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PETROLOGY OF A MODERN SUBTIDAL STROMATOLITE, LEE STOCKING ISLAND, BAHAMAS

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ABSTRACT

The petrology of a stromatolite, growing at a depth of 6.7 m in a flood tide-dominated subtidal channel north of Lee Stocking Island, Exumas, Bahamas, is investigated by analysis of thin sections made from both interior and exterior portions of the structure. It is anchored on Holocene subtidal rubble hardground overlain by ooid-rich dunes. The stromatolite is a curved club, with a shingled pustulate surface, and a height of 33 cm, breadth of 20 cm and width of 14 cm. Individual shingles curve upwards and overlap one another so as to effectively trap sediment on the sides of the structure. The stromatolite contains crudely developed, irregularly spaced, crenulated, discontinuous, convex-up laminations that are defined by variations in the grain size, packing and/or the degree of infilling of pores by cement. Laminations are not present in all portions of the stromatolite. There are as well irregularly shaped patches or 'clots' which are defined by non-uniform packing and/or degree of cementation of particles, or the irregular distribution of finer and coarser grains.

The stromatolite as a whole consists of 67% grains, 25% cement and 8% unfilled inter- and intraparticle micropores. Meso- and megapores account for about 21.5% porosity. Grains consist of an average 7% pelloids, 9% skeletal fragments, 42% intraclasts, 1% grapestone, 40% ooids. The basal portion of the stromatolite is richer in skeletal debris, and the core contains locally-derived sand to pebble-size pelmicrite and biopelmicrite intraclasts. Some curvilinear micritic veins, interpreted to be traces of algal filaments, weave between grains. On the margins of the stromatolite, packages of these define the shingles. Primary inter- and intraparticle pores are partially to wholly filled with micritic and/or acicular high-Mg calcite and aragonite. Micritic cement commonly coats grains and is succeeded by isopachous fringes of acicular needles that in places grow inward to fill entire pores. More densely cemented areas have solely micritic cement. X-ray diffraction indicates that both the stromatolite and local dune sands, are composed of 90-95% aragonite and 5-10% high-Mg calcite. The substrate commonly contains slightly less aragonite and both low- and high-Mg calcite.

The portion of the stromatolite that was buried beneath oolitic sands at the time of sampling is more tightly cemented. In thin section, the contact between the covered and uncovered portions of the stromatolite appears as a sharp, somewhat crenulated, convex-up boundary defined by contrast in degree of cementation. Below this boundary, acicular aragonitic cement is uncommon and grain boundaries are somewhat obscured by dense cementation. Dense, light gray aphanitic cement pervades a subspherical area of the core of the basal portion of the stromatolite, suggesting that it might have originated as an oncolite.

INTRODUCTION

Giant subtidal stromatolites were recently discovered growing amongst ooid sand shoals in shallow (less than 10 m water depth), current-swept tidal channels situated on the eastern margin of the Bahama Platform (Dravis, 1983; Dill *et al*., 1986, 1989; Shapiro, 1989 and this volume). These researchers speculate that stromatolites can flourish and grow as high as dune height, up to two meters in some areas, provided that they are in an oceanic bank margin water mixing zone and are periodically buried beneath migrating dunes. Periodic burial beneath ooid sands inhibits biodegradation and colonization of the stromatolites by a variety of organisms, the presence of which could lead to cessation of stromatolite growth. In their studies of stromatolites in the vicinity of Lee Stocking Island (Fig. 1), Dill *et al*. (1986, 1989), Kendall *et al*. (1989)

and Shapiro (1989) recognized that morphologic variations among stromatolites principally relate to the flow direction and strength of tidal currents and consequent geometry of ooid dunes. Preferential growth upward and into the dominant flood current results from the entrapment of relatively greater amounts of sediment on the crestal region and side of stromatolites oriented toward this current, which in many cases results in a streamlined appearance of the structure in plan view.

In 1989, the authors sampled a whole stromatolite from a dune field situated in the bank margin end of the northern Lee Stocking Island tidal channel, termed area 'A' by Shapiro (1989 and this volume). The Holocene hardground upon which the stromatolite was anchored and surrounding dune sands were also sampled. The purpose of this study is to provide a brief description of the petrology of these sediments and internal and external portions of the stromatolite. This might aid in development of a modern analog that may be used in the interpretation of ancient stromatolites that are associated with oolitic sands (eg. Hoffman, 1967, 1974; Griffin, 1987).

