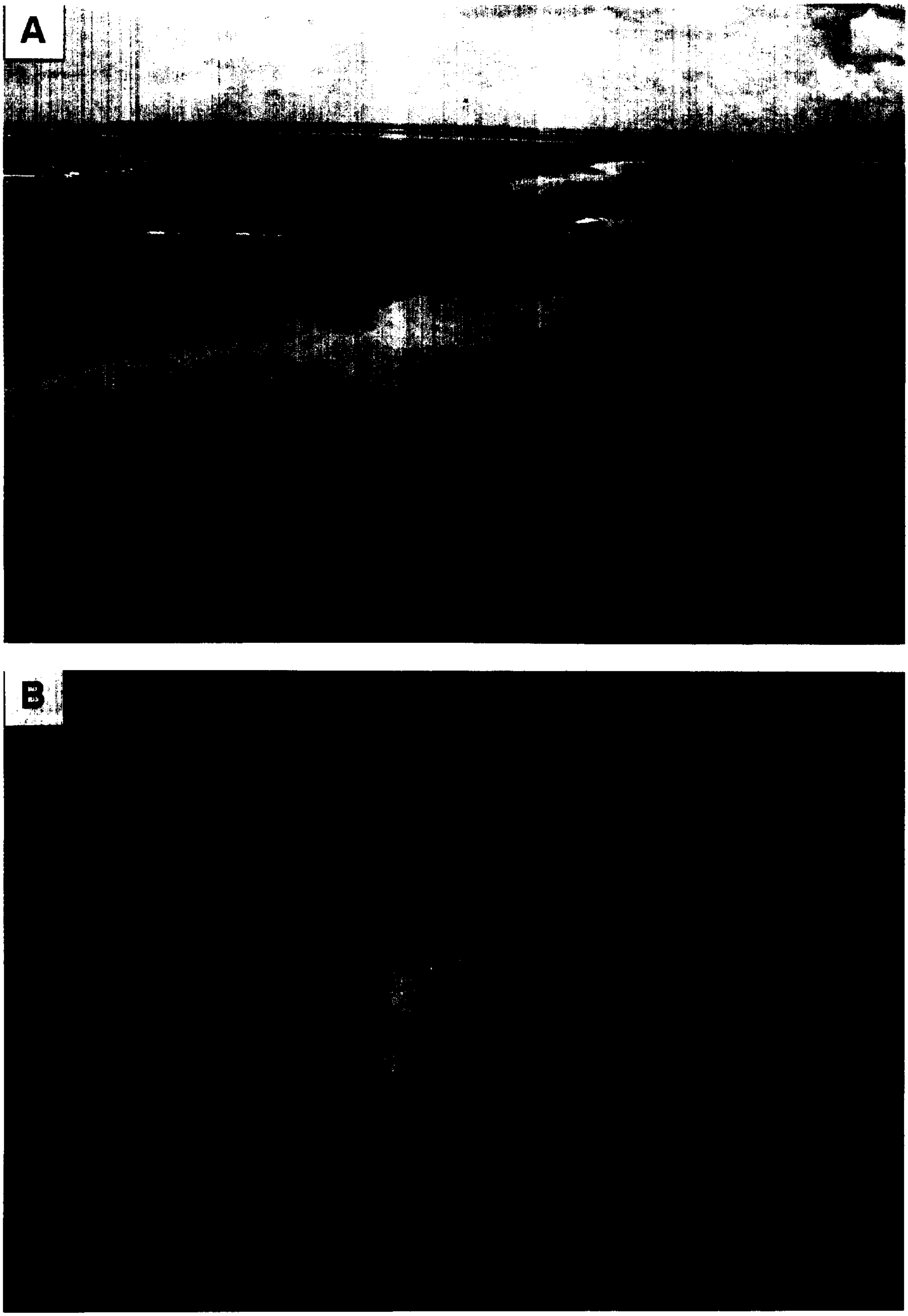
FIG. 3.—Environments of Lee Stocking Island channel. A) Aerial view of the tidal channel north of Lee Stocking Island. View is bankward (to west) with Lee Stocking Island on the left. Megaripples dominate the central portion of the channel. These bedforms are approximately 1 m in height and several meters from crest to crest. Stromatolites and mud layers are being engulfed and exhumed by the migration of these bedforms. B) Mud is being exposed and exhumed in the troughs of the megaripples. Mud chips up to 10 cm across litter the troughs and adjacent portions of the ooid-filled channel.


A
B

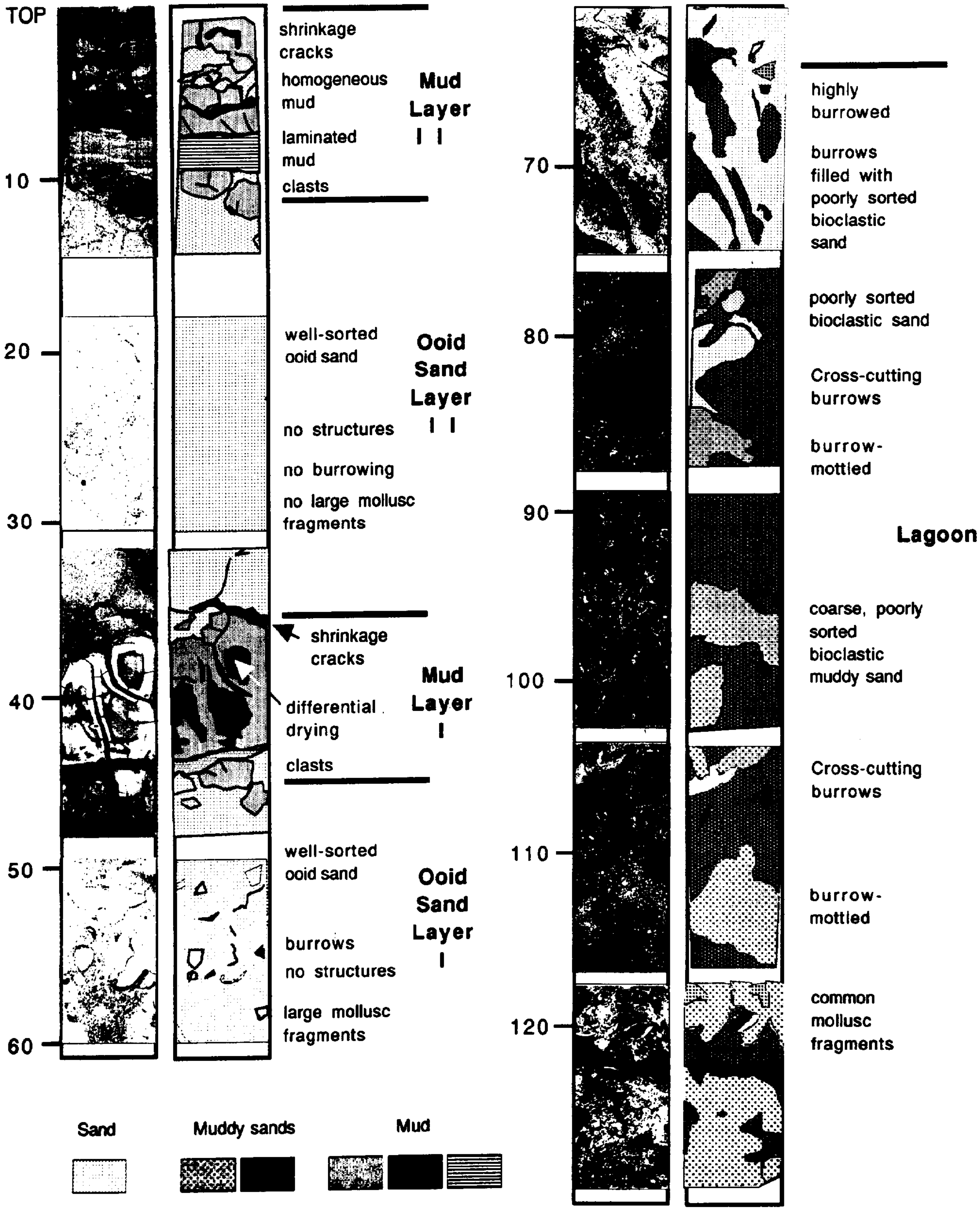


FIG. 4.—Megascopic examination of the 1.3-m core reveals several different lithologies. The lower portion is a burrow-mottled, muddy sand with abundant megafossils. Above this layer are two layers of ooid sand and two layers of creamy mud. The core was taken from a trough, so above the topmost mud layer are the ooid sands that presently floor the channel.

