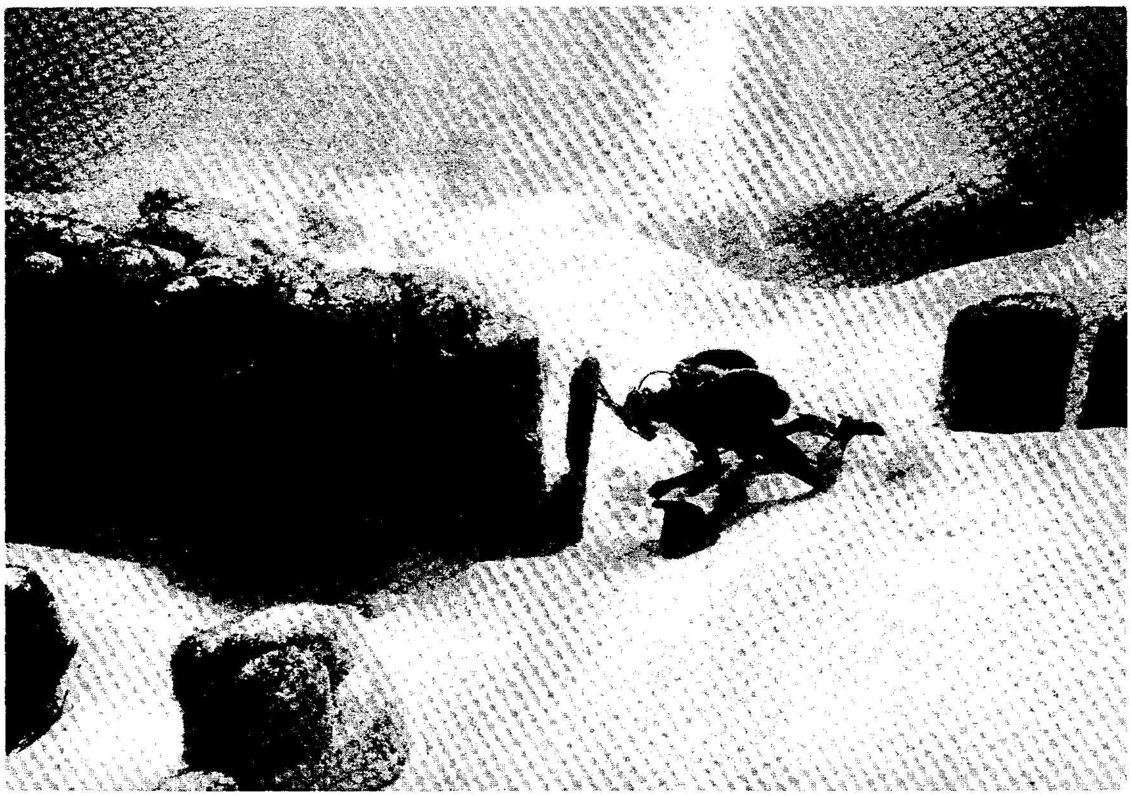
28th International Geological Congress

Giant Subtidal Stromatolites and Related Sedimentary Features

Field Trip Guidebook T373

Leaders:
Robert F. Dill, Christopher G. St. C. Kendall
and Eugene A. Shinn



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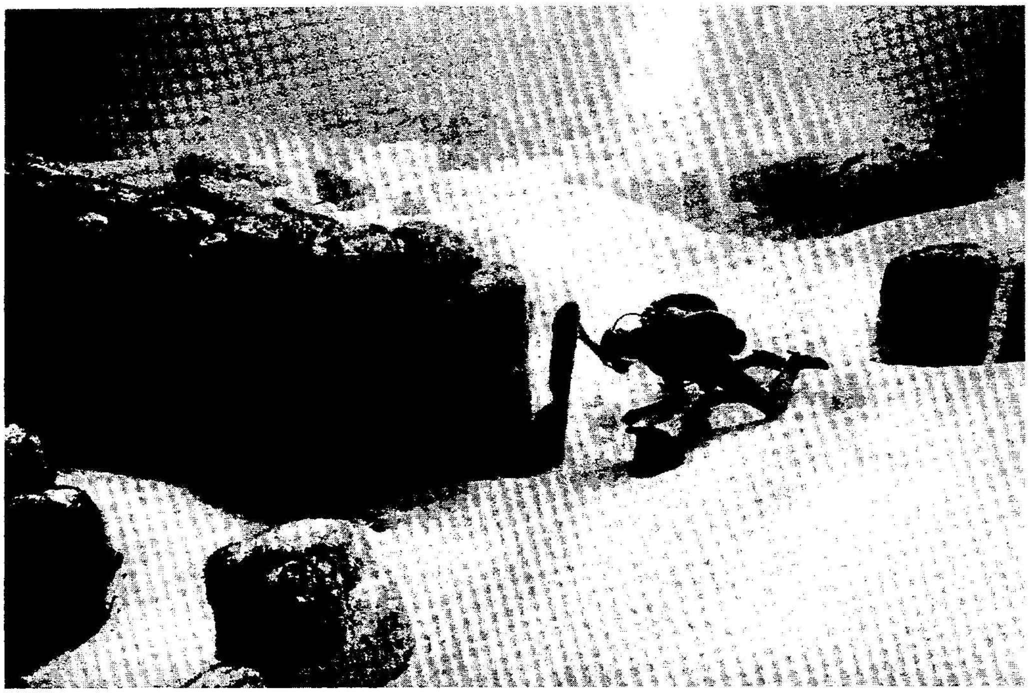

COVER Giant stromatolites in the channel north of Lee Stocking Island at a depth of 6 meters. Photo taken at slack tide at a depth of 6 meters. Individual columns have a maximum height of 2 meters above bedrock but due to partial burial have a water surface exposure of about 1 meter even in the troughs of migrating ooid sand dunes. The tops of the stromatolites rarely exceed the crests of the migrating dunes.

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Giant Subtidal Stromatolites and Related Sedimentary Features

IGC FIELD TRIP T 373:
Giant Subtidal Stromatolites and Related Sedimentary Features, Lee Stocking Island, Exumas, Bahamas

Robert F. Dill[1], Christopher G. St. C. Kendall[2], Eugene A. Shinn[3]

Introduction

This guidebook was prepared to provide background information for field trip T-373 of the 1989 International Geological Congress. It presents a overview of the marine geology, the depositional settings, oceanography, and associated marine organisms found in the area of subtidal stromatolites forming near Lee Stocking Island, located at the southern end of the Exuma chain of islands in the Bahamas (FIGURE 1). The material represents a synthesis of the field research by the authors and their colleagues. Starting in 1984, this research continues as part of the UNESCO-IGCP Project 261 for Stromatolite Research and the long-term geological program of the Caribbean Marine Research Center (CMRC). The Appendix to this guidebook also provides a description of the field support facilities at the CMRC on Lee Stocking Island and suggestions for the equipment needed to enhance your three day stay in the Bahamas. Daily schedule are also presented that will help keep the field programs organized. However, please realize that the sequences of events and locations for field studies may change so as to optimize observations during good weather and favorable tidal conditions.

Regional Geology.

This guidebook covers the eastern margin of the Great Bahama Bank near the islands and cays at the southern end of the Exuma chain of islands. In this region, giant lithified stromatolites form in subtidal channels separating the many islands and smaller cays. Lee Stocking Island is formed of both Holocene and older Pleistocene eolian dunes, as are most of the islands and cays that form the boundary between the eastern rim of the Great Bahama Bank and the deep Exuma Sound. The Bank itself, is part of a thick sequence of segmented carbonate platforms which extend to the west across the northern Caribbean and Gulf of Mexico Basins, forming parts of Florida, Cuba, Hispaniola, the proto-U.S. Gulf Coast and Yucatan. The shallow waters covering the Great Bahama Bank have a surface area of over 100,000 km^2. Located in tropical latitudes the bank forms a unique oceanic region for heating and modifying the chemistry of the oceanic waters that flow across the shallow regions.

Borehole cores and seismic sections show that a thick section of Tertiary through Cretaceous shallow-water limestones and dolomites underlie the Pleistocene. The total carbonate section has a thickness in excess of 11,000 meters (Dietz *et al.*, 1970; Meyerhoff and Hatten, 1974; Schlager and Ginsburg, 1981; Beach and Ginsburg, 1980; Beach, 1982; Eberli and Ginsburg, 1987). Many of the islands and cays have paleosols and a well-developed karst topography that extend both above and below present sea level. Cave systems are extensive and related to solution along joint patterns. All of these features are evidence of fluctuating sea levels during Pleistocene glacio-eustatic events and provide a means of determining the geochronology of this history.Most of the broad, flat-topped platform has water depths of less than ten meters. However, this broad plateau is dissected by several large, deep, steep-sided submarine valleys and oceanic reentrants with depths of 850 to 3,500-m (Schalk, 1946; Hurley and Shepard, 1964; Shepard and Dill, 1966, p.191-198). The Tongue-of-the-Ocean (TOTO) and Exuma Sound are examples of these deep oceanic submarine valleys and reentrants that bisect the platform massif. Islands have a low relief and rarely exceed an elevation of 35 m .

Features on flight from Miami to Lee Stocking

Bimini to Joulters Cays. During our flight to Lee Stocking Island (see arrows in FIGURE 1), weather permitting, we should seemost of the facies and physiographic features that are characteristic of the Great Bahama Bank. Our first land fall after leaving Miami will be the Bimini Islands, which delineate the northwestern rim of the Great Bahama Bank platform. The resistant rocks forming the islands and cays are mostly Pleistocene cemented dune deposits. Continuing east from Bimini, we fly out over the central part of the Great Bahama Platform. On this part of the flight we will see excellent examples of; 1) submarine dunes and ooid shoals with bed forms created by tidal and tropical storm generated currents, 2) blue holes (submerged sink holes), 3) patch reefs with halos of clean sand, formed by grazing organisms living in the protection of the isolated coral head-reefs, and 4) the occasional "whiting." The latter, consist of turbid clouds of lime mud that form in "mysterious ways" in the usually clear bank waters. Some say they are from fish stirring up the bottom, others (the authors of this guidebook) think they are precipitates, because underwater observations, fish traps and seining have shown a lack of fish in many areas where whitings are forming (Shinn *et al.*, 1985; Shin *et al.*, 1989). Regardless of their origin they are potentially important sources of lime mud and must be considered when developing a sediment budget to account for muds carried over the platform margin by ebb-tidal currents and to the lee sides of the larger islands where lime muds form an important component of extensive mangrove mud flats.

Andros and Joulters Cays. Continuing east we reach the northern tip of Andros Island and Joulters Cays. This area has been extensively studied and depicted as a modern analog to many ancient limestone platforms (Black, M.; 1933, Cloud, P.E., 1962; Shinn, *1968;* Shinn *et al.*, 1969; Ginsburg and Hardie, 1975; Hardie and Ginsburg, 1977; Hardie and Garrett, 1977; Shinn, 1983). These shoals contain cemented ooids and represent excellent examples of early diagenesis and marine and fresh water cementation (Halley and Harris, 1979). Many field trips have utilized this region over the years and it is probably one of the best known modern carbonate sites in the

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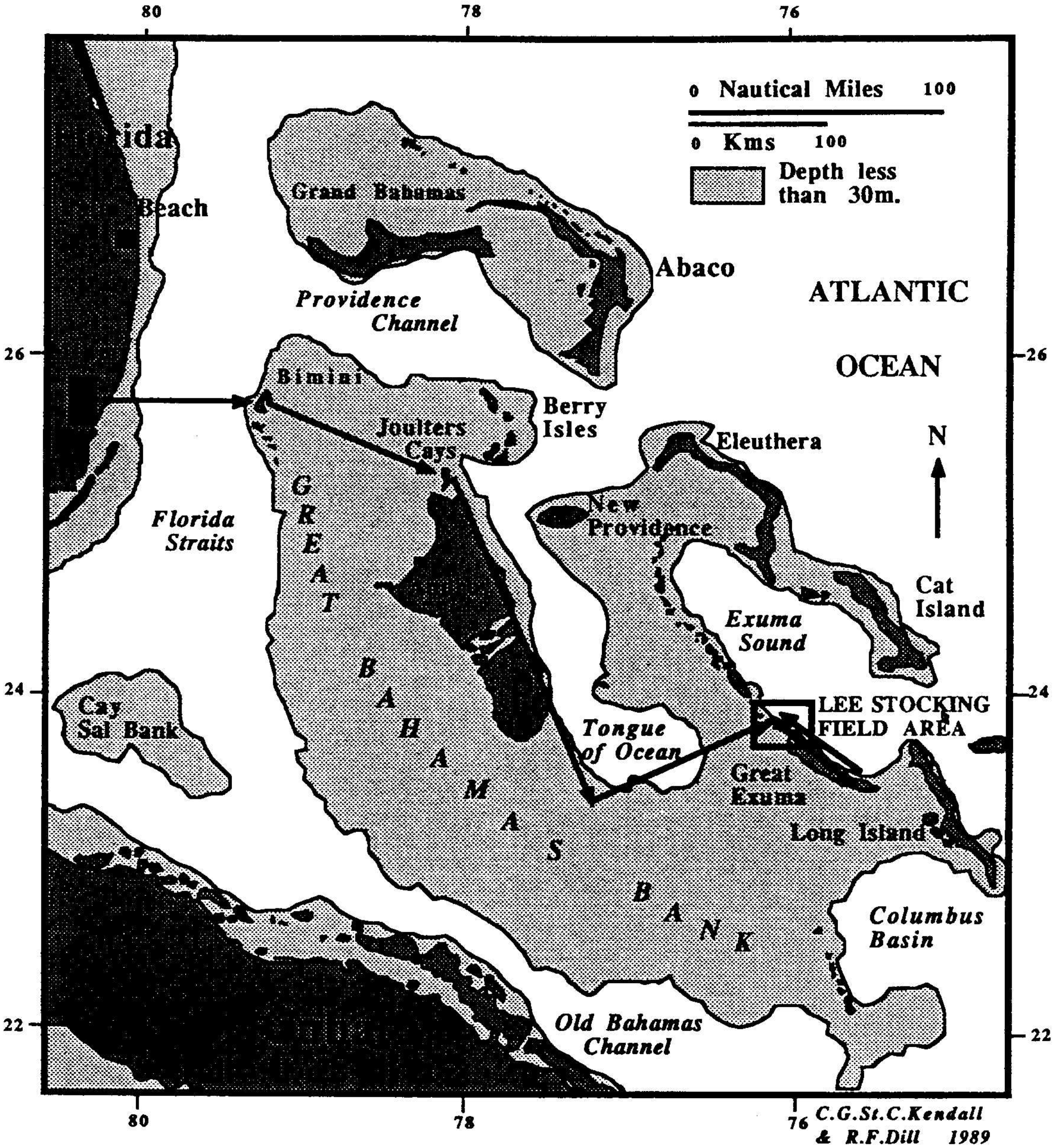


FIGURE 1. Flight Path (Arrows) from Miami International Airport to Lee Stocking Island via Georgetown for the International Geological Congress Field Trip T373 to observe Modern Stromatolites and tropical carbonates.

Bahamas. You will probably recognize many of the features seen in our over flight that are depicted in AAPG Memoir 33, "Carbonate Depositional Environments." (Scholle, *et al.*, ed., 1983).

Our route from Joulters Cays, is south along the eastern edge of Andros Island. The main insular masses are broken by broad shallow tidal creeks bordered by mangroves (Bourrouilh, 1974). Relate the breaks of the bank barrier reefs to these channels. The eastern shore line is protected by a narrow lagoon and a well-developed offshore bank barrier reefs made up of *Acropora palmata,* one of the main shallow-water reef builders of the Caribbean and eastern tropical Atlantic. Note the exposed eastern sides of the bank barrier reefs located a few hundred to a thousand meters offshore. They are marked by a well-developed spur-and-groove system that diverts sediment produced on the reef proper into deeper water to the east. The deep blue water marks the drop-off into the Tongue- of- the-Ocean. Because this margin is so steep and "cliff-like," it has been termed the "wall" and is immensely popular as a diving tourist attraction. It is almost vertical and in places even overhanging. On-shore and on the offshore terraced insular margin, elongated and continuous joint patterns cut through the limestones forming the upper rim of the platform. Most large joint patterns run parallel to the drop-off (Newell and Rigby, 1957; Dill, 1977; Carew and Mylroie, 1988). One particularly well-developed joint system near the eastern shoreline is associated with numerous blue holes and cave entrances.

It has been traced by Dill over 25 km along this eastern margin of Andros. Many of the junctions, where joints intersect, have been enlarged by dissolution during lowered sea level forming entrances to an extensive subterranean cave system. Intense karsting of the region permits a free flow of water through the cavernous limestones and tidal flushing of the internal cavern systems. The submarine caves have been used by speleologists and geologists to explore the inner anatomy of the platform down to depths beyond 80-m (Benjamin, 1970; Dill, 1977; Palmer, 1985; and Whitaker and Smart, 1988).

Tongue-of-the-Ocean. As we reach south Andros we will turn east out over the deep blue waters that mark the southern terminus of the TOTO. Look for giant submarine dunes at its southern rim. Large volumes of ooid sand, *Halimeda* plates and pelleted muds spill over this south side into the head of a large submarine canyon that runs along the bottom of the TOTO (Crevello, P.D. and Schlager, W., 1979) This canyon diverts bank sediments down the axis and eventually spills out onto the floor of the deep Atlantic east of the Bank, forming a giant deep sea fan. On entering the Atlantic, the walls of this canyon, between New Providence Island and Great Abaco, form the oceans steepest and deepest submarine canyon system (Shepard and Dill, 1966).

Continuing to the east, away from the TOTO we reach the Exuma island chain. In the early 1960's, Taft showed this region between TOTO and the Exumas to be actively undergoing submarine cementation and forming shallow subtidal marine hard grounds (Shinn and Ginsburg, 1964; Taft *et al.*, 1968; Shinn, 1983). The southern rim of the TOTO has dark rounded features which Dravis (1983) suggested looked like stromatolites, an occurrence that has yet to be verified.

Exuma Islands to Georgetown. At the Exumas we will turn south flying over the islands north of and then over Lee Stocking Island, eventually reaching the main island Great Exuma. The open waters of Exuma Sound to the east provide a large fetch for wave development in this region that is subjected to trade winds from the east and southeast. Therefore, the seaward sides of many of the islands and cays are exposed to high energy wave attack and have submerged reefs. Many of the deep reefs have a well-developed spur-and-groove structures running perpendicular to the shoreline. Even with this exposure, eastern part of Bahama Bank does not have well developed bank barrier reefs that reach present sea level like those just seen off Andros. However, there is an extremely well developed deep-reef system between 15 to 20-m that trends parallel to the shoreline approximately 0.25 to 0.5-km offshore.

Although there are no well developed reefs, there are numerous small linear cays and resistant rock stacks just offshore of the larger islands. Most are formed by dunes that have well-cemented, case hardened surfaces. Many of the larger cays have a veneer of a relatively uncemented dune facies that has a crusted cemented surface where subjected to sea spray. This young dune facies rests on an older well cemented dune limestone. One of the interesting questions yet to be answered is when these dunes formed, was it during the regressive or the progressive stages of Holocene sea level? The contact between this youthful dune system and the older is often marked by a orange-colored, caliche paleosol that extends both above and below present sea level.

