

<b>FACIES</b>	<b>33</b>	1-18	Pl. 1-7	1 Fig.	1 Tab.	<b>ERLANGEN 1995</b>
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## **Modern Marine Stromatolites in the Exuma Cays, Bahamas: Uncommonly Common**

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KEYWORDS: STROMATOLITE – THROMBOLITE – BAHAMAS – HOLOCENE OR RECENT

### **SUMMARY**

Modern stromatolites in open marine environments, unknown until recently, are common throughout the Exuma Cays, Bahamas. They occur in three distinct settings: subtidal tidal passes, subtidal sandy embayments and intertidal beaches. These stromatolites have a relief of up to 2.5 m and occur in water depths ranging from intertidal to 10 m. Surfaces near the sediment-water interface are typically colonized by cyanobacterial mats, whereas high relief surfaces are commonly colonized by algal turf and other macroalgae such as *Batophora*, *Acetabularia*, and *Sargassum*. The internal structure of the stromatolites is characterized by millimeter-scale lamination defined by differential lithification of agglutinated sediment. In thin section, the lithified laminae appear as micritic horizons with distinct microstructures: they consist of thin micritic crusts (20-40  $\mu\text{m}$  thick) overlying layers of micritized sediment grains (200-1000  $\mu\text{m}$  thick); the micritized grains are cemented at point-contacts and are truncated along a surface of intense microboring. The Exuma stromatolites are built by cyanobacterial-dominated communities. These laminated prokaryotic structures grade to unlayered thrombolites built by eukaryotic algae. The variety of sites, settings and shapes of stromatolites in the Exuma Cays present excellent opportunities for future studies of stromatolite morphogenesis.

### **1 INTRODUCTION**

Stromatolites are macroscopically layered, lithified sedimentary structures formed by interactions of microbes and sediment. These structures potentially contain records of the interactions of geological and biological

processes for the 3.5 billion year history of life on this planet (AWRAMIK, 1992). Interpretation of ancient stromatolites is, however, presently limited by what has been described as a "profound ignorance regarding the morphogenesis of Holocene stromatolites" (WALTER 1983, p. 212).

Living examples of ancient stromatolites were unknown in modern marine environments less than 35 years ago. The first examples of modern stromatolites comparable in size and shape to ancient examples were discovered in a hypersaline lagoon, at Shark Bay, western Australia (LOGAN, 1961). The Shark Bay discovery strongly influenced interpretation of ancient stromatolites: for the next 20 years, these structures were generally interpreted as nearshore deposits formed in hypersaline environments like those at Shark Bay (WILSON, 1975).

Discoveries of stromatolites in open marine settings in the Bahamas in the 1980's provided important new analogs for stromatolite interpretation. DRAVIS (1983) reported the occurrence of subtidal stromatolites forming on a high energy platform margin in the Schooner Cays, on the east margin of Exuma Sound (Fig. 1). This discovery was followed by reports of stromatolites in the Exuma Cays, on the west margin of Exuma Sound. DILL et al. (1986) described subtidal stromatolites in the vicinity of Lee Stocking Island, in high energy settings similar to those in the Schooner Cays. In addition, REID & BROWNE (1991) documented intertidal stromatolites in a fringing reef complex at Stocking Island.

In the present paper, we report a variety of new stromatolite locations throughout the Exuma Cays. The new sites provide expanded opportunities for future studies that will allow fundamental questions of stromatolite development in modern marine environments to be addressed. Such studies are long overdue and will provide essential data for interpreting the early history of life on Earth.

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Location	Site# (Plates 1-6)	Depth	Maximum Height	Shapes	Dominant Surface Community
<b>I. Subtidal: Tidal Channels</b>					
<i>Lee Stocking area, Pl. 1/1-2</i> (Dill et al., 1986 and numerous subsequent papers)					
<b>Adderly Channel</b>	1	3.5-10 m	2.5 m	columnar, molar, linear	high relief stromatolites: <i>Batophora</i> and <i>Sargassum</i> low relief: <i>Schizothrix</i> mats
<b>Iguana Key</b>	2	4-6 m	1 m	columnar	<i>Sargassum</i> and other macroalgae
<b>Bock Cay</b>	3	2.5 m	1 m	linear, columnar	<i>Batophora</i> , <i>Sargassum</i>
<i>Bell Island area, Pl. 2</i>					
<b>South Halls Pond</b>	4	2-4 m	2.5 m	columnar, molar, ridge conforming	high relief stromatolites: <i>Batophora</i> and <i>Sargassum</i> low relief: <i>Schizothrix</i> mats
<b>Conch Cut</b>	5	2-3 m	~1 m	columnar, molar	viewed from boat only
<i>Warderick Wells area, Pl. 3</i>					
<b>Warderick Wells</b>	6a	0-1 m	0.5 m	columnar	<i>Schizothrix</i> mats, <i>Batophora</i>
	6b	2-3 m	1 m	columnar, molar, linear	corals, sponges, <i>Sargassum</i>
<b>south Warderick Wells</b>	7	1-5 m	1.5 m	columnar, molar, linear	<i>Schizothrix</i> mats, <i>Batophora</i>
<b>White Bay Cay</b>	8	3-4 m	1 m	columnar, ridge conforming	<i>Batophora</i> , some coral
<b>Warderick Wells-Halls Pond cut</b>	9	2-4 m	~1 m	columnar	viewed from boat only
<b>Long Rock, Wide Opening</b>	10	< 5 m	~1 m	molar, columnar	viewed from boat only
<b>II. Subtidal: Sandy Embayment</b>					
<b>Little Darby, Pl. 4</b>	11	1.5-2 m	0.5 m	columnar, linear	<i>Schizothrix</i> mats, <i>Batophora</i> , <i>Acetabularia</i> , and other algae
<b>III. Intertidal</b>					
<b>Stocking Is., Pl. 5</b> (REID & BROWNE, 1991)	12	exposed at low tide	1 m	tabular, columnar	<i>Schizothrix</i> mats, turf algae
<b>Highborne Cay, Pl. 6</b>	13	exposed at low tide	1 m	tabular, columnar	<i>Schizothrix</i> mats, <i>Cladophoropsis</i>
<b>Lee Stocking Is., Pl. 1/3</b>	14	exposed at low tide	0.3 m	tabular	<i>Schizothrix</i> mats and <i>Gardnerula</i>

Table 1. Stromatolite localities in the Exuma Cays, Bahamas

## 2 METHODS

Potential stromatolite localities in the Exuma Cays were identified on aerial photographs at a scale of 1:36,000, obtained from the Bahamas Lands and Survey Dept. Subsequently low-level color air photographs were taken from a small aircraft chartered out of Georgetown, Great Exuma. All promising sites were ground-truthed using the R/V Calanus and small motor boats. Snorkeling and SCUBA gear allowed detailed observations and sample collection at many of the subtidal localities; an underwater pneumatic drill was used to collect well indurated samples. At a few sites, the bottom was observed only with an underwater viewer from a small boat. Stromatolite morphology was classified simply as columnar, tabular or linear; columnar forms include pillars, vase or club-shaped stromatolites and 'molar' structures, characterized by ridges around a central depression (GRIFFIN, 1988).

All samples collected were slabbed to observe internal structure and petrographic thin sections were made of more than 150 specimens. Microbial mats collected from

the surfaces of many of the stromatolites were examined using phase contrast microscopy to identify dominant microorganisms.

## 3 SITE LOCATIONS AND MACROSTRUCTURE

The Exuma Cays form a northwest-southeast trending chain of islands on the eastern rim of Great Bahama Bank, along the west margin of Exuma Sound (Fig. 1). Stromatolites in the Exuma Cays occur in three distinct settings: subtidal sites in tidal passes, subtidal sites in sandy embayments, and intertidal sites along sandy beaches (Table 1).

