PROCEEDINGS
OF THE
FIFTH SYMPOSIUM
ON THE
NATURAL HISTORY OF THE BAHAMAS

Edited by
Lee B. Kass

Conference Organizer
Daniel R. Suchy

Bahamian Field Station, Ltd.
San Salvador, Bahamas
1994

Cover photo by
Sandra Buckner

Printed in USA by Don Heuer

ISBN 0-935909-52-4

STROMATOLITES OF THE BAHAMAS

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ABSTRACT

Stromatolites are mats of cyanobacteria that trap and/or precipitate sediments to form "blue-green algal reefs". So far stromatolites have been found on or near four Bahamian islands: San Salvador, Andros, Great Exuma and Eleuthera. During 1992 I visited the habitats of stromatolites from all these islands and located stromatolites on all islands except Eleuthera.

Stromatolites are restricted to environments where there are few grazers on cyanobacteria. Bahamian stromatolites can be categorized on the basis of characteristics in their habitat which exclude grazers: those from habitats of high energy oceanic currents or those that occur in habitats with fluctuating salt concentrations. Stromatolites of Eleuthera and Exuma belong to the first category; those of Andros and San Salvador belong to the second. High energy stromatolites are low in species diversity and simple in organization. Fluctuating salt stromatolites are composed of many species of cyanobacteria that form complex layers.

INTRODUCTION

When stromatolites evolved 3.5 billion years ago, they were the first form of macroscopic life on earth and would dominate the biota for the next two billion years. They are therefore of great interest to both biologists and geologists. Cyanobacteria (formerly called blue-green algae) are the major stromatolite-building organisms. Schopf (1993) described the earliest cyanobacteria, Archean fossils from Northwestern Australia in basalts dated at over 3.5 billion years old. Eleven species of cyanobacteria, most new to science, were described, and all these species were remarkably similar in appearance to modern cyanobacteria. Stromatolite building organisms were clearly present very early in earth's history. The oldest stromatolites were found in rocks from western Australia and dated at between 3.4 and 3.5 billion years old (Walter, 1980).

Awramik *et al.* (1976) defined stromatolites as organo-sedimentary structures produced by microbial mats, usually of cyanobacteria. Anyone who has observed a eutrophic lake in late summer knows that cyanobacteria form mats of intertwining filaments. Under certain conditions these mats can become encrusted with sediments. The mat itself can trap sediments, the gelatinous capsule outside the filament's cell wall can bind sediments and its metabolism can alter the carbonate equilibrium so that calcium and magnesium carbonates are precipitated. By one or more of these processes, cyanobacteria can produce sediments.

Cyanobacteria can rise above these entrapping sediments. Some species, such as *Oscillatoria* move above the sediments by their gliding locomotion. Others produce gelatinous stalks which push them above the sediments. Still others simply grow above the sediments. Stromatolite building is a dynamic process in which cyanobacteria continuously become encrusted with sediments then rise above these sediments. This characteristic produces the typical layered (stroma = layer) appearance of stromatolites.

Stromatolites are algal reefs, produced by cyanobacteria rather than corals. In Precambrian times they reached sizes comparable to those of modern coral reefs. Their abundance and diversity increased throughout the Riphean period. Then, at the beginning of the Cambrian they suffered a dramatic decline. They still survive today, but in very restricted habitats. What happened to the stromatolites? During the Cambrian animal diversity increased greatly. There were now many species of grazers which fed on algal mats, and of burrowers which destroyed the sedimentary laminations. Garrett (1970) protected areas along the west coast of Andros Island in the Bahamas from predators, particularly gastropods, and found that under these conditions cyanobacterial mats formed in great abundance. When he removed the protective barrier, grazers such as gastropods, quickly consumed the mats. Others have suggested that cyanobacterial reefs can not compete with coral reefs. Today stromatolites form only in habitats that for some reason are free of grazers, burrowers and competitors.

Modern stromatolites from the Bahamas were the first recognized as analogues to ancient stromatolites (Black, 1933). The Bahamas have a greater abundance and diversity of columnar stromatolites than any other location. The Bahamas is an archipelago of coral islands that begin about 50 miles off the Florida coast, extend over 500 miles in a southeasterly direction to within 30 miles of Cuba (Fig 1). Living columnar stromatolites have been found on four Bahamian Islands: Andros, Eleuthera, Exuma and San Salvador. During 1992 I visited each of these island in search of stromatolites and succeeded in finding them on all islands except Eleuthera. My principal goal was to determine the species composition and organization of cyanobacteria in these stromatolites.