GEOLOGIC SETTING OF THE STROMATOLITE

A detailed description of area 'A', the stromatolite patch from which the samples were taken is provided by Shapiro (1989 and this volume). The stromatolite (Fig. 2) was found growing at a depth of 6.7 m in a flood tide-dominated subtidal channel north of Lee Stocking Island, Bahamas. It is an area characterized by low sand dunes and dominated by a west-directed flood current, which floods the bank from the deep Exuma Sound. The stromatolite used in this study was collected from the area of the channel closest to the bank margin (Fig. 1). Here, oolitic and bioclastic sands (with some grapestone) have accumulated in a large flood tidal delta. The sands are piled in low angle, long wavelength sand waves, approximately 1 m high. Ripples are present on the top-surface and slipface of the dunes.

The area of the channel with stromatolites is underlain by a gray Holocene rubble hardground composed chiefly of partially cemented lag deposits of shell debris, oncolites, sand-lined burrows and mud chips. The dunes that overlie this surface are considered to be 'starved dunes' (Dill *et al.*, 1989), for in the troughs between dunes, algae-coated hardground is exposed. Rubble mud chips consist chiefly of pelmicrite and biopelmicrite. Oncolites have formed by algal accretion around cemented burrows, shells and mud chips. Stromatolites of this area are small ('juvenile') and sparsely and randomly distributed (Shapiro, 1989 and this volume).

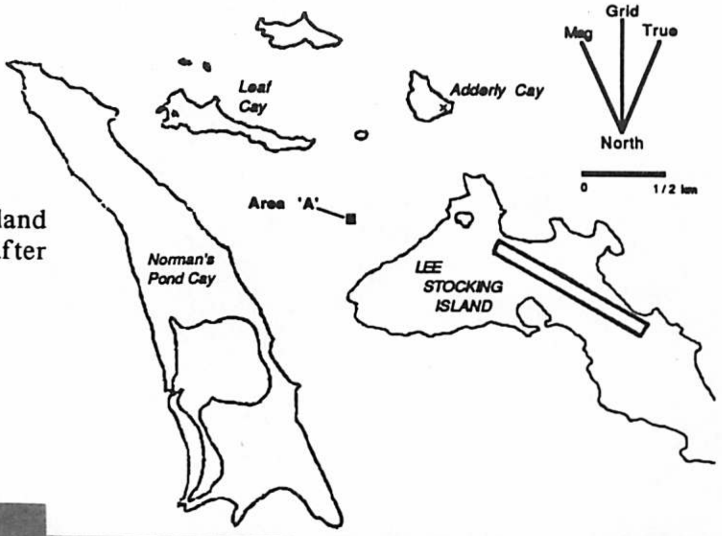
The stromatolite was anchored on the hardground and tilted into the flood current, reflecting a higher growth rate on this side. Morphologically, it is a curved dome with a pustulate shingled surface, and a height of 33 cm, breadth of 20 cm and width of 14 cm. Shingle structures are developed on all sides of the stromatolite. Individual shingles are commonly less than a cm thick and several cm in width and length. They curve upwards and overlap one another so as to effectively trap sediment on the sides of the structure (Fig. 3).

The dunes bounding the channel are stabilized by the sea grass *Thallasia*. This entrapment of sands dictates the low height of the sand waves in the channel. Blowouts on the margins of the stabilized dunes are produced by both flood and ebb tidal currents. The north side of the channel in area A has exposed, partially lithified mud beds. The mud beds are composed of several layers of aragonitic needles, separated by thin, cemented crusts. The origin of the mud beds is controversial. They are believed to have been deposited either during major storm events (Dill *et al.*, 1989) or in a lagoonal setting (Boardman, *et al.*, 1989). Rubble mudchips in dune troughs, as well as in the substrate, are very likely derived by erosion of these beds.

METHODS

The stromatolite was sawn in half down its vertical axis and one half was impregnated with blue epoxy. Seven thin sections were made from both interior and exterior portions of the structure (Fig. 3). Half of each section was stained using alizarin red S and potassium ferricyanide. Point counts of 300 points per thin section were made to determine relative percentages of grains, cement and unfilled pore space on a microscopic scale. Two 200-point grid counts

Fig. 1: Location map of Lee Stocking Island stromatolite patch 'A'. Figure modified after Shapiro (1989).



