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## Pleistocene and Holocene Carbonate Environments on San Salvador Island, Bahamas: A Field Trip Guide

H. Allen Curran  
*Smith College, [acurran@smith.edu](mailto:acurran@smith.edu)*

Roger J. Bain  
*The University of Akron*

James L. Carew  
*College of Charleston*

John E. Mylroie  
*Mississippi State University*

James W. Teeter  
*The University of Akron*

*See next page for additional authors*

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**Authors**

H. Allen Curran, Roger J. Bain, James L. Carew, John E. Mylroie, James W. Teeter, and Brian White



28th International Geological Congress

# Pleistocene and Holocene Carbonate Environments on San Salvador Island, Bahamas

Field Trip Guidebook T175

Leader: H. Allen Curran, *Editor*



San Salvador Island, Bahamas  
July 2–7, 1989

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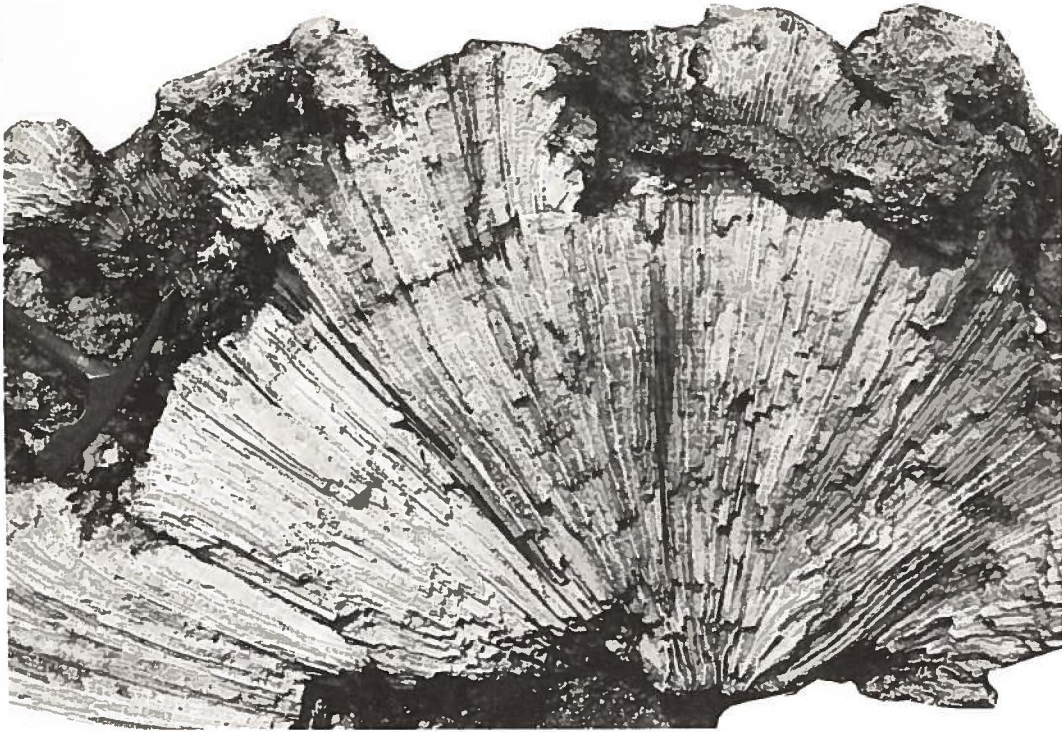


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Cover : *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangomon age) on San Salvador Island. Photo by Al Curran.

**Leader:**

H. Allen Curran  
Department of Geology  
Smith College  
Northampton, MA 01063

**Associate Leaders:**

Roger J. Bain  
Department of Geology  
University of Akron  
Akron, OH 44325

James L. Carew  
Department of Geology  
College of Charleston  
Charleston, SC 29424

John E. Mylroie  
Department of Geology and Geophysics  
Mississippi State University  
Mississippi State, MS 39762

James W. Teeter  
Department of Geology  
University of Akron  
Akron, OH 44325

Brian White  
Department of Geology  
Smith College  
Northampton, MA 01063

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## PREFACE

Although isolated and small in size, San Salvador Island is in many ways a unique place - an all carbonates setting on a small, tectonically stable platform, surrounded by deep oceanic waters, and an historical footnote as the widely accepted first landing site of Christopher Columbus in the New World in 1492. Columbus' stay here was brief, and the major events of subsequent history largely have passed San Salvador by. This is not a tourist island; the natural beauty, floras, and faunas of the Bahamas are well preserved here.

The overview theme of this series of field excursions on San Salvador will be interpretation of paleodepositional environments for the well-exposed Pleistocene and Holocene carbonate rocks that cap the island and recognition of modern analogues from the varied carbonate environments found on the island and its surrounding shelf. Questions of sea level history, diagenetic change, and the surficial processes operating on carbonate island terranes also will be considered. Our trip will begin with a low-altitude overflight to view features of the main Bahama platform enroute to San Salvador, which lies just beyond the eastern edge of the platform.

The field trip leaders all have been working on San Salvador and elsewhere in the Bahamas for the past decade. We have experienced the good and the bad - a pleasant tropical climate, warm and alive marine waters, a generally unspoiled setting, and the friendly Bahamian people, along with sometimes fierce "no-see-um" attacks, sun-burnt skin, and unexpected soakings from tropical storms. Throughout, the experiences have been rewarding and the challenges of geologic interpretation great. We look forward to sharing some of our findings and experiences with you. Welcome to the Bahamas and San Salvador Island!

## ACKNOWLEDGMENTS

The field trip leaders wish to express their gratitude to the Bahamian Field Station and its staff on San Salvador Island for full logistical support provided to each of us during our periods of field work and for the sponsorship of this field trip. The efforts of Dr. Donald T. Gerace and Kathy Gerace, Director and Associate Director respectively of the Bahamian Field Station, have been tireless in support of our research, and to them we extend our most sincere thanks.

The editorial work for this volume was accomplished at Smith College. I thank Kathy Bartus for her full assistance with word processing and for her patience and good humor. Kate Whittaker assisted most conscientiously with copy editing and layout. Finally, I thank Janet Evans at AGU for her work with final production of this guidebook and for her assistance with many questions throughout the assembly process.

H. Allen Curran  
Smith College  
Northampton, Massachusetts



# INTRODUCTION TO THE GEOLOGY OF THE BAHAMAS AND SAN SALVADOR ISLAND, WITH AN OVERFLIGHT GUIDE

H. Allen Curran

Department of Geology, Smith College, Northampton, Massachusetts

## GEOLOGIC SETTING OF THE BAHAMA ISLANDS

The Bahama Archipelago is an arcuate system of carbonate platforms, commonly capped with low islands, located to the east and south of the continental margin of North America (Fig. 1). The archipelago extends for a distance of some 1,400 km (870 mi.), from Little Bahama Bank to the north (27.5° N latitude), off the coast of Florida, south to the Turks and Caicos Islands, Silver Bank, and Navidad Bank (20° N), off the island of Hispaniola. Water depths on these banks normally are less than 10 m, but the banks are separated by inter- or intra-platform, deep-water basins and troughs with depths of up to 4,000 m (Northeast Providence Channel).

These shallow-water banks are underlain by thick sequences of carbonate rock; drill hole data reveal a thickness of at least 5.4 km (Meyerhoff and Hatten, 1974), and magnetic data suggest thicknesses of up to 10 km in the southeastern Bahamas (Uchupi and others, 1971). It appears that shallow-water carbonate sedimentation on the banks has kept pace with the subsidence of the Bahamian continental margin platform since Early Jurassic time (Mullins and Lynts, 1977).

Indeed, the shallow-water banks of the Bahamas truly are "carbonate factories" as described by Multer (1977). The products are a diverse array of carbonate sediments formed by both physical and biogenic processes and deposited in a spectrum of environments ranging from lakes and dunes to deep-sea basins. The environments on and adjacent to the banks and the rates of carbonate production have been in a considerable state of flux with changing sea levels since the onset of Pleistocene glaciations. Today, as eustatic sea level continues its slow but steady rise, the banks of at least the northwestern part of the Bahamas are thought to be either tectonically stable or subsiding slowly, perhaps at the approximately 3 m/125,000 yr. rate determined for Andros Island (Garrett and Gould, 1984).

A longstanding debate concerns whether the Bahamian platforms are underlain by oceanic or continental crust. Mullins and Lynts (1977) reviewed carefully the large body of geophysical and geologic literature on this subject. They favored an interpretation of a basement of originally pre-Triassic continental material that was pervasively intruded by mafic and ultramafic rock during rifting of North America from Africa and South America in Late Triassic time. In a sense, this was a compromise position with the result being formation of a crust of intermediate density that would have geophysical properties somewhat similar to oceanic crust. More recently Ladd and Sheridan (1987, see Fig. 17) have shown that seismic reflection profiles in the northwest

Tongue of the Ocean area suggest deposition on thinned continental crust, whereas the areas of the central and southeast Tongue of the Ocean and Exuma Sound appear to have been built on oceanic crust.

Mullins and Lynts (1977) also proposed a rotation of about 25° to the northeast for the Bahamas Platform, generated by the eastward impinging motion of the Caribbean plate during Cretaceous and early Tertiary time. The pre-rotation position permits an excellent pre-rift fit between North America, South America, and Africa prior to the opening of the North Atlantic Ocean.

The origin of Bahamian banks and basins recently has been a topic of considerable debate and disagreement. Again, two quite different concepts have been proposed. The "graben" hypothesis of Mullins and Lynts (1977) proposes strong fault control on the bank-basin pattern, with the basins originating from grabens during the rifting stage of North Atlantic Ocean opening. By contrast, the "megabank" hypothesis of Meyerhoff and Hatten (1974), Sheridan et al., (1981), Ladd and Sheridan (1987), and others holds that the Bahama platform was part of a more extensive, shallow-water carbonate bank that existed in Early Cretaceous time. Later drowning and erosion of the Bahamian platform by erosive oceanic processes is thought to have produced the deep troughs that penetrate and subdivide the banks today. Austin and Schlager (1987) interpreted ODP Leg 101 drilling data as supporting the "megabank" hypothesis.

However, from a detailed seismic study of the northwestern Great Bahama Bank, Eberli and Ginsberg (1987) proposed origin by coalescence of three smaller platforms with significant bank progradation. They argued against the "megabank" hypothesis and proposed that the present bank-basin configuration results from progressive modification through time by segmentation events and incomplete coalescence. In sum, a final answer to the banks-basins origin question is not yet available, and one can quickly conclude that much remains to be learned about the development of the Bahamas.

The literature on the modern deep and shallow water carbonate sediments of the Bahamas is voluminous and contains many classic studies. Much of this literature is cited in recent summary papers by Harris (1982), Hine (1983a,b), Mullins (1983), Carew and Mylroie (1985), and in this guidebook. By contrast, published geologic and paleontologic reports on the exposed Pleistocene and Holocene rocks of the Bahamas Islands are considerably less numerous; indeed, the geology of many Bahamian islands is today virtually unknown. This situation has been somewhat alleviated in recent years with publication of the Bahamian Field Station geology symposia series



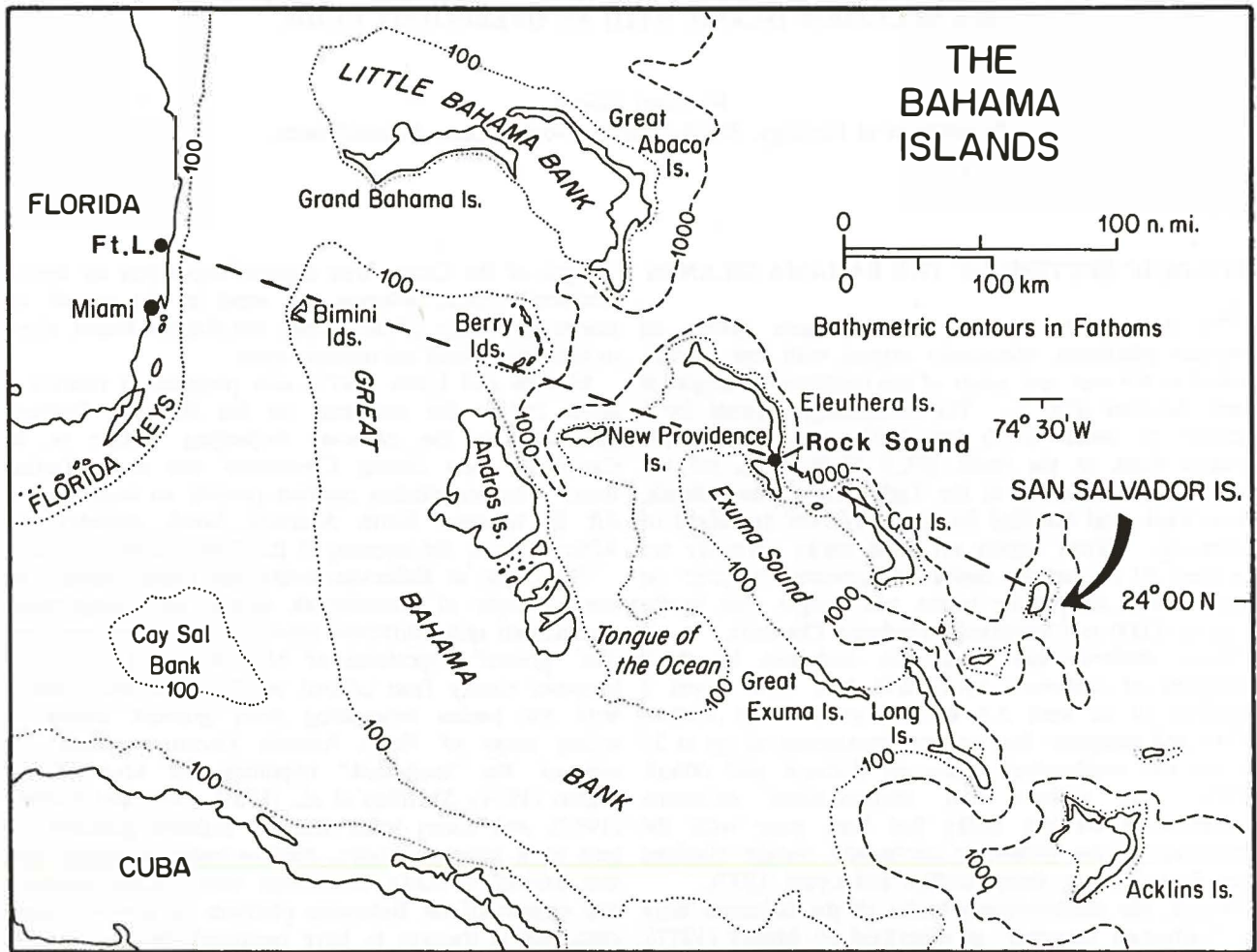


FIGURE 1 Index map to the Bahama Islands and the location of San Salvador Island. Dashed line indicates the approximate flight route. Mayaguana and Great Inagua islands of the Bahamas lie to the south of Acklins Island.

(Teeter, 1984; Curran, 1987; Mylroie, 1989). It is hoped that the chapters of this guidebook and the described field trip stops on San Salvador will demonstrate clearly that much can be learned from study of the many interesting aspects of carbonate geology and Pleistocene and Holocene geologic history to be found in the sediments and rock record of Bahamian islands.

#### OVERFLIGHT TO SAN SALVADOR

When weather conditions permit, an excellent overview of the Great Bahama Bank and its associated features can be obtained during the flight to San Salvador (Fig. 1). The island is located about 620 km (385 mi.) ESE of Ft. Lauderdale; flight time should be 2.5 to 3 hours. A short stop for refueling and/or Bahamas immigration may be made at Rock Sound Airport on Eleuthera. The following is a brief guide to points of geographic/geologic interest to be found along the flight route.

1. Waters of the narrow continental shelf (width = 7 km)

east of Ft. Lauderdale quickly give way to the Straits of Florida channel, with its dark-colored water and a depth of about 800 m. The channel is about 85 km wide.

2. The Bimini Islands, 93 km east of Ft. Lauderdale, likely will be visible on the starboard side of the aircraft. The islands lie at the NW edge of the Great Bahama Bank. This northern part of the bank between the Biminis and the Berry Islands is largely an area of relict to intermittently active sand sheets composed of skeletal grains, ooids, lithified pellets, and composite grains (Hine, 1983a,b). Large relict sand waves lie to the north of the Biminis, and westward offbank sediment transport occurs immediately to the north of the islands.

3. Chub Cay of the Berry Islands chain lies about 147 km east of the Biminis. This small island is developed and has an airstrip and marina. Just prior to reaching Chub Cay, large and active oolitic sand shoals can be seen to port, on the leeward side of the Berry Islands. To starboard, the Joulters ooid shoal, described by Harris (1983), can be found off the north end of Andros Island.

4. East of the Berry Islands, waters quickly deepen into the Northeast Providence Channel (4,000 m depth), which

extends south to form the Tongue of the Ocean. The channel is about 40 km wide.

5. After crossing the channel, New Providence Island and the city of Nassau, the capital of the Bahamas, can be seen to starboard. The island forms the NW corner of Exuma-Eleuthera Bank. We will be over the bank for a distance of about 100 km. The western part of the bank is covered by inactive to intermittently active sand sheets similar to those crossed earlier. This region of low bottom activity gives way to an area of active oolitic shoals with varied bedforms on the eastern part of the bank at the head of Exuma Sound (Hine, 1983a,b). A shallow, protected lagoon with diverse bedforms can be seen off of the western coast of Eleuthera.

6. After crossing Eleuthera (and possibly making a stop at Rock Sound), the narrow, windward shelf of Eleuthera will be visible on the Atlantic side of the island. Breaking waves and brownish areas mark the occurrence of patch and bank/barrier coral reefs. Similar features can be seen on the northern and eastern shelf of Cat Island, the next island to be encountered, about 58 km SE of Eleuthera.

7. The distance between the northern end of Cat Island and San Salvador is about 135 km. Here open waters of the western North Atlantic Ocean are crossed (water depth to 4,600 m), and floating masses of *Sargassum* often can be seen.

8. San Salvador Island lies on a small, isolated bank at the eastern edge of the Bahamas. On the approach to the island from the west, one will see that the narrow shelf drops precipitously to deep water. The interior of the island is occupied by numerous shallow, hypersaline lakes separated by ridges composed of carbonate eolianite.

## GEOLOGIC SETTING OF SAN SALVADOR ISLAND

San Salvador is a small island, about 11 km wide by 19 km long, and it is bordered by a narrow shelf with an abrupt shelf-edge break leading to a very steep slope. The topography of the island is dominated by arcuate ridges interpreted as representing successive stages of carbonate eolian accretion (Adams, 1980). Shallow lakes occupy the low inter-dune ridge areas. The island's shoreline is characterized by cliffed headlands of eroded eolianite; fine- to medium-grained carbonate sands form beaches between headlands, and Holocene beachrock is common.

Natural rock outcrops largely are confined to the coastal areas of the island. A dense vegetation cover restricts access to the island's interior, a karst surface with calcrete or caliche crusts, red soils, and solution phenomena, all of which further obscure characteristics of the underlying rock. Road cuts and several quarries along the island's coastal highway also can provide good exposures for study. The Pleistocene and Holocene stratigraphic framework of San Salvador was carefully reviewed and revised by Carew and Mylroie (1985). Further stratigraphic discussion is given in the Carew and Mylroie chapter of this guidebook. Locations of the

principal geographic features and field trip stops referred to in this guidebook are indicated on Figure 2.

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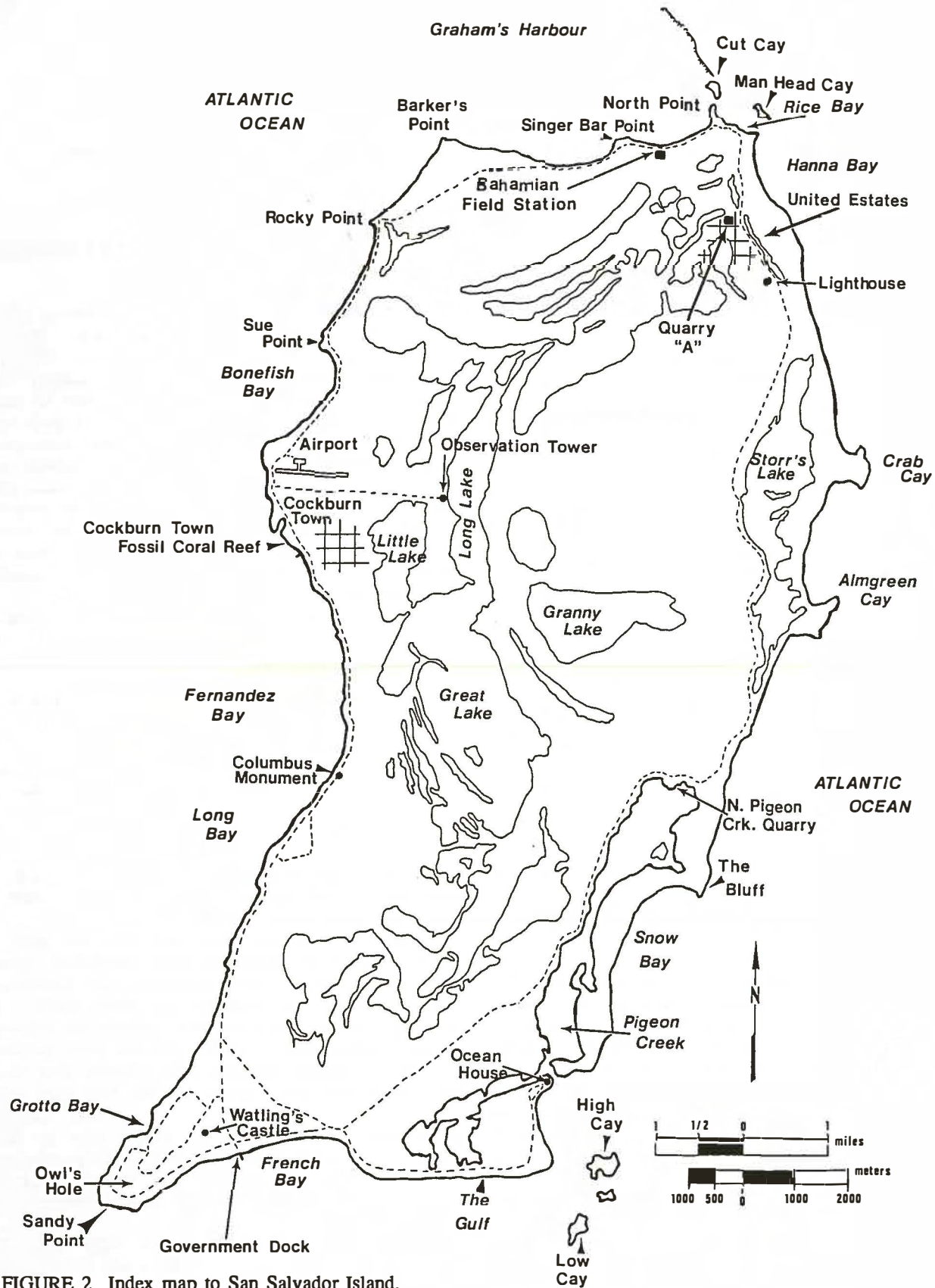


FIGURE 2 Index map to San Salvador Island.

