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MORPHOLOGICAL VARIATIONS WITHIN A MODERN STROMATOLITE FIELD: LEE STOCKING ISLAND, EXUMA CAYS, BAHAMAS

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ABSTRACT

The morphologic, size, current alignment, and distributional variations within a modern stromatolite field are examined to improve the new model for stromatolite genesis. Morphological characteristics include shingles, cavities, degree of coalescence, and pustules. Four areas within the Lee Stocking Island stromatolite field are delineated on the basis of the above criteria.

The first area has single clubs that show widespread and random distribution, small heights, and high levels of degradation by burrowing organisms and corals. This is due to a lack of net sediment accumulation resulting from dune stabilization and the location of the area relative to the main tidal channel. The second area has large (>2 m high) heads and coalesced biohermal walls with pustulate surfaces, which are distributed perpendicular to the main channel axis and exhibit streamlining in plan view. This area is bounded by large, sinusoidal, oolitic sand dunes. The third area has stromatolites with extremely variable heights, pustulate surface textures, sunken cavities on upper surfaces (molar form), and random distribution with respect to the channel geometry. The tidal currents in this area showed the greatest path variability, often with "shimmer" lamina at the boundary between water masses. There is an exposed Pleistocene hardground capped by a caliche paleosol in this area. The fourth area is a series of highly coalesced clubs, forming walls in excess of 30 m long, perpendicular to current flow. In plan view, the walls appear like "arabesque writing" and display the molar form. The tops of these stromatolites are markedly concave-upward.

Most of the stromatolites tilt toward the incoming tidal current, with tops that are aligned parallel to the crests of the dunes in the area. Therefore the angularity to their shape and their orientation is probably influenced by preferential growth into the nutrient rich flood current, and is not controlled entirely by the position of the sun.

These variations in size, shape, amount of coalescence, orientation relative to the prevailing current and other stromatolites, and degree of degradation are all linked to the physical stress exerted upon their organic community by the high velocity currents in the area. Therefore, these variations may be used to infer physical stresses that existed in paleochannel environments. The Lee Stocking stromatolites offer one analog for interpreting fossil stromatolites. However, a more rigorous study of the processes by which the stromatolites form and the events that lead to their preservation is needed to establish a comprehensive stromatolite facies model.

INTRODUCTION

Stromatolites are organosedimentary structures formed of successive layers of sediments, trapped and cemented by communities of cyanobacteria and other microbialites (Kalkowsky, 1908; Burne and Moore, 1987). Although these structures are found throughout the geologic column, dating back to 3.45 Ga (Aschauer and Johnson, 1969; Walter, 1976), their abundance decreased in the Cambrian and Ordovician because of both environmental changes (Pratt, 1982) and the development of more advanced herbivores (Garret, 1970). Today, stromatolites are growing in areas free of predators, such as: intertidal, hypersaline pools (Logan *et al.*, 1970); insular lagoons (Neumann *et al.*, 1988); subtidal current-swept channels (Dravis, 1983; Dill *et al.*, 1986); intertidal, normal salinity island margins (Browne and Reid, 1990); and deep African rift lakes (Cohen *et al.*, 1984).

These modern analogues provide a means to assess paleoenvironments in which ancient stromatolites flourished.

In 1984, stromatolites were found growing offshore from Lee Stocking Island, in the Exumas Island chain, Bahamas (Dill *et al*., 1986). The Lee Stocking Island stromatolites are growing in a subtidal, high energy, normal salinity environment. This location is much different from the better known stromatolite locality that exist in Hamelin Pool, Shark Bay, Western Australia area (Logan *et al*., 1970), which is an intertidal, low energy, hypersaline stromatolite field. The stromatolites offshore from Lee Stocking Island also differ from their Shark Bay counterparts in that they are larger and their morphologies are controlled chiefly by physical stress, and they do not exhibit heliotropism (Awramik and Vanyo, 1986).

