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## Guide to Bahamian Ichnology: Pleistocene, Holocene, and Modern Environments: A Field Trip Guide

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# Guide to Bahamian Ichnology: Pleistocene, Holocene, and Modern Environments

Edited by  
H. Allen Curran



Bahamian Field Station • San Salvador, Bahamas

**Guide to Bahamian Ichnology:  
Pleistocene, Holocene, and Modern Environments**

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San Salvador, Bahamas**

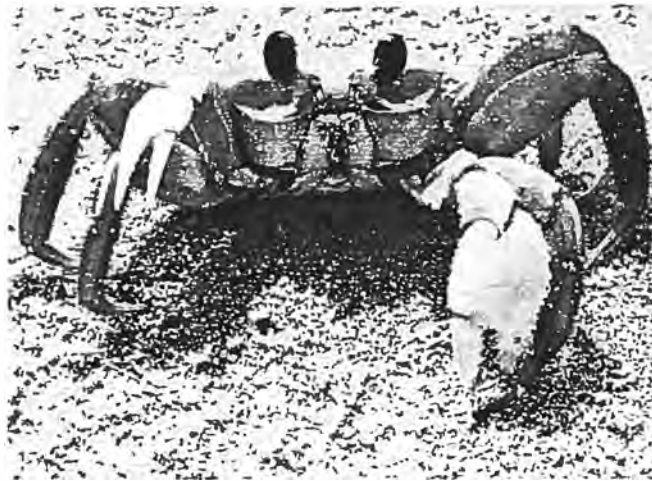
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Frontispiece: Holotype of *Psilonichnus upsilon* Frey, Curran, and Pemberton, 1984  
Hanna Bay Member of the Rice Bay Formation, San Salvador, Bahamas  
(length of shaft = 1.2 m)  
and  
The ghost crab *Ocypode quadrata* - maker of *P. upsilon* burrows in Bahamian beach backshore  
environments

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## Preface

This guide was prepared for the Fourth International Ichnofabric Workshop (IIW-4) to be hosted by the Bahamian Field Station and held on San Salvador Island on March 15-22, 1997. About 35 scientists representing 15 countries are registered to attend the workshop.

The focus of discussion in the informal scientific sessions will be the uses of ichnofabric analysis in sedimentary geology. An **ichnofabric** is the texture or internal structure created within a sedimentary substrate from the bioturbating activity of organisms. Ichnofabric analysis is a new and emerging area of ichnology (the study of trace fossils), and its methods are proving useful in enhancing sedimentary facies recognition and interpretations, event correlation, paleoenvironmental and paleoecological reconstructions, reservoir prediction, and more.

Ichnologists are field oriented, and San Salvador Island, with its diverse and largely pristine modern tropical, carbonate environments and well exposed Pleistocene and Holocene rock record, provides provides a fantastic natural laboratory for the study of all aspects of carbonate geology. San Salvador also is a geologically and ichnologically well known island, so proven field localities are readily available. This doesn't mean that new ichnologic discoveries and interpretations won't be forthcoming - they certainly will be, and probably some will occur during the time of the IIW-4 workshop. My colleague Brian White and I have been working in the Bahamas for just over 15 years. We know a great deal about Bahamian geology, but with every field excursion we find something new, and I often think that we have just scratched the surface!

The centerpiece of this guide is the descriptions of six Ichno-localities on San Salvador Island that provide outstanding examples of modern traces or trace fossils and illustrate a variety of ichnologic principles. In addition, in composite form, the stops provide a good overview of the Pleistocene, Holocene, and modern geology and environments of San Salvador. All of the stops are readily accessible from the main roads on the island. The initial chapter provides a brief introduction to the geology of the Bahamas and San Salvador for first-time visitors. The three chapters at the end of the guide are thematic and designed to expand the ichnologic perspectives to include borer organisms, plant trace fossils, and ichnologic sites in the Bahamas beyond San Salvador. I hope this guide will be useful to a broad spectrum of visitors to the Bahamian Field Station for several years to come, as well as to ichnologists unable to attend this workshop but with an interest in carbonates.

## Acknowledgments

There are many people to thank for their valued contributions to IIW-4 and the preparation of this guide. My most sincere thanks go to Dan and Nicole Suchy and the staff of the Bahamian Field Station for their full logistical support in the planning and conduct of the workshop. Don and Kathy Gerace have been tireless in their support of our research over many years, and we owe them a great debt of gratitude. I particularly thank my colleagues Brian White and Mark Wilson for their contributions to this guide and to the activities of IIW-4, for their companionship in the field on many expeditions, and for their ever-active intellectual stimulation. Lora Harris provided much help as IIW-4 student assistant. Smith students Heather Sawick, Gena Schwam, and Sarah Smalheer, and Kathy Bartus, Geology Department secretary, provided invaluable assistance with the layout for this guide. Finally, I thank my wife Jane for her good humor and support during the final preparation stages of this guide and for the workshop!

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

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## 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 typically 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 platform(s) 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 the Bahamas are thought to be tectonically stable with some isostatic subsidence, perhaps at the approximately 3 m/125,000 yr. rate determined for Andros Island by 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, 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 has been another topic of long-standing debate and disagreement. Again, two quite different concepts have been suggested. 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 Myerhoff 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 of the Bahamian platform and erosion by oceanic processes is thought to have produced the deep troughs that today penetrate and subdivide the banks. Austin and Schlager (1987) interpreted Ocean Drilling Project (ODP) Leg 101 data as supporting this "megabank" hypothesis.

However, from a detailed seismic study of the northwestern Great Bahama Bank, Eberli and Ginsberg (1987) proposed origin of this bank by coalescence of three smaller platforms with significant bank progradation. They argued against the "megabank" hypothesis and proposed that the present bank-basin configuration of the Bahamas 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 mechanisms of development of the Bahama Archipelago.

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 summary papers by Harris (1982), Hine (1983a,b), Mullins (1983), and Carew and Mylroie (1985, 1995). 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 significantly alleviated in recent years with publication of the Bahamian Field Station geology symposia series (Teeter, 1984; Curran, 1987; Mylroie, 1989; Bain, 1991; White, 1993, and Boardman, 1995) and the GSA Special Paper on Bahamas geology (Curran and White, 1995). We hope that the materials of this guide and our field excursion ichno-localities will demonstrate clearly that much can be learned from study of the many aspects of carbonates geology and Pleistocene and Holocene geologic history to be found in the sediments and rock record of San Salvador Island.

## **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. On some trips, 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 located along the flight route.

1. Waters of the narrow continental shelf (width about 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, about 92 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.



6. After passing close to or crossing Eleuthera, 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 the brown alga *Sargassum* commonly 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. The Club Med complex can be seen to port, and the village of Cockburn Town is to starboard, south of the runway.

## **GEOLOGIC SETTING OF SAN SALVADOR ISLAND**

San Salvador is a small island, about 11 km wide by 21 km long, and it is bordered by a narrow shelf with an abrupt shelf-edge break leading to a very steep slope (along the west side of the island, this slope is known as "The Wall"). The topography of the island is dominated by arcuate ridges interpreted as representing successive stages of carbonate eolian accretion. Shallow hypersaline 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 skeletal 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 has been a topic of considerable debate in recent years. This stratigraphy was carefully reviewed and revised by Carew and Mylroie (1985), and further revisions have been made by Hearty and Kindler (1993), and Carew and Mylroie (1995). The stratigraphic column of Carew and Mylroie (1995) is shown in Fig. 2a. This stratigraphic framework and its associated questions and problems will be addressed further in our lectures and field stops. Shallowing-upward sequences as shown in Fig. 2b are an important depositional theme in the development of Bahamian islands. Figure 3 presents a model for the Quaternary development of a Bahamian island as envisioned by Carew and Mylroie (1995).

The geologic map of San Salvador by Carew and Mylroie (1995) is given in Fig. 4, and the locations of the principal geographic features and field trip stops referred to in this guide are indicated on Fig. 5.

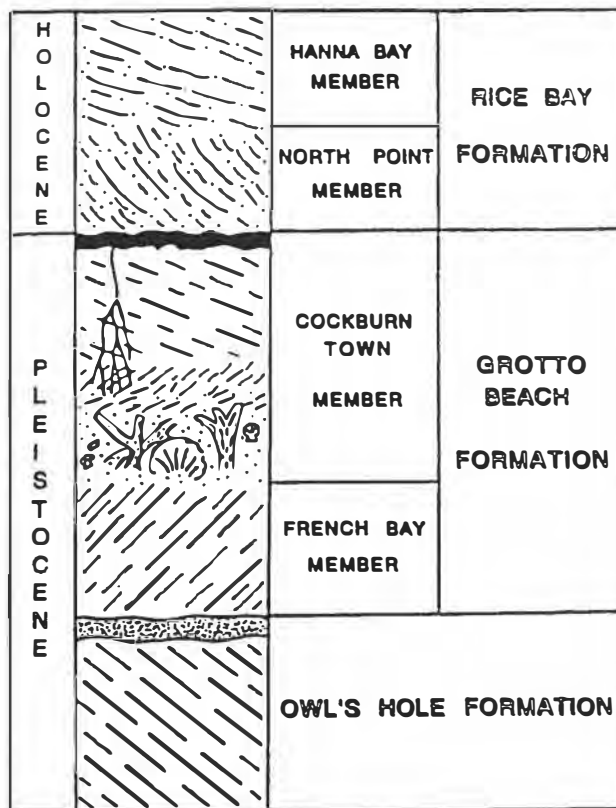


Figure 2a. Stratigraphic column for the Bahama Islands as determined by Carew and Mylroie (1995) and largely derived from stratigraphic relationships found on San Salvador Island. In the field, individual units are not necessarily stacked atop one another, but commonly crop out lateral to each other. The thin stippled and black layers represent terra-rossa paleosols that separate deposits formed during separate glacioeustatic sea-level highstands. (from Carew and Mylroie, 1995)

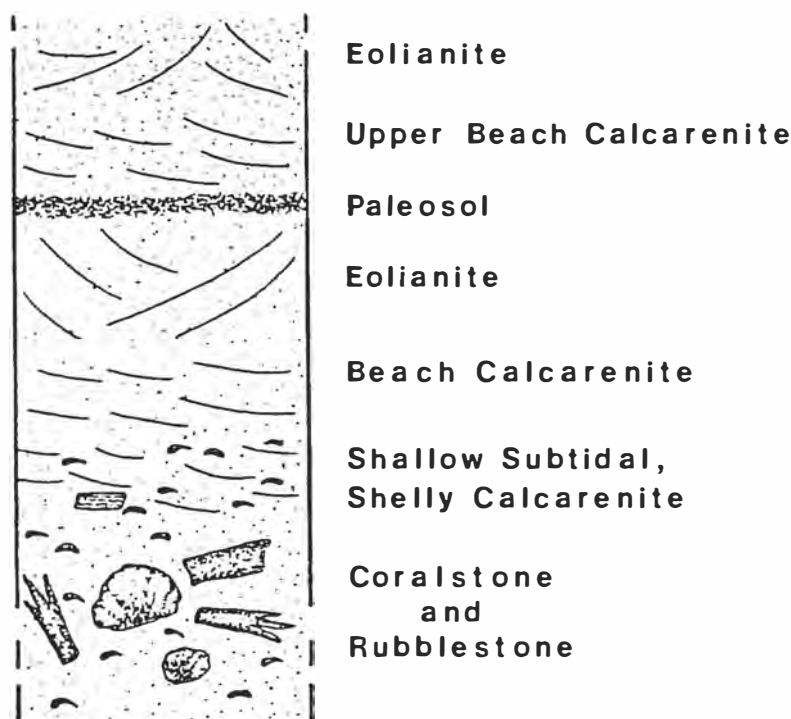


Figure 2b. Model shallowing-upward facies sequence for Bahamian carbonate rocks.

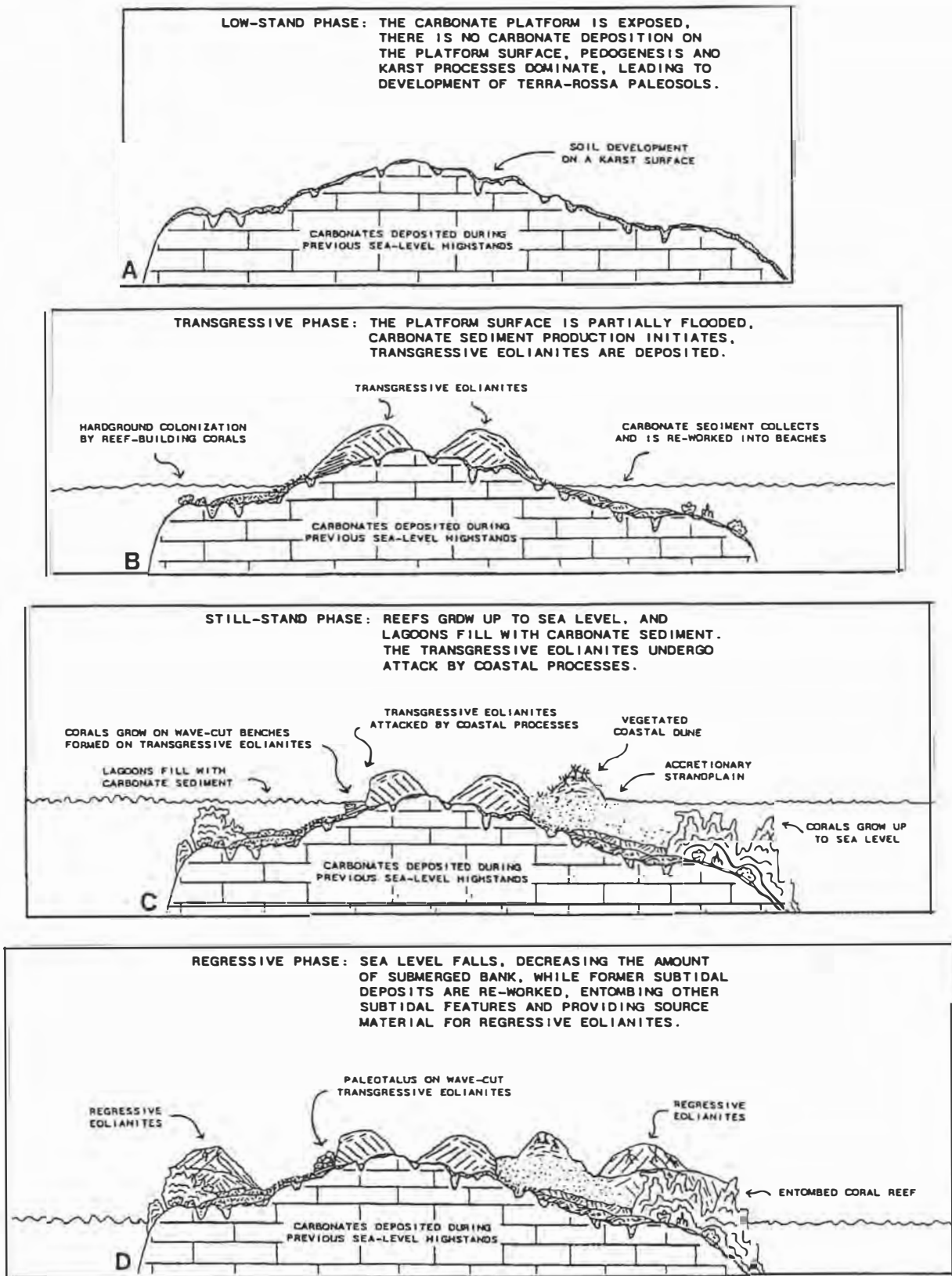


Figure 3. The four-stage depositional model of Carew and Mylroie (1995) for the development of Bahamian islands during each Pleistocene glacial/interglacial sea-level fluctuation. During highstands, islands are restricted to the highest parts of the steep-sided platforms; during lowstands (greater than -10 m), the entire surfaces of the platforms are islands. A. Low-stand phase; sea level > 10 m below present. B. Transgressive phase; sea level is above -10 m and the platform tops are progressively inundated. C. Still-stand phase; sea level hovers around its maximum (usually for about 10,000 to 15,000 yrs.). D. Regressive phase; sea level falls, eventually below the platform edge. (from Carew and Mylroie, 1995)