. 3. Cross-sectional cut through the stromatolite. Note shingles, mesopores and presence of a subspherical ne (outlined with dashes) of dense cementation at the e of the structure. The locations of thin-section are licated by letters following the nomenclature of tables nd 2.

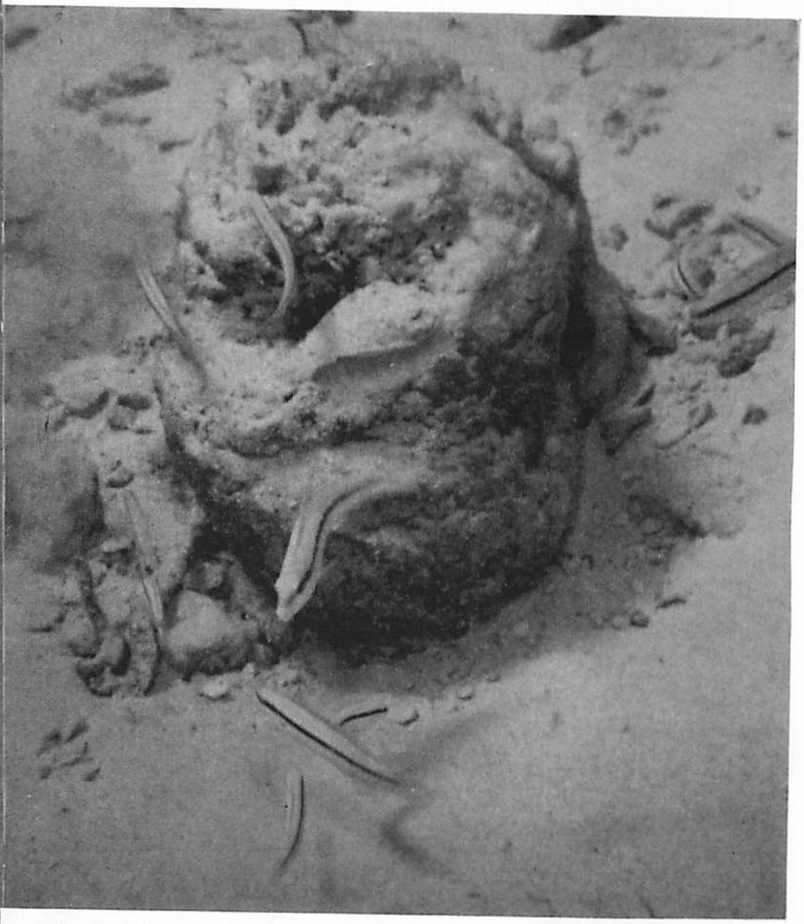


Fig. 2. The stromatolite prior to sampling. Flood current is directed towards the reader. Note the shingled appearance of the supper surface, the presence of rubble and the hardground upon which the stromatolite is anchored.

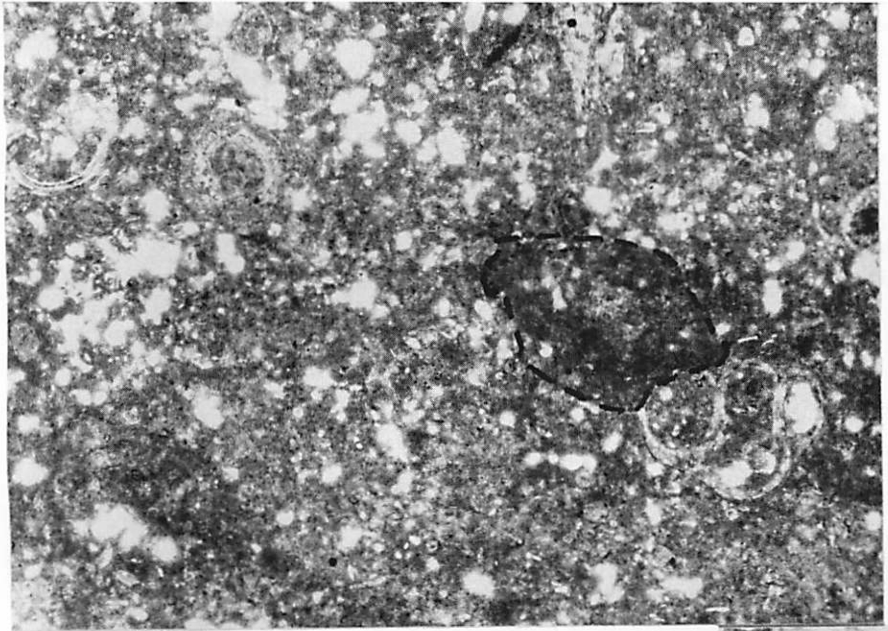


Fig. 4: Photomicrograph of dense cryptocrystalline cement surrounding and obscuring grains in sample F (plane light; field width is 3.2 mm). Pores are largely filled (section microporosity by area=1%) and grain margins hard to define (some are dashed in). Note the shell fragment filled partially with sediment and cement in the lower right. Most white areas are skeletal fragments.