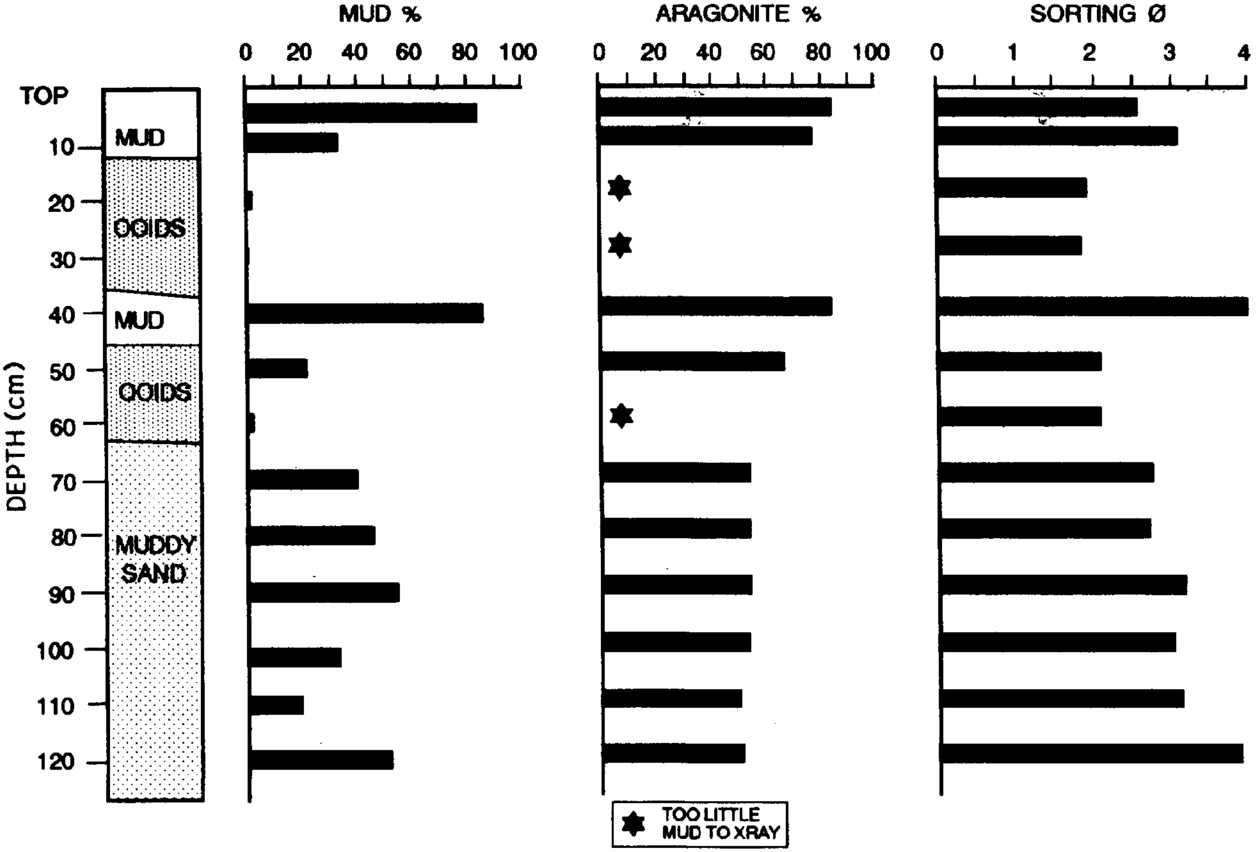


FIG. 5.—Distinction of the several lithologies differentiated megascopically is reinforced by other quantified sedimentary characteristics. **Mud Percent**: The proportion of mud varies directly with changes in lithology. Mud layers have abundant mud, while the ooid sand layers have very little mud. The lower muddy sand unit has a moderate, but variable quantity of mud. **Mud Mineralogy**: Mineralogy of the mud fraction was determined by quantitative x-ray diffraction techniques (Boardman 1976) and also varies with core lithology. Mud layers have high proportions of aragonite; while the lower muddy sand unit contains mud with about equal proportions of high-Mg calcite and aragonite. **Sorting**: Sorting is very poor in the mud layers, moderately poor in the lower muddy sand and moderate in the ooid sand layers. Sorting improves from the base of the core to the first ooid sand layer.

sorted (3.4 ϕ; Fig. 5), and petrographic examination shows that the sediment is comprised of whole shells and angular fragments of molluscs (10.5%), foraminifera (13%), algae (9.5%) and peloids (31.5%) floating in a matrix of lime mud (Table 1; Fig. 6B). Large (> 2 mm) mollusc shells show little evidence of abrasion. Twenty-nine (29) mollusc species were identified in the > 1 mm size fraction. The principal mollusc species include *Codakia costata, Codakia orbicularis, Chione cancellata, Cerithium algicola, Cerithium variabilis, Gouldia cerina,* and *Tellina* sp. which are typical species of a normal marine vegetated carbonate lagoon (Turney and Perkins 1972; Jackson 1972; Miller 1988). Based on the megascopic description, mollusc assemblage, texture and grain composition, we interpret this section of the core as a normal marine lagoon sediment.

The mineralogy of the mud fraction contains an average 52% aragonite (the remainder is mostly high-Mg calcite), which is typical of carbonate lagoons in which benthic foraminifera and encrusting red algae (both high-Mg calcite producers) are mud contributors (Land 1970; Patriquin 1972; Husseini and Matthews 1972; Stieglitz 1972; Boardman 1976), in addition to the green algal contribution of aragonite (Stockman et al. 1967; Stieglitz 1973; Neumann and Land 1975). Scanning electron microscopy of the mud fraction (Fig. 7B) shows both elongate aragonite needles and needles of other origin (presumably high-Mg calcite).

Ooid Sands (I: 45-63 cm; II: 12-37 cm Core Depth; and III: Surface Sediments).—Ooid sands are found in two layers (each about 25 cm thick) within the core and as the surface sediment in this portion of the channel (Fig. 3A). The ooid sediment is better sorted (1.9 ϕ) than the lagoon sediment (Figs. 5, 8). The mean grain size is 0.3 mm and the sands contain little mud (< 2%; Fig. 5). Petrographic examination reveals that, in all three ooid units, the sediment is comprised of ooids ($\bar{x}$ = 70.5%), peloids ($\bar{x}$ = 14%, many of which may be micritized ooids), foraminifera ($\bar{x}$ = 7.3%), molluscs ($\bar{x}$ = 2.5%), algae ($\bar{x}$ = 2.8%), and aggregates ($\bar{x}$ = 2%; Table 1). The ooids are 0.3 to 0.5 mm in diameter and usually have 3 to 4 (but up to 11) thin laminae coating a nucleus which is usually a peloid, although skeletal fragments are also common nuclei (Fig. 8). These ooids are most similar to the type 1 ooids of Strasser (1986).

Most of the grains are rounded, abraded and occasion-

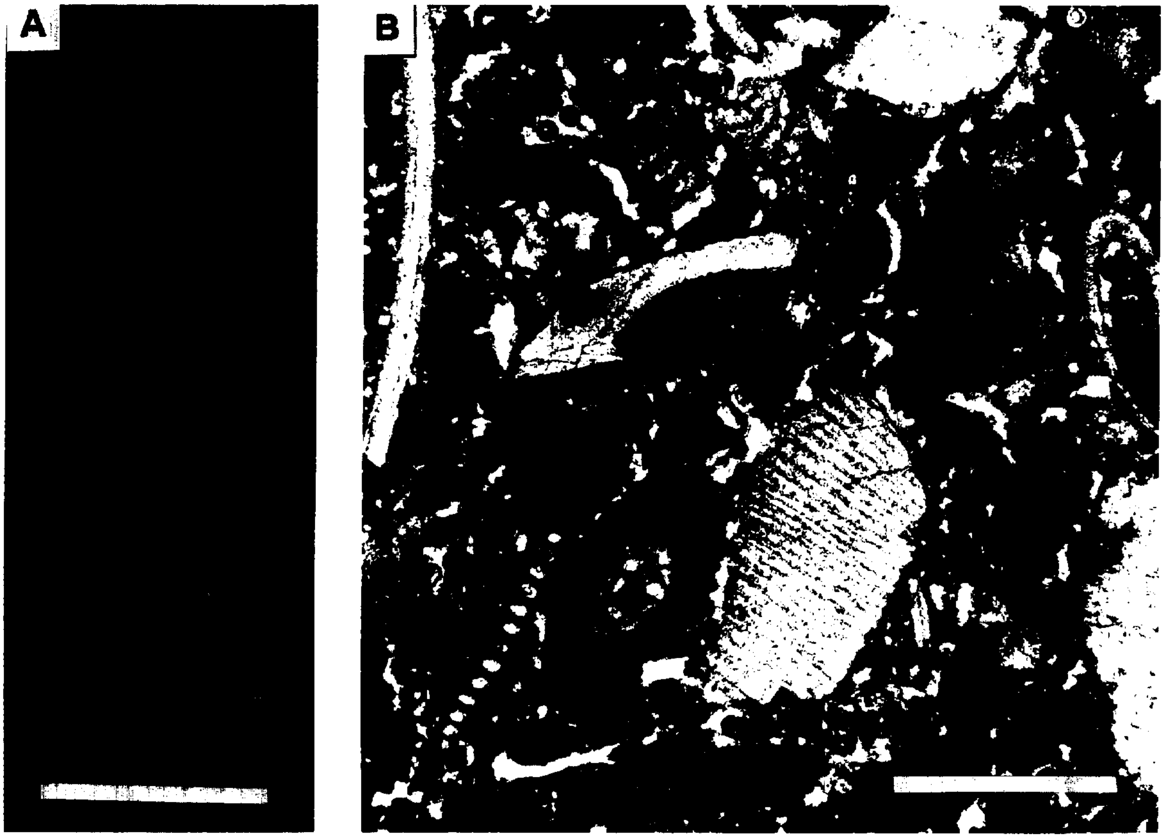


FIG. 6.—Lagoon sediments. A) Polished slab of a plastic-impregnated section of the lagoonal sediments (104–116 cm core depth). Burrows up to 2 cm in diameter and large, disarticulated mollusc fragments are common. Color changes are caused by brown, sand-filled burrows in a dark gray muddier sediment. B) Thin section of a representative portion of the lagoonal section. The lithology is basically a skeletal-rich packstone to wackestone.

ally polished as expected for transported grains of an active ooid sand shoal. Some (≈3%) of the sand-sized grains are blackened, which may indicate prior exposure of these grains in a reducing or hypersaline environment or exposure of the grains to fire (Pilkey et al. 1969; Ward et al. 1970; Strasser 1984; Shinn and Lidz 1988).

Ooid Sand Layer I (45–63 cm core depth) contains large (> 1 cm) disarticulated mollusc fragments and some faint evidence of burrows (Fig. 4). Ooid Sand Layer II (12–37 cm) contains no large mollusc fragments and no evidence of burrowing. Ooid Sand Layer III is the surface sand unit presently migrating as megaripples. No layering within the ooid sand units is recognized in megascopic examination of the split core, polished sections (Fig. 4), or microscopic examination of thin sections (Fig. 8).

The contact of Ooid Layer I with the underlying lagoon sediment is gradational over a 20-cm interval with obvious burrows (1 to 1.5 cm diameter) which individually can be traced up to 10 cm (Fig. 4). In contrast, the contacts with the mud layers (see below) are basically sharp with no evidence of burrowing, although angular, blocky mud clasts (up to 2 cm diameter) are found floating in the sand matrix up to 8 cm from the nearest mud layer (Fig. 4).

Lime Mud (I: 37-45 cm; II: 0-12 cm Core Depth).—Two mud layers, 8 and 12 cm thick, are interbedded with ooid sands (Fig. 4). The mud is tan to white, contains approximately 69% mud-sized material (≤ 63 μm, by sieve), and is poorly sorted (3.2 ϕ; Fig. 5). Gentle sieving confirms that some of this sediment is pelleted to sizes > 63 μm, and pipette analysis coupled with SEM and petrographic examination confirms the finding of Dill et al. (1989) that much of the mud is comprised of coarse-silt sized pellets.