Note the many crescent shaped beaches forming between resistant headlands. In many areas they have filled old channels that formerly lead back onto the bank proper. Lee Stocking has a number of these crescent shaped beaches. Most of the sands forming these prograding beaches are skeletal or coral debris unlike the predominantly ooid and pelletoid sands that form islands, ribbon shoals and flood-tidal deltas back on the bank and in inter-island channels. Many of the beaches are backed by a series of crescent-shaped ridges. They are evidence of beach progradation, and confirm estimates of high carbonate production on the narrow insular margin seaward of the beach. The composition of the biogenious sands indicates it is produced by offshore reefs with some reworking of Pleistocene islands. High production rates during the past 3000 years of a relative stable sea level has resulted in a progradation that is filling in the areas between resistant headlands. The crescent ridges are storm berms, showing former positions of the shore.

Well-developed beachrock ramps are forming in the swash zone both bordering and under many of the crescent beaches. These shoreline beachrock deposits are covered and exposed by beach sands, a cut and fill process that is controled by the direction of waves and tidal variation at different times of the year. We will investigate this relation later during the field trip.

On this part of the flight the waters of Exuma Sound are seen as a deep blue to the east. Exposure to open marine water greatly affects the tidal flow and nature of oceanographic patterns along the bank margins, especially where reversing tidal currents bring together the relatively cool oceanic waters from the Exuma Sound and more saline, warmer bank waters. This is a region of intense oceanographic turbulence, that facilitates mixing and chemical reactions. Tropical oceanic waters of the region are saturated with respect to calcium carbonate. When the physical properties of the water masses are rapidly changed they become susceptible to the precipitation of marine cements. Many of the features we will see on this field trip such as stromatolites, crusted mud beds, hardgrounds and mud chips are dependant on this mixing to create the marine cementation for preservation.

As we fly over Lee Stocking Island observe its location relative to the shallow bank. The island is bounded on the west, north and south by the broad shallow Great Bahama Bank. Adderly Cay to the north and Norman's Pond Cay to the west form a restriction to the flow of waters onto and off the Bank (FIGURE 2). As an eastern boundary island this restriction to flow increases turbulence and velocities of tidal currents in inter-island channels. If there is an ebb-tide during our flight look for the jet of bank water and an area of choppy water marking the seaward margin of bank waters flowing out over the upper rim of the Sound. The islands to the south of Lee Stocking are

FIGURE 2. Air photo of Lee Stocking Island (island with air strip) and associated Cays. Taken at an altitude of 20,000 ft looking south towards Great Exuma and small town of Barriterre. Note ribbon ooid shoals light areas. The islands in the background are the Brigatines.

the Grenadines. This chain runs anomalously east-west versus the normal north-south direction of most of the islands of the Exuma chain. The islands have a well developed paleosol between 2 to 4 meters above present sea level that has been breached by karst features and shallow caves in the cemented ooid/pelletoid dune sands forming the islands. Similar features on San Salvador Island approximately 100 miles to the east, have been dated as Sangamon or older (Carew and Mylroie, 1986; Mylroie and Carew, 1987).

The deep blue water of the well developed channels between the islands mark areas of tidal scour that expose the bedrock of the region. The dark green areas are meadows of sea grass predominantly *Thallasia*. The approach to the Georgetown airport on Great Exuma just beyond the Grenadines is over extensive tidal flats and mangrove forests. Several "blue holes," most of them filled with sediment, are also seen in the tidal channels. The supra, intra, and subtidal mud flats in this region have features similar to those described by Shinn (1983) forming along the west margin of Andros Island. One to two meters of lime mud and a thin peat layer cover the Pleistocene (?) paleosol that crusts old eolian deposits forming the bedrock of the island. The low rolling hills that create the relief of the island are a series of north-south trending Pleistocene dune fields that on Great Exuma reach a maximum elevation of 37 meters (120 ft.)

After a short stop to clear Bahamian Customs we will fly north over Great Exuma Island back to Lee Stocking. On this return flight we plan to make several passes over mud flats, Norman's Pond Cay and over the subtidal stromatolite area before landing at the Island's 1000-m long airstrip. Those of you who wish to take photographs should take advantage of the aerial overview of the stromatolite setting and the regional location of the various cays and islands we will visit during the next three days. FIGURES 2 and 3 will help you identify where you are and the names of the different islands.

Platform margin sediments. Bank boundary islands are separated from the deep Exuma Sound by a narrow kilometer-wide terraced shelf. Sediments caught in the ebb-tidal jet are swept off the bank to the steep drop-off that starts at a depth of about 40-m. Here, the "wall" forms the upper-rim of the 1000-m deep Exuma Sound. Waters from the Sound flow on the bank for 6 hours during flood-tide then they reverse and flow offshore for 6 hours during the ebb-tide. Note how many of the small island and cays constrict the flow forming ribbon shaped ooid sand banks, shoals and flood-tidal deltas on the broad shallow bank to the west. Note also the lack of ebb-tidal deltas. Sediment swept to the narrow terraced margin is lost over the steep edge and falls to the base of the "wall" to depths of 100 to 200 meters. There, our submersible dives have shown an extensive talus slope has built up of shallow-water debris and eroded wall-rock rubble that is onlapping and covering exposed platform wall-rock. The surface of this talus slope has large dune shaped features with their crests running perpendicular to the "wall." These deep-platform marginal dunes extend to beyond 900-m, the greatest depth our submersibles dives have penetrated to date. The dunes have crest-to-crest wavelengths of 50 to 100-m and heights of up to 10-m. The surfaces of the dunes are covered with fine grained pelagic, lime-mud and *Halameda* sands. Beneath this thin layer of unconsolidated sediment, the mixed sediment and talus debris has become densely cemented, having the hardness of concrete. Large house-sized blocks of wall rock have become detached from the platform margin and are found as giant olistoliths in this deep platform margin setting. Similar features have been described in ancient carbonate, platform-margin environments. Components of the talus around the olistoliths are coral, rock rubble, *Halameda* sand and a mix of pelagic biogenesis sediment. Another interesting feature on the rock walls is the development of a ten meter high zone of caves, discontinuous terraces, and what appears to be a karst topography at a depth of 105-m and another set at about 140-m. This cave system is also encountered at about the same depth as a zone of cavernous limestone in water and liquid-waste discharge wells on many of the Bahamian Islands (Cant, 1977; 1988). We will describe and show video tapes of this extremely interesting deep area of the Great Bahama Bank Platform during one of our evening lectures.

Lee Stocking Island

Upon arrival at Lee Stocking Island, we will be met by a truck and vans at the CMRC airstrip to transport us to our living quarters. The daily schedule of meetings and the areas we will be working for the next three days are listed in the Appendix. Snorkel tows, behind our large catamaran will allow us to observe the depositional settings, oceanographic conditions, and biological processes active in the vicinity of Lee Stocking Island and the nearby small islands and cays. This part of the Bahama platform is free of industrial and resort development and exemplifies a typical and relatively pristine environment for studies of the carbonate depositional and diagenetic systems in the Bahamas. Water visibility typically exceeds 20-m and the water temperatures in July averages 30° C (86° F). Air temperature will range between 28° to 30° C (82° to 100° F) and are comfortable due to trade winds.

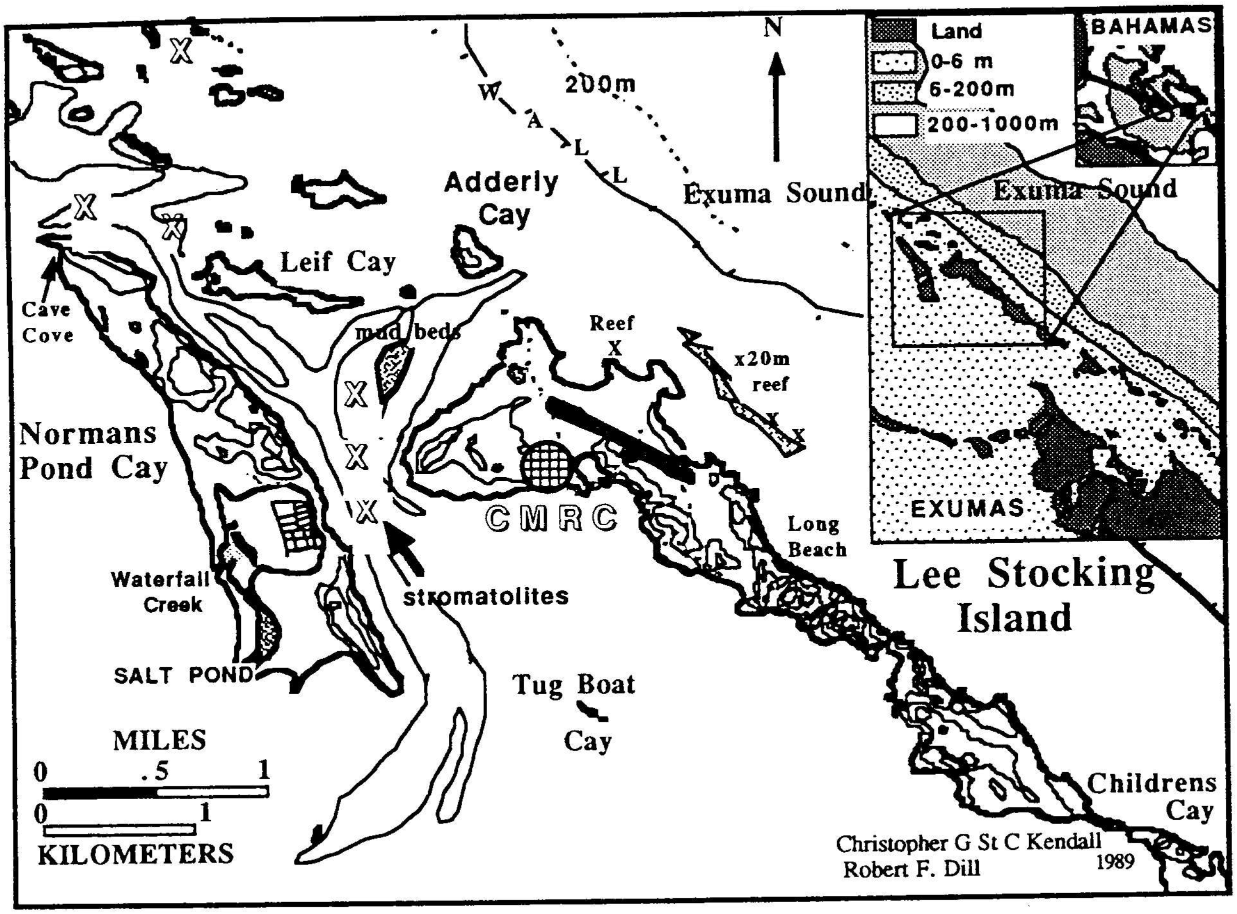
Field trip objectives In the sections that follow, the general physiographic, geologic and geophysical settings of the Bahama Bank complex are examined to provide a better understanding not only of stromatolites, but also of their relation to carbonate deposition and related oceanographic, biological, and geochemical processes active in the Lee Stocking region. We will introduce you to the concept that the features which contain marine cements such as stromatolites, lime mud beds, ooids, and grainstones are all related and are products of oceanographic mixing of bank and oceanic waters in the presence of microbial mats.

We hope to demonstrate how the modern Bahamian stromatolites and their associated sedimentary structures and features **can** and **cannot** be related to similar organosedimentary buildups that have occurred throughout geologic history.

Our first dives on stromatolites will be in the channel north of Lee Stocking Island (FIGURE 3). This is where they were first discovered in 1984 by chance, during a drift dive to observe migrating ooid dunes (Dill and Shinn, 1986; Dill *et al*., 1986; Shinn, 1987). We will duplicate the discovery dive starting at the seaward end of the channel north of Lee Stocking near Adderly Cay dune field and be towed over first, small and then larger and larger forms between Leif and Norman's Pond Cays. The tow will end over "molar-form" stromatolites at a ribbon shoal formed of ooid sands in the channel between Lee Stocking and Norman's Pond Cay (see Appendix for a more detailed schedule of activities).

Collections of living organisms forming the mats on stromatolites will be possible during the field trip for those who wish to take samples for later study. Laboratory facilities on Lee Stocking Island are available for preliminary culturing and identification of species but you will have to bring your own sample containers and culture medium.

As stated earlier, you will visit the stromatolites and oolites by first being towed over the area during an incoming flood-tide when ooids are in motion, forming macro bed forms. We will then go back to the same area of giant stromatolites during slack tide. During slack tide



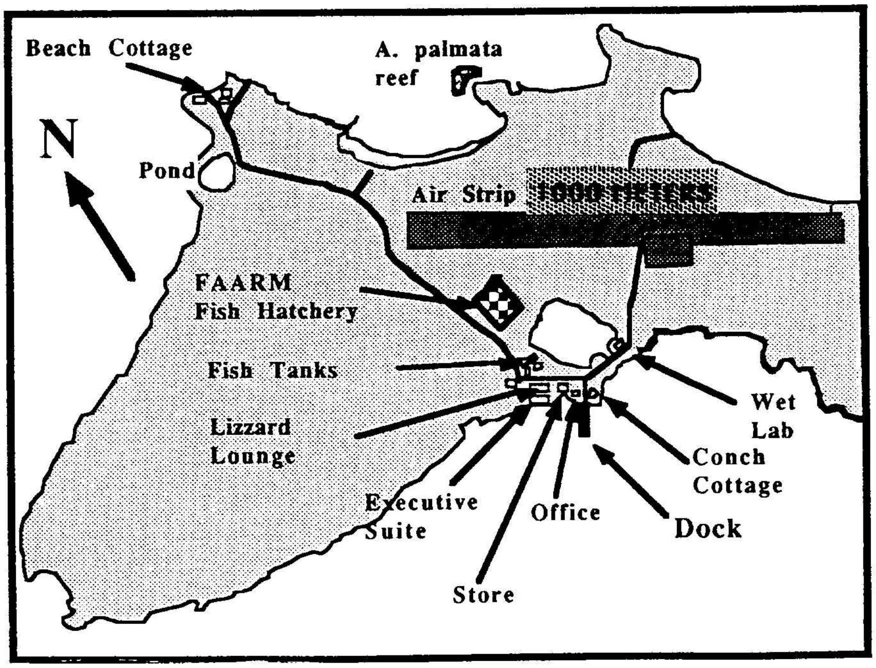


FIGURE 3. Location of Lee Stocking Island, stromatolites (X), nearby islands and cays, and the Caribbean Marine Research Center (CMRC). Our main objective will be to study the stromatolites north of Lee Stocking and look at the cemented crusts at waterfall creek and on the ribbon shoals east of Norman's Pond Cay. Lower figure shows location of facilities on the island.

we will anchor the boat and you will have the opportunity of diving down and examine the columns more closely. The use of scuba by qualified divers during slack tide will allow closer examination and a better understanding of the complex organic community which is trapping ooids to build the large stromatolites. During your field observations note the relation of the crests of giant dunes to the tops of stromatolite columns and observe the underlying hardgrounds on which they grow. Other important features to observe are the complex ripple mark patterns and rubble filled scour depressions caused by turbulent flow around the stromatolitic structures.

Oceanographic conditions. The inter island channels in which all of the features described in this guidebook are found, are 3 to 8-m deep and up to 500-m wide. Large ooid dune fields occupy the central axis of most channels forming flood-tidal banks and shoals. Strong currents keep the upper surfaces of the giant dunes and shallow banks in motion throughout most of the tidal cycle. Flood-tides bring oceanic waters from Exuma Sound onto the Great Bahama Bank's eastern margin and ebb-tides and wind driven circulation return warm and more saline waters formed by evaporation and solar heating on the shallow bank, back to the margin. Maximum tidal range is one meter, but sea level is also dependent on the intensity, direction and duration of the winds over the shallow bank. During large tropical storms and hurricanes, low barometric pressure also raises sea level creating a storm surge that increases current velocities around stromatolites and over shoal areas of the bank.

Upwelling occurs when winds favor movement of surface waters away from the bank margin. This brings cold, nutrient-rich deep water up onto the shallow bank during windy periods as underflows along channel lows. During the summer months the relatively warm, dense saline waters formed on the bank flow all the way to the wall as underflows and spill into the Exuma Sound as "falling currents" along parts of the "wall" opposite passes. The contact between the interflows of bank and oceanic water are seen as "shimmering" zones and marked changes of underwater visibility. The changes in light reaching the algal mats associated with the sedimentary features in the mixing zone undoubtedly affects photosynthesis and productivity. These density currents could be extremely important in explaining why cementation is so active in the Lee Stocking region.

Constriction of tidal flow over shoals and between islands accelerates current. Tidal currents around stromatolites and over hardground shoals have turbulent velocities at maximum peak flow of up to 150-cm/sec. Tides are diurnal and create currents in the channels between bank-margin islands that usually peak between 60 and 100-cm/sec depending on wind conditions. At slack tide there is a period of no current flow that lasts between 30 to 40 minutes. This short period is when we must make most of our detailed *in situ* studies. Following tide reversal the currents again gradually build-up reaching peak flow conditions in about two hours. This condition provides an excellent natural flume in which to study the development of bed forms and other features that can be used to characterize the oceanographic processes active in the bank margin setting and their association with stromatolites and associated sedimentary features. Current patterns, turbulence and duration of flow on and off the bank are also greatly affected by storms. As a consequence, the sedimentary topography of the shallow bank top is continually changing as the submarine dune fields migrate and stromatolites are covered and uncovered by the ooid dune sands.

The waters from Exuma Sound which flood the stromatolites at high tide are exceptionally clear and have the normal oceanic salinity of 37°/oo to 38° /oo. Underwater visibility in the tidal channels during flood-tide often exceeds 20 meters, having a clear blue color. Ebb-tidal waters from the shallow bank by contrast, have a greenish cast, contain much more suspended organic debris, and are more saline (often reaching 40°/oo) due to evaporation. Bank waters have a visibility between 5 to 15 meters, depending on weather conditions that stir up bank sediments and organic material that gives it its greenish cast.

In August of 1987, on the bank just south of Lee Stocking (Barriterre Cut), median maximum sea water temperature decreased from 32° (90° F) (range 29° to 33° C) to 29° C (range 27° to 31° C) in October. During the same interval, the median minimum oceanic sea water temperature was 29° C in August and September (ranges 28° to 30° C and 29° to 30° C respectively). Open sea water temperatures begin to decrease in October (median 28°C, range 24° to 30° C). Lowest temperatures in 1987 was 24° C (75° F) in upwelling water from the Sound (Lang *et al.*, in press, Robert Wicklund, (CMRC), personal communication, 1988). By the time of the field trip we will have a much longer period of continuous temperature data available from the temperature monitoring network which is part of the research program at the Caribbean Marine Research Center on Lee Stocking Island.

A special, and we believe important, oceanographic condition occurs when large tropical storms pass over the region. These create strong storm surges and wave induced bottom currents that suspend bottom sediment. During these periods the waters on the bank turn a "milky white." Strong ebb-tidal flow carries these sediment charged waters to the bank margins and over the areas where, as we will discuss later, we find mud beds. We presently believe, based on limited observations, that the bankward flowing flood-tides hold this turbid water in the mixing zone long enough for mud deposition to take place. There must also be a mechanism not yet identified that causes the muds to form aggregates (possibly the presence of organic material and a change in the temperature) and cause rapid settling even in a high energy channel setting. The wide ranges of salinity, temperature and visibility, when coupled with the rapid changes brought about by tidal reversals in the mixing zone, are important factors to consider when deciphering the environmental conditions fostering marine cementation, needle aragonite mud formation and deposition and stromatolite formation and preservation.