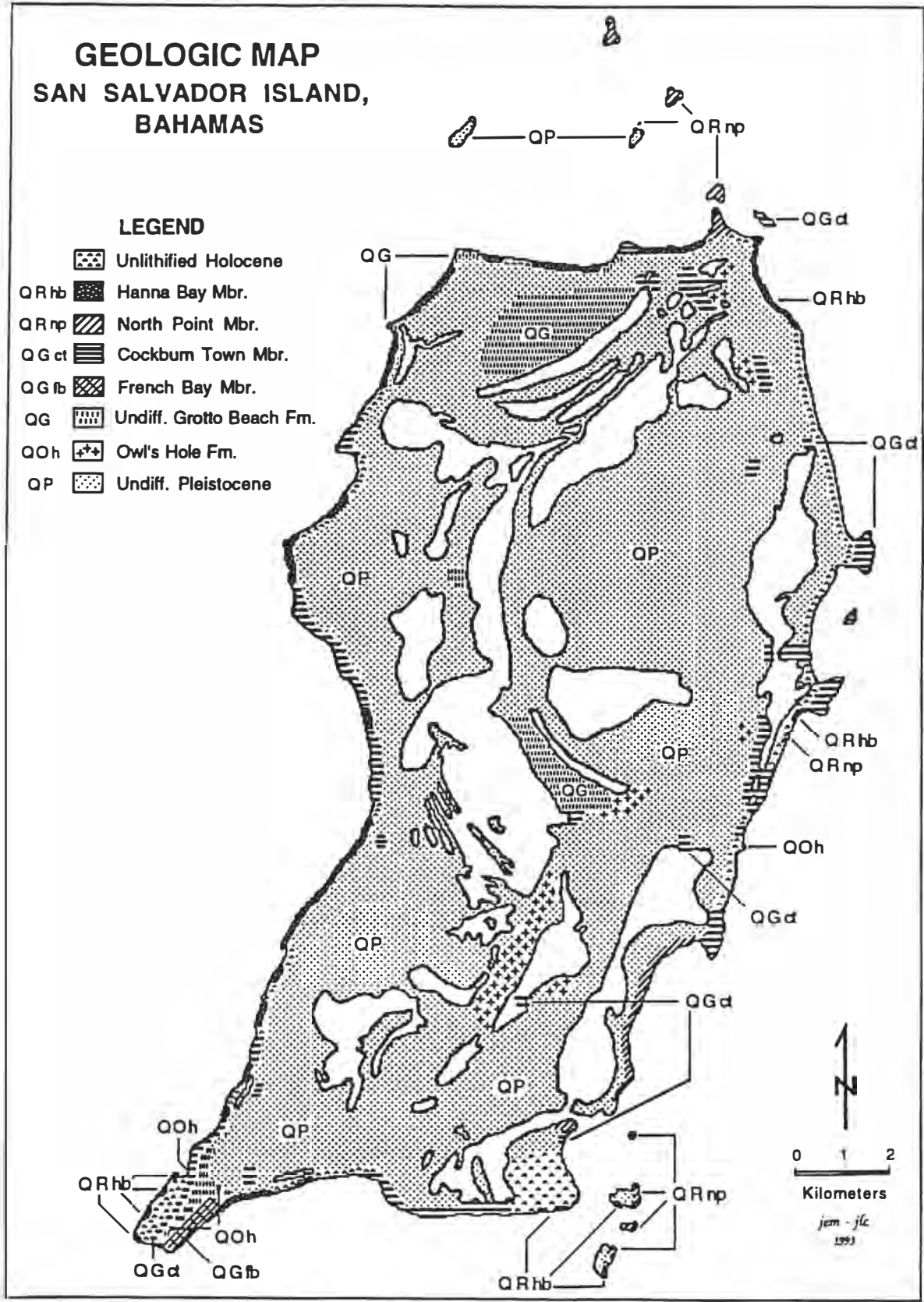


Figure 4. Geology of San Salvador Island as mapped by Carew and Mylroie. The largely inaccessible areas of the island are mapped as undifferentiated Pleistocene (QP); rocks in these areas may belong to either the Owl's Hole Formation or Grotto Beach Formation. (from Carew and Mylroie, 1995)

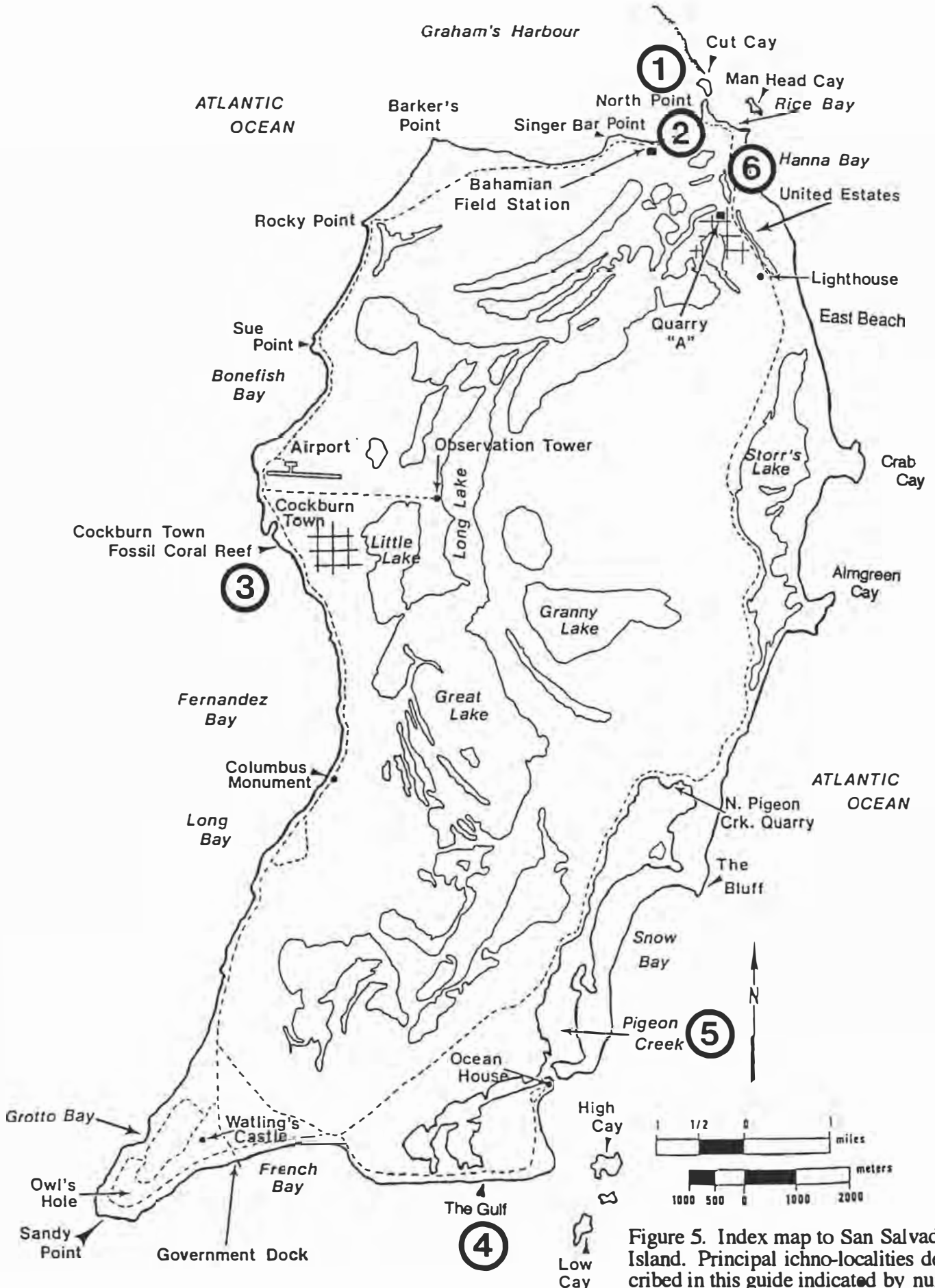


Figure 5. Index map to San Salvador Island. Principal ichno-localities described in this guide indicated by numbers in circles.

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# AN INTRODUCTION TO BAHAMIAN ICHNOLOGY AND ICHNO-LOCALITIES ON SAN SALVADOR ISLAND

H. Allen Curran

On a global basis, trace-making organisms are a common and diverse component of the biota of tropical, shallow marine and coastal carbonate environments. For example, in shallow subtidal zones of the tropics, the burrowing activity of callianassid shrimps commonly is the dominant process in the modification of primary sedimentary fabrics (Tudhope and Scoffin, 1984; Tedesco and Wanless, 1991). Burrowers, borers, and terrestrial plants all have great potential to modify and to leave their mark in tropical carbonate sediments and rocks, and thus to become part of the fossil record.

The many islands of the Bahama Archipelago provide a fantastic natural laboratory for the study of Pleistocene, Holocene, and modern carbonate sediments and rocks and the processes that create and modify these materials, including organism-sediment / rock interactions. The modern shallow marine and coastal sedimentary environments have close counterparts in the Holocene and Pleistocene rocks that cap the islands. In many cases, this permits direct study of the stages of transition from modern trace-maker activity to the fossil record.

The purpose of this section of the guide is to describe six key ichno-localities on San Salvador Island that are both highly ichnologically informative and readily accessible. In composite, the sediments, rocks, traces, and trace fossils of these localities illustrate the ichnologic model for ichnocoenoses in Bahamian-style calcarenites as shown in Fig. 1. In addition, observations from these localities will reveal much about the modern to fossil transition. As an example, the burrowing activity of callianassids that easily can be observed by snorkeling in Graham's Harbour or walking over the intertidal sand flats of Pigeon Creek has its ichnologic result displayed in the *Ophiomorpha* trace fossils and ichnofabrics of the late Pleistocene Cockburn Town Coral Reef complex.

A list of the most common trace fossils formed by burrowing and their probable trace-maker organisms is given in Table 1. With the exception of *Conichnus conicus* (rare on San Salvador, but common at some other localities in the Bahamas, see final chapter of this guide), all of the trace fossils on this list can be seen within the context of the rock localities described herein. Undoubtedly the list of trace fossils and trace-maker organisms will expand as ichnologic studies continue in the Bahamas. Indeed, the author has identified several other trace

fossil forms that are not included on this list, and new evidence of and information about the ichnologic work of modern organisms is gained with virtually every field trip.

Notably absent from the list are the borer organisms, owing to the fact that our past work has concentrated on the ichnology of burrowers. However, the borer void initially has been filled by the chapter later in this guide by Mark Wilson.

Readers wishing to expand their knowledge of Bahamian ichnology beyond the limits of this guide are urged to investigate the following three papers: White and Curran (1988) on the physical sedimentary structures and ichnology of Holocene carbonate eolianites; Curran and White (1991) on the ichnocoenoses of shallow subtidal to dunal facies; and the review by Curran (1994) of Bahamian-style ichnology. Pemberton and Jones (1988) reported on Pleistocene trace fossil assemblages from Grand Cayman, and their work provides a useful comparison with the ichnocoenoses reported from the Bahamas. The work of Tedesco and Wanless (1991 and other papers) has provided important perspectives on the generation of ichnofabrics in modern shallow subtidal carbonate sediments of south Florida and the Turks and Caicos.

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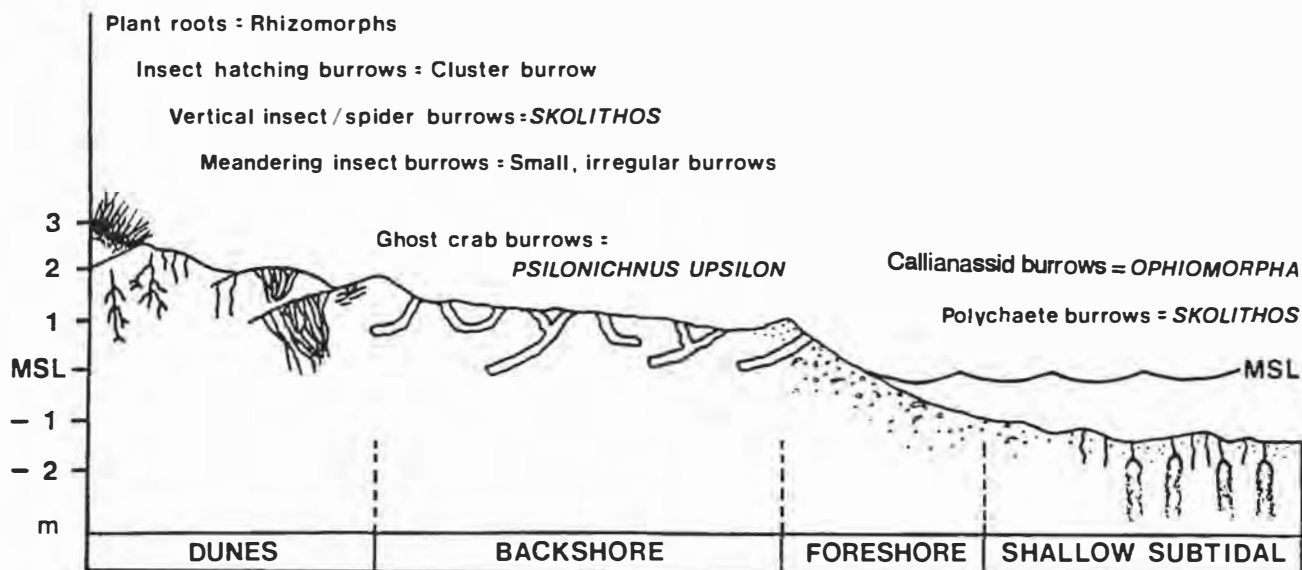


Fig. 1. Ichnologic model for Bahamian-style calcarenites showing ichnocoenoses in the transition across an open coast from a shallow shelf, commonly with coral reefs to a beach and then a dunal environment. Various lagoonal environments will differ from the shallow subtidal zone as illustrated here; for example, see the description of ichno-locality 5 in this guide. (From Curran and White, 1991).

Ichnocoenosis	Ichnotaxon	Probable tracemaker organism(s)
Open shelf:	<i>Ophiomorpha</i> <i>Skolithos linearis</i>	Callianassid shrimps Tube-dwelling polychaetes
Lagoonal(?):	as above, plus <i>Conichnus conicus</i> <i>Planolites?</i>	Burrowing sea anemones Balanoglossid worms
Beach:	<i>Psilonichnus upsilon</i>	The ghost crab <i>Ocypode quadrata</i>
Dunal:	<i>Skolithos linearis</i> Cluster burrow Small, irregular burrow Rhizomorpha – horizontal	Tube-dwelling insects or arachnids Burrowing (digger) wasps, family Sphecidae Insects or insect larvae Plant stems and branches, railroad vine ( <i>Ipomoea pes-caprae</i> ) and bay geranium ( <i>Ambrosia hispida</i> )

Table 1. Starter list of trace fossil burrows and trace-maker organisms of Bahamian carbonate rocks and environments. (From Curran, 1994).

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# ICHNO-LOCALITY 1: HOLOCENE CARBONATE EOLIANITES FROM RICE BAY TO NORTH POINT

Brian White and H. Allen Curran

## INTRODUCTION

The goals at this locality 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. Here the mechanisms of how eolian deposition of carbonate grains occurs, how organisms interact with dunal beds, and how dunes are initiated and evolve are well illustrated in the rocks. Toward the end of this excursion, a short snorkel dive can 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 and organisms. 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 a 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

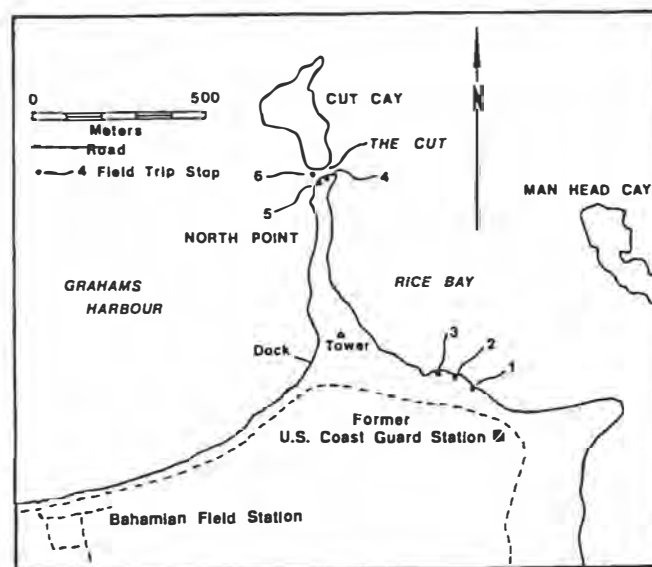


Fig. 1. The North Point area with locations for described stops.

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). More recently, White and White (1991) and White (1995) have shown that these eolianites do bear evidence of diagenesis from the ongoing episode of Holocene marine transgression.

## The Eolianites of Rice Bay to North Point

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 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. 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).

Although fossil burrows previously have been thought to be rare in eolianites (McKee and Ward, 1983), there are large and well preserved burrows 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 (Curran and White, 1987; White and Curran, 1988). Rhizomorphs, trace fossils produced by plant roots, are common in these eolianites. An overview of the significance of this trace fossil assemblage was given by Curran and White (1991).

## DESCRIPTIONS OF THE FIELD STOPS

### Introduction

The beach in front of the former U.S. 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 (late Pleistocene strata). 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



Fig. 2. A - Rhizomorphs on an eolianite bedding surface, Stop 1. Lens cap = 5.5 cm. 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.

immediately overlying this trace fossil, rhizomorphs are prominently displayed on some bedding planes, where they weather out in relief (Fig. 2A). See the following section in this volume on plant trace fossils by White and Curran for further discussion of these structures.

In detail, this trace fossil consists of multiple, straight to gently curved, unlined shafts. Shaft diameters are 1 to 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 tend 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). The burrow construction scenario is shown in Fig. 3. Similar cluster burrows have been found in the Exumas - in Holocene rocks on Lee Stocking Island (White and Curran, 1993) and in late Pleistocene rocks exposed in a submarine cave on Norman's Pond Cay (Curran and Dill, 1991).

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 (Fig. 4). 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.

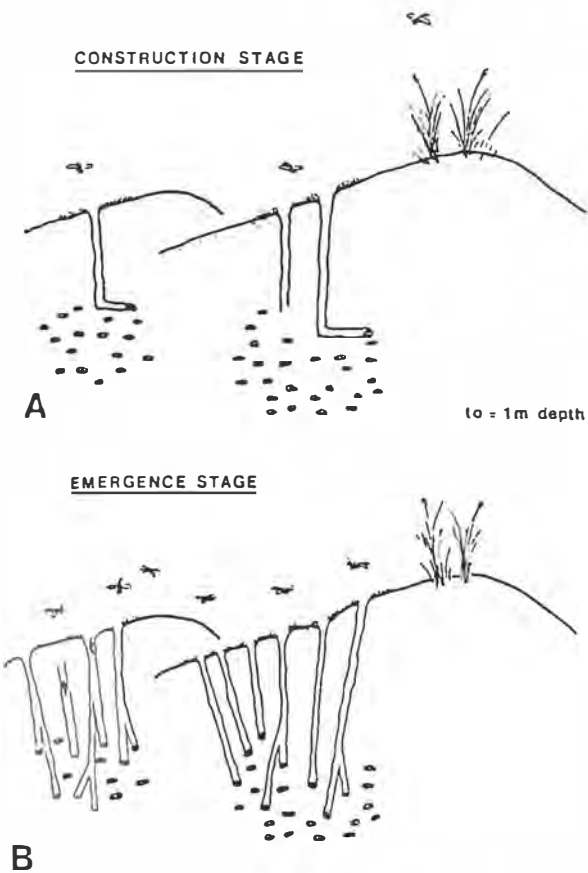


Fig. 3. Scenario for the formation of the cluster burrow by digger wasps. A - Females excavate a main shaft to their nests. Cells are formed, provisioned with insect prey, eggs are laid, and the cells closed. At a later time the entire nest may be closed. B - Following an incubation period, eggs hatch, juveniles eat cell provisions, and grow. At the proper time individuals, now of full size, burrow upward and emerge at the surface (from Curran and White, 1987).