# STRATIGRAPHY, DEPOSITIONAL HISTORY, AND KARST OF SAN SALVADOR ISLAND, BAHAMAS

James L. Carew  
Department of Geology, College of Charleston, Charleston, South Carolina

John E. Mylroie  
Department of Geology & Geography, Mississippi State University, Mississippi State, Mississippi

## INTRODUCTION

The purpose of this part of the field trip is to introduce the participant to the geology and geomorphology of San Salvador by visiting outcrops of rocks exposed primarily along the northern and western coasts of San Salvador. The stratigraphy used in this guide (Fig. 1) is that of Carew and Mylroie (1985). This stratigraphic sequence comprises depositional units that were stacked as a result of sea level changes during the Pleistocene.

Please do not hammer on rocks or collect samples without first checking with the trip leaders, as many of the sites to be visited are unusual and need to be protected. The trip will begin at the base of the concrete ramp directly opposite the entrance to the grounds of the Bahamian Field Station, on the shore of Graham's Harbour.

## DESCRIPTIONS OF THE COASTAL STRATIGRAPHY FIELD STOPS

### Stop 1. Hanna Bay Member of the Rice Bay Formation at Graham's Harbour

At the base of the concrete ramp turn to the west (left). Along this section of coast are rocks assigned to the Hanna Bay Member of the Rice Bay Formation of Holocene age. This unit comprises the youngest rocks on San Salvador.

Along this cliff line, rocks assignable to beach face through back-beach dune lithofacies can be seen to have depositional dips congruent with current sea level (Fig. 2a). These rocks are bioclastic and peloidal, weakly cemented calcarenites. Cement where present is primarily meniscus style low-Mg calcite. Radiocarbon ages for whole rock samples from outcrops assigned to this unit range from 420 yBP to about 3,500 yBP (Carew and Mylroie, 1987).

To the east (right) are rocks that are very young. These flat slabs of beachrock have yielded a cannonball cemented into the rock (Adams, 1983) and even more recent objects such as bottle caps and glass.

### Stop 2. North Point Member of the Rice Bay Formation at North Point

From the Government Dock, walk east onto the nearly

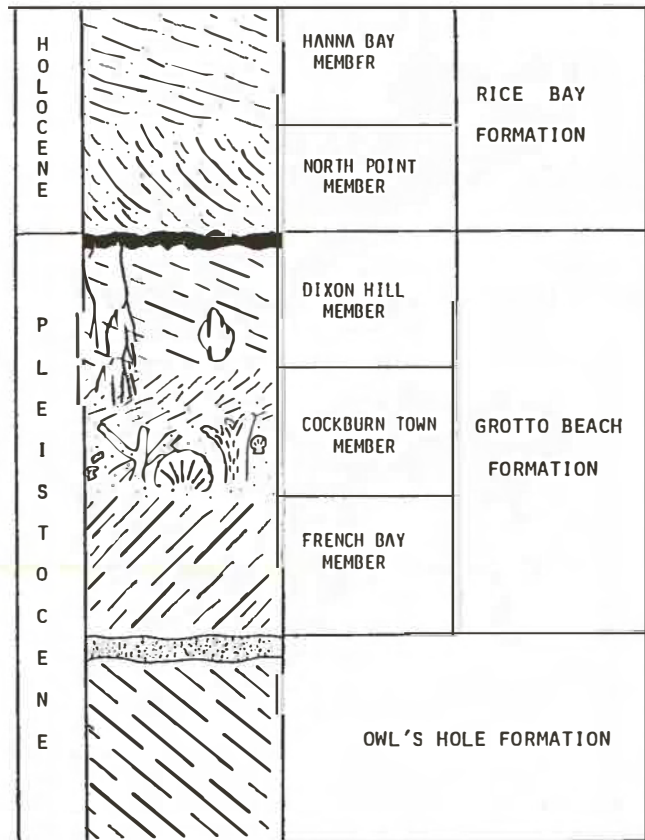


FIGURE 1 Physical stratigraphy of subaerially exposed rocks on San Salvador Island, Bahamas.

flat rocky platform. Notice the swirling, crosscutting patterns of variously truncated eolian bedding. The morphological form of North Point and the bedding style clearly indicate the eolian origin of this rock. Petrographically, these rocks are similar to those seen at Stop 1, but they are assigned to the North Point Member of the Rice Bay Formation based upon the bedding relationships relative to sea level. At various places along this outcrop, it is quite evident that the bedding dips steeply (approx. 28°) below present sea level and can commonly be seen to continue at least 1 m below present sea level (Fig. 2b).

It is clear that these dunes were formed at a time when sea level was at least 1 m below its present position. The rocks, then, are necessarily older than those rocks seen at Stop 1. Radiocarbon ages of whole



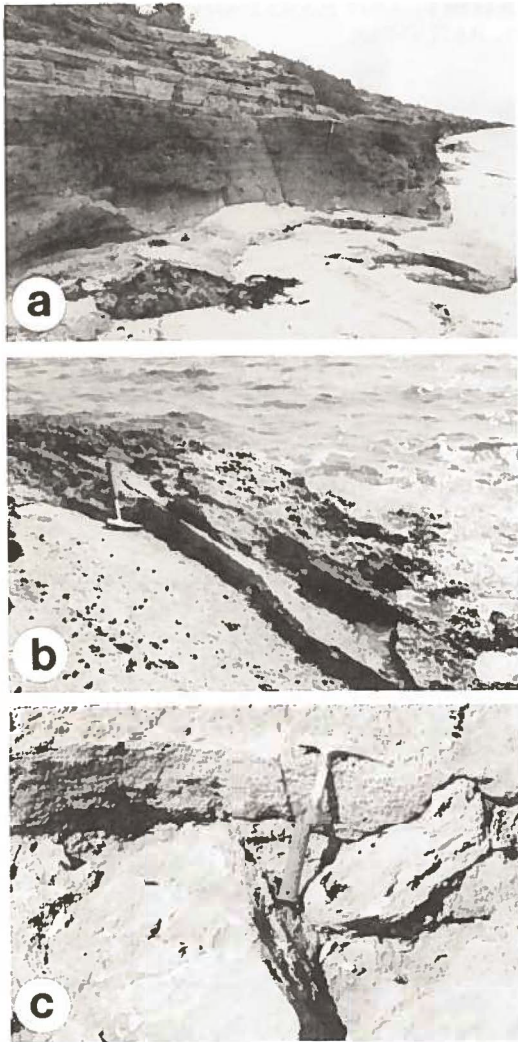


FIGURE 2 a. Rocks of the Hanna Bay Member that crop out along coast of Graham's Harbour. Note that bedding at base of section is nearly parallel to present sea level surface. b. View on the west side of North Point. Note that bedding dips steeply below sea level. c. Back-beach, large-block breccia facies at the Grotto Beach sea cliff.

rock samples from these outcrops are about 5,300 yBP. Detailed studies of these rocks have been reported by White and Curran (1985, 1988, and this volume).

The rocks of the Rice Bay Formation seen at Stops 1 and 2 are Holocene, and they characteristically lack a capping paleosol or calcrete. In addition, they generally are weakly cemented and usually exhibit little karst development beyond coastal phytokarst.

### Stop 3. Pleistocene/Holocene Boundary

At this stop a paleosol marking the unconformity between the Holocene Rice Bay Formation and underlying Pleistocene Grotto Beach Formation is well exposed. Note the color, hardness, and "undulatory" nature of the paleosol. The paleosol is thought to have

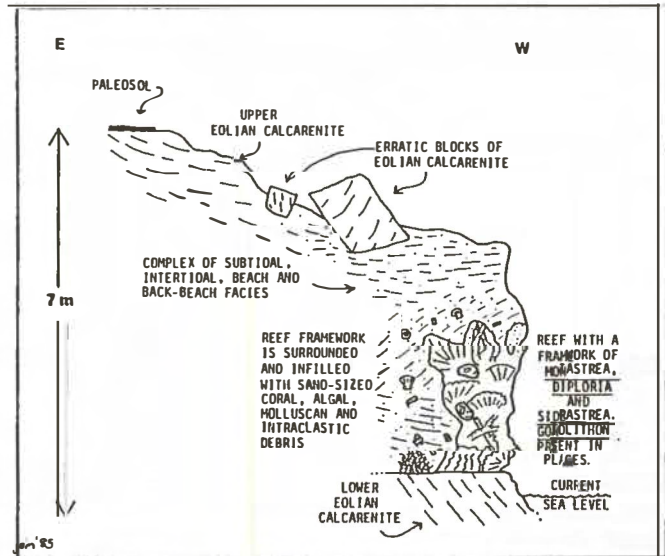


FIGURE 3 Diagrammatic representation of the type section of the Cockburn Town Member at the Grotto Beach cliff.

gone through final stages of development around 13,000 years ago (Carew and Mylroie, 1987). More detailed study of this and other paleosols has been conducted by McCartney and Boardman (1987) and Foos (1987).

### Stop 4A. Grotto Beach Formation, Cockburn Town Member

At the east end of Grotto Beach are sea cliffs with grottoes eroded out at present sea level. The rocks of these cliffs are Pleistocene in age and are assigned to the Cockburn Town Member of the Grotto Beach Formation.

As the cliffs are approached from the beach, a fossil coral reef with capping patches of *Neogoniolithon* coralline algae can be seen at eye or foot level (depending upon the volume of sand on the beach). The reef facies is buried by subtidal sands and overtopped by beach to beach-dune facies (similar to the Cockburn Town Reef described by Curran and White, 1985, and this volume), as shown in Figure 3. Petrographically, these rocks are a mixture of fossils, peloids, ooids, and intraclasts with a sparite cement. There is a tendency for greater ooid content toward the top of the section. This sequence is capped with a paleosol that is preserved as patches and solution pocket fills. Proceeding along the cliffs, strata with coarse shell hash and rounded beachrock pebbles can be seen. Also very prominently displayed are large- to moderate-sized, angular, erratic blocks (Fig. 2c). These blocks are laminar bedded oosparites and oolitic biosparites and are distributed in all orientations relative to the surrounding, petrographically similar, sediments. These were contemporary back-beach rubble and cliff collapse features at the time of deposition (oxygen isotope substage 5e; U/Th ages of corals from these outcrops date at approx. 125,000 years).

If the observer does not mind getting wet, enter the



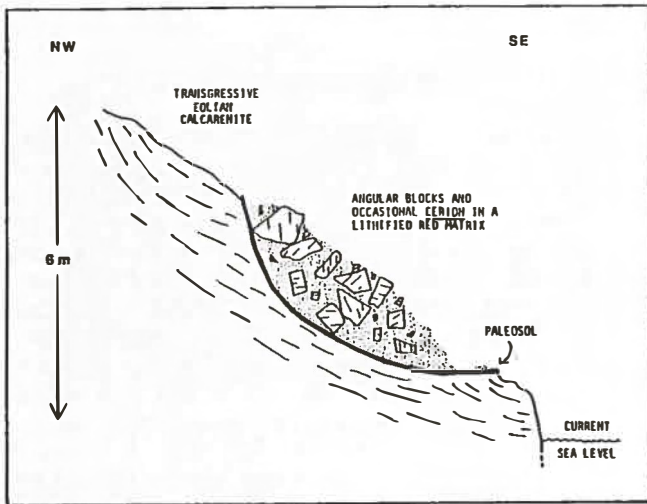


FIGURE 4 Diagram of a representative talus-breccia outcrop on the French Bay cliff, Stop 5A.

water where the beach and cliffs meet. There, dune foreset beds that dip at about 28° to the southwest are truncated at the top. Upon that surface lies the reef and its associated facies. Those eolian deposits are either transgressive, substage 5e dunes, planed off by continued rise of sea level that ultimately led to the reef growth, or they are pre-substage 5e. Alveolar texture, commonly interpreted as evidence for subaerial exposure and vegetative cover, can be seen in thin-sections of this bioclastic eolianite taken from just below the contact. This texture indicates a substantial period of subaerial exposure which supports a pre-substage 5e origin.

#### Stop 4B. Holocene Analog for Pleistocene Back-beach Rubble Facies

At the western end of Grotto Beach are outcrops of Holocene (Hanna Bay Member, Rice Bay Formation) rocks. These rocks exhibit intertidal to back-beach facies and were deposited in equilibrium with current sea level. There is no paleosol/calcrete cap. Radiocarbon age of whole rock is about 3,200 yBP.

Note that these cliffs are breaking down, and large- to moderate-sized slump blocks are being entombed in modern sands. These outcrops serve as a modern analog for the Pleistocene erratic blocks seen at the cliffs described in Stop 4A. Phytokarst is poorly developed here, compared to Stop 4A. This would indicate that these rocks, although 3,200 years old, have only recently been uncovered from modern sands and exposed to sea spray.

#### Stop 5A. Grotto Beach Formation, French Bay Member

Follow the trail approximately 100 m to the cliffs overlooking French Bay. Here you will see an outcrop of angular blocks in a paleosol matrix. These blocks, ranging in size from a few centimeters to over one meter in diameter, are all laminar bedded oosparites that are

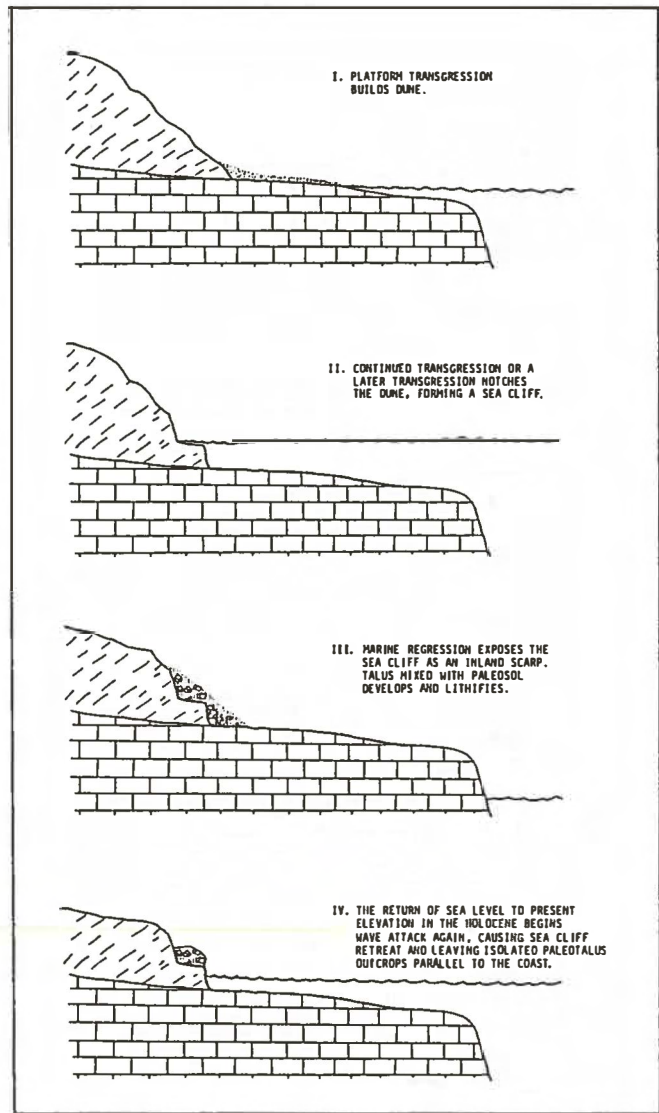


FIGURE 5 Sequence of events for the origin of the French Bay paleotalus deposits.

indistinguishable from the existing rock outcrops upslope of their present position. The deposit varies irregularly from grain to matrix supported. The contact of these deposits with the surrounding eolianites is marked by a reddish calcrete which tends to extend downslope in a cup-shaped manner, concave up and seaward. The deposit is well lithified and weathers out in positive relief. Figure 4 is a diagrammatic representation of this deposit.

The proposed origin of this deposit is as a substage 5e (Sangamon) transgressive dune, notched to produce a sea cliff at the substage 5e sea level maximum (or possibly some more recent high stand of sea level, see Fig. 5). As a result of sea withdrawal at the end of substage 5e (or a more recent regression), the notch was exposed as an inland scarp. This inland scarp then underwent typical erosional mass wasting to produce a cliff-base talus and associated soil, which subsequently became lithified. Return of the sea to the present position during Holocene

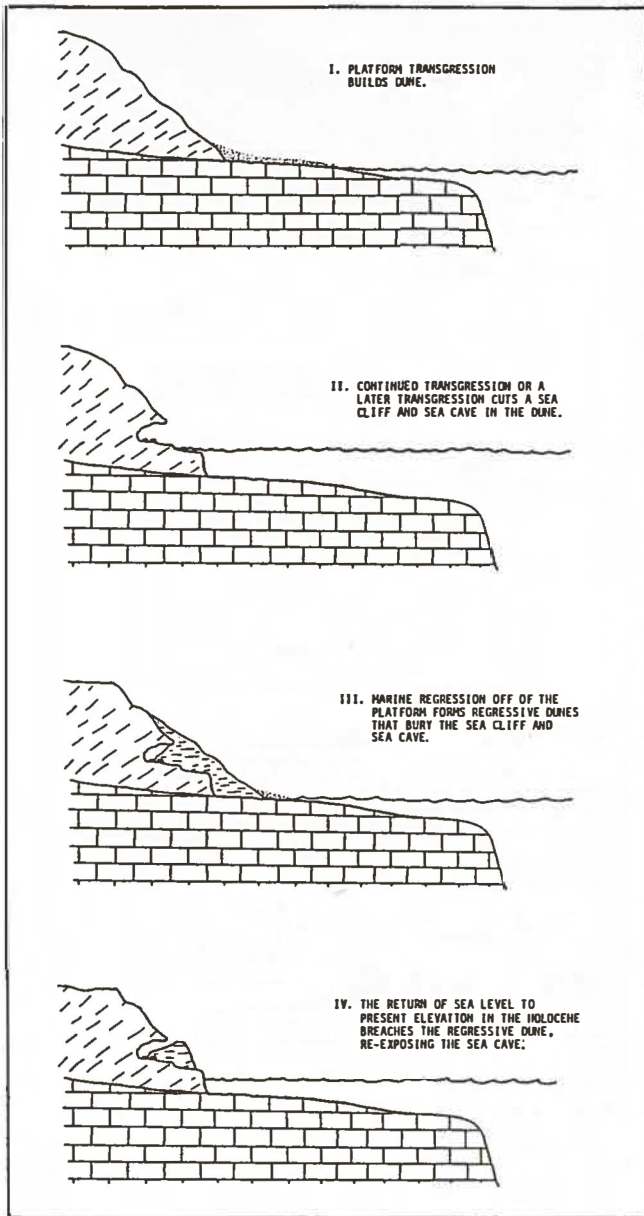


FIGURE 6 Sequence of events for the origin of the rocks seen at the French Bay cliff, Stop 5B.

time has brought the dune and resistant paleotalus under renewed wave attack. More than 30 similar deposits can be found in isolated patches on the edge of this sea cliff for a distance of over one kilometer (Marshall et al., 1984). Such deposits are not known inland or on any other coast of the island, although we have recently discovered similar deposits on the south coast of New Providence Island. Amino acid racemization ages for *Cerion* in the paleotalus soil matrix (Myroie et al., 1985; Carew and Myroie, 1987) suggest a late Wisconsinan age (approx. 15-20,000 yBP) for the paleosol lithification.

Proceed west approximately 100 m along the cliffs to a small cave that opens to the south about 4 m above sea level. Note, along the way, several solution pillars or "palmetto stumps." For a discussion of their origin

see Myroie (1988).

### Stop 5B. French Bay Member

This cave was formed by wave action at a past higher stand of sea level, and it is analogous to the grottoes at Grotto Beach. At the back of this shallow cave, a lithified deposit of rounded boulders is overlain by a set of eolian deposits that presently choke off part of the cave, and which in the past probably entombed the cave.

Petrographically, there is no dramatic difference between the host eolianite and the infilling eolianite. Both are oosparites, although the infilling eolianite contains somewhat larger ooids and is less well sorted. These observations lead to the interpretation of an emplaced transgressive dune, notched with a sea cave during the substage 5e sea level high stand maximum (or a somewhat more recent high stand), infilled by a dune deposit during the regression at the end of substage 5e (or a more recent transgression or regression), and now being attacked by erosion at Holocene sea level (Fig. 6). At various localities on this section of coast, the transgressive eolianite has patches of other rocks lying unconformably over it. These are currently being stripped away by modern marine erosion. A small biosparite outcrop of this type is located below the sea cave about 1 m above sea level. A measured section at this type locality for the French Bay Member of the Grotto Beach Formation is shown in Figure 7.

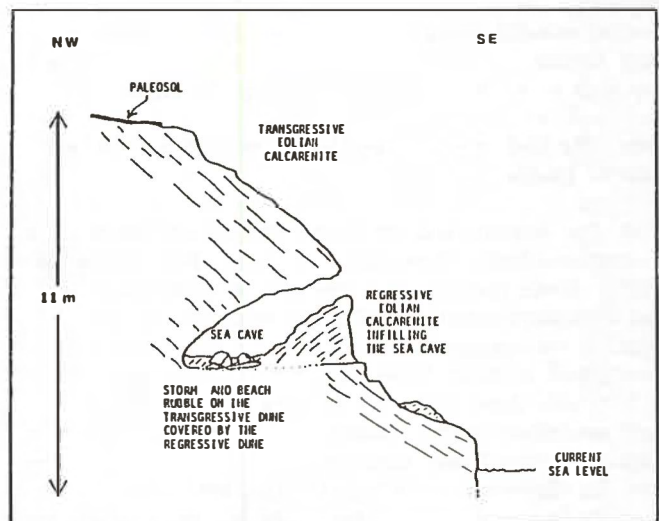


FIGURE 7 Diagrammatic representation of the measured section at the type locality of the French Bay Member, Grotto Beach Formation, Stop 5B.