STROMATOLITES OF ANDROS

In 1933 Maurice Black of Cambridge University published a seminal article on stromatolites from Andros Island. Logan (1961), who studied stromatolites in Hamlin Pool, which is a hypersaline lagoon off Sharks Bay in western Australia, is often given credit for recognizing the relationship between living and fossil stromatolites. In fact, it was Black (1933) who first recognized this relationship: "In the course of a geological reconnaissance of Andros Island it was found that blue-green algae play an important part in the process of sedimentation. Such sediment-building algae usually impart characteristic structures to the medium in which they grow and in the interior of Andros structures are being produced which are reminiscent of those found in some of the great limestone formations of the upper Precambrian."

Andros is the largest of the Bahamian islands, located on the eastern most part of the Great Bahama Bank. The largest and most abundant stromatolites are found along Fresh Creek, which is a tidal inlet, not a true creek (Fig. 1a; Black, 1933; Monty, 1965). Black identified seven species of cyanobacteria from the stromatolites of Fresh Creek, four from the order Chroococcales and three Oscillatoriales (Table I).

In 1992 I visited Fresh Creek under the auspices of the Forfar Field Station. These stromatolites were unusually gelatinous and had many distinct layers. The outer brownish layer was composed of dead cells that probably served to protect the underlying layers from ultraviolet light. The green layer directly below contained most of the species of cyanobacteria. This layer was particularly rich in coccoid forms. In this layer I identified *Gleocapsa*, *Plectonema*, and *Scytonema*, genera that were also reported by Black (1933). In addition, *Spirulena* was also present. The red layer below this zone was probably composed mainly of photosynthetic bacteria. Below these photosynthetic zones were four distinct brown layers, probably containing anaerobic bacteria involved in decomposition. Lime mud was found underneath the stromatolites.

The area around Fresh Creek where stromatolites occur contained fresh water when I was there. Black (1933) also reported that the creek contained water of very low salinity. The area however contained many red mangroves indicating that at certain periods, probably due to tidal flow, the creek contained salt water. Fresh creek probably provides an environment of fluctuating salt concentrations.

STROMATOLITES OF SAN SALVADOR ISLAND

San Salvador is on the eastern flank of the Bahamas, separated from the Great Bahama Bank by a deep oceanic channel (Fig. 1). The most striking feature of the island is its great number and extensive network of inland lakes.