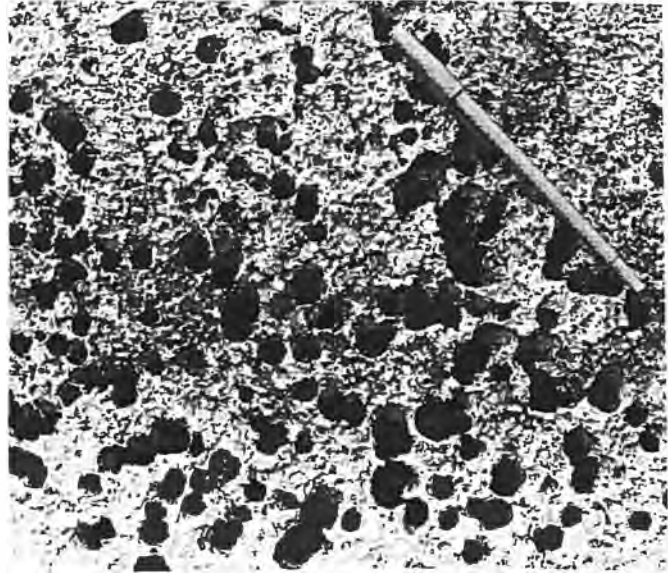


Fig. 4. Openings of cluster burrow shafts on a bedding plane surface. Pen = 15 cm.

## 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. 5A). 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. 5B), 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

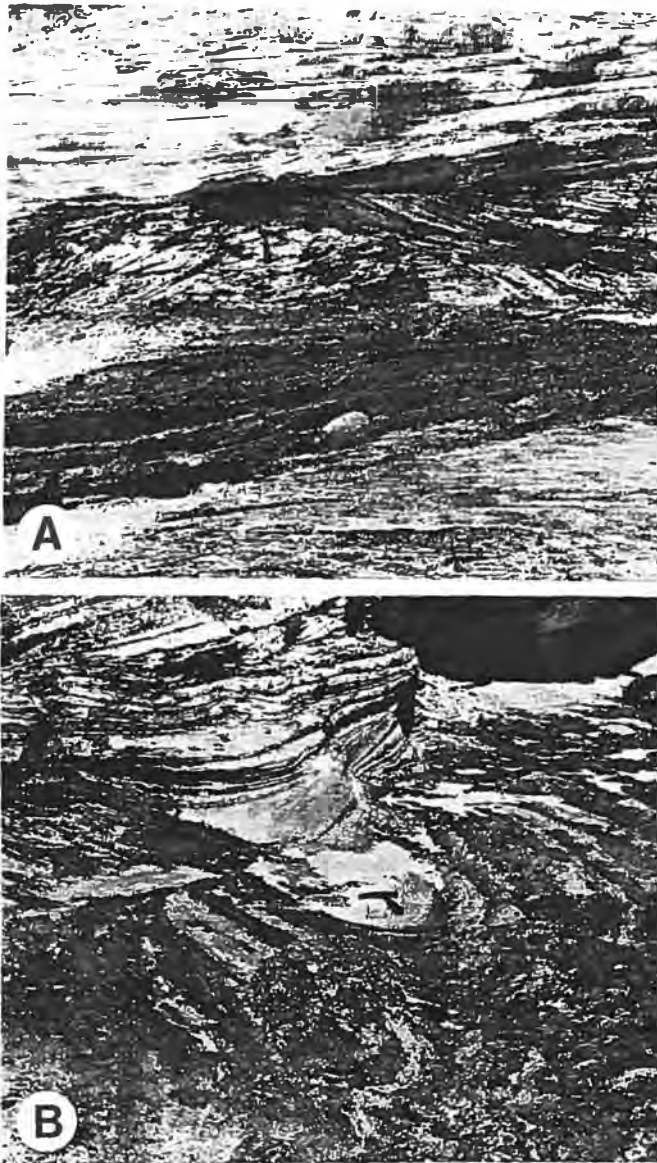


Fig. 5. A - Eroded remnant of an older dune overlapped by younger eolian strata, Stop 2. B - Trough cross beds occur adjacent to an older dune core at Stop 2.

have cross strata with acute angular relationships to the underlying set, whereas others show a tangential relationship. 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 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.

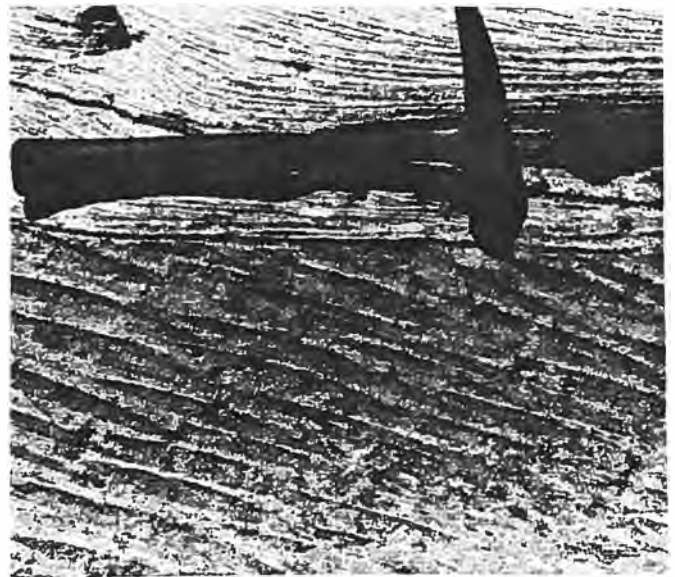


Fig. 6. Sandflow strata occur within grainfall strata at Stop 3, with both overlain by wind-ripple-formed strata.

### 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. 6).

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.

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.

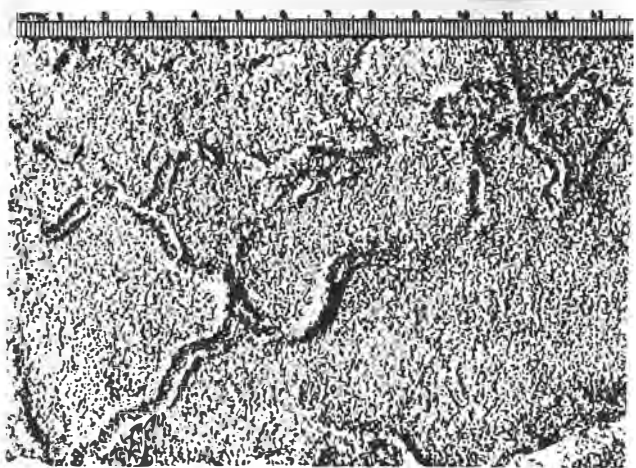


Fig. 7. Small, irregularly meandering burrows on horizontal surface of North Point Member eolianite. Sandflow and grainfall beds commonly show mottling produced by these burrows.

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 (Fig. 7; White and Curran, 1988; Curran and White 1991). 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. We have found similar small, irregular burrows in the Holocene eolianites on Lee Stocking Island of the Exuma Cays (White and Curran, 1993).

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. The sandy areas between patches of the *Thalassia* meadows sometimes are heavily burrowed by callianassids. See the description of Ichno-locality 2 for further information.

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.



Fig. 8. View from the west of lobate dune forming the north end of North Point, 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 (Fig. 8). 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.

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## ICHNO-LOCALITY 2: GRAHAM'S HARBOUR FROM THE BFS BEACH

H. Allen Curran

### INTRODUCTION

A snorkel dive in Graham's Harbour from the Bahamian Field Station (BFS) beach can be both enjoyable and ichnologically informative with respect to observing organism - sediment interactions. Recently, Curran and Harris (1996) surveyed an area in the nearshore zone of Graham's Harbour for the study of bioturbation of these lagoonal sediments by callianassid shrimps. As noted in the introduction to this guide, the burrowing activity of callianassids in modern tropical, shallow subtidal environments is common globally and can be a powerful agent of sediment modification. This topic will be addressed more thoroughly in the discussion of Ichno-Localities 5: Pigeon Creek. The purpose here is to give a brief overview of the study area.

### ZONATION

The master transect line for the study area is located offshore from the third main telephone pole located 190 m east of east entrance (the "back-door" entrance) to the BFS. Walk down the road to this pole and take any one of several small paths down to the beach. The transect line runs normal to the beach and offshore for a distance of 100 m. Zonation along the line is shown in Fig. 1. On a fair weather day at low tide, the swash zone will be on beachrock. Slip into the water and swim slowly offshore. Initially small sand waves in the swash zone will be the dominant bedform, but at about 1 m water depth one will begin to see burrow openings.

If storm waves have not recently scoured the bottom, it will be mounded owing to the burrowing activity of callianassid shrimps. Sediment cones or "volcanoes" mark the excurrent flow from the burrow system, and nearby burrow opening "funnels" lie in depressions and mark the incurrent flow direction. Occasionally a shrimp can be seen at the opening to the burrow system, but these shrimp are fossorial and presumably never willingly leave the burrow system. Under fair weather conditions, a mounded-cratered topography is developed that can be truly impressive in the open sand area between 20 to 45 m offshore.

At about 50 m offshore the bottom changes dramatically with the beginning of a thick *Thalassia testudinum* seagrass meadow. Burrowing activity is present within the area of seagrass, but mounds tend to be smaller and less densely spaced. Although the presence of *Thalassia* doesn't prevent burrowing, it is obvious that burrowing activity is curtailed and our measurements of mound densities confirm this.

Using a yabby pump, we have successfully captured a number of shrimp from the study area, and they have been identified by Dr. Austin Williams (Smithsonian Institution). Two species of callianassids are present, *Neocallichirus nickellae* Manning, 1993 and *N. rathbunae* (Schmitt, 1935). The preliminary indication is that *N. nickellae* is the most common species, but capture numbers are low at this point (and probably will remain so - these shrimps are hard to catch!). The abundant presence of *N. nickellae* here is interesting because this species only recently was described from Tobago, and this is just the second report of its occurrence. Obviously much remains to be learned about the distribution and habits of tropical callianassids.

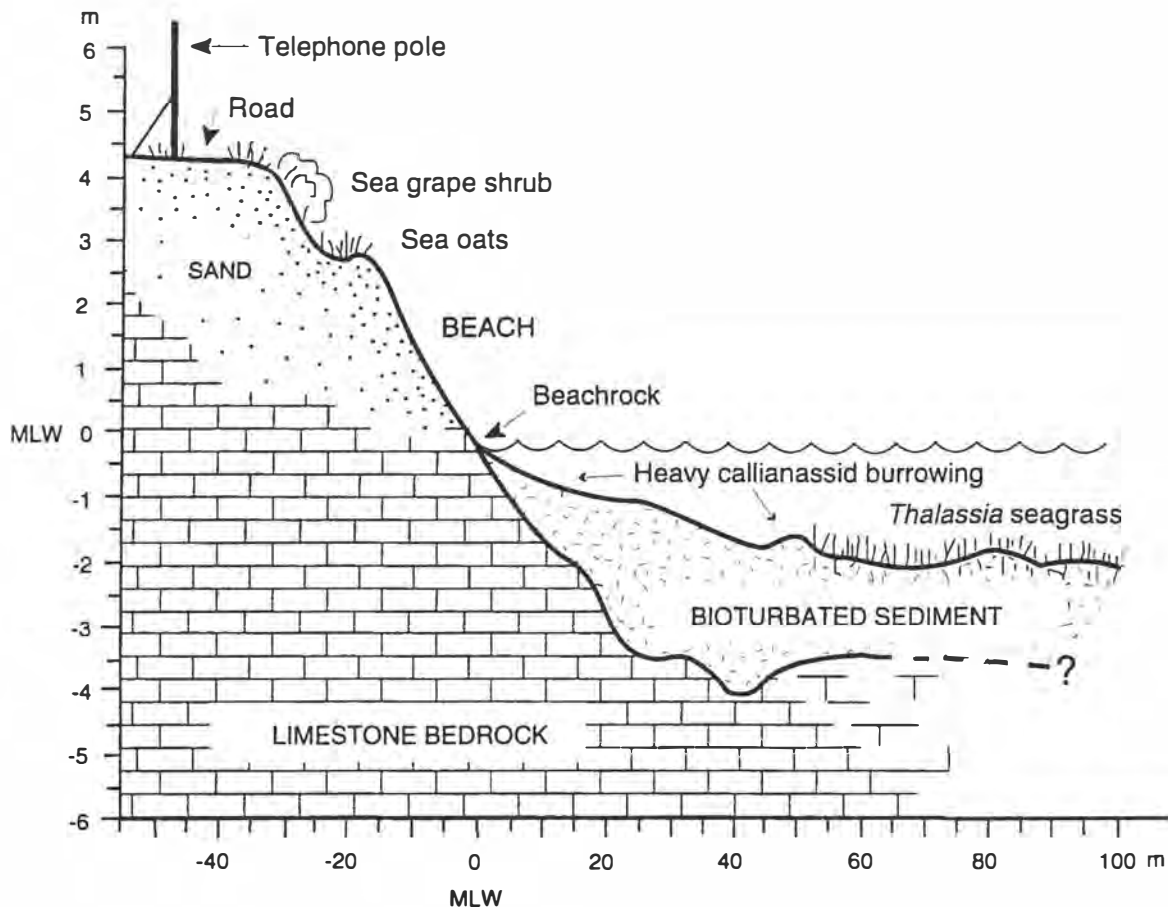


Fig. 1. Profile from the beach across the Graham's Harbour study area showing surface topography, zonation, and thickness of the modern sediment layer over the bedrock surface.

## STUDY RESULTS

Bioturbation rates were determined from data obtained by placing sediment traps over burrow excurrent openings for 24 hr. periods. Following retrieval, the volume of trapped sediment was measured by weight. Both the open sand and *Thalassia* grass substrate areas were studied. For 37 trials in the sand area, the trapped sediment mean was 164 g/24 hrs. and mean active cone density was 3 cones/m<sup>2</sup>; at this density the sediment turnover rate = 182.4 kg sediment/m<sup>2</sup>/yr. and 7.4 yrs. to process 1 m<sup>3</sup> of sediment. Rates are significantly less for the *Thalassia* grassbed substrate. Here the trapped sediment mean was 48.1 g/24 hrs. based on 34 trials, and the mean active cone density was 1.7 cones/m<sup>2</sup>. The sediment turnover rate = 29.8 kg sediment/m<sup>2</sup>/yr. and 45.6 yrs. required to process 1 m<sup>3</sup> of sediment.

These are preliminary results, and they do not take into account possible seasonal and storm effects. Nonetheless they do indicate that callianassids have the capacity to move fairly rapidly large amounts of sand-sized sediment in tropical lagoonal settings. Undoubtedly a distinctive ichnofabric also is being created in the sediment layer below.

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## ICHNO-LOCALITY 3: THE COCKBURN TOWN FOSSIL CORAL REEF

H. Allen Curran and Brian White

### 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).

A total of 20 radiometric dates has been obtained from coral samples from the Cockburn Town reef (Chen et al., 1991); these  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  dates were determined using newly developed mass spectrometric techniques for the measurement of  $^{230}\text{Th}$  abundance. Typical errors for dates from this method are  $\approx 1.5$  ka, 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 dates was given by Curran et al. (1989) and by Chen et al. (1991). More recently, the distribution of dates and the physical and ichnologic evidence for vertical changes within the reef sequence have been analyzed in detail by White et al. (1997) to interpret the history of sea-level changes during Sangamonian time. This work is discussed at greater length in the chapter of this guide by Mark Wilson.

The oldest coral dated from the reef is an *Acropora palmata* specimen at  $132.6 \pm 1.3$  ka from the oceanward end of Profile C-C' (Fig. 5). The youngest coral date is  $120.7 \pm 1.5$  ka 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, punctuated by a sea-level lowstand at approximately 124 ka (White et al., 1997).

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. cervicomis*. 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 guide to the Cockburn Town reef have been published by Curran and White (1985, 1989).

### Location and Field Trip Procedure

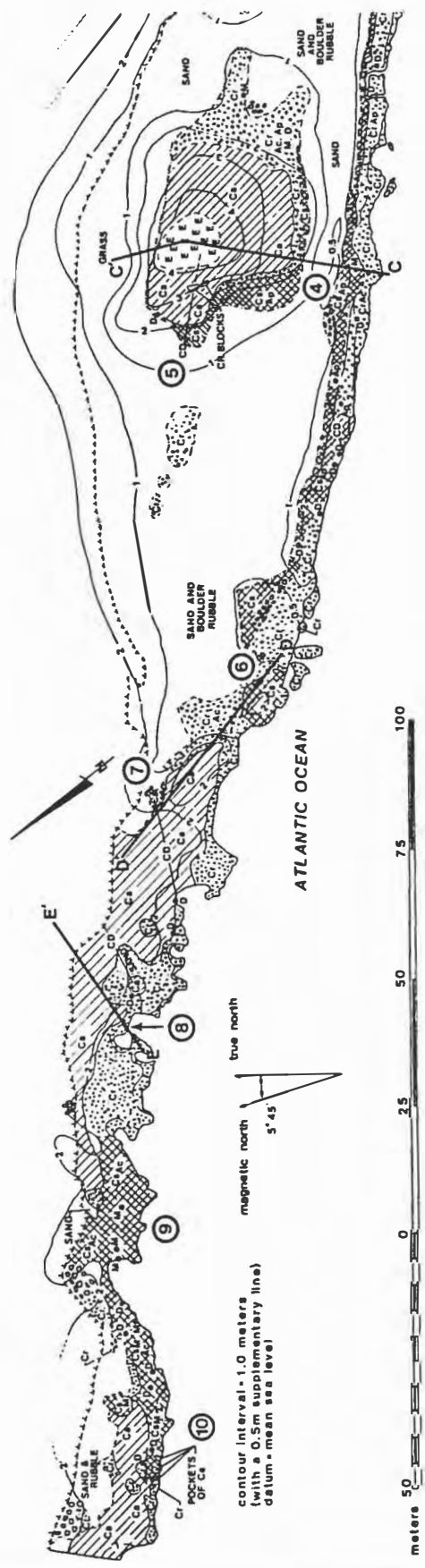
The Cockburn Town fossil coral reef is exposed along coastal outcrops and in a small quarry located a short distance northwest of the center of Cockburn Town. Reefal rocks extend in a northwesterly direction from the old town dock for a distance of about 650 m, terminating within the area of the new marina cut into the north end of the reef. Here late Pleistocene shallow subtidal and beach calcarenites flank and overtop the reef.