Stops 5A and 5B provide evidence for an interpretation of the dunes of the French Bay coast as transgressive, formed during the Sangamon substage 5e sea level rise. They form the French Bay Member of the Grotto Beach Formation, and they are the oldest deposits of that formation.





FIGURE 8 Westward-looking view of the Watling's Quarry wall showing an upper colianite separated from an underlying eolianite by a prominent paleosol. The entire sequence is capped by a younger paleosol. Contact between colianites is marked by a dashed line.

### Stop 6. Watling's Quarry - Pre-Grotto Beach Rock

There are very few localities on San Salvador and elsewhere in the Bahamas where more than one paleosol horizon can be seen at the same location. This quarry, which lies northwest and downslope from the ruins of a plantation house (commonly known as Watling's Castle), is one such location. Exposed on the west face of the quarry is an upper oolitic dune unit approximately 7 m thick overlying a prominent, extraordinarily hard, red paleosol. Underlying the paleosol is approximately 1 m of exposed, older bioclastic eolianite (Fig. 8). A relatively thin, but well developed calcrete caps the entire sequence and appears to merge with the lower paleosol on the northwest side of the cliff face. Note how the upper paleosol thickens and becomes more complex as the dune swale is approached.

### DESCRIPTIONS OF THE KARST FIELD STOPS

The karst part of this field trip is designed to familiarize the participant with a number of different caves and karst features of San Salvador.

### Stop 7. Island Overview and Watling's Blue Hole

From the top of the observation platform above French Bay, one can view the entire south end of the island. Those with good eyesight will be able to look north and see Cockburn Town, identifiable by the radio mast and dish and the *Cassurina* trees on the west coast. To the northeast, the Dixon Hill Lighthouse, site of Lighthouse Cave, can just be seen. The lighthouse represents one of the most distant spots from Stop 7 and gives the observer a feel for the size of the island. Note the uninhabited nature of the island's interior, with its long, high dune ridges and lakes that occupy the interdune swales. Close to hand can be seen the road and golf course pattern (now disappearing beneath new vegetation) of the Columbus Landings development.

Looking downslope past the foot of the platform, one sees the circular, light blue form of Watling's Blue Hole.

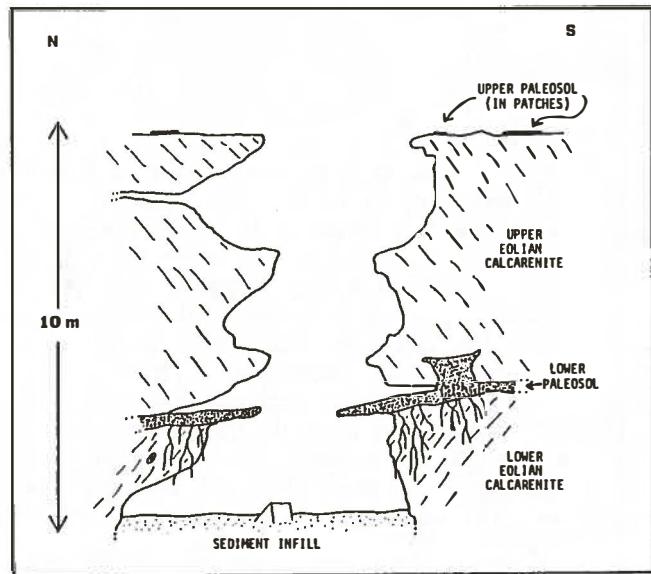


FIGURE 9 Diagrammatic representation of a measured section within Owl's Hole.

Watling's Blue Hole has a tidal range almost equal to that of the nearby ocean. It is a shallow bowl with a shaft in the center that leads to a horizontal cave passage at about 9 m depth. The cave conduit has a strong current when tide is rising or falling, but silt on the floor comes to within 15 cm of the ceiling. The initial chamber at the bottom of the blue hole is quite roomy, but becomes low as the actual conduit is entered. Because of the conduit flow of water into and out of the blue hole, the geochemistry of the water is substantially different from that of freshwater ponds. Crotty and Teeter (1984, see this volume also) have conducted a survey of the geochemistry and micropaleontology of this blue hole. The rock wall around the blue hole is made up of an unusual collection of rock slabs, composed of material that has been informally referred to as lake facies. This rock contains large numbers of shells of the mollusks *Batillaria*, *Pseudocyrena*, and *Anomalocardia*, which are indicative of brackish or hypersaline conditions. Rocks of this facies are found as a veneer over older Pleistocene rocks, but usually as float and rarely in place.

### Stop 8. Infilled Solution Pit

On the south wall of this road-cut in eolian calcarenite of the Grotto Beach Formation is a 2+ m deep solution pit almost entirely filled with eolianite clasts and soil. The material at the bottom of the pit is a well lithified micritic paleosol with fractured clasts. Above that is a similar deposit, but it is not as well lithified, and the clasts are not fractured. One or more unindurated layers occur above that, and they are probably the result of the current cycle of infilling. Such infilling cycles may be related to Pleistocene climatic oscillations.

## Stop 9. Sandy Point Pits

Do not confuse this area with the Sandy Point Caves of Stop 10. This amazing area contains over 50 pits ranging from tubes 0.5 m in diameter that penetrate downward 2 to 3 m, to large, open shafts up to 8 m across with depths up to 10 m. The elevation of the area where the truck is parked is 18 m above sea level, and the entire terrain surface is well above any past sea level high stand. No pit is deep enough to reach current sea level, and all pits end in sediment fill. Many of the pits are complex, and some interconnect to provide a short but varied caving experience. Please exercise caution in walking around and exploring these pits.

From the eastern cairn where the truck is parked, walk due east through the scattered brush and bare rock. Watch your footing, as many shafts are small and open flush with the ground surface. The first large feature encountered is an 8 m shaft with an entrance diameter of about 1.5 m. The shaft leads to a small, dead end chamber.

Just beyond is Owl's Hole, one of the largest pits in the area. It is 10 m deep and was named for a snowy white owl that used to live here. Access into the pit is easiest by going down the trunk of the tree and working your way to the bottom. At the bottom is a chamber with stalactites and a sediment floor. The top of the section within Owl's Hole consists of about 8 m of oolitic eolianite of the Grotto Beach Formation (approx. 125,000 years old). Below that is a paleosol exposed about 1.5 to 2 m above the floor of the pit. This paleosol has been repeatedly analyzed for its paleomagnetic record. Original data (triplicate analyses) revealed that it is magnetically reversed, indicating that the paleosol formed during the last major paleomagnetic reversal episode (or earlier) about 740,000 years ago. The underlying bioclastic eolianite, assigned to the Owl's Hole Formation, must then be that old or older. As such, this would be the oldest surface rock in the Bahamas. More recent analysis of the paleosol and rocks in Owl's Hole by cryogenic paleomagnetic methods has found no magnetic reversal in this paleosol or the underlying bioclastic eolianite, thus placing the original age interpretation of approximately 740,000 years into question. Regardless, the bioclastic eolianite most likely correlates with the lower unit at Watling's Quarry (Stop 6) and at Grotto Beach (Stop 4A) and is the oldest rock exposed on San Salvador and probably in the Bahamas. Figure 9 is a diagrammatic cross section of the pit, showing the major geologic features.

About 50 to 60 m south-southeast of Owl's Hole, along a route marked by cairns, is a suite of interconnected pits. These pits are connected by passages which are high in the section, and they exhibit a number of features which cast doubt on a purely vadose origin. In the bottom chamber there are some shattercone-like structures that have a variety of orientations in the Grotto Beach Formation wall rock. Their origin is unknown, but similar features have been reported from 6 m underwater in a cave in the Exuma Islands of the Bahamas (R. Dill, pers. comm.).

Just to the northwest is a sloping plain of bedrock

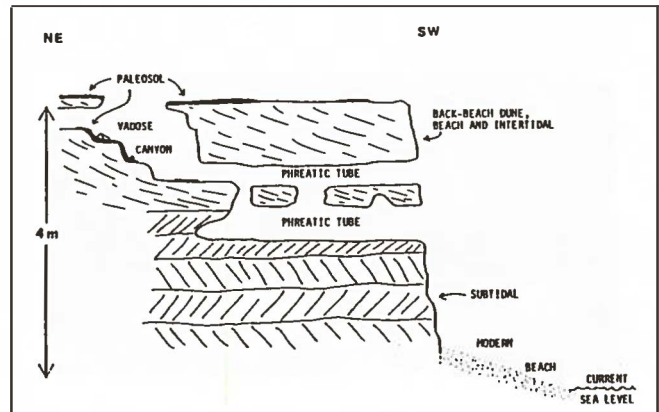


FIGURE 10 Diagram of the rock section at Chinese Fire Drill Cave showing vadose and phreatic solutional features.

with a number of surface-truncated cavelets and tubes, which seem to converge on larger pits. The pits are developed in the 125,000 year old Grotto Beach Formation and present interesting implications concerning the time required for development of conduits and their subsequent exposure by erosional denudation.

The participant can wander around in the bush and find a number of other features. Some of the smaller, tightly descending tubes have never been entered (ask to be shown some).

## Stop 10. Sandy Point Caves

A trail leads from the cairn across a surface of Pleistocene bedrock to cliffs above the sea. The coastline here is very dynamic, with large quantities of sand moving in and out depending on wave activity. When the sand is out, the waves break against the base of the cliff about 2.5 m below. If sand is packed in, one can step from the top of the cliff down onto a beach of variable width. How much can be seen of the karst features in cliffs depends on how much sand is present.

Following the trail straight to the cliffs, a small, rocky point will be seen immediately to the observer's right. There are a number of small holes just a meter or two back from the cliff edge. The largest of these leads into a very short cave called Chinese Fire Drill Cave. The cave can be entered from the small collapse entrance on top of the cliff. In its inland section, the cave has the form of small vadose canyons that bifurcate and rise to small holes on the surface. In the paleo-downstream portion, the floor of the cave changes from a vadose notch to a series of stacked phreatic tubes with numerous interconnections that eventually exit on the cliff face (unless there is too much sand). The point of transition from vadose to phreatic morphology is an indicator of the paleo-water table at the time of cave development (Fig. 10). This indication of paleo-water table position is also a good measure of sea level position at that time. The present position of the cave, and its truncated nature, suggests that there has been some scarp retreat since the cave developed.



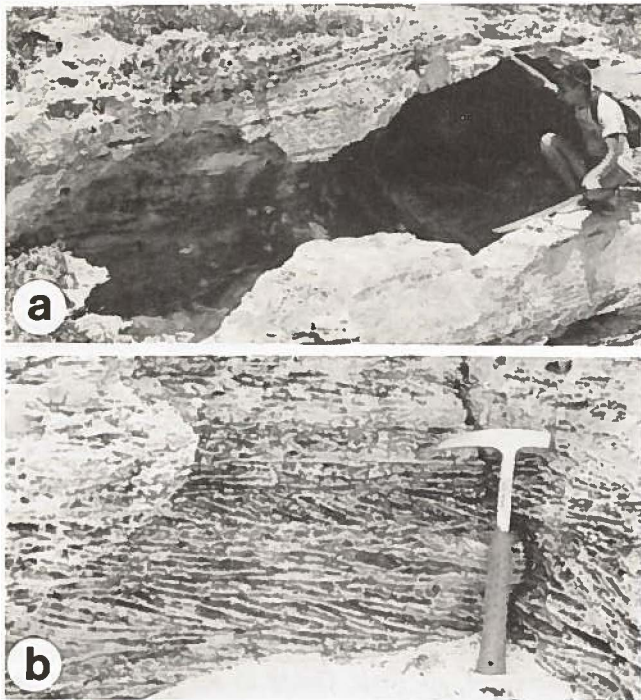


FIGURE 11 a. Phreatic tube of Chinese Fire Drill Cave truncated by cliff retreat due to marine erosion. Subtidal herring-bone cross bedding can be seen in the cliff below the tube. b. Close-up of subtidal herring-bone cross bedding in the Sandy Point cliffs.

Walking west a few meters to the small promontory and looking back at the cliff, one can see a truncated phreatic chamber in the cliff (Fig. 11a). This could be a relict continuation of Chinese Fire Drill Cave. The cave and cliff rocks record evidence of past sea level conditions. The cliff that contains the cave exhibits excellent herring-bone cross bedding indicative of subtidal deposition during a sea level higher than that at present (Fig. 11b). The conduit could have formed during the fall from that sea level high stand or during a later high stand.

Proceeding east along the cliff, about 75 m from Chinese Fire Drill Cave, Blowhole Cave can be seen. This short cave (even shorter if the sand is in) reveals a paleosol that drapes from the surface down into the cave. This indicates that the cave void was present prior to the development of the paleosol. When the sand is entirely out, the cave leads east to another low entrance, and then down and west to another entrance at the base of the cliff face. The infilling paleosol contains a number of "black oolite" pebbles. Once thought to have come from a former island-wide deposit (Titus, 1983), it is now believed that the black color, which was more than just a coating, was caused by weathering activities that occurred in the San Salvador soils, and/or hypersaline lake margin settings. Fire also may have caused or contributed to the oolite-blackening process.

From here, reverse direction on the trail and return to the truck.

## Stop 11. The Gulf Exposures

This site is called The Gulf. Dismount from the trucks and examine the north wall of the road cut. It is an oolitic eolian calcarenite capped by a thin paleosol. Isolated vegemorphs and perhaps burrows can be seen in the face of the cut. Step back (watch for vehicles) and note that there is a well developed set of joints in the road cut that often form a classic "X" pattern. Examination of the joints reveals a calcrete layering along them, indicating that they predate the excavation of the road cut and did not form as a result of the stress produced by bulldozing. Rocks this young and poorly lithified, which were never buried, are not a prime candidate for joint development. The joint orientation and pattern does not support a platform edge subsidence model for their formation. These joints may have implications for cave and karst development.

Cross the road (south) and proceed around the west end of the road cut onto the flat platform above the sea. Walk to the coast and look back at the large re-entrant that lies behind the south wall of the road cut. The paleosol here is well developed, with many layers and hollows, a form called pillow paleosol, or multilobate, by Carew and Mylroie (1985). Very large vegemorphs (often called rhizocretions or rhizomorphs) dangle from the paleosol surface and extend downward in excess of 3 m (Fig. 12a). If the tide is low, the bedrock flat between the cliffs and the outlying stack can be seen to



FIGURE 12 a. View, looking north, of rocks exposed at The Gulf. Note the spectacular development of vegemorphs beneath the paleosol crust near the top of the photo. b. Paleo-soil profile with breccia developed in the lower soil horizon seen in a detached block of rock at The Gulf. Note that brecciation decreases going down the section.

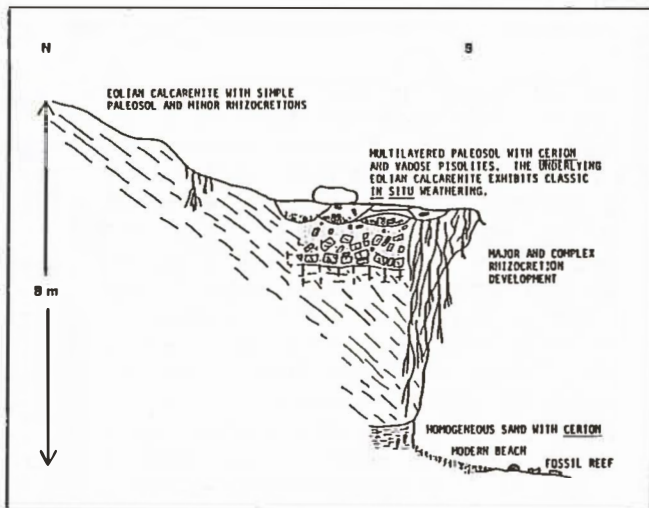


FIGURE 13 Diagram of a measured section at The Gulf showing representative features seen in outcrop there.

consist of a coral reef rubble facies, which dates to the Sangamon (substage 5e) high sea level approximately 125,000 years ago. These features indicate a regressive (in the sea level sense) origin for the dune that overtopped an abandoned reef facies. Large vegemorph structures such as seen here are known only from dune suites that are interpreted as regressive in nature (i.e. deposited as sea level fell). Figure 13 presents a diagrammatic representation of this outcrop.

Examine the paleosol closely; it contains abundant *Cerion* sp. fossils and vadose pisolites. The route down to the fossil reef facies passes by a large block of rock which clearly shows the characteristic disruption of bedrock by past soil-forming processes (Fig. 12b).

## SUMMARY

The oldest rocks on San Salvador were seen at Grotto Beach, Owl's Hole, and Watling's Quarry. In each of these localities there is a basal eolian calcarenite which is composed primarily of bioclastic grains and peloids. These calcarenites are either erosionally truncated as seen at Stop 4A or covered by a paleosol as seen at Stops 6 and 9. These rocks are assigned to the informally recognized Owl's Hole Formation, and they are all thought to be of pre-Sangamon age (>125,000 years old), and may be as old as 740,000 years.

Overlying the Owl's Hole Formation is the Grotto Beach Formation. Rocks assigned to this unit and consisting of a variety of facies from subtidal to eolian were seen at Stops 4A, 5A, 5B, 6, and 11, as well as at many of the karst stops. These rocks differ from both older and younger rocks in that the eolian facies in particular are primarily oolitic rather than bioclastic. The Grotto Beach Formation rocks seen on this trip all were deposited in association with the Sangamon (circa 125,000 years) highstand of sea level. Grotto Beach Formation rocks are capped by a calcrete/paleosol that marks the Pleistocene/Holocene boundary. This was

illustrated at Stop 3.

The youngest (Holocene) rocks on the island are assigned to the Rice Bay Formation, and were seen at Stops 1, 2, 3, and 4B. These rocks yield radiocarbon ages of 5,500 yBP to 480 yBP. Eolian facies of these rocks are bioclastic and peloidal.

Stops 8, 9, and 10 illustrated karst features developed in Grotto Beach Formation rocks. These features provide information about past sea level and climatic events.

## Acknowledgments

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# THE HOLOCENE CARBONATE EOLIANITES OF NORTH POINT AND THE MODERN ENVIRONMENTS BETWEEN NORTH POINT AND CUT CAY, SAN SALVADOR ISLAND, BAHAMAS

Brian White and H. Allen Curran  
Department of Geology, Smith College, Northampton, Massachusetts

## INTRODUCTION

The goals of this field trip are to study the types of strata, sedimentary structures, trace fossils, and dune morphologies of the Holocene eolianites excellently exposed along the coasts of Rice Bay and North Point. We will explain how eolian deposition of carbonate grains occurs and how dunes are initiated and evolve. Toward the end of this excursion, a short snorkel dive will be conducted in the shallow, sheltered waters between North Point and Cut Cay to study grass beds, sandy substrates, and hard substrates and to compare their associated sediments, plants, and animals. The area to be visited and the locations of field stops are shown in Fig. 1.

## Previous Work

Adams (1980), in his pioneering study of the geology of San Salvador, briefly described the eolianites of North Point. He distinguished lobate dunes that have large-scale cross beds on their leeward faces and flanks and smaller, more varied, cross beds on their windward slopes. In their overview study of the petrography of the eolianites of San Salvador, Hutto and Carew (1984) found that most are dominantly oolitic. However, this was not true for their North Point samples, which have a higher proportion of skeletal grains and pellets. The North Point eolianites were assigned to the North Point Member of the Rice Bay Formation by Carew and Mylroie (1985). Samples of North Point Member rocks from North Point gave radiocarbon dates of  $5,345 \pm 125$  and  $5,360 \pm 110$  years B.P. (Carew and Mylroie, 1987).

In her more detailed study of the eolianites of the Rice Bay area, Lawlor (unpublished data, 1985) found that these rocks are pelsparites with lesser proportions of ooids and skeletal grains. The rocks are dominantly aragonite with incomplete cementation by vadose low Mg calcite. Inverse graded bedding is a common feature of the rocks on a microscopic scale, with somewhat more complete cementation in the finer layers (White and Curran, 1988).

## The Eolianites of the Rice Bay to North Point Area

The Holocene dunes of this area are composed of carbonate sand which was blown landward from marine beaches by onshore winds. Initially, small dunes developed landward of the beach, a few around cores formed of the eroded remnants of earlier dunes. In some cases two small adjacent dunes were enveloped by later

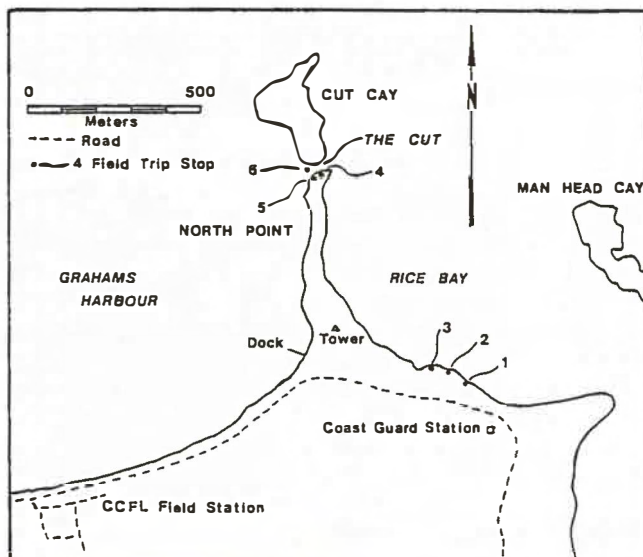


FIGURE 1 The North Point area with locations for described stops.

dune strata to form a compound dune. Elsewhere, dunes grew higher and migrated inland as individual lobes, with slip faces sloping not only downwind, but to the right and left on the flanks of each lobe. Eventually the lower parts of the flanks of adjacent dunes overlapped to cover the interdune areas and thereby form a long, hummocky dune ridge. This dune morphology is clearly reflected in the undulating topography of the west side of North Point as seen from the campus of the Bahamian Field Station.

Large-scale, steeply-dipping cross beds occur on many lee slopes and flanks of the lobate dunes. Windward dune slopes reveal a greater variety in scale and type of cross bedding, including examples of tabular-planar, wedge-planar, and trough sets. The latter are more numerous in the lower parts of the dunes. Wind ripples are visible on some bedding surfaces, but they are scarce. Although fossil animal burrows are believed to be rare in eolianites (McKee and Ward, 1983), there are several large and well preserved trace fossils and numerous smaller burrows here, all thought to have been formed by invertebrates in dunal sands that now are the eolianite exposures along Rice Bay (White and Curran, 1988). Rhizomorphs, trace fossils produced by plant roots, are common in these eolianites. In some of the cross bedded exposures, it is possible to distinguish the different strata



produced by climbing wind ripples, grainfall, and sandflow as described from modern coastal dunes by Hunter (1977).