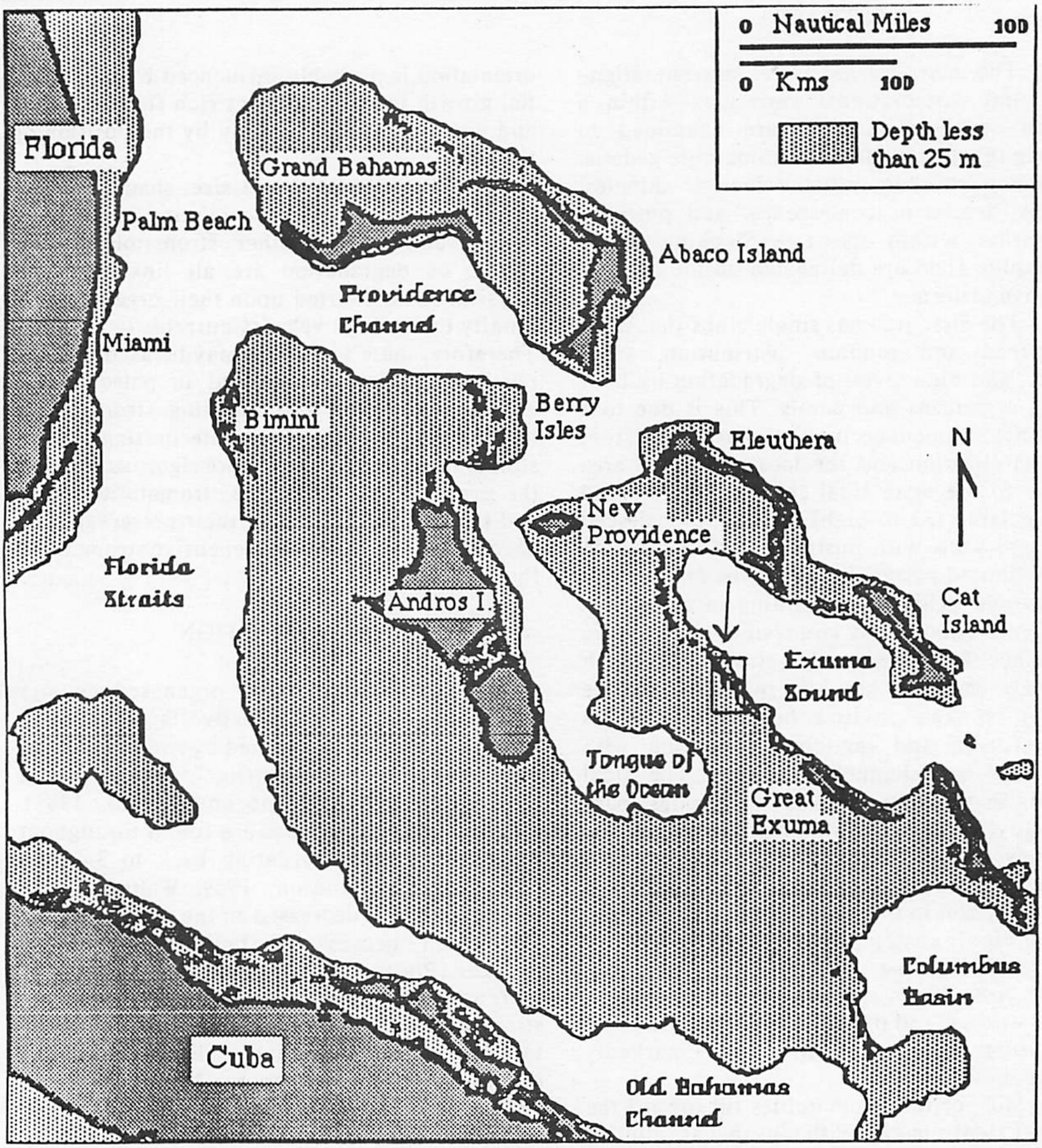

Fig. 1. Map of the Bahama Islands showing the location of the southern Exumas (box). Lee Stocking Island is 20 km northwest of Great Exuma along the Exuma Chain.

GEOLOGY OF THE REGION

Lee Stocking Island and the Great Bahama Bank

Lee Stocking Island is one of the 365 islands and cays in the Exuma chain. The Exumas are a series of low-lying islands (<35 m in elevation) located along the southern end of the Bahamas (Sealey, 1985) (Fig. 1). They are situated on the eastern rim of the Great Bahama Bank, a large carbonate platform with a volume of about 1.5 x 106 km^3. This carbonate platform resembles many ancient limestone regions with economic importance, and has received extensive study (Dietz *et al.*, 1970; Meyerhoff and Hatten, 1974; Schlager, 1981; Schlager and Ginsburg, 1981; Beach and Ginsburg, 1980; Beach, 1982; Eberli and Ginsburg, 1987). Dietz *et al.* (1970) think that this platform developed during the breakup of Pangea in the Late Triassic to Early Jurassic.

The geologic history of the Great Bahama Bank is beyond the scope of this paper. Several workers have already described the setting and its history with respect to deposition, tectonics, and lithology (Newell, 1955; Hess, 1959; Talwani, 1960; Ball, 1967; Dietz *et al.*, 1970; Schlager and James, 1978; Mullins and Lynts, 1977; Kendall and Schlager, 1981; Burton *et al.*,1987).

The Exuma Sound, one of the several large, deep, steep-sided submarine valleys and oceanic reentrants that dissect the Great Bahama Bank, lies 1 km to the east of Lee Stocking Island (Hurley and Shepard, 1964; Shepard and Dill, 1966; Dill *et al.*, 1989; Kendall *et al.*, 1989). The Exuma islands and cays generally have a cemented Pleistocene core of oolitic and bioclastic sands that were deposited in eolian dunes during eustatic sea level low stands. Many of these islands are set back from the bank margin and have a Holocene dune cap covering on the inner Pleistocene core. The boundary between these two eolianites is often delineated by a Pleistocene paleosol. Many of the islands have a well developed karst topography that extends both above and below modern sea level.