This excursion will start from the parking area adjacent to the now abandoned town dock (across the road from the municipal center area). 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.

LEFT SIDE OF MAP

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



SMITH COLLEGE CARBONATES RESEARCH GROUP, JUNE 1983 AND 1984

RIGHT SIDE OF MAP

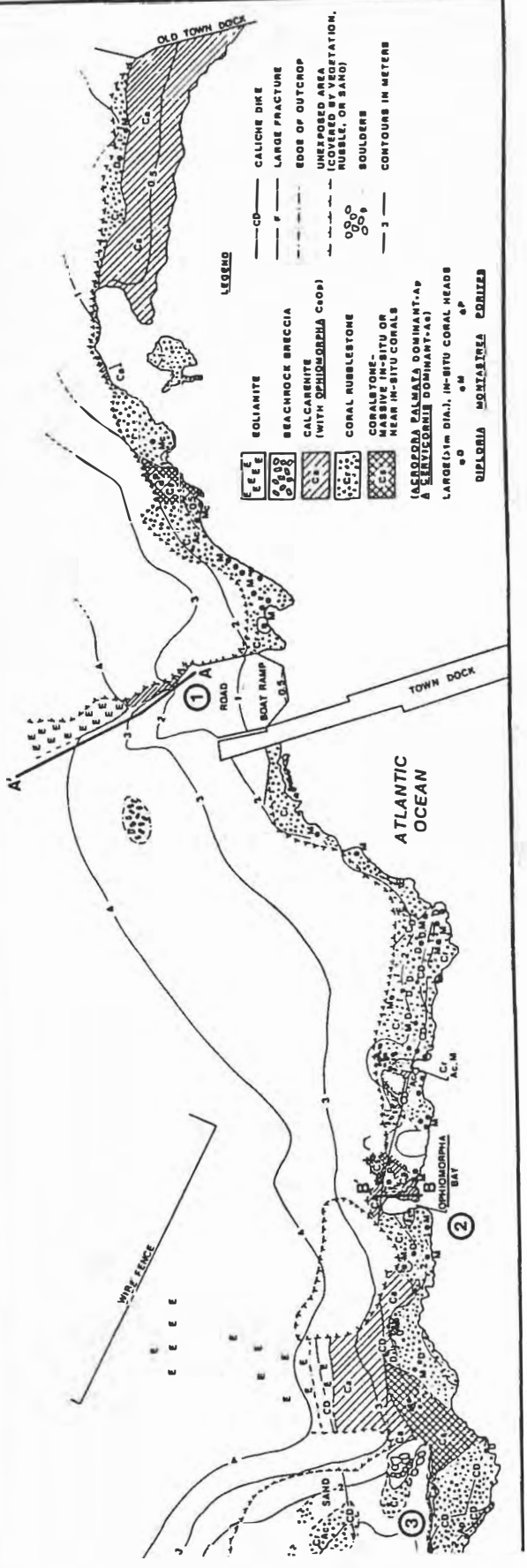


Fig. 1. Geologic map of the Cockburn Town fossil reef complex, showing locations of the stratigraphic profiles and field trip stops (numbered areas).

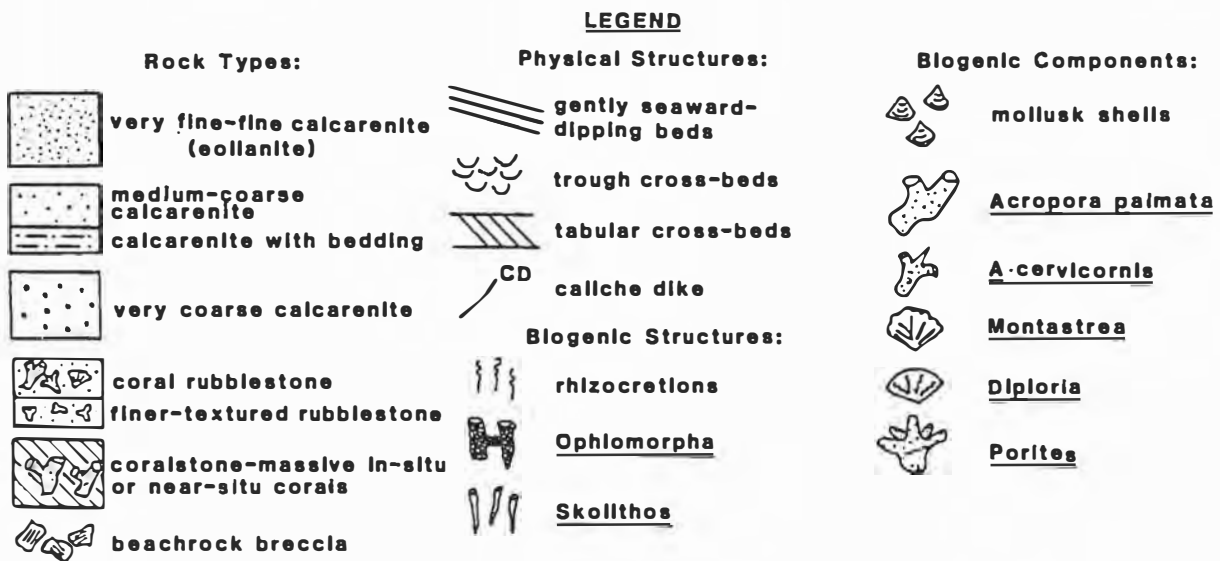
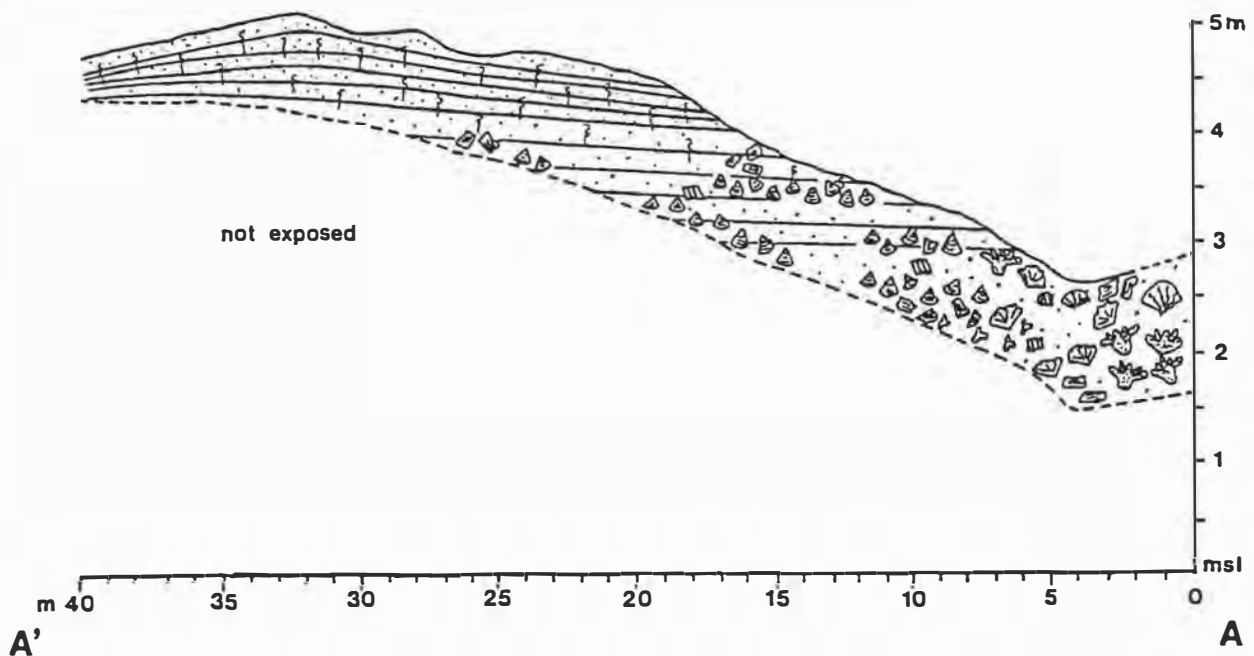


Fig. 2. Stratigraphic profile A-A'; exposure along road leading to Cockburn Town dock and launch area. Lower part of the figure presents the legend of symbols used in the stratigraphic profiles.

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 edge, several large coral heads (*Diploria strigosa*, *Montastrea annularis*, and *Porites asteroides*) are preserved in near growth position in a



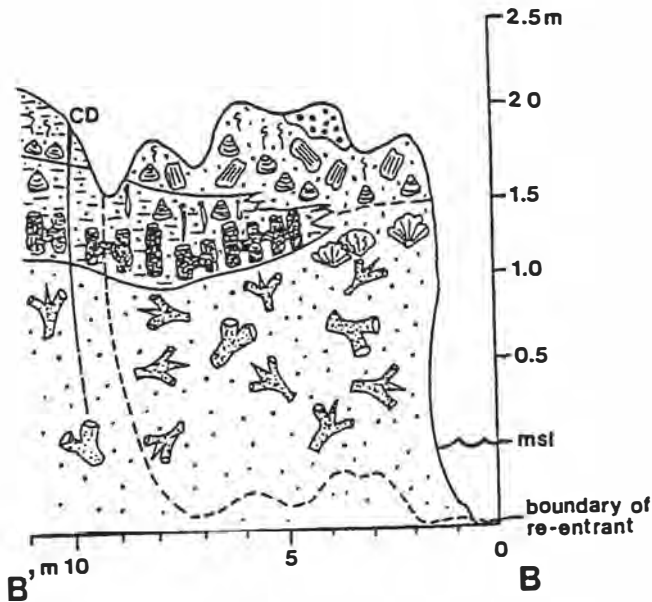


Fig. 3. Stratigraphic profile B-B'; exposure along southeast wall of *Ophiomorpha* Bay.

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 contains 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 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 in subtidal beds 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) and Curran and White, (1991). Tunnels and shafts of *Ophiomorpha* sp. are particularly abundant and well developed here (Fig. 4), creating an ichnofabric of 3 to 4 on the Droser/Bottjer Ichnofabric Index scale. 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

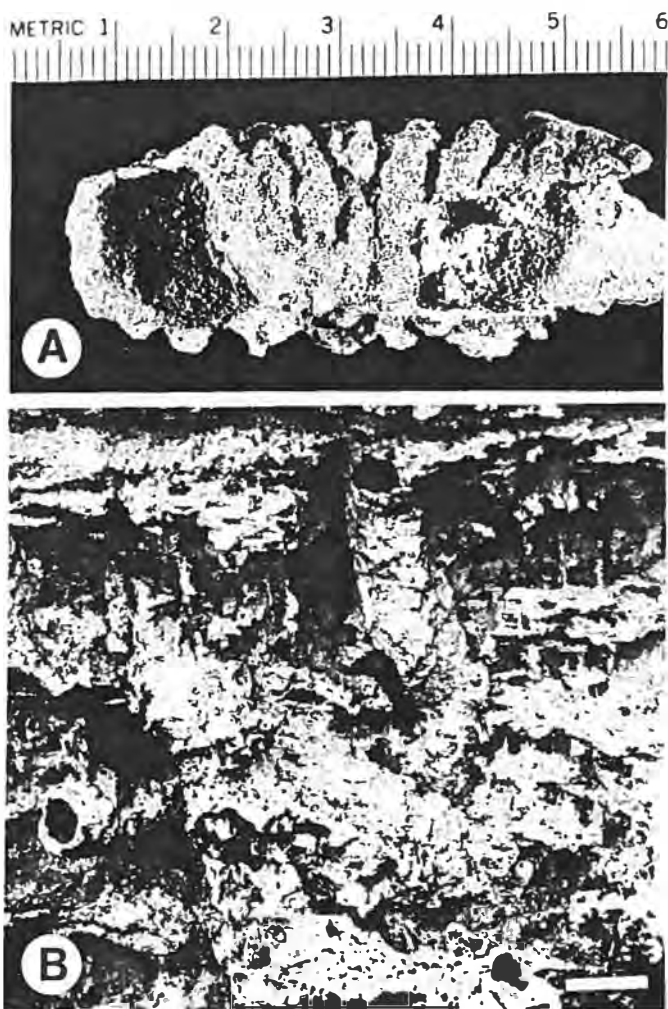
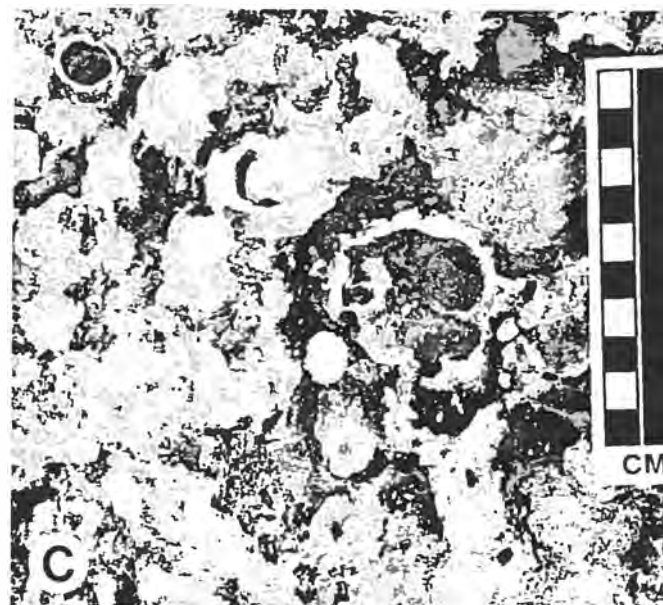


Fig. 4. A - Segment of an *Ophiomorpha* sp. burrow showing the somewhat rugose character of the outside surface of the wall. B - *Ophiomorpha* sp. shafts and tunnels in vertical view. Note small *Skolithos linearis* in the background. Scale bar = 2 cm. C - Horizontal surface showing the closely packed occurrence of *Ophiomorpha* sp. shafts.

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. This occurrence of *Ophiomorpha* vouches for the ability of the tracemaker shrimp to cope with a very coarse-grained substrate. 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. 5). 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.

### 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

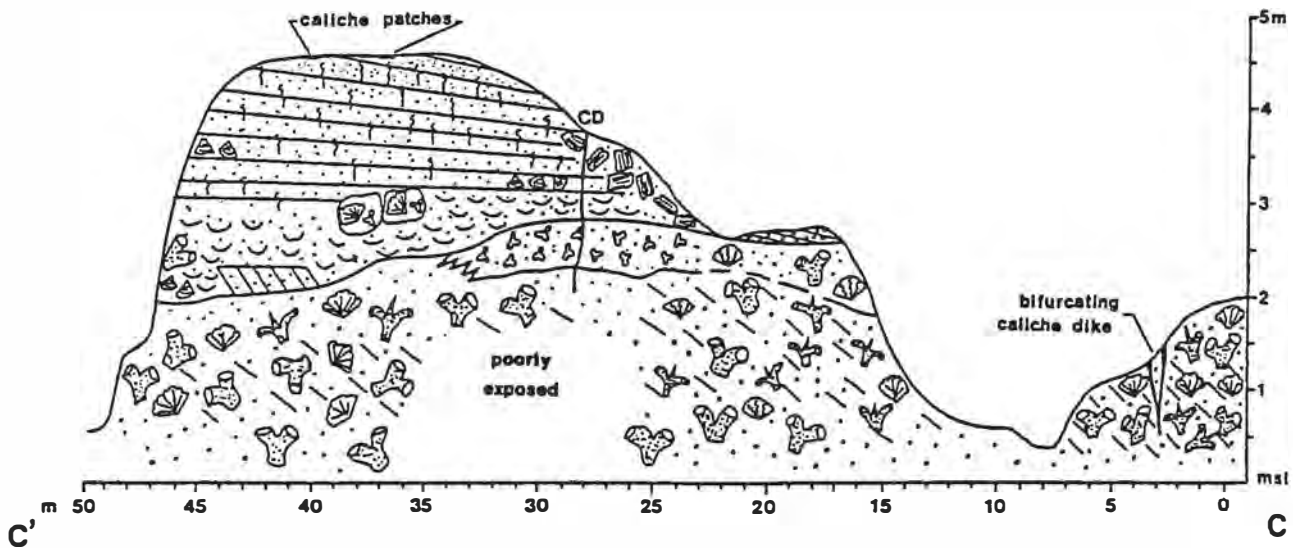


Fig. 5. Stratigraphic profile C-C' in the quarry area; exposure from the water's edge along the northwest face of the knoll.

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. 6, 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).

Careful observers will be able to find rare but well preserved segments of *Ophiomorpha* sp. shafts and tunnels in this exposure area. Again, this attests to the ability of the *Ophiomorpha* sp. tracemaker to colonize successfully a coral rubblestone-dominated substrate. A similar but much more common occurrence of *Ophiomorpha* in coral rubblestone exists in the large Devil's Point fossil coral reef (age = to the CT reef) on Great Inagua Island (Curran, 1994, Fig. 3.3B,D; White and Curran, 1995).

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 an *A. palmata* specimen from this area of the reef yielded an age of  $122.7 \pm 1.5$  ka (Chen et al., 1991).

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.