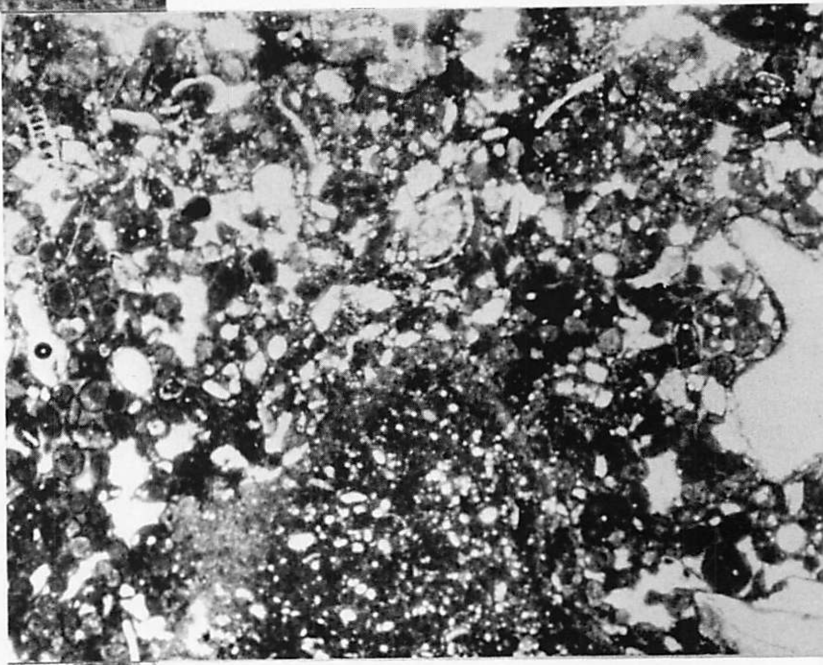


Fig. 5: Photomicrograph of sample G (plane light; field width is 6.5 mm). Note the ripup clast rich in skeletal fragments and pellets in the bottom center and the large shell fragments to the right. The cement is all micritic. Some irregular white areas are pores (section microporosity by area=5%), but most are skeletal fragments.