Chemical oceanography. A pilot study, to obtain chemical oceanographic data was conducted in June and July of 1988 near Lee Stocking Island. The primary objective was to compare the carbon and oxygen isotopic composition of modern platform carbonates with the isotopic chemistry of the sea water in which they form. The goal was to determine the timing of carbonate precipitation and the influence of biological, physical and chemical factors on precipitation. Samples of sediment and water for stable isotopic analysis were collected from areas of subtidal columnar stromatolites, hardgrounds, crusted muds, and in "whitings." Analyses for $\delta^{13}C$ of total dissolved inorganic carbon (total CO_2) of water samples, $\delta^{18}O$ of water samples, and the stable carbon and oxygen isotopes of carbonate samples were made by our associate Fred Falls at the Stable Isotope Laboratory of the University of South Carolina .

In the past, carbon isotopic studies of total dissolved inorganic carbon (total DIC) have primarily been applied to open ocean water masses (Sackett and Moore, 1966; Deuser and Hunt, 1969; and Kroopnick, 1985). Although the oxygen isotopic composition of platform waters has previously been studied (Lowenstam and Epstein, 1957), the stable carbon isotopic analysis of total CO_2 in the ambient seawater in general has been ignored or only used to normalize carbon-14 data in previous studies of the Bahamian platform and Exuma Sound (Smith, 1940, 1941; Broecker and Takahashi, 1966).

Early results from our study of the shallow water platform around Lee Stocking Island indicate that $\delta^{13}C$ values of total CO_2 for the platform water (-2.00 to 0.59 ppm) are significantly depleted relative to the published values for the Atlantic Ocean (1.34 to 2.13 ppm) at roughly the same latitude (Kroopnick, 1985). Our samples were taken from Exuma Sound east of Lee Stocking Island and on the shelf margin at a depth of 20-m both above and below a sharp thermocline that was about one meter above the bottom clearly delineating two different water masses. One from the sound and the other from the bank.

Water samples from the tidal channel off the north end of Lee Stocking Island were processed by standard CO_2 extraction procedures in preparation for carbon isotopic analysis of total CO_2 (Tan *et al.*, 1973). During slack high and slack low tide, water samples were collected within 2-m of the bottom and in the upper 3-cm of both columnar and molar-form stromatolites and in the upper few centimeters of the sediment using a needle syringe. Our results show the following:

1) a carbon isotopic enrichment for total CO_2 during slack low tide ($\delta^{13}C$ = 0.55 °/oo) versus slack high tide $\delta^{13}C$ = -1.50 °/oo)

2) no significant difference in isotopic composition between the water column and the water within the upper 2-cm of microbial mat on the top of stromatolite heads

3) isotopically depleted water samples just above the sediment/water interface relative to the overlying water column in the channel (2-m above the bottom).

The isotopic enrichment observed during slack low-tide relative to slack high-tide in the channel presumably reflects the exchange between enriched platform water from the bank west of Lee Stocking Island and isotopically depleted water from the Exuma Sound side of the island. It is already known that portions of the platform water system can have long residence time in areas of restricted circulation (Broecker and Takahashi, 1966). During an extended period of residence on the platform, the carbon isotopic composition of the water mass is subjected to preferential fixation of Carbon-12 by photosynthesis and salinity increases by evaporation and increased temperature by solar heating. The resulting enrichment of the stable carbon isotope reservoir by photosynthesis is a diel process and is partially compensated by the process of respiration. However, the abundance of organic material produced on the shallow platform, as shown by its greenish cast and the export of decaying organics from the shallows during ebb-tides, should result in significant differences between the carbon isotopic composition of the open oceanic, bank waters from the platform and the semi-enclosed Exuma Sound. Our present studies are focusing on determining if the carbon isotopic composition of the carbonate precipitants in these two settings reflect this difference in isotopic composition and we can use this tool as a means of differentiating between cements formed by organisms and those precipitated directly from interstitial waters.

SUBTIDAL STROMATOLITES

Stromatolite Shapes and Forms. The stromatolites near Lee Stocking Island cover over 50% of the bottom area. However, when seen from above while snorkeling they appear to cover a much smaller area because they are often covered with migrating sand dunes. Only on rare occasions, usually after large tropical storms, can one see their bases and the substrate upon which they have developed They are usually only visible as "in crops" in scour depressions or the troughs between the dunes. The large submarine sand dunes and mega-ripples associated with the giant stromatolites have troughs that not only contain small developing "juvenile" stromatolites but also a lag deposit of oncolites and shells covered with microbial mats. Strong currents and winnowing of finer sediments have compacted this biogenious lag deposit forming a compacted interlocked "hardground." These rubble surfaces are especially well developed in the troughs of "starved" sand dunes that occupy the outer seaward parts of the Lee Stocking channel near Leif and Adderly Cays (see FIGURE 4.). These rubble areas also contain small oncolites, and vase- shaped hollow sand tubes.

The lag deposits forming in the troughs of dunes contain a mix of anomalous large nodules and small juvenile stromatolites building on crusted mud chips. The nodules when examined closely are hollow and probably cemented burrows.that have gradually settled to the the bottom of troughs with migration of dunes and concentrated by

FIGURE 4. Migrating dune and rubble filled trough with small juvenile stromatolite. Diver held pole is one meter long.

currents within the channel bottoms. The form is similar to the burrows made by the shrimp *Callianassa sp.* (Shinn, 1968). These oncolites look like small vases, with a cemented crust and hollow centers. Many have bulb shaped ends resembling the living and food chambers made by burrowing shrimp. Also found in the lag deposits are large numbers of shells, especially the large queen conch, *Strombus gigas*. Many of the large and highly bleached gray-colored conch shells have round holes broken into their spiral chambers, a feature which indicates they were originally harvested for food by Indians in the pre-Columbian era. Modern conch shells have an elongated slit chopped into the spiral by an ax, hammer or other iron implements.

There are many other man-made artifacts which have been observed in the lag deposits both around stromatolites and in the troughs between migrating dunes that deserve special mention. These are objects such as tin cans, bottles, milled lumber, anchors and junk from ships that have become encrusted with microbial mats and have cemented crusts. We have even found a large termite nest with a cemented microbial mat several cm thick encrusting it. This lag deposit is important because many of the larger stromatolite are found growing on lithified lag deposits similar to the ones found in the troughs of migrating dune fields.

Observations at different times of the year and over the past four years show that in all areas of the channel the dunes are migrating, both covering and reexposing buried stromatolites. In the area of giant stromatolites, burial times average about four months before a buried head is again reexposed. In places our giant stromatolites reach heights of 2-m often coalescing to form biohermal structures several tens of meters across. As such, this makes them the largest and best developed yet discovered in a marine environment. They occur in water depths between 3 and 8-m in the central axis of the thickest migrating dune fields. Their shape is dominated by club shaped forms that lean towards the direction of flood-tidal currents and are primarily composed of vertically accreted dome shaped layers of cemented oolitic sand.

Tops of the larger fence-like stromatolites are parallel with the crests of submarine ooid sand dunes. Nearly all individuals, regardless of size, are streamlined by tidal currents. Many display higher growth rates on the side facing the incoming tide, which causes them to lean noticeably toward the clear water. Many larger stromatolites have a soft botryoidal or pustular surface. Individual 1 to 10-cm diameter botryoids are composed of uncemented ooid sand bound by mucus and as yet unidentified microbial filaments. Small stromatolites, as much as 1-m high, may also have a pustulate surface, but most are smooth and slightly elongate (i.e., streamlined) parallel to tidal currents. The surface of the small smooth individuals is usually hard or crusty and lacks the loosely held sand coating (FIGURE 5 and 6). The hard surfaced stromatolites are usually found where they can be demonstrated to have been recently reexposed after coverage by a migrating dune crest.

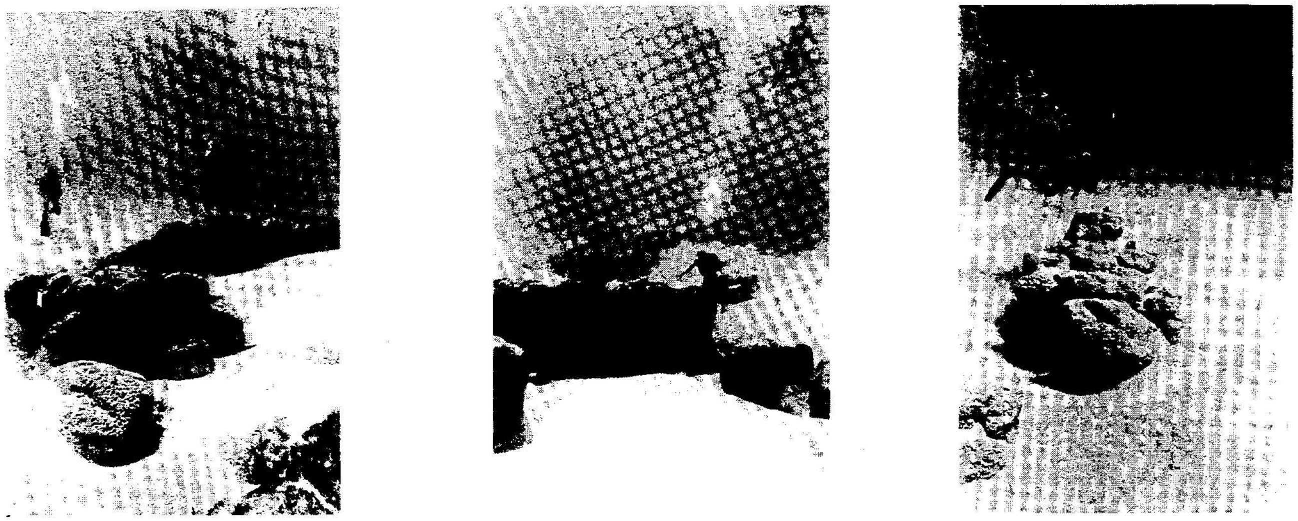
Interestingly, the tops of the stromatolites are seldom higher than the highest dune, and those that do rise above the sand dune crests become colonized by corals, *Sargassum* weed, and a variety of other epiphytes. Determining the cause of this maximum growth height and its relation to dune height and sediment burial depth is an important objective of ongoing research, because it will provide us with a modern analog for determining "synoptic relief," a value used to describe and classify ancient forms (Dill *et al.*, 1986; Shinn, 1987).

Primary stromatolite forms consist of hemispheres and clubs that often coalesce to form biohermal walls (FIGURES 7A,B,C). A striking feature of the Lee Stocking stromatolite columns is the streamlining and tilt of the growth axis into the direction of the prevailing flood-tidal current (FIGURE 7C). In parts of the tidal channel that trend east-west, stromatolites are oriented east-west and show both streamlining and/or tilt toward the incoming tide, i.e., toward the east. The surface of the stromatolite facing the east inflow of tidal waters is often covered by a series of shingle like plates that are separated by a small space from the main structure (FIGURE 8). These shingles are also reflected in the internal structure of large stromatolites that have been sectioned. They appear as cross laminations at the edge of the normal donal structures, tilting back toward the main body of the stromatolite. If this different growth pattern developing on the side of the stromatolite facing the incoming oceanic waters proves to be universally common, it could be useful in determining the direction of the bank margin in ancient carbonate platforms with similar stromatolitic growth forms.

Degraded stromatolites. In areas where the dunes that are usually in motion are stabilized by sea grass such as *Thalassia*, epiphites like sponges, corals and boring organisms become active and thestromatolite forms go into a destructive phase (FIGURE9). This is most commonly seen at the edges of channels or where the amount of ooid sand is insufficient to create dunes. This comparison has lead the authors to conclude that migrating dunes and an abundant supply of sediment are necessary for stromatolite formation. It could also indicate that the conditions forming ooids themselves also controls the preservation and development of modern subtidal high energy stromatolites.

FIGURE 5. Hard, crinkly algal surface, covers recently exposed surface. This texture traps loose ooids. Note rubble at the base of stromatolites in the background and the smooth texture of the sides of heads.

FIGURE 6. Pustulant to botryoidal microbial mat with abundant ooid grains cover the upper surface of an energing head. Note ripple marks and the fuzzy texture of the surface. Depth 5m in Lee Stocking north channel.



A B C

FIGURE 7. Biohermal walls of coalesced stromatolites in general have the same trend as migrating dune crests. Note that the height of the tallest heads in 7B are level with the crests of the dunes. In 7C the stromatolites are leaning towards the incoming flood-tide from the east. Scour depressions with ripple marks show refracted current patterns around heads. Depth 5-m Lee Stocking channel..

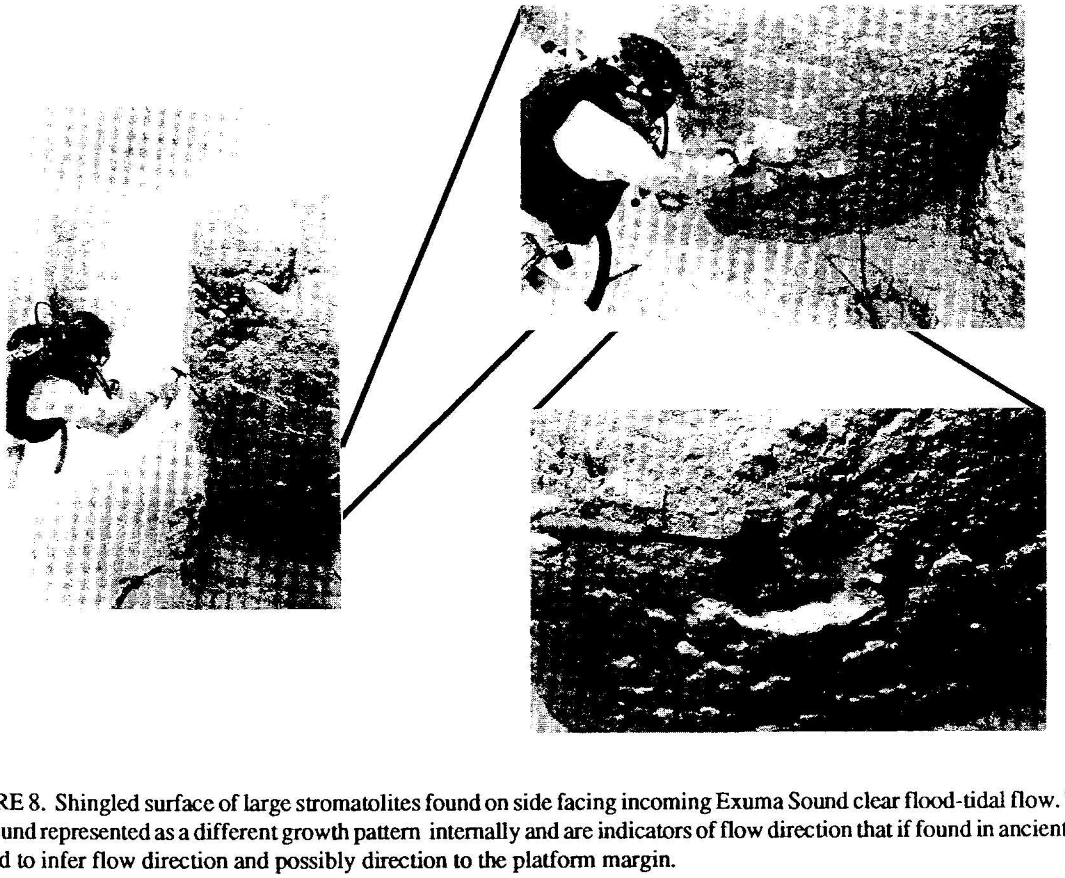


FIGURE 8. Shingled surface of large stromatolites found on side facing incoming Exuma Sound clear flood-tidal flow. These structures are also found represented as a different growth pattern internally and are indicators of flow direction that if found in ancient stromatolites could be used to infer flow direction and possibly direction to the platform margin.

Some of the older stromatolites in areas of stabilization have a hard cap of growing coral which leads one to speculate that some of the patch-reefs in the area in less high energy currents could have originally been stromatolite fields that have been colonized by corals after dunes stopped moving through the area. In areas of stabilization the inner core is dense and highly bored by pholads, sponges, boring molluscs, and worms. Numerous cycles of boring and refilling with marine cement obliterate the original structure of the stromatolites.

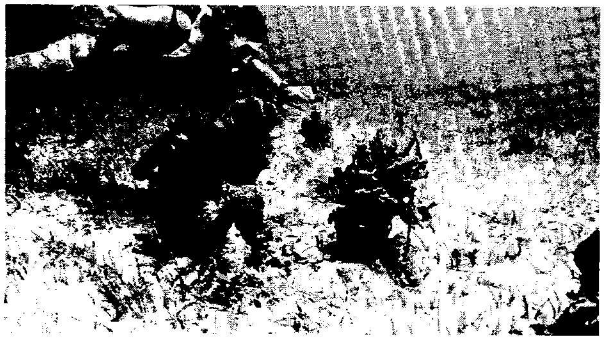


FIGURE 9. Where dunes are stabilized, stromatolites become colonized by epiphites consisting of sponges, coral and algae. The internal structures are degraded by bioerosion. Many fish use the structures as a haven from strong currents.

Internal structures. The unlithified upper surface of the stromatolites ranges from smooth to pustulate. Our observations indicate that this textural variation may be related to the length of time of exposure and the different seasons in which they become exposed. The seasons also control the colonization of the different components of the microbial mat community after reexposure. The internal structures viewed in cross sections form hemispherical laminations and digitations. In the larger columns these laminations reflect the streamlined shapes and connections between heads that form linear ramparts, walls and bioherms oriented perpendicular to tidal currents (see FIGURE 7 A,B,C). The biohermal walls and individual columns parallel the crests of large 1 to 2-m high dunes. Some internal structures can be related to the way the crests of these dunes migrate with each tidal cycle covering first and then reexposing the upper surfaces of stromatolites as they migrate back and forth across the area but in directions that parallel the trend of the channels. During maximum tidal flow, when current velocities range between 60 and 150 cm/sec, suspended and avalanching ooid sand is swept over the crests of dunes to collide with all exposed surfaces of the growing stromatolites. These suspended sands form dense clouds that look like a submarine blizzard during peak flow periods (Dill and Shinn, 1968). During every six hour tidal cycle currents transporting ooid sand bombard the stromatolite surfaces for a period of about two hours. Our observations and underwater video documentation (Shinn, 1987 EAS video presentation), coupled with our initial staining experiments have shown that most stromatolites receive a dusting of ooid sand each tidal cycle (Dill and Shinn, 1986; Dill *et al.*, 1986; and Shinn, 1987). The outer surfaces of the stromatolites are usually formed of a soft organic layer that forms a mat containing ooid sand grains. It is often up to ten-cm thick, but this thickness is highly variable. Sawed cross- sections of small heads show laminations, void spaces and dome like internal growth structures typical of ancient stromatolites. Outer layers are less cemented and crumbly whereas the central core is usually "cement hard."

The internal structures found in dissected columns are strikingly similar to some early Paleozoic and Precambrian forms. They consist of convex upward laminations composed of ooid and pelletal sand having structures like those described by Hoffman (1976) and James (1983) for the Great Slave Lake region of Canada. Laminae are caused by a combination of variations in grain size, cementation and alignment of pores. Some columns have incorporated siliceous spicules of sponge origin. The laminations occur in two styles: nested small scale convex upward laminations that form 1 to 4-cm wide columns, and larger convex upward laminations that encompass the large portions of columnar stromatolites. The small columns are often separated by unlaminated cemented sand. Many laminations thin toward the edges of the stromatolite and in places are truncated by near vertical wall structures along the sides of the stromatolites with columnar shapes. The larger stromatolites that have been sampled, are composed of both coalesced small and large columns as much as one meter high or more. The maximum synoptic relief, determined by using any one lamina in the stromatolite structure is only 16 cm, whereas the total exposed relief of the structure itself may exceed 100 cm. Maximum synoptic relief of the small scale columns is usually less than 12-cm.