### 3.1 Subtidal sites in tidal passes (Table 1, Sites 1-10; Pls 1-3)

The most common occurrence of Exuma stromatolites is within actively migrating ooid shoals in tidal passes between islands; current velocities in these cuts range up to 150 cm/sec (DILL 1991). The stromatolites in the vicin-

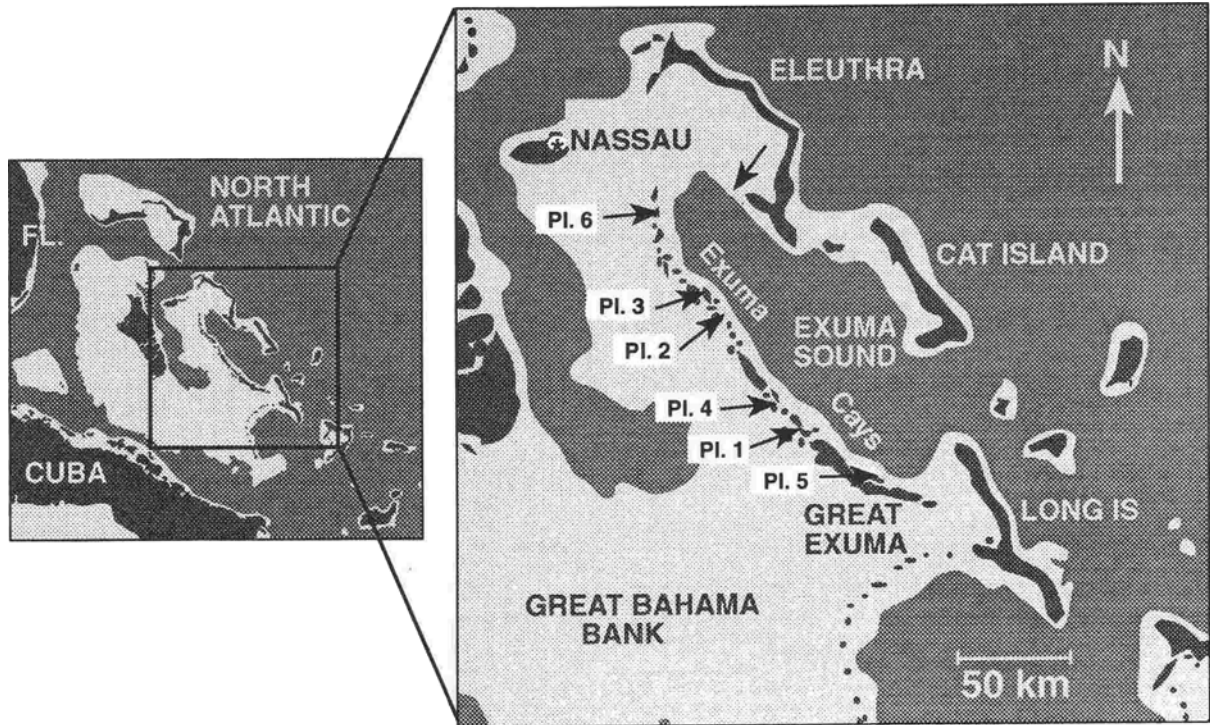


Fig. 1. Distribution of stromatolite localities in the Exuma Cays, on the west margin of Exuma Sound; specific sites are mapped and illustrated in Plates 1 to 6. The arrow on the northeast margin of Exuma Sound indicates the Schooner Cays, where stromatolites in open marine environments were first discovered by DRAVIS (1983).

ity of Lee Stocking Island (Pl. 1) have been described in numerous studies (e.g. DILL et al., 1986; DILL 1991; GRIFFIN, 1988; SHAPIRO, 1991; BROWNE, 1993). In addition to the Lee Stocking area, subtidal stromatolites in tidal passes also occur in a variety of locations in the Exuma Land and Sea Park (Pls 2, 3); although the occurrence of stromatolites in the Exuma Park was noted by DILL (1991), locations and descriptions of these stromatolites were not published. Depths of the stromatolites in tidal passes range up to 10 m, with some stromatolites at the north end of Warderick Wells (Table 1, Site 6a) breaking the surface at low tide. Most of the subtidal stromatolites are 0.5-1 m high, but they range from only a few centimeters (Pl. 2/1f) to 2.5 m (Pl. 2/1b, c). Maximum height of stromatolites in each locality is typically correlated with height of the surrounding sand waves, in accord with previous observations in the Lee Stocking area (DILL et al., 1986; DILL, 1991).

Subtidal stromatolites in tidal passes occur mainly as columnar and linear forms. Columnar stromatolites include straight-sided pillars (Pl. 3/2b), vase-shaped structures (Pl. 2/1c), and molar forms (Pl. 1/2b). Tall heads or columns are commonly asymmetric, appearing to 'lean' into the strong, incoming flood current (Dill et al., 1986; Shapiro, 1991); the upper portions of adjacent columns sometimes coalesce (Pl. 1/2a). The sides of some columnar stromatolites are characterized by overlapping, upward growing 'shingles' (GRIFFIN, 1988) or 'petals' (BROWNE, 1993). Most heads are relatively dense, solid structures, but some form more open leafy frameworks (Pl. 2/1f). Linear stromatolites form ridges that are both perpendicu-

lar (Site 4 and Site 8, Table 1) and parallel (Site 3, Table 1) to strong tidal currents. The cross-current linear features at South Halls Pond (Site 4) and White Bay Cay (Site 8) conform to underlying calcarenite ridges. The linear stromatolites at Bock Cay (Site 3), which were described by DILL et al. (1991), are reported to have developed on Pleistocene paleosols. In addition to linear ridges, columnar stromatolites coalesce to form linear walls perpendicular to tidal currents (e.g. DILL et al., 1986; BROWNE, 1993). Columnar stromatolites typically form on pieces of hardground (Pl. 2/1f), conch shells or other rubble.

The upper surfaces of stromatolites in tidal passes are commonly covered with cyanobacterial mats composed dominantly of *Schizothrix* sp. Some mats form small knobs or pillars with a relief of several centimeters (Pl. 1/2d). On other stromatolites, typically those with significant relief above the sandy bottom, *Schizothrix* mats are absent or poorly developed. The upper surfaces of these stromatolites are colonized by diverse communities, consisting of macroalgae, such as *Batophora* sp. and *Sargassum* sp. (Pls 1/2a, c; 3/2b), corals, sponges (Pl. 3/1b), diatoms and/or feather duster worms. The sides of subtidal stromatolites are typically colonized by a brown microbial mat consisting mainly of an unidentified unicellular coccoid eukaryotic organism, encrusting red algae and worm tubes (BROWNE, 1993).

The internal structure of subtidal stromatolites in tidal passes is characterized by millimeter-scale lamination defined by differential lithification of agglutinated sediment. Lithified laminae are generally less than 1 mm thick.

Laminae are typically convex upward and are discontinuous (Pl. 3/2d); some form digitate structures 1-3 cm wide and several centimeters high (Pl. 1/2c).

Although layering is a characteristic feature of stromatolites and is well developed in many subtidal structures, some subtidal microbial buildups lack any indication of lamination and others show only patchy development of layering. In some cases, the lack of layering is a result of boring activities by organisms such as molluscs or sponges and infilling of the bore holes with unlaminated sediment. In other cases, the unlayered structures are original microbial deposits, which are designated as 'thrombolites', following FELDMANN & MCKENZIE (1994) and FELDMANN (1995). Microstructures of the stromatolites are distinct from those of the thrombolites; these differences are discussed in a subsequent section.

### 3.2 Subtidal sites in sandy embayments

(Table 1, Site 11; Pl. 4)

In contrast to the current-swept setting of the stromatolites described above, subtidal stromatolites at Little Darby

Island occur in a sandy embayment that lacks strong currents. Such a setting for modern marine stromatolites is previously unknown. The Little Darby stromatolites occur in 0.5-2 m water depth on an otherwise bare, rippled sand bottom. The stromatolites are about 0.5 m high and occur as pillars and vase-shaped columnar structures and oblong ridges of coalesced columns perpendicular to the beach (Pl. 4/1b-d). The substrate for these stromatolites is unknown. *Schizothrix* mats are well developed on the upper surfaces of many of the Darby stromatolites (Pl. 4/1e), although some of the nearshore buildups are extensively colonized by *Batophora*, *Acetabularia*, and minor *Halimeda*. The internal structure of the Darby stromatolites shows well developed, fine-scale lamination with knobby to digitate features (Pl. 4/1f).