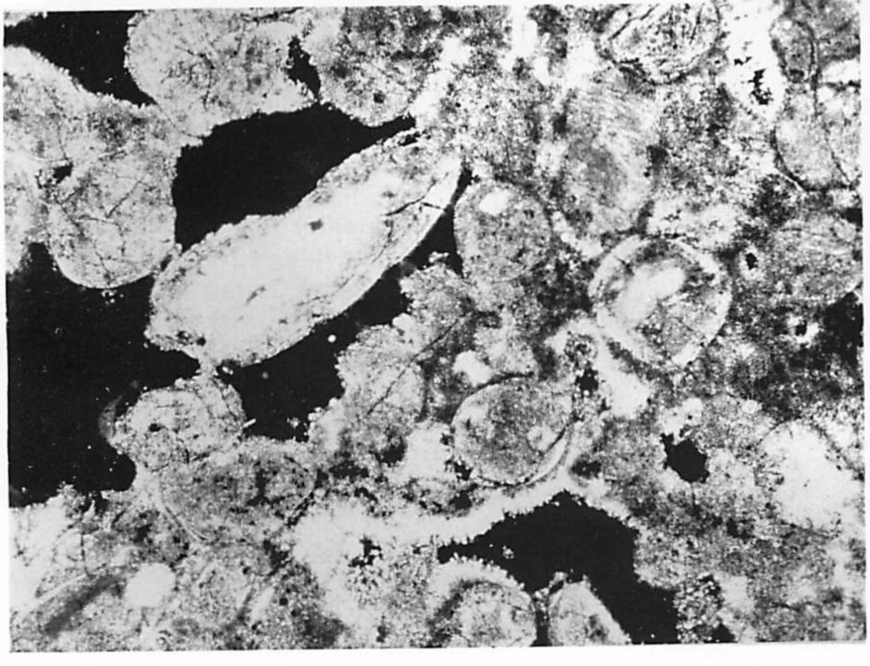


Fig. 6: Photomicrograph of a lamination in sample A (polarized light;field width is 1.3 mm). The lamination runs from the lower left to upper right corner and is defined by dense, dark micritic cement and some finer grain size material. Note the presence of a dark cryptocrystalline cement coating the grains, succeeded by isopachous fringes of acicular crystals growing into pores(black areas;section microporosity by area=13%), oriented perpendicular to grain margins. In the centers of some pores micritic cement succeeds the acicular cement.Most oolites are superficial, developed around intraclasts (although micritization has undoubtedly obscured some of their original internal structure). The interiors of some have aggraded to microspar.

made on an axial cut through the stromatolite to determine the relative percent of meso- and megapores in the upper and lower halves of the stromatolite. From 300-grain thin section point counts, relative percentages of grain constituents were determined. In order to compare grain assemblages within the stromatolite and those in the surrounding dunes, 200 grain counts were completed on sediment samples collected in this stromatolite field. Half of the stromatolite was disaggregated to determine fossil content.

X-ray diffraction study of bulk samples of the upper and basal portions of the stromatolite, as well as of local dune sands and the substrate of the area, was undertaken to determine carbonate mineralogy. Relative percentage of aragonite versus calcite was determined by comparing the heights of the 3.40Å aragonite and 3.03Å calcite peaks following the method of Griffin (1971). C_{14} dating on the core of the base of the stromatolite was completed by S. Valastro of the University of Texas Radiocarbon Laboratory (sample # x6796).

GRAIN COMPONENTS AND MINERALOGY

From thin section point counts, the stromatolite is determined to contain an average of 7% pelloids, 9% skeletal fragments, 42% micrite, pelmicrite or biopelmicrite intraclasts, 1% grapestone, 38% superficial ooids with intraclast nuclei, 2% ooids with pelloid nuclei, and trace amounts of ooids with skeletal fragment nuclei and composite ooids (Fig. 4 - 8; Table 1). The basal portion of the stromatolite is richer in skeletal debris. Most non-skeletal grains are sand-size. However, the stromatolite core contains locally-derived, subrounded but bored and irregularly-shaped, sand to pebble-size pelmicrite and biopelmicrite intraclasts (Fig. 4 - 5). These are similar in composition, respectively, to semilithified crusted aragonitic seafloor muds exposed nearby and to the subjacent hardground mud chips. Similar pebble- to cobble-size intraclasts are found in the central depressions of many actively growing molar-shaped stromatolites (Dill *et al.*, 1986, 1989; Shapiro, 1989 and this volume).

Based upon grain counts, dune sand of this area consists of an average of 57.5% skeletal debris, 12% grapestone and 30.5% ooids, intraclasts and pelloids (Shapiro, 1989). The greater proportion of the latter in the stromatolite likely reflects their smaller size and the consequent ability of currents to toss them higher upon the growing structure. The enrichment of the base of the stromatolite in skeletal debris and coarser intraclasts may reflect both contact with a coarser traction population and, possibly, more extensive bioerosion of the stromatolite in its early stages of development. Gebelein (1969, 1976) noted that size of sediment entrapped in low-relief subtidal algal mats in Bermuda was finer than that of the surrounding area and attributed this to coarse sediment bypassing.

X-ray diffraction study of bulk samples indicates that both the top and basal portions of the stromatolite, as well as local dune sands, are composed of 90-95% aragonite and 5-10% high-Mg calcite (Fig. 9).

INTERNAL STRUCTURE AND DIAGENETIC HISTORY

The stromatolite contains crudely developed, irregularly spaced, crenulated, discontinuous, convex-up laminations that are defined by variations in the grain size, packing and/or the degree of infilling of pores by cement (Fig. 6). The thickness of individual laminations varies laterally, commonly from 50-400μ. Laminations are not present in all portions of the stromatolite. There are as well irregularly shaped patches or 'clots' which are defined by non-uniform packing and/or degree of cementation of particles, or the irregular distribution of finer and coarser grains. Some curvilinear micritic veins weave between grains. The veins vary in width from 20-50μ and are interpreted to be calcified traces of algal filaments, based upon the interpretation of similar features discovered within Bahamian subtidal stromatolites by Dravis (1979, 1983). Browne and Reid (1990) interpret similar filaments found within intertidal stromatolites on Stocking Island to the south to have originated as '*Ostreobium* -like' green algal tubules. On the margins of the stromatolite, packages of these tilt at a moderately steep angle toward the interior of the stromatolite and define 'shingles' which grew upwards along the side of the stromatolite and trapped sediment (Fig 7). While most filaments are of chasmolithic habit, occupying pore space, a few appear to crosscut preexisting