TABLE 1.—*Petrographic results (%)*

Location	Mud	Ooids	Forams	Algae	Molluscs	Peloids	Others
Lee Stocking							
Lagoon	32.5	0.0	13.0	9.5	10.5	31.5	3.0
Ooid Layer I	0.0	65.0	3.5	6.5	3.5	18.5	1.5
Ooid Layer II	0.0	66.0	8.5	3.0	3.5	16.5	2.5
Ooid Layer III	0.0	75.0	6.0	2.5	1.5	11.5	3.5
Mud Layer I	99.0	0.0	1.0	0.0	0.0	0.0	0.0
Mud Layer II (homogeneous)	98.0	0.0	2.0	0.0	0.0	0.0	0.0
Mud Layer II (layered)	33.0	0.0	16.0	0.0	1.0	48.0	2.0
Joulters Cays							
Ooid layer	0.0	66.0	2.5	0.0	1.5	24.5	4.5
Mud layer	52.3	4.7	0.0	0.0	0.0	43.0	0.0

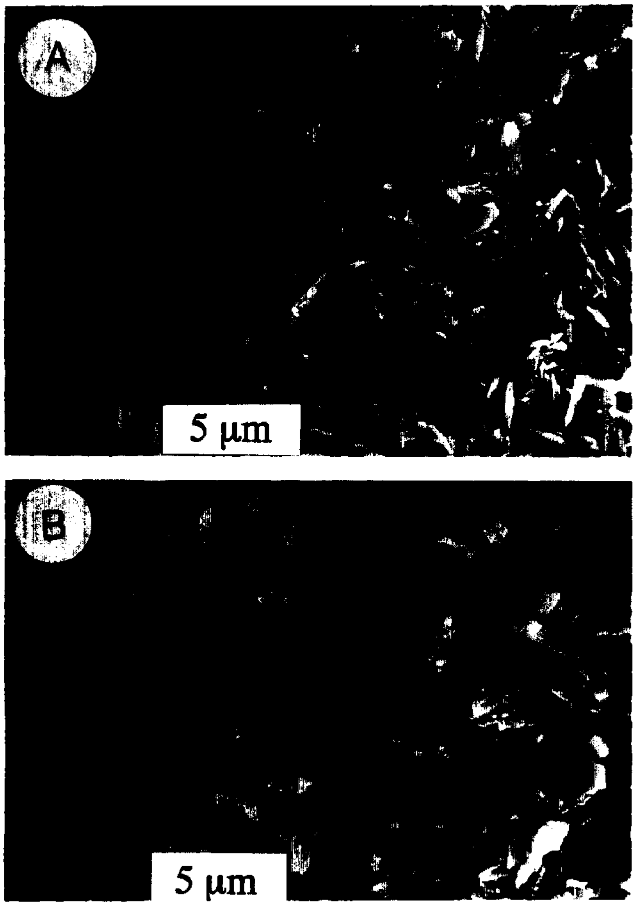


FIG. 7.—SEM photomicrographs of unconsolidated mud from the core from the channel north of Lee Stocking Island. **A)** Mud from the mud layers is comprised of long needles (10 by 0.5 μm), suggesting that the origin of the mud is dominated by a single aragonite source. XRD analysis shows that this mud is comprised of 80% aragonite. **B)** Mud from the lagoonal section of the core is comprised of a mixture of short, stubby "needles" and longer needles. This composition probably represents a mixture of sources of mud. XRD analysis indicates that this lagoonal mud is comprised of high-Mg calcite (50%) and aragonite (50%).

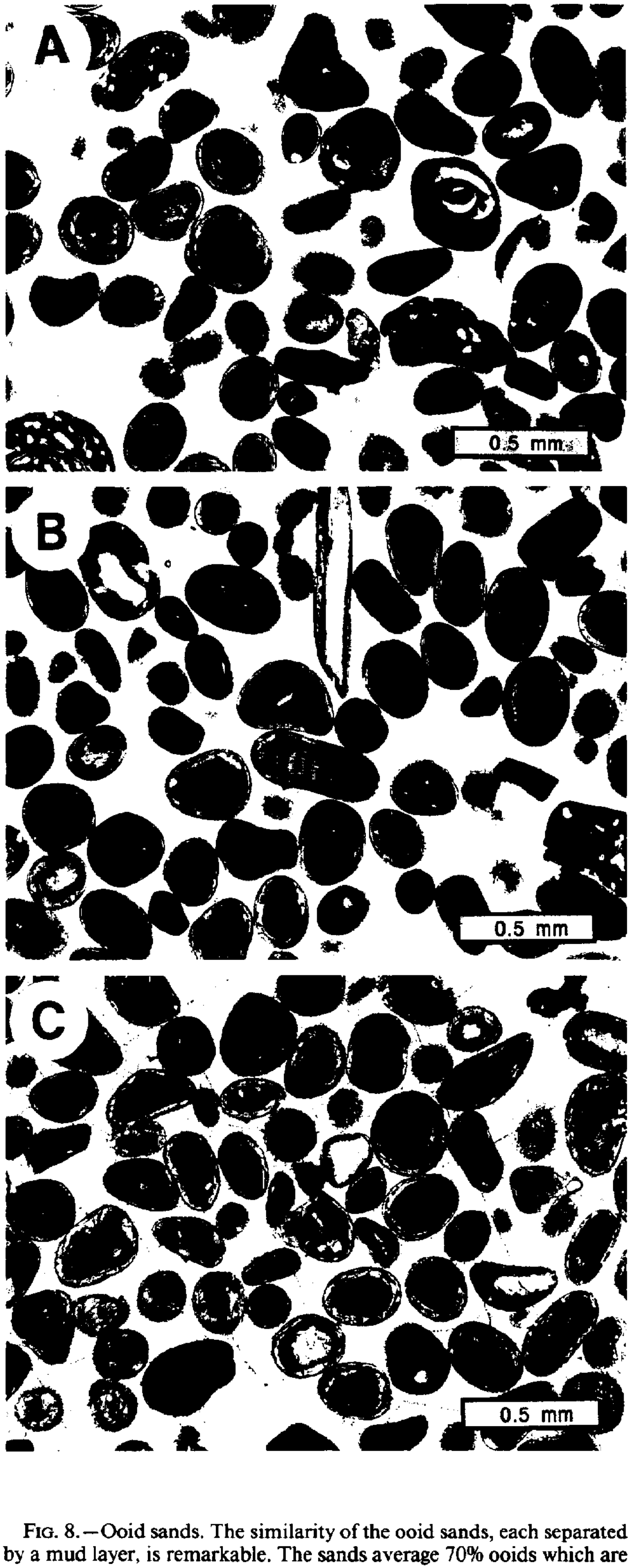


FIG. 8.—Ooid sands. The similarity of the ooid sands, each separated by a mud layer, is remarkable. The sands average 70% ooids which are about 0.3 mm in diameter. The nuclei are mostly cryptocrystalline (peloids), and the number of laminae is usually less than than 3. **A)** Ooid Sand Layer I. This layer contains large mollusc fragments floating in an ooid sand matrix. The other ooid sand layers lack mollusc fragments. **B)** Ooid Sand Layer II. **C)** Ooid Sand Layer III.

The mud is mostly homogeneous with sharp lower and upper contacts with the enclosing ooid sand (Fig. 9A, D). The petrography of the homogeneous mud of both layers reveals that it contains 98% mud and 2% foraminifera (Table 1; Fig. 9B). Small, blocky, angular mud clasts (up to 1.5 by 3 cm) are found at the upper and lower boundaries of the mud layers (Fig. 4) and extend for a few centimeters into the enclosing ooid sands below Mud Layer I (37–45 cm). The space between clasts (a few mm) is filled with ooid sands (Fig. 9A), and the outer edges of the clasts are partially cemented (Fig. 9E).

Mud Layer II (0–12 cm core depth) contains a light tan, finely laminated portion 2 cm thick at the base of the mud layer (Fig. 9A), but there are no other laminated beds in this mud layer as have been found by Dill et al. (1989). Petrographic examination indicates that 81% of the laminated section is comprised of mud (48% pelleted/aggregated needles and 33% non-pelleted; Figs. 7B and

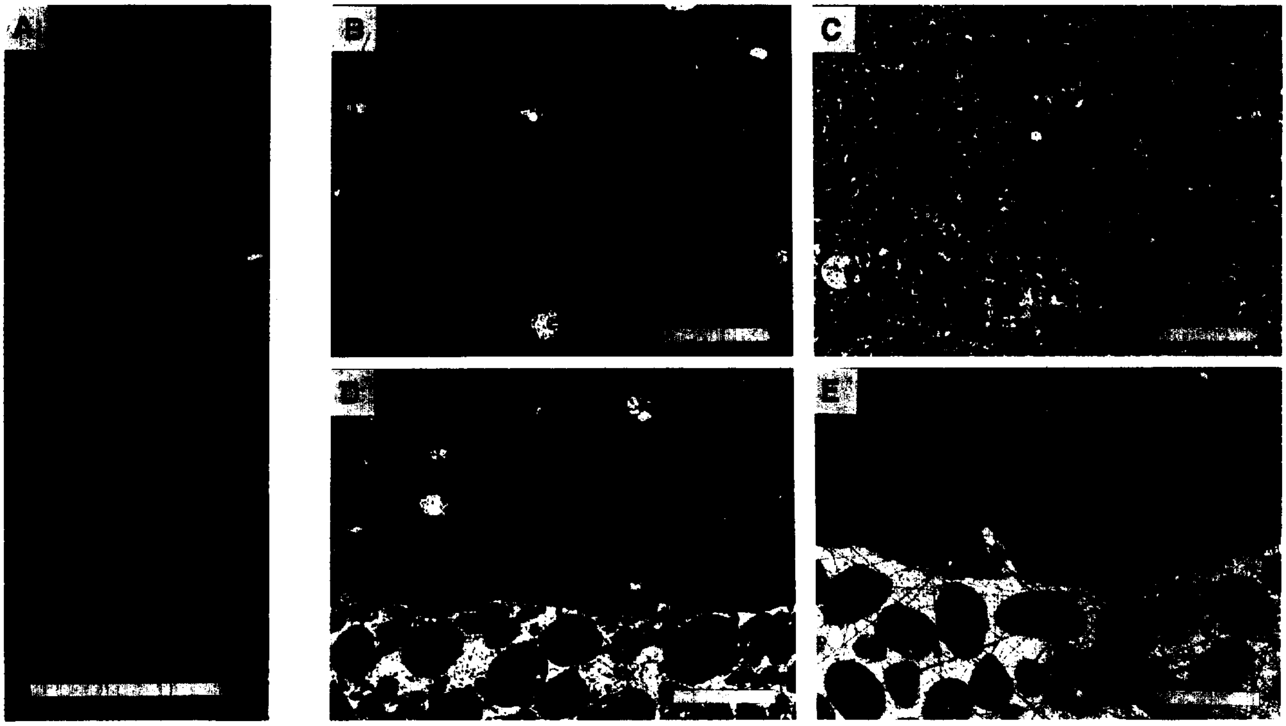


FIG. 9.—Mud layer. A) Polished slab of a plastic impregnated section of a mud layer (0–12 cm core depth.) The mud is mostly homogeneous, although the lower portion contains very thin laminations (< 1 mm thick). The contacts with the enclosing ooid sand units are sharp. Angular mud clasts up to 2 cm across are separated from each other by thin (0.5 cm or less) sections of sand. Cracking of the homogeneous mud occurred during drying prior to impregnation. B) The homogeneous portion of the mud layer contains 98% mud. C) The laminated portion of the mud layer contains 81% mud in the form of peloids (48%) and matrix (33%). Laminae of silt-sized peloids are approximately 0.5 mm thick. D) Contacts of the mud and ooid sands are sharp. Little mixing or blending of textures is seen. E) Mud clasts at the contacts of the mud layers are angular and show evidence of cementation along the outer surface.

9C; Table 1). The remainder of the laminated portion is comprised of foraminifera (16%), molluscs (1%) and miscellaneous grains (2%).

The mineralogy of the sieved mud fraction (< 63 μm) in both mud layers is 80% aragonite (versus ≈52% for the lower, lagoonal mud; Fig. 5). SEM examination shows that the mud from the layers is comprised primarily of aggregated elongate needles (0.2 by 10 μm), which is markedly different from the mud of the lower, lagoonal unit (Fig. 7).