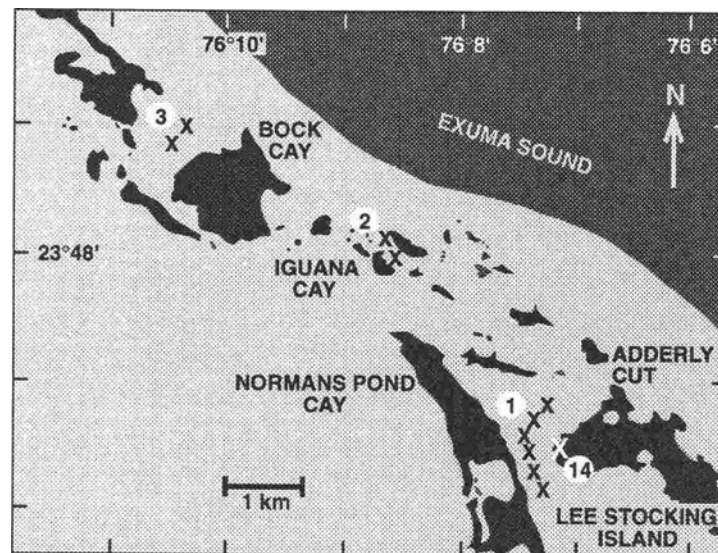
### 3.3 Intertidal sites along sandy beaches

(Table 1, Sites 12-14; Pls 1/3, 5, 6)

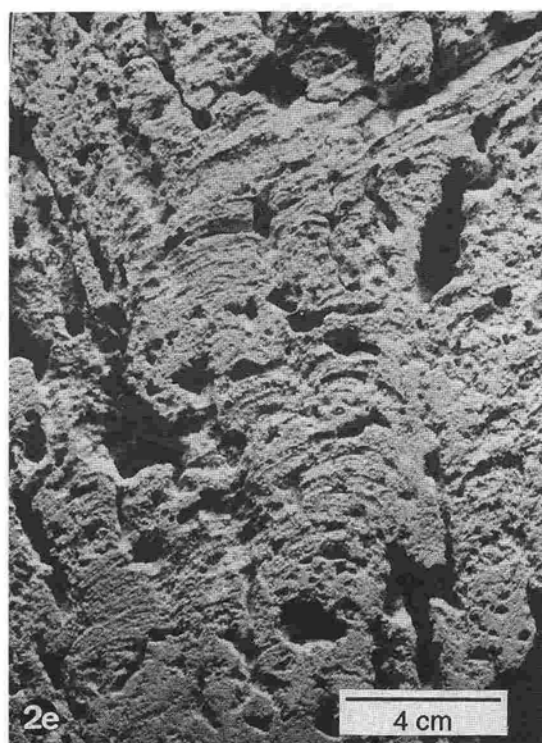
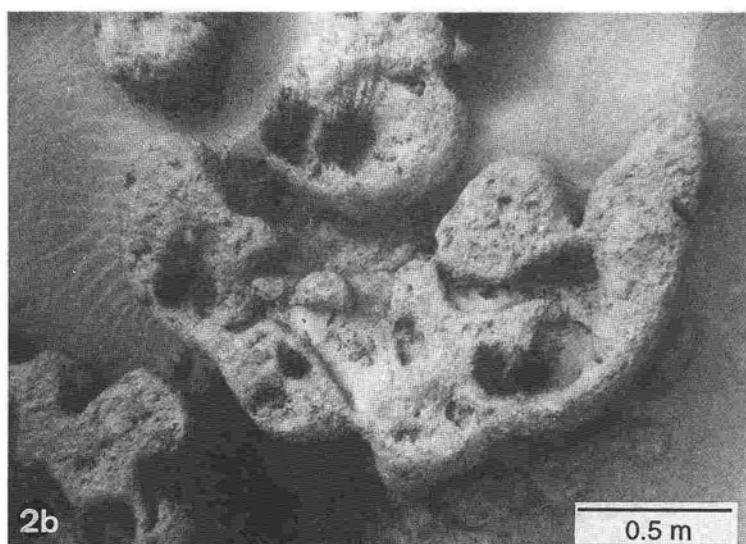
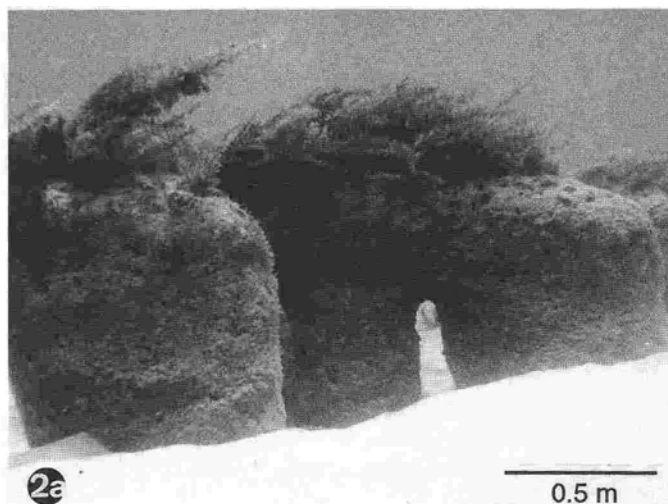
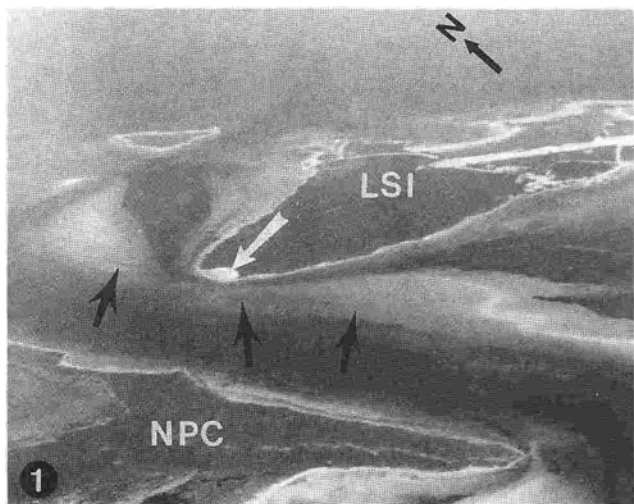
Intertidal stromatolites are extensively developed along beaches at Stocking Island (Table 1, Site 12; Pl. 5; REID & BROWNE, 1991) and at a newly discovered locality at

#### Plate 1

Stromatolites in the vicinity of Lee Stocking Island. Index map- stromatolite sites, as listed in Table 1, are indicated with x's.



- Fig. 1. Aerial photograph of the channel between Lee Stocking Island (LSI) and Normans Pond Cay (NPC). Subtidal stromatolites (Site 1) occur within the ooid shoal in the tidal channel (black arrows). Intertidal stromatolites (Site 14; Fig. 4) occur on the small beach on Lee Stocking Is. (white arrow).
- Fig. 2. Subtidal stromatolites in tidal channels; Figs. 2a-d are underwater photographs.  
 Fig. 2a: Columnar stromatolites at Iguana Cay (Site 2); note that adjacent columns are coalescing and that the surfaces of these high-relief structures are colonized by *Sargassum*.  
 Fig. 2b: Molar stromatolite in Adderly Cut channel (Site 1).  
 Fig. 2c: Linear stromatolites about 1 m high at Bock Cay (Site 3) colonized by *Sargassum*.  
 Fig. 2d: Knobby *Schizothrix* mat on the surface of a low relief stromatolite in Adderly Cut channel; finger in upper left points to knob.  
 Fig. 2e: Slabbed section of a sample from Adderly Cut showing the fine scale lamination and digitate structures that characterize these subtidal stromatolites.
- Fig. 3. Intertidal stromatolite with a relief of ~30 cm on a beach at Lee Stocking Island (Site 14); surface is colonized by *Schizothrix* and *Gardnerula* cyanobacteria; pen in lower right is 15 cm.