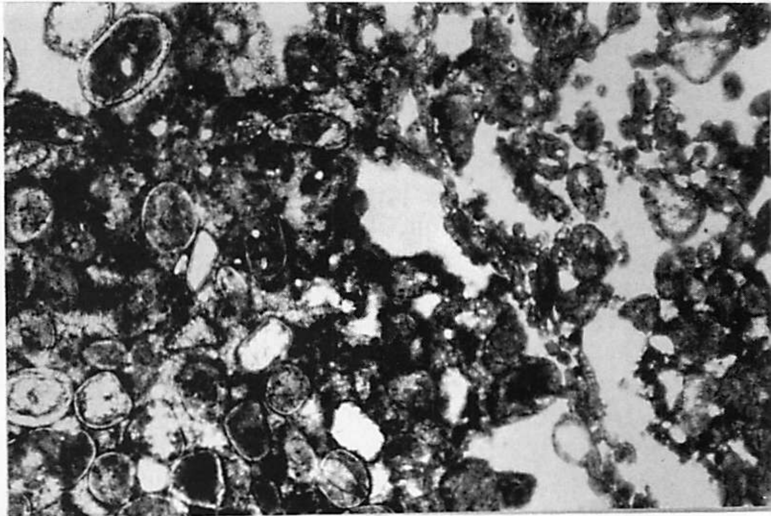


Fig. 7: Photomicrograph of algal filaments (central region) defining a 'shingle' in sample D (plane light; field width is 3.2 mm). Porosity is greater adjacent to the filaments. Irregular white areas are pores (section microporosity by area=10%), most of which are surrounded by acicular isopachous cement. Neomorphic microspar is present within the nuclei of some ooids.

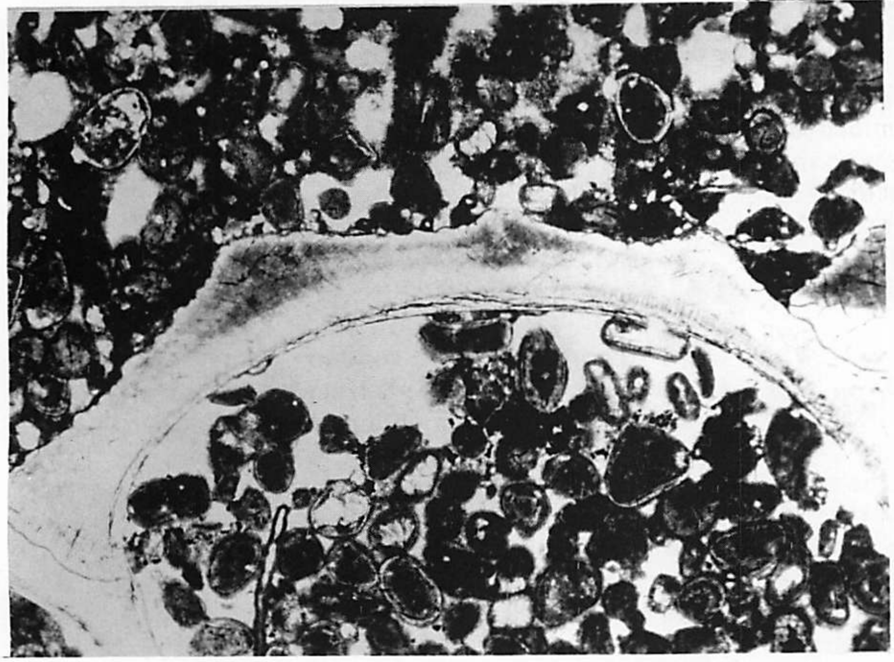


Fig. 8: Photomicrograph of sample B(plane light;field width is 3.2 mm.).Most irregular white areas are pores(section microporosity by area = 5%). Unfilled pore space is locally more abundant within the large shell fragment.