Voids are numerous, and at least some are borings. Others are constructional formed by the bridging of sand grains. Borings, whether excavated by pholads, serpulids, or sponges, are characterized by truncated grains and cement. Except for those made by pholads, the borings tend to be irregular in shape and orientation. Constructional voids are plainer and parallel local laminations formed by the initial growth form of the trapping algal mats. Grains and cement are not truncated by constructional plainer voids. Planar voids can form when fleshy epiphytes such as sponges and the alga *Batophora sp.* are entombed by subsequent deposition of laminated sand. The organism decays and a void, essentially parallel to depositional laminae, is formed and preserved by rapid cementation. Finer grained sand and silt may form geopetal fillings in both kinds of voids. Uncemented ooids are often found in the voids along with mud chips and broken shell debris.

The microbial mat as will be shown, is formed by a complex community of plants and microorganisms with mucilaginous append-

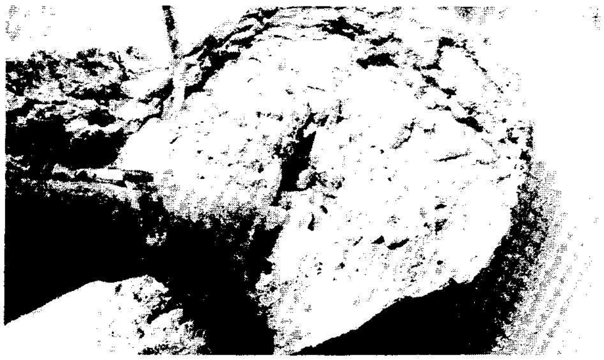


FIGURE 10. Internal structures of a head with its crusted cap removed. The outer rind is crusty and thinly laminated, the center is filled with uncemented ooid sand, shell debris, and crusted mud chips. This head is made up of three columns that have grown together and then been covered by a continious algal cap forming a larger head.

ages that behave like "sticky flypaper." When the heads are not covered by dunes, the microbial mat covering the internal cemented stromatolite efficiently catch ooids during each tidally induced "blizzards." As successive layers build up they form a distinctive growth stratum that is easily seen in stromatolite cross-sections. The open pore space between grains leaves space for additional growth in a protected micro-habitat free from bombardment. Thus, when the stromatolites are exposed in the troughs of the migrating sand waves, a potential accretion of one or possibly two layers of ooid sand is possible each day.

Rate of growth. To determine if these accreted layers become permanent cemented structures, we have used dye staining and nails driven into tagged stromatolites. Staining experiments confirmed that stromatolites can grow rapidly. Three specimens were stained *in situ* with Alizarin Red S by injecting the solution into a clear inverted plastic bag cinched tightly around the base of each specimen. The bag and stain were removed after six hours. Twenty four hours later, scraping the accumulated grains from the surface showed a layer of sand approximately one ooid thick (200mm) had been deposited over the stained surface. Sediment even adhered to vertical sides. Sand thrown against vertical surfaces sticks instantly to form a layer. We now have ongoing measurements to determine if stromatolites covered by dune migration cease accreting layers when the photosynthesis required for microbial mat growth stops. You might see some of the marked stromatolites during our dives in the area which have nails and "rebar stakes" protruding from their surfaces.

Episodic and differential rates of accretion are evidenced by examining the banding and the variability in thickness of lamination forming internal structures. We have yet to determine when banding occurs or what causes this variability of both composition and thickness but we believe it to be closely related to dune migration and to the composition of the microbial community.

There is one C_{14} date (480 yBP ± 50) on a conch shell within a 90-cm high stromatolite taken from the channel north of Lee Stocking that indicates their modern age. If we use this height as a means of determining growth rate it would indicate that the 15-cm high conch had accumulated about 70-cm of growing stromatolite in this time or a long term average of about 0.1 to 0.2-cm/year. This is nearly the same rate as proposed for the Shark Bay stromatolites, however, average long term accretion, based on a few dye measurements, appears to be about one cm/yr. (Dill *et al.*, 1986), a hypothetical value 10 times the instantaneous rate of mat accretion recorded at Shark Bay by Logan *et al.*, (1974) and 3 times the long term growth rate of the Shark Bay stromatolites when some of the large columns were actively accreting 1,000 yrs BP.

Cementation gradient. Marine cementation is rapid in this ooid forming environment, and a portion of the Bahama Bank a few kilometers west of the Exuma Islands is where the process was first documented in the Bahamas (Taft et al., 1968; Shinn, 1983). Although durable enough to resist removal by the strong tidal currents, the upper layers of the microbial mat are easily removed with a knife or crumbled between one's fingers. This laminated mushy layer merges transitional with cemented laminae of oolite and can be carved with a knife to depths of approximately 10-cm. The outer laminated crust can be sawed with a carpenter's saw to a depth of approximately 20-cm. Below that depth, the interior becomes well enough cemented to resist sawing.

As Dravis (1983) recorded, the uncemented ooid sand at the surface gradually changes to hard limestone in the interior. The gradient from organically bound sediment to rock extends from the upper surface to a depth of 45 cm and is best appreciated by sawing vertically into a stromatolite with a carpenter's hand saw. Sawing begins easily but slows and becomes impossible beyond 30 cm as cementation increases.

The cement is mainly acicular aragonite, similar to that observed in other areas of marine cementation. In localized areas aragonite crystals are tightly bundled to form what has been termed acicular fan druses (Shinn, 1969) or botryoidal aragonite (Ginsburg and James, 1976). Botryoidal aragonite occurs as a partial filling in voids. Micrite textured Mg-calcite is patchy and is more common in finer grained geopetal internal sediments. Magnesian calcite also occurs as cryptocrystalline cement in 20 to 25 mm diameter tubules and represents calcified filamentous algae (Dravis, 1983). Because of their habit of penetrating both pore space and grains, Dravis (1979) defined the tubules as chasmolithic/enterolithic algae, probably of the genus *Ostreobium*. We are unsure of their affinity or the timing of their entry into the stromatolite matrix. They are not common in the uncemented growth zone and thus are not considered significant as primary sediment trappers. Our ongoing studies will attempt to show when and how they invade stromatolites and become diagenetically altered to micritic Mg-calcite.

Some of the larger stromatolites have cores that are "concrete hard." Others have crumbly centers with entrapped uncemented sand, cemented mud chips and shell fragments (FIGURE 10). This cementation gradient is highly variable, and in some cases stromatolites are well cemented at the surface. This variability is currently being investigated by the detailed sampling, coring, photo micrography, and SEM photography of the internal cements. The stromatolites we have examined are cemented by fibrous and botryoidal aragonite and micritic magnesian calcite (Dill *et al.*, 1986; Shinn and Dill, 1986; and Dill and Steinen, 1988), but we do not know the relation of these forms to the organisms forming mats, if they are precipitates or where or when they occur during the lithification process.

Submarine cementation is believed to be fast when carbonate supersaturated water passes rapidly through a sediment (Land and Goreau, 1970; James and Ginsburg, 1979; Shinn, 1983). At the margin of Exuma Sound, oceanic water is supersaturated with respect to calcium carbonate. As it warms by as much as 6°C on reaching shallow depths it beceomes chemically unstable, especially when it is in a setting of turbulent mixing. This process may drive the precipitation observed in the successive carbonate layers seen in ooid layers and quite possibly the marine cements in the stromatolites. Thus, these Bahamian stromatolites form in a natural laboratory, which offers an unparalleled opportunity to determine rates of carbonate cementation and the nature of the cements. This is an ideal area for studying the influence of intraparticle hydrological flow and the *in situ* hydrochemistry of the pore space on lithification. There is an obvious influence and close association of the mat acting as an endolithic community on cementation.

Microbial mats contain and have been shown to trap ooid sands and finer carbonate grains causing them to adhere to the outer stromatolite surfaces. SEM photos show binding by aragonitic needles in the form of filamentous growths that are probably related to the trapping organisms (Dill and Steinen, 1988). We currently believe that cementation of the Bahamian stromatolites is like that in Shark Bay as reported in Burne and James (1986).

Microbial mat. Living algal and microbial filaments occupy only the upper 2 to 4 cm of the soft growth zone. Our present studies are designed to determine if the organisms are in part or even completely responsible for the cementation processes which gradually solidify and lithify these large stromatolites. Drs. R. Riding and S. Awramik made collections of mat during an IGCP field trip to Lee Stocking in July 1988. The results of that collection is presented in the following section. These preliminary identifications of the organisms in microbial mats were collected from the top and sides of growing stromatolites and reveal a complex assemblage of blue green algae, epiphytic diatoms, red algae and the *Dasyclads*, *Batophora sp.* and *Acetabularia*. The dominant organisms forming the mats are microscopic algae and cyanobacteria. Three components of this flora are repeatedly present and are frequently mutually associated in creating a complex, layered microbial mat. These are:

Bryopsis (filamentous unbranched chlorophyte) 50 to 70-µm in diameter, forming a dense felt of recumbent filaments with erect growing tips. The mucilaginous surfaces of this algae readily agglutinate ooids which commonly cover all but the growing tips of the filaments.

Schizothrix (filamentous cyanobacterium) approximately 7-µm in diameter, with a well defined sheath. Trichome at the surface are blue green, while slightly below the surface they are pink. They occur tangled around ooids and green algal filaments and are intimately associated with benthic diatoms in gelatinous masses.

Benthic diatoms, commonly associated with the filamentous cyanobacterium, are also epiphytic on the *Bryopsis*. They are attached to the ooids and larger algae by means of stalks, tubes or mucilaginous secretions. The average number of diatom species observed to date are 40 but most have not been identified. The species of *Mastogloia* are most abundant in the late summer and seven (7) species appear to dominate.

Additional common components are other filamentous cyanobacteria, planktonic diatoms, coccoid cyanobacteria including *Gloeocapsa*, *Gomphosphaeria*, and *Coelosphaerium* and filamentous chlorophytes, rhodophytes, and chrysophytes. Animals associated with the microbial mats commonly include harpacticoid copepods, spinoid polychaetes, foraminiferas, cladocerans, nemerteans, ostracodes, polyps of colonial hydroids, encrusting bryozoans, flagellated and testate protozoans and several species of sponges. On the taller stromatolites that are not periodically covered with migrating dunes the coral *Siderastraea* is occasionally found colonizing the exposed surfaces along with *Sargassum* seaweed.

Of special interest is a distinctive branched filamentous green algae, first described by Dr. John West of the University of California, Berkeley, that has fine "hairlike" sticky appendages that appear to have evolved in order to trap sediment particles. Several species of gelatinous colonial chrysophytes and green algae have also been collected which could be important in developing the protective grain supported organic mat. A number of epiphytic diatoms have been identified in the mat, one species of which has mucilageous tubes extending from its body.

The green algae *Batophora sp.*, documented by Dravis (1983) as significant to stromatolite growth in the Schooner Cays area, only occurs locally and is seasonal on the stromatolites of Lee Stocking. Thus, we conclude that the cyanobacteria forming in the mat are the dominant form and responsible for trapping suspended ooids and biogenic sands in what is admittedly a complex consortium of blue green algae, bacteria, specially adapted diatoms, and many as yet unidentified plants and organisms. This community structure probably varies with season and time depending on when buried columns are reexposed. Like other oceanic communities, we also suspect there is a succession of community development with time. It is also significant that the micro-ecosystem has adapted to high-energy conditions with life forms having "sticky flypaper" surfaces that trap sand grains, which in turn, upon stabilization, protect the mat community from further bombardment by suspended grains.

As previously pointed out the unlithified upper surface of the stromatolites ranges from smooth to pustulate. Our observations indicate that this textural variation may be related to the length of time of exposure during different seasons and the accompanying recolonization by the growth forms of the different components of the microbial mat. Thus, the overall shape and morphology of stromatolites at different locations in the channel appears to be related to the physical processes. Conversely, the surface textures which can be related to internal structures seen in cross-sections, are a combination of current and organically derived structures built by the dominant organisms forming the microbial mat.

In areas near the sides of the channels the ooid sand dunes have been stabilized by dense mats of the marine grass *Thallasia*. The stromatolites in these areas appear to be relict forms that are being slowly destroyed by bioerosion. Crevasses and holes in these stromatolites are densely populated by grazing fish and their surfaces covered by epibionts such as *Acetabularia*, *Batophora*, *Sargassum*, *Siderastraea sp.* and a variety of unidentified sponges and crustose coralline algae. Most have been invaded by boring pholad clams, and the boring sponge *Cliona* sp. has attacked many specimens.

Crusted mud beds. One of the remarkable finds in addition to stromatolites has been their association with laminated mud beds deposited in the high energy tidal channels. Mud beds are found at depths of 4 to 8 m (12 to 25 ft.) with a total thickness of up to one meter. However, the normal thickness is usually about 10 cm (4 inches) and made up of a series of laminated beds 2 to 5 cm thick (FIGURE 12 A, B, C). Bedding surfaces exposed to flowing sea water become crusted with millimeter thick marine carbonate cement. If exposed for several weeks the hard crusts become colonized by a diverse microbial community of algae, diatoms, and marine plants, similar to the ones growing and trapping ooids on nearby lithified stromatolites. The almost pure white lime muds forming the interior of the crusted beds are cohesive, appearing at first glance to be homogeneous, and soft having the sticky smooth consistency of "tooth paste." Some of the bedding plane crusts have encased broken blades of sea grass (*Thalassia*), small pieces of drift wood, and shells but very little material other than needle shaped aragonite mud is found in the interiors of the beds, indicating that the muds are deposited in a different hydraulic regime than the plant debris. It is important to emphasize that the mud beds have uncemented ooid sand both above and below the laminated, crusted mud beds showing that they occupy the same depositional environment. Of more importance, it shows that the muds are not a relict deposit related to a previous lowered sea level.

Because of the obvious problem of depositing a fine mud in a high energy environment microscopic examinations were made of freshly collected samples of the soft mud between the crusted bedding planes. It appears to be a homogeneous mud when first viewed. However, if the fresh mud surfaces are gently washed by a stream of water from a pipette (FIGURE 13), small pelletoid- aggregates, of what SEM photographs show are aragonite needles, become separated from the main body.

The individual pellets have diameters of up to 50-microns, a size similar to the smaller grains of ooid sands in the area. This similarity

FIGURE 12A .Crusted mud bed exposed in the trough of a migrating dune. Exposed surfaces have a thin cover of microbial mat that catch ooids. Note how the edges have broken away by scour undermining laminae. These then form crusted mud chips.

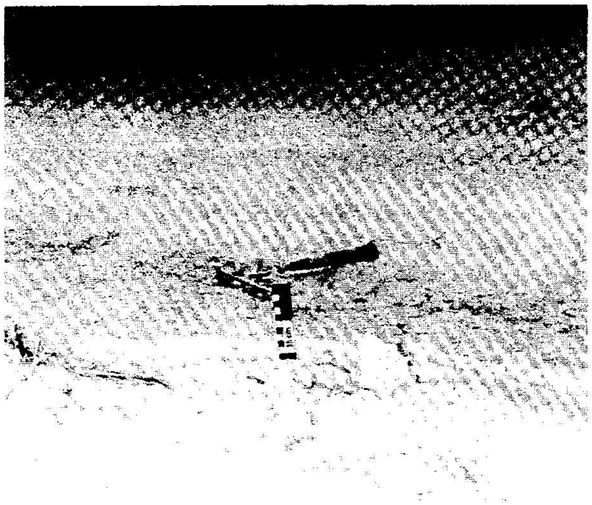


FIGURE12B. Closer view of laminations showing exposed edge and the internal white, soft cohesive aragonitic- muds. Surface is crusted with a marine cement. Note dunes in the background. The ruler is marked off in cm lengths.

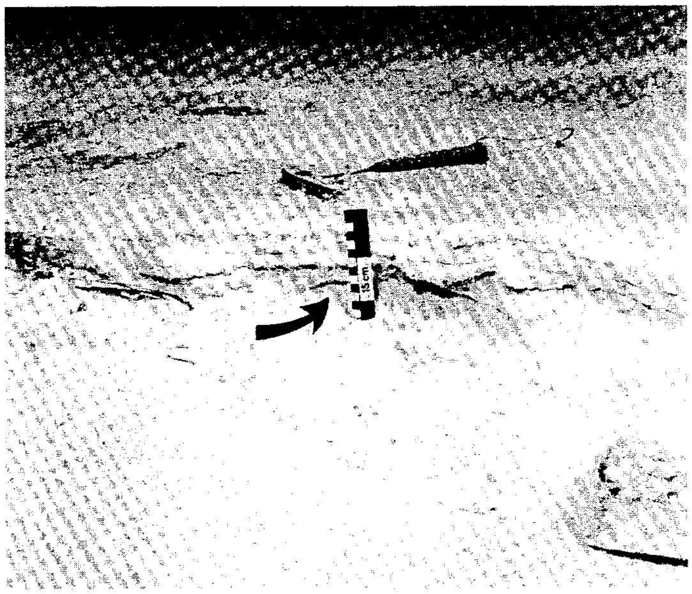


FIGURE 12C. Same location as 11B but with the sand removed showing that the mud beds are underlain by uncemented ooid sand (see arrow) and interbedded with uncemented ooid sands in dune field. Four distinct beds can be seen in this deposit with an average thickness of 2 cm. The bedding surfaces have mm thick crusts composed of aragonite needles.

could explain why the fine mud aggregates are found in similar high energy hydraulic regimes as the ooid sands. Scanning electric micro scope (SEM) images also reveal the pelletoids and the nature of the needle shaped carbonate crystals forming the muds (FIGURE 14) (Dill and Steinen, 1988).

SEM photos show that the crusts are formed of blunt ended crystals with their long axis oriented in a horizontal plane with marine cements binding them together. Under reflected light crusts have a shiny appearance and have micro-borings revealing the underlying randomly oriented, noncemented needle muds. There is a clear indication of resolution of crystals. At the contact between the uncemented and cemented layers there are small rhomboid crystals that look like dolomite. It is clear from the SEM photos that the surface crust is actively undergoing diagenetic changes, but much less so in the en-

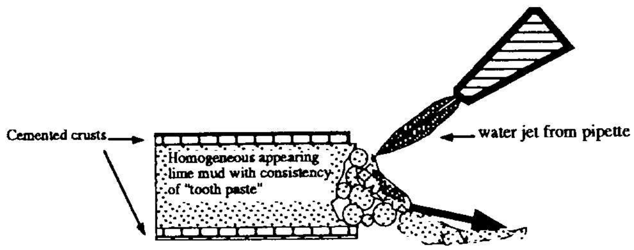


FIGURE 13. When the homogeneous appearing lime mud beds are gently washed by a stream of water from a pipette, small ooid sized aggregates of mud appear. This pellitization could explainwhy the muds are deposited in a high energy environment. SEM photos show the mud is composed aragonite needles.

capsulated internal muds which still retain their original sharp-ended needle crystals within the pelleted structure. The crust is composed of needle-like crystals that have a knobby appearance similar to that seen in dissolution. The crust contains many small borings some of which have marine cements beginning to fill them in.