The Stromatolite Channel

Chemical Oceanography

The channel in which the stromatolites are located is approximately 2.5 km long by 750 m wide. The depth in the channel varies between 6 and 10 m. This channel serves as a large, natural mixing zone of oceanic and bank waters. Cold oceanic water from the Exuma Sound is brought onto the shallow Bahama Bank twice daily during the flood tide (Ball, 1967, Sealey, 1985; Shinn *et al.*, 1989). The water is then heated and calcium carbonate is precipitated out of solution. The waters, enriched with CO_2, leave the bank and come into contact with the cool oceanic waters during the ebb tide in the mixing zones between the islands. The mixing zone is the most important factor in the creation of ooids and cements, the location of the stromatolites, and possibly the aragonitic mud beds found in the same area (Harris *et al.*, 1985; Dill and Steinen, 1988).

Sediments

The bottom sediments in this channel are sands composed of ooids, grapestones, and coralgal clastics. Other sediments include pelletal muds. The sands here, and elsewhere in the Exumas, occur in bands roughly parallel to the platform margins (Illing, 1954). They include shoal sand bars (less than 3 m below MSL) and flood-tidal deltas (Kendall *et al.*, 1989). The sands in the stromatolite channel occur as a ribbon-shaped flood-tidal delta, upon which the sands are built into dunes and ripples. Aragonitic ooids constitute the bulk of the sands. The grapestones occur where currents are insufficient to move or rework sand-sized material on a regular basis (Purdy, 1963; Taft and Harborough, 1964, and Winland and Matthews, 1974). The grains within the grapestones are cemented together by aragonite to form aggregate clumps (Kendall *et al.*, 1989).

Substrata

Other facies encountered in the region are mud beds, hardgrounds, and a Pleistocene paleosol. A brief description of the mud beds is given in Aalto and Shapiro (this volume). The hardgrounds are a conglomerate facies of rip-up mud clasts, broken coral and stromatolites, oncolites, shells (mostly Strombus gigas), and clasts of the paleosol. Over 90% of the objects are covered with microbial mat material. Once cemented by marine carbonate cements, the hardgrounds provide an ideal surface for the initiation of stromatolite development, as long as there is a net aggradation of sediment. Hardground rubble is accumulating continuously in the troughs of the larger oolitic dunes. Clasts in this rubble zone are soon covered by microbial mats. Stromatolitic structures that are actively developing in Hamelin Pool and Eleuthera also appear to be growing on hardground substrata (Logan *et al.*, 1970; Dravis, 1983).

During the eustatic low at the end of the Pleistocene (ca. 100,000 ybp), a soil cover developed on the dunes that was later cemented under subaerial, and possibly submarine, conditions. This paleosol is seen on most of the islands and appears as a smooth, reddish-brown solution surface between the Pleistocene dunes and the Holocene cover. Scattered throughout this paleosol are cemented pisoliths. This layer continues underwater to as much as 7 meters below MSL.

The stromatolites offshore from the western edge of Lee Stocking Island are growing on the paleosol, suggesting that the stromatolites are less than 10,000 years old.