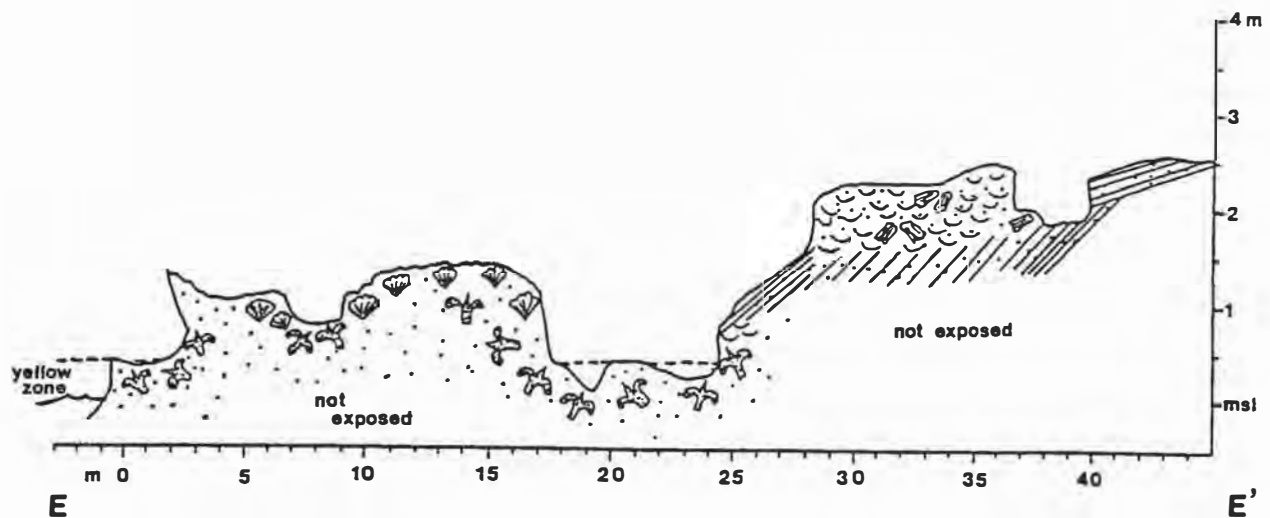


Fig. 6. Stratigraphic profile D-D', northwest end of quarry area; exposure includes the main part of the zone of *Acropora palmata* in near growth position.

### 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.

### Stop 8. Profile E-E'

The exposures of Profile E-E' (Fig. 7) 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).

### Northwest End of the Cockburn Town Reef

With the development of Club Med in the early 1990's, the northwest part of the reef was excavated to create a new marina. The formerly excellent reefal exposures northwest of Profile E-E' were lost. Nonetheless, there was some gain in the form of the large boulders of blasted reefal material that now are found at the end of the reef exposure and that armor the front wall of the marina.

Many of these boulders are composed of subtidal calcarenite with an *Ophiomorpha*-generated ichnofabric of up to Ichnofabric Index 5 level (Fig. 8A). These calcarenites reveal much about the high intensity of callianassid burrowing in subtidal sands surrounding reefal areas. Also present in some of the subtidal calcarenite boulders are well-defined, gently meandering, smooth burrows formed of well-lithified infill material. These *Planolites*-like burrows range from 0.75 up to 2.5 cm in diameter (Fig. 8B,C); their concentrated presence can give the host rock a very distinctive appearance.

Boulders formed largely of coral material commonly display excellently preserved borings, particularly *Gastrochaenolites* produced by the activity of lithophagid bivalves. These borings and their significance to interpretation of the geologic history of the reef are discussed in the chapter in this guide by Mark Wilson.

The reef proper ends very abruptly. The final visible exposures of coral rubblestone are virtually

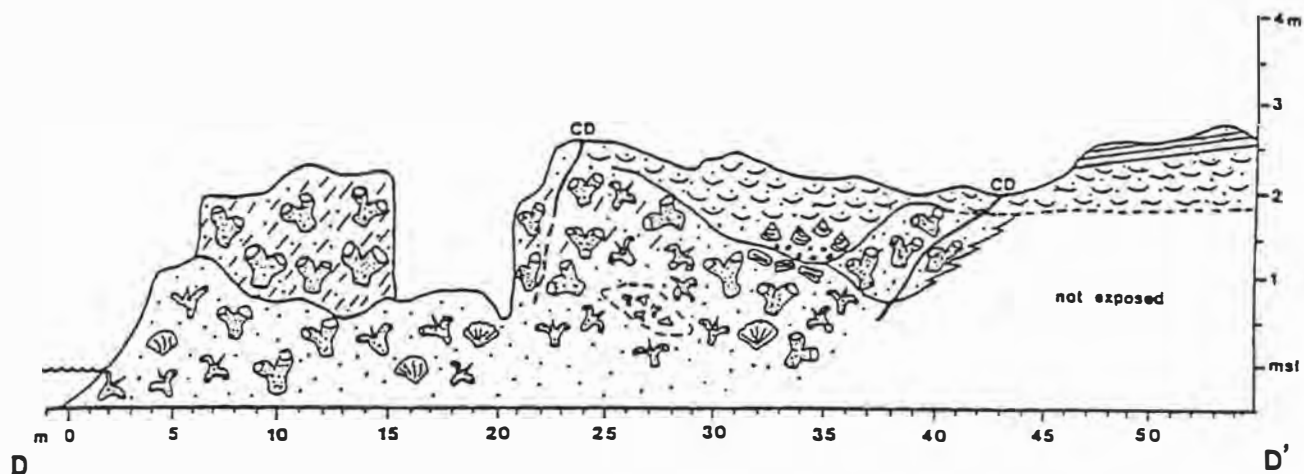


Fig. 7. Stratigraphic profile E-E', northwest of the quarry area.

surrounded by calcarenites. Looking northwestward along the coast from the last coral rubblestone exposures (now largely obscured beneath boulders), one sees only the gently seaward dipping calcarenites that entombed the Cockburn Town reef.

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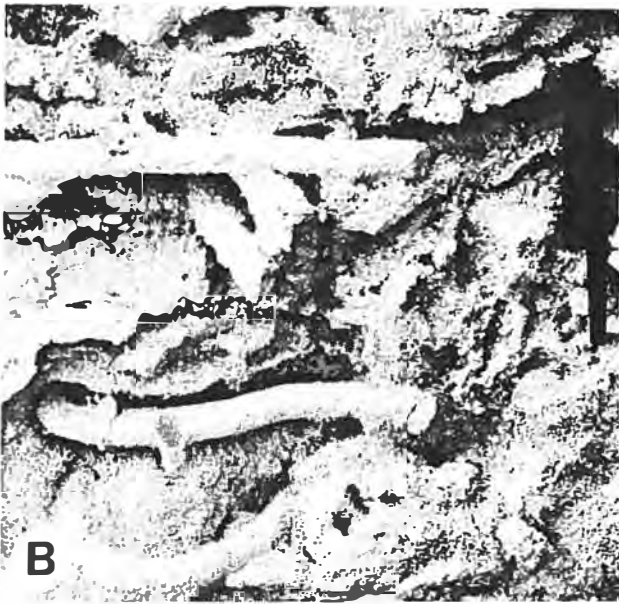


Fig. 8. A - Subtidal calcarenite with an *Ophiomorpha*-generated ichnofabric. B. *Planolites*-like burrows in subtidal beds. C - Large *Planolites*-like burrow overlain with an *Ophiomorpha* sp. tunnel.

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#### ICHNO-LOCALITY 4: THE GULF or "RHIZO CITY"

H. Allen Curran

#### INTRODUCTION

This locality is locally known as The Gulf. Given that the upper parts of the sea cliffs exposed here bear prolific concentrations of rhizomorphs, those who are more ichnologically inclined may prefer the informal name "Rhizo City". The rocks exposed here are mostly oolitic eolianites, but the beds change at the base of the exposure, in the surf zone, where fossilized corals crop out (Fig. 1). The corals identify the strata as belonging to the Cockburn Town Member of the Grotto Beach Formation (see the 1995 geologic map of Carew and Mylroie in the front part of this guide).

#### ROAD CUT

The north wall of the road cut is oriented very close to perpendicular to the axis of a large dune, and it provides a good example of windward (to the east) and leeward (west) bed forms. There is a well developed set of joints in the eolianite that commonly form a classic "X" pattern. A close look will reveal calcrete layering along the joints, indicating that they predate excavation of the road cut. Carew and Mylroie (1989) ruled out origin by platform edge subsidence and speculated that the joints may be related to nearby cave and karst development.

A thin paleosol caps the outcrop and isolated rhizomorphs are present, some of which look "burrow-like" and commonly have been mistaken for burrows. The give-away clue is that the core of these structures consists of hard micrite, usually with a pin-hole opening in the center, indicating biogeochemical precipitation by roots or rootlets. The terminology and possible modes of formation for Bahamian plant trace fossils are discussed at greater length in a later chapter of this guide by White and Curran.

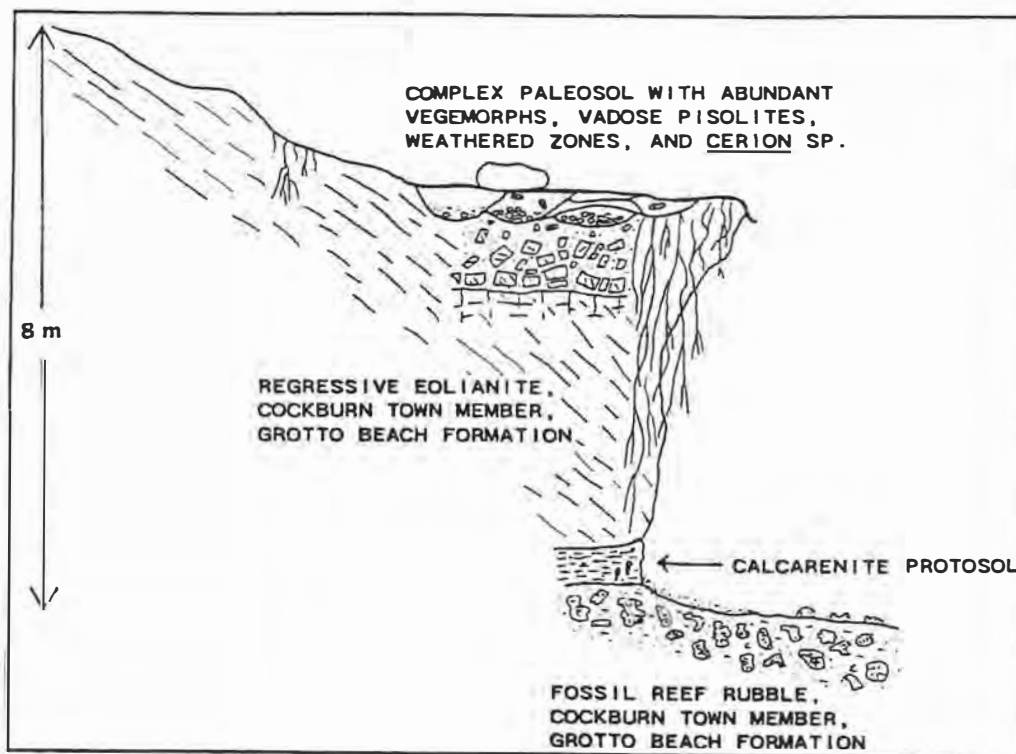


Fig. 1. Facies relationships at The Gulf (from Carew and Mylroie, 1995).

## THE SEA CLIFFS

Head south across the road and walk to the west end of the road cut onto the platform-like area above the sea. Proceed to the coast and cliff edge and look back at the large re-entrant present behind the south wall of the road cut. Here the paleosol is well developed and multi-layered, with many hollows, a form referred to by Carew and Mylroie as pillow or multilobate paleosol.

At the cliff edge, the paleosol can be seen to contain abundant fossil *Cerion* shells and vadose pisolites, as well as evidence of other aspects of past soil-forming processes. On the seaward cliff edge, in the spray zone, there is excellent development of phytokarst.

Of course, the spectacular item here is the large and complex masses of rhizomorphs that extend downward from the paleosol surface, sometimes in excess of 3 m (Fig. 1). If sea conditions permit, use caution and climb down to the base of the cliff exposure and investigate carefully the great variety of rhizomorph forms.

The geologic interpretation here is that the dunal beds covered the reef facies during sea-level regression, presumably toward the end of Sangamonian time. Carew and Mylroie (1989, 1995) interpret prolific rhizomorph occurrence such as seen here as an indicator feature of regressive dunal sequences (again, further discussion is given

in the later chapter on plant trace fossils). Similar, but even larger and more spectacular masses of rhizomorphs occur on the seaward margin of Crab Cay (particularly on the southerly side) and, to a somewhat lesser extent, around Almgreen Cay.

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## ICHNO-LOCALITY 5: PIGEON CREEK CHANNEL AND INTERTIDAL SAND FLATS

H. Allen Curran

### INTRODUCTION

Pigeon Creek is a large, tidally influenced, slightly hypersaline, carbonate lagoon located in the southeastern corner of San Salvador Island. The lagoon has two arms or branches that connect by a single channel to the larger, offshore Snow Bay Lagoon. A well defined ebb tidal delta lies just seaward of the channel mouth. There is no continuous freshwater flow into Pigeon Creek, and salinities within the lagoon can be elevated up to 50 ‰ (Mitchell, 1987, Fig. 4), although 36-38 ‰ is the norm in the areas described herein.

Both branches of the lagoon have a central channel that is 1 to 3 m deep, and reversing tidal currents are strong in these channels. The normal tidal range in the mid-reaches of each branch of the lagoon is 60-75 cm, and the sand flat areas normally are completely flooded at high tide. Low tide lags predicted tide-table times by at least 45 minutes for most areas of the lagoon. With fair weather conditions, sand flat areas begin to become emergent about two hours before a predicted low tide.

The margins of the lagoon are fringed by mangroves that in many areas merge lagoonward with extensive intertidal sand flats. These sand flats have a "moonscape" topography of mounds and craters formed by callianassid bioturbation. Secondary burrowing by other decapods occurs on these large mounds.

The Pigeon Creek area has been the site of numerous geological research projects, and many of them are briefly reviewed in the guide to the area by Boardman and Carney (1992). Comprehensive sedimentological studies by Mitchell (1987) and Cummins et al. (1995) indicate that a complex array of lithofacies exists within Pigeon Creek, but the foram-rich "grainstone" and mollusc-rich "packstone" facies of Cummins et al. (1995) are the most widespread and dominant lithofacies within the parts of the lagoon to be described here. The mud content in the heavily bioturbated sand flat areas averages about 10%.

Two specific areas of Pigeon Creek are described here for investigation - a snorkel dive excursion from near the mouth of the south arm of the lagoon through the main channel to the tidal delta, and a visit to a heavily burrow-mounded sand flat

site on the west side of the north arm of Pigeon Creek.

### CHANNEL SNORKEL DIVE

It is best to plan the dive for an ebbing tide so that one will be carried by the current toward Snow Bay and the ebb tidal delta. Enter the water at the public dock located near "Ocean House" and the mouth of the south arm of the lagoon. The area near the dock supports a *Thalassia testudinum* meadow that is even thicker than that found in Graham's Harbour. The contact with the central channel is abrupt, and one will immediately encounter deep scour pits with coarse sediment and shell lag deposits at their bases. Bivalve shells of *Codakia* spp. are dominant, but a diverse molluscan shell assemblage is present.

The walls of the scour pits expose the rhizome systems of the *Thalassia* meadow and commonly reveal segments of large callianassid burrows, most likely formed by *Glypturus acanthochirus* as described below. A vivid account of the energetics of the channel system is given by Boardman and Carney (1992).

Continue around the corner to the main channel and let the current move you seaward toward the area of the tidal delta. The sediment is mostly abraded grainstone. Callianassid burrow mounds and craters normally are common on the flanks of the channel, while large sand waves moving with the ebb current are present along the channel axis.

The surface of the tidal delta appears to be a real biological "desert" - there is not much obvious life here. However, one soon will notice occasional mounds of fecal castings formed by deposit-feeding worms, probably balanoglossids. On or just beneath the surface of the sediment one also usually can find agglutinated worm tubes, commonly in seemingly obligatory entanglements. The maker of these tubes has not been identified, but the well-cemented nature of the tubes would seem to offer good potential for fossilization.

The edges of the delta have been sites of an experiment by Mark Boardman to measure the rate of progradation of the delta over the seaward *Thalassia* meadow. PVC and aluminum pipes were enplaced along several transect lines at 10 m intervals in 1986



and many are still in place. In some areas the delta has prograded more than 10 m, whereas in other areas there has been no movement. At this point head south toward the shore and return to a predetermined pickup point on the beach.

### INTERTIDAL SAND FLAT - ICHNOLOGY

Heavily bioturbated sand flats line the mid-reaches of both arms of Pigeon Creek and merge landward with red mangrove (*Rhizophora mangle*) thickets. These flats are well exposed at low tide. Recently Curran and Williams (1997) have described the ichnology of a sand flat on the south arm of Pigeon Creek, but this area is accessible only by use of a boat. Larger groups are advised to visit the flats that line the north arm of Pigeon Creek immediately adjacent to the main road between the localities marked Old Place Settlement and Pigeon Cay on the San Salvador topographic map. At several points in this area one can find an opening or follow a small path through the mangroves and out onto the flats.

Here one will be greeted by a “moonscape” topography (Fig. 1A) that is the result of the prodigious bioturbation activity of the callianassid shrimp, *Glypturus acanthochirus* (Fig. 1B). *G. acanthochirus* is widespread in the shallow marine carbonate environments of the Bahamas and Caribbean (the “callianassid burrower of Shinn, 1968, and Tedesco and Wanless, 1991). The characteristics of these deep burrows have been described in some detail by Dworschak and Ott (1993). The distinctive form of these well-lined burrows is shown in Fig. 1C. Such burrows should be readily preservable as fossils, and would be assigned to the ichnogenus *Ophiomorpha*, but the spiral form of the *G. acanthochirus* burrow has not yet been discovered as a trace fossil.