Rip-up clasts form where scour undermines laminated, crusted beds. Pieces broken off by strong currents form "mud chips" (FIGURE 15). Some of the larger chips are then colonized by microbial mats which in turn trap ooid sand forming small soft stromatolites. During 1988, over a six month period, some of these were observed to grow and become part of larger structures. Sawed cross-sections of lithified stromatolites show that they have internal clasts of mud chips incorporated in their laminated internal structure. This shows that the stromatolites are forming contemporaneously with mud beds and in the same environmental setting. It is also an indication that the muds are not relic features of a different period prior to sea level reaching its present stand.

Possible sources of the aragonite needles forming the lime mud are precipitation from "whitings" and biogenious sources, such as the algae *Penicillus* and *Rhipocephallus*. These muds slowly accumulate in the thin layer of Holocene sediments that blanket the Pleistocene surface of the Bahama carbonate platform (Ginsburg, and Lowenstam, 1958; Shinn, et al. 1987; Steinen, et al, 1988). As previously pointed out, during tropical storms and hurricanes, this fine grained sediment is set in suspension as dense clouds of muddy bank water and is moved to the bank margins by ebb-tidal currents. There, every six hours it comes in contact with oceanic flood-tidal water and an intense mixing takes place. As previously shown the mud beds below the zone of mixing are formed of aggregates of pelleted aragonite needles. We have yet to determine if they are primarily a precipitate or possibly the resuspended muds of algal origin. We are currently analyzing the cements and muds to determine if their isotopic ratios provide an insight as to the origins of the muds. One thing is clear however, the

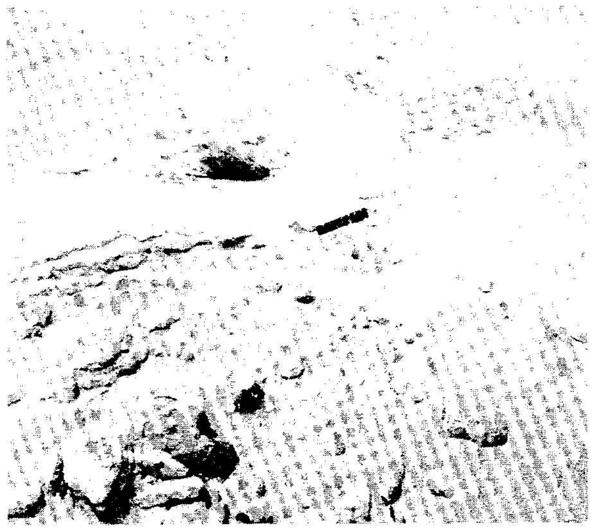


FIGURE 15. Crusted mud chips in ooid sand as a result of under mining of laminated beds. Note large conch shell often associated with both the mud chips and ooid sands.

muds are primarily formed of needle aragonite that is not usually found in the water masses that daily flow over the area. A special and uniquely occurring processes must be causing them to be deposited as relatively thick laminated beds in the high energy environment. It is important to point out that as of 1989, we have only found the mud beds below areas where there is a mixing of storm-generated, sediment-laden, slightly hyper-saline bank waters and the cooler open oceanic waters from Exuma Sound. In this setting one finds not only the crusted, laminated mud beds, interbedded with well developed ooid sand bodies, but also lithified stromatolites.

Grapestones. Extensive deposits of grapestones are found in the distributaries at the bankwards edge of flood tidal deltas. It may turn out to be significant that they are also found along the beaches of the leeward side of most islands and cays just beyond the surf zone. They have not been found in areas where *callianassa* shrimp are actively reworking sediments or in most of the areas where *Thalassia* beds have stabalized the bottom. This facies has yet to be adequately studied in the Lee Stocking area. However, we feel that these cemented multi-grained sands are important because of their large areal extent and the apparent restriction of this facies to the bottom below the bank margin mixing zone. Much of our future work in this area will focus on the habitat of grapestones formation (both skeletal and ooid grains), their distribution patterns relative to the currents of the region, the physical chemistry of the water in which they are apparently forming and the cements binding grains to form grapestones. Algal mats commonly are found growing in the areas of grapestones. In summer months, a marked temperature gradient is present grading from warm at the surface to markedly cooler temperatures several cemtimeters down into the sediments. The waters over the grapestone areas are usually less than two meters and with the one meter tidal variation often much less, especially in areas where migrating dunes create shoals.

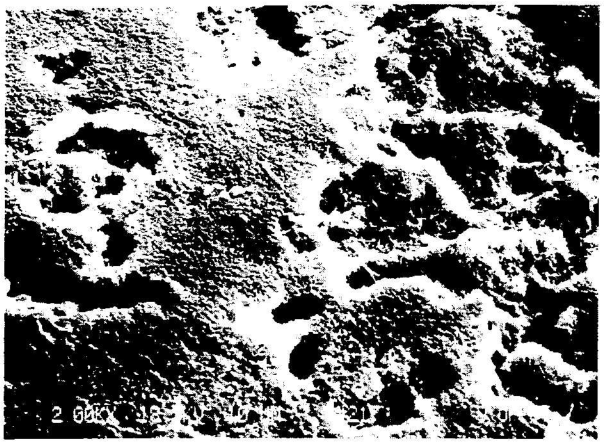


FIGURE 14 A. Surface of crusted mud. Note blunt crystals are aligned forming a smooth surface. Borings are 4-5 um in diameter. See 14 B taken where the borings in the center of 14 A (arrow)provide a window into the uncemented underlying needle aragonite substrate. Crust is composed of elongated crystals with irregular, nubby surfaces.

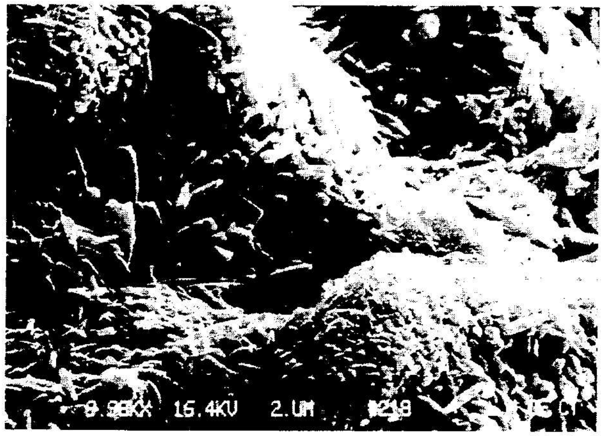


FIGURE 14 B. Lightly cemented needle mud. Note rombic crystals that have partly grown around needles. These xls. have similar shapes to dolomites like those seen in the mixing zones of Andros (Gebelein *et al.*, 1980).

FIGURE 14 C.Aragoniteneedle muds viewed through the crust in a burrow seen in FIGUTR 14A

FIGURE 14 D. Pelatoid mud from the interior of a crusted mudbed. Pellets can reach diameters of 60 microns.

FIGURE 14 E. Crusted mud beds at a depth of 8 meters in Lee Stocking channel. Pipe is marked in centimeters. Note that beds are layered and each layer has a crust.

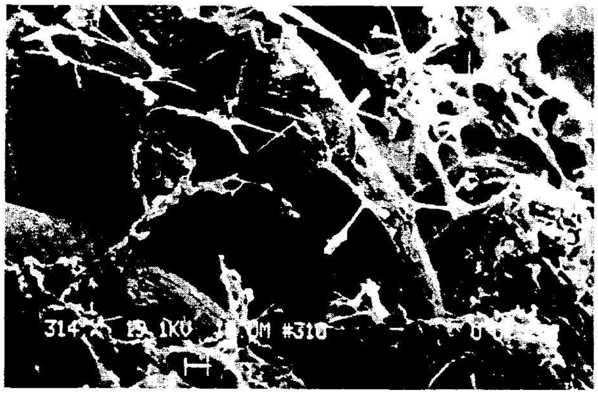


FIGURE 14 F. Filaments of organic material holding ooid grains together in the outer rim of a cemented stromatolite,

FIGURE 14. Under water occurrences of mud beds andSEMphotographs of lime muds in Lee Stocking channel. (from Dill and Steinen, 1988).

Comparison with other Holocene stromatolites

Great Bahama Bank. Dravis (1983) was the first to report lithified, subtidal marine stromatolites at the eastern margin of the Great Bahama Bank in the Eleuthera Cays approximately 160 km (100 mi) to the north of Lee Stocking Island. There, stromatolites up to one meter high are found in subtidal high-energy settings. Following our finding of stromatolites off Lee Stocking we have continued to search for other areas where they might occur both on the eastern margin of the Great Bahama Bank and the western and northern rims as well. Three new sites of stromatolite and mud bed occurrences have been found in channels north of the Lee Stocking Island discovery site (see X in FIGURE 3). Also stromatolites were found in 1987 by Eugene Shinn and Robert Halley of the USGS in a large area within the Exuma Land and Sea Park near Norman's Cay approximately 93 km (50 n. mi) north of Lee Stocking Island. They have stated however, that although stromatolites are forming there in abundance, the Lee Stocking stromatolites are still the largest and best developed of those seen to date. It is also important to note that lithified stromatolites have not been found in any of the other well studied areas along the western and northern margins of either the Great or Little Bahama Bank. However, reconnaissance overflights made by Dravis (1983) and ourselves strongly indicate that stromatolites are forming near the southern rim of the TOTO, approximately 50 kilometer to the east of Lee Stocking. This region could also be a mixing zone for bank , oceanic and upwelling water, a setting that is similar to Lee Stocking.

The Great Bahama Bank stromatolites now have a demonstrated wide enough distribution to allow them to be considered as a new site with an entirely different set of sedimentary parameters for comparing modern stromatolites with those that formed in the past, possibly as far back as 2 billion years ago. By knowing the environmental conditions and areas of occurance on a bank margin subjected intense mixing by tidal currents one can begin to predict where they will occure. They certainly are not rare as some reviewers of our early reports have stated.

San Salvador Island Saline Lake Site. Neuman, et al, (1988) report yet another new Bahamian site after discovery of the Mg-calcite stromatolites forming in subtidal hypersaline lagoons on San Salvador Island, Bahamas. These are forming in a different type of setting than those reported in the literature and provide another comparison for use in trying to decipher ancient environments using modern analogs. The San Salvadorian forms are growing in Storrs Lake in water depths of up to 2 meters and attain a height of about one meter. They have a club-like to mushroom shapes with diameters of up to one meter. The heads are draped by a microbial mat with hard cemented knobby protrusions extending above the organic structures into the overlying water by as much as 10-cm. The exterior of the individual heads is densely cemented. The interiors often crumble into loose stacks of mm thick laminae and thick intervals of thrombolytic, nonlayered growth. Sediments enclosing the heads are composed of carbonate, gypsum and organic matter. The sediment is in a reducing anaerobic state, highly organic, and produces hydrogen sulfide. The waters above the mat by contrast are aerobic from the high production of O_2 by mat photosynthesis.

Salinities range from 60 °/oo to 80 °/oo and have a seasonal variation that depends on rainfall, wind and solar heating. The Storrs Lake calcified heads are both thrombolytic and strombolithicappearing to be accreted by chemical precipitation at the contact between the microbial mat and the cemented hard heads. There is some inclusion of sediments in the heads but unlike the Lee Stocking heads this trapping seems to be a secondary process.

The microbial mat community forming the Storrs Lake stromatolites must have evolved into a carbonate producing body within the past 3000 years following the cresting of sea level over the island shelf following the Holocene rise. Before that period the lakes were either fresh or did not exist. It is intriguing to speculate whether or not the cyanobacteria and possibly the bacterial assemblages were in existence in the open sea or whether they rapidly evolved to live in the harsh environment of a supersaline lake.

The ongoing studies of this interesting community by Neuman and his colleagues should reveal a new insight in this modern subtidal analog for ancient stromatolite occurrence.

Australian sites. Our studies have shown that the stromatolites growing and becoming lithified within the Bahamian setting are found in an entirely different environmental setting but are not markedly different from the well publicized modern marine examples in Shark Bay, western Australia (Noel James and John Gotzinger, personal communication. There, the oceanographic conditions are those of high salinity, low current velocities and wave energy, and a semi-restricted intertidal to shallow subtidal setting (Logan *et al.*, 1974). Until the discovery of the Bahamian sites, Shark Bay was the only known area of open marine occurrence, resulting in its being the most commonly used and cited modern marine stromatolite analog for many fossil forms (Logan, 1961; Davis, 1967, 1970; Logan and Cebulski, 1970; Awramik and Vanyo, 1986). However, as Monty (1977) pointed out the sedimentary features and the sediments associated with many ancient stromatolites could not have been produced by conditions presently found in Shark Bay.

Recent discoveries of a number of new sites in Australia have further opened up that continent's potential for analog comparative studies (Moore, 1988; and Burne, and Moore, 1988). The Bahamian stromatolites both the open marine version and those in super saline lakes of San Salvador along with the new areas in Australia, give us other options for comparison.

Ancient/Modern Comparisons of Stromatolites Deposits

Definition. "Stromatolites" are defined as organosedimentary structures produced by the trapping of sediment. Cyanobacteria (blue green algae), and their ancestral precursors are generally accepted as being the first undisputed multicellular life on earth capable of building the stromatolitic structures that left a fossil record (Walter, 1976). Our modern marine structures form as the result of the growth and metabolic activities of microbial mats, which in turn trap sediment, forming a structure that is then lithified and will leave a fossil record. This certainly classifies them as true stromatolites. Stromatolites have been found occurring in sedimentary rocks found on all continents and range in age back to 3.5 billion years BP (Byerly *et al.*, 1986). Ancient stromatolites dominated the geological record for a period of time exceeding 3 billion years and have thus been the focus of paleoecologists studying early life on earth. In most Precambrian rocks, they represent the only fossil evidence of evolution. Sedimentologists have attempted to use these fossil structures as indicators of sedimentary processes and depositional setting (Awramik, and Margulis, 1976; Awramik, 1986). They have also been used as stratigraphic marker beds in the simpler ecosystems of the Precambrian and early Paleozoic rocks. Many stratiform ore deposits are closely associated with stromatolites. The cause of the association is not clear. Because of this association with mineralization, attempts have been made to use them as index fossils and stratigraphic marker beds with limited success (Hoffman, 1967; Schopf, 1970; Monty, 1973; Walter, 1976; Flugel, 1977; Awramik, 1981). One of the main problem with using stromatolites as index fossils and as environmental indicators has been the lack of modern comparative models. Further, as our studies indicate, it may well be that evolving species did not create their morphology but instead the physical characteristics of the setting may be responsible for growth forms. The setting may also be responsible for mineralization as suggested by Brongersma-Sanders (1988) in a recent symposium on "Fossil Microbial Ecosystems of the Stromatolitic Type and Modern Analogs sponsored by ICGP 261." The use of the new stromatolite finds in providing an alternate possibility in deciphering environmental conditions and depositional settings has not been extensively applied to the ancient forms and may be important in reevaluation of early deposits containing stromatolites, mud beds and ooid sands.

The physical nature of the sediments and the physical processes forming internal structures indicate that the Bahamian stromatolites have associated sedimentary features and internal structures that may satisfy many of the environmental conditions that Monty (1977) inferred must have existed and been necessary for ancient stromatolite growth but not exhibited by those at Shark Bay. These are ooid sand, crossbedding, oncolites, algal nodules, laminated-mud beds and mud chips often seen in ancient deposits containing stromatolitic structures. Thus, as Ginsburg (1986) pointed out in his key-note address before the SEPM Symposium on Stromatolites in 1986, "the Bahamian stromatolites may provide a new avenue of comparative research for interpreting the past environmental processes that led to the development of ancient stromatolites." We also believe that the associated features may be equally significant. However, there are also major and to be expected differences between ancient and recent Bahamian forms. We must stress that Bahamian studies are in their early stages and that we need much more data on the internal structures, distribution and cements in the Lee Stocking area and other Bahamian sites coupled with environmental parameters before they can be used as modern analogs of the environmental conditions and processes that existed one to two billion years ago in seas devoid of the higher forms of life that are obviously an important part of modern stromatolite development.

However, comparisons are possible as demonstrated in the use of the setting for the Bahamian stromatolites to explain Cambrian forms found in the Death Valley region of California and Nevada by Griffin (1987) where she found stromatolites having similar shapes and concluded they had formed in similar setting that created similar sedimentary associations.

By contrast, and as Awramick (personal communication, 1987) and Griffen (1987) have pointed out, and our review of the literature along with our personal observations have shown, there are also major differences between ancient and recent Bahamian forms. One commonly discussed difference is the micritic nature of the cores of ancient stromatolites (thrombolites) which do not contain internal banding or zonation. The stromatolites we have examined off Lee Stocking are usually formed of banded layers of ooid and skeletal sands in a micritic cement. However, we have found one stromatolite that has a core that is almost completely micritic in nature with almost no evidence of original ooid sands (see lone pillar in front of diver in the cover photo). Is this difference from other stromatolites something that takes place after formation, is it a diagenetic change or is it a process related to modern marine boring and recementation? At this time these are questions that will remain unanswered until we obtain many more rock cores of heads in the area and from them determine the cause of this major difference in what appears to be the same environment.

The cemented crusts found on the micritic mud beds if lithified, would result in a structure not unlike many laminated micritic Precambrian limestones that have been classified as stromatolitic. The rounded blocks of undermined crusted mud beds contain a pure aragonite needles and form a mud that appears structureless and if fully lithified it would be micritic. In ancient limestones these would be identical to large oncolites. Many ancient depositscontaining stromatolites are are also associated with ooids and mud chips within the containing matrix. Do we then possibly have an unrecognized modern analog that answers some of the questions arising about micritic stromatolites and associated sedimentary forms?

We are continuing to gather more data on the mass physical properties of sediments, internal structures and associated accumulations of lag deposits so we can gain a much broader understanding of the present sedimentary settings that contain stromatolites, ooid sands, grapestones and mud beds. Bed forms are preserved in many ancient environments and can therefore be used on a comparison basis to relate modern with past settings. Once we know what conditions forstr the formation of todays structures we feel it will be valid to postulate conditions whichbrought about the world wide development of stromatolites 2 to 3 billion years ago. We must further emphasize that the Lee Stocking structures are not applicable to understanding all the stromatolites that formed prior to the development of higher life forms in the Paleozoic. However, a knowledge of the Bahamian forms and their depositional setting along with their organic associations certainly help us make this comparison with ancient forms with a much more experienced eye. In many ways, the differences may help us to understand how and what conditions prevailed in a ancient setting without present day predation, coarse grained biological produced sediments and growing in waters that probably had a chemistry that differs from today's oceans.

There is a common belief that the types of microorganisms and the succession of different organisms forming the organic mats may be responsible for the different growth forms found on the surface of the larger stromatolites. Our studies suggest that the water flow patterns may be an equal or even a more important factor in controlling the overall shape and growth rate and morphology of the giant stromatolitic columns. Also, water clarity, chemistry, and nutrient content of both interstitial water and the ambient environment may be as important as currents in determining morphology and species makeup of the organic mats that are trapping suspended sediment. Different species names have been given to the different shapes and morphologies of fossil stromatolites. Our studies indicate care must be used in applying this "morphospecies" concept to ancient forms.

The high-energy currents carrying a suspended load of ooid sand across a migrating submarine dune field is a not normally considered to be conducive to plant growth. Our studies show that the microbial mats contain organisms with special adaptations and appendages useful for trapping and holding sand grains. We now believe that these organisms catch and stabilize the ooid sands using this trapping mechanism as an evolved defense and the resulting protective structure as a means of existing in what would normally be considered a hostile setting. In many ways these could be considered as arenaceous microbial organisms similar to arenaceous foraminiferas that also use sand grains to form protective tests.