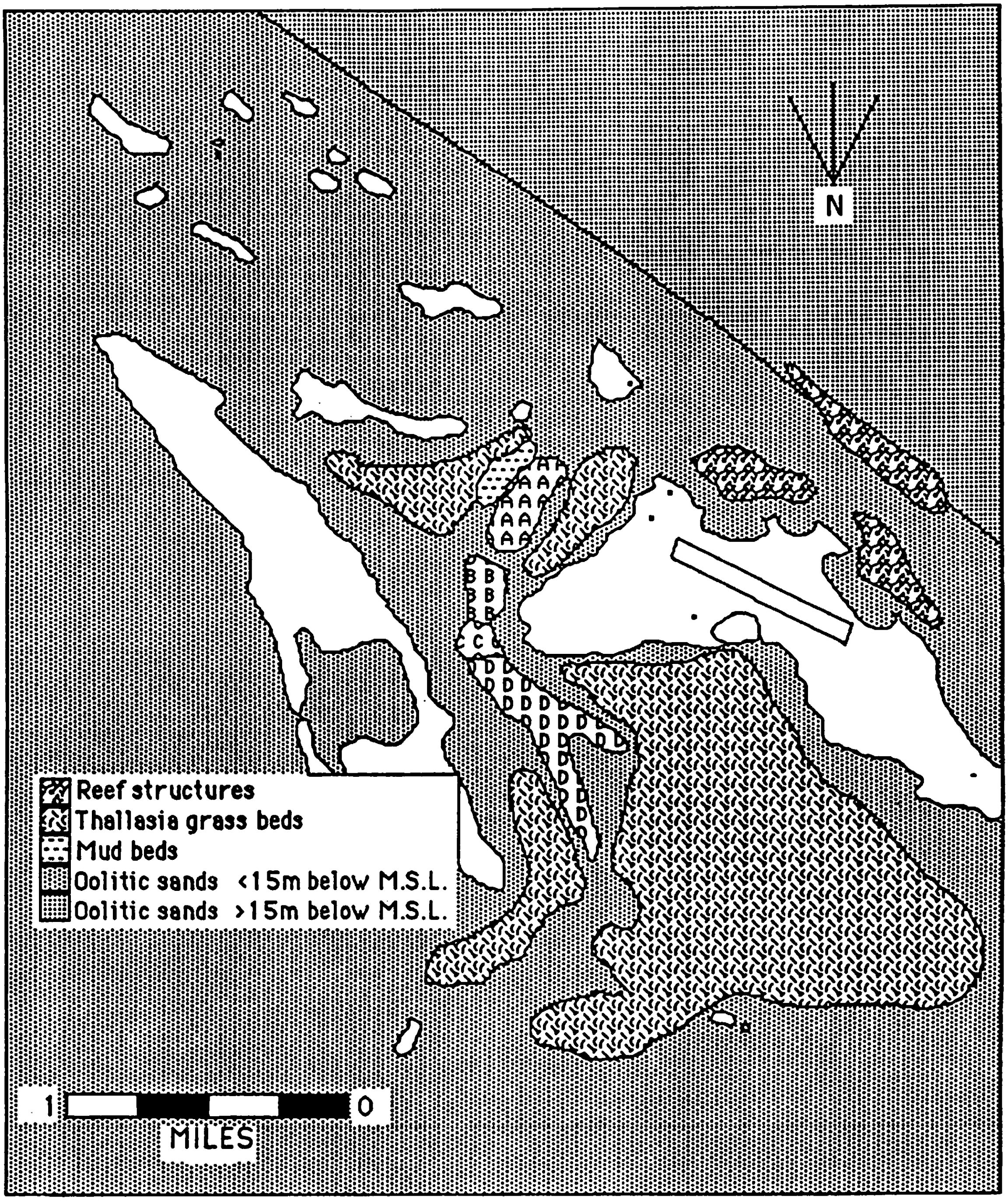

Fig. 2. Locations of the studied stromatolite areas A-D. The bank margin appears in the upper right. Lee Stocking Island is in the lower right.

During the Holocene eustatic rise, it is possible that algal blankets formed on the now subaqueous paleosol. The ooid sands produced in this mixing zone became entrapped and bound by the algae, initiating stromatolite developement. Therefore, the stromatolites started forming during the Holocene sea level rise. The substratum plays a critical role in the location and formation of the stromatolites. Other areas in the Bahamas, which lack some of the above substrata, do not contain growing stromatolites.

METHODS

The initial concept for this study was developed during reconnaissance and drift dives in the stromatolite field between July, 1988, and June, 1989. It became apparent that morphological differences among the stromatolites permitted one to separate the field into distinct areas. The four areas were delineated based on: small heights, degradation of the stromatolite, and random orientation (area A); large, streamlined, bulbous heads (area B); molar cavities, randomly oriented heads (area C); and highly coalesced walls, perpendicular to channel flow (area D) (Fig. 2).

Once the areas were established, a 1 m long rebar stake was placed at a location that most typified the area. Each stake was located on a regional map using sextant angles between stationary landmarks that had been previously surveyed and located on the map. Then, the stake locations were plotted on a map using standard triangulation. Buoys were placed on each stake to assist in reoccupation of the site on successive dives.

Several dives were made in each area prior to sampling to make observations and to take photographs. Underwater photographs were made using a Hanimex Amphibian 35 mm camera with a 50 mm lens for close-ups, and a Nikonos V 35 mm camera with a 20 mm lens for constructing a photo mosaic of the area. The film used was T-Max 400 B/W, shot at either ASA 100 or 400, depending on the conditions. Because of the swiftness of the tidal currents in the region, dives could only be planned for the slack water. This allowed approximately 30 minutes for each dive. The low slack waters had a lower visibility (6-10 m) and a greenish color, so these dives were utilized for close up photographs, observations, and sediment sampling. The high slack waters were much clearer (15-50+ m) and had a bluish color. All photographic mosaics were made during the flood-tidal periods of slack tide.

Oncolites and stromatolites collected during previous visits were photographed under the microscope. The photographs were then analyzed to determine the amount of bioerosion taking place within the cemented structure. One stromatolite was collected from area A, and cut in half to study its internal structures (Aalto and Shapiro, this volume).

DESCRIPTIONS OF THE AREAS

Morphological variations between the four areas include height, current-induced orientation, surface structures (i.e. "shingle" structures, botyroids), frequency of coalescence between individual stromatolite heads, presence of cavities in the upper surface (molar form), and their orientation with respect to neighboring heads (Fig. 3).