## DESCRIPTIONS OF THE FIELD STOPS

### Introduction

The beach in front of the abandoned Coast Guard Station makes a convenient starting point for this trip. From here the view extends northeast over the sandy beach and across the waters of Rice Bay to Man Head Cay. To the northwest (left) some of the North Point eolianite exposures can be seen and the first of these are reached by walking about 90 m along the beach in a northwesterly direction.

Continuous exposures of Holocene dunes in sea cliffs and on narrow, rocky shore platforms along this reach of coast reveal numerous features of the eolianites. The stops described below were selected to demonstrate particularly good, and readily accessible, examples of trace fossils, sedimentary structures, and stratum types found in the eolianites, and of dune morphology. After walking about 1 km along the peninsula, the end of North Point is reached, where final observations of the dunes can be made. The small beach on the west side of the point is a good place to begin a snorkel dive to view the nearby hard substrates, *Thalassia* grass beds, and sandy substrates and to examine their associated sediments, floras, and faunas.

### Stop 1. Cluster Burrow Trace Fossil Type Locality

To reach this stop, walk northwest along Coast Guard Beach to the first rock exposures and then continue over outcrops and a small sandy bay for 60 m. Here sea cliffs 3 to 4 m high are cut into an 85 m wide fossil dune. Along much of this dune's width cross bed dip directions are rather variable, but generally towards the southwest, and dip angles range from almost flat-lying to 15°. On the northwest flank of the dune, dips are northwesterly and steepen to 30°, with some sandflow cross strata evident. At the southeast end of the dune, steepening cross strata dip to the south at angles of up to 20°. Most of the strata are in small wedge-planar sets, suggesting variable wind directions, and climbing wind-ripple strata are evident in some places.

A prominent trace fossil consisting of a cluster of vertically oriented burrows is exposed in a small cliff face here, and in a large counterpart block that has fallen away from the cliff. The trace fossil cuts vertically across 1.4 m of small-scale, wedge-planar and trough cross strata sets, which are obscured in places by bioturbation. Fine, millimeter laminations are evident on much of the cliff face and weathered surfaces reveal some very thin laminations of slightly coarser calcarenite. In the rocks immediately overlying this trace fossil, rhizomorphs are prominently displayed on some bedding planes, where they weather out in relief (Fig. 2a).

In detail, this trace fossil consists of multiple, straight to gently curved, unlined shafts. Shaft diameters are 1 to



FIGURE 2 a. Rhizomorphs on an eolianite bedding surface, Stop 1. b. Vertical, straight to gently curved, unlined shafts of the cluster burrow trace fossil at Stop 1. Burrow shafts are up to 1.4 m in length; about 45 closely spaced shafts occur in this exposure.

2 centimeters (average 1.2-1.4 cm), and shaft lengths can be as long as at least 1.4 meters (Fig. 2b). This is a minimum length for the shafts of this specimen because a break in the cliff face in which it is exposed terminates the lower part of the specimen. Shafts occasionally branch in the upward direction and some definite cross-overs also occur. Shaft diameters appear to contract somewhat toward their upward ends.



The apparently obligatory clustered nature of the shafts and their large number suggest that the structure records the brooding/hatching activity of an invertebrate organism, very possibly a species of burrowing (digger) wasp of the Family Sphecidae, with the shafts having been formed by the juvenile wasps burrowing up to the surface. This hypothesis was discussed in some detail by Curran and White (1987).

About 50 m northwest of the trace fossil just described, a similar one is revealed in horizontal cross-section. Here the circular nature of the cluster and the large number of individual burrows (about 800 shafts) that it contains are clearly revealed. Here, too, this trace fossil is within a sequence of small-scale, wedge-planar and trough cross strata sets, with scattered rhizomorphs and climbing-ripple laminations. Of additional interest is a small bedding surface at least 1 m below the cluster trace fossil and within the present day intertidal zone. On this bedding plane there are ripple marks with their crests oriented perpendicular to the strike of the bedding plane, a feature believed to indicate an eolian origin (McKee and Ward, 1983). The ripples have a very low amplitude and ripple indices of 25 to 30, further evidence that they are wind-formed ripples (McKee, 1979; Tanner, 1967). Two interesting conclusions may be drawn from these observations. As wind-deposited strata are located in the present intertidal zone, this clearly means that sea level was lower at the time of formation of these beds than at present. The presence of wind-formed ripples beneath the trace fossil confirms that the burrowing took place in an eolian dune and not in a beach or nearshore environment.

## Stop 2. Fossil Proto-dunes on Rocky Shore Platform

This next locality is reached by dropping down the northwest flank of the dune at Stop 1 to a broad, rocky shore platform, some 80 m long and up to 20 m wide, backed on its landward side by low cliffs and extending seaward into the intertidal zone. Because of the extensive horizontal and vertical exposures, this is an excellent place to study sedimentary structures and the early stage of dune development.

In the landward cliffs several small dune cores are exposed (Fig. 3a). Some of these are better lithified and contain more abundant rhizomorphs than overlying strata and appear to be the eroded remnants of earlier dunes. Large-scale trough cross beds occur immediately adjacent to some of the dune cores (Fig. 3b), and these may have formed by windscouring around the dune remnants. Subsequent deposition of wind-blown sand buried the dune cores and the growing dune extended laterally and vertically to encompass them into a form of compound dune.

Other sedimentary structures well-displayed here are convex-upward cross strata sets, trough cross beds, and wedge-planar sets. Some of the latter have cross strata with acute angular relationships to the underlying set, whereas others show a tangential relationship (Fig. 3c). Several bedding surfaces have ripple marks with ripple indices between 23 and 32, clearly wind ripples (McKee, 1979; Tanner, 1967). Again, some of these are within

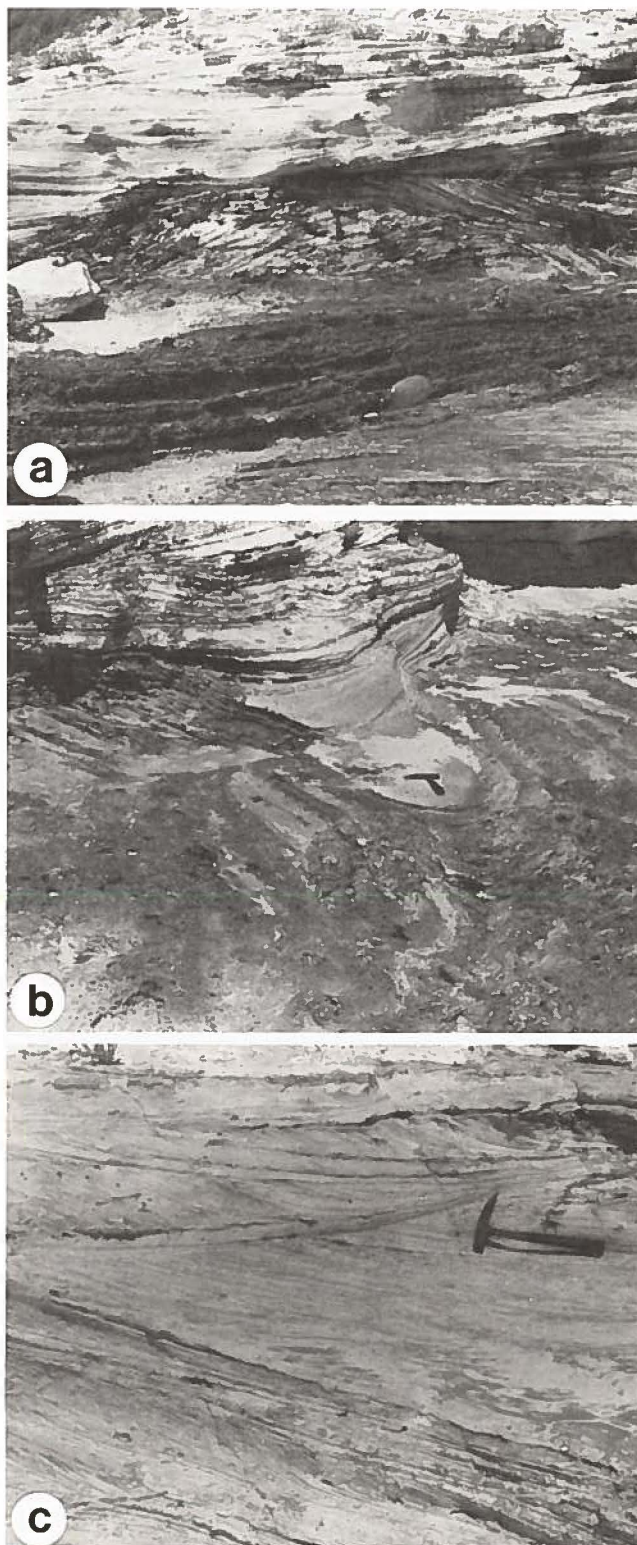


FIGURE 3 a. Eroded remnant of an older dune overlapped by younger eolian strata, Stop 2. b. Trough cross beds occur adjacent to an older dune core at Stop 2. c. Wedge-planar cross bed sets show a tangential relationship towards underlying strata, Stop 2.



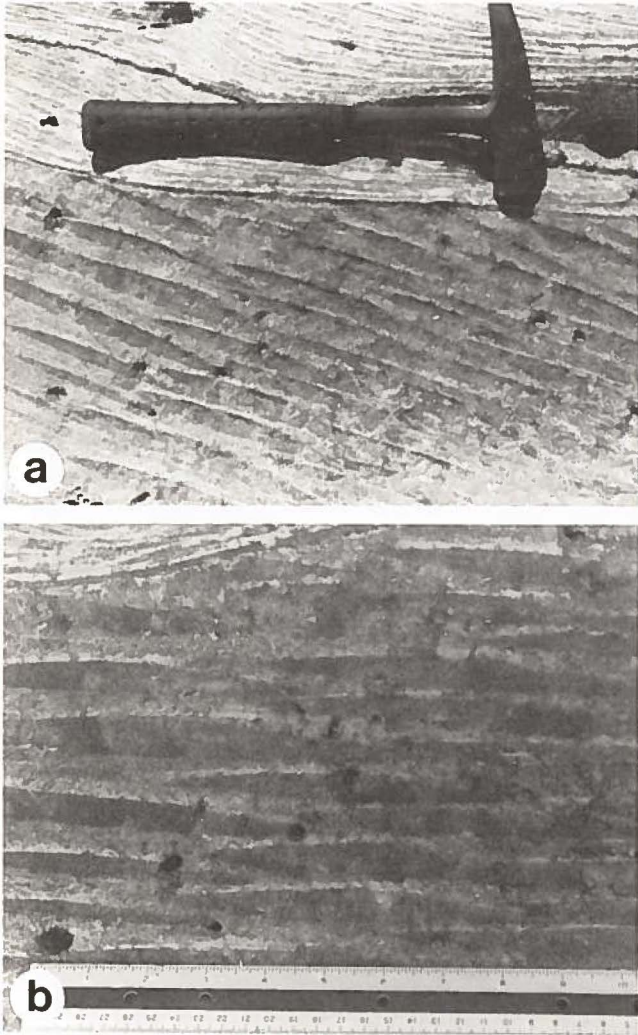


FIGURE 4 a. Sandflow strata occur within grainfall strata at Stop 3, with both overlain by wind-ripple-formed strata. b. Lenticular sandflow strata within grainfall deposits, Stop 3.

the present intertidal zone, confirming the conclusions drawn at Stop 1 about lower sea level at the time of eolianite deposition.

Beyond the rocky terrace of Stop 2, follow the coast as it takes a short jog to the west, then cross a 30 m wide bay with a sand and rock floor, to reach another promontory. Scramble down the northerly side of this headland and traverse the narrowing beach for about 40 m, until a small rock arch is reached. Progress along here will be blocked at some point, exactly where depending on wind conditions and the state of the tide. In any case, from the vicinity of the small arch, climb upward obliquely across the cliffs to a small gully, which constitutes the next stop.

### Stop 3. Eolianite Stratification Types

In this locality are exposed, in close proximity, three types of wind-deposited strata that were produced by

mechanisms described by Hunter (1977, 1981) as grainfall, sandflow down lee slopes, and climbing wind-ripples (Fig. 4a).

The strata produced by climbing wind-ripples are millimeter laminations with even thickness and sharp contacts resulting from inverse size grading, although the latter detail is not always readily visible in the field. If net sedimentation is to occur by the migration of wind-ripples, then each successive ripple must climb relative to the stratum deposited by the previous one. Grain size segregation in wind-ripples concentrates relatively coarse sediment on the crests and relatively fine sediment in the troughs. As the crests and troughs migrate, they deposit a layer of relatively coarse grains overlying a layer of relatively fine ones; hence the upward size grading within each stratum produced during deposition by a migrating wind-ripple. Wind-ripples may climb up, down, or along both lee and stoss sides of dunes. Thus the dip angle and direction of the resulting strata are more a function of the geometry of the surface over which they have migrated than the direction of the driving wind. The passage of many wind-ripples can lead to the accumulation of sets of ripple-formed strata. On lee slopes these strata may be preserved under grainfall sediments or sandflows, providing the latter are not erosive.

Grainfall occurs when moving air currents carry saltating and suspended sediment into a sheltered area, for example the zone of separation to the lee of a dune crest. The sediment settles like falling snow and accumulates on the lee slope of the dune, where it may be joined by grains that crept over the dune crest in response to collisions with saltating grains. Grainfall strata tend to be thin and indistinct, and, because they commonly form on lee slopes, they often have a high initial dip (Hunter, 1981). On small dunes, though, grainfall could occur as far forward as the toe of the dune, and the strata would lie at low angles. In wind tunnel experiments conducted by Fryberger and Schenk (1981), grainfall strata deposited on lee slopes consistently wedged thinner downslope, and this may be anticipated on natural dune lee slopes as well.

Sandflow strata form by resedimentation of sands that accumulate on the upper part of lee slopes, often by grainfall, until the slope oversteepens and becomes unstable. If the sands are dry, they will flow non-cohesively, but, if crusted or partially lithified in some way, they may founder as blocks subject to all kinds of jumbling and deformation. Sandflow strata are typically thicker than other wind-deposited strata, commonly exceeding 1 cm. They have sharp contacts, lie close to the angle of repose, and tend to pinch out towards the base of a foreset (Hunter, 1981). They have a distinctive lenticular shape when seen in strike cross-section or in horizontal exposures (Fig. 4b).

These types of wind-formed strata were recognized by studying modern coastal dunes (Hunter, 1977). Several attempts have been made to use these strata to identify and more closely characterize ancient siliciclastic rocks believed to be of eolian origin. A sampling includes: Pleistocene of Oregon (Hunter, 1980); Permian of Arran, Scotland (Clemmensen and Abrahamsen, 1983); and



various Paleozoic and Mesozoic formations of the western United States (Fryberger and Schenk, 1981; Hunter, 1981). Prior to this study, similar analyses do not seem to have been reported for carbonate rocks, and these various wind-deposited strata are not mentioned by McKee and Ward (1983) in their review of carbonate eolian environments.

Small, irregularly meandering burrows 3 to 4 mm in diameter and reaching greater than 20 cm in length occur within and upon grainfall and sandflow strata in the North Point Member eolianites (White and Curran, 1988). Examples of these trace fossils are common in the vicinity of Stop 3. We suggest that these burrows also probably were formed by insects or insect larvae, but a specific modern trace-maker analogue for this burrow type has not yet been identified.

To continue this field trip, stay at the top of the sea cliffs and walk around the small bays and headlands for about 200 m. Hereabouts a more prominent trail joins from the south, and the wreck of a misplaced tanker scars the coast to the northeast. Follow the winding trail northward along the spine of the narrowing peninsula. Along the way one will pass many exposures of eolianites, and one can enjoy fine views to the west (left) over Grahams Harbour and to the east over Rice Bay and Man Head Cay. After walking about 400 m beyond the wreck, the edge of a cliff is reached, overlooking a tidal inlet and an island to the north. This is the next field trip locality.

#### Stop 4. Cut Cay Overlook

Here, at the north end of North Point, the cliffs are formed by the north flank of a well-developed lobate dune, and the cross bedding dips north and steeply down into the sea. A 40 m wide inlet, The Cut, separates North Point from the nearby island of Cut Cay. The cliffs of the south end of Cut Cay are part of the south flank of another dune, and the cross bedding dips down into the sea on that side too, but in a southerly direction. Evidently, the sea has driven through along a low interdune area and separated Cut Cay from the rest of the peninsula. According to legend, The Cut did not exist at the time of Columbus' visit in 1492.

From this location a good view of the seafloor to the west out into Grahams Harbour and to the northwest towards Cut Cay can be obtained. This perch provides an excellent overview of the three different substrates which are easily explored by snorkeling in this calm (usually) water. The dark green grassbeds are dominated by *Thalassia*, the pale green areas are sandy bottoms, and the tan areas are hard substrates. Calcareous green algae, including *Halimeda*, *Penicillus*, *Udotea*, and *Acetabularia*, grow in the grassy and sandy areas, their abundance and distribution varying from time to time, perhaps seasonally. A considerable variety of invertebrate animals lives among the various plants of these different environments and awaits careful and sharp-eyed explorers.

Following this preview, climb down the west side of North Point by taking the only obvious (and safe) route to the small beach. This is the location of the next field trip stop and the starting point for the snorkel dive.

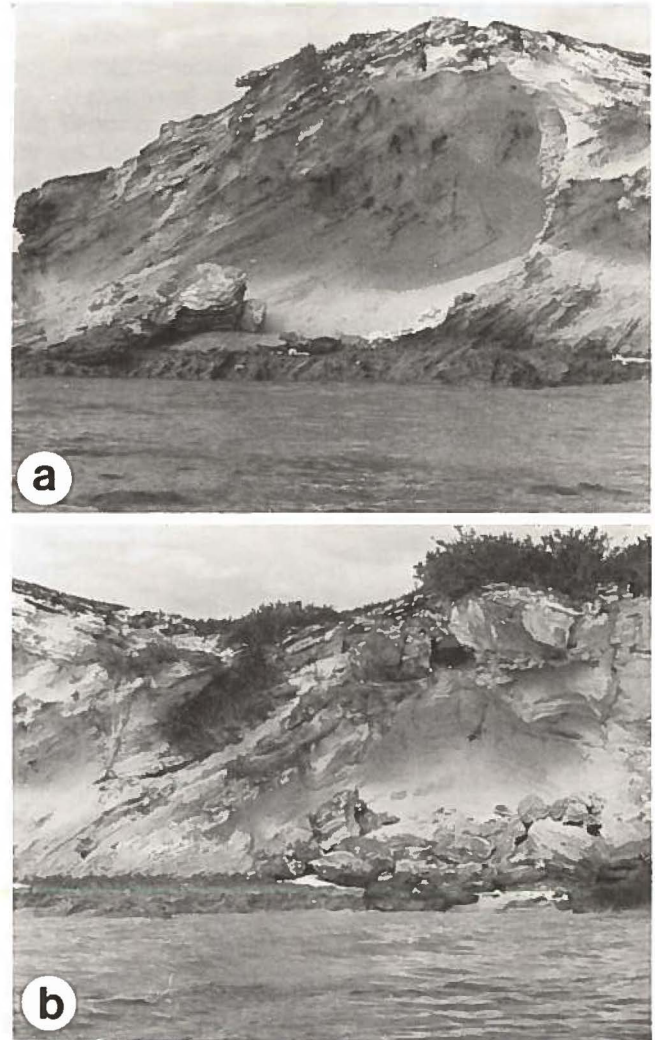


FIGURE 5 a. View from the west of lobate dune forming the north end of North Point, Stop 5. b. View from the west of lobate dune immediately to the right (south) of the dune shown in Fig. 5a, Stop 5.

#### Stop 5. Dune Morphology Revealed in Sea Cliffs

A number of well-developed lobate dunes are clearly exposed in the cliffs on the west side of North Point (Figs. 5a and 5b). Here the dunes have reached a more mature stage of development than some seen along Rice Bay. The opposing flanks of each dune dip steeply and in opposite directions. Along this part of the coast the relationships between adjacent dunes are revealed. In some cases, one dune flank overlaps the flank of the nearest dune, suggesting that the former was mobile and the latter stabilized, at least temporarily. In other situations, adjacent dune flanks interfinger and both dunes appear to have been mobile. This entire coastline is made up of a row of these coalesced lobate dunes that is clearly visible from the vicinity of the Bahamian Field Station, especially when illuminated by the setting sun. Dune lobes that coalesce to form such a transverse dune ridge have been described from Pleistocene carbonate



rocks of other parts of the Bahamas by Ball (1967) and from Bermuda by MacKenzie (1964a,b).

The fact that wind-deposited cross beds dip down into the sea here at North Point adds further evidence that these eolian dunes formed before sea level rose to its present position. Additionally, such evidence shows that the wind-blown sands were sufficiently lithified by the time sea level rose to resist simple reworking of the sand.

#### Stop 6. Snorkeling Beach

The small beach here is an excellent place to begin a snorkel dive to explore various substrates and associated flora, fauna, and sediments between North Point and Cut Cay. From a short distance offshore an excellent view of several of the coalescing dune lobes may be obtained.

#### Acknowledgments

We thank the staff of the Bahamian Field Station for full logistical support of our field work on San Salvador. Valuable contributions to the North Point research project were made by Smith College geology majors: Liz Dole, Kate Japy, Karen Kurkijy, Jean Lawlor, and Kim Pirie. Acknowledgment is made to the donors of the The Petroleum Research Fund, administered by the American Chemical Society, for partial support of our work through separate grants to Curran and White. Generous financial support also was provided by the Merck, Pew, and Shell foundations, and we extend our thanks to each of them.

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# PLEISTOCENE BEACH ROCK IN A SUBTIDAL-BEACH-DUNE SEQUENCE, QUARRY A

Roger J. Bain  
Department of Geology, University of Akron, Akron, Ohio

## INTRODUCTION

The deposits of Quarry A formed in a setting and environment very similar to the present-day nearshore area of French Bay, San Salvador. The sediments indicate a variety of depositional environments, including shallow subtidal, tidally affected beach, rocky bottom, and dune. The rocky bottom or hard substrate was provided by exhumed beach rock and inundated subsoil micrite crust. At Quarry A we will observe features which lead to these interpretations, including fenestral porosity, bored substrate, coral and vermetid gastropod "encrustations," rocky bottom fauna, and other lithologic characteristics. The strata here consist of coarse- to fine-grained bioclastic sand and oolite.