Highborne Cay (Site 13, Table 1; Pl. 6). The stromatolites at these locations form back-reef and reef-flat facies of algal ridge fringing reefs that extend for more than 1 km along the shores (Pl. 5/1; Pl. 6/1). In addition to the reefal sites, two isolated intertidal stromatolites occur on a beach at Lee Stocking Island (Site 14, Table 1; Pl. 1/3).

Intertidal stromatolites occur mainly as columnar and tabular forms. In at least some cases, tabular stromatolites are formed by coalescing columns. Stromatolites in the Stocking Island reef complex are up to a meter thick and began forming approximately 1500 years ago. Lithologies identified in eight cores from across this reef, together with plots of 13 radiocarbon dates in relation to a Bahamian sea-level curve (MACINTYRE et al., 1993, and in press), indicate that the reef began as an intertidal vermetid buildup on a Pleistocene terrace. Subsequent flooding of the terrace allowed the branching coralline alga *Neogoniolithon strictum* to overgrow the vermetids and eventually form an emergent algal ridge. Stromatolites formed, and continue to grow, in the lee of the algal ridge, in shallow lagoons characterized by migrating beach sand.

The surfaces of the intertidal stromatolites are colonized primarily by microbial mats dominated by *Schizothrix* (Pl. 5/2a, Pl. 6/2). These cyanobacterial mats sometimes grade laterally to communities dominated by diminutive turf algae, such as *Ernodesmis verticillata*, *Laurencia papillosa* and *Cladophoropsis macromeres* (Pl. 5/3a). In general, turf algae are more common on buildups with significant relief or subaerial exposure, whereas low lying

stromatolites close to the shoreline, which are continually buried and unburied by migrating beach sand, are colonized almost exclusively by *Schizothrix*-dominated communities.

Like the subtidal stromatolites, the internal structure of intertidal stromatolites is characterized by millimeter scale laminations reflecting differential cementation of sediment. Laminations in the intertidal structures are, however, generally thicker than in subtidal stromatolites (Pl. 5/2b, Pl. 6/2c), with the distance from the top of one lithified layer to another being 1-5 mm, compared ~0.5 mm in subtidal stromatolites. Laminations tend to be flat or convex upwards; knobby or digitate structures, which are common in subtidal stromatolites are lacking in intertidal buildups. Disruption of lamination by boring organisms is common. In addition, as in subtidal environments, microbial buildups range from well layered stromatolites to poorly or unlaminated reworked stromatolites and thrombolites (Pl. 5/3b; Pl. 6/3).

#### 4 MICROSTRUCTURE

Microstructures of subtidal and intertidal stromatolites are similar. Both are composed dominantly of well sorted, fine sand, 100-250  $\mu\text{m}$  in size; this sediment contrasts with the coarser (sand to gravel-size), poorly sorted, sediment in cavities within these structures and on the adjacent sea floor. Lithified laminations in the stromatolites, which are

#### Plate 2

Subtidal stromatolites in tidal channels in the vicinity of Bell Island. Index map- stromatolite sites, as listed in Table 1, are indicated with x's; both sites are within the Exuma Cays Land and Sea Park.

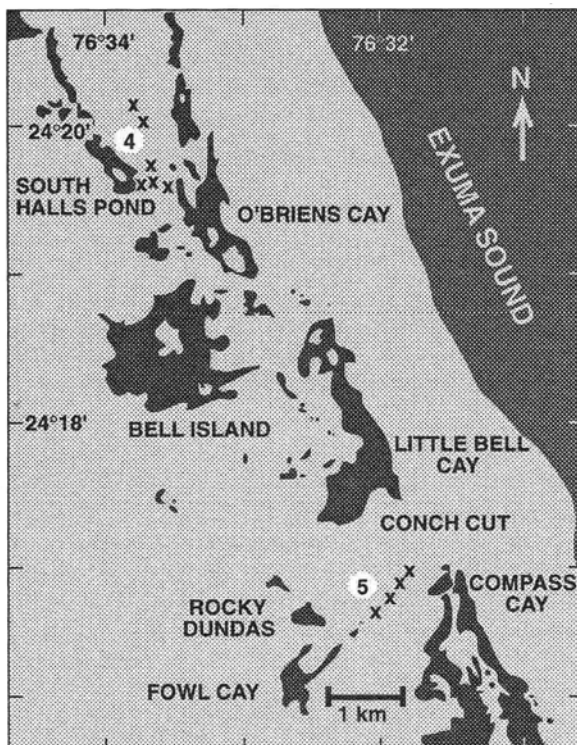


Fig. 1. Stromatolites in the channel between South Hall's Pond Cay and O'Briens Cay (Site 4).

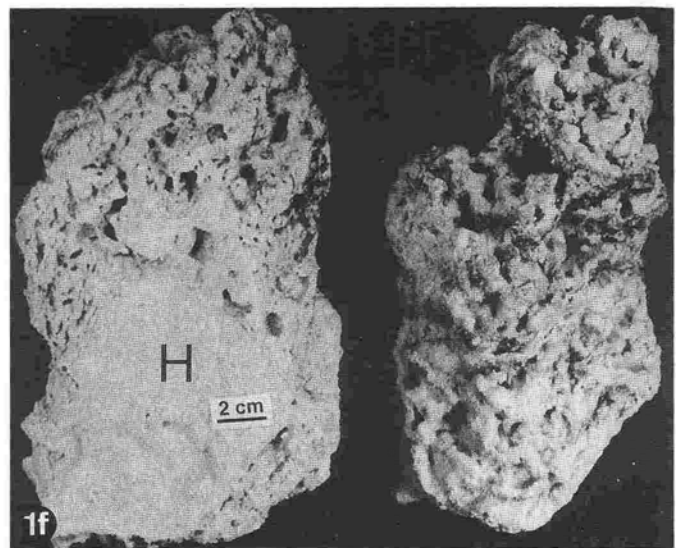
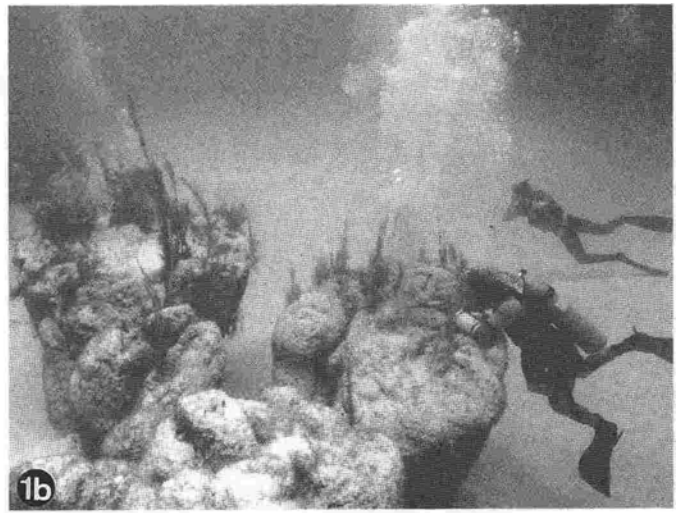
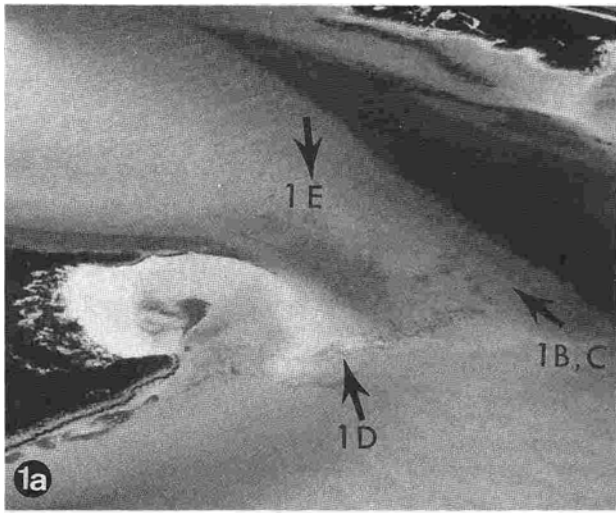
Fig. 1a: Aerial photograph showing that the stromatolites (arrows) occur within an actively migrating ooid shoal; letters indicate corresponding figures.