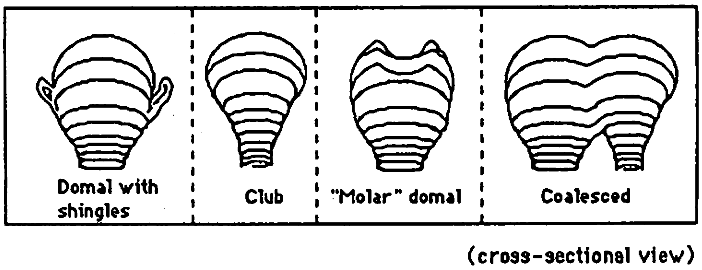

Fig. 3. Diagram showing the four major morphologies of stromatolites offshore from Lee Stocking Island.

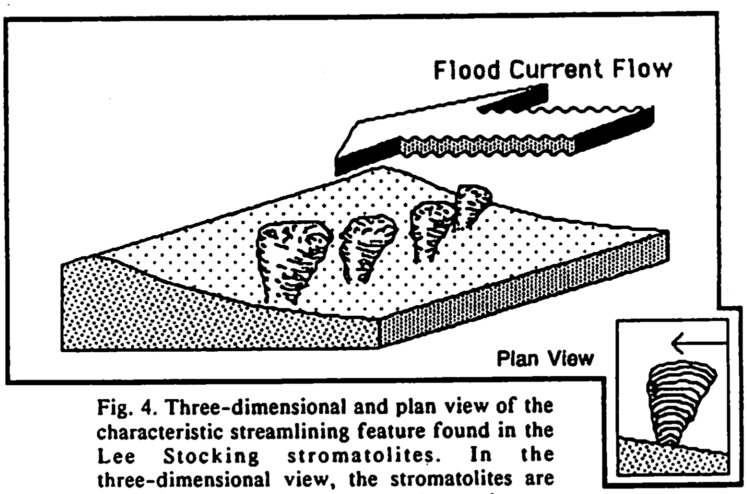

Fig. 4. Three-dimensional and plan view of the characteristic streamlining feature found in the Lee Stocking stromatolites. In the three-dimensional view, the stromatolites are shown oriented normal to current flow, a feature often noted in the field.

The sands in area A are formed into low active sand waves (<1m) with sinusoidal crests. The dunes north and south of the channel, toward Lee Stocking Island, are stabilized by *Thallasia*. The area is shallow, relative to the rest of the channel, with depths at high tide averaging 5-6 m. The underlying substrate is a Holocene hardground, cemented by aragonite and high-Mg calcite. The stromatolites in this area are smaller on average than the other areas (20 cm in height). Their average circumference is 75 cm. This relatively small circumference is the result of the lack of coalescence in this area. The stromatolites are singular clubs with rounded and pustulate tops (Fig. 7). Commonly, they are 1 to 2 m apart with no apparent orientation with respect to the current flow, although some show streamlining into the flood current (Figs. 4 and 5). The stromatolites occur in patches, and these patches are randomly placed in the channel. The stromatolites on the margin of the area are bioeroded.

In area B, dunes are up to 2 m high, with crests oriented normal to current flow. Near the stromatolites, the dunes become contorted around the stromatolite heads, reminiscent of "island shadowing" of ocean waves. The stromatolites are located between 6 and 8 m below the mean high tide level. I have not observed the substrate on which the stromatolites are anchored in this area because of the presence of large dunes, and there is no reference to the substrate in the literature. The stromatolites in area B are the largest living examples found as of this writing. Heights from the sediment surface to the top of the head commonly exceed 2.5 m (Fig. 6). The stromatolites here have coalesced to form large bulbous shapes with circumferences in excess of 10 m. Where two or more individual heads have coalesced, their different heights give the new head a lumpy shape. "Shingles", which grow from the main stromatolites, show internal laminations. The area B stromatolites show the greatest amount of streamlining into the current. In all instances, stromatolites show streamlining into the flood current. As coalesced bioherms, the stromatolites line up perpendicular to the prevailing current flow. The line connecting the tops of the stromatolites is subparallel to the lobate cross-sectional crests of the dunes in the area. The surface texture of the stromatolites is soft and pustulate, whereas the surface below is cemented. The stromatolites in area B appear to be free of grazing herbivores. All are receiving and binding sediments. The dunes here are actively migrating, although exact rates of migration have yet to be determined.

In area C, the channel bottom is a Pleistocene paleosol, with a thin veneer of Holocene sediments. The stromatolites are anchored on this paleosol. Because currents are swift and variable at this site, sand is sculpted into 1 m high star dunes. The stromatolites in area C are highly variable in all regards (Fig. 8). Some show streamlining, whereas others do not. Their average height is 70 cm (range: 10-80 cm). The stromatolites have cavities as deep as 20 cm on their upper surface, termed "molar" form. The lip around this top is several cm thick, and displays growth on all sides. The stromatolites often coalesce through "algal bridges." Small stromatolites are located next to larger ones and they are oriented randomly with respect to the geometry of the channel. The morphological randomness and lack of orientation within area C can be attributed to the variability of the currents.