Quarry A (Index Map for San Salvador) was described by Adams (1980) as containing shallow marine, fossiliferous sand and gravel and scattered brain corals. The quarry is located in the northeastern portion of the island and consists of a two-lobed excavation into the hill west of the road. A generalized stratigraphic section for the quarry is given in Figure 1. Most of the lithologic and environmental variation present in the quarry can be seen in the northern lobe; however, the best exposures of coral and vermetid gastropod-encrusted beach rock are in the south lobe. Exposed in the floor of the quarry are low "knobs" of dense micrite which are the stratigraphically lowest deposits. Overlying this micrite is a medium- to coarse-grained bioclastic sand and gravel that comprises the majority of the lower portion of the quarry exposure. Along the western wall of the quarry, the calcarenite is finer grained, consisting of a mixture of bioclastic debris and ooids and displaying fenestral porosity. Above this porous horizon the bioclastic content decreases as ooid content increases; there also is a decrease in grain size upward.

In the southern lobe of the quarry, at the approximate position of the bioclastic facies, heads of the corals *Diploria* and *Montastrea* as well as vermetid gastropod encrustations occur. In a similar fashion above this coral horizon, but in rocks not as well exposed, bioclastic content decreases, ooids increase, and grain size decreases.

Cores taken at four locations within the quarry aided greatly in the interpretation of the exposed sequence. The following commentary will describe and discuss features which can be observed in the quarry, as well as features of the cores at specific points.

## MICRITE KNOBS

### Petrography

Micritic areas exposed in the northern portion of the

quarry consist of a dense, hard rock that contains shell material, apparent infilled borings, and clasts of subaerially laminated crust. Thin sections show that the micrite is the result of micritization of a biocalcarenite in a subaerial or subsoil environment. Root traces can be observed throughout the rock, and micritization is related to these root penetrations (Bain, 1984). The micrite is approximately 30 cm thick, and micritization decreases downward until loose sand is encountered at a depth of 1 m.

Borings into the micrite are infilled by two distinct sediment types. One is a bioclastic sand rich in Foraminifera, red algae, pelloids, and molluscan fragments. The other is an oolite-pelloidal, well sorted, fine-grained sand which appears to infill borings into both the micrite and the previously mentioned bioclastic sand infillings. Overlying the micrite, and cemented to it is a coarse bioclastic sand and gravel which contains abundant limpet shells, *Goniolithon*, and molluscan fragments, along with less abundant *Halimeda*, pelloids, and coral fragments.

### Interpretation

Bioclastic calcarenite was exposed to subaerial or subsoil conditions which produced micrite through diagenetic micritization of the biocalcarenite. Later submergence of this hardened micrite offered a rocky substrate which was populated by limpets as well as other shallow marine nearshore organisms. This rocky substrate, or shore zone, was bored as well as excavated by organisms that formed cavities which were filled with bioclastic sediment, probably in a nearshore to shoreline environment.

## BIOCLASTIC SAND AND GRAVEL

### Petrography

The majority of the quarry floor is covered by a bioclastic sand and gravel which, in the southern part of the quarry, contains *Diploria* and *Montastrea* corals and vermetid gastropod encrustations. The bioclastic debris is dominated by *Halimeda*, *Goniolithon*, molluscan fragments, and low percentages of ooids. Strata throughout the quarry floor and lower part of the west wall appear very similar; however, there is variation in grain size and in the abundance of specific constituent grains.

Of particular interest is the occurrence of the vermetid gastropod encrustations and corals which appear to be in growth position. Both prefer a hard substrate upon which to grow, and yet they seem to have grown in loose sand. Petrographic analysis of thin sections from



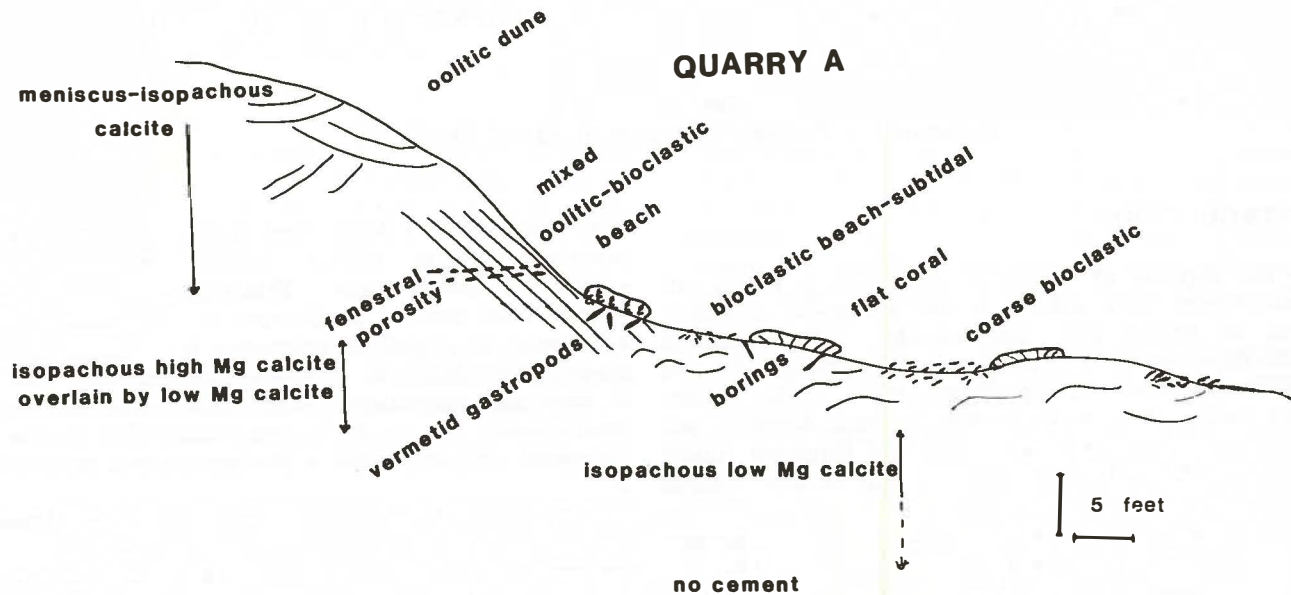


FIGURE 1 Generalized diagram of exposures in Quarry A showing the distribution of facies, fauna, and cement types within the sequence.

cores which penetrated both the coral and vermetid growths yielded an explanation and posed an interesting question to be asked of other nearshore carbonate sequences.

Bioclastic rock collected from above the coral-vermetid horizon is comparable to that from beneath the horizon. However, rock beneath both the coral and vermetid encrustations possesses an initial micritic, high-Mg calcite cement and a later, blocky, low-Mg calcite cement. Rock from above the coral-serpulid horizon contains only the low-Mg calcite cement. Also, rock from beneath the coral-vermetid horizon displays sediment-filled borings and fenestral or bubble porosity. Such porosity has been interpreted as a characteristic of intertidal beach deposits (Shinn, 1968).

At several locations in the north lobe of the quarry, numerous clasts and beds of moderately well-cemented bioclastic limestone can be observed. Some smaller, disk-shaped clasts measuring upward from several inches in diameter are well rounded. Beds which are in place stand in positive relief relative to the loose bioclastic sand on the quarry floor. Examination of these lithified clasts and beds reveals encrustation by vermetid gastropods, serpulid worms, and borings, both open and infilled by coarse sediment.

### Interpretation

The bioclastic sand and gravel represents a shallow subtidal to intertidal deposit which locally was cemented by high-Mg calcite forming beach rock. Following this deposition and cementation, a period of increased erosion exhumed or exposed this beach rock, under conditions similar to those found along French Bay today. Such conditions allow the hard beach rock and clasts of beach rock to be bored and encrusted by corals, vermetid gastropods, red algae, and serpulid worms. At the same

time this beach rock was being exhumed, conditions similar to those that produced the beach rock sediment continued. For that reason, lithologically, the beach rock and overlying material are very similar. Both contain a late low-Mg calcite cement which formed in a vadose setting. The presence of a marine cement, a rocky bottom fauna and flora, lithified and bored clasts and beds, and an increase in grain size and decreased sorting of sediment enabled the recognition of this erosional episode. Could we recognize this depositional pause in an older rock sequence? If so, how would we interpret it?

### BIOCLASTIC-OOLITIC BEACH-DUNE SEDIMENTS

#### Petrography

From the floor of the quarry and proceeding up the west wall, grain size and bioclastic content of the sediment decrease, whereas ooid content and degree of sorting increase. Near the base of the wall, bioclastic material dominates the sediment; however, ooids are more common than in sediment below this position. Bioclastic material consists of fragments similar to sediment below this horizon, namely *Halimeda*, *Goniolithon*, and mollusks. Grains are cemented by blocky, low-Mg calcite, largely as meniscus cement. Here, as well as along the south wall of the northern lobe of the quarry, easterly dipping laminations contain fenestral or bubble porosity which has been interpreted as having been formed by intertidal beach processes.

Above the fenestral porosity zone, bioclastic content and grain size decrease, and ooid content and degree of sorting increase. Cross bedding also becomes more complex in the upper part of the west wall. Ooids are cemented by blocky low-Mg calcite meniscus cement.



## Interpretation

The lower portion of this sequence is a beach deposit indicated by uniform east-dipping laminations and fenestral porosity. The upper portion of the wall is a dune deposit. The meniscus low-Mg calcite cement indicates that cementation occurred in the fresh water vadose zone. An interesting question arises concerning the origin of the ooids, which are not present in subtidal deposits but appear in abundance only in beach and dune deposits. Normally, ooids are thought to form on shallow, moderate energy shelves which produce more extensive deposits than seen in Quarry A and on San Salvador. Lloyd et al. (1985) described bioclastic-oolitic deposits from the Turks and Caicos Islands and suggested that laterally restricted but vertically thick oolitic accumulations such as those in the Turks and Caicos and Bahamas might, at least in part, have formed in a beach swash zone. Perhaps such a swash zone mechanism

explains the ooid dunes of San Salvador.

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# THE COCKBURN TOWN FOSSIL CORAL REEF OF SAN SALVADOR ISLAND, BAHAMAS

H. Allen Curran and Brian White  
Department of Geology, Smith College, Northampton, Massachusetts

## INTRODUCTION

The Pleistocene coral reef located along the western coast of San Salvador northwest of the center of Cockburn Town is well exposed and is the best known and described ancient reef in the Bahamas. The Cockburn Town reef is an excellent fossil example of a bank/barrier reef as defined by Kaplan (1982); such reefs are common today on the narrow, wave-cut shelves of islands in tropical western Atlantic and Caribbean waters. Modern bank/barrier reefs normally are only hundreds of meters from a land mass, not thousands of meters offshore as is the case for true barrier reefs, and bank/barrier reefs are much shorter in linear extent than barrier reef complexes. This guide provides a general overview of the reef and more detailed information for ten field stops in the reef area. The locations of these stops and the stratigraphic profiles appearing herein are shown on the geologic map of the reef complex (Fig. 1). This map was prepared with the help of Smith College geology students, and topography was mapped using plane table and alidade. Reference starter points for the topographic survey were bench marks 1 and 2, which were originally tied directly to accurately measured mean sea level (Adams, 1980).

Recently 16 radiometric dates have been obtained from coral samples from the Cockburn Town reef. These  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  dates were determined by J.H. Chen and G.J. Wasserburg at the California Institute of Technology using newly developed mass spectrometric techniques for the measurement of  $^{230}\text{Th}$  abundance (Edwards et al., 1987). Typical errors for dates from this method are  $\pm 1.5$  ky, permitting detailed chronologic study of the reef with time resolution sufficient to define stages of reef development. These stages and an overall discussion of the significance of the 16 dates have been given by Curran et al. (1988, 1989). The oldest coral dated from the reef is an *Acropora palmata* specimen at  $130.75 \pm 1.5$  ky from the oceanward end of Profile C-C' (Fig. 4). The youngest coral date is  $119.2 \pm 1.5$  ky from a *Diploria strigosa* specimen between Profiles D and E. Thus we know that this reef arose and flourished during the Sangamon interglacial at the time of oxygen isotope substage 5e. The span of coral age dates indicates a minimum longevity for the reef of 12,000 years.

The main part of the Cockburn Town reef, the fossil reef crest zone, consists of coralstone composed of near *in situ* *Acropora palmata* and subordinate *A. cervicornis*. This part of the fossil reef bears close resemblance to the modern Gaulins Reef located off of the northern coast of San Salvador. The shallowing-upward sequence and diagenetic history of the reef complex and their

significance with respect to reef development and sea level change were described and discussed by White et al., (1984). Earlier, more extended versions of this field guide have been published by Curran and White (1984, 1985).

## Location and Field Trip Procedure

The Cockburn Town fossil coral reef is exposed along coastal outcrops and in a small quarry located a short distance northwest of the center of Cockburn Town. Reefal rocks extend in a northwesterly direction from the old town dock for a distance of about 650 m, terminating near an abandoned cable trench cut into the Pleistocene shallow subtidal and beach calcarenites that flank and overtop the reef at its northern end.

This excursion will start from the parking area adjacent to the new town dock. The shallowing-upward sequence of calcarenites overlying reefal rocks is well exposed in the roadcut on the east side of the road leading to the dock and launch area (Stop 1). The main part of the reef can best be reached by walking WNW from the parking area through the woods to the coast in the vicinity of *Ophiomorpha* Bay (Stop 2, see map). The reefal facies are particularly well exposed in the quarry area a short distance beyond Stop 2.

Sturdy shoes with thick rubber soles are recommended for hiking over the reefal rocks; some exposures have rough surfaces with many sharp edges, particularly in the heavily bioeroded zone near the water. Wet, algae-covered surfaces in the intertidal zone are very slippery, so caution is advised. The quarry area of the reef can be hot and glary on sunny days; hats and sun glasses are recommended.

Because this fossil reef is an attraction of considerable geologic and biologic importance, every reasonable effort should be made to preserve it for future visitation and study. Accordingly, we ask that no rock hammers be used to collect samples from the reef exposures. Fossil corals and mollusks can be collected from rubble in the quarry area, but specimens should not be removed from outcrop. Your cooperation in preserving the reef will be appreciated by future visitors.

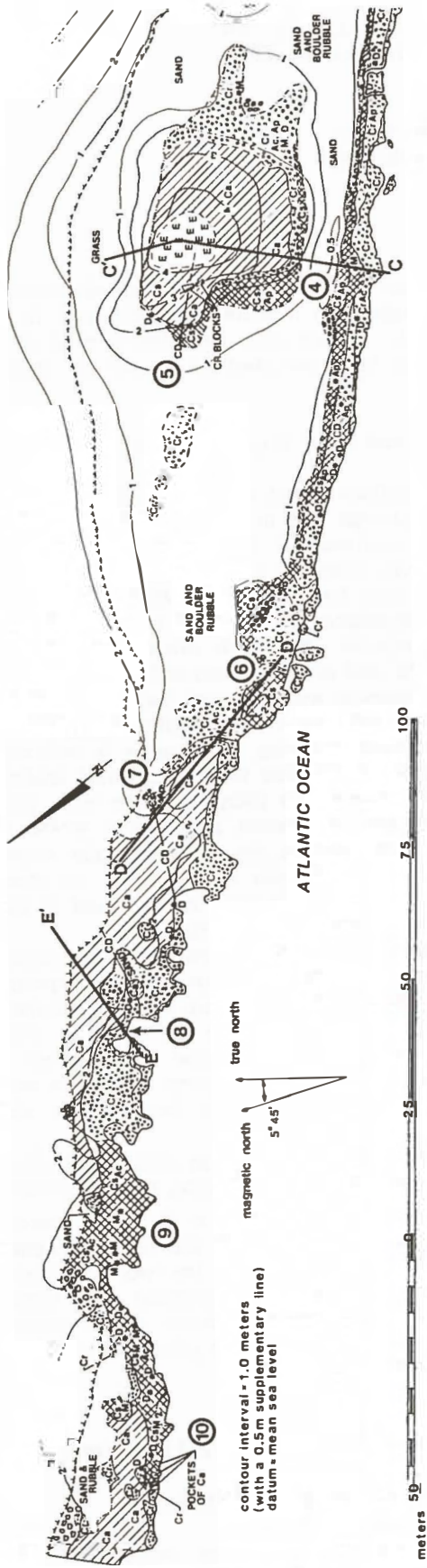
## DESCRIPTIONS OF THE FIELD STOPS

### Stop 1. Shallowing-upward Sequence

This exposure demonstrates clearly the shallowing-upward nature of the reef complex and associated facies as described by White et al., (1984). Near the water's

TOPOGRAPHY AND GEOLOGY — COCKBURN TOWN PLEISTOCENE REEF — SAN SALVADOR, BAHAMAS

LEFT SIDE OF MAP



SMITH COLLEGE CARBONATES RESEARCH GROUP, JUNE 1983 AND 1984

RIGHT SIDE OF MAP

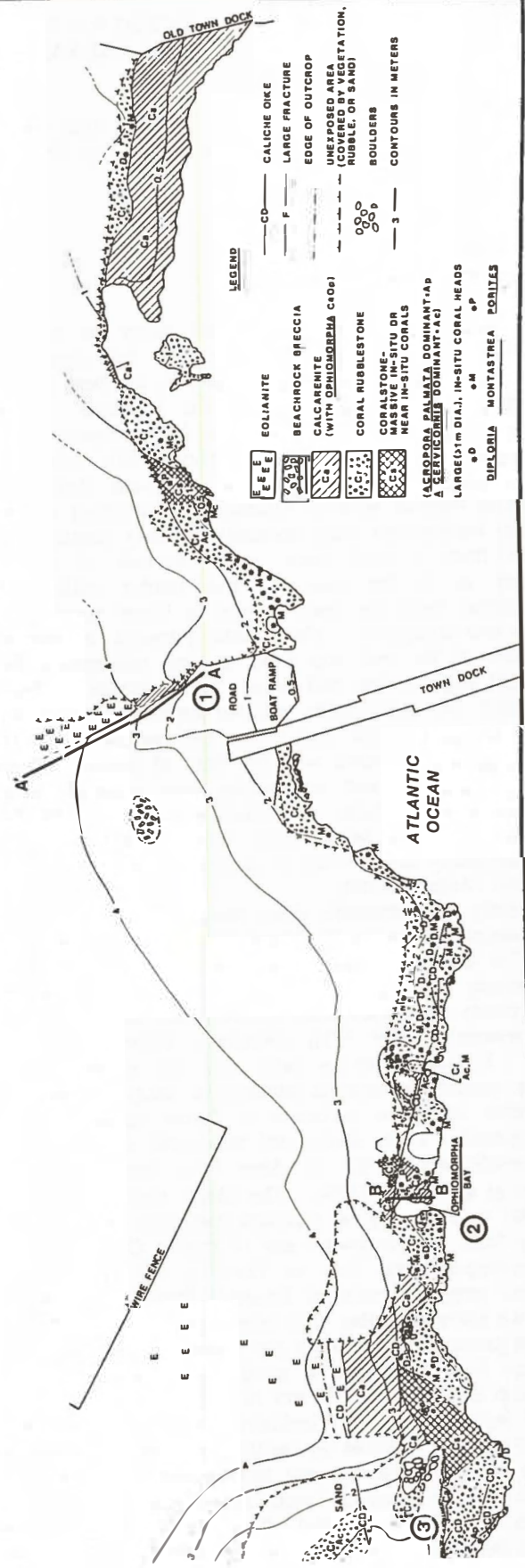


FIGURE 1 Geologic map of the Cockburn Town fossil reef complex, showing locations of the stratigraphic profiles and field trip stops (numbered areas).



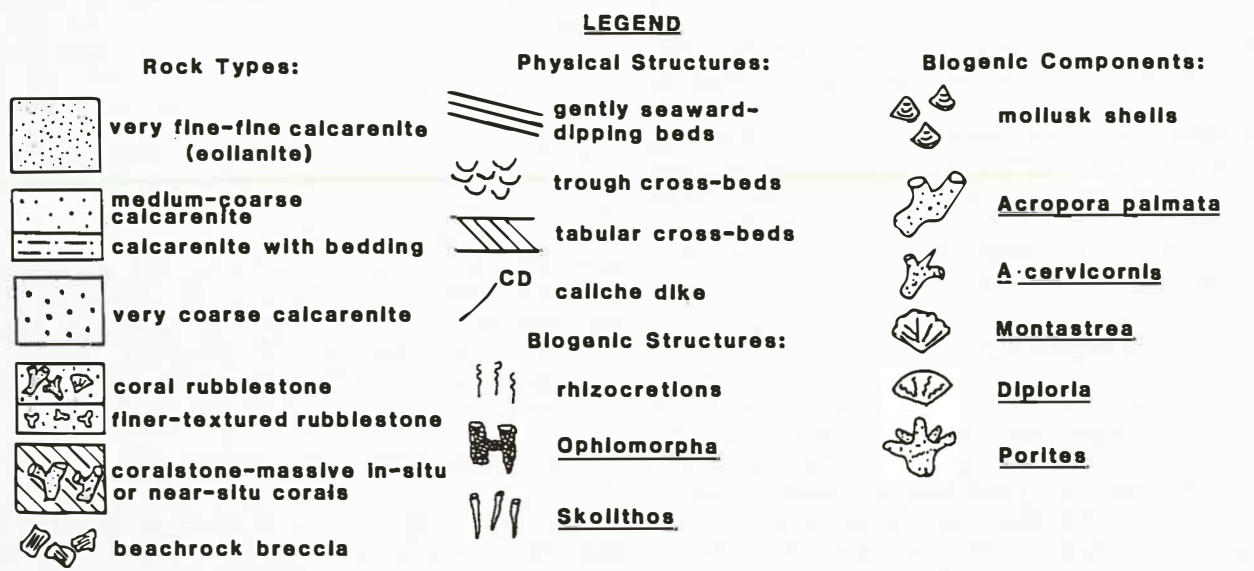
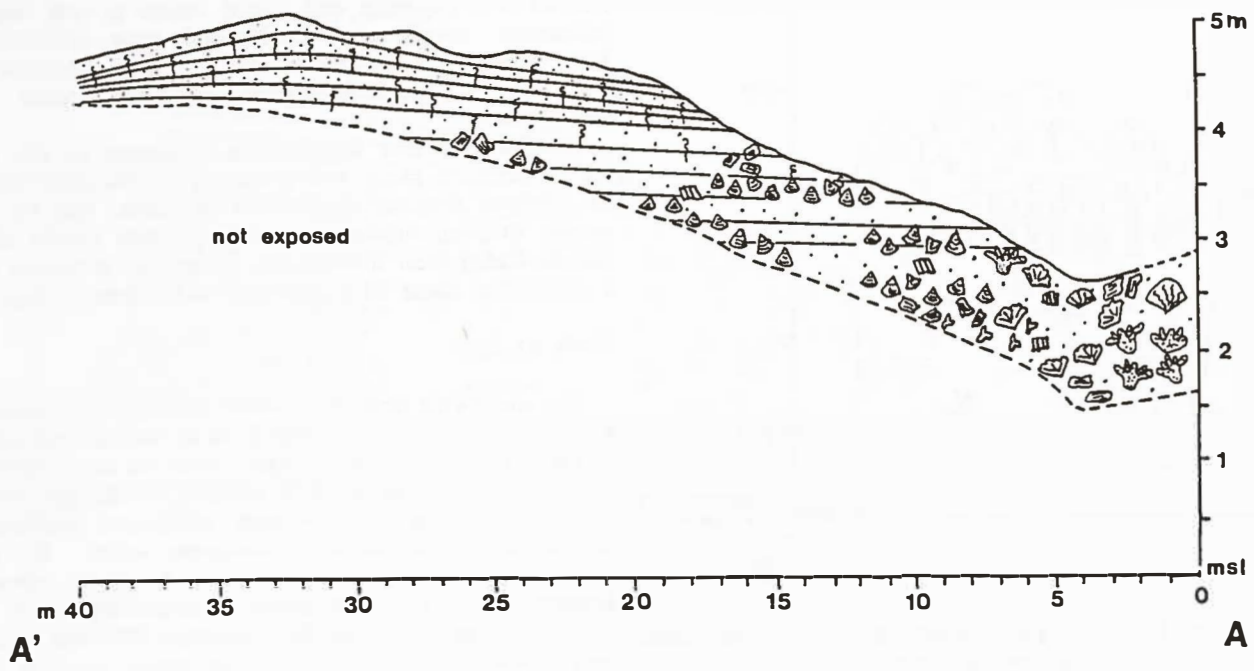


FIGURE 2 Stratigraphic profile A-A'; exposure along road leading to Cockburn Town dock and launch area. Lower part of the figure presents the legend of symbols used in the stratigraphic profiles.

edge, several large coral heads (*Diploria strigosa*, *Montastrea annularis*, and *Porites asteroides*) are preserved in near growth position in a matrix of shelly, coarse to very coarse calcarenite (Fig. 2, Profile A-A', 0-8 m).