Table 1- Stromatolite point count data (300 grains per sample). The bracketed numbers under 'skeletal' give percentages for algal filaments encountered and the numbers under 'intraclasts' percentages for locally derived rubble.

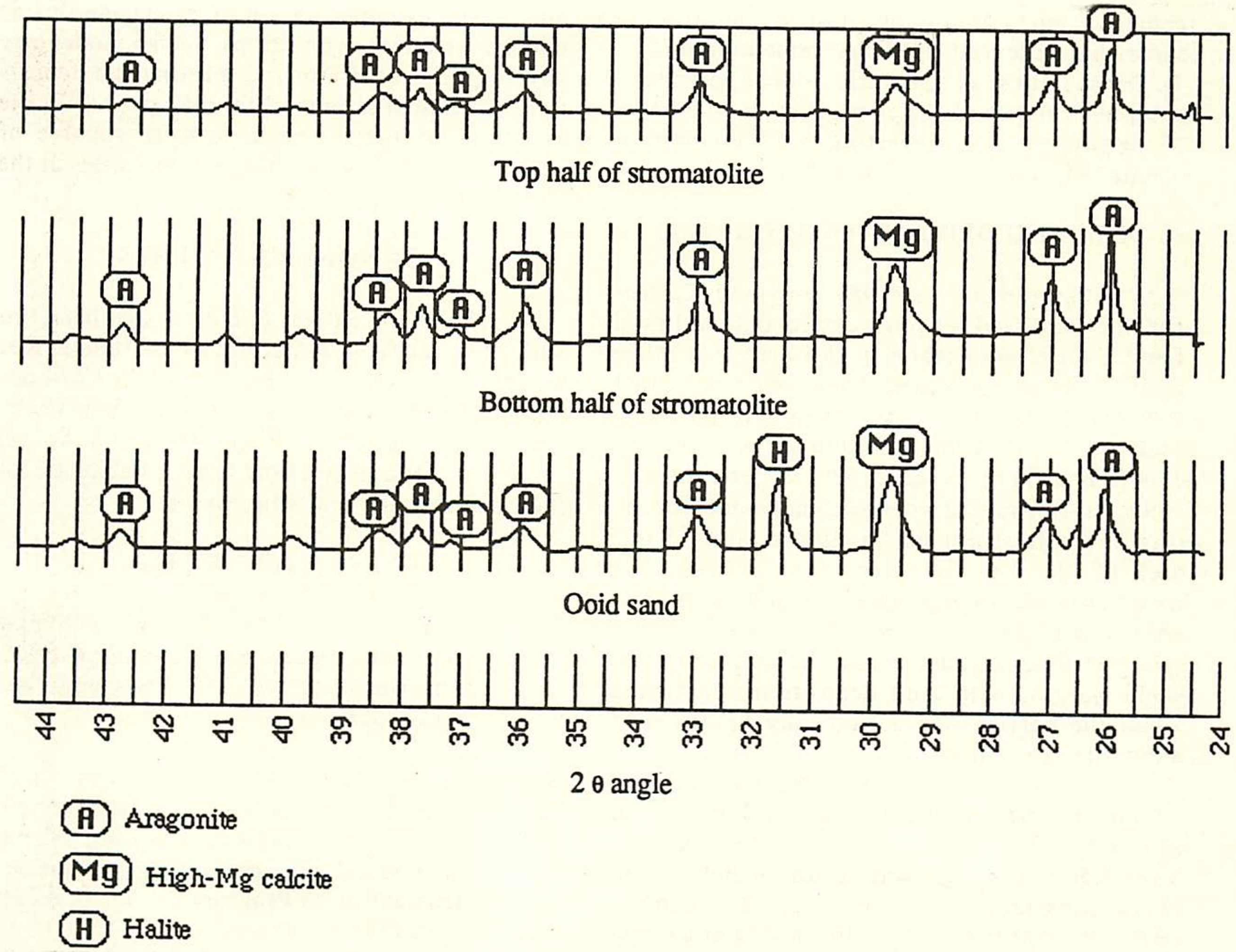
Sample:	% pelloids,	skeletal,	intraclasts,	grapestone:	ooids w/ intracl	- skel	- pel:	composite ooids
A	4	2	43	1	46	1	3	-
B	7	8	36	Tr	48	-	1	Tr
C	7	1	43	1	43	-	5	-
D	9	Tr	38	2	50	-	1	-
E1	4	12-(9)	36-(4)	1	46	-	-	Tr
E2	7	15-(2)	50-(2)	2	25	-	1	Tr
F	16	15-(1)	49-(4)	1	16	1	2	Tr
G	7	18	40-(10)	3	26	1	3	2
mean	7	9	42	1	38	Tr	2	Tr

Table 2- Stromatolite point count data (300 points per sample)

Sample:	%grains	%cement	% unfilled pores
A	59	28	13
B	77	19	5
C	68	16	16
D	63	27	10
E1	65	23	12
E2	66	31	3
F	70	29	1
G	71	24	5

laminations.