On a daily basis, these shrimp expel sediment from their burrows, forming sediment cones that can reach heights of >30 cm. Surface sediment can enter the burrow systems through the adjacent funnels. On several occasions we placed

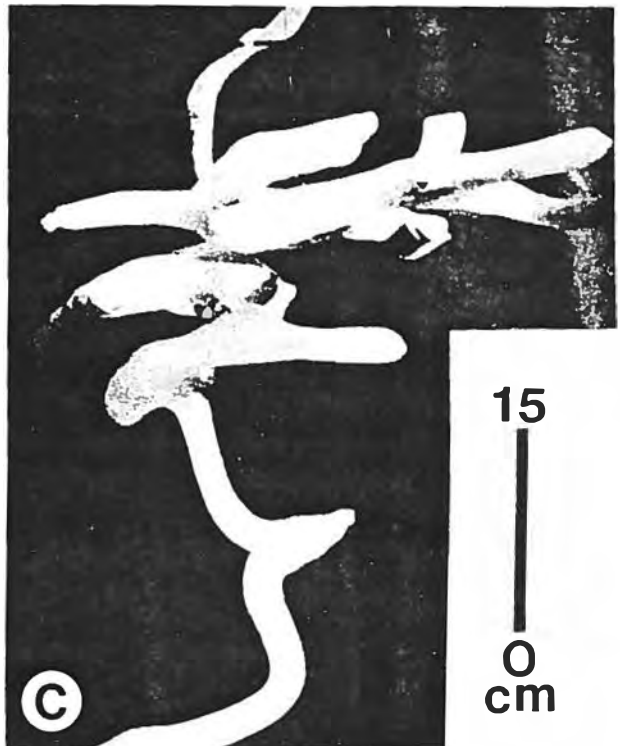
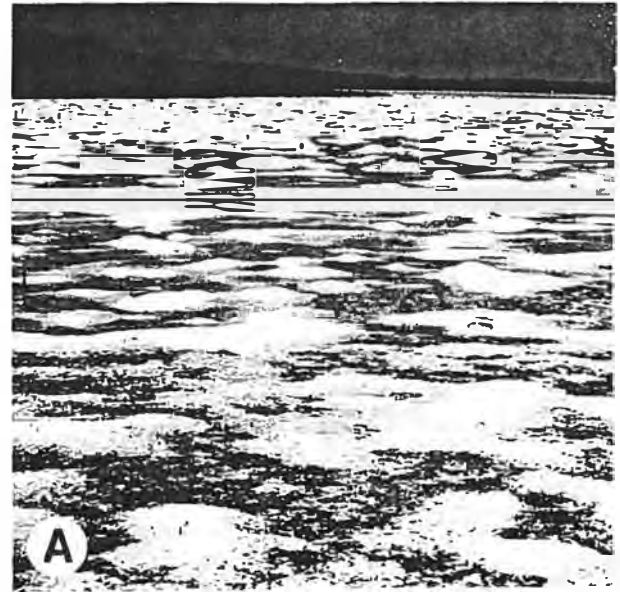


Fig. 1. A) “Moonscape” topography of mounds and craters on sand flat surface bordering part of the north arm of Pigeon Creek. B) Mature specimen of the callianassid shrimp, *Glypturus acanthochirus*. C) Resin cast of a presumed *Glypturus acanthochirus* burrow which is similar in form to those made by *G. acanthochirus* in the study area (modified from Tedesco and Wanless, 1991).

dyed sediment into what appeared to be active burrow funnels, and, in all cases, the dyed sediment appeared on the surfaces of adjacent cones by the next day. Using sediment traps on the south arm flat, Curran and Harris (1996) reported a trapped sediment mean of 154.6 g/24 hrs. for 28 trials and a mean active cone density of 2.1 cones/m<sup>2</sup>. At this density *G. acanthochirus* can move to the surface 118.6 kg sediment/m<sup>2</sup>/yr. and would require 12.1 years to process 1 m<sup>3</sup> of sediment. The work of Tedesco and Wanless (1991) further explores the important work of these shrimp in modifying tropical, shallow subtidal carbonate sediments and forming distinctive ichnofabrics.

With time, closely-spaced sediment cones tend to coalesce, forming large mounds that become flattened by tidal currents. Such mounds commonly grow to > 1 m in diameter. The surfaces of the mounds tend to become stabilized by the development of *Schizothrix*-dominated microbial mats which armor their surfaces. Thus the mounds can be long-lived and are not destroyed by waves and currents, as would be the case in shallow subtidal settings.

The stabilized, coalesced mound surfaces present an ideal habitat for colonization by other decapod burrowers that require a stable, relatively firm substrate surface. The burrowers are a upogebiid shrimp, *Upogebia vasquezi*, and fiddler crabs.

The *Upogebia vasquezi* burrows are indicated by paired, small burrow openings (2-6 mm) on the stabilized surfaces. Typically another pair of burrow openings will be close by (2-5 cm). Lines connecting the four openings normally make a roughly rectangular outline on the surface. Digging with a trowel will reveal that a hard burrow structure beneath the surface, typically extending to depths of 10-15 cm.

Burrow casts made with polyester resin show that the *Upogebia vasquezi* burrow system consists of a pair of U-shaped burrows in very close proximity to each other, sometimes actually criss-crossing (Fig. 2). The entire double-U burrow system is encased in an incredibly thick lining of agglutinated, fine to very fine sand and mud. The burrows are polished smooth on the inside by the shrimp, but the outside surface is textured by very coarse pellets with a diameter of about 1 cm. As the shrimp typically are only 2.5-3 cm in total length, it is remarkable that they can construct such large pellets and such thick walls! Further details of the characteristics of these distinctive burrows and the natural history of *U. vasquezi* is discussed in by Curran and Williams (1997).

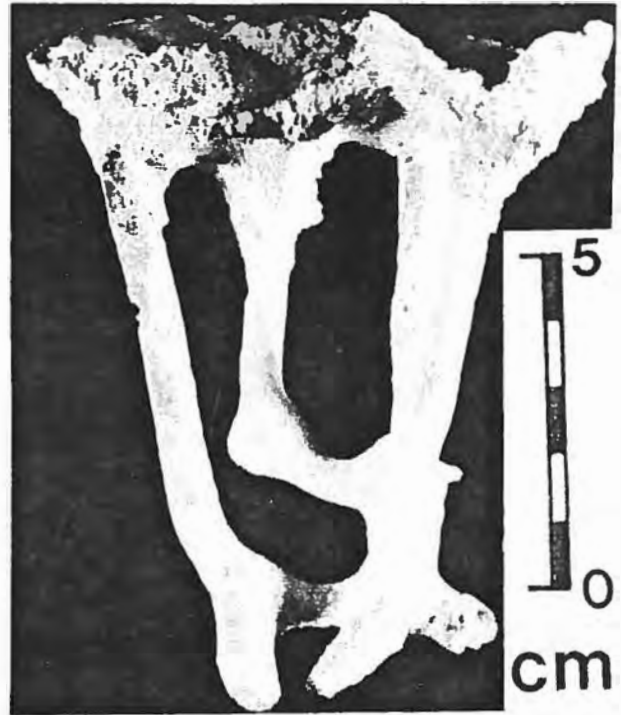


Fig. 2. Resin cast of *Upogebia vasquezi* burrow complex showing the distinctive double-U form and short tunnels at bases of the U's.

These thick, well-agglutinated *Upogebia vasquezi* burrows obviously have high potential for fossilization; and, in fact, fossil casts (lithified infilling sediment) have been reported in late Pleistocene lagoonal rocks from San Salvador Island (Noble et al., 1995). To date, the walls of the burrow system have not been recognized in fossil form, although the potential for such a find seems high. If such trace fossils are found, it would be tempting to assign the burrows to the ichnogenus *Ophiomorpha* based on the pelleted form of the exterior surface of the burrows; however, the burrow system architecture of these upogebiids is different from anything previously described for *Ophiomorpha*, presenting something of an ichno-taxonomic dilemma.

Also present on the stabilized surfaces of the coalesced mounds are larger burrow openings up to 3-4 cm in diameter. They can be distinguished from *Glypturus acanthochirus* burrow openings in that they do not have the characteristic funnel form, are oblique to the surface as opposed to vertical, and commonly exhibit radiate scratch marks and feeding and excavation sand pellets typical of fiddler crabs. These obliquely-oriented burrows are made by *Uca major*, a moderately large fiddler crab.

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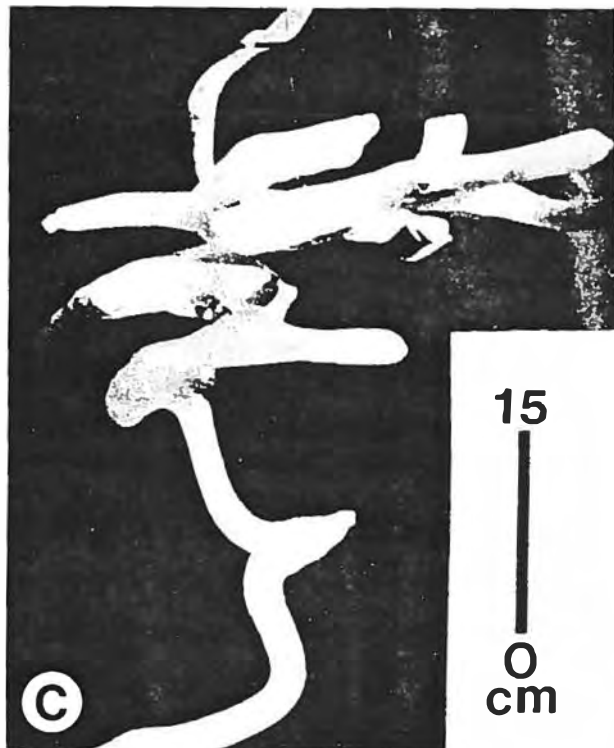


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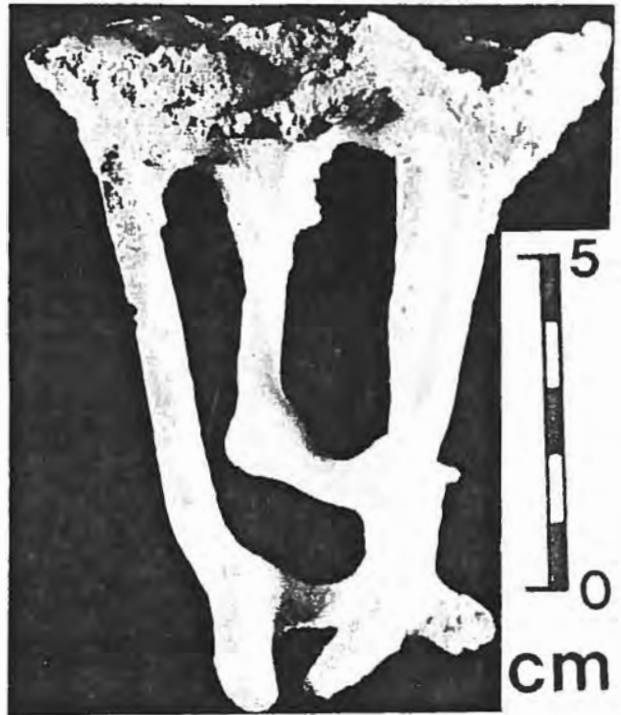


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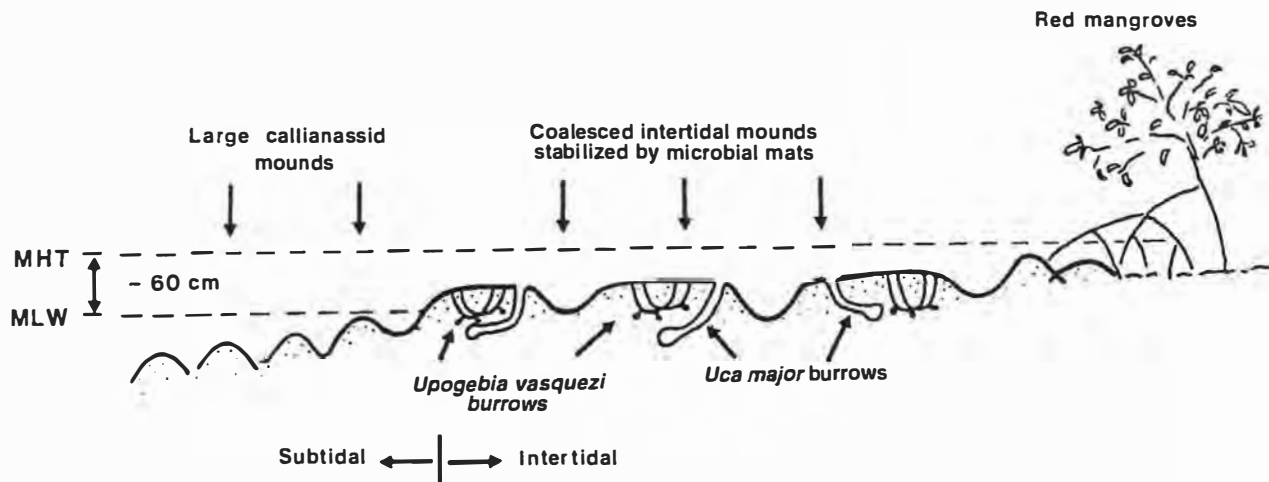


Fig. 3. Generalized profile across a Pigeon Creek sand flat showing the intertidal zonation and the position of the dominant shallow tier burrows in the coalesced mounds that initially were generated by the deep burrowing callianassids.

This species has a wide geographic range throughout the tropical western North Atlantic and Caribbean. The dwelling burrows are unlined, have diameters of 2-5 cm, and extend obliquely into the mound substrate following a gently meandering, somewhat irregular course for distances of up to 50 cm or more. The burrows end with a bulbous turnaround where the crab commonly is encountered. The general form of these burrows is shown in the summary diagram of sand flat ichnology (Fig. 3).

These semi-permanent, unlined dwelling burrows have a much lower potential for preservation than the thickly-lined burrows of *Upogebia vasquezi*. As part of the shallow tier, they likely would be destroyed by deeper-tier bioturbation with the build-up of sediment during lateral accretion or marine transgression. However, the burrow walls are sufficiently coherent so that if filled and lithified, there would be a distinct boundary between the wall of the burrow and the infilling material. With this scenario, these burrows could be preserved with a regressive event; however, at present, trace fossils of this form have not been reported from rocks of the Bahamas.

### GEOLOGICAL IMPLICATIONS

Facies representing deposition in lagoonal environments are widespread in the rock record of the Bahamas, and specifically on San Salvador (Noble et al., 1995). The Pigeon Creek sand flat example reported here, plus the work of Tedesco and Wanless (1991), and others, clearly illustrates that

bioturbation by callianassids is a major sedimentologic process in such environments, and produces distinctive ichnofabrics. Efforts to recognize such ichnofabrics in the rock record of the Bahamas are needed.

As deep-tier burrowers, bioturbation by callianassids would destroy burrows of the shallow tier under conditions of lagoonal sediment build-up that might occur with marine transgression. However, the shallow-tier burrows, particularly the thick-lined burrows of *Upogebia vasquezi*, do have good potential for fossilization, particularly under conditions of sea-level still-stand and regression. An example is provided by the work of Noble et al. (1995) on late Pleistocene rocks and shell beds in the interior of the north end of San Salvador. There, lithified burrow infill material was found in sizes and shapes nearly identical to the resin cast forms of the *U. vasquezi* burrows. Based on the sediment characteristics, fossil molluscan fauna, and these trace fossils, those ancient sediments probably were deposited on a sand flat similar to the one in modern Pigeon Creek reported on here. Furthermore, given that *U. vasquezi* has a narrow, intertidal range of occurrence, the trace fossils can be used as markers of a former sea-level position. The occurrence of similar trace fossils in other areas of the Bahamas, and beyond, would be highly useful in interpreting the sea-level history of the rocks containing them.

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## ICHNO-LOCALITY 6: THE HANNA BAY CLIFFS - MORE HOLOCENE STRATA AND ICHNOLOGY

H. Allen Curran

### INTRODUCTION

The sea cliff exposures along Hanna Bay comprise the type section for the Hanna Bay Member of the Rice Bay Formation as defined by Carew and Mylroie, 1985. The sediments of these rocks were deposited in late Holocene time essentially in equilibrium with present sea level. From the base of the cliffs, these beds represent a transition from beach backshore to protodune to dunal facies (Fig. 1). Similar late Holocene rocks and facies occur at a number of places on San Salvador and are widespread elsewhere in the Bahamas, as noted by Carew and Mylroie (1995). These rocks almost always bear interesting trace fossils and can be a real ichnologic delight.

To reach the cliffs, park on the main road near the new auto repair shop and walk south a very short distance to the second house (not in good repair and possibly abandoned). In the back of the property there is a narrow path (likely overgrown) that will head gently uphill and past a much older house in ruins. Continue along the path for about 150-200 m to the beach. Head north along the beach to the cliffs exposure, only a short distance away. The cliffs are best visited on a low tide; if not, wading will be necessary, and the going can be very slow and somewhat treacherous.

### ICHOLOGY OF THE CLIFFS

The rocks of the Hanna Bay cliffs display a fascinating array of animal and plant trace fossils representing the backshore beach and dunal ichnocoenoses as defined by Curran and White (1987, 1991) and reviewed by Curran (1994). Since

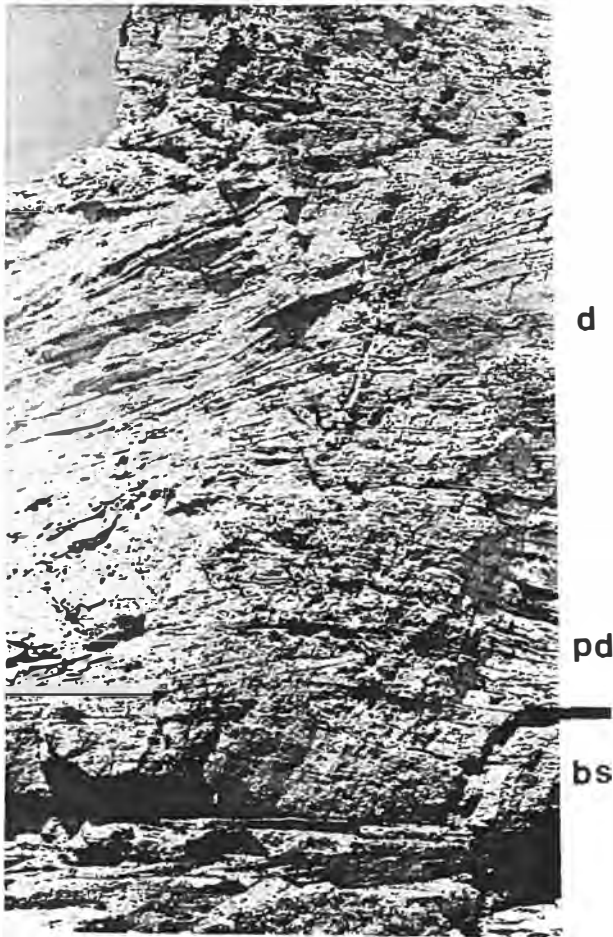


Fig. 1. The sea cliffs of late Holocene rock at Hanna Bay are about 6 m high; bs = backshore beds; pd = proto dune beds with gradual transition to d = dunal beds. Atlantic Ocean is immediately to the right of photo.