The mineralogy (80% aragonite) and SEM characteristics of mud chips scattered in the trough and in nearby areas are similar to the mud layers. A C-14 age of one of the chips (590 ± 60 Y.B.P) is statistically identical to that of the upper mud layer (560 ± 90 Y.B.P.; Fig. 10). These data support the idea suggested by Dill et al. (1989) that the mud chips result from erosion of the exposed mud layer.

ORIGIN OF MUD

The origin of lime mud is controversial, and the evaluation of the lime mud in this core allows a critical comparison of the ideas concerning lime mud genesis. Based on megascopic descriptions, texture, grain composition, mineralogy and petrographic examination, we believe that the mud in the lowest portion of the core originated by skeletal breakdown in a normal-marine lagoon setting. However, we do not believe that the mud in the two upper mud layers (nor the mud in the mud chips) originated in a normal-marine lagoon. Rather, much of the evidence suggests that this mud is similar to that from areas west of the tidal flats of Andros Island, Bahamas, and formed in part by inorganic precipitation.

Normal Marine Lagoonal Muds

A normal marine lagoonal community is likely to contain a variety of organisms and to produce abundant high-Mg calcite in addition to aragonite mud by breakdown of larger skeletal fragments (Humm 1964; Land 1970; Bosence et al. 1985; Nelson and Ginsburg 1986; Andersen et al. 1988; Colby and Boardman 1989). Lime muds in lagoons which generally maintain a normal-marine salinity (near 36‰), have a mixture of aragonite, high-Mg calcite and calcite in the proportions of about 5:4:1 (e.g., Bosence et al. 1985; Colby and Boardman 1989). Comparisons of potential production and sediment accumulation have conclusively proven that in some areas there is more than enough biogenic production of lime mud (Stockman et al. 1967; Neumann and Land 1975), and no need exists for another important source. Further,

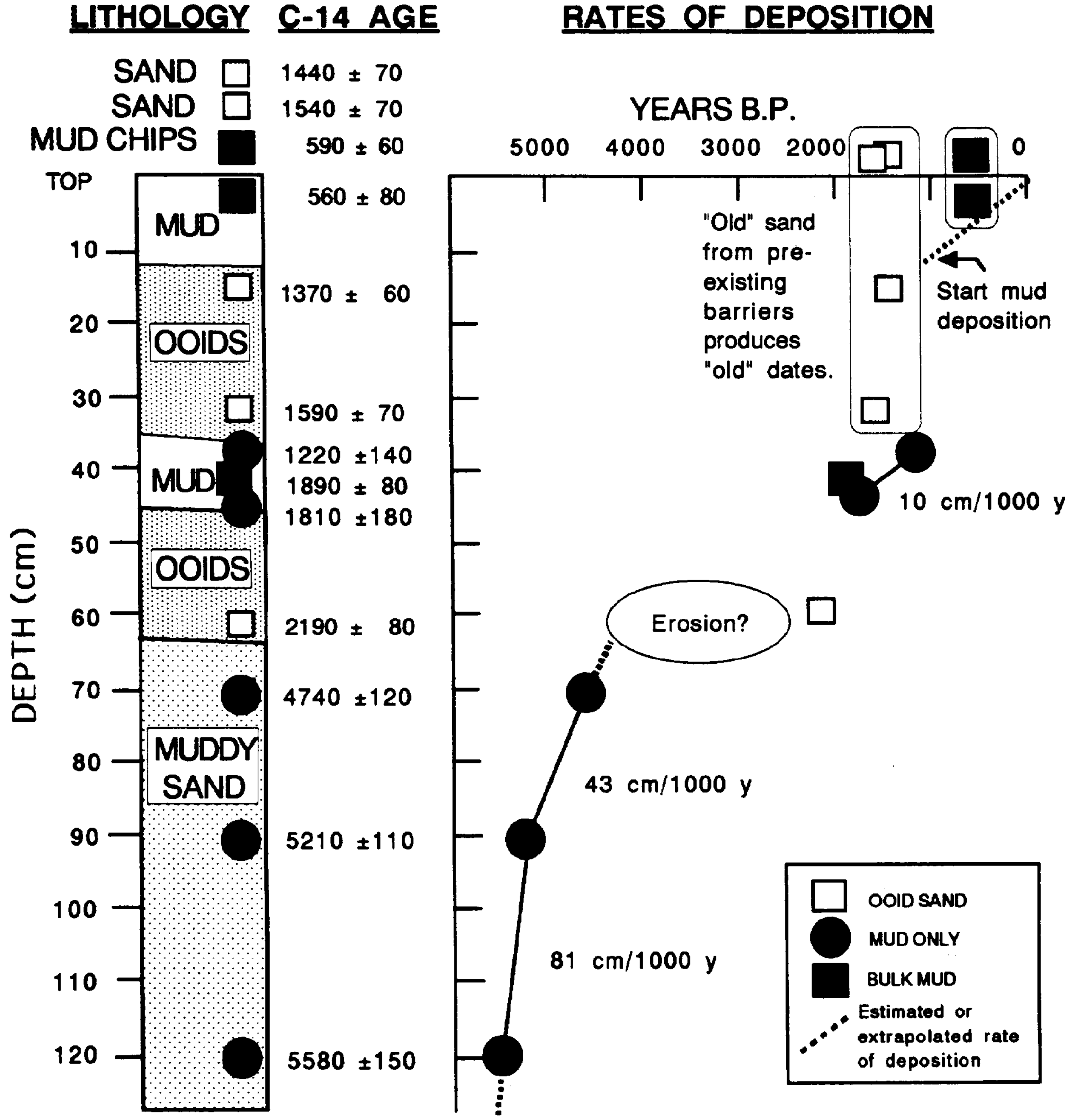


FIG. 10.—Lithology of Lee Stocking core, C-14 dates, and rates of deposition. C-14 dates of the lagoon section are in stratigraphic order and suggest deposition rates of 43 to 81 cm/1000 yr (solid lines). A major gap in time between the 4740 Y.B.P. date at 70 cm and the 2190 Y.B.P. date at 60 cm may be the result of erosion of the upper portion of the lagoon section and deposition of a much younger (ooid) sand directly on an older lagoon sediment. The dates of the mud from the mud layer (38–45 cm core depth) suggest a rate of deposition of 10 cm/1000 yr (solid line) and a duration from 1900 to 1100 Y.B.P. The sand dates overlying this mud layer as well as the dates from the surface ooid sands are not in stratigraphic order and reflect a mixture of sand sources. The bulk mud dates of the upper mud layer and mud clasts show that the area was a quiet-water environment until very recently. Using the rate of deposition determined for Mud Layer I (10 cm/1000 yr), we estimate that deposition of Mud Layer II (which is 12 cm thick) began 1200 Y.B.P. and continued until very recently (dashed line). Thus, there is an estimated overlap of the times of deposition of the mud layers, and the available time for deposition of Ooid Sand Layer II separating the two mud layers was "short" (−100 years!). The resumption of the present ooid sand environment of deposition probably began very recently.

SEM studies of silt-sized carbonate grains have clearly shown the biogenic origin of many of these grains (Stieglitz 1972; Boardman 1976).

Mud from Stressed Marine (High-Salinity) Environments

Biogenic.—Where environmental parameters create stressed conditions such as high salinities (> 50‰), the production of lime mud is likely to be different from that of a normal marine, shallow-water, vegetated environment. The mineralogy of the lime mud may be modified, because the assemblage of organisms or relative production of lime mud by organisms is altered. In the Persian Gulf, for example, high salinity (> 50‰) is associated with the absence of corals and green algae (major sources of aragonite), yet benthic forams (a source of high-Mg calcite) are still abundant (Wagner and van der Togt 1973). These conditions should produce a sediment poorer in aragonite such as the imperforate foraminiferal/gastropod mud (20% aragonite, 50% high-Mg calcite, 30% calcite) common in shallow, protected embayments in the Persian Gulf (Wagner and van der Togt 1973, p. 149). In portions of Florida Bay (a partially enclosed lagoon) salinity fluctuates around the seawater norm of 36‰ (22–30‰ in December 1953 to 46–52‰ in August 1957), and the percent aragonite (average ≈63%; range = 40 to 100%; Ginsburg 1972) is different from that of other lagoons with a more normal and constant salinity.

Inorganic.—A lime mud accumulation rich in aragonite (ca. 80%), therefore, is unlikely to be produced from a biogenic source, and in some areas inorganic precipitation may be an additional source of carbonate mud (Cloud 1962; Shinn et al. 1989). In fact, an inorganic origin of lime mud in modern high-salinity environments is likely. The evidence is overwhelming that the shallow banks of the Great Bahama Banks (salinities measured up to 50‰; Bathurst 1971) are supersaturated with respect to all major carbonate minerals (Morse et al. 1984), and inorganic production of lime mud is possible. Studies of the mineralogy of whitings from the Great Bahama Bank indicate that the mud is dominated by aragonite (average 86%) and can have up to 20% high-Mg calcite (Shinn et al. 1989). Proponents of an inorganic origin point to "whitings" as evidence of lime mud precipitation, and geochemical studies of whitings and associated waters and sediment partially support an inorganic origin (Steinen et al. 1988; Shinn et al. 1989).

The difficulty of distinguishing between an inorganic and biogenic origin of lime mud by direct analysis of the muds themselves is unfortunate. SEM studies designed to determine the origin of aragonite-rich, needle muds are as yet inconclusive. The skeletal microarchitecture of most biogenic carbonates is based on "needles", and the critical examination and distinction of needles of different origins is still inadequate. Isotopes of carbon and oxygen and trace element signatures (Sr, Na, Mg) of lime muds have been studied, but there is little conclusive evidence that the difference between inorganic and biogenic lime muds is sufficient to distinguish these two sources (Lowenstam and Epstein 1957; Matthews 1966; Boardman and Neumann 1986; Steinen et al. 1988; Shinn et al. 1989).

Summary of Mud Origins in the Lee Stocking Core

It is clear that the mud from the mud layers is different in texture, mineralogy, petrography, and SEM characteristics from that of the underlying lagoonal muds. The mud in the ooid tidal channel, then, is apparently of two origins. The mud in the lower unit of the core is part of a normal-marine lagoonal sediment accumulation. This mud is associated with a normal-marine lagoonal assemblage of allochems, including whole and unabraded mollusc and foraminiferal skeletons and a normal marine mollusc species assemblage. The mineralogic signature of the mud fraction reflects multiple (biogenic) sources, and the sediment is obviously bioturbated. For these reasons, we believe the mud in this section of the core is derived from the breakdown of biogenic precursors.