In area D, dunes become more regular, with an average wavelength of 10 m and an average height of 1 m. The crests of the dunes are sinusoidal and parallel. They form an oolitic flood tidal ribbon shoal. The stromatolites average a height of 1 m, with their tops aligned to the crests of the dunes (Fig. 9). This area has the greatest amount of coalescence, with long biohermal walls composed of joined heads in excess of 30 m long. In plan view, the outline of the walls appear like arabesque writing. The walls are aligned parallel to the dune crests and perpendicular to current flow. Individual heads in this area are club-shaped and are streamlined into the flood current. The stromatolites here are also of the molar form. Shingles are found on the side of these stromatolites, but not in the abundance of area B. The stromatolites are anchored on a Pleistocene caliche paleosol.

DISCUSSION

The stromatolites developing near Lee Stocking Island, Bahamas exhibit external morphologic variations. They vary in size, shape, amount of coalescence, orientation relative to the prevailing current and other stromatolites, and degree of degradation. These variations are also recognized in ancient stromatolites and thrombolites; e.g., Middle Cambrian to Early Ordovician (Griffin and Awramik, 1988) and

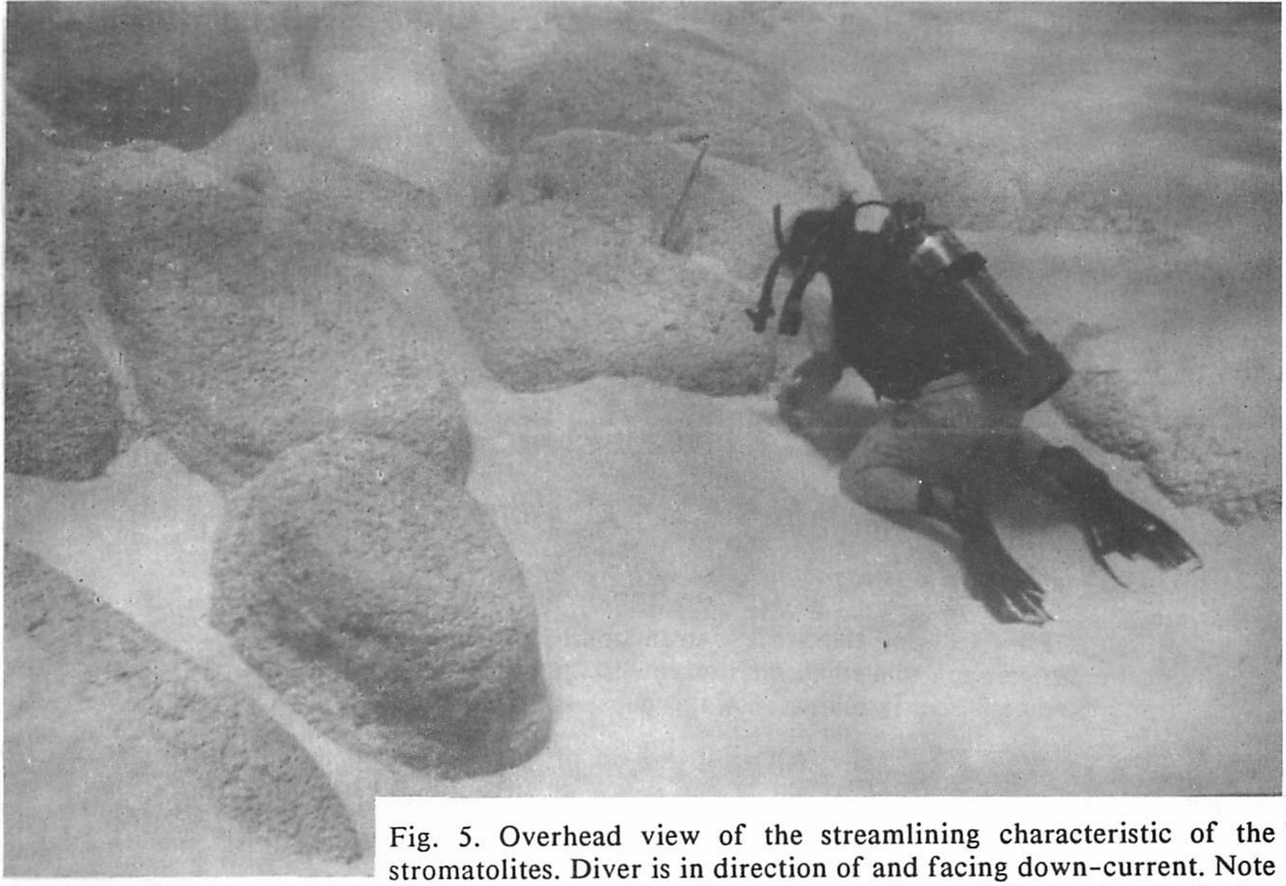

Fig. 5. Overhead view of the streamlining characteristic of the stromatolites. Diver is in direction of and facing down-current. Note that the bulbous side of the stromatolite to left of diver is facing up=current. Water depth is 6 m. Area B stromatolites. (photo by R.F. Dill)