Moving along the outcrop, coral rubblestone gives way to shelly, medium to coarse calcarenite. The most prominent shells are single valves and valve fragments of the bivalve *Chione cancellata*. Gently seaward-dipping bedding begins to become apparent here, and there is some weakly developed trough cross bedding. A few clasts of beachrock breccia also are present.

Farther up along the outcrop, the calcarenite becomes progressively finer-grained and less shelly. The last shell fragments occur at about the 23 m mark on Profile A-A'. The uppermost part of the outcrop is composed of fine to very fine calcarenite beds (=eolianite), which contain some rhizomorphs.

The facies present here represent three distinct environments of a regressive sequence: a shallow subtidal environment with corals such as *Diploria*, *Montastrea*, and *Porites*, all characteristic of patch reefs; a very nearshore to beach environment with gently seaward-dipping beds and beachrock breccia clasts; and a

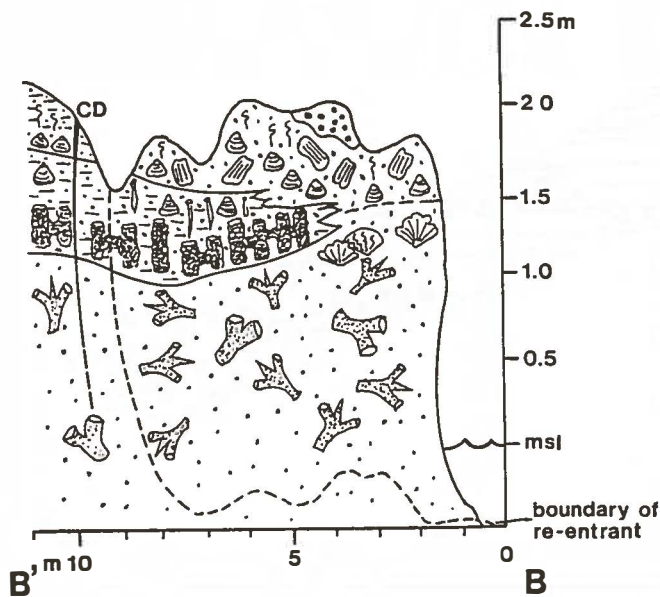


FIGURE 3 Stratigraphic profile B-B'; exposure along southeast wall of *Ophiomorpha* Bay.

coastal dune environment with fine to very fine calcarenites containing rhizomorphs.

The area of coastal exposure to the southeast of the new town dock is rugged and not easily traversed by groups, but it does display good outcrops of coral rubblestone with many prominent heads of *Montastrea annularis* and *Diploria strigosa*. Less common are heads of *M. cavernosa*, *D. labyrinthiformis*, and *Porites asteroides*. In the vicinity of the old town dock, the coral rubblestone is overlain by ancient beachrock beds that terminate the reefal exposure.

### Stop 2. *Ophiomorpha* Bay

A small, wave-cut re-entrant is located about 100 m northwest along the coast from the new town dock. The stratigraphic profile here is shown in Figure 3. This is one of the best trace fossil localities found to date on San Salvador. Coral rubblestone dominated by fragments of *Acropora cervicornis* forms the lower and middle part of the re-entrant exposure. These beds are overlain by and interfinger with shelly, coarse calcarenites containing the trace fossils *Ophiomorpha* sp. and *Skolithos linearis*. These trace fossils have been described and their paleoenvironmental significance discussed by Curran (1983, 1984). Tunnels and shafts of *Ophiomorpha* sp. are particularly abundant and well developed here. The interfingering of the coral rubblestone and *Ophiomorpha*-bearing calcarenites indicates the contemporaneous subtidal nature of the coral reef and the surrounding environment of current-bedded carbonate sands. Burrowing of the subtidal sands by callianassid shrimp produced the *Ophiomorpha* sp. burrows, the dwelling tubes of the shrimp.

The *Ophiomorpha*-bearing calcarenites are overlain by a shelly, coarse to very coarse calcarenite that contains clasts of beachrock breccia and some rhizomorphs.

Patches of a generally well sorted, coarse to very coarse calcarenite overlie the beachrock-bearing calcarenite. Both units suggest a near beach to beach environment; thus, the shallowing-upward sequence again is demonstrated.

The outcrop area immediately southwest of the re-entrant contains many well-preserved *in situ* coral heads of *Diploria strigosa*, *Montastrea annularis*, and *Porites porites* in coral rubblestone. A prominent caliche dike can be traced from immediately behind the re-entrant for a distance of about 60 m southeast to the water's edge.

### Walk-by Stop

The shallowing-upward sequence again is well exposed about 35 m northwest of Stop 2 on an unvegetated slope upwards from the water's edge. Here an amphitheater-like, wave-cut re-entrant, with boulders in and just above the intertidal zone, exposes coral rubblestone containing several large *Diploria* and *Montastrea* heads. On the northwestern side of the exposure, *Acropora palmata* appears for the first time as an important constituent of the rubblestone, a change that continues into the quarry area. Shelly, medium to coarse calcarenite overlies the coral rubblestone. As seen earlier at Stop 1, the calcarenites show a fining-upward trend to eolianite toward the top of the hill slope.

### Stop 3. More *Ophiomorpha*

A pocket of shelly, coarse to very coarse calcarenite with coral clasts and several *Ophiomorpha* sp. shafts and tunnels is exposed on an interior face of the quarry, about 13 m beyond its south entrance. The calcarenite is surrounded by *Acropora cervicornis* and *A. palmata*-dominated rubblestone. Some of the calcarenite may have been deposited as void fill in the rubblestone, but at least the upper part of the calcarenite appears to interfinger with the rubblestone, again indicating the contemporaneous deposition of the two facies.

### Stop 4. Profile C-C'

Particularly good exposures of coralstone dominated by large, near *in situ* chunks of *Acropora palmata* are found here along the first 20 to 25 m of Profile C-C' (Fig. 4). Coralstone makes up the major part of the rock forming the oceanside quarry wall and parallels the N50°W strike of the wall, a trend that may well reflect the life orientation of the *A. palmata* crest of the Cockburn Town reef. A large, bifurcating caliche dike is prominently exposed on the top of the wall, and several large heads of *Diploria* also occur here.

Move across the quarry floor to the front (oceanward) face of the prominent knoll located within the quarry area. This knoll largely has been created by quarrying operations on all sides. The front face (15-20 m on Profile C-C') reveals a zone of *Acropora palmata*-dominated coralstone overlain by coarse, *A. cervicornis*-dominated rubblestone. Beds of shelly, coarse to very coarse calcarenite overlie the rubblestone on this front face of the knoll.



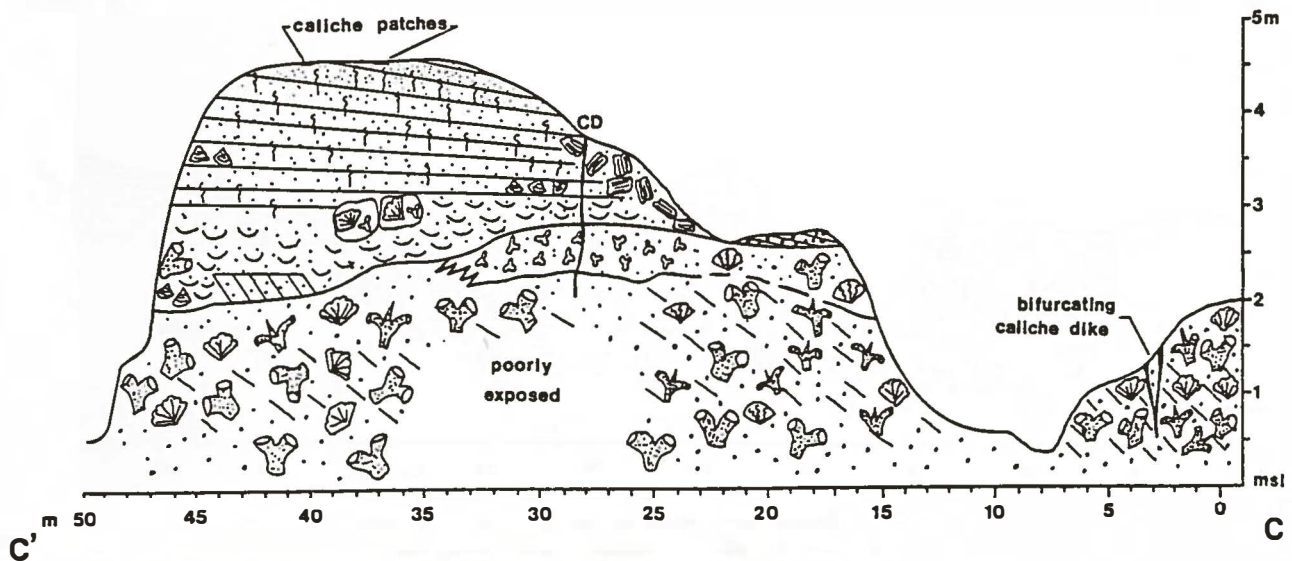


FIGURE 4 Stratigraphic profile C-C' in the quarry area; exposure from the water's edge along the northwest face of the knoll.

### Stop 5. The Knoll

The full range of facies occurring in the Cockburn Town fossil reef complex can be seen in this exposure on the flank of the knoll (Profile C-C', 20-50 m). *Acropora palmata*-dominated coralstone forms the lower part of the exposure, and the overlying rubblestone can be traced along the side of the knoll to about the 30 m point on Profile C-C'; in this area, the rubblestone has a distinctly finer texture.

Shelly, medium to coarse, tabular and trough cross bedded calcarenites overlie the coralstone and coral rubblestone and are well exposed on the sides of the knoll, particularly between 25-50 m along Profile C-C' and to the rear of the knoll (northeast side). The most prominent set of tabular cross beds dips in a westerly direction, essentially perpendicular to the flow direction of currents that produced the surrounding trough cross beds. Our interpretation is that the tabular cross beds were deposited by a storm event, possibly a hurricane. The trough cross beds were deposited by northerly flowing, longshore currents possibly created by wave refraction around the south end of ancient San Salvador Island (White et al., 1984). Two blocks of coral rubblestone, probably deposited by storm waves, are prominent in the exposure and are completely surrounded by the trough cross bedded calcarenites.

The upper part of the section consists of gently westerly dipping, shelly, medium-grained calcarenites with beachrock breccia clasts. These beds grade upward into eolianites. Facies contacts, patterns of bedding, and other physical sedimentary structures are particularly well displayed on the steep rear (northeast) face of the knoll.

### Stop 6. *Acropora palmata* Reef Crest

Move toward the northwest end of the quarry, at water's edge along Profile D-D' (Fig. 5, 0-17 m).

Exposed here is a large mass of coralstone on a base of *Acropora palmata*-dominated coral rubblestone similar to that found elsewhere in the quarry. The exceptional aspect here is the coralstone which is formed of large trunk sections of *A. palmata*. Although the coral heads are collapsed, they are essentially *in situ* and represent the palisades of *A. palmata* typical of a reef crest zone. This reef crest zone appears to extend at least for the full length of the oceanside quarry exposure (about 200 m).

The top of the *Acropora palmata*-dominated coralstone mass is at an elevation of just over +2 m. Assuming a growth height of 3 to 4 m for living, fully mature *A. palmata* heads and assuming that the tips of the fronds rose to mean low sea level, this suggests a minimum sea level of +5 to +6 m above present at the time of coral growth. This time now is known, because two specimens of *A. palmata* have been dated from this area of the reef, and they yielded ages of  $122.5 \pm 1.5$  ky and  $121.2 \pm 1.4$  ky (Curran et al., 1989).

The interstices of the *Acropora palmata* coralstone mass are filled with poorly lithified, shelly, coarse to very coarse calcarenite. Here molluscan fossils can be well preserved; the fauna is dominated by ark shells of the species *Arca imbricata*, *Barbatia cancellaria*, and *B. domingensis*. These bivalves today are common inhabitants in and around living coral heads.

### Stop 7. Channel Exposure

The exposure along the north end of Profile D-D' (Fig. 5, 20-55 m) reveals *Acropora palmata*-dominated coralstone continuing to overlie coral rubblestone. The new feature of interest here is a well developed channel cut into the rubblestone and filled with calcarenite. Fill at the base of the channel consists of shelly, coarse to very coarse calcarenite. Upwards in the channel, trough cross bedding is obvious and the calcarenite texture becomes finer.



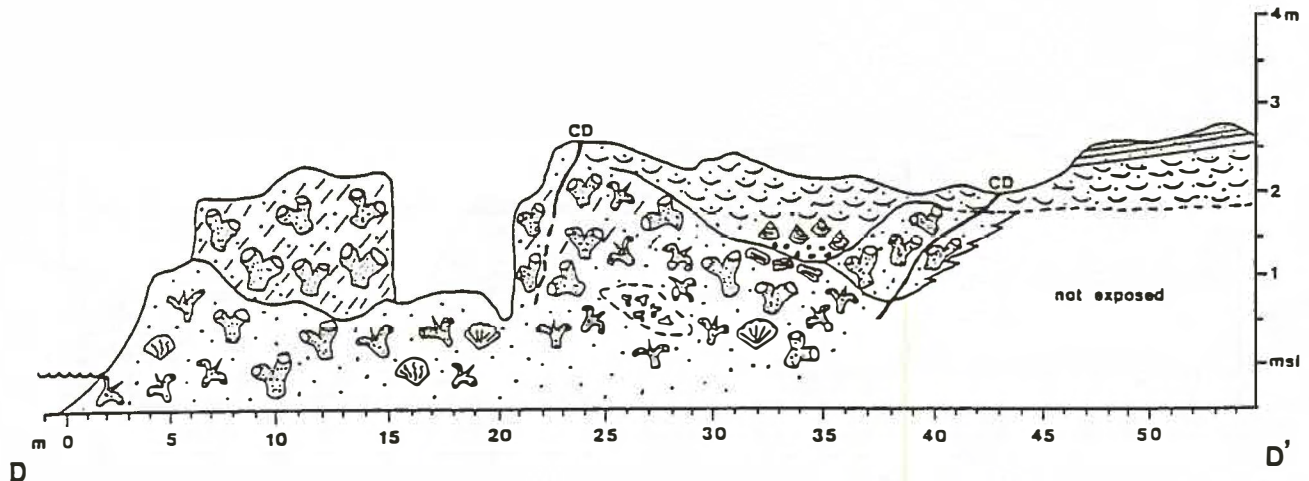


FIGURE 5 Stratigraphic profile D-D', northwest end of quarry area; exposure includes the main part of the zone of *Acropora palmata* in near growth position.

The north side of the channel is bounded by *Acropora palmata*-dominated coralstone which has a different character from that seen previously. Here the coralstone consists primarily of tightly lithified fronds of *A. palmata*; coral trunk pieces are much less abundant than elsewhere. Again, we interpret the rock as representing coral head fronds that collapsed, were compacted, and then were lithified essentially *in situ*. Several large boulders of this type of *A. palmata*-dominated coralstone can be seen in this area on the floor of the quarry.

#### Stop 8. Profile E-E'

The exposures of Profile E-E' (Fig. 6) are located about 50 m beyond the northwest end of the quarry. The oceanward half of the profile consists of coral rubblestone exposures dominated by *Acropora cervicornis*. Fragments of *Diploria* and *Montastrea* are common, and the importance of *A. palmata* has decreased markedly from its dominant levels in the rock of the quarry area.

The principal features of interest along this profile are the overlying calcarenite beds and their sedimentary structures (Profile E-E', 25-45 m). Particularly prominent is a set of steeply dipping tabular cross beds up to 1 m thick in places. These tabular cross beds dip in a westerly direction as do the similar beds described earlier at Stop 5 (Profile C-C'), and we interpret them as representing deposition by the same large-scale storm event.

The overlying trough cross bedded calcarenites were deposited by northerly flowing, perhaps longshore, currents (White et al., 1984). Overlying the trough cross bedded calcarenites are westerly dipping calcarenites with low angle cross beds and beachrock clasts. These beds progressively overstep the trough cross bedded, subtidal calcarenites and represent the deposits of a westerly facing and westward migrating beach formed during sea regression (White et al., 1984).

#### Stop 9. *Acropora cervicornis* Thicket

Move to an area of coralstone and coral rubblestone about 40 m northwest of Stop 8 (Profile E-E'). Here medium to coarse calcarenite is packed in and around exposures of coralstone and coral rubblestone; the calcarenites clearly overlie the coralstone on the landward side of the outcrop area.

The main point of interest here is the nature of the coralstone. It is dominated by *Acropora cervicornis* in what we think is essentially growth position; also present are several large heads of *Montastrea annularis*, smaller heads of *Diploria*, and clumps of the finger coral *Porites furcata*, all in growth position. This marks the first common occurrence of *P. furcata* in growth position seen in the reef complex. Although *A. cervicornis* is widespread in the coral-bearing rocks of the reef complex, it usually occurs fragmented and in rubblestone. We interpret the coralstone of this area of the reef as representing an *A. cervicornis* thicket with its associated coral species. Thus we see here another aspect of the Cockburn Town reef complex.

#### Stop 10. Northwest End of the Cockburn Town Reef

Exposures in the northwestern-most area of the reef are located about 20-70 m beyond Stop 9 across a small stone bridge. This is an area of coralstone and coral rubblestone exposure, and, once again, the coralstone is composed largely of *Acropora cervicornis*. Several large heads of *Montastrea annularis* and *Diploria* are prominently exposed in growth position. Calcarenite is packed in and around the coral heads, and calcarenite beds overlying the reefal rocks are well exposed on the landward side of the outcrop area.

The reef proper ends very abruptly. The final visible exposures of coral rubblestone are virtually surrounded by calcarenites. Looking northwestward along the coast

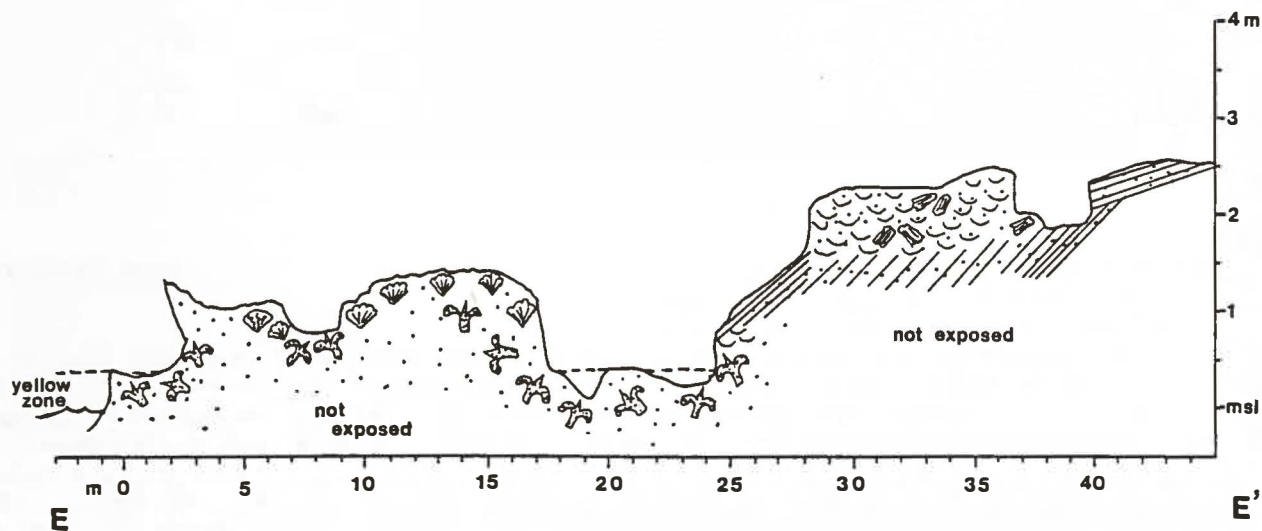


FIGURE 6 Stratigraphic profile E-E', northwest of the quarry area.

from the last coral rubblestone exposures, one sees only gently seaward dipping calcarenites. The texture and bedding of these calcarenites is well exposed in vertical section in the cable trench immediately beyond the last rubblestone outcrop. This trench marks the northwestern boundary of the geologic map and the study area.

#### Acknowledgments

We are grateful to the Bahamian Field Station and its staff on San Salvador Island for full logistical support during our field studies of the fossil reef. Smith College geology majors, including Kim Besom, Veronica Blette, Elizabeth Dole, Kate Japy, Karen Kurkijy, Laine Landau, Jean Lawlor, Patricia Pierce, and Kim Pirie, made a significant contribution to this study through field mapping conducted in June 1983 and 1984. Financial support for our studies came from several sources, including grants to Smith College from the Shell Foundation and the Merck, Olin, and Pew Foundations. Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research through separate grants to both Curran and White. We extend our thanks to all of these foundations for their generous support.