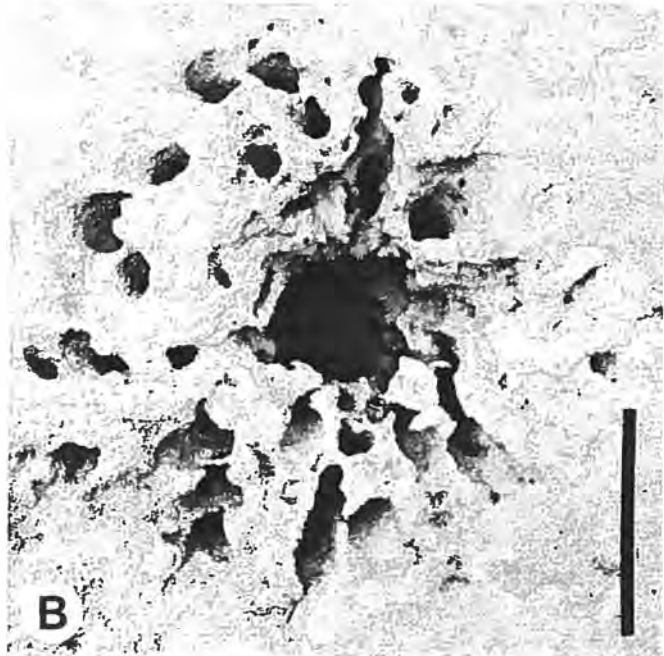


Fig. 2. A - A large "stellate" burrow at the first exposure of the Hanna Bay cliffs encountered when approaching from the south along the beach. Bar scale = 20 cm. B - Cross-sectional view of the "stellate" burrow showing the large main shaft and smaller shafts radiating outward and upward. Bar scale = 5 cm.

one or more of these references should be readily available, only a brief review of the various trace fossils will be given here.

The first cliff exposure presents a potentially most interesting ichno-stop. If the modern beach sands are not packed too high against the cliffs, a face of rock at about chest level will reveal a set of newly discovered, large (up to 1 m height), generally U-shaped burrows with a complex pattern of shafts radiating upward from the main part of the structure (Fig. 2A). A large boulder immediately adjacent to the cliff face reveals a bedding plane surface that displays well the pattern of a main shaft with smaller shafts radiating outward and upward (Fig. 2B). The radiate pattern of smaller shafts has given rise to the informal name "stellate" burrow.

These burrows occur in protodune to dune beds, predominately in the lower half of the cliffs.

An initial interpretation is that the burrow system represents some type of insect hatching structure, but no firm analogue has been established yet. My hope is that ichnologists of the IIW-4 workshop will be able to offer helpful suggestions for origin when this stop is visited.

In the immediate vicinity of the first occurrence of the "stellate" burrows are more cluster burrows (Fig. 3), as occur in the North Point eolianites. Apparently this proto-dune to dunal environment was a real breeding ground for a variety of insects. Fig. 4 shows a less well organized array of the "stellate" burrows, indicating their potentially prolific occurrence.

Specimens of *Skolithos linearis* also are fairly common in the proto-dune and dunal beds of the Hanna Bay cliffs (Fig. 5). The shafts are lined and typically are 2-4 mm in diameter and up to 30 cm in length, although most are much shorter (but likely incomplete). These specimens clearly expand the environmental range of occurrence of *Skolithos* to the dunal setting, and the tracemakers likely were insects or arachnids or both (Curran and White, 1991).

As one moves farther along the cliffs, more insect burrows of various sorts will be encountered. The beds of the cliffs also display a variety of root molds, rhizomorphs in various stages of initial formation, and structures generated by live roots. See the later chapter on plant trace fossils for more discussion of the various types of plant structures that might be observed here.

About 150 m along the cliffs the easy walking area narrows. Just beyond this point one will encounter a magnificent trace fossil specimen - the holotype of *Psilonichnus upsilon* (see frontispiece figures). In the Bahamian setting, the *P. upsilon* burrow was and is formed by the ghost crab *Ocypode quadrata*, and the trace fossils are rather widespread (Curran and White, 1991; White and Curran, 1993; Curran, 1994). Owing to the narrow distribution range of *O. quadrata* on Bahamian beaches - it is largely confined to the backshore zone - the occurrence of *P. upsilon* has real usefulness as a marker of past sea-level position. Examples of such usage are in the Belmont Formation (middle Pleistocene) of Bermuda (Curran, 1994) and in Holocene beds equivalent to the Hanna Bay Member on Lee Stocking Island of the Exuma Cays, Bahamas (White and Curran, 1993).

Obviously Holocene carbonate rocks harbor many ichnologic surprises. The ichnologic information gained from these rocks can be of



Fig. 3. A cluster burrow in the Hanna Bay cliffs.

significant value in geological interpretation and likely can reveal much about the infaunal habits and natural history of a number of modern burrowing organisms that are poorly known today.

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Fig 4. A somewhat disorganized array of “stellate” burrows, illustrating the prolific occurrence of these burrows in some places along the Hanna Bay cliffs.

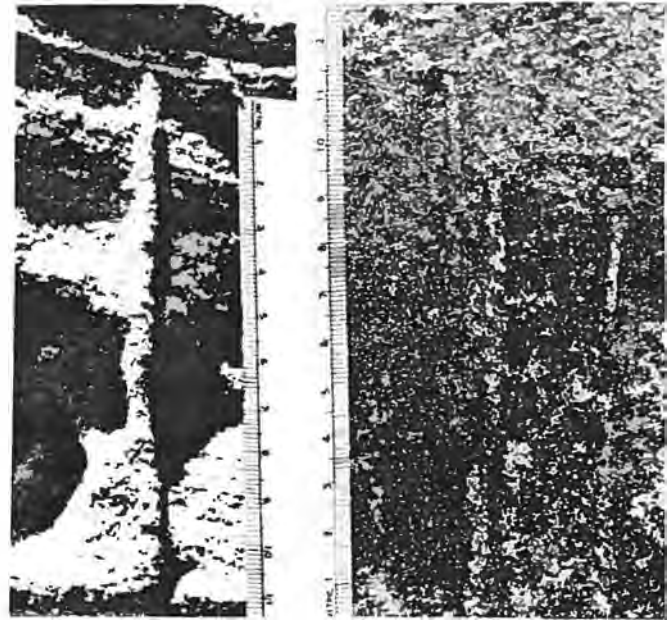


Fig. 5. *Skolithos linearis* specimens in the Hanna Bay Member.

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# PLEISTOCENE AND RECENT BORINGS IN LITHOLOGIC SUBSTRATES ON SAN SALVADOR ISLAND, BAHAMAS

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## INTRODUCTION

The shallow waters around San Salvador Island host an extraordinary diversity of organisms exploiting almost every conceivable microenvironment, from the spaces between sand grains and the interstices of corals to the tidal muds and weathered promontories in the highest splash zone of the supratidal. It is not surprising that several benthic invertebrate groups are also found in a niche which has been occupied since the Early Paleozoic: borings in carbonate substrates. This contribution is a survey of those common groups which bore into lithologic carbonate substrates on San Salvador, such as Pleistocene grainstones and Holocene beachrocks and eolianites. Borings in shells, corals and other biological substrates are not covered here, although many are also found in lithologic substrates. Scrapings and raspings made by such organisms as chitons, herbivorous gastropods, and carbonate-excavating fish are also not included. By concentrating on those animals which bore macroscopic domichnia into lithological substrates, we can limit the complications of changing biological substrates and make more direct comparisons with ancient boring communities preserved in the rock record (Bromley, 1994).

The modern borers surveyed here include sipunculids, barnacles, polychaetes, sponges and bivalves. I have concentrated on the general morphology of their borings and their ecological distribution rather than their ichno-taxonomy. Borings such as these have proven very useful in sorting out sea level changes in the Sangamonian (roughly 125,000 years ago) as recorded on San Salvador. These fossil borings and their interpretation are described at the end of this paper.

Since this is a guidebook presentation, the material will be presented primarily by localities, with the most common borings highlighted for each.

## BORINGS IN HOLOCENE BEACHROCK (FRENCH BAY) AND LATE PLEISTOCENE LIMESTONE (FERNANDEZ BAY)

French Bay on the south coast and Fernandez Bay on the west coast of San Salvador Island are relatively low energy environments protected from

the prevailing northeasterly winds. Sediment accumulation in these bays is low, so large portions of the beach and subtidal regions experience wave and current erosion. This erosion exposes large units of Holocene aragonitic beachrock at French Bay and late Pleistocene limestone along the shore of Fernandez Bay (Carew and Mylroie, 1995). The beds generally dip seaward and strike parallel to the shore. The cementation of these units varies considerably within each bay. Some beach-rocks are very hard and can only be broken with a hammer, whereas others are easily crumbled with fingers. The Pleistocene rocks normally are better indurated. This gradient of cohesiveness influences the number and type of borings found in the substrates.

## Barnacle Borings

The barnacle *Lithotrya dorsalis* produces a narrow, nearly cylindrical boring in beachrocks and eolianites on San Salvador Island (Fig. 1). The borings are by far most common in the softer beachrocks of French Bay, with a few also found in the eolianite of North Point. They are excavated parallel to bedding and thus perpendicular to the vertical beachrock faces. The typical barnacle boring is about 40 mm long, with an average apertural diameter of 8 mm and a diameter of about 4 mm at their bases. These long, tapered tubes are usually excavated on the landward and nearly vertical sides of the beachrock ridges in French Bay, apparently to avoid burial in the loose sediments which wash over the seaward and sloping sides.

A close examination of the internal surfaces of the boring walls with a scanning electron microscope has shown them to be very smooth near the base and sculpted with fine striations parallel to the axis of the borings near the aperture (Lahm, 1989). These striations match the tiny "teeth" present on the anterior portions of the *Lithotrya* peduncle. The implication is that barnacles at least partially excavate their borings by mechanical means, as suggested by Ahr and Stanton (1973). Tomlinson (1969) has suggested that *Lithotrya* also uses carbonic anhydrase or an enzymatic solution to soften the rock before abrading it with its skeleton.



Fig. 1. A modern boring excavated by the barnacle *Lithotrya dorsalis* in an exposed carbonate eolianite in the upper subtidal region off North Point. Note the clionid sponge borings near the aperture. Magnification is 2X.



Fig. 2. Modern boring formed by the bivalve *Lithophaga bisulcata* in an eolianite exposed in the upper subtidal off North Point. Note as well the clionid sponge borings on the exposed surface. From Lahm, 1989, fig. 22. Natural size.

### Sponge Borings

Clionid sponges are very common in the intertidal and subtidal waters of San Salvador Island, especially *Cliona dioryssa*. Clionid borings are found in the more indurated limestones of Fernandez Bay, and the well-cemented eolianites at North Point, especially in the fine-grained laminae (see Figs. 1 and 2). *C. dioryssa* prefers crevice surfaces, the walls of other borings, and cryptic overhanging surfaces. The borings of *C. dioryssa* are a network of spherical chambers, each ranging from 0.5 to 1.5 mm in diameter, connected with small tunnels. These sponges are usually found within the upper two or three centimeters of the substrate in the upper subtidal zone.

SEM examination of the clionid borings shows the familiar scalloped surface of small pits (about 20  $\mu\text{m}$  in diameter) excavated by the sponges (Lahm, 1989). Clionids appear to bore by primarily chemical means, as discussed by Warburton (1958), Cobb (1969), and Savazzi (1994).

### Sipunculid Borings

Two species of sipunculid worm, *Phascolosoma antillarum* and *P. scolops*, produce borings in the less indurated beachrocks of French Bay, and a few individuals of *P. antillarum* have been noted in the Fernandez Bay limestones. The borings are rare and often in such crumbly beachrock that they erode quickly after the organism's death. Sipunculid borings have thus far been found only in the upper subtidal zone. The shapes and sculptures

of the borings of the two sipunculid species are indistinguishable from each other. They are circular in cross-section, flask-shaped and straight, with their longitudinal axes perpendicular to the substrate surface. The typical sipunculid boring is about 30 mm long, with an aperture approximately 5 mm in diameter expanding evenly down to a base about 10 mm wide.

The sculpture of the sipunculid boring walls shows that the grains of the substrate were mostly cut, but by what means is unclear. In the material examined by Lahm (1989), the cut grains are smooth and show no evidence of etching or abrasion. They are usually heavily microbored, probably by fungi. Some grains were clearly not cut by any method; they appear to have been plucked out of the matrix. The methods by which sipunculids bore is unknown. They have a set of hard papillae extending from the dermis which may be related to their boring. Rice (1969) pointed out that each papilla has an epidermal gland which secretes an unknown substance. It is possible that this secretion may soften the rock so that the sipunculid could wear it away by rubbing it with the protruding papillae.

### BORINGS IN HOLOCENE EOLIANITES (NORTH POINT)

North Point is on the northeast coast of San Salvador Island. The shoreline is of considerably higher environmental energy than French and Fernandez Bays because it receives the northeast prevailing winds. Sediment accumulation is minor,



Fig. 3. Complex polychaete borings in subtidally exposed Holocene eolianite of the Rice Bay Formation. Borer undetermined. Bore hole diameter about 6 mm.

and well-cemented Holocene carbonate eolianites are exposed from the supratidal down through the subtidal zones. The eolianite consists of alternating laminae of fine and coarse-grained aragonitic sediment, which has an effect on the distribution of benthic borers.

### Bivalve Borings

The bivalve *Lithophaga bisulcata* inhabits the upper subtidal zone at North Point, boring into the eolianite (Fig. 2). Most lithophagid borings at North Point are found along cryptic overhanging surfaces in the subtidal. The borings are circular in cross-section with an average depth of about 40 mm. The apertures have an average diameter of approximately 8 mm, and the widest section near the middle of the boring averages about 10 mm in diameter. The borings taper to a rounded point at the basal end. The long axis of the boring is nearly perpendicular to the substrate surface.

The *L. bisulcata* borings are partially lined with a cryptocrystalline calcium carbonate layer about 1 mm thick in the upper half of the boring. SEM examination of this lining shows that it mimics the grains in the matrix, reproducing the grain boundaries (Lahm, 1989). The method of boring by lithophagid bivalves is still debated, with hypotheses ranging from chemical to mechanical to a combination of both (Savazzi, 1994). Jones and Pemberton (1988) hypothesized that the calcareous lining may be produced by carbonate particles becoming entangled in the mucus secreted by the pallial glands.

### Polychaete Borings

Polychaete worms are an enormously varied and abundant group in the shallow waters surrounding San Salvador Island. Their borings are ubiquitous in virtually all subtidal carbonate substrates, and they are nearly as diverse as the polychaetes themselves. An interesting set of borings found in subtidally-exposed eolianites, however, merits some notice (Fig. 3). These borings are inhabited by at least four polychaete species: *Eunice vittata*, *Lumbrineris inflata*, *Capitella capitata*, and *Lysidice* sp. The first two are very common, and the second two are rare. It has not been possible to determine which of these species, if any, produced the borings they inhabit. The borings follow the coarse-grained laminae in the eolianite and tend to be oval to circular in cross-section. The tunnels are from 4 to 8 mm in diameter and follow highly sinuous paths with occasional bifurcations. A few vertical tunnels connect the horizontal galleries.

The walls of these borings are seen to be highly etched under the SEM, with a considerable amount of fungal microboring (Lahm, 1989). Grains in the eolianite matrix are clearly cut at the boring boundaries. Haigler (1969) has suggested that polychaetes bore into carbonate substrates with an acid, and then scrape away loose debris with their stiff setae. This acid production of polychaetes has not yet been observed, but the significant etching of the boring walls may be an indication that it does occur.

### BORINGS IN PLEISTOCENE CORAL REEF LIMESTONES (COCKBURN TOWN)

Cockburn Town Reef is a Pleistocene (Sangamonian) coral reef exposed on the western shore of San Salvador Island on the north coast of Fernandez Bay. It has been described and interpreted in several papers, most notably White et al. (1984), Curran and White (1985), and Curran et al. (1989). Chen et al. (1991) presented uranium-thorium ages for the fossil corals, providing a precise chronology of its development. The northern portion of the fossil reef was dynamited in 1992, revealing fresh surfaces of the reef rock and exposing an extensive mid-reef erosion surface perforated by spectacular borings and encrusted with corals, vermicularid gastropods, and serpulids. This surface of truncation was new evidence of a major cycle of regression and transgression in the midst of the Sangamonian, and ichnology played a key role in its recognition.

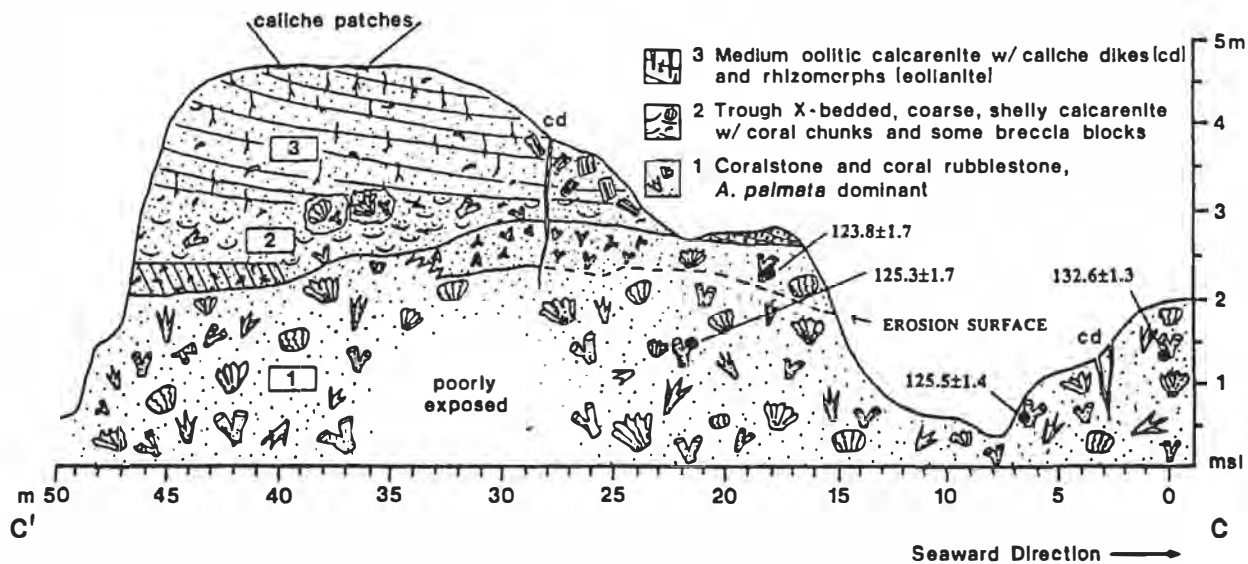


Fig. 4. Profile of Cockburn Town fossil reef, showing U-Th dates for corals and the mid-Sangamonian erosion surface. From White et al., 1997, fig. 8.