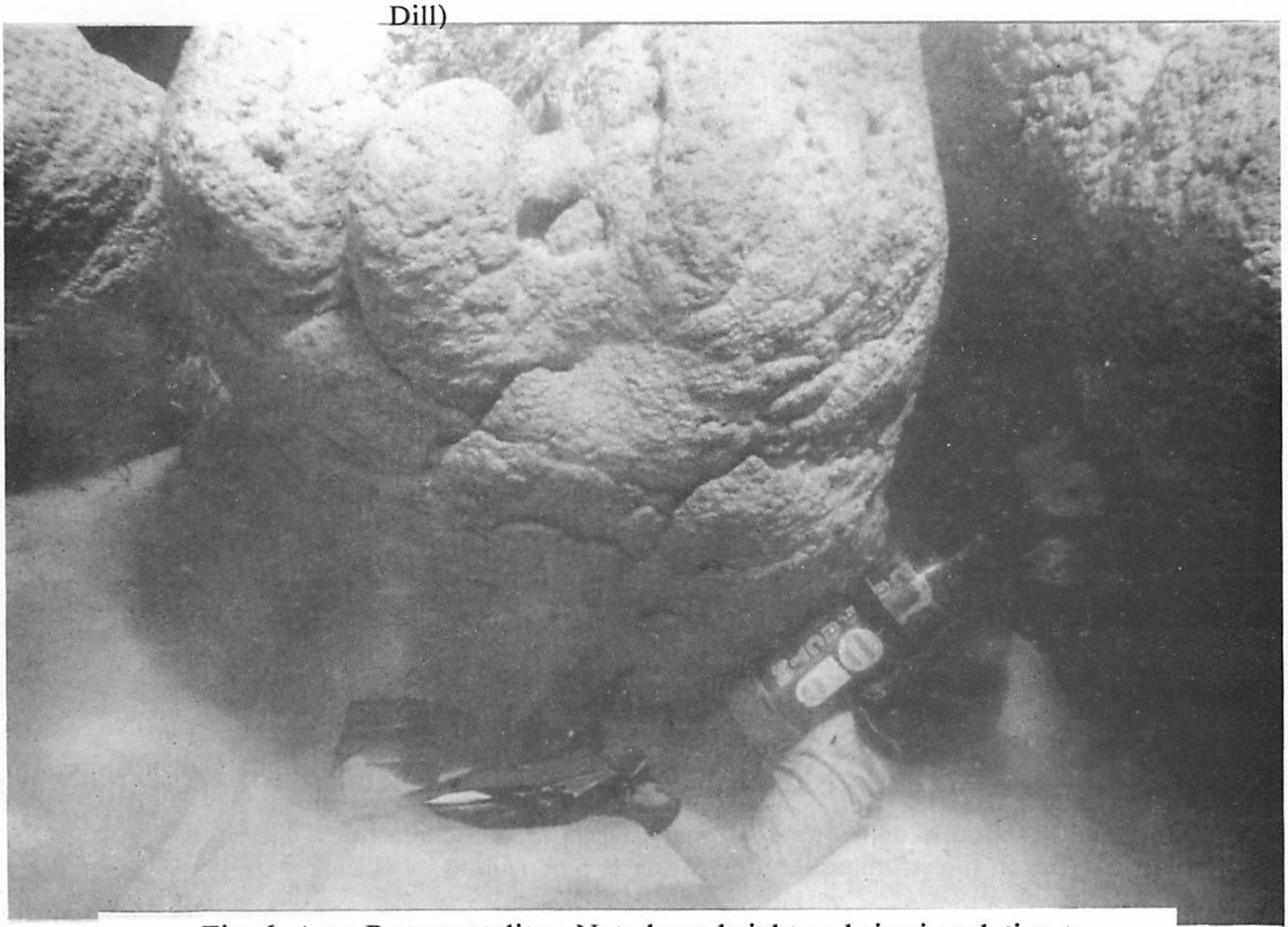

Fig. 6. Area B stromatolites. Note large height and size in relation to the diver. Shingle-like features are seen growing off of the main domal form above diver's feet. Also note the close spacing of the stromatolites. Water depth is 6 m. (photo by R.F. Dill)

Fig. 7. Plan view of the area A stromatolites protruding out of a rubble-zone next to a small sand wave. Stromatolites are 80 cm high and average 30 cm in diameter. Water depth is 6.5 m.