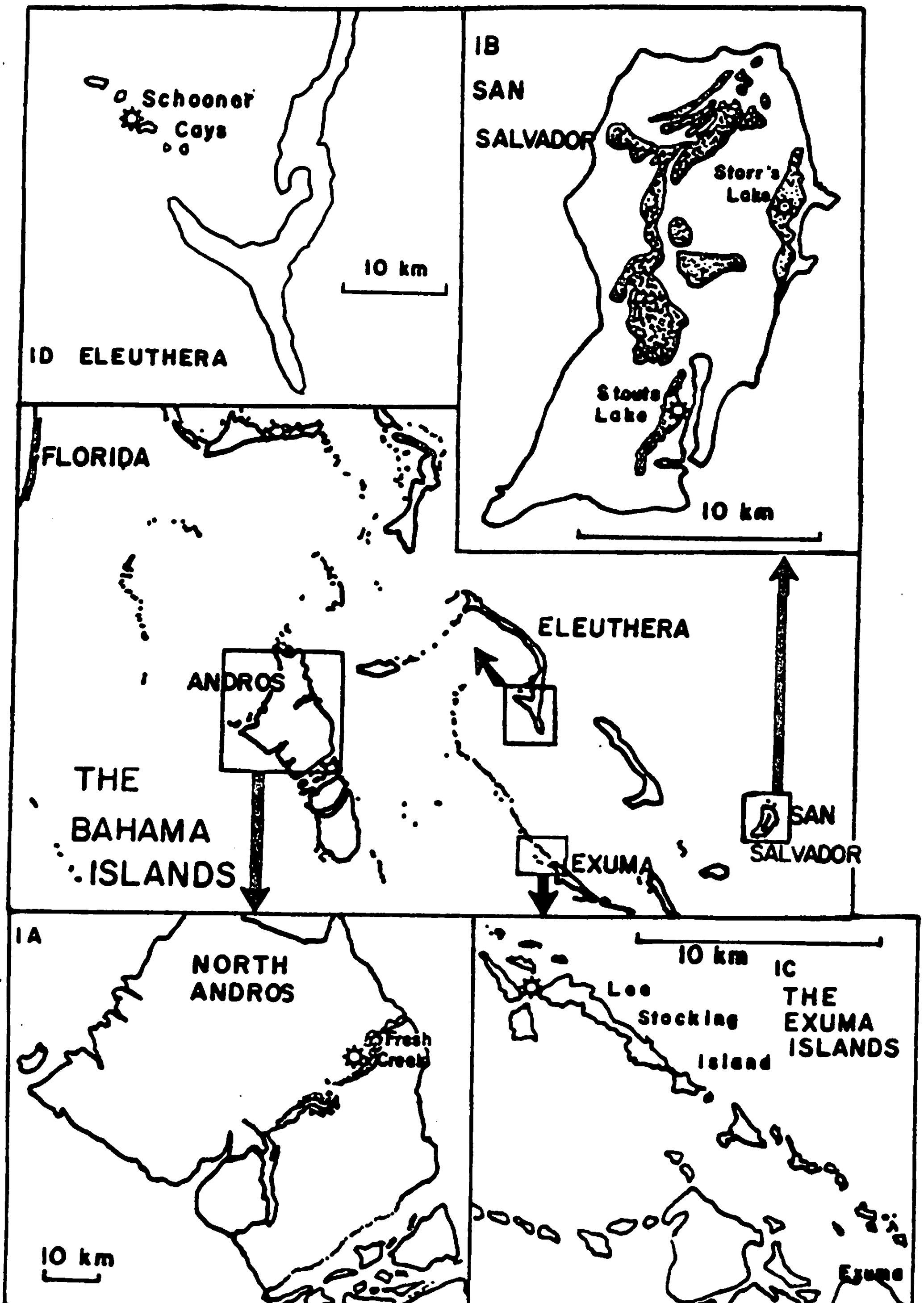

Figure 1. Map of the Bahamas. The main map shows the islands of the Great Bahama Bank and nearby islands. Map a: North Andros Island showing the location of stromatolites along Fresh Creek. Map b: San Salvador Island showing the location of stromatolites in Storr's and Stouts Lakes. Map c: Lee Stocking Island, just north of Exuma Island, showing location of stromatolites in the channel between Lee Stocking Island and Norman Pond Cay. Map d: Eleuthera Island, showing location of stromatolites in the channels between the Schooner Cays. Location of stromatolites is indicated by ✲.

TABLE I

Species of Cyanobacteria found in the four types of columnar stromatolites from the Bahamas.

ANDROS	SAN SALVADOR	EXUMA	ELEUTHERA
Gloeocapsa	*Gloeocapsa*	*Schizothrix*	filamentous
Aphanocapsa	*Aphanotheca*	*Calothrix*	cyanobacteria
Plestonema	*Phormidium*	*Phormidium*	
Scytonema	*Microcoleus*	*Microcoleus*	
Spirulina	*Spirulina*	*Gomphosphaeria*	
	Scytonema	*Coeleosphaerium*	
	Lyngbia		
	Oscillatoria		
	Chroococcus		

Columbus described the island where he first made landfall in the new world as having a great inland lake. Of the several islands where Columbus might have first landed only San Salvador fits this description.

Columnar stromatolites have been found in two of these inland lakes: Storr's Lake (Neumann *et al.*, 1989; Paull, 1992) and Stouts Lake (Elliott, 1992)(Fig. 1b). Both are hypersaline, with fluctuating salt concentrations (Marshall, 1982). Stromatolites of Stouts Lake are found in abundance along a 750 m stretch on the western shore in water about 0.5 m deep. They are found in several remarkable straight rows running parallel to the shore. They are typical columnar stromatolites except their tops have a rather characteristic bulbous appearance.