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# HOLOCENE SALINITY HISTORY OF THE SALINE LAKES OF SAN SALVADOR ISLAND, BAHAMAS

James W. Teeter  
Department of Geology, University of Akron, Akron, Ohio

## INTRODUCTION

The most conspicuous physiographic features on San Salvador are its numerous lakes. Several, such as Storr's Lake and Fresh Lake, lie on the perimeter of the island and, during part of their Holocene history, have been tidally influenced lagoons much as Pigeon Creek is today. Most lakes, however, lie inland and have probably been isolated from direct marine influence during the Holocene.

For working conditions, the lakes certainly do not have the appeal of the island's open marine shelf with its diverse and abundant biota. However, the lakes offer the possibility of a more complete stratigraphic record by virtue of their internal drainage and low rates of sedimentation. During at least one lower stand of Holocene sea level, some lakes appear to have persisted, becoming brackish or fresh. On the other hand, the depositional record of the open shelf has been interrupted by storms, currents and fluctuating sea level.

## PRESENT LAKE CONDITIONS

All lakes reside in Pleistocene carbonate bedrock-floored basins containing a veneer of Holocene sediments. Maximum water depths are typically less than 2 m. Saline water from the surrounding ocean infiltrates the porous carbonate bedrock, flooding the lake basins. Some lakes experience tidal flood and ebb through conduit systems that interconnect with the ocean. Volumes of flow are sufficiently low, however, so that only small sinkhole lakes (e.g. Watling's Blue Hole and Fortune Hill Pond), register observable tidal effects. Larger lakes have small or apparently lack conduit feeders, and their levels are controlled more by local climate than slow infiltration through the bedrock. Such lakes (e.g. Granny Lake) experience declining levels during prolonged dry conditions and rising levels during a succession of wet years. As a result, lake levels vary about sea level through time.

Each lake exhibits a typical salinity range over a period of years. The few small sinkholes that lie at or slightly above sea level and in which the conduit system is plugged (e.g. Line Hole Sink) contain fresh water in amounts proportional to rainfall. Other small sinkholes with active conduits (e.g. Watling's Blue Hole and Fortune Hill Pond) exhibit salinities ranging from brackish to approximately normal marine. Small lakes with active conduits (e.g. Reckley Hill Pond, Little Lake, and Six Pack Pond) vary from normal marine to

approximately 65‰ during a period of several years. Larger lakes lacking any obvious conduit feeders (e.g. Storr's Lake, Granny Lake, and Great Lake) display salinities ranging from approximately 55‰ to 85‰. Some small shallow coastal ponds (salinas) exhibit exceptionally high readings. For example, salinities recorded at French Pond and Salt Pond in January, 1985, were 186‰ and 283‰ respectively.

Thus the average salinity of a lake's waters is a direct reflection of its size, elevation with respect to sea level, rainfall and the degree of interchange with the open ocean. Small lakes having good exchange exhibit salinities close to normal marine. Larger lakes, whether they have conduit systems or not, experience relatively less interchange and more evaporation, producing higher salinities. Evaporation in small, isolated ponds also causes hypersalinity. Small sinkholes fed by active conduits may reveal brackish salinities if they tap fresh ground water beneath adjacent hills, as appears to occur at Watling's Blue Hole and Fortune Hill Pond.

Precipitation tends to be seasonal, most coming during the tropical storm season of July through December. However, this pattern can vary considerably. Salinity fluctuation from year to year is strongly controlled by precipitation (Fig. 1).

## LAKE BIOTA

### Phytoplankton

Marshall (1982) studied the phytoplankton from Little Lake and Great Lake, San Salvador Island. Among the taxa of blue green algae he listed are several genera known to exhibit increased red pigment at higher salinity. Turbidity and color of the water varies considerably between lakes. The most turbid, red to brown colored lakes are typically the most saline.

### Mollusca

The molluscan lake fauna is dominated by the gastropods *Batillaria minima* and *Cerithidea costata* and the pelecypods *Anomalocardia auberiana* and *Polymesoda maritima*. The latter two species have been found live on San Salvador at salinities ranging from 26‰ to about 65‰. Recent observations suggest that the adult size of these pelecypods varies inversely with salinity. Shell hash beaches composed primarily of these mollusc species are common on the windward shores of the larger lakes.

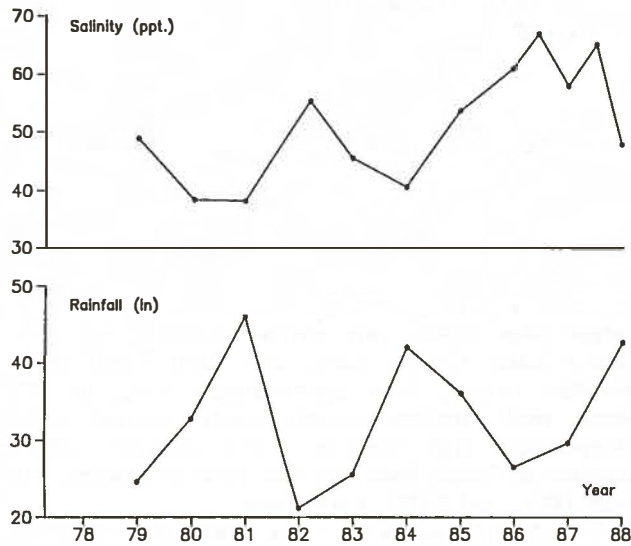


FIGURE 1 Salinity of Little Lake and yearly rainfall total on San Salvador for the years 1979 to 1987.

### Microfauna

The microfauna of San Salvador lakes consists primarily of foraminiferans and ostracodes. The foraminiferans of Little Lake have been studied by Bowman and Teeter (1983), who found that two species, *Quinqueloculina boschiana* and *Q. costata* predominate, usually comprising 70% to 90% of the living and Holocene populations. The abundance of the two species is inversely related, with *Q. costata* predominating at shallower depths on coarser substrates. This depth distribution pattern may be a response to light dependence.

Ostracodes have proven especially useful in interpreting Holocene salinity changes within the lakes of San Salvador (Sanger and Teeter, 1982; Luginbill, 1983; Crotty and Teeter 1984; Corwin, 1985; Zaleha, 1987; Teeter et al., 1987; Teeter, in press). Three distinct assemblages of ostracode species (Fig. 2), characteristic of different salinities, can be recognized within Holocene deposits. Fresh water species (Fig. 2a-c) occur rarely. Ostracode species characteristic of normal marine salinities are more frequently encountered. Three of the more common representatives are shown in Fig. 2d-f. The lacustrine assemblage (Fig. 2g-j) predominates. Of the four species in the lacustrine assemblage only *Perissocytheridea bicelliforma* is restricted to brackish water (typically 10-20‰). *Hemicyprideis setipunctata* exhibits a salinity range of approximately 10-60‰ and has a peak abundance at about 30-40‰. This species also lives on the open shelf. *Cyprideis americana* survives over a salinity range of approximately 10-98‰ but is least abundant from 30-40‰. The salinity range of *Dolerocypria inopinata* is approximately 10-76‰.

Because of the infrequent occurrence of the fresh water and marine assemblages, and the broad salinity

tolerances of most species of the more frequently encountered lacustrine assemblage, it is sometimes difficult to interpret paleosalinity within Holocene lake deposits. An alternative method of paleosalinity interpretation is the use of minor element shell chemistry. Teeter (1988) has demonstrated an inverse relationship between Mg concentration and salinity in the shells of live specimens of the broadly salinity tolerant ostracode, *Cyprideis americana*.

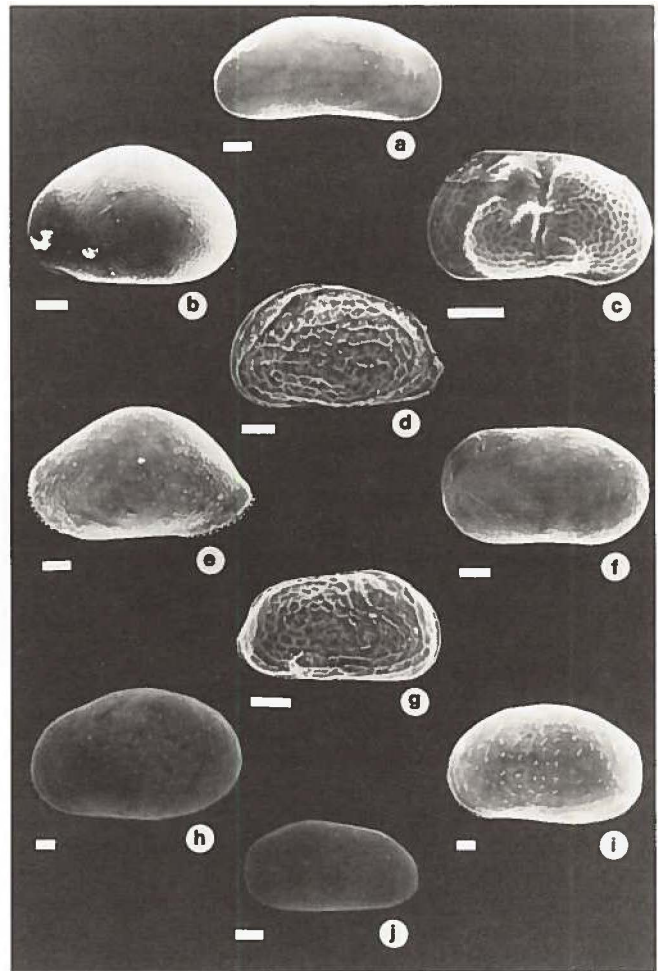


FIGURE 2 Holocene lake ostracode species. Fresh water: a. *Candona annae* Mehes, male, right valve. b. *Cypridopsis vidua* (Muller), left valve. c. *Limnocythere floridensis* Keyser, female, left valve. Marine: d. *Aurila floridana* Benson and Coleman, male, left valve. e. *Bairdia harpago* Kornicker, female, left valve. f. *Cytherella arostrata* Kornicker, male, left valve. Lacustrine (brackish to hypersaline): g. *Perissocytheridea bicelliforma* Swain, female, right valve. h. *Hemicyprideis septipunctata* (Brady), female, left valve. i. *Cyprideis americana* (Sharpe), female, left valve. j. *Dolerocypria inopinata* Klie, male, left valve. Bar scale equals 0.10 mm.



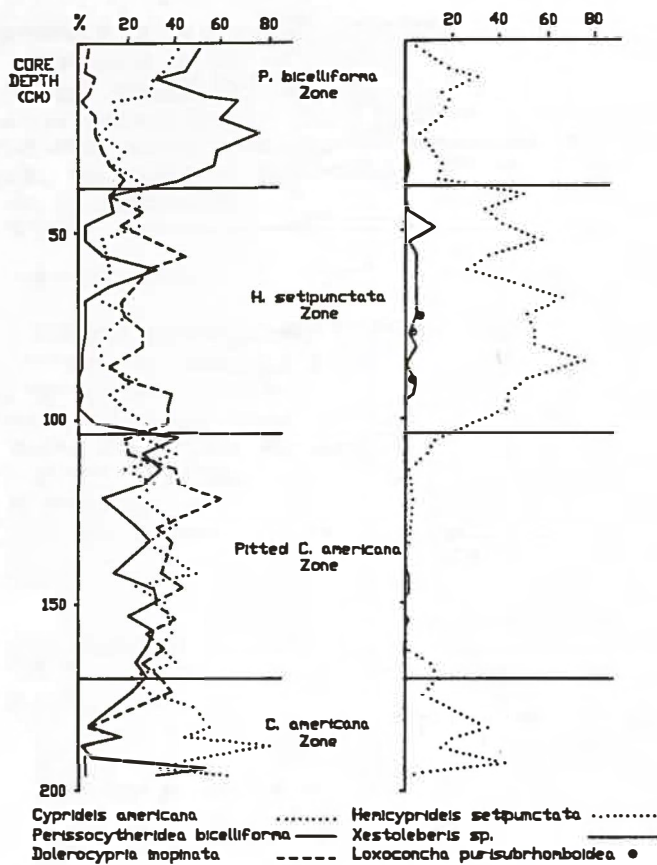


FIGURE 3 Distribution and abundance of ostracodes in the Holocene sediments of Watling's Blue Hole.

## HOLOCENE PALEOSALINITY FLUCTUATION

Piston cores taken through unconsolidated Holocene lake sediments to Pleistocene bedrock provide numerous ostracodes whose varying abundance can be used to interpret the paleosalinity history of the inland lakes. Watling's Blue Hole (Crotty and Teeter, 1984) is a good example (Fig. 3). Here varying ostracode species abundances can be used to subdivide the Holocene into four distinct zones, from oldest to youngest as follows: *Cyprideis americana* Zone; Pitted *Cyprideis americana* Zone; *Henicyprideis setipunctata* Zone; *Perissocytheridea bicelliforma* Zone. Paleosalinity interpretation of these zones is provided in Fig. 4a.

Other inland lakes, for example Little Lake (Sanger and Teeter, 1982), and Six-Pack Pond (Zaleha, 1987) also reveal a similar succession of four zones representing salinity fluctuation paralleling that of Watling's Blue Hole. Preliminary work using alloisoleucine/isoleucine ratios in *Polymesoda maritima* and *Cerithidea costata* reveals the contemporaneity of the boundaries between the youngest three zones in Watling's Blue Hole and Little Lake.

Figure 4b represents paleosalinity using Mg concentrations in shells of *Cyprideis americana* from the Holocene of Watling's Blue Hole. This represents a spline curve drawn through the means of 15 analyses at each of 23 horizons. This curve is probably a more

realistic representation of paleosalinity changes than that estimated from ostracode assemblages in Fig. 4a. At first glance the two curves do not seem particularly comparable. However, if the paleosalinities calculated from Mg concentrations are averaged for the horizons within each zone, these averages fall within 2 to 3‰ of those estimated by Crotty and Teeter (1984) from ostracode assemblages (Teeter, in press).

Interestingly, salinity minima, using Mg concentrations, occur at each of the zone boundaries previously established by ostracode assemblages. The youngest two salinity minima correlate with marked minima, using the same method, in Salt Pond (Teeter et al., 1987). The earliest salinity minimum in Watling's Blue Hole correlates with a fresh water ostracode assemblage at the boundary separating the oldest two zones in Little Lake (Sanger and Teeter, 1982).

Lowered salinity can be caused by climate change or by falling sea level. Climatically, increased rainfall or decreased temperature, causing less evaporation, will produce lower salinity. If sea level falls so does the amount of sea water infiltrating the lake basin. Thus precipitation and fresh ground water seepage will lower salinity. Should sea level fall below the floor of the lake basin and if the lake floor is impermeable, a fresh water lake would result.

Accelerator mass spectrometry carbon 14-dates for the zone boundaries are also recorded in Fig. 4. These dates are based on lake molluscs and are corrected for the influence of "dead" carbon entering the system from limestone bedrock. DePratter and Howard (1981) recorded a stand of sea level at least 3 to 4 m below present along the coast of Georgia and adjacent South Carolina between 2,400 and 3,000 years before present. Their interpretation was based on dredged archeological remains and tree stumps. Martin et al. (1986) record a low stand of sea level at 2,700 years before present in the Salvador region of coastal Brazil based on submerged shell middens. Thus the oldest salinity minimum (2,680±80 RCYBP) in Watling's Blue Hole appears to represent a low stand of sea level. This horizon lies 3.2 m below average water level (approximately mean sea level) in tidally-influenced Watling's Blue Hole and is characterized by a brackish water assemblage. Thus this horizon must have been at or below sea level at that time. The correlative horizon in Little Lake lies at 2.7 m below present lake level (approximately mean sea level), is marked by a fresh water assemblage, and thus must have stood above sea level. Thus at 2,700 RCYBP, sea level was 2.7 to 3.2 m lower than present on San Salvador. If the younger two salinity minima (1,900±80 and 1,360±90 RCYBP) represent lowered stands of sea level, their faunas and positions relative to lake level indicate that sea level was lowered by no more than 2.5 and 1.9 m respectively.

## DESCRIPTIONS OF THE FIELD STOPS

### Stop 1. Watling's Blue Hole

The yellow zone on the rock wall surrounding Watling's Blue Hole attests to tidal fluctuation. The



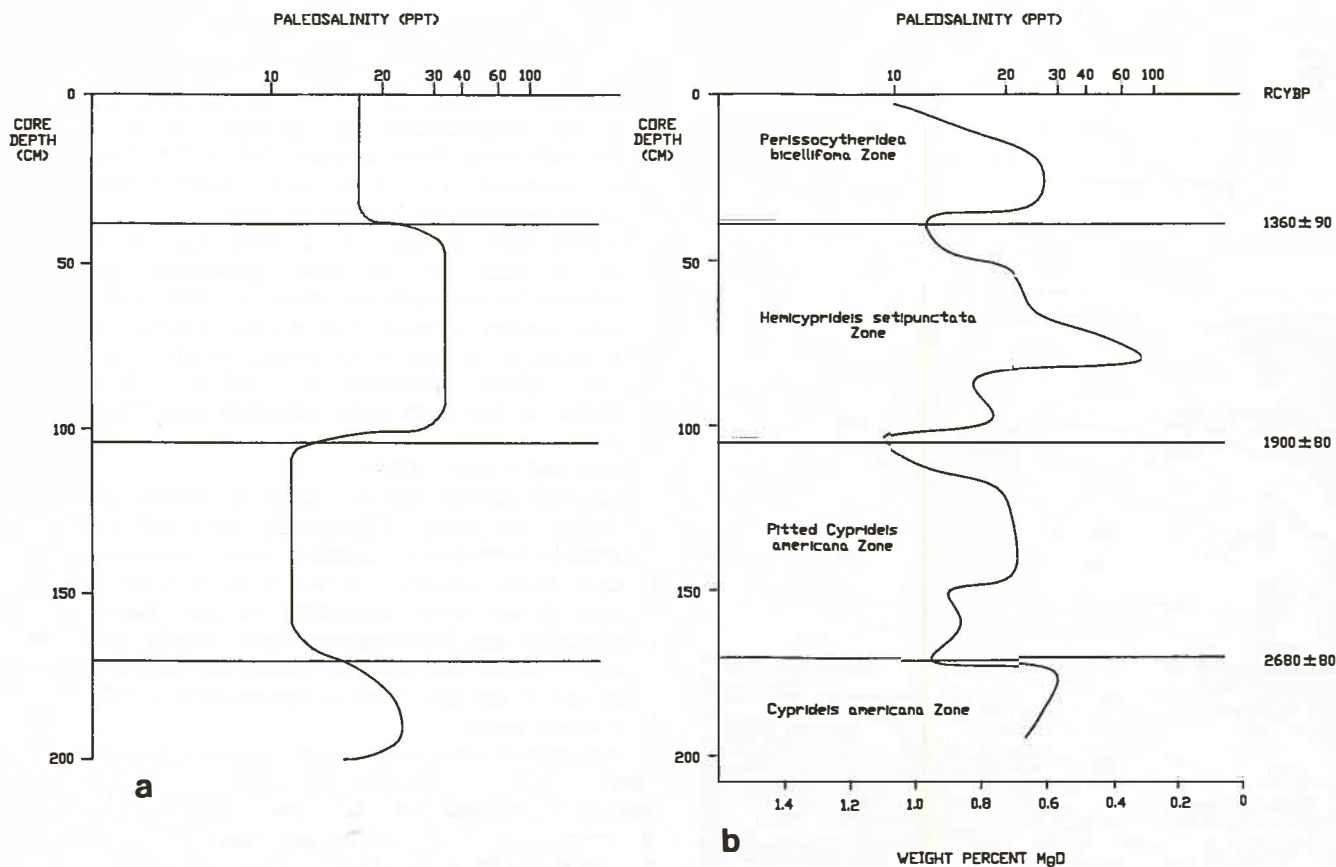


FIGURE 4 Paleosalinity interpretations for the Holocene section of Watling's Blue Hole. Horizontal lines at approximately 168, 104, and 38 cm represent boundaries between the four ostracode zones and are dated at  $2,680 \pm 80$ ,  $1,900 \pm 80$  and  $1,360 \pm 90$  RCYBP respectively. a. Curve based on ostracode assemblages (modified from Crotty and Teeter, 1984). b. Spline curve based on means of weight percent MgO in *Cyprideis americana*.

Pleistocene bedrock is steeply funnel-shaped and is exposed surrounding the conduit at a depth of 7 m. Elsewhere within the sinkhole, a cover of unconsolidated Holocene sediment mantles the bedrock. The sediment surface slopes gently inward around the edge to a depth of 1 to 2 m where it sharply steepens, descending to the conduit. The greatest thickness of probed sediment, between 2 to 3 m, underlies the area where the slope changes.

The most obvious faunal elements present are the gastropod *Batillaria minima* and the pelecypods *Anomalocardia auberiana* and *Polymesoda maritima*. The occurrence of these molluscs in bedrock blocks of the surrounding wall suggests the presence of another lake in this area during Pleistocene time. The relatively large size of the fossil pelecypods further suggests lowered salinity conditions.

## Stop 2. Storr's Lake

Storr's Lake is divided into northern and southern parts by a large Pleistocene dune at the Narrows. Although the water is too turbid to see it, sounding reveals the presence of an approximately 1 m deep channel adjacent and parallel to the western shore and

extending from the Narrows almost to the north end of the lake. The channel is floored by about 1 m of muddy sediment containing a few thin carbonate crusts. Extensive shallow flats flank the channel and are underlain by numerous hard carbonate crusts. Probing across the flats and channel reveals the presence of a bedrock channel beneath the present one.

South of the Narrows the channel opens into a broad depression with water depths of a meter or less. Another channel can be traced by sounding and probing eastward along the south side of the dune forming the Narrows. The bedrock channel extends eastward to a tidal inlet on Green's Bay. The tidal inlet has been filled by Holocene dune sand. Along the shoreline of Green's Bay, a steeply cut exposure of Pleistocene limestone marks the southern edge of the tidal inlet.

Ostracodes in the initial Holocene deposits of Storr's Lake indicate hypersaline conditions (Corwin, 1985). This, and the presence of the bedrock channel in northern Storr's Lake, suggests that some earlier bedrock barrier prevented free circulation between the ocean to the east and the Storr's Lake basin. Flooding of the basin was probably accomplished by slow seepage through the porous carbonate barrier. In other words, the bedrock flooring Storr's Lake may have formed in a tidally

influenced lagoon similar to present-day Pigeon Creek.