The mud in the two mud layers in the upper part of the core and in the mud chips is not derived from a normal-marine lagoon but rather from a stressed marine environment similar to the subtidal environment west of Andros Island. The lack of normal-marine lagoonal fossils or fragments in the mud and limited evidence of bioturbation suggest that the environment was harsh—too harsh for many normal-marine organisms to flourish. The high proportion of aragonite in this mud (ca. 80%) and subordinate amount of high-Mg calcite (ca. 20%) suggest that it did not originate entirely from breakdown of biogenic precursors but is likely to have formed by inorganic precipitation in a manner reported elsewhere on Great Bahama Bank (Shinn et al. 1989).

ENVIRONMENTS AND HISTORY OF DEPOSITION

By combining the suspected origin and C-14 age dating of sediments with the Holocene history of banktop flooding of Bahamian platforms (Boardman et al. 1989), the history of deposition and environments of deposition of the ooid tidal channel can be reconstructed. Thirteen C-14 analyses of the mud layers, mud chips, ooid sand layers and lagoon sediments reveal that the sequence is in stratigraphic order and that the sand-sized material has been excavated and remobilized (Fig. 10).

In general, C-14 ages of carbonate sands (especially ooid sands) are not reliable indicators of the time of deposition, because bulk dates may result from a mixture of several carbon sources. Sand may be buried for hundreds or thousands of years and then exhumed and added to newly-formed sand. For example, exhumation and erosion of beaches, strand plains and eolian dunes are common in the Bahamas (Harris 1979; Strasser and Davaud 1986; Boardman et al. 1987). For ooids, there is an additional concern because the ooid cortex clearly postdates the nucleus and contains laminations of different ages (Martin and Ginsburg 1965). Dates from ooid sands are always "old" (620 to 3720) in the shoal, beach and dune portions of Joulters Cays, Bahamas (Harris 1979; Halley and Harris 1979), Turks and Caicos Islands, BWI (Lloyd et al. 1987) and Lee Stocking (this paper, Fig. 10).

Lagoon Deposition

The lower lagoonal sediment was deposited beginning about 5500 Y.B.P. in a normal marine, shallow-water environment with moderate energy in water depths of a few meters (Fig. 11). There must have been some barrier to the east (Fig. 12A) to permit the accumulation of approximately 44% mud. The environment of deposition was probably similar to that of other Bahamian lagoons which have about 50% mud composed of about half aragonite and half high-Mg calcite.

Based on the C-14 dates and the depth intervals separating them, the average rate of deposition of sediment within the lagoon was 60 cm/1000 yr (Fig. 10), which is comparable with other Bahamian lagoonal sediments (Boardman 1976; Colby and Boardman 1989; Andersen and Boardman 1989). The rate of deposition of the upper portion of this lagoon section (90–70 cm) is 43 cm/1000 yr, less than the rate of deposition during the early stages of lagoon filling (120–90 cm) which is 81 cm/1000 yr. By extending these rates to the ends of the section, this lagoon (65 cm thick) persisted for approximately 1100 yr (5700 to 4500 Y.B.P.; Fig. 10). Water depth at this time was between 1 and 3 m below sea level (Fig. 11). During this time, the environment was certainly not a high-energy channel similar to the one present today.

Initial Ooid Sand Deposition
(Ooid Sand Layer I)

The transition to a high-energy, ooid sand environment of deposition occurred between 4500 and 2190 Y.B.P. The lagoon-ooid sand contact is gradational over approximately 20 cm and is highly burrowed, suggesting that the ooid sand prograded over the lagoon while burrowing organisms were active. Biologic activity is supported by the presence of numerous large bivalve fragments. The water depth at this time was 4.5 m (and sea level was 0.5 m lower than present (Figs. 11 and 12B).

A bulk sand date of 2190 ± 80 Y.B.P. is quite a bit younger than the uppermost date of mud from the lagoon sediment (4740 Y.B.P.; Fig. 10), and it is likely that the 2550-year interval included erosion of the lagoonal unit or a period of slow deposition prior to the onset of conditions producing Ooid Sand Layer I. The composition of the sand from this layer (predominantly ooids) is markedly different from the underlying lagoonal sediments (predominantly skeletal fragments; Table 1), so the sand in Ooid Sand Layer I is not simply a lag of winnowed lagoonal sediment.

Cessation of lagoonal deposition and initiation of ooid sand deposition certainly reflects a change of energy. A seaward barrier such as a Pleistocene topographic high (sill) or an early Holocene barrier such as a beach or dune system may have been breached (Boardman 1976; Boardman et al. 1986, 1987; Colby and Boardman 1989). Alternatively, sea level may have risen enough to flood large portions of the banktop, thus generating larger volumes of water involved in tidal exchange and greater tidal currents.

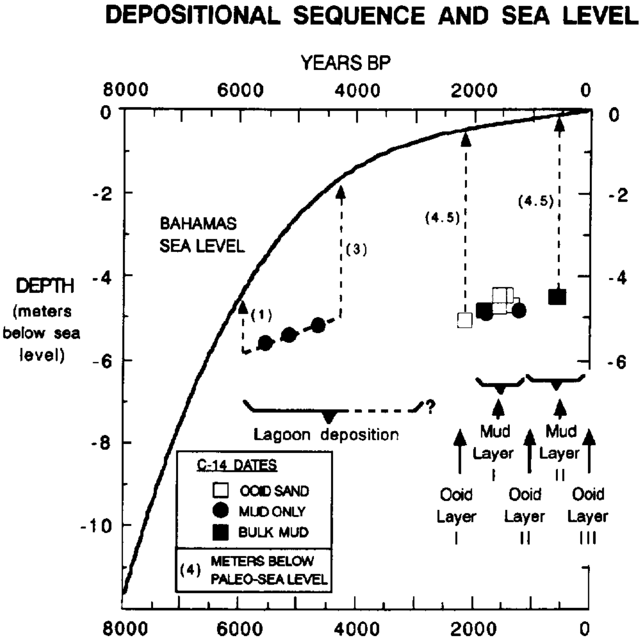


FIG. 11.—Sea level and depositional sequence in Lee Stocking channel. All of the sediment in the Lee Stocking channel was deposited in a subtidal setting, including the mud layers. Although it contains sediment which could be interpreted as intertidal muds and ooids overlying a subtidal lagoon, this sequence is an example of deepening-upwards rather than shallowing-upwards deposition. Paleo-water depths are shown in parentheses. The nearly continuous accumulation of mud is contrasted with the deposition of ooid sands, which have C-14 ages which are not in stratigraphic order. The sea-level curve is from C-14 dates of peat on Pleistocene bedrock from Bahamian localities (Boardman et al. 1989).

First Lime Mud Layer (Mud Layer I)

The first mud layer in the Lee Stocking Island channel formed about 1500 years ago (C-14 ages of 1890, 1810 and 1220 Y.B.P.; Fig. 10) in water depths of about 4–5 m (Figs. 11 and 12C). Thus, during the time of mud accumulation, the site of deposition was subtidal.

The presence of mud layers in this tidal channel is problematic, as recognized by Dill et al. (1989). One possibility is that the mud (inorganically precipitated or biogenically produced?) was transported from the nearby lagoon during a storm and settled in the tidal channel during slack tide (Kendall and Dill 1987; Dill and Steinen 1988; Dill et al. 1989; Shinn et al. 1989). Transport of fine sediment from lagoons to offbank (periplatform) regions is documented by direct observations (Ball et al. 1967; Perkins and Enos 1968), comparisons of lagoon production and accumulation (Neumann and Land 1975), and examination of the periplatform sediment (Boardman and Neumann 1984; Wilbur et al. 1990).

Today the channel where the core was taken is 4–5 m

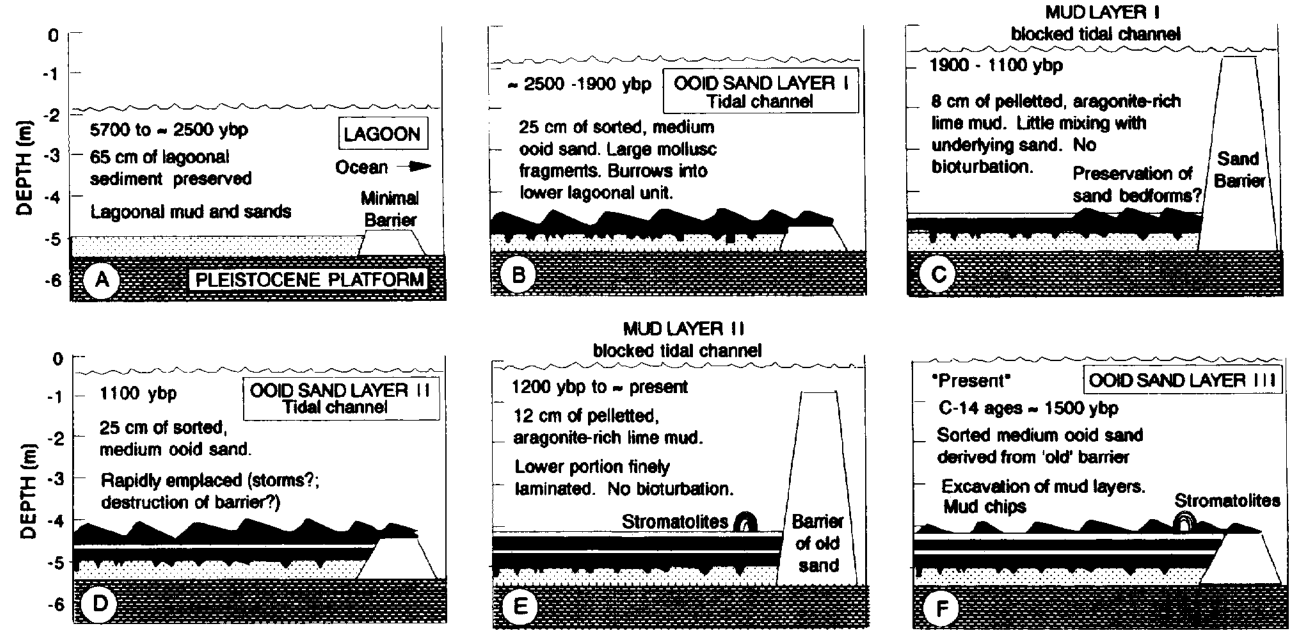


FIG. 12.—History of deposition of Lee Stocking tidal channel. A) Lagoon deposition. A minimal energy barrier permitted accumulation of 50% mud. This barrier may have been a topographic high or other energy-restricting condition. B) Ooid Sand Layer I. This ooid sand may have accompanied or caused erosion of the upper lagoon sediment. C) Mud Layer I. A sudden and significant reduction in energy is indicated. An energy barrier may have been comprised of ooid sands. D) Ooid Sand Layer II. The ooid sand may be the remains of the energy barrier existing when Mud Layer I was accumulating. Ooid sand deposition was a short-term event. E) Mud Layer II. An energy barrier was re-established, permitting accumulation of mud. At some point, stromatolites began to form. F) Ooid Sand Layer III. The dates of this actively moving ooid sediment are ≈1500 Y.B.P. Mud layers are being exhumed and eroded, mud chips created and dispersed, and stromatolites buried and exhumed.

deep, has tidal currents up to 100 cm/s, and the period of slack water is less than one hour (Dill et al. 1989). If settling of lagoonal detritus took place following a storm event, one might expect 1) some evidence of graded bedding (none was noted), 2) mixing of ooid sands with the mud (none was noted), 3) the inclusion of skeletal debris from the nearby lagoon (none was noted), and 4) a uniform age of the sediment layer (rather than a 600-yr spread of ages). The texture, composition, structures and ages, then, are not those expected for a high-energy event. Also, there should be very little fine mud (less than 10 μm), yet abundant fine mud and pellets are seen petrographically (Fig. 9). If this is indeed a high-energy deposit, it certainly is unusual and requires a more complete explanation.