Like their counterparts from Andros, Stouts Lake's stromatolites are layered. Zone 1 is about one mm thick, dark brown/green in color and composed mainly of the cyanobacterium *Lyngbya*. This bacterium has a multi-layered sheath impregnated with brown pigments that effectively absorb ultraviolet light. Zone 2 is bright green in color and dominated by *Microcoleus*, the major stromatolite builder. Zone 3 is a salmon pink layer of true photosynthetic bacteria. Finally, Zone 4 is an anaerobic, black zone of decomposition. Each of these zones is between one and two mm thick. Below this organic layer are many layers of rather coarse sedimentary rock. Neumann *et al.* (1989) has found that stromatolites of Storr's lake form sediments by precipitating Mg and Ca carbonates and because Stouts Lake's stromatolites are rather similar in appearance and found in a similar environment, they too are probably produced by the sediment forming ability of their cyanobacteria.

In addition to these dominant microbes, many other species are also found in these stromatolites (Table I). Cyanobacteria include *Chroococcus* (at least two species), *Aphanotheca* (a small coccobacillus producing copious amounts of gelatinous materials), *Oscillatoria*, *Scytonema* (a species that forms false branches), and *Phormidium* (with its hard sheath). Several other species of cyanobacteria were found but not identified. In addition, these stromatolites contained two species of diatoms, one green alga (*Dunaliella*) and a nematode.

For the past four years (1988-92) I have measured the growth rate of Stouts Lake's stromatolites by inserting galvanized nails into them (see Elliott, 1992, for details of the method). For the first three years of the study, stromatolites increased in height about a mm per year. However, in 1992 there was a drastic decrease in the size of these stromatolites (Fig 2). This decrease was probably due to the surface layers of the stromatolite drying out and shrinking from the nails. It appears that the growth of these stromatolites might be episodic, with periods of steady growth followed by harsh environmental conditions that actually result in the stromatolite shrinking. Alternatively, the stromatolites might increase in height so that they rise above the water surface and become susceptible to drying.

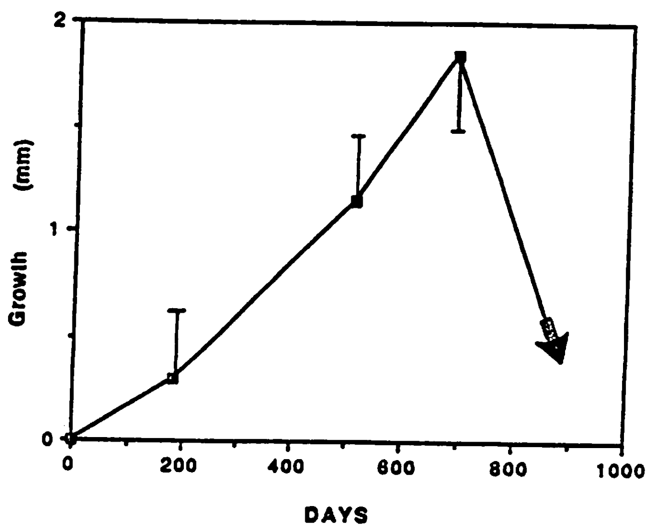

Figure 2. Growth rate of stromatolites from Stouts Lake, San Salvador Island.

STROMATOLITES OF EXUMA

Giant subtidal stromatolites are found in the current swept channels between the Exuma Islands on the eastern edge of the Great Bahama Bank (Dill, et al. 1986; Fig. 1c). These stromatolites often grow to about 3 m in height and therefore are probably the largest extant stromatolites. They trap sediments that are swept over them as the tides come in and out and Dill (1988) suggested they also precipitate sediments. These stromatolites contain several genera of cyanobacteria (Table I) and an abundant flora of epiphytic eucaryotic algae. During a brief visit to Exuma in 1992 I observed these stromatolites as the tide was going out. High energy currents passed over the stromatolites carrying oolitic sand particles. The scene was reminiscent of a desert sand storm. It is the energy of the currents and the abrasive sand they carry that probably prevent grazers from destroying these stromatolites.

The dominant cyanobacterium in these stromatolites is *Schizothrix*, a genus with multiple filaments within a single sheath. Other filamentous cyanobacteria present in these stromatolites were *Caloxthrix*, *Phormidium*, and *Microcoleus*. Coccoid forms included *Gomphosphaeria* and *Coeleosphaerium*. Also present were diatoms, and filamentous green and red algae.