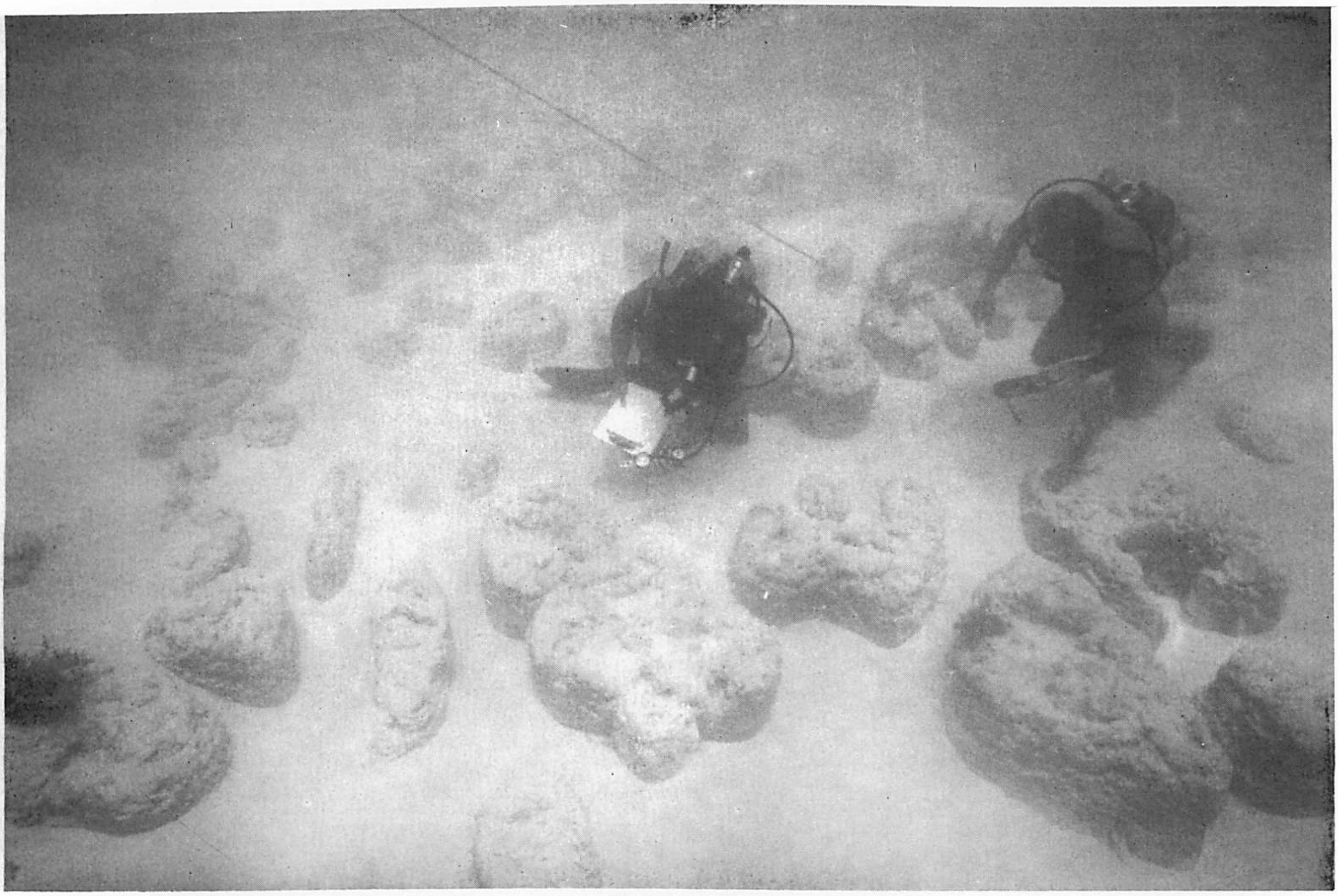

Fig. 8. Small, randomly distributed stromatolites in area C. Note the "molar" cavities in the stromatolite tops. Water is 6 m. (photo by R.F. Dill)

Fig. 9. Plan view showing molar cavities in the top of a stromatolite, area D. Note refraction of ripples around stromatolites. Water depth 6 m.

Middle Proterozoic (Horodyski, 1977)]. These variations must be linked to the physical stress exerted upon their biological constituents by the high velocity currents in the area because the internal characteristics between the above stromatolites are remarkedly different (Griffin and Awramik, 1988). Therefore, these variations may be used to infer environmentally induced physical stresses that existed in similiar paleochannel environments. One other possible model can be developed by assuming that these physical stresses are variable due to the proximity of the platform margin to the island/channel system, and therefore the Lee Stocking stromatolites offer one analog for interpreting environmental parameters that acted on ancient carbonate bank margins. However, a more rigorous study of the processes by which they form and the events that lead to their preservation is needed to establish the Lee Stocking Island analog for the comprehensive stromatolite facies model.

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