Using Stokes law for settling of fine (solid) particles, it takes a 20-μm size particle almost 3 hours and a 10-μm size particle 12 hours to settle 5 m. The fine mud found in the layers could certainly not have been deposited as individual particles during a slack tide. Measurements of settling rates and possible accumulation of mud from natural carbonate systems (Shinn et al. 1989) reveal that mud in whitings are aggregated into sand and silt-sized particles which still take hours to settle. Settling of mud, then, even as aggregates should take longer than the one-hour interval available during slack tide. But some mud certainly settles.

Sediment traps in areas of active whitings recorded sedimentation rates up to 35 g/m^2/hr (Shinn et al. 1989). Thus, in one hour each cm^2 could accumulate 0.0035 g of solid carbonate, most of which is aragonite. Using 2.9 g/cm^3 as the density of a mud which is 80% aragonite and 20% calcite, this 0.0035 g of sediment would add 0.0012 cm (rate/density) of pure solid, and using 70% as an estimate of the porosity of carbonate mud (Enos and Sawatsky 1981) this 0.0012 cm of solid would accumulate 0.004 cm of sediment. A one-hour settling interval with the sedimentation rate measured by Shinn et al. (1989) is hardly enough to account for the several centimeters thick mud units.

Shinn et al. (1989) also report concentrations of suspended sediment up to 2 g/l (0.002 g/cm^3). If the entire water column of the channel (500 cm deep) were filled with this suspended sediment and if all of it (500 cm × 0.002 g/cm^3 = 1 g/cm^2) were able to settle in about one hour, the total vertical accumulation (using 70% porosity and 80% aragonite) would be 1.1 cm. A single whiting (with the most concentrated suspension reported by Shinn et al. 1989) has insufficient suspended sediment to cause the accumulation of the several centimeter thick mud layers. Neumann and Land (1975) report one suspended sediment concentration (during a storm) of 8.5 g/l. This concentration of sediment (a mixture of clay, silt, and sand) would accumulate approximately 4.7 cm of sediment. While this is closer to the thickness of mud layers found in tidal channels, the observed suspended sediment contains a mixture of sediment sizes including sand. Certainly, graded bedding would be expected, and none was found in the mud layers from Lee Stocking Island.

Even if mud aggregates are formed and deposited in a short time, the ensuing high-velocity tidal currents would surely winnow this uncompacted, newly deposited mud layer during the succeeding few days. Dill et al. (1989) report that the mud pellets are up to 50 μm in diameter and suggest that the mud aggregates are hydrodynamically similar to the smaller ooid sands. Our analysis of the ooid sands shows that the ooids are 300 to 500 μm in size and fairly well sorted (1.9 ϕ), so pellets of 50 μm are not hydrodynamically similar to the ooids, even if formed and deposited, such pellets should be winnowed from this high-energy environment.

Instead of a single, short-lived, high-energy event, the mud in the layers might have been deposited in a quiet-water, restricted environment over an extended period of time or by repeated transport of lime mud into an already restricted channel. The major requirement for accumulation of lime mud is extraordinarily calm energy conditions, and low-energy environments usually result from physical protection from winnowing by waves and currents. Modern sediments with high proportions of lime mud (> 70% mud) are only reported from some tidal flat deposits (Shinn et al. 1969; Hardie and Shinn 1986) and portions of some lagoons (e.g., Cloud 1962; Ginsburg 1972; Boardman 1976). Most other lagoons, even those with dense growth of seagrass, do not contain such high concentrations of mud (Colby and Boardman 1989; Miller 1988; Andersen and Boardman 1989; Boardman et al. 1990).

To produce this vertical succession of an abrupt transition from an ooid tidal channel environment (high-energy) to a lime mud depocenter (quiet-water environment), the close lateral association of an environment accumulating lime mud and an ooid sand shoal must be considered. A close lateral association of ooids and mud is unlikely. Modern ooid sand shoals are not in direct lateral contact with environments of significant mud accumulation (Gebelein 1974; Hine 1977; Harris 1970; Halley et al. 1983). The ooid shoal of Joulters Cays is located nearly 25 km from the mud tidal flats and pelleted subtidal muds of Andros Island, separated by broad areas of muddy sands and sandy muds (Gebelein 1974). The "tidal flat" subenvironment on Joulters is not a mud tidal flat and contains only 7% mud (Harris 1977). Near Lee Stocking Island, the closest muddy tidal flat is located on Exuma (≈10 km to the south; Kendall and Dill 1987, Dill et al. 1989). The Bahamian ooid shoals and deposits of Schooner Cays, southern Tongue of the Ocean, Lily Bank, Cat Cays and Turks and Caicos Islands are not situated adjacent to muddy environments (Hine 1977; Dravis 1979; Palmer 1979; Lloyd et al. 1987), and the ooid shoals of the Persian Gulf are also located far from environments in which high proportions of mud accumulate (Purser and Evans 1973; Loreau and Purser 1973; Wagner and van der Togt 1973).

Alternatively, rapid changes of environment of deposition might have occurred. Today the channel is a high-energy environment, but as in many high-energy environments with abundant wave energy and an abundant sand supply, sand movement can create barriers and choke inlets (by spit accretion, for example). We suspect that in order to form the mud layers in this ooid tidal channel, the tidal channel must periodically be closed off (partially or completely), perhaps by longshore transport and spit migration. Substantial movement and subaerial accumulation of oolitic sands (such as spit elongation, eolian dunes and strand beaches) are reported associated with the longshore transport of the ooid sands of Joulters Cays (Harris 1979), Turks and Caicos Islands, Bahamas (Lloyd et al. 1987) and the southern Persian Gulf (Loreau and Purser 1973; Purser and Evans 1973).

Spit elongation and channel blockage may have occurred in the Lee Stocking channel as well. Such sand migration would create a quiet-water environment for mud accumulation, and the restricted water conditions could permit (cause) the precipitation of aragonite as an inorganic sediment. The aragonite-dominated, silt-sized mud aggregates are similar to the sediment described from the lower-energy interior of Great Bahama Bank (Cloud 1962; Shinn et al. 1989; Wilbur et al. 1990). When the channel reopened or became more energetic, sand wave migration entombed the mud layer. Destruction of the barrier and opening of the channel to form a high-energy ooid sand unit must have been rapid because the upper contact (mud to ooid) is sharp.

The C-14 ages of the mud from the mud layer are in stratigraphic order and span nearly 600 years (Fig. 10). A single storm or precipitation event would not deposit a layer of mud with this C-14 age structure. This observation, along with the other data, suggests that the environment of deposition was biologically harsh and inimical to many organisms including those responsible for bioturbation. The rate of deposition for this mud layer is 10 cm/1000 yr; thus this 8-cm-thick mud layer represents approximately 800 yr of mud deposition from ≈1900 to 1100 Y.B.P. (Fig. 12C).

Second Ooid Sand Deposition (Ooid Sand Layer II)

Above the first mud layer (just described) are ooid sands (12–37 cm core depth). No lamination within the ooid sand is evident, suggesting rapid emplacement, and the composition of the sand is identical to that of the other sand units. Thus the environment of deposition of this unit was likely similar to that of the preceding oolitic unit (Ooid Sand Layer I), although the burrowing into the underlying unit is absent.

The average age of these ooid sands is nearly identical to the average age of the underlying mud (Fig. 10). This similarity may indicate that the ooids and the mud were forming at about the same time, the ooids being transported to the site of mud accumulation after the mud was deposited (after 1100 Y.B.P.). The C-14 ages of the ooid sands of the second ooid sand unit are unlikely to be a good estimate of the time of deposition. The dates of Ooid Sand Layer II are statistically similar to each other, and the fact that they are in stratigraphic order (Fig. 10) may be coincidental or may suggest that a greater amount of younger material was added later in the accumulation of the ooid sands and that mixing (mechanical or biological) was incomplete in these high-energy sands. Exactly where the sand was accumulating during the time of mud deposition (1900–1100 Y.B.P.) is uncertain. However, if the mud were forming behind a sand spit barrier, it is reasonable that the ooid sands were part of that barrier. Growth of the spit and obstruction of the channel must have been rapid, because the transition from ooid to mud is sharp.

Second Mud Layer (Mud Layer II)

On top of the second ooid sand layer is another mud layer (0–12 cm core depth). This is the layer exposed in the ooid megaripple trough, so there are ooids above it as well. The characteristics of the mud are similar to the earlier mud layer, and the environment of deposition is presumably similar. The bulk C-14 age of this mud layer (at 3 cm core depth) is 560 Y.B.P. and confirms that the mud was deposited in a subtidal setting (4.5 m below sea level).

Present Conditions (Ooid Sand Layer III)

Ooid sands in megaripples are the dominant feature of this high-energy channel today. Megaripples are engulfing stromatolites, and in the troughs of some of the megaripples are mud chips and outcrops of a mud layer (Dill et al. 1986, 1989; Dill and Steinen 1988). Cemented mud chips within the channel sediment clearly form from exhumation of mud layers and exposure to rapid water movement (Kendall and Dill 1987; Dill et al. 1989). Petrographic and SEM analyses show that the surfaces of the mud lumps cement first by subtidal precipitation of aragonite (Fig. 9E). Thus, these mud chips form in a very different environment from mud chips cemented in supratidal environments such as tidal flats (Shinn et al. 1969; Lasemi et al. 1989). Bulk C-14 ages of the oolitic sands at the surface are 1440 ± 70 Y.B.P. and 1540 ± 70 Y.B.P. which are similar to other Bahamian sediments of mixed carbon sources and from areas of active erosion and redeposition (see above). The "old" dates of these "present-day" sands are analogous to previous ooid sands. For example, Ooid Sand Layer II is older than the top of Mud Layer I (by approximately 500 years).

Duration of Barriers

Examination of the C-14 ages and the rates and times of deposition determined from them suggests that the times when the channel was as active as it is today were very short-lived (Figs. 10 and 11). Based on multiple C-14 ages, deposition of Mud Layer I ended 1100 years ago. In the subsequent 1100 yr, a sand layer (25 cm thick) and a mud layer (12 cm thick) were accumulated. Using a rate of deposition of 10 cm/1000 yr calculated from the first mud layer (Mud Layer I), we estimate that the 12-cm-thick top mud layer (Mud Layer II) represents 1200 yr of deposition (and began 1200 yr ago). The overlap of time suggests that deposition of the ooid sand layer separating the two mud layers was a relatively rapid, punctuated event (the time calculated from the C-14 dates is −100 years!) in an otherwise mud-dominated environment. Clearly there is very little time for deposition of the oolitic sand unit (Ooid Sand Layer II) separating the two mud layers.