Once ooids are trapped, the resulting loosely packed granular structure not only acts as a protective shield from the continued bombardment by sand grains, but also provides new pore spaces between grains, in essence an expanded favorable habitat that encourages more microbial mat producers to trap grains. Cementation of the stabilized grains then permits marine cements to form and build an upward growing structure that is continually washed by larger volumes of nutrient carrying water. This mechanism could compensate for the adverse setting of "sediment bombardment and shifting sands" and create a more favorable "biological" niche for the mat-forming organisms over a colony settling on a flat rock surface. By fostering the development of the stromatolitic structures the organisms are exposed to a higher rate of nutrient exposure during high currents periods even in the nutrient-poor tropical oceanic waters. They are also above saline bank waters that act as density flows along the bottom during summer months. This communal growth strategy would give the stromatolite building organisms a distinct advantage in obtaining nutrients over the quiet water organisms. The stromatolitic structure therefore provides protection from destructive grazing organisms, which cannot cope with the high currents, crunchy sand grains and bombardment.

We concludethis section by stating that all stromatolites in the Lee Stocking are subtidally formed, their shapes are controlled by hydraulic conditions and they must have a mobil sand body periodically covering them to develop. Further, an entirely new mechanism for rapid fine-grained deposition of mud is called for to explain the occurrence of pure aragonitic mud layers within uncemented mobile submarine dune fields and their relation to stromatolites. An understanding of the causes and occurrences of these mud deposits, interbedded with mobile ooid sand bodies of the high-energy subtidal channels, could provide geologists, who use bed forms and mud clast associations to interpret ancient paleoenvironments, another setting in which these ancient stromatolitic forms developed. It now appears that the association with fine grained aragonite needles in dense suspensions, when encountering the bank margin mixing zone, form aggregates that must rapidly settle and act hydraulically like sand grains. Why this deposition takes place, its relation to organic material in the water, or if it is caused by organisms, we have yet to determine. These remain intriguing questions that need answering by further research in the bank margin mixing zone.

SHELF-EDGE, FRINGING REEF FRONT AND PATCH REEFS OF LEE STOCKING

Introduction. Part of the field seminar will be devoted to studying the reefs surrounding Lee Stocking. We have therefore provided in this guidebook a brief description of the types we will visit along with the dominate corals at each site. The southern tip of Norman's Pond Cay also has a good example of a Pleistocene reef formed during a higher stand of sea level of possible Sangamon age which we will visit for comparative purposes. Most of the reef we will visit can be classified as *patch reefs* or *fringing reefs* and will be in shallow water reachable by snorkling.

Reefs in the Bahamas tend to occur on the high energy seaward side of Pleistocene islands located along the edge of the platform. Reef development requires a relative high energy setting to provide currents for bringing nutrients to the coral polyps and carrying away waste products from reef destruction. In the vicinity of Lee Stocking, it is possible to examine the morphology, biota, and geologic development of all the classical reef types except for the "bank barrier/lagoon" which does not yet exist because the offshore reef has not reached a depth where *Acropora palmata* can take over reef development (approximately 7 meters, Adey, *et al.*, 1975; 1976; 1977). Reefs available for study are the deep shelf edge feature at 30 to 40-m, a shallow 20-m reef system growing on a Pleistocene cliff face, fringing reefs attached to the shoreline, and both deep and shallow patch reefs. A well developed patch reef is just north of the dock at Lee Stocking Island and will be visited on our check-out dive on the first day of the field trip.

Many small patch reefs are found in the channels leading back to the bank proper that have a typical coral assemblage. The fringing reefs are dominated by *Acropora palmata* and *A. cervicornis*. Protected depressions behind the *Acropora*, also have a good representation of small head corals prmarily *Diplorea sp.*, *Aggricia sp.*, and *Monastria sp.* . Many of the fronds of dead *Acropora* have been encrusted with the mustard colored "fire coral", *Milipora sp.* and should not be touched during our snorkel dives in the area. Also many of the long whip like *Gorgonian* fan corals have been coated with *Milipora* and should also be avoided.

Distribution. There is no well-developed platform margin bank barrier-reef on the high-energy, windward side of Lee Stocking Island; instead, a rock pavement with topographic highs (possibly relict reefs or even regressive dunes) mark the eastern platform margin. There is however, a well-developed submerged reef starting at a depth of about 20 meters with a relief of 8 to 10 meters running parallel to the present shore line. This reef system is approximately one kilometer off the eastern shore of the island. We do not have an explanation why there are no well developed bank barrier reefs off the eastern margin of the Great Bahama Bank. It may be that there are insufficient nutrients, not enough wave energy, or that the chemistry of the water is not conducive for rapid *Acropora palmata* growth. This reef building species is poorly represented and is only found in isolated areas near resistant headlands. The poorer reef development of the Exumas could possibly be related to the discontinuous character of the island chain. The lack of barriers enables hot saline bank waters to reach the bank margin, so inhibiting reef development. At Lee Stocking, the flow of warm, saline waters from the interior of the bank reach the open oceanic waters of Exuma Sound through channels between the islands. Strong currents insure that this water is agitated. The seaward side of the islands off channels does not have a deep reef system only a hard ground covered by a thin blanket of skeletal sand and numerous small head-corals dominated patch-reefs, gorgonian soft corals and a diverse assemblage of sponges including extremely large basket sponges. Off the islands away from the channels by contrast, relict ridges resembling ribbon reef structures have been colonized by a highly diverse coral assemblage dominated by head corals such *Montastrea ,sp.* *,Diplorea, sp.*, *Agaricea ,sp.* and *Acropora cervicornis*. The ridge has numerous small caves and a poorly developed spur-and-groove system running perpendicular to the trend of the ridge, similar to present day bank barrier reefs.

The position of the rock platform, its patch reefs and the deeper terrace edge reef is thought to coincide with the position of bedrock highs in the underlying Pleistocene limestone. Elsewhere in the Bahamas and the Caribbean *Acropora* dominated barrier reefs occur in this windward platform margin setting, often where the Pleistocene barrier islands prevent bank water from flowing across the reef. The *Acropora palmata* bank barrier reefs off Eleuthera and Andros are not continuous, and lose their identity off major creeks or passes through the large islands. For this reason we are currently working on the hypothesis that the bank barrier reefs are related to their not being closely connected to bank waters.

A Caribbean wide occurrence of coral "bleaching," caused by a loss of zooxanthella from coral polyps, has been related to abnormally high water temperatures in 1987 and 1988. This temperature control of coral health indicates that it might also be related to reef development in general and may explain the lack of a bank barrier reef off passes and inter island channels leading back to shallow bank regions where hot saline waters are produced.

Morphology. Off the Exuma Cays and Lee Stocking, the coral and sand-covered fore-reef bottom rises gradually from the cliffed platform edge "the wall" at about 50 meters to some 20 meters. Here, the sea floor is covered by hardgrounds, patches of head corals, and wide ribbons of carbonate sand. Westward is the just described ribbon reef of the inner terrace edge. Leeward of this are the patch reefs of the inner platform edge that are elongate, and nearly parallel to this edge.

Locally "spurs" of living reef extend seaward perpendicular to the trend of the reef patches. These spurs are 10-30 meters wide. The spurs are separated by "grooves" or channels, which deepen seaward, so that the relief below adjacent spurs may reach 1 to 12 meters. The bottom of grooves is floored with coral rubble, coarse to fine *Halimeda* sands, and some micrite probably formed as a product of clionid sponge boring. Sediments in the grooves normally move only during storms, and at those times supply reef sediments to the adjacent deep waters of the Exuma Sound. Both constructional and destructional processes help create the "spur and groove" morphology. In some localities off Lee Stocking, the spur and groove morphology has been rounded and is not now covered by living corals. The dominant organisms are sponges and *Gorgonian* soft corals. The exposed surfaces are encrusted with a lush growth of algae and crustosecorallin algae. Erosion may deepen the grooves whilst local coral construction may extend the spurs seaward; bioerosion at the base of the spur undercuts the living coral-covered reef lobe.

Fringing Reefs. Two areas of well developed fringing reefs are found off Lee Stocking Island. These are on exposed headlands seaward of the airstrip in a region that has high wave energy, is not usually subjected to bank waters and commonly reached by upwelling Exuma Sound waters. Weather and wave conditions permitting we will snorkel the main *Acropora palmata* reef (see FIGURE 3 for location). This reef has excellent examples of the control of wave approach on the morphology of *A. palmata*. On the exposed side of the reef the fronds are perpendicular to the main approach of the wave fronts. The reef crests in areas of high wave energy support a luxuriant growth of *A. palmata* occurs with a stout branch morphology that is oriented perpendicular to wave surge. By contrast, in local areas where there is shelter and a lower energy regime, the branches are without orientation and are flattened (FIGURE 16). Where the fronds die, or at their stocked bases where there is insufficient light to support active growth, the coral becomes encrusted by red algae and become highly burrowed by *clionid* sponges. This undermines the strength of the fronds and they break falling to the substrate. These broken pieces then begin growing anew and form the base of an expanded reef system. Note the white tips, this is the growing of the coral that has not as yet acquired *Zooxanthellae* the symbiotic algae that give coral their color.

The Deep Terrace Reefs. This reef system is located just seaward of the airstrip approximately one half kilometer from the shore. It is characterized by massive corals, including, *Montastrea sp.*, *Diploria, sp. Agaricia agaricites*, *Siderastrea sp.*, *Porites sp.*, *Millepora sp.* and isolated thickets of *A. servicornis*. In the deeper portions of the margin to seaward (greater than 15 meters) a columnar form of Montastrea is the dominant coral; while in still deeper water the encrusting *Montastrea* and plate-like *Agaricia* predominate.

A sediment coverd terrace, extends seaward of the main reef and is marked by numerous rock mounds and rubble beds. The hard substrate is characterized by abundant calcareous algae and by encrusting organisms (red algae, bryozoans, foraminifera, bivalves, sponges) which help to hold the framework together. The sands have an abundance of *Halimeda* sand and are often covered with a microbial mat. This mat is also an important food source for a large breeding population of conch which populate this setting. Fine lime mud is also an important component of the terrace sediment. At Lee Stocking Island this deeper fore reef slope is quite luxuriant and merits a visit by those capable of scuba diving.

Internal Structure and Sediments. Cavities in the reef are created both by constructional and destructional processes. The net result is an extensive system of cavities, lined and supported by encrusting organisms "cripto fauna" and by inorganic cement. Cavities may be partially to completely filled with sediments. The internal sediments vary from sand to micrite.

Development of marine cements is pervasive within this seaward occurrence of reef though we have yet to establish how extensive. Cements include aragonite and high Mg-calcites of several morphologies (acicular, spherule, micritic and blocky). Coarser grained internal sediments are usually cemented within a meter or two of the living surface of the reef. These sediments may be subsequently bored, the borings filled with sediments, cemented and so on -- thus providing preservable evidence of the very early precipitation of this cement.

Patch Reefs. Two types of patch reefs are found in the vicinity of Lee Stocking and much of the Bahamas along the windward edge of the banks.

1. Low Mound Red Algal Patch Reefs. These consist of low mounds up to 1 meter high and several tens of meters across which are covered by a solid mass of encrusting red algae. Attached to this smooth, hard surface are numerous *Gorgonians* and *Alcyonarians* (sea fans and sea whips). Sediment production is low, but sediment movement and water turbulence over and around the mounds is high. Algal mats prevent the establishment of most corals due to a lack of grazing organisms in the high energy areas.

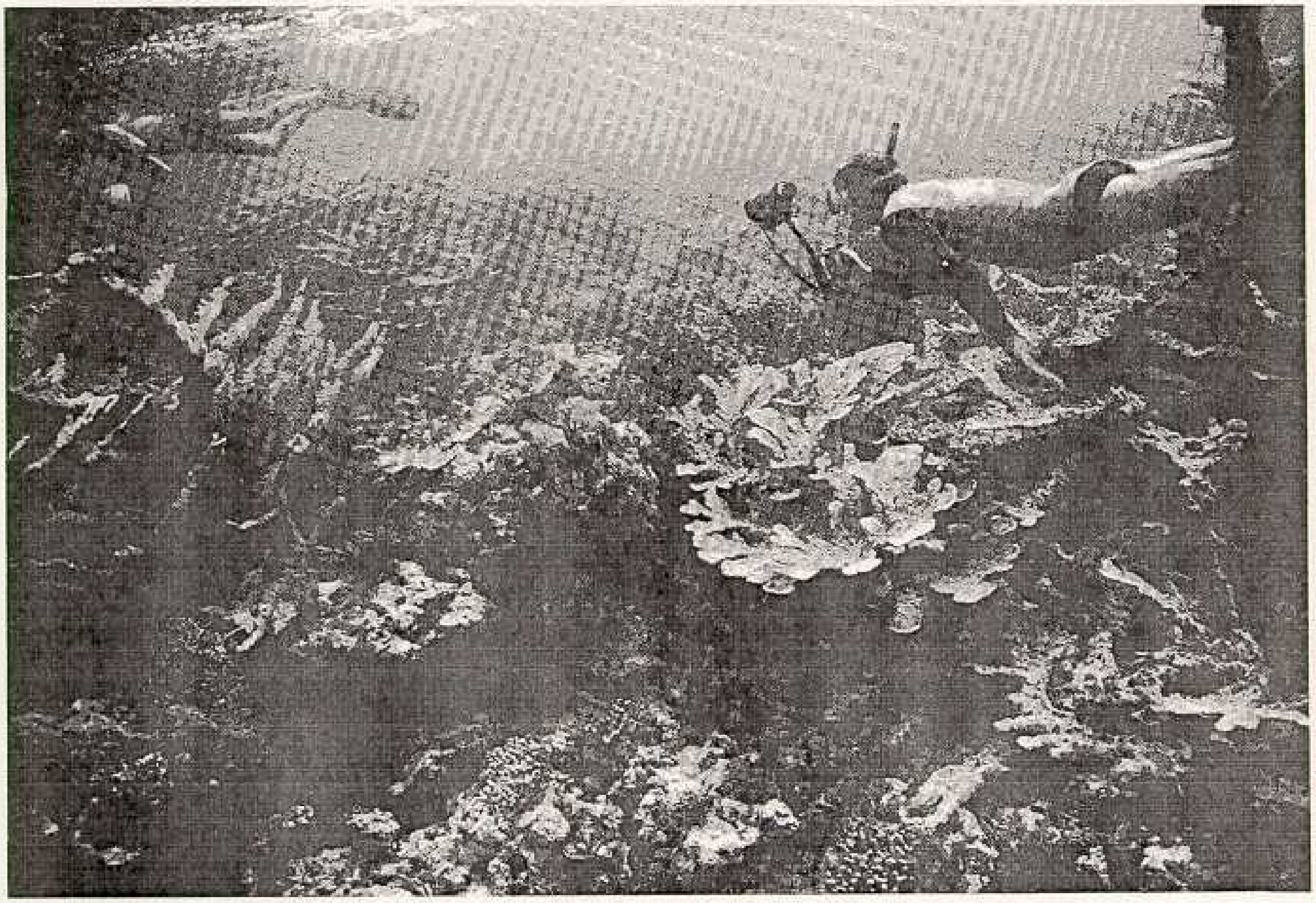
2. Coral Patch Reefs. The continued upward growth of the above red algal patch reefs allows colonization by branching corals and by small massive corals. These latter patch reefs may have measurable relief (2 to 3 meters) and produce considerable sand-sized sediment by breakage of coral sticks and by growth of calcareous green algae (*Halimeda*) on the coralgal substrate.

Sediments. Skeletal calcarenite occur with patches of silty calcarenite in protected pockets. Sediments are composed of coral, *Halimeda*, molluscs, coralline algae, foraminifera, and echinoderms. Before 1982 halos of open sand aprons surrounded most patch reefs and were largely created by the grazing ofthe spiney sea urchin, *Diadema*. Once prolific, these long spined and menace to swimmer suddenly died back greatly changing the nature of the ecosystem of reefs primarily by permitting algae to dominate the corals. In recent years they have become more apparent and appear to be on the road to becoming re-established.

Internal reef sediments vary from medium sands to calcilutites, depending on the position of the void. In large patch reefs, sediment grains are volumetrically more common than coralgal framework.

Biota.

1) Algal patch reefs -- encrusting red algae, gorgonians, rare small corals.
2) Coral patch reefs -- branching corals (*Porites* and the delicately branching *A. cervicornis*) occur in deeper low energy water around the patches and while small head corals (*Montastrea,*



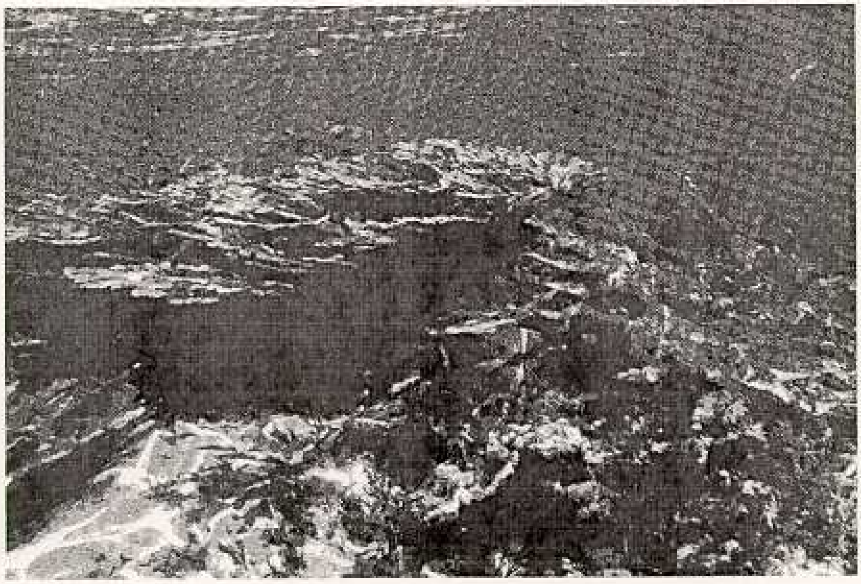


FIGURE 16. Fringing reef of *Acropora palmata* off the eastern side of Lee Stocking Island. This coral is the major reef builder in the Caribbean andwestern Atlantic tropical waters. Note the changes in morphology and how it is related to wave energy and the direction of swell advancement.

Diploria, Siderastrea, and *Porites Asteroides*) occur just shallower. *Millepora* "the mustard colored stinging fire coral" occurs in the near crestal position while the platey coral *Agaricea* occurs within the patches. *A. palmata* occurs in crestal position on the patch reefs in areas where wave energies across the shelf are high, or the water is sufficiently shallow.

High concentrations of *Halimeda*, various echinoids, cementing molluscs and sponges are also common species in this assemblage. Encrusting red algae, bryozoans and encrusting foraminifera acicular cements do occur and are found within corals and beneath the sediment interface.