Fig. 1b and 1c: Large columnar stromatolites colonized by *Sargassum* in about 4 m water depth near the edge of the ooid shoal.

Fig. 1d: Stromatolites coating a ridge that extends from the point of land on South Halls Pond Cay.

Fig. 1e: Early stages of development of columnar stromatolites forming on a hardground in the trough of a migrating sand wave; hammer handle is 35 cm.

Fig. 1f: Slabbed section of a sample from Fig. 1e, showing that the stromatolite formed on a piece of hardground rubble (H); this stromatolite has an open, leafy growth form.



prominent in hand specimens, are subtle in thin section, but once recognized, are distinct. The lithified layers correspond to micritic horizons with characteristic petrographic features. The tops of the micritic horizons are typically defined by thin micrite crusts (20-40  $\mu\text{m}$ ), which bridge grains and can be traced laterally in a thin section for several centimeters (Pl. 7/1); these crusts are commonly encrusted by *Ostreobium*, foraminifera and/or coralline algae. The micrite crusts generally overlie a layer of micritized sediment grains, 200-1000  $\mu\text{m}$  thick, which are cemented at point-contacts and are truncated along a surface of intense microboring (Pl. 7/2). The zone of micritized grains extends well below the densely microbored surface and consists of grains that have lost all evidence of their original color and texture. In plane polarized light, these micritized grains appear gray brown, contrasting with the golden brown color of most unaltered grains (Pl. 7/1).

Micritization of grains in the micritic horizons is more readily apparent in intertidal than in subtidal stromatolites. Because of the closer spacing of lithified laminae in subtidal stromatolites, most of the grains are micritized and there is no distinct alternation of gray brown and golden brown bands, as seen in intertidal stromatolites (Pl. 7/1). Another difference between intertidal and subtidal stromatolites is that calcified filaments of cyanobacteria

are common in some intertidal stromatolites (Pl. 7/2a), but were not observed in subtidal structures.

Initial lithification of the stromatolites results from the periodic formation of micritic horizons, involving precipitation of micrite crusts and micritic point-contact cements between micritized grains. In highly indurated layers, outlines of the micritized grains become indistinct and the grains appear welded together (Pl. 7/1b). Subsequent hardening of the entire stromatolite occurs by processes of submarine lithification associated with precipitation of micritic infillings, commonly with peloidal textures, in interstitial spaces and acicular aragonite rim cements (crystal length 10-20  $\mu\text{m}$ ) in sediment-filled cavities.

The fine-grained laminated microfabric of the stromatolites is identical to that observed in living *Schizothrix* mats, which colonize the surfaces of many of these structures; in particular, many of the *Schizothrix* mats have crusty to hard surfaces, which, in thin section, are seen to correspond to micritic horizons. In contrast, reworked stromatolites and thrombolites are generally poorly sorted, with an abundance of medium and coarse sand and even gravel-sized sediment, which is commonly fringed with aragonite cement (Pl. 7/3a). In addition, micritic horizons in these poorly layered deposits are absent or poorly developed, occurring only in isolated patches. A diagnostic feature of many of the thrombolites is the occurrence of

Plate 3 Subtidal stromatolites in tidal channels in the vicinity of Warderick Wells. Index map- stromatolite sites, as listed in Table 1, are marked with x's, all sites are in the Exuma Cays Land and Sea Park.

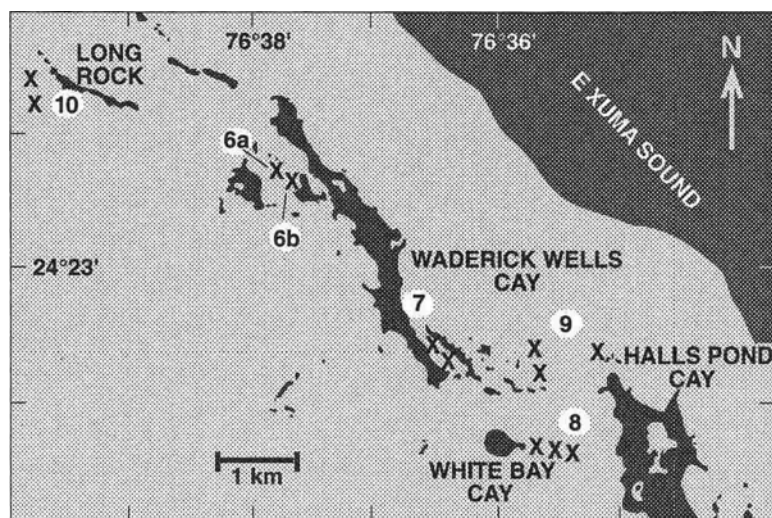


Fig 1.

Sites 6a and 6b, at the north end of Warderick Wells.

Fig 1a: Aerial view showing the spectacular sand accumulations in this area; stromatolite sites are indicated by arrows. The Exuma Park headquarters building is on the point of land in the lower left; a sea plane is in the bay to the right.

Fig 1b: Underwater photograph of a stromatolite colonized by corals and sponges at Site 6b. Stromatolites at this site are being actively bioeroded; when sectioned, they show almost

Fig. 2.

no original lamination. Hammer handle is 35 cm.

Site 7, at the south end of Warderick Wells.

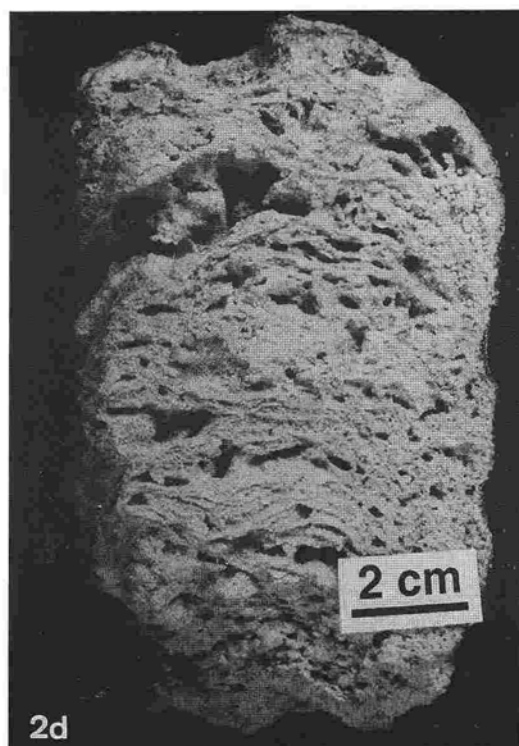
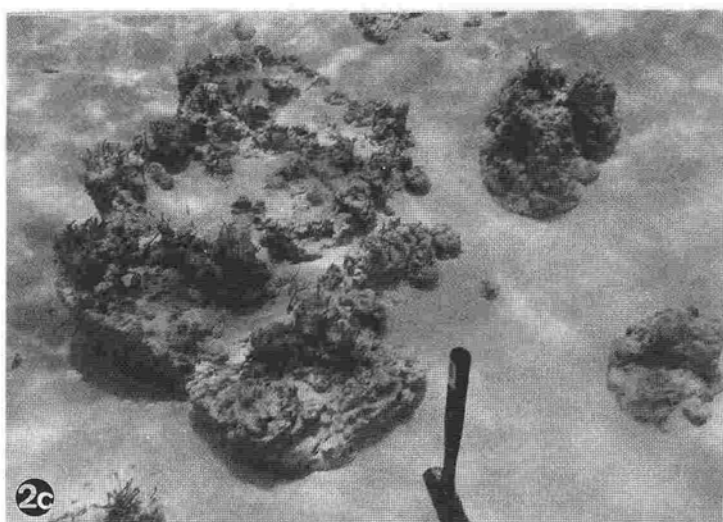
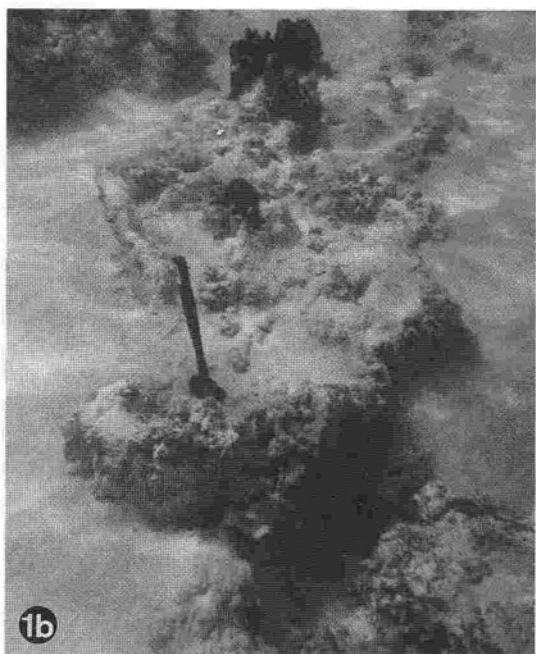
Fig. 2a: Aerial view showing that the stromatolites (arrow) occur at the edge of an active ooid sand shoal; a sailboat is anchored in the upper left portion of the channel.