Primary inter- and intraparticle pores are partially to wholly filled with micritic and/or acicular high-Mg calcite and/or aragonite. Micritic cement commonly coats grains and is succeeded by isopachous fringes of acicular needles that in places grow inward to fill entire pores (Fig. 6 & 8). This pattern is similar to cements in Holocene ooid hardgrounds (Bathurst, 1975; Harris *et al.*, 1985; Sandberg, 1985). In other places the needles grade into micritic cement in the center of the filled pore (Fig. 6). More densely cemented areas have solely micritic cement coating grains and filling pores (Fig. 4). Intraparticle porosity in skeletal debris may be partially to wholly filled by uncemented to cemented small carbonate grains, or pure micritic and/or acicular cement (Fig. 8). Grains have suffered little apparent dissolution and only


Top half of stromatolite

Bottom half of stromatolite

Ooid sand

Fig. 9. X-ray diffraction patterns for bulk samples taken from the dunes and base and top of the stromatolite.

minor neomorphic change, chiefly in the formation of patches of microspar within intraclasts (Fig. 6 - 8).

Although the top of the stromatolite has the highest value for combined filled and unfilled microporosity (41%), variations of total porosity throughout the structure are not great. However, the portion of the stromatolite that was buried beneath oolitic sands at the time of sampling, and which lacked a living microbial coat, is more tightly cemented and exhibits less than 5% unfilled pore space. At the time ofsampling this portion appeared light gray, in contrast to the greenish hue of the algae-coated surface of the upper portion of the stromatolite. In thin section, the contact between the covered and uncovered portions of the stromatolite appears as a sharp, somewhat crenulated, convex-up boundary defined by contrast in degree of cementation. Below this boundary, acicular aragonitic cement is uncommon and grain boundaries are somewhat obscured by dense cementation (Fig. 4). Dense light gray aphanitic cement pervades a subspherical area of the core of the basal portion of the stromatolite, suggesting that it might have originated as an oncolite (Fig. 3).

AGE AND DEPOSITIONAL SETTING

Boardman *et al.* (1989) obtained C_{14} ages for interstratified aragonitic mud and ooid sand from a 1.2 m core taken in this area that range from 2,190 to 560 years. They report ages that range from 4,740 to 5,580 for muddy sand that underlies the lowermost ooid sand (pers. comm., 1990). Boardman *et al.* (1989 & pers. comm., 1990) have proposed a depositional model for the origin of interstratified muds and sands in this area of the Lee Stocking tidal channel that involves intermittent mud accumulation in a low energy lagoonal environment at times when a sand barrier prograded across the channel on the shelf margin, with mud deposition punctuated when the barrier was periodically breeched to allow the sand influx.

A C_{14} date on the densely cemented basal core of the stromatolite we sampled indicates an age of 3,710±90 years. Given the fact that sea level 4,500 years ago was approximately 7.5 m below present level (R. F. Dill, pers. comm., 1990) and that the stromatolite was sampled at a depth of 6.7 m, it is reasonable to speculate that the oncolite originated in a shallow intertidal setting (although, of course, the radiocarbon age for the oncolite might chiefly reflect the age of the grain components, and the actual structure might have developed more recently). The nature of the sediment incorporated into the stromatolite indicates that it originated and grew in a high energy environment. There is no indication of the episodic change in energy level of the environment of the sort proposed by Boardman and others, and thus their model should be reexamined.

CONCLUSION

Definition of the mineralogy, grain components, texture and internal structure of this modern subtidal stromatolite contributes to the formulation of a facies model that can be utilized in interpreting ancient stromatolites that may have developed in a normal marine setting under high energy conditions. Such a model may have especial utility in interpreting the depositional setting of stromatolites that grew after the evolution of life forms that were capable of colonizing and biodegrading stromatolites at the end of the Precambrian.

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