The upper region of these stromatolites is composed of three zones, each with a characteristic flora. The upper zone is composed of a variety of epiphytes including *Batophora*, *Sargassum*, *Laurencia*, *Polysiphonia* and *Acetabularia*. This zone is in contact with the high energy currents that sweep over the stromatolites. The next living zone of these stromatolites is composed of filamentous green algae, which are also in contact with the high energy currents. The lower, protected layer is composed of diatoms and *Schizothrix*, which traps sediments in its gelatinous sheaths.

STROMATOLITES OF ELEUTHERA

In 1983 Jeffrey Dravis of Exxon reported his discovery of oceanic stromatolites between the Schooner Cays which extend north from central Eleuthera between Rock Sound and Eleuthera Sound (Fig 1d). The discovery of these stromatolites was particularly important because they were the first found in oceanic waters of normal salinity.

Like the stromatolites of Exuma, these are found in a high energy, tidal oolitic sand environment. High energy currents sweep over them as the tidal flow falls off the bank platform. These stromatolites are however much smaller than Exuma stromatolites: they are about a half meter high and are found in waters only a couple of meters in depth. Although no studies have been done on the species of cyanobacteria and other algae found in these stromatolites, they appear to be rather similar in organization to Exuma stromatolites.

similar in organization to Exuma stromatolites. They contain several species of epiphytes. Although we spent several days in the Schooner Cays, we were not able to locate these stromatolites. They have either died, not an unlikely possibility since they are found in shallow, high energy waters, or we missed them.

CONCLUSION

Today, stromatolites are found only in environments that restrict grazers. In fact, stromatolites can be divided into two groups, depending upon the factors restricting these grazers. For high energy stromatolites, grazers are restricted by the currents that sweep over them, carrying vast amounts of abrasive, oolitic sand. High salinity stromatolites are found in habitats that have a high and\or fluctuating salinity (Table II).

In the Bahamas, high energy stromatolites are found on the Great Bahama Bank at the edge of Exuma sound near either Exuma or Eleuthera Islands. Tidal flows carrying oolitic sands fall off or rise over the bank platform preventing grazers from establishing purchase on the stromatolites. They are somewhat unusual in having a rich epiphytic flora, they are relatively poor in diversity of stromatolite-building cyanobacteria, and are relatively simple in community structure. The Bahamas contain the only reports of stromatolites that exist in oceanic waters of normal salinity.

In contrast, high salt stromatolites are found in inland waters of Andros and San Salvador Islands. Those on San Salvador are found in waters that are several times the salinity of oceanic water and those on Andros are found in tidal marshes that experience rainy periods in which they are in fresh water, tidal flows in which they are in salt water and probably periods of drying in which they are in hypersaline waters. They have no epiphytic flora. They have a relatively high diversity of stromatolite-building cyanobacteria. And they exhibit a complex community structure, which is highly layered. Because each layer contains species with different pigments, this layering produces a dramatic testimony to their complex community diversity.

Modern cyanobacterial reefs were first recognized as analogues of ancient stromatolites from studies conducted in the Bahamas. And the Bahamas has the richest and most diverse collection of stromatolites.

ACKNOWLEDGEMENTS

I thank the following organizations and individuals who provided logistic support and invaluable encouragement: the staff of the Forfar Field Station on Andros Island, the staff of the Caribbean Marine Research Center on Lee Stocking Island of the Exumas, Tylor, a skilled boatsman of Eleuthera, and Don and

TABLE II

Comparisons of the two basic types of stromatolites found in the Bahamas

CHARACTERISTIC	HIGH ENERGY STROMATOLITE	HIGH SALT STROMATOLITE
Habitat	shallow ocean banks near Exuma Sound	saline inland lakes
Salinity	normal ocean water	high and/or fluctuating
Factors Restricting Grazers	high energy ocean current	fluctuating salinity
Epiphytes	present	absent
Community Structure	simple	complex

Kathy Gerace of the Bahamian Field Station, San Salvador Island. Nancy Elliott helped with collecting stromatolites and with the preparation of the manuscript.

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