Fig. 2b: Underwater photograph of high-relief columnar stromatolites colonized mainly by *Batophora* and turf algae.

Fig. 2c: Underwater photograph of low-relief stromatolites colonized mainly by knobby *Schizothrix* mats, with scattered *Batophora*.

Fig. 2d: Slabbed sample with well developed, millimeter-scale lamination. Stromatolites in Fig. 2b and Fig. 2c are in water depths of about 2 m.





irregular millimeter-sized holes, suggestive of space originally occupied by algae; in addition, the encrusting green alga, *Ostreobium*, is extremely abundant in many thrombolites. Thrombolites in intertidal settings commonly contain abundant small (5-10  $\mu\text{m}$ ) and large (25-100  $\mu\text{m}$ ; Pl. 7/3) calcified filaments; these filaments may disrupt the continuity of intermixed micritic horizons (MACINTYRE et al., in press).

## 5 DISCUSSION AND CONCLUSIONS

Our observations of stromatolites throughout the Exuma Cays together with detailed studies at Lee Stocking Island (BROWNE, 1993) and Stocking Island (MACINTYRE et al., 1993, and in press) indicate that these laminated structures are built by cyanobacterial mats dominated by *Schizothrix*. Although surface communities vary according to the position of a stromatolite with respect to migrating sand waves or shifting beach sand (exposed surfaces on high relief structures are typically colonized by macroalgae and turf, whereas surfaces close to the sediment interface are colonized primarily by *Schizothrix*), BROWNE (1993) has shown that accretion of laminated fine sand is restricted to those surfaces colonized by *Schizothrix* mats. Moreover, thin section observations that both texture and microstructure of living *Schizothrix* mats are identical to those in 'fossil' portions of the stromatolites argue that the stromatolites were formed by these cyanobacterial mats.

Processes causing formation of lithified micritic horizons within *Schizothrix* mats are unknown and are a subject of continuing investigation. MACINTYRE et al. (in press) hypothesized that these horizons develop as a result of microbial activities within mature, stratified mats formed during hiatuses in sediment accretion. Micritization of

grains within the micritic horizons was suggested to be a pervasive process that occurs by processes of 'crystal alteration' (as documented by REID et al., 1992), rather than by precipitation in algal borings; alteration of size and/or shape of the original carbonate crystals within the micritized grains could have been induced by changes in pH within the cyanobacterial mats caused by diel variations in rates of photosynthesis and respiration. MACINTYRE et al. (in press) further hypothesized that the micrite crusts represent precipitation within organic films on the surface of a stable mat, or precipitation associated with microbial degradation of a surficial organic film. Similarities in thickness and texture of these crusts and micritic laminations in some ancient stromatolites (see, for example, WALTER, 1983, BERTRAND-SARFATI, 1976, and MONTY & MAS, 1981, who described micritic films 10 - 60  $\mu\text{m}$  thick in Archean, Riphean and Cretaceous stromatolites) suggest that biogeochemical processes creating both modern and ancient micritic laminae could be similar.

Our studies further indicate that stromatolites in the Exuma Cays are end members of a continuum of microbial deposits that range in degree of lamination from well layered (e.g. stromatolites in Pl. 1/2e, Pl. 3/2d, Pl. 4/1f, Pl. 5/2b; Pl. 6/2c) to totally unlayered (e.g. thrombolites in Pl. 6/3, Pl. 7/3). Whereas the stromatolites are products of cyanobacterial mats, the thrombolites are formed by algal turf and other eukaryotic algae. The role of eukaryotic algae in forming poorly layered microbial buildups has been recognized in previous studies (AWRAMIK & RIDING, 1988; RIDING et al., 1991). However, AWRAMIK, RIDING and others did not distinguish these poorly layered thrombolitic buildups from well laminated stromatolitic structures formed by cyanobacterial communities and consequently overlooked the role of cyanobacteria in creating the lamination.

The variety of sites, settings, and shapes of stromatolites

### Plate 4

Stromatolites in the sandy embayment at Little Darby Island. Index map- stromatolite site is marked by x's.