The duration of deposition of each of the oolitic sands overlying the mud layers is remarkably short. During most of the past 2000 yr, then, the channel might have been a quiet-water, restricted environment behind an ooid sand barrier (Fig. 12). The fact that the age of the ooid sands at the surface is nearly identical to the age of the ooid sands separating the two mud layers (1540 and 1440 at the surface versus 1590 and 1370 in the ooid sand layer separating the mud layers) and that the petrography of the ooid sands are essentially identical (Table 1) is compatible with the idea that the ooid sands are part of a dynamic sand system. We suggest that the "old" dates of the ooid sands found at the surface indicate that they are derived from ooid sand of mixed ages which was laterally adjacent to the mud depocenter at the time of deposition of the mud, and that these sands likely formed a barrier that permitted mud accumulation. The abrupt cessation of mud deposition and of emplacement of ooid sands suggests that the barrier was quickly destroyed, sand was emplaced for a short time period, and then the barrier was rebuilt. The presence of mud layers up to 1 m thick in other parts of this channel (Dill et al. 1989) suggests that mud may have accumulated uninterrupted and at high rates over a long period of time. Additional coring and dating should explore this possibility. Major storms of short duration are likely to have been important in these transitions. Storm (hurricane) frequency is approximately 800 per 1000 years in the Bahamas (Hine 1977), and to initiate the two times of sand deposition recorded by the two layers of ooid sand (destroy the barrier) requires that only two major storms in 2000 years be strong enough to destroy the barrier.

Subtidal Stromatolites in Lee Stocking Channel

Based on the grain types (ooids) incorporated within the stromatolites, Dill et al. (1986, 1989) suggest that the stromatolites found in this channel grew in a high-energy environment similar to that found today, and a C-14 date of 480 ± 50 Y.B.P. from a conch shell at the base of a stromatolite was reported. However, our study suggests that during most of the last 2000 years the channel was characterized by environmental conditions conducive to precipitation and accumulation of aragonitic mud. To resolve this conflict, more research needs to be completed

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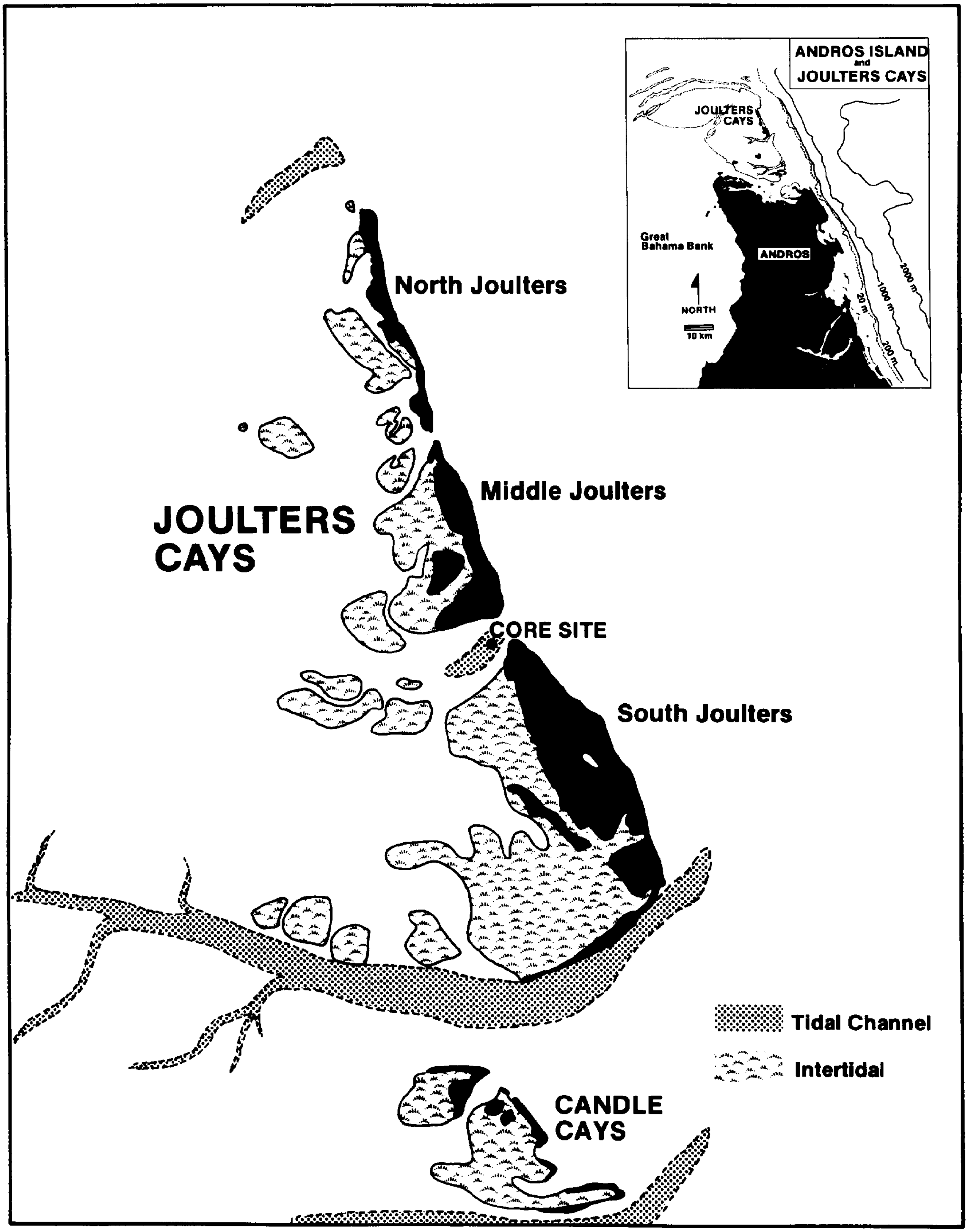
FIG. 13.—Map of Joulters Cays. The three main islands of Joulters are separated by tidal channels. Pure mud layers have been found in each of the four channels adjacent to the major islands. A short core was extracted from the channel separating South Joulters from Middle Joulters. The channel separating Middle Joulters from North Joulters is presently blocked.


ANDROS ISLAND and JOULTERS CAYS
JOULTERS CAYS
Great Bahama Bank
ANDROS
NORTH
10 km
20 m
200 m
1000 m
2000 m
North Joulters
Middle Joulters
JOULTERS CAYS
CORE SITE
South Joulters
Tidal Channel
Intertidal
CANDLE CAYS

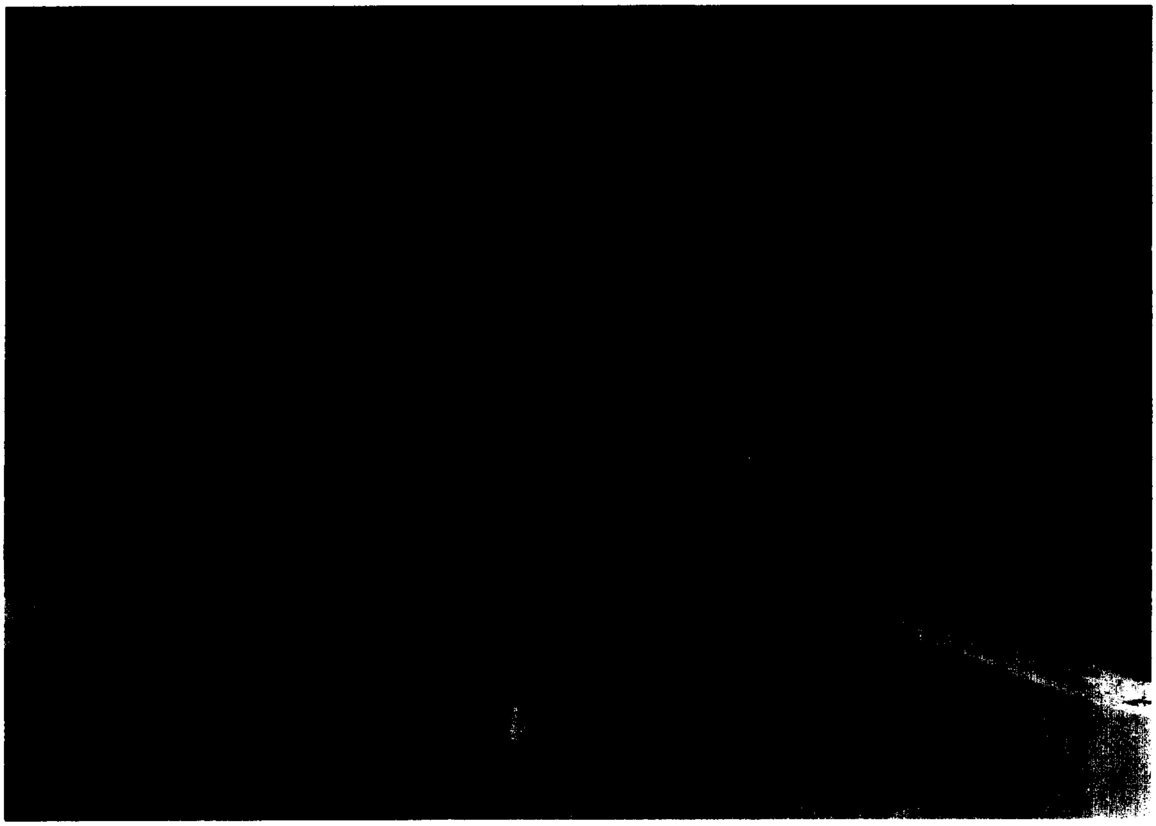


FIG. 14.—Aerial view (to west) of the tidal channel separating Middle Joulters (right) and South Joulters (left) shows the large flood tidal delta presently being stabilized by mangroves and the ebb tidal delta (foreground). The channel is being choked off by sand spit elongation caused by longshore transport of ooid sand to the north (to the right). The channel contains ooid sand megaripples. A mud layer was found in one of the megaripple troughs.

on both the mud layers and the growth of these stromatolites.

JOULTERS CAY TIDAL CHANNEL

The geography and physical conditions of the environment have been described (Harris 1977, 1979). The channel separating South Joulters from Middle Joulters (Fig. 13) is approximately 2 m deep and is partially blocked on the seaward side (east) by a spit prograding towards the north and a shallow ebb-tidal delta (Fig. 14). Ooid sands in megaripples attest that high-velocity currents periodically flow in and out of the channel. The channel ends on the platform side (west) in a shallow (< 1 m deep) *Thalassia*-bound, sand lagoon (stabilized sand flat of Harris 1979).