?ROTECTED INTERTIDAL MUD FLATS AND PONDS OF NORMAN'S POND CAY

Immediately leeward of many of the Pleistocene Eolian islands of the Bahamas, wave and current energy related to the prevailing trade winds are reduced to their lowest levels. Sediment produced on the bank and eroded from islands accumulates along the lee side of islands forming broad beaches, which inturn, migrate to the southwest forming a protected low area behind the storm berm and sandy points along the southwest corner of islands (see Norman's Pond Cay in (Figure 3). The low regions behind the storm berm of these lee side beaches develop into intertidal flats. Tidal flooding during storm surges and perculating sea waters fill the lows with sea water coming mainly from the western platform and the lee side of islands. These flats are enclosed by storm berms that are sometimes capped by beach rock forming a barrier to flow. This loss of permeability, permits evaporation and heating of the ponded waters during dry seasons, creating supersaline conditions. During the rainy season the playa ponds rapidly fill with rain water and the waters become brackish. The resultant fluctuations of salinity, brackish during the rainy season and suprahaline during the hot dry season, create an extremely harsh environment for most organisms to survive. Thick algal mats are associated with these areas and have in other areas been compared to stromatolitie structures. However, a lack of cementation does not bring about a permanent structure so they really are not stromatolites in the classical sense even though they are formed by microbial mats.

Mass mortality is evident in large accumulations of shell beds and skelatons of stranded fish. We will visit two such landlocked ponds on the southwest margin of Norman's Pond Cay. July is sometimes the end of the dry season and the Ponds may be supersaline. It could also be the begining of the summer wet season and the ponds may be brackish either way these are interesting regions and have important sedimentary structures and a unique fauna with algal mats worth investigating during the IGC field trip.

Norman's Pond "Saltworks" Pond. The eastern side of Norman's Pond Cay is formed by cemented Pleistocene dunes with an elevation of up to 15 m (50 feet) above sea level. The Saltworks Pond occupies the south-central part of the Island just west of this Pleistocene ridge. This pond was a salt factory in the 19th Century and has numerous old buildings and structures that are remnants of its early use. The pond is flooded and drained through a man-made channel each tidal cycle (6 hours). During low tide, a small waterfall occurs at the seaward end of the channel of the western shore of Norman's Pond Cay when the trapped pond water from high tide rapidly flows from the pond through the narrow entrance channel. For our visit it is significant that well carbonate cementedcrusts are forming in the sediments flooring the channel. This like other areas of the bank where marine cements form, is a setting with significant temperature changes and an abundant microbial mats. A well-developed flood tidal delta has been formed from sediment carried from offshore up the channel into the interior of a large pond in the center of the island. This delta (birds-foot type) has several distributaries which are gradually filling the eastern side of the pond. Mangrove plants planted by our classes since 1984 show the progress of the delta growth. Cores show that the delta is prograding over the muds and anr algal flat peat that accumulated on the floor of the pondprior to cutting the entrance channel..

The base of a man-made wall and sluice gate protecting the sides of the channel entrancehas been undercut by a bioerosion forming a "nip." Bottles found offshore indicate that the pond was producing salt that was shipped north between 1845 and 1850. Thus the erosion notch has formed in less than 150 years since the development of the salt works. It further demonstrates how the islands rocky coast lines are being "eaten away" by bioerosion at a significant rate. In this case where the nip is about 20 cm (8 in.) this erosion would be about 0.13 cm per year. If one assumes that sea level reached its present relatively stable stand approximately 2500 yBP, it would then be possible for approximately three meters of erosion of the present rocky shore line by bioerosion. If one includes the amount of weakened rock broken away by wave action this value would be much greater.

Sediments. The sediments of this protected lagoon are enclosed by the sandy prograding beach ridges composed of well-sorted carbonate sands containing a variable admixture of ooids and abundant calcareous skeletons including fragments of *Goniolithon* and the foraminifera *Marginopera*. Within the vicinity of waterfall creek the beach is cemented to form beachrock. Typically, many of the ooids are highly micritized.

Offshore to the west. in one to two meter water, the main sediments are grapestone sands thinly blanketing a hard cemented surface that we believe to be the Pleistocene surface of the Platform. Small coral heads form isolatedpatch reefs with sponges protruding through this thin blanket of grapestone sand. Dead coral heads are often colonized by clumps of *Goniolithon* which are the probable source of the sands found in the channel leading to the internal saltpond. A small ebb tidal delta has formed at the entrance to the channel from sediment carried over the waterfall and out onto the offshore margin of the Cay. The sediments of this delta apparently has the proper sediment size and packing to encourage the colonization of juvenile conch. Literally thousands have been observed here having an age of one to two years. This is an important nursery ground and they should not be disturbed during field investigations. It is important to realize that the sedimentary patterns and currents controlling facies is also important to many of the organisms living in the area. The biologists and geologists working at CMRS often use the same data for their respective research projects. This site also supports at different times of the year abundant growths of *Batophora, Acetabularia, Goniolithon, Penicillus, Rhipocephallus, Halimeda, Thallasia, Siderastrea, Porites,* and sponges.

Biota. In the submerged portions of the flats and along the tidal channels draining the pond, the fauna and flora is surprisingly cosmopolitan and includes coverings of the marine grass *Thallasia*, the calcareous green algae, *Pennicillus, Acetabularia, Batophora* and a number of different species of molluscs. Colonies of the coral *Siderastrea* coat the submerged Pleistocene rock that underlies and is exposed over much of the pond. It is interesting to note that the Siderastrea is often a red in contrast to its normal cream color.

Red mangroves line the channels and the margins of the pond. Further back, these give way first to black mangrove and then white mangroves. The subterranean paths of the black mangrove can be seen by the radiating pneumatophores around the main plants.The shrimp *Callianassa* is burrowing and reworking the sediments in the tidal channel and the margins of the flood delta.

In the higher, intertidal portions, blue-green algal mats cover the surface of the flood delta flats, and predatory gastropods (e.g. *Batillaria*) are abundant. The beach rock seaward of the pond is colonized by green algae, *Batophora* and *Acetabularia*. The dark gray to black color of beach rock is due to algal growth and is the main food of grazing snailes The rough surfaces of the beach rock and Pleistocene limestones near the shore, called biokarsting, is mostly caused by grazing gastropods.

Sedimentary Structures. Laminated bedding occurs in algal peat that lie at the base of the sedimentary section. These consist of alternating laminations of algal peat and carbonate mud with some sands. In the higher portions of the sedimentary section of the flats, particularly on the flood delta, calcareous sands are common and are covered by algal and diatomaceous mats. Along the edges of the flood delta, *Callianassa* mounds are extremely common and are associated with very soft muddy sediments. Mangrove peats are common along the shores of the western edge of the pond. The beach shows several berms and seaward dipping swash laminations. These swash features are incorporated in the beach rock.

Dynamics of Sedimentation. Sediments of the protected mud flat are accumulating in the most "quiet water" environment of the complex. Even though these flats are immediately adjacent to the high energy active shoal, island development has effectively damped wave and current action. Both fine-grained and coarse-grained materials are brought into the area from all over the complex, primarily during storms. Subsequent reworking of the materials by organisms, particularly *Callianassa* and *Cerethids*, destroys sedimentary structures around the edge of fan. Despite this activity, algal mats and peats are preserved below these surface sands..

Norman's Pond Playa. At the southwest end of Norman's Pond Cay, a series of north-south trending beaches have isolated an elongate brackish to hypersaline pond that lies against and caps the Pleistocene rock surface. This playa may represent what was once the seaward entrance of the "Salt Works" pond before "waterfall" creek was cut through the prograding Holocene beach ridges. Marine bioclastic lime muds and sands lie directly on the Pleistocene and we hypothesize accumulated before "waterfall" creek was cut. Lying on these light grey sediments is a soft slurry of black algal peat that is locally mud cracked at its surface when the water level of the pond drops. This algal slurry probably began accumulating after "waterfall" creek was cut and the playa became isolated at its southern end. Its northern margin is marked by a low ridge of Pleistocene carbonate and coral debris. With the exception of its eastern shore, most of this pond is ringed by red and black mangroves.To the west and south of the mangroves are beach sediments capped by freshwater plants and bushes, including palmettos. The beach sediments show several storm level berms and have their seaward edge marked by beach rock.

Sediments. The sediments of the playa are formed by grey bioclastic sands and bioclastic-rich lime muds overlain by black noxious algal material. The sediments of the beach are composed of oolites and bioclastic material, including dominant fragments of *Goniolithon*.

Biota. The playa has a highly variable organic community that is controled by the salinity at different times of the year. During dry periods brine shrimp are abundant along with some small fish. Of course all die if the pond goes dry. The flora includes cyanobacteria forming mats on the pond bottom, the edges have red mangroves, and further shoreward above pond level black mangroves along with a number of species of salt tolerant grasses form the major flora.

NORMAN'S POND CAY PLEISTOCENE REEF

Location. The southern end of Norman's Pond Cay (FIGURE 3) is the site of a well lithified coral reef assemblage of probable Pleistocene age. This is the only known occurrence of a well preserved fossil reef yet found near the Caribbean Marine Research Cente. It is similar to previously described fossil reefs found on San Salvador Island (Mylroie and Careau, 1985; 1987; 1988; White and Curran, 1986), the northern Bahamas (Neuman, and Moore, 1975), areas of the Caribbean such as Jamaica (Land,1973), Barbados (Steinen, R.P., 1974) and St. Croix (Whetton, 1966). Most of the fossil reefs from other areas, when dated, appear to be Sangamon, ranging in age between 125,000 to 170,000 y BP.. Samples have been submitted to the U.S. Geological Survey for dating but ages were not yet unavailable in time for this publication.

The upper surface of the reef is 1.2 m (4 feet) above present day mean low water and appears to have been truncated in places by subaerial erosion. The surface contains solution pits filled with cemented paleosol and a brown to red soil breccia with limestone chips These are remnants of a well developed paleosol the caps the reef. The reef exposure forms a terrace that is over 200 m (660 ft.) long and over 10 m (33 ft.) wide where it is lost under a cover of paleosol. The surface of the paleosol is smooth rock with a brownish color. This then merges upward with a densely cemented ooid/ pelletoid cross-bedded dune sequence that extends to the top of the island, an elevation of about 15 m (50 ft.) above present sea level. Other occurrences of much smaller fossil reef remnants have been found on the northwestern margin of Norman's Pond Cay near the entrance of a deep subterranean cave and a site called "Tug Boat Cay" approximately one quarter of a mile south of the main reef. Neither of these are extensive however, and there is some question as to whither or not they contain in place coral heads. Eugene Shinn and Robert Halley (personal communication, 1989) have observed a fossil reef above sea level with about the same dementions an in the same general setting at Fowl Cay, approximately 30 miles north of Norman's Pond Cay. The reef on Fowl Cay also has a paleosol overlying the coral reef and is at the south end of the island. The reef proper, also forms a similar low terrace just above sea level.

Reef composition. The coral assemblage forming Norman's Pond fossil reef consists of a basal unit dominated by thickets of *Acropora cervicornus* and *Porites porites* the matrix around the sticks of these corals is a micritic cement with numerous broken mollusc shells, red to pink, colonial foraminifera (*Homotrema*) and occasional pockets of *Goniolithon* sand. The sticks of *A. cervicornus* are badly weathered and stick out from the matrix as intertwining branches. The matrix contains cemented ooid sand also highly weathered, having dull non-lustrous surfaces.

About one meter (3 ft.) above the present low water the assemblage becomes much more diverse and contains many corals common in present day relatively quiet, shallow-water patch reefs. The capping corals must have grown on a hard ground indicating the underlying *A. cervicornus* was cemented together prior to the growth of the capping corals. This indicates environmental conditions were encouraging early marine cementation, a setting similar to that now in the region.

The capping corals consists of weathered heads of *Monastria annularis, M. cavernosa, Siderastrea sp., Diploria sp. Porites sp., Oculina sp.* and numerous mollusks in a shell and ooid sand matrix. There are also many broken shells of indefinable species and broken and probably displaced fronds of *Acropora palmata*. Pockets of *Goniolithon* sand are also found in the matrix along with abundant encrusting *Homotrema*.

To the west of the main exposure of the fossil reef, At the same stratigraphic level, the corals die out and the main rock is made up of a shell hash cemented together by the pink foraminifera *Homotrema*, similar to those that are cementing together the "boiler reefs" in Bermuda. The contact between the reef debris and the overlying dune sequence is marked by a well developed paleosol containing numerous *Cerion sp.* land snails, vados pisolites and rhizomorphs.

Paleosols and sedimentary relationships. In the main reef area, many of the solution pot holes which penetrate the underlying coral contain soil breccias. The soil zone is up to 50 cm (20 inches) thick. Small one to two centimeter (1/2 to 3/4 in.) diameter soil pisoliths are also common with a reddish brown coating of soil stain. This stain is also found on the *Cerion* land snails. The paleosol contains many large brown to reddish solution casts filled with soil breccia that is densely cemented andmore resistant to solution then the surrounding reefal material. This results in the features, originally holes and voids, standing out in relief as the surrounding limestones were dissolved away. Numerous stacked lenses of caliche crust are found in this lower soil zone indicating solution and recementation as fresh water peculated through the overburden and was stopped at perched localized water tables.

The sediment in which the soil formed was a ooid sand. The contact between the soil zone and the overlying dunes is not distinct. It grades from a highly vuggy lower zone with numerous intertwined rhysoliths to a densely cemented ooid limestone. Cross bedding in this sequence indicates that the soil was covered by a migrating dune system that later became stabilized. This permitted lithification in its present location by vados cements. The lower part of the soil zone has numerous cavities that appear to have been filled by ooid sands as the dunes migrated over the soil zone. These fills contain a honeycomb like structure probably developed around root tubes that penetrated the cavity after filling with organic material and ooid sands from above.

Moving shoreward the insular margin has several terraces. The lowest marks the top of the coral reef. This is followed by a series of small steps with widths of 2 to 5 m wide (6 to 15 feet) with a relief one half to one meters, on the steep side facing the ocean. The lower terraces have a smooth rounded surface that is capped by a densely cemented caliche crust several cm thick. The limestone beneath the crust is a ooid sand that is less densely cemented than the crust. Approximately 100 m (300 ft.) back from the shore a 3 to 5 meter high cliff with small caves forms a sharp break in the slope of the island. The upper surface of this cliff is a flat plain, however, the surface is highly dissected by solution pits and sharp "rillenstein" micro-karst appearing to have developed after the upper surface was planed off.

The small caves in the cliff below the upper terrace are similar to those forming today along the rocky shore associated with "nip" development by bioerosion and wave induced abrasion. However, the rough, sharp surfaces seen at the present shore line are lacking. This in not unexpected when one considers these fossil surfaces have been subjected to extensive solution by rain water and are no longer subjected to bioerosion. It is not difficult to conceive that the present day rocky shores would probably take on the same appearance as the upper cliff if they were exposed to fresh water runoff and removed from the bioerosion and degradation by algae and grazing organisms. The upper cliff surfaces are coated by a thin layer of pink lichen

The small caves have a diameter of up to one and a half meters and open to the south. These, like those in the solution pits in the fossil reef, often contain the honeycomb structured fill and rhysoliths that formed after the formation of the cave. This fill rests on caliche crusts and must be a later event than the formation of the caves. We therefore interpret these caves and fill to be evidence of several episodes of deposition and erosion. With out definitive ages it makes the deciphering of the stratigraphy more difficult. The numbers of rhysoliths within the caves is much less than those found in the soil zone directly overlying the fossil reef.

Geochronology. Until our age dating is completed our tentative interpretation of what the sequence of formation of the reef complex, soil zone development and final burial are, is as follows:

1.) Rising sea level during the Sangamon high stand flooded the Great Bahama Banks eastern margin. There could very well have been a series of older islands formed of cemented dunes complexes from prior periods of glacial low stand. These would have formed the hard ground and nucleus for shoal/bar development and hard grounds upon which reef building corals could colonize.

2.) The fossil reef now 4 feet above low water and seen exposed at the shoreline today, is dominated by *A. cervicornus*. This species indicates the environmental setting of low energy relatively quiet water probably less than 10 meters (30 ft.) deep. We don't know what underlies the fossil reef at the south tip of Norman's Pond Cay,but if present day patch reefs in other areas can be used as a criteria, the *A. cervicornus* probably overlies head corals or a hard ground (Adey, *et al.*, 1977). This can only be determined by drilling. Thickets of *A. cervicornus* reached a thickness of a little over one meter (3 ft.) before head corals became dominant. This is a reversal of the sequence we see in the present day cores of Holocene reefs. Using the criteria developed by Adey and others this would indicate that the reef was forming in waters that were getting deeper or during a transgression. It could also indicate that dune islands were forming to the east near the edge of Exuma Sound and cutting down wave energy from the prevailing trade wind from the east and southeast.

3.) The base of the fossil coral reef could not be much below present low water because an eolianite dune sequence is exposed in the walls of a cave at the northern end of Norman's Pond Cay at about one meter below present low water. This eolian deposit extends to a depth of 8 meters (20 ft.) where it overlies a highly bioturbated fine grained shallow water marine formation made up of fine grained biogenious sediment. This marine formation extends down to a depth of 16 meters (50 ft.). The eolianite is capped in places by broken coral debris and some head corals that appear to be in place. This occurrence of coral just above the cross bedded dunes and just under a well developed paleosol is stratigraphically similar to the larger fossil reef at the south tip of the island. The actual relationships will require drilling to be resolved.

4.) The upper part of the fossil reef changes from a *A. cervicornus* dominated thicket to an area of head corals. The scattered and broken fronds of *A. palmata* indicate the reef was less than 7 meters (21 ft.) deep and that sea level was probably not more than 8 to 9 meters (28 to 30 ft.) above its present stand when the reef was developing.

5.) Sea level began falling with the beginning of the Wisconsin ice age and exposed the fossil reef to shallow and shallower water, eventually exposing it as a relict feature. At this point rain water began dissolving the reef structures and vados cements began cementing the structure and a developing cover of ooid sands.

6.) Continuing regression exposed all of the reef forming a small island. Vados and rain water forming small solution pits and caves. Dune fields formed from ooid sands and pelletal muds exposed to subaerial conditions. Winds and runnoff moved this bank gererated sediment to the bank margins where it accumulated around highs such as the reef. These sediments were colonized by plants and soils formed along with caliche crusts at the water table. Continued leaching and reprecipitation of calcite cements lithified the dunes migrating over the paleosols preserving them as a cap on the fossil reef.

7.) Paleosols continued to forming near the regressive shoreline, gradually creeping seaward and to lower elevation. This cap of caliche present above sea level at the fossil reef can be seen in the channel north of Lee Stocking island near the stromatolites at a depth of 9 meters (30 feet.). The paliosol therefore transgressed over near shore sediments and hardgrounds during this fall of sea level. The drop was beyond 125 m if present day submerged caves and speleothems represent a maximum lowering of sea level (Dill, 1977) . Approximately 18,000 y BP sea level began rising marking the beginning of the Holocene.

8.) Rising sea level then reestablished marine conditions all along the bank margin. Small sea cliffs were formed as the rising level stood still forming a terraced shelf seaward of the ancient dune islands formed during the glacial regression.

9.) Our present data indicates sea level broached the Bank margin and began flooding the shallow regions about 11,000 y BP. By 5,000 y BP the shore line was at a depth of about 10 to 13 meters (30 to 40 ft.) and still rapidly rising relative to present sea level. Erosion at the shore line and between inter island channels stripped all soil zones down to the hard densely cemented caliche crusts and the hard cemented dunes. As the waters rose flooding the entire bank these surfaces then became the hardgrounds upon which sessile marine organisms could then colonize and form the foundations present day reefs and stromatolites.