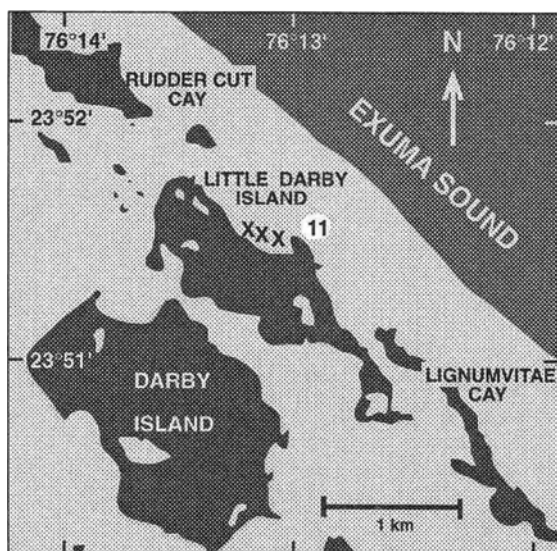


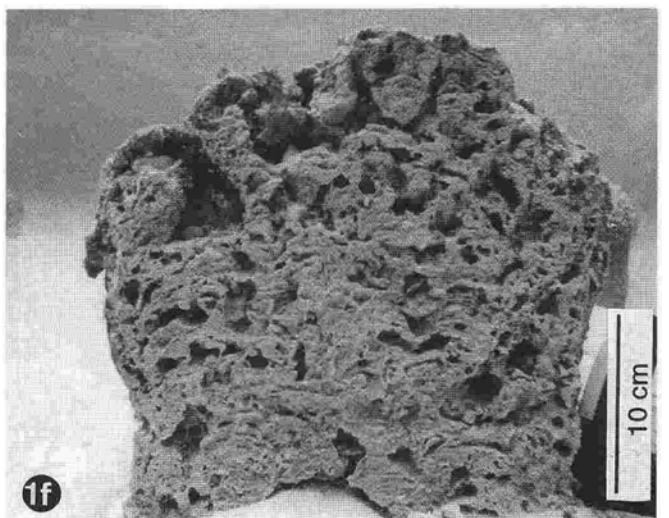
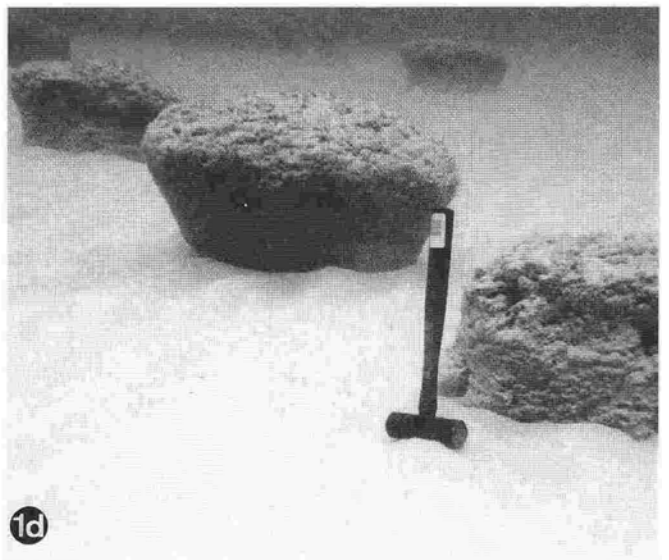
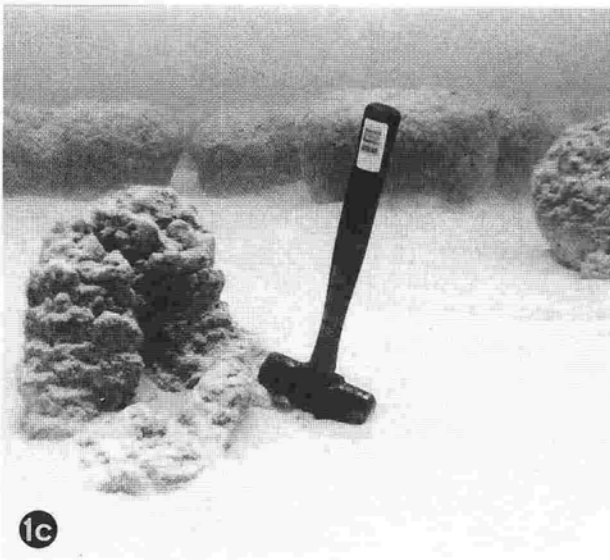
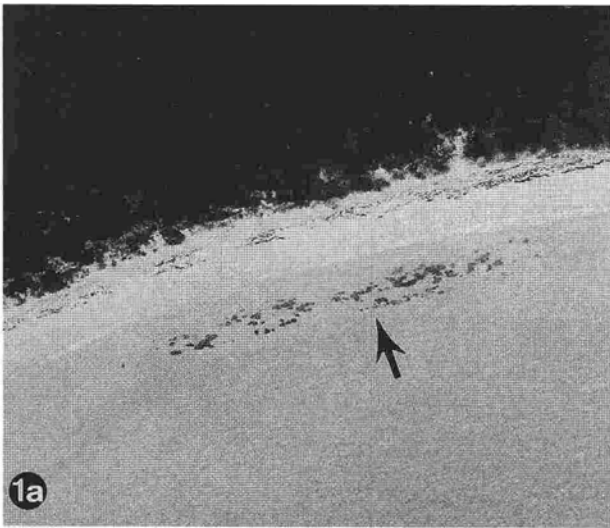
Fig. 1.

Fig. 1a: Aerial photograph showing stromatolites (arrow) close to the beach.

Figs. 1b-d: Underwater photographs of columnar stromatolites on a rippled sandy bottom; relief of the stromatolites is 0.25 to 0.5 m; water depth is less than 2 m. Some columns in Fig. 1b have coalesced to form linear structures; the columnar head in the foreground of Fig. 1c has shingled sides. Hammer handle is 35 cm.

Fig. 1e: Knobby *Schizothrix* mat on the surface of a stromatolite.

Fig. 1f: Underwater photograph showing the internal structure of a stromatolite that has been sawed in half; note the fine scale lamination and knobby to digitate structures.



in the Exuma Cays offer an opportunity to address long standing questions concerning stromatolite development. One such question concerns stromatolite morphology: what are the relative effects of environmental and biological factors in determining stromatolite shape? Previous studies of stromatolites in the vicinity of Lee Stocking Island suggested that morphology is controlled by currents (DILL et al., 1986; SHAPIRO, 1991) and wave energy (DILL et al., 1989). Our initial observations of sites throughout the Exuma Cays present a different perspective. We propose that although waves and currents may be important as secondary controls that streamline or modify stromatolite shapes, the primary factor controlling morphology is the underlying substrate. Stromatolite accretion begins on hard surfaces (shells, corals, pieces of hardground etc.; e.g. Pl. 2/1f), which occur as point sources. If the point sources are isolated, the stromatolites form individual heads. If the point sources are aligned in a linear trend, for example along a ridge or on lag deposits in a sand trough, the heads may eventually coalesce to form linear stromatolites, such as those at White Bay Cay and South Halls Pond. If the point sources occur on laterally extensive topographic features, such as fringing reefs, stromatolite heads coalesce to form tabular structures, such as those at Stocking Island. Detailed studies of stromatolite morphologies in the Exuma Cays is a prime area for further research.

Reasons for the unusual abundance of stromatolites in the Exuma Cays are uncertain, but one factor that is critical is sediment stress. Our observations that introduction of erect algae to the flat lying cyanobacterial mat community disrupts formation of continuous micritic horizons, which

create the characteristic laminated fabric of stromatolites, indicate that stromatolite formation necessitates exclusion of these algae. In the Exuma Cays, colonization of many hard substrates by biotic communities other than cyanobacterial mats is excluded by high rates of sediment movement (STENECK et al., 1993). All known stromatolite localities in the Exuma Cays, except one, occur in highly sediment stressed environments (Pl. 5/1). The exception is Little Darby Island. The occurrence of beautifully layered stromatolites draped with cyanobacterial mats in a shallow sandy bay at Little Darby Island (Pl. 4) is an enigma. There is no evidence of large migrating sand waves in this area and it is not known whether or not these stromatolites are periodically buried. If they are not buried, it would be important to know what prevents algal covers from colonizing these structures.

A second factor promoting widespread stromatolite growth in the Exuma Cays is syndepositional lithification of *Schizothrix* mats. Why cyanobacterial mats lithify to form stromatolites in the Exuma Cays but not in other areas of the Bahamas (e.g. GINSBURG, 1955; MONTY, 1965, 1967) or in other known normal marine settings is not known. Cementation processes are probably complex and may involve both oceanographic and biologic factors. As hypothesized above, formation of lithified micritic horizons within *Schizothrix* mats may be induced by microbial activities. On the other hand, general oceanographic conditions may be responsible for creating a water chemistry favorable for precipitation. It has been suggested the mixing of cool oceanic water from Exuma Sound and warm bank water causes degassing (loss of CO<sub>2</sub>), increase

Plate 5 Intertidal stromatolites and associated deposits in the fringing reef complex at Stocking Island. Index map- stromatolite site is marked with x's.

Fig. 1. Photographs taken at low tide showing varying degrees of sediment inundation in the back reef and reef flat in two successive years; arrows point to same location in each photograph.

Fig. 1a: Stromatolites, the major component of the back reef and reef flat zones, are largely unburied in 1993; waves are breaking on a submerged coralline algal ridge. Exposed area of reef is ~25 m wide.

Fig. 1b: A year later, stromatolites in the back reef and the inner part of the reef flat are covered by sand.

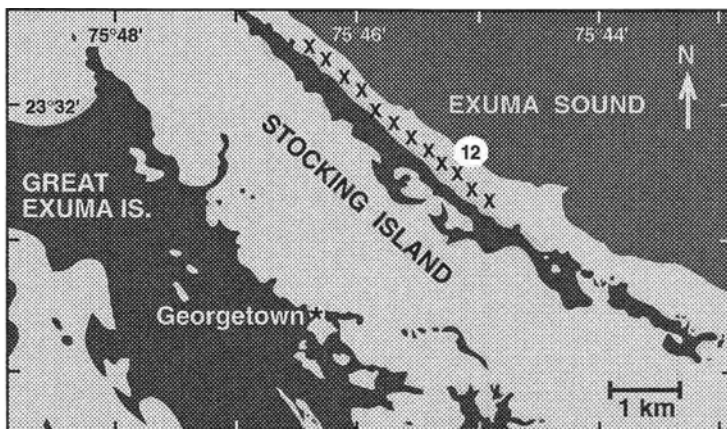
Fig. 2. Fig. 2a: Surface of back-reef stromatolite with pustular *Schizothrix* mat; photo taken at low tide.