The presence of "layers of semicompacted lime mud" in tidal channels separating the Joulters Cays was first reported by Shinn et al. (p. 159, 1989). Bebout et al. (1990) encountered mud layers during intensive coring north of North Joulters Cay, and we have observed mud layers in 4 tidal channels at Joulters. We extracted a 16-cm sediment core from a trough of an ooid sand wave located in the tidal channel which separates South Joulters and Middle Joulters, Bahamas (Figs. 13 and 14). Scattered on the seafloor at the core site were numerous mud chips.

Facies Descriptions

Ooid Sands (10 to 16 cm and 0 to 3 cm Core Depth).—The ooid sands consist of ooids (66.5%) and peloids (24.5%) with minor amounts of aggregates, foraminifera, algae and mollusc fragments (Fig. 15A; Table 1). The ooids have thick cortices (0.1 to 0.15 mm) and are bimodal in size (0.2 mm and 0.4 mm; Carney and Boardman 1990). The allochems are well rounded and polished, as expected from this high-energy environment.

Lime Mud Layer (3 to 10 cm Core Depth).—The mud layer is 7 cm thick and is pale gray to white. Petrographic examination shows that it contains 95% microcrystalline carbonate (52% mud and 43% peloids) and 5% skeletal grains (foraminifera; Fig. 15B; Table 1). No lamination is seen megascopically, but microscopic examination shows that some of the pelleted mud is laminated. Mud-filled burrows are not observed, although a few large (up to 1 cm) burrows are filled with ooids. The mineralogy of the mud is aragonite (87%), and SEM examination (Fig. 16) shows that this mud is comprised of elongate

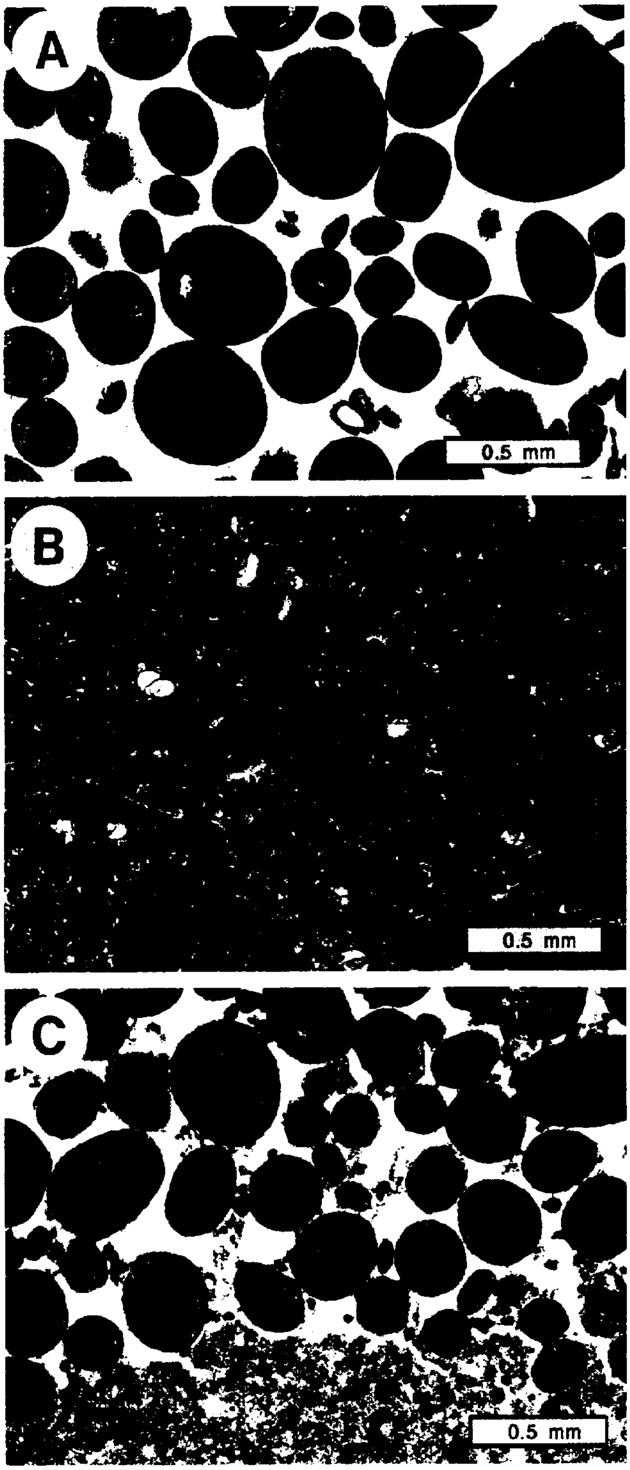


FIG. 15.—Photomicrographs of lithologies within the Joulters tidal channel. A) Ooid sands. Ooid sands contain abundant ooids with cryptocrystalline nuclei (peloids) and cortices comprised of several laminae. The sand is 90% ooids. B) Mud layer. Mud comprises 95.3% of the mud layer and is composed of silt-sized peloids (43%) which are often layered and matrix (52.3%). C) Contact of mud and ooid sands. The contact is sharp. Little blending or mixing of mud and ooids occurs.

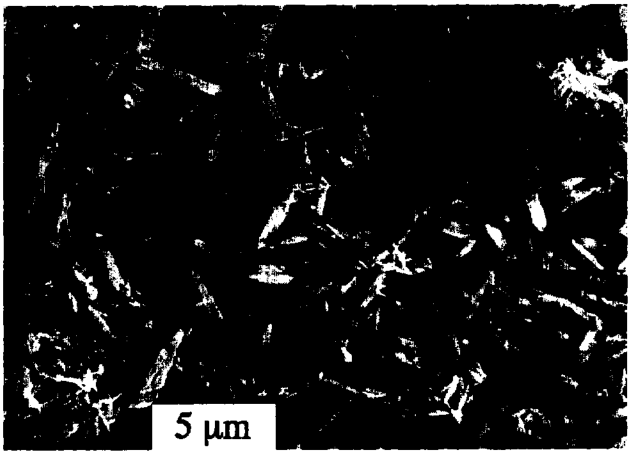


FIG. 16.—SEM photomicrograph of mud from the mud layer of Joulters Cays. This mud, like the mud from Lee Stocking Island is comprised of elongate needles and is aragonite-rich (> 80% aragonite).

needles (10 by 0.5 µm). The contact between the mud and ooid sand is sharp (Fig. 15C).

ORIGIN OF THE JOULTERS CAYS MUD

The mineralogic, textural, SEM and petrographic characteristics of the mud from Joulters Cays indicate that it is not a lagoonal unit but rather formed in a low-energy, restricted environment. This mud is indistinguishable (texture, composition, mineralogy and SEM characteristics) from the mud from the mud layers of Lee Stocking channel and probably had a similar origin. Petrographic analyses, however, show that all mud from the Joulters samples are pelleted, whereas only one portion of the mud layer from Lee Stocking Island is pelleted.

In a perspective on inorganic precipitation of lime mud, Shinn et al. (p. 159, 1989) suggest that lime mud in channels at Joulters probably results from transport of lagoonal mud from the platform to the channel during storm events. However, based on SEM photos Harris (p. 110, 1977) reports that the lagoonal mud around Joulters is primarily derived from biogenic breakdown products. The mud in the mud layers does not contain significant quantities of particles of certain biogenic origin, and the mineralogy of the mud in the mud layer (87% aragonite) is significantly different from the mineralogy of muds from nearby environments (stabilized sand flats, tidal deltas, channels, tidal flats, offshore areas) which average 53% aragonite (average of 21 samples). Thus, we suggest that the mud did not accumulate by simple winnowing of the nearby sediment and transport to the channel. Instead, the presence of the mud in this high-energy channel is likely a result of a previous low-energy situation and inorganic precipitation and aggregation, as suggested by Shinn et al. (1989) for other parts of Great Bahama Bank. C-14 ages of this mud layer are 420 Y.B.P. (9-cm core depth) and 240 Y.B.P. (3-cm depth), suggesting that restricted conditions existed in this area a short time ago, and that the channel was recently reopened to return to an environment with high-energy currents. Today, the channel is nearly blocked by the northward progradation of a sand spit (Fig. 14), and it is possible that it could be blocked again within the next several decades to hundreds of years, creating a restricted environment where mud could once again accumulate. There should be areas in the Bahamas where this is occurring today, and channels known to be blocked should be investigated further.

CONCLUSIONS

Mud layers intercalated with ooid sand and lime mud clasts mixed with sand exist in at least two ooid tidal channels: north of Lee Stocking Island and in the Joulters ooid shoal. The intimate association of nearly pure lime mud and ooid sands may be a modern analog of some ancient examples of lime mud layers and clasts associated with ooid grainstones.

The accumulation of ooid sands can be episodic, and the creation of lobes of ooid sand (approximately 1 m thick) on Joulters Cays and Lily Bank has been ascribed to storms (Halley et al. 1983). In Lee Stocking channel, we suggest that layers of ooid sand 25 cm thick were deposited essentially instantaneously by the overwash or destruction of a barrier, and that the barrier was re-created rapidly allowing restricted pond sedimentation to continue. The data from the Lee Stocking core suggest that accumulation of the mud layers (8 cm and 12 cm thick) accounts for approximately 2000 yr of deposition; whereas the ooid sand layers (each about 25 cm thick) probably account for less than a few tens of years.

Ooids sand shoals are always undergoing change. Tidal currents, waves and major storms exert an enormous impact on the distribution of grains and environments of deposition. We extend this idea in a logical direction by illustrating that ooid tidal channels can be closed off and restricted subtidal environments can be created, especially in areas where wave energy is particularly effective in generating longshore transport of sediment and barrier islands. Both Lee Stocking and Joulters Cays are located along windward margins where waves generate longshore currents, and Holocene dunes and islands are present. The creation of restricted areas by barrier island formation may be less likely to occur in areas where wave energy is less effective relative to tidal currents, such as the tidal bars of southern Tongue of the Ocean or Schooner Cays (Ball 1967; Dravis 1979; Halley et al. 1983). The association of lime mud clasts and lime mud layers with ooid grainstones, especially with sharp contacts between them, should be an indication of a site of accumulation where rapid changes of environmental energy such as that described for Lee Stocking Island and Joulters Cays can occur.

Previously, some researchers of ancient oolitic deposits have suggested that lime mud layers and clasts interbedded with ooid grainstones were derived from a locally adjacent tidal flat (Smosna 1984; Strasser 1988). The association of a lime mudstone with an ooid grainstone should not immediately be considered an alternation of a tidal flat with an ooid sand shoal. In fact, without clear evidence of an exposure surface separating the ooid grainstone and the lime mud layer and/or clear sedimentary structures indicating supratidal deposition, a tidal flat-ooid shoal sequence is not indicated.

Lagoonal sediments (mud and skeletal grains) overlain by ooid sands and nearly pure lime mud would quite naturally have been considered a shallowing upwards sequence (James 1984). However, the data and model of deposition presented here are entirely subtidal (4–5 m) and suggest a deepening-upwards sequence. At least one other alternative is possible, then, to explain a lagoonal wackestone/packstone-ooid grainstone-lime mudstone sequence.

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