Subsequent to the early hypersaline phase, flooding occurred through the tidal inlet, developing primarily within southern Storr's Lake a small lens of sediment containing marine ostracodes. The existence of the tidal inlet was short-lived, and restricted conditions returned with its abandonment.

#### Acknowledgments

Grateful acknowledgment is extended to the following University of Akron students who, through their research projects, have provided information useful to the understanding and interpretation of the Holocene history of the lakes on San Salvador: Perry Honaker, Charles Luginbill, and Nancy Stoltz. Computer graphics were generated by Thomas Quick. Dick Mitterer of the University of Texas at Dallas kindly provided amino acid ratios.

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# ORIGIN OF BEACH ROCK AND ITS INFLUENCE ON BEACH PROCESSES, FRENCH BAY

Roger J. Bain  
Department of Geology, University of Akron, Akron, Ohio

## INTRODUCTION

French Bay is located at the south end of San Salvador (Index Map for San Salvador). Near Government Dock, one can observe a variety of features that form on a high energy carbonate shore. A barrier reef and patch reefs offshore act as a carbonate factory, producing skeletal material. The barrier reef is located at the seaward edge of the narrow and shallow shelf of San Salvador Island. This shelf provides an environment in which patch reefs add to the carbonate sediment volume and where high to moderate energy levels permit reworking of bioclastic material. Beaches on French Bay consist of coarse- to medium-grained, bioclastic sediment derived from reefs as well as from the skeletons and activities of other organisms, both plant and animal, living in the shelf environment. Dune deposits are reworked fine- to medium-grained material derived from the beach by eolian and storm transport. The tidal range at French Bay is approximately one meter.

Our reason for visiting French Bay is to observe exposures of beach rock west of Government Dock and to discuss characteristics of beach deposits, beach rock, exhumed beach rock, and processes responsible for beach rock origin. Beach rock forms by penecontemporaneous cementation of sediment. It has the same composition, sedimentary structures, and dip as overlying and/or adjacent uncemented beach sediment (Fig. 1a).

The general setting and process for the formation of beach rock first requires the existence of carbonate sand located on a beach between marine water and a coastal dune or beach ridge system. Meteoric water percolates through the dune or ridge sand, residing there for a period before migrating to the beach. During this residence period, some carbonate material is taken into solution, in response either to pH or to CO<sub>2</sub> content of the meteoric water. Where the carbonate-rich water moves through the beach, owing either to the mixing of meteoric and sea water (Moore, 1973) or to the loss of CO<sub>2</sub> (Hanor, 1978), carbonate cements are precipitated in the beach sand, converting it to beach rock. The cement is either aragonite or high-Mg calcite. Basal dune sands similarly can be cemented by the migrating water; however, dune sands are cemented by calcite.

## BEACH

Carbonate sand of the beach on French Bay is derived from an offshore carbonate factory that includes a barrier reef, patch reefs, and a shallow shelf inhabited by a rich marine fauna and flora. *Halimeda*, pelloids, molluscan

fragments, forams, and red algae dominate the sediment. Sand is deposited on the beach face in relatively uniform laminations. The cusped nature of the beach is reflected in shoreline exposures of beach rock (Fig. 1a). Tidal fluctuations of about one meter cause migration of the swash zone, and during low tide, escaping bubbles of air trapped during high tide produce small holes in the intertidal sand deposits. By digging into the intertidal sand, one can observe the porous texture of the sand. This texture is preserved through rapid cementation, such as in the formation of beach rock, and such texture has been termed fenestral porosity, bubble porosity, and/or keystone vugs. In general, it is considered to be an excellent intertidal indicator (Shinn, 1968).

By digging into the beach, one encounters, at varying depths, a transition from loose sand grains to loosely cemented sand to semi-consolidated beach rock. The beach rock cementation process previously described is presently cementing the sand beneath the French Bay beach. If one visits this area after several days of strong wind and erosion, this modern beach rock may be exposed (Fig. 1b). This normally buried, presently forming beach rock is not to be confused with the exhumed beach rock that parallels the shoreline (Fig. 1a). Similarly, at several locations west of the dock, basal dune sands can be observed in poorly lithified exposures.

## EXHUMED BEACH ROCK

Many geologists who have visited beaches like French Bay have attempted to understand and explain the origin of beach rock in terms of its exposed state. One must recognize that at French Bay or similar beaches where beach rock is exposed, the rock did not originate in that exposed, wave-washed setting. Such beach rock formed beneath the beach or beneath subtidal sediment, and it has been exposed as a result of erosional conditions of the beach. On a rapidly prograding beach, one will not see beach rock.

A closer examination of exhumed beach rock allows one to study the compositional and textural similarities between beach rock and contemporaneous beach sediment. It also allows recognition of dissimilarities, not only between exhumed beach rock and beach sand, but also between exhumed beach rock and beach rock that was never exhumed (Bain, 1989).

Early and rapid cementation of beach sediment to produce beach rock preserves the open porosity (Fig. 2a), laminations (Fig. 2b), and other features of the beach deposit; and, except for recognition of an early cement, the two may be difficult to distinguish in the sedimentary





FIGURE 1 a. French Bay looking west from Government Dock showing exhumed beach rock. b. An exposure of beach rock that normally is covered by beach sand. Note seaward dipping laminae. Scale = 30 cm.

rock record. However, if, as is the case at French Bay and Quarry A, erosion of the beach exposes the beach rock, features can develop which may have stratigraphic significance. The exposed beach rock provides a hard substrate in a normally sandy environment. Fauna and flora which live on hard substrates can be present, whereas they are absent in the loose sand beach environment and deposits. Examining the exhumed beach rock, one finds corals, vermetid gastropods, serpulid worms, limpets, encrusting red algae, gastropods, chitons, boring clams, boring barnacles, and other organisms living on and in the beach rock. In thin sections, one can recognize algal and fungal borings, as well as larger, normally infilled, borings of clams. These clam borings are readily visible on the exposed rock (Fig. 2b), and would be visible in older beach rock outcrops.

In the deposits of an ancient coastal setting, it might be difficult to distinguish beach rock from rocks formed in subtidal, backshore, or dunal environments because of the similarities in sediment type and texture. However, the presence of encrusting organisms such as corals, vermetid gastropods, and red algae, borings, and organisms such as limpets and chitons, which live on rocky surfaces, would indicate exposed beach rock. Also, as can be observed along the beach of French Bay, cemented blocks of beach rock commonly are dislodged,

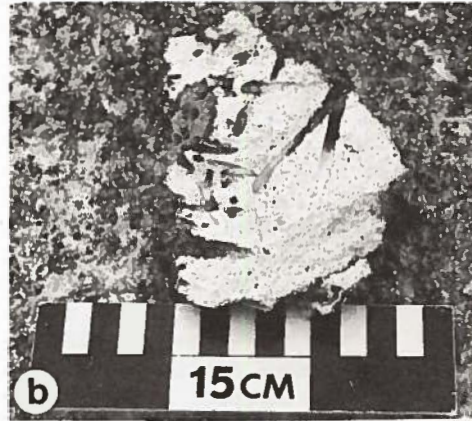
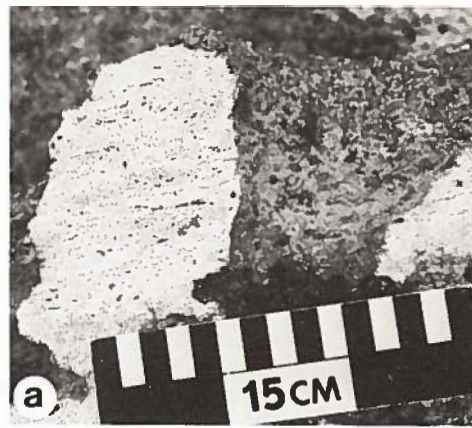


FIGURE 2 a. Freshly broken, exhumed beach rock showing fenestral porosity, laminae, and a bored and encrusted surface. b. Freshly broken surface of exhumed beach rock showing clam borings.

deposited, and incorporated into beach sand. The laminae of these chaotic blocks will not be aligned with beach laminations and thus the beach rock should be recognizable. Such chaotic blocks of beach rock are observable at the west end of French Bay (Conch Point) and at Grotto Bay. It is important to recognize these deposits as penecontemporaneous and not to misinterpret them as representing an unconformity.

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# PIGEON CREEK LAGOON, A MODERN ANALOGUE OF THE PLEISTOCENE GRANNY LAKE BASIN

James W. Teeter

Department of Geology, University of Akron, Akron, Ohio

## INTRODUCTION

Pigeon Creek lagoon (Fig. 1) lies in the southeastern section of San Salvador Island. The major part of the lagoon extends north-south approximately 6 km and has a maximum width of 1.5 km. Pigeon Creek is bounded on the west by Pleistocene carbonate bedrock and on the east primarily by loosely consolidated carbonates. At its southern end, a tidal inlet maintains the connection between the lagoon and the open marine carbonate platform.

The Granny Lake basin (Fig. 1) lies to the north of Pigeon Creek. The basin is floored by Pleistocene carbonate bedrock. Granny Lake occupies a depression, maximum depth 4.3 m, at the northern end of the basin. The Granny Lake channel extends generally southward from the lake almost to the north end of Pigeon Creek. South of Granny Lake, bordering the channel, the basin is broad and relatively flat. The basin is bounded on the west by arcuate ridges and on the east by an irregular ridge.

## PIGEON CREEK LAGOON

### Bathymetry, Biota, and Substrate

A prominent tidal channel, approximately 1 to 3 m deep, extending north from the entrance of Pigeon Creek, can be seen in Figure 1. This channel runs for approximately 4.5 km and terminates at a large basin, maximum depth 2 m, at the north end of Pigeon Creek. Tidal fluctuation here (15 to 20 cm) is about one fifth that at the entrance to Pigeon Creek. As a result of the sluggish exchange of water, salinities at the north end of Pigeon Creek are greater than normal marine.

Shallow subtidal flats border the tidal channel. These flats support a lush growth of the marine grass *Thalassia*, between which grow the calcareous green algae *Halimeda*, *Penicillus*, and *Udotea*. Molluscs abound within the subtidal channel.

Locally (e.g. southeastern side of Pigeon Creek), tidal flats are developed and support dense stands of red mangrove. Tidal and subtidal flat sediments are finer and more poorly sorted than those of the tidal channel.

A prominent ebb tidal delta extends seaward from the entrance of Pigeon Creek. Water depth across the delta is approximately 1 to 2 m, and maximum tidal fluctuation is approximately 1 m. The sediment of the tidal delta is a well winnowed carbonate sand. The barren upper surface of the delta is covered by current ripples which migrate and change direction with the ebb

and flow of the tide.

The seaward edge of the delta is marked by a gentle descent to a *Thalassia* meadow over which the delta appears to have advanced. In places, the delta presently appears to be at a developmental stillstand. Elsewhere, the edge of the delta is presently experiencing erosion. Stillstand is indicated by the local encroachment of the *Thalassia* meadow up the toe of the delta. Undercutting of the shallow edge of the encroaching *Thalassia* grass and exposure of vertical and horizontal callianassid shrimp burrows on the seaward edge of the delta indicate erosion.

Seaward of the delta edge, the flat bottom is densely covered by *Thalassia*. Here the fauna and flora are much more diverse and abundant, and the sediments are more poorly sorted than on the tidal delta.

The offshore islands, especially High Cay, represent erosional bedrock remnants of formerly more extensive eolian ridges. The Pleistocene bedrock ridge to the west of the Pigeon Creek entrance anchors a series of Holocene beach ridges lying to the south and southwest.

## Holocene History

Along its eastern side Pigeon Creek is isolated from the open marine shelf by dune-beach ridges. These ridges appear to have been formed by longshore transport and are anchored to rocky headlands (eg. The Bluff) which represent former offshore cays, the erosional remnants of earlier eolianite ridges.

Two cores, 3.62 and 3.75 m long, taken to Pleistocene bedrock, in submerged, sediment-filled sinkholes revealed the Holocene history of Pigeon Creek (Nutt, 1985). In both cores, the ostracode fauna indicated initial open shelf conditions, followed by subsequent, more restricted environments. Thus, the development of Pigeon Creek during the Holocene was marked by the progressive growth of, and restriction by, dune-beach ridges to the east. It is possible that future growth of the dune-beach ridges may link cays (eg. High Cay) to the south, extending Pigeon Creek and shifting the position of the tidal inlet.

## GRANNY LAKE BASIN

### Topography, Lithology, and Depositional Environment

The Granny Lake basin represents a Pleistocene, tidally-influenced lagoon comparable to Pigeon Creek today (Thalman, 1983; Thalman and Teeter, 1983a,b; Teeter and Thalman, 1984). Granny Lake channel represents a tidal channel extending from a deeper basin,



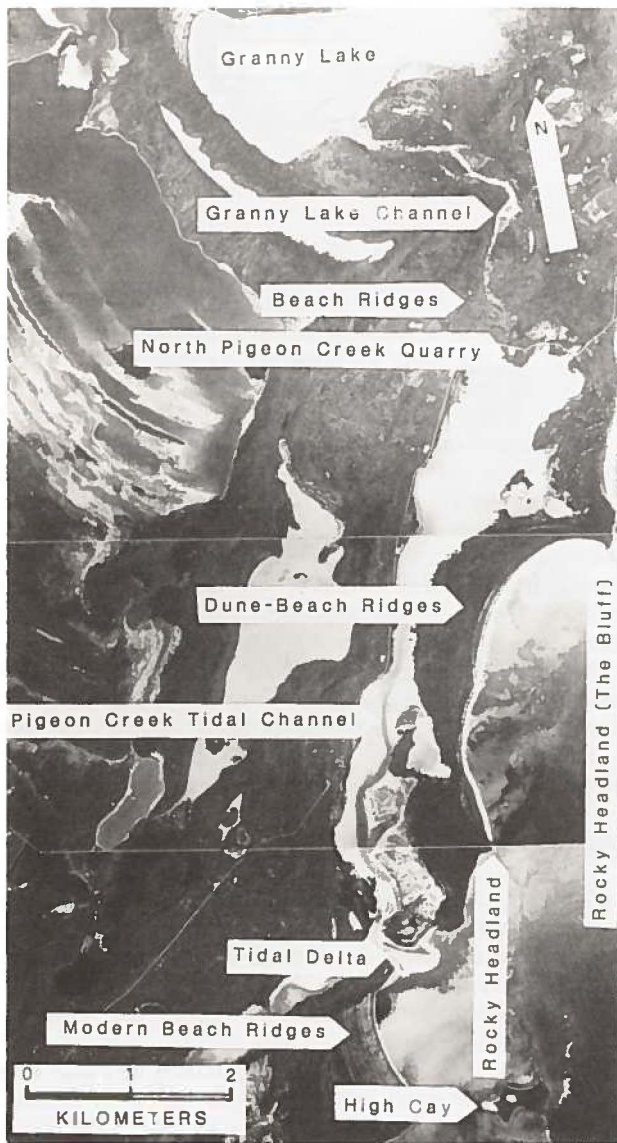


FIGURE 1 Index map to the Pigeon Creek-Granny Lake area (from Thalman, 1983).

now occupied by Granny lake, southward almost to North Pigeon Creek Quarry. Bedrock in the vicinity of the channel is oomicrite, having ooid contents of 30 to 65%. Micrite abundance and fossil size and abundance appear to increase away from the channel. The flat areas bordering the channel represent subtidal and perhaps intertidal flats. The arcuate ridges to the west of the flats and the irregular ridge to the east consist of oosparite. Both ridges are extensively cross bedded and represent dune deposits. The flanking dunes restricted and preceded the development of the Granny Lake basin. Flanking the channel at the south end of the Granny Lake basin lies a series of low, gently arcuate beach ridges. The beach ridges are thinly bedded and consist of oosparite and biosparudite.

Near the southern end of the Granny Lake channel, the north shore of Pigeon Creek exhibits a pronounced bulge, comparable in size and outline to the present ebb tidal delta at the mouth of Pigeon Creek. Here a fortuitously situated quarry, the North Pigeon Creek Quarry, exposes a classic tidal delta sequence. The floor of the quarry reveals a micritized subaerial crust. As noted by James Carew and John Mylroie (personal communication), this unconformity appears to rise to the west.

The north wall of the quarry rises approximately 3 m above sea level and exposes the following sequence from bottom to top. Resting on the subaerial crust is a massive biomicrudite in which molluscs predominate. The middle unit is an avalanche cross bedded oosparite. The upper unit is a massive oosparite in which the micrite content increases upward. The middle unit exhibits specimens of the ichnogenera *Ophiomorpha*, the fossilized burrows of callianassid shrimp, and *Skolithos*, interpreted as fossilized polychaete burrows (Curran, 1983, 1984).

Environmentally, the lowest unit represents a prodelta *Thalassia* meadow over which the middle unit, a cross bedded delta sequence, prograded. The upper unit was probably a *Thalassia* bed such as exists today on subtidal flats inside the entrance to Pigeon Creek.

Flanking this Pleistocene delta at present sea level are scattered fossil patch reefs. Initially these were thought to be contemporaneous with delta deposition, much like the modern rocky bottom community developed along shore to the west of the entrance to Pigeon Creek. However, recent rock coring through the crust in the quarry floor and in the rocks flanking the delta at sea

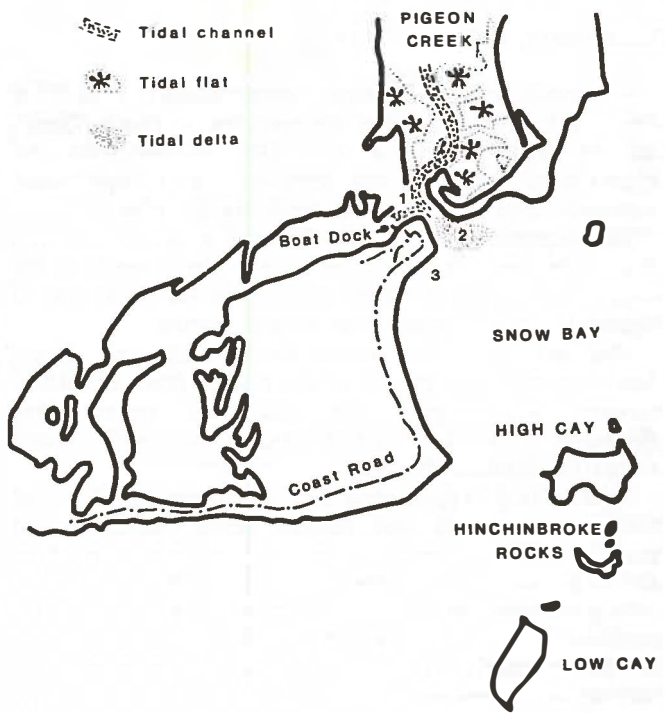


FIGURE 2 The Pigeon Creek tidal delta area.





FIGURE 3 Major units exposed in the stratigraphic section of the North Pigeon Creek Quarry (from Thalman, 1983).

level has revealed compositionally and texturally similar biopelmicrites. Thus, the patch reefs and associated sediments appear to precede the development of the delta.

Elevation of the sequence exposed in the quarry is approximately 3 m above sea level. Based on present conditions at the Pigeon Creek delta, this suggests sea level at 4 to 5 m above present. When this higher sea level occurred is, at present, unknown, but possibilities include the Sangamonian (approx. 125,000 years ago) or the Wisconsinan (approx. 70,000 or 49,000 to 37,000 years ago) (Carew et al., 1984).

## DESCRIPTIONS OF THE FIELD STOPS

### STOP 1. Pigeon Creek Tidal Delta

We will enter the water at the dock just inside the mouth of Pigeon Creek, near Ocean House, and drift with the ebbing tide through the entrance to Pigeon Creek and out onto the tidal delta. Wade and/or swim to the seaward edge of the delta, and then swim west along the shore to our awaiting field vehicles. Along the way we will traverse the following environments (Fig. 2).

1. Tidal channel and adjacent subtidal flats. Immediately downstream from the dock is a deep (3 to 4 m), steep-sided tidal channel. A thin veneer of coarse molluscan shell hash floors the channel. Locally, in shallower parts of the channel, thick lenses of *Halimeda* plates migrate with the tides. Adjacent shallow subtidal flats are densely covered by *Thalassia* and *Halimeda*. The *Halimeda*-rich sediments trapped and bound by *Thalassia* can easily be observed in the steeply eroded walls of the tidal channel.

2. Tidal Delta. Well sorted calcareous sands on the surface of the delta exhibit current ripples which reverse orientation with the ebb and flow of the tide. Constant motion of the sediment prevents colonization by most

plants, although localized patches of *Cymodacea* are present. Along the edge of the delta, decreased sedimentation and quieter water depth have permitted encroachment by *Thalassia*. Locally, the delta front exhibits erosion.

3. Rock floored, shallow, subtidal and seaward *Thalassia* meadow environments. The west shore of Pigeon Creek entrance and the adjacent shore of Snow Bay reveal a rocky shore environment. For a short distance along Snow Bay, a rock bottom extends seaward a few tens of meters. This subtidal bedrock surface supports a variety of scleractinian corals, the most obvious of which is *Diploria*, thickets of the red calcareous alga *Goniolithon*, and sparse growths of calcareous green algae and *Thalassia*. Farther seaward a dense stand of *Thalassia* grows in poorly sorted carbonate sediments.

### STOP 2. North Pigeon Creek Quarry

The section exposed in the North Pigeon Creek Quarry (Fig. 3) rests unconformably on a subaerial micritized crust and consists of 3 units, a lower massive biomicrudite overlain by a cross bedded oosparite and an upper massive oosparite. The cross bedded unit represents a tidal delta sequence that prograded over a *Thalassia* meadow and was, in turn, buried by a later growth of sediment-binding *Thalassia*.

Ostracodes reflect changing conditions within the section (Thalman, 1983). The assemblage that occurs at the base of the lower massive unit reflects restricted conditions (brackish, or perhaps hypersaline) during initial flooding by rising sea level. Ostracodes in the rest of the lower massive unit suggest improved circulation, and in the cross bedded unit and base of the upper massive unit, indicate normal marine conditions with possibly some hypersaline influence. Although diversity decreases in the remainder of the upper massive unit, the ostracode

fauna indicates stable marine conditions.

#### Acknowledgments

Grateful acknowledgment is extended to the following University of Akron students who, through their research projects, have provided information useful to the understanding and interpretation of the Pigeon Creek and the Granny Lake basin deltas: Scott Murdoch, Doug Perisutti, Ray Robinson, and Eric Schmidley.

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