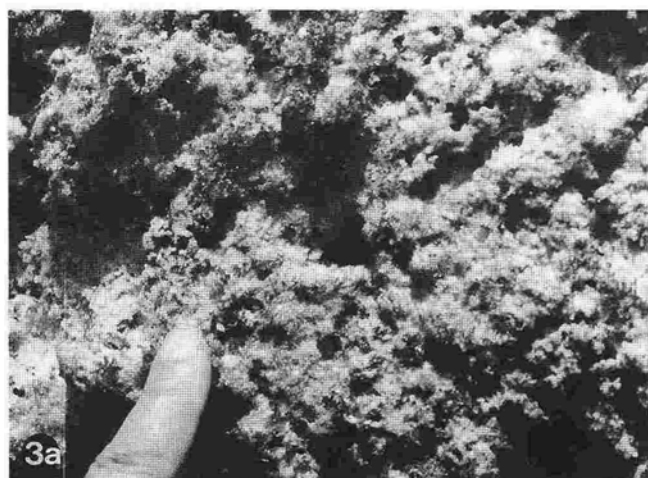
Fig. 2b: Cut section showing the internal structure of a back-reef stromatolite; note that the laminations,

which range from 1 to 3 mm, are thicker than in subtidal stromatolites (e.g. Pls 1/2e, 3/2d, 4/1f) and are not developed into digitate structures; laminae are disrupted by numerous bore holes.

Fig. 3. Fig. 3a: Diminutive turf algae on the surface of the reef flat.

Fig. 3b: Fractured surface of an unlaminated sample from the seaward edge of the reef flat. This could be a reworked stromatolite, in which original lamination has been obliterated by bioerosion by urchins, molluscs etc., or it could be a thrombolite built by algal turf.





in temperature, and resultant  $\text{CaCO}_3$  precipitation (WHITTLE et al. 1993; DILL 1991). The question of lithification is another critical area in need of further investigation.

## 6 SIGNIFICANCE

Stromatolites in the Exuma Cays, which are products of cyanobacterial mats, are potential analogs of ancient stromatolites, which are also thought to have been built by communities of phototrophic prokaryotes. Improved understanding of stromatolite morphogenesis in the diverse localities afforded by this region will undoubtedly lead to new insights into ancient stromatolites and the potential records of Earth history which they contain.

## ACKNOWLEDGEMENTS

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Plate 6 Intertidal stromatolites and associated deposits in the fringing reef complex at Highborne Cay. Index map- stromatolite site is marked with x's.

Fig 1. Aerial view of the fringing complex; stromatolites (arrows) occur shoreward of a coralline algal ridge, in the back reef zone; the dark patches seaward of the fringing reef are hardgrounds and patch reefs.

Fig 2. Fig.2a: Tabular stromatolites with smooth *Schizothrix* mats; these low-relief structures occur in the beach zone of shifting sand.

Fig. 2b: *Schizothrix* mats coating the zone shoreward of a coralline algae ridge with a relief of 20-30 cm. Photos Fig. 2a and Fig. 2b are taken at low tide.

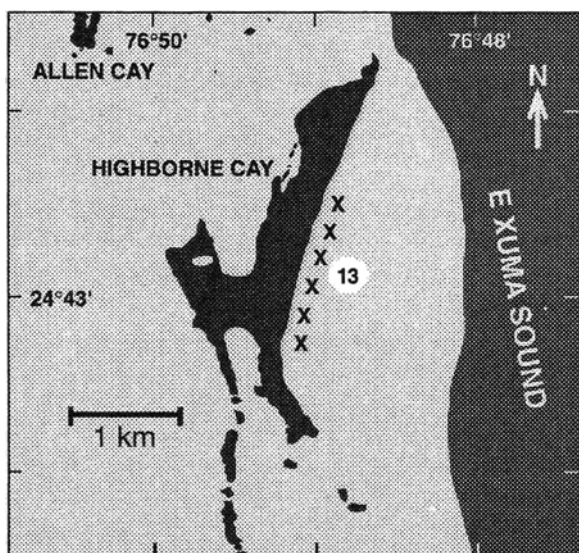
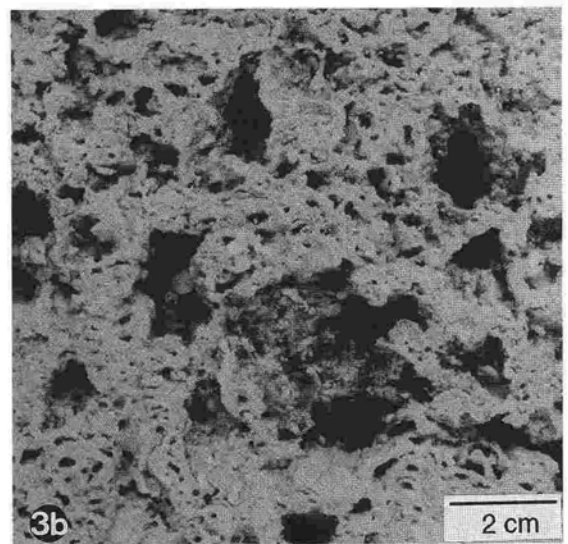


Fig. 2c: Fractured surface showing early stage of stromatolite formation; sediment below the smooth *Schizothrix* mat has a laminated fabric created by preferential lithification of sediment.

Fig. 3a: High relief (0.3-0.5 m) thrombolites, which occur together with stromatolites in the back-reef zone. These buildups are referred to as 'cauliflower' mounds due to their knobby appearance; they are colonized mainly by *Cladophoropsis* sp.

Fig. 3b: Cut section showing the internal structure of a sample from a 'cauliflower' mound; lamination is absent or poorly developed in these thrombolitic structures, which are permeated with small holes (see also Pl. 7/3b).



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## Plate 7

### Microstructures of stromatolites and associated thrombolites.

- Fig 1. Thin section photomicrographs of stromatolites; plane polarized light.  
 Fig. 1a: Micritic horizon in an intertidal stromatolite from Highborne Cay; this horizon consists of a micrite crust (arrow), which overlies a layer of micritized (gray) grains; unaltered grains in adjacent layers appear golden brown.  
 Fig. 1b: Subtidal stromatolite from Iguana Cay (Site 2), with closely spaced micritic crusts; note that most of the grains in this sample are micritized; extensively micritized grains in the lower layers appear welded together.
- Fig. 2. Photomicrographs showing the truncated surface that characteristically occurs at the top of micritized layers in subtidal and intertidal stromatolites; samples are from Stocking Island.  
 Fig. 2a: Thin-section view in crossed nicols showing truncation of grains (arrows). Note also the abundance of calcified filaments, which are about 10  $\mu\text{m}$  in diameter and probably of cyanobacterial origin; these filaments are common in some intertidal stromatolites, but were not observed in subtidal stromatolites.  
 Fig. 2b: Scanning electron photomicrograph showing the intense microboring that is responsible for grain truncation; note that the microborings are generally restricted to the upper surface of the grains.
- Fig. 3. Thin section photomicrographs of thrombolites; plane polarized light.  
 Fig. 3a: Poorly sorted sample from the reef flat at Stocking Island; note the aragonite fringe cements, which appear as dark coatings (arrows) around many many of the grains, and the large calcified algal filament.  
 Fig. 3b: Sample from a 'cauliflower' mound at Highborne Cay (see Pl. 6/3); note the abundance of calcified algal filaments, which may serve to baffle and trap sediment.