10.) Between 18,000 and 3,000 y BP the rate of sea level rise was much higher than to days with but a few still stands that formed the terraces. After 3,000 y BP there has been an relatively stable sea level that is an anomaly within the Holocene period. Further ,this still stand has caused a marked change in the offshore topography of pre-existing islands and cays. It has also allowed the further colonization of slow growing corals on hardgrounds and permitted them to obtain optimal growth and development, a condition they could not realize when rising sea level exceeded their upward rate of growth and left them in water depths beyond their desired light levels. The erosional debris from reefs that reached shallow waster then began to form skeletal sands that have now formed the dominant grain type for the beaches of the region vs the ooid sands formed during the regression.

The Recent still stand has also caused islands to lose their hard rock perimeters by bioerosion at the intertidal zone through the formation of nips. Historical data indicates this intertidal regression by bioerosion can be as much as 25 cm per 100 years. Extrapolation back to when sea level reached its present position (3,000 y BP) indicates that bioerosion could account for as much as 7 meters (22 ft.) of rocky shoreline loss and probably more if one includes losses from wave erosion and collapse of overhanging nips. This is important because it indicates that almost one half of the 30 foot wide fossil reef on Norman's Pond Cay could have been eroded away in the last 2 to 3 thousand years. This would further indicate we are not seeing the true extent of the original reef when viewing the present site. The thickness of the original reef probably has not sustained nearly as much loss due to the low rain fall and its protection by a partial covering of cemented fossil dunes and paleosol caliche crusts.

The fossil reef at the end of Norman's Pond Cay is an important and useful stratigraphic marker in deciphering the geological history of the development of the bank margin. It provides positive proof that sea level was higher than it present stand prior to the last Wisconsin lowering and an insight into the conditions that followed the regression and transgression during the last ice age.

CONCLUDING STATEMENT

The active cementation occurring in the tidal mixing zone at the margin of the Great Bahama Bank constitutes a setting similar to that active in many ancient carbonate platforms. The processes presently causing this cementation were also active in the past. The role of organisms can not be neglected nor can the physical/chemical relationships of water mass mixing. This region is complex, highly variable and difficult to study in short periods often dictated by the timelimitations of yearly grants to study such regions. The tendency of funding agencies to limit field investigation by suggesting models and comupter studies can provide acceptable and cheaper substitutes certainly will not work in this region until a much more extensive data base is obtained. The studies that have lead up to this guidebook have not suffered from a lack of time only a lack of funding. We have made progress, but it must be stressed that our studies are not complete and in reality are in their beginning stages. We are just now beginning to realizethat the occurrences of stromatolites, crusted mud beds, ooid sand, grapestone sands, and hardgrounds are related and depend on the organic constituents of water masses in the bank margin environment. The stromatolites and their related sedimentary features need further work. The microbial mats have not been properly identified nor has their role in cementation been proven. We therefore encourage the participants of this field seminar to pick out a research problem, develop a field project and join with us in developing a broader knowledge of this intriguing region.

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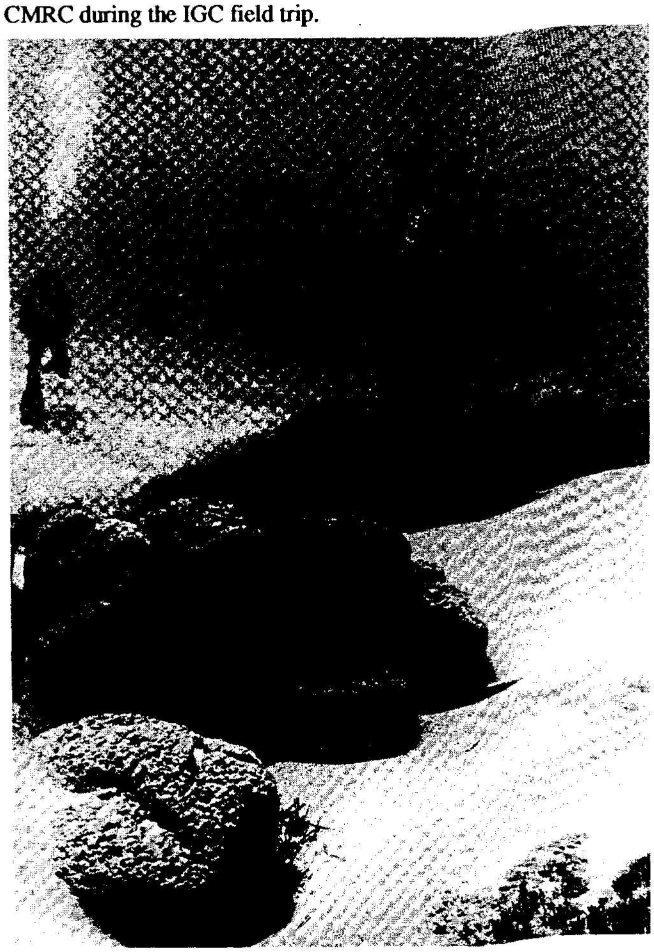
Further reading. A more detailed description of the stromatolites and the marine geology of the region is available in: Kendall, C. G. St. C., Dill, R. F., and Shinn, E. A., 1988, GUIDEBOOK OF THE MARINE GEOLOGY AND TROPICAL ENVIRONMENTS OF THE SOUTHERN EXUMA ISLANDS AND CAYS, BAHAMAS; Their carbonate facies, geologic history, giant stromatolites, oceanography and biological associations, *Special Pub. of the Caribbean Marine Research Center and the Department of Geology, University of South Carolina*, Columbia, S.C. 29208, 200 p. Information from Kendall, et al, (1988) was used to provide background data for this IGU Guidebook and is available at the Caribbean Marine Research Center (CMRC), on Lee Stocking Island, Bahamas or from the Department of Geology, University of South Carolina. Another useful book on the biota and flora of the region is Voss, G., 1980, Seashore Life of Florida and the Caribbean, *Baynan Books Inc.*, Miami, FLA. 33143, 199 p. it will also be available to participants at CMRC during the IGC field trip.



APPENDIX
THE CARIBBEAN MARINE RESEARCH CENTER
Welcomes you to our island!

Because this is a post congress field trip, there may be participants who wish to spend more time on Lee Stocking studying other tropical carbonate settings and the geological aspects of the surrounding islands. Please let the field trip leaders know if you wish to say on and we will make the necessary the arrangements for additional time. A modest fee will be assessed for each additional day you wish to spend on Lee Stocking to cover expenses and field support costs. Contact Dr. Kendall at the Geology Department, University of South Carolina, Columbia, SC, 29208 or Gerri Wenz, Assist. Director at CMRC (address in Appendix) if you wish to extend your stay beyond the three days allotted to IGC.

The staff of the CARIBBEAN MARINE RESEARCH CENTER welcomes you to Lee Stocking Island! FIGURE 1 shows its location near the southern end of the Exuma chain of islands and cays on the central eastern edge of the Great Bahama Bank. FIGURE 3 gives the layout of the island facilities along with some of the major features you will find near our Island research laboratory. We would like to offer a few suggestions and house keeping hints that over the years we have found will make your stay as members of IGC 1989 more enjoyable and help you optimize your time with us.

BUGS Mosquitoes and sand flies (""no see ums") can, at times, be a nuisance and, to some persons allergic to their bites, a source of infection. There are some precautions which can be taken to avoid the discomfort and dangers of these nasty "bad guys." When you leave your room or house, be sure that no doors or screens are left open, especially at dusk. In case of rain, please close doors and windows if you intend to be away for any length of time. Also, it is a good idea to leave lights off while you are away. "No see ums" love visitors, especially their ankles, and will come through screens to get at their "prey." Insect repellent and room spray are available at the Island store. Covering up is the best defense, e.g. socks, but OFF or CUTTERS insect repellent works very effectively. A quick room spritz with area spray before retiring tends to "knockout" whatever insects happen to be there at the time (leave the room for few minutes after using this spray it's effective, but should not be inhaled).

WATER We have a very efficient water making/roof rain collection system. However, our water supply is limited. We must be mindful of conservation, especially with showers and toilets. When washing gear dunk first in the fresh water tub and clean only once a day. A simple rinse is all that is needed after being in salt water.

SUPPLIES There is a small commissary store located next to the Lizard Lounge where snacks, sunscreen, liquor, T-shirts and gifts can be purchased. If necessary, special arrangements can be made at the Office to open the "store" to fit your schedule. You will not need cash your credit is good, but your store bills must be paid before your departure by cash, money order, or check .

TELEPHONE There is a phone located in the main office which is available for required business or urgent calls (8:00 a.m. 5:30 p.m.). We have only one line out however, and it is used for our every day business so please be flexible and do not make needless personal calls. Please check with the CMRC staff for the proper procedure to use and pay for your phone calls.

LIZARD LOUNGE This is the gathering place for meals, presentations, class meetings, etc. Meals are at 7 a.m., 12 noon, and 7 p.m. unless otherwise prearranged. The bar opens from 67 each evening and after dinner if requested. Drinks will be put on your personal "tab" for payment before leaving the island.

SOME NECESSARY REGULATIONS

Before using any Island facilities or equipment, all guests must sign a liability waiver. This is required by our insurance company a modern legal nuisance of which we are sure you are aware. Because we are a marine research facility and not a resort, we adhere strictly to the fisheries laws of the Bahamas copies of which are available upon request at the Office of CMRC. We use the surrounding waters as a natural laboratory, therefore there are a few other self imposed conservation regulations with which we ask residents and visitors to comply. Spear fishing by visitors is not allowed. We actively protect the reefs around Lee Stocking Island in order to maintain these areas in as pristine a state as possible for research purposes. The taking of live corals is prohibited by law and we do not allow the collecting of live shells. Beachcombing is excellent with many dead shells and specimens, the taking of live specimens is unnecessary.

OF INTEREST Tours can be arranged of our aqua culture project if you are interested. We invite you to ask questions of any of the staff if they don't know the answer, they will direct you to someone who can help you.

We have several resident giant iguanas. The Bahamian Rock Iguana is an endangered species and is protected by law. One of ours, "Iggy," is very friendly and can be seen at the north point. However, Iggy will bite if you attempt to hand feed him!

All animals on Lee Stocking Island are protected and there are many interesting species, including migratory waterfowl, boa constrictors (small ones!), burrowing owls, several varieties of lizards, and West Indian ospreys. There are no indigenous mammals on our Island. The only species for which we allow open season are mosquitoes and "noseeums"!

SAFETY Our vehicles are driven on the left, so please remember this if you are walking on the roads especially during the workday when tractors and trucks are being used.

Use the buddy system for both diving and snorkeling. It is always wise to let someone know where you are going if hiking in the bush, walking the beaches or going for a swim in an isolated area of the island. BE SURE TO LET SOMEONE KNOW when you intend to come back to the settlement area. It's always better not to go swimming or exploring alone.

ALWAYS get prior permission to use boats and make sure the office is informed of where you intend to go and when you intend to return (be sure to go there and not wander off on an exploration mission)!

Let us know if you have allergies to insect bites, or any medical problem of which we should be aware. We have a trained medical officer on staff and are equipped for first aid, so please do not hesitate to ask if you need something band aids anyone?

One extremely important point: please don't stay out in the sun without protection sunscreen or clothing. A bad sunburn makes it difficult to enjoy anything.

We want you to have a pleasant stay. Let us know if there is something we can do to help you enjoy your stay.

ADDRESS
CARIBBEAN MARINE RESEARCH CENTER
EXUMA CAYS, LEE STOCKING ISLAND, BAHAMAS
100 East 17th StreetRiviera Beach, FL 33040
Telephone: (809) 3362557
DIRECTOR: ROBERT WICKLUND
ASST. DIRECTOR: GERRI WENZ

WHAT TO TAKE TO THE BAHAMAS

YOU WILL BE ON LEE STOCKING ISLAND FOR ONLY THREE DAYS. THEREFORE REMEMBER YOU SHOULD TRAVEL LIGHT! THE FOLLOWING LIST WAS DEVELOPED FOR OUR STUDENTS AND SCIENTISTS VISITING THE ISLAND FOR THREE TO FOUR WEEKS. PLEASE USE IT AS A GUIDELINE FOR THE TYPE OF EQUIPMENT TO BRING FOR YOUR SHORT VISIT.

Equipment

1. Money for fun & emergencies (small denominations approx. $100)
2. Mask & Snorkel
3. Fins
4. Garden gloves, 1 pr for diving
5. Pens and Notebooks
6. Hand Lens
7. Pack (small personal bag)
8. Zip lock plastic bags (large and small)
9. Trowel or spade (opt.)
10. Waterproof log book
11. Camera (opt.)
12. Film and spare batteries for Camera

Clothing

1. Long sleeved shirts blue for sun protection
2. 2 pairs of jeans (light weight)
3. Floppy hat (for sun protection)
4. Swim Suit
5. Socks
6. Windbreaker or sweat shirt
7. T-shirts (can be purchased on Lee Stocking)
8. work shorts
9. 1 pr. tennis shoes (old for walking on mud banks and over coral)

Cosmetics, etc.

- sun screen and sun oil (Block value R15 or above)
- Cutters or Off insect repellent spray (one can for three days)
- Avon "Skin So Soft" also repels "no see ems."
- Bandaids (several sizes) and antiseptic
- Special soaps as needed
- Hair conditioners (special)
- Skin lotion
- Dramanine or ear "seasick" tabs or equivalent (if you are prone to *Mal de mer*)
- Baby powder
- All prescription drugs you will need during your stay
- Spare pair of eye glasses (prescription) and a pair of Polaroid sun glasses with head band

Snorkel and Diving Equipment

Scuba tanks and weights are available to qualified investigators who dive, BUT arrangements must be made prior to arriving on the island for their use through the main office of CMRC or by contacting one of the field trip leaders! Diving will not be a scheduled event for
the IGC field trip.

All swimmers and divers will be requested to sign a liability waiver. Divers must also present written evidence of a current nationally recognized scuba certification card before diving (i.e. NAUI, PAD, YMCA, Navy, NASDS, NOAA or an international equivalent). All divers and snorkelers will be given a proficiency swimming and diving test prior to using CMRC equipment or using their facilities. Diving Regulations in effect are those recommended by the NOAA Diving Manual, the National Academy of Underwater Scientists, CMAS or their International equivalents. All diving will be under the supervision and at the discretion of the Director of CMRC or his designee.

Diving regulators <u>ARE NOT</u> available from CMRC. If you want to dive bring your own regulator with a pressure view gauge and make sure they are in good working order before leaving the United States or your home base. It is strongly recommended that scuba divers bring their own face mask, large fins (currents are strong and swims are long), a buoyancy compensator (BC) inflatable from your tank (with prearrangement these can be rented at CMRC), your weight belt(no weights), booties, a 1/8 inch wet suit (summer) and 3/8 inch suit for (winter), a net "goodie bag" for carrying loose gear and hanging out your equipment to dry after a dive. Spare line, several rolls of Duct and electrical tape and a spool of nylon string are useful items to have in your dive bag. You will need a depth gauge and u/w watch. A compass and thermometer are also useful items to have on dives Underwater photographers: Bring spare batteries and chargers for strobe lights, U/W lights (for cave and night dives), scale rulers for photos, and lots of film (color and B/W, ASA 25 to 400). U/W video photographers must bring their own Video tapes, the Island has Video tape players both 8 and regular VRC.

Field trip Daily Schedule

July, 19th 1989

Lv: IGC meetings in Wash. D.C. via air to Miami, Florida.

Ticketing and reservations are the responsibility of the participants. Flight time to Miami is about two and one half hours.

Arr.: Miami International Airport and check into Airport Hotel. Meet with field trip leaders and check in for air flight to the Bahamas next morning (July 20, 1989) on a chartered aircraft. Leave name at hotel desk so that your attendance can be confirmed. Participants will be given written instructions as to where to meet chartered plane when they check into the hotel at the desk.

July 20th

0700 Leave Miami International Airport for Georgetown, Great Exuma Islands, clear customs and then fly to Lee Stocking Island. **BE SURE TO HAVE PROOF OF CITIZENSHIP** (passport, U.S. voter registration, birth certificate) Arrival will be before lunch. Have breakfast before leaving Miami airport as there is no food service on the flight to the Bahamas.

1200 Lunch at the Lizard Lounge at the Caribbean Marine Research Center (CMRC). Fill out waivers, and lecture on field procedures and housing locations. Following lunch vans and truck from CMRC will take you to living quarters.

1430 Meet at dock with swimming and snorkel equipment ready for swim check and snorkel study of a small patch reef near the dock. This swim will allow you to check out your equipment and become familiar with the waters near Lee Stocking. Field trip leaders will be assigned to the group and "buddy pairs' established This check out swim should take about 2 hours.

1700 Wash gear and return to your living quarters. There will be a free hour before "happy hour" in the Lizard Lounge. This would be a good time to walk around the area and observe the ongoing mariculture program, the ooid and pelletoid sands which form the Island, the excellent beaches, and view the vegetation and fauna.

1800 Happy Hour The Island store will also be opened for participants to purchase beverages, T-shirts, snacks, etc. It is next to the Lizard Lounge (LL) see Figure 2 of Field Guidebook.

1900 Dinner will be served in the Lizard Lounge (LL).

2100 Short evening lecture showing slides, video tapes, and giving a description of the next days activities.

July 21st

0700 Breakfast in LL. Announcements on the days activities will be made following the meal.

0900 Meet at dock ready to leave by boat for stromatolite area in the channel just north of Lee Stocking. The exact time of leaving the dock will depend on the state of the tide and the completion of a short walking field trip on the island which may be added so that we will be over the stromatolites during slack tide and clear water. Swimmers will be taken to the stromatolite area aboard the Exuma Hunter a large catamaran with an internal ramp that can be used as a swimmer launch and retrieval platform. A tow rope with safety buoys will then be used to pull the snorkelers over the stromatolites, crusted mud beds and ooid mega dunes.

1200 Lunch at the Lizard Lounge (LL).

1400 Snorkel tow behind the Exuma Hunter over stromatolites not visited during the morning and ending at a shallow ooid sand bar with well developed submarine cements and crusts.

1700 Return to Island. Free time until "happy hour."

1800 Happy Hour and review of video tapes of days activities.

1900 Dinner

2100 Evening lecture

July 22nd

0700 Breakfast (LL)

0830 Meet at dock ready for snorkel tow.

0900 Leave for patch reefs on the eastern side of Norman's Pond Cay aboard the Exuma Hunter. Examine a second site of stromatolite formation along with shore features of Norman's Pond Cay, beachrock, delta, mangroves and a channel leading to an old salt works with marine cemented, skeletal sand crusts.

1200 Lunch (LL).

1330 Weather permitting group will go to seaward side of island via truck and van and snorkel on fringing reefs of Acropora palmata. We will return along the rocky shore of the eastern side of the island observing recent sand dunes and Pleistocene limestone equivalents. Bring tennis shoes, the rocks on shore are rough and sharp and there are burrs in the sand dunes.

1800 Happy Hour (LL).

1900 Diner followed by evening lecture.

July 23rd

0700 Breakfast

0830 To Dock

0900 Leave aboard the Exuma Hunter for stromatolite area for a final tow and snorkel diving in the giant stromatolite area north of Lee Stocking Island.

1200 Lunch then check out at the Office of CMRC, pay tabs, pack up and get ready for return to Miami. Plane will pick us up on Lee Stocking Island at about 1400.

1400 Leave Lee Stocking for Miami International Airport with a stop to clear Bahamian customs. When clearing customs from the Bahamas a $5.00 government airport tax will be assessed that must be paid in cash. The departing group should arrive back in Miami at about 1800.