The Cockburn Town Reef erosional surface truncates coralstone, coral rubblestone and oolitic calcarenite near the stratigraphic middle of the reef complex (Fig. 4). It is planar through most of its exposure, but in the southern part of the reef it is slightly undulatory. Uranium-thorium dates on the corals indicate that the surface formed about 124,500 years ago (White et al., 1997). Sea level apparently fell about 4 meters to near present levels, deeply eroding the earlier reef, producing the truncation surface, erosional channels, and several caves. The walls of these channels and caves were encrusted with serpulids and bored by lithophagid bivalves. When sea level rose again less than 1,500 years later (White et al., 1997), the caves and channels filled with sediment and reef debris. These sediments were often burrowed by crustaceans, leaving *Ophiomorpha* and other traces. "Ophiomorpha Bay" may be one of these ancient erosional caves.

### Bivalve Borings

The most prominent borings along the Sangamonian erosional surface are those of lithophagid bivalves (Fig. 5). The best preserved are found in the channel and cave walls, some up to 5 cm wide at the apertures and up to 15 cm deep. Most can be easily classified as *Gastrochaenolites torpedo*, but several lack the diagnostic shape of the ichnospecies and must be considered as only *Gastrochaenolites* ichnosp. The *Gastrochaenolites* on the upward-facing erosional surface are almost always truncated, leaving only cup-shaped depressions. Many of these borings are in turn

bored by clionid sponges, and often both sets of borings are encrusted by corals and vermicularids. Large *Gastrochaenolites* are only rarely found truncating sponge borings, or other *Gastrochaenolites*, but occasionally small *Gastrochaenolites* are found penetrating sponge borings, sometimes with the bivalve shell still present inside (see Fig. 6). *Gastrochaenolites* in the channel and cave walls usually possess their original calcareous linings, which are often internally lined themselves with a thin brown to red caliche which apparently formed during the brief sea-level lowstand.

It appears that the majority of the bivalve borings, at least the large ones, formed during the mid-Sangamonian regression. The thin caliche inside the best preserved *Gastrochaenolites* is evidence that the vacant borings were exposed to subaerial soil-forming conditions. It is likely that



Fig. 5. *Gastrochaenolites* excavated in coral and coral rubblestone from the Cockburn Town fossil reef. Photograph by H. A. Curran. Scale is in centimeters.



Fig. 6. *Entobia* and *Gastrochaenolites* (with *Lithophaga* sp. in place) in grainstone from the Cockburn Town fossil reef. Magnification is 2X.

these large bivalve borings played an important role in the development of the truncation surface and its associated channels and caves. *Gastrochaenolites* does not seem to be a significant part of the transgressive ichnofauna, although it certainly is present.

### Sponge Borings

Clionid sponge borings (*Entobia* ichnosp.) are common on the upward-facing portions of the truncation surface in the Cockburn Town Reef (Fig. 6). These borings have not been found in channel or cave walls in this fossil reef complex. As mentioned above, *Entobia* often truncates *Gastrochaenolites*, but not commonly vice versa. *Entobia* penetrates the reef rock up to 3 cm deep. Corals and vermicularid gastropods commonly encrusted over sponge-bored reef rock.

The distribution of *Entobia* on the erosion surface shows that clionid sponges were not significant components in the channel and cave ichnofauna, but they were prominent on the upward-facing, exposed portions. Because small borings produced during the mid-Sangamonian regression could have been eroded away after exposure of the surface, we cannot determine whether clionid sponges were common bioeroders during the sea level fall, but we know they were significant when sea level rose again and the erosion surfaces were recolonized. The sponges appear to have been greatly reduced by the spread of encrusting corals and vermicularids on the upward-facing surfaces during and immediately after the transgression.

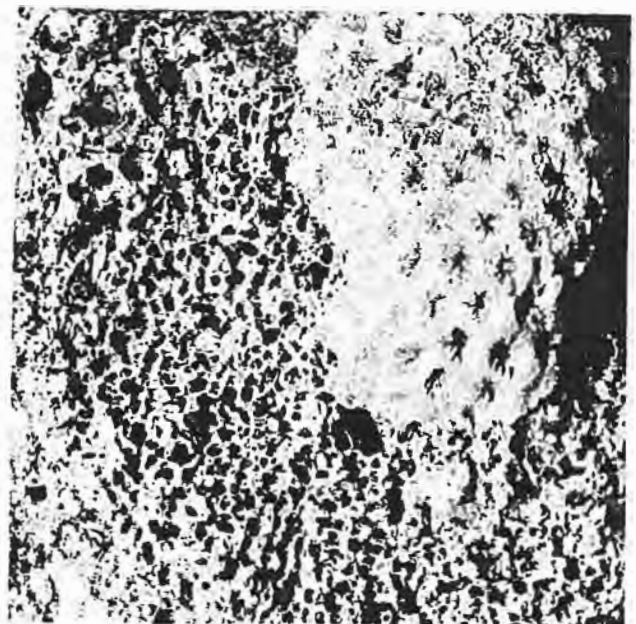


Fig. 7. *Montastrea annularis* encrusting an *Entobia*-riddled surface in grainstone from the Cockburntown fossil reef. Natural size.

### Encrusters

Two sets of encrusting invertebrates are common on the erosional surface. The upward-facing surface is encrusted by an initial layer of flat corals (*Montastrea annularis*, *Diploria strigosa* and *D. clivosa*) and vermicularid gastropod tubes. The channel and cave walls are encrusted by a variety of serpulid tubes. These encrusters are usually superimposed over *Entobia* and *Gastrochaenolites*, and are only rarely bored themselves (Fig. 7). They thus occupied the erosion surface near the end of an intense interval of boring.

### CONCLUSIONS

The borings and encrusters near the stratigraphic middle of the Cockburn Town fossil reef indicate a deep erosional surface formed during a mid-Sangamonian regression and transgression. Its position relative to radiometrically-dated corals has permitted geologists to date the timing and duration of this event with a high level of precision not common in Pleistocene sea level studies (White et al., 1997; see also Precht, 1993, Sherman et al., 1993, and Eisenhauer et al., 1996). The precise dating of this event has important implications for hypotheses concerning the control of sea level during inter-glacial intervals. The distribution of the borings also suggests that lithophagid bivalves were important bioeroders during the regression, and that clionid sponges were prominent during the later transgression. The lithophagids bored upward-facing surfaces as well as the walls of channels and caves; the clionids were primarily on the upward-facing surfaces.

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# ARE THE PLANT-RELATED FEATURES IN BAHAMIAN QUATERNARY LIMESTONES TRACE FOSSILS?: DISCUSSION, ANSWERS, AND A NEW CLASSIFICATION SCHEME

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## INTRODUCTION

Root-like structures and features attributed to the former presence of plant roots have been known from Bahamian limestones for over a century. A variety of terms have been used to classify these plant-related structures. Few geologists have described these plant traces as trace fossils and the issue of whether they are legitimate ichnofossils is a complex and unsettled question. Splendid examples of a wide variety of these features are exposed at many locations on San Salvador Island, and they will figure prominently in the field trips associated with this workshop. As background for these excursions, we here outline the history of the terminology of plant traces and explore their validity as trace fossils. We will propose a new classification and provide examples of its utility as applied to the Pleistocene and Holocene limestones of San Salvador and the Bahamas in general.

## HISTORICAL OVERVIEW

Northrop (1890) introduced the term rhizomorph for cylindrical root-like masses found in Bahamian limestones. He described the structures as masses of limestone concentrically arranged around a tubular axis formerly occupied by a plant root. He extended this usage to refer to tubular ferruginous masses found in clays in other localities. Kindle (1923) pointed out that the term rhizomorph was preempted because of earlier use by botanists. He proposed that rhizocretion replace rhizomorph for concretions having a root-like shape or that had had a root as a nucleus. In the summary of his paper, Kindle replaced rhizocretion with rhizoconcretion. In a subsequent paper he used only the term rhizocretion and concluded that they grew only during the lifetime of the enclosed root and that their growth was facilitated by soil microbes (Kindle, 1925).

Klappa (1980) made a comprehensive review of fossilized root structures and concurred with Kindle (1923) that the term rhizomorph, although attractive, was preempted by prior, specific botanical usage. He maintained, however, that rhizocretion is too restrictive as it applies only to concretionary growth and does not include petrification of plant

anatomical features. He introduced the term rhizolith as a general term to describe root materials fossilized either by enclosing sediment and/or cement or by permineralization. Klappa divided rhizoliths into five basic types. Root molds are tubular voids which mark the position of now decayed roots. Root casts are sediment and/or cement-filled molds. Root tubules are cemented cylinders around root molds. Rhizocretions are pedigenetic mineral accumulations around plant roots. Root petrifications are mineral replacements of organic matter that preserve some of the anatomical features of roots. The Klappa terminology was used by Brown (1984) for his work on caliche of San Salvador Island.

In our early work on San Salvador we used rhizocretion as a general term to describe fossilized root features (Curran, 1983, 1984; Curran and White, 1984, 1985; White et al., 1984). However, this began to change as we were influenced by Northrop's early use of rhizomorph to describe fossilized root structures found in the Bahamas (Northrop, 1890). In White and Curran (1985) we used rhizocretion in the text but reintroduced the term rhizomorph in a figure caption. Since then we have used the term rhizomorph for preserved root features (Curran and White, 1987, 1991; White 1989; White and Curran, 1987, 1988). Other workers have continued to use Klappa's (1980) terminology (for example Kindler, 1995) and some have adopted Northrop's term (for example Caputo, 1995). Some authors have even used Klappa's terminology and rhizomorph in the same article (for example Foss and Bain, 1995; Shapiro et al., 1995).

Carew and Mylroie (1995) pointed out that not all fossilized plant features represent roots, but also include other vegetative parts of plants that were buried in sediments and preserved in some fashion. They proposed that the term vegemorph be used as a replacement for all previously used terms that had rhizo- as a prefix.

Although rhizomorph seemed to us a good term for the features found in limestones that are the product of plant root growth, especially as it was first used by Northrop (1890) specifically for the very features that are found in Bahamian rocks, we have reluctantly concluded that this term should not be part of any classification scheme of plant trace fossils. Investigation of the etymology of the term



rhizomorph, for example in the Oxford English Dictionary, shows that rhizomorph was in use by botanists some 50 years prior to Northrop's use of the term. It continues to be used today, albeit not frequently. A search of the computer data base "Biological and Agricultural" yielded only seven citations for the period from July 1983 through December 1996, and a similar search in the data base "Agricola" for the period January 1992 through December 1996 yielded 18 citations.

## ARE PLANT TRACES TRACE FOSSILS?

Although the literature on the fossilized remains of roots is extensive, few authors have specifically addressed the question whether it is appropriate to consider them as ichnofossils. Sarjeant (1975, 1983) pointed out that ichnofossils are generally regarded from an animal-forming perspective and that a somewhat different approach may be needed when considering the issue of plant trace fossils. Of the four categories of plant traces that he discussed, only the topic of what he called root molds and casts will be discussed here. Sarjeant suggested that these root features could legitimately be regarded as trace fossils for the following reasons that seem relevant to this discussion. Roots are questing structures that grow through previously deposited sediments in search of water and mineral nutrients. The morphology of roots is not determined entirely by their genetic make-up, but can be strongly influenced by their environment. Thus the same plant species can have different overall root morphologies depending, for example, on the type, abundance, availability, and location of water in the substrate. Individual components of root systems have a lifetime significantly shorter than that of the plant and its total root system as a whole. Thus the total root structure is produced by the lifetime activities of the plant. Sarjeant (1975) concluded that if a structure was produced by the activities of a plant and only indirectly reflects the morphology of the plant it should be regarded as a trace fossil.

In his study of ichnofossils found in calcarenites on San Salvador, Curran (1983, 1984) concurred with Sarjeant (1975) and considered rhizocretions to be plant trace fossils. He presented criteria whereby such traces may be distinguished from those produced by animals and suggested that their mode of formation and distribution merited further study. In subsequent studies we have interpreted some fossilized plant features as plant trace fossils (Curran and White, 1987, 1991; White, 1989; White and Curran, 1985, 1988). Examples of these are described in a later section. Carew and Mylroie (1995) considered the structures that they termed vegemorphs to be plant trace fossils.

## A NEW CLASSIFICATION

Predicated on the assumption that the term rhizomorph is unavailable, we propose that the term phyto-ichnomorphs be used as a general term for trace fossils demonstrably produced by the life activities of plants. Where the traces were produced by the activities of roots we propose the term rhizo-ichnomorphs, and for those formed by other components of plants we propose that thallo-ichnomorphs be used. If fellow ichnologists convince us that our basic assumption is overly restricting, we would delete "ichno" from our proposed classification to give simply phytomorph, rhizomorph, and thallomorph respectively.

### Rhizo-ichnomorphs

Plant roots invade previously deposited, and in some cases lithified, sediments by biophysical and biochemical processes as they search for water and nutrients. In the process they disturb, distort, and, in some cases, destroy depositional fabrics and primary sedimentary structures in ways analogous to the bioturbation caused by invertebrates moving within sediments. During this activity they also produce new features in the sediments that may be preserved in the rock record (Fig. 1). Carbonate sediments are particularly prone to changes caused by the biogeochemical activity of plants, plant roots, and their associated microbial symbionts. Such activities cause both dissolution and precipitation of calcium carbonate depending on whether acids are produced or whether carbon dioxide or water is withdrawn from the system. Precipitation is especially important as it can lead to concentric micrite deposition around a plant root or to preferential cementation of the enclosing sediment in the immediate vicinity of the root. This would produce respectively what Klappa (1980) called rhizocretions and root tubules and which Northrop (1890) collectively called rhizomorphs.

Rhizo-ichnomorphs occur abundantly in the limestones of The Bahamas, especially in those of late Pleistocene age (Figs. 2A, B, C). They are particularly prominent in the upper 2 to 3 meters of fossil dunes composed of carbonate eolianites (Fig. 3). These dunes appear to have been deposited largely in the absence of vegetation and became colonized by vegetation only following their formation, probably as a result of a change from an arid to a more humid climate (Caputo, 1995). The roots of such colonizing plants invaded the dunes from above and extended down into the upper few meters of the sediments, presumably in search of water and mineral nutrients (Fig. 4). This root activity effectively destroyed pre-existing

sedimentary structures and produced new ones that are now preserved in the upper parts of the dunes. Together with the associated caliche and paleosol, this horizon of more resistant rhizo-ichnomorphs has tended to protect the fossil dunes from erosion and led to the preservation of complete dune forms that we see today. All of this activity took place in a non-marine environment, but it is important to realize that rhizo-ichnomorphs can develop on any facies that becomes exposed to the terrestrial environment as a result of changes of sea level, including coral reefs (Curran and White, 1991).

### Thallo-ichnomorphs

The above-ground part of a plant (the shoot) may be partly or completely buried in sediment, particularly by wind-blown sand. Here the active role is played largely by the moving sediment and the plant is mostly passive, even though it may facilitate the accumulation of sediment by acting as a baffle. Molds of the roots of the sea grape (*Coccoloba uvifera*) occur in the Holocene Rice Bay Formation on San Salvador (Figs. 5A, B). They are regarded as body fossils and criteria for their distinction from animal trace fossils are given in Curran and White (1987, 1991).

For many plants the active growth of the shoot is upwards, commonly in the search for sunlight needed for photosynthesis. In some plant species, however, the horizontal growth of runners or stolons takes place either along or a little below the soil surface. This may be to spread the roots widely in areas of sparse water or nutrients or as a reproductive mechanism. In this case parts of the shoot are actively interacting with the sediments into which their roots are anchored. Plants with runners extending for several meters across the surface of sand dunes are abundant on San Salvador, for example the railroad vine (*Ipomoea pes-caprae*) and bay geranium (*Ambrosia hispida*). In some cases narrow ridges of hardened sand lie immediately beneath trailing plant runners. These ridges are believed to form as a result of the activity of the plants as they protect the sand from wind scouring and cause lithification due to the biochemically induced precipitation of low magnesian calcite micrite (Curran and White, 1987, 1991). Fossil analogs of such features found in the Rice Bay Formation on San Salvador are described in Curran and White (1987, 1991) who consider them to be plant trace fossils.

### UTILITY OF PHYTO-ICHNOMORPHS

Even though few geologists have addressed the issue of whether plant traces are ichnofossils, many



Fig. 1. Rhizo-ichnomorphs produced in late Pleistocene eolianites by the biogeochemical action of plant roots that also modified the original sedimentary structures. The Gulf, San Salvador Island.

have used them as aids in interpreting Bahamian limestones. Although phyto-ichnomorphs form in the terrestrial, non-marine environment their presence cannot be used as proof that all facies in which they are found were deposited in non-marine environments (Curran and White, 1991). Rhizo-ichnomorphs can be found directly on the surface of corals preserved in growth position (Fig. 6), in which case they do provide compelling evidence of a fall in relative sea level and a change from marine to non-marine environments (White and Curran, 1997). In cases where rhizo-ichnomorphs are clearly within eolianites, as shown by independent criteria, their formation within contemporaneous or closely time-related non-marine environments can be demonstrated. An example of this situation from the late Pleistocene is given by Caputo (1995), who also used the sediment-plant trace relationships to determine climatic changes, as mentioned above.

Micritic crusts with micritic ridges and thallo-ichnophytes occur commonly on bedding surfaces at 10 to 15 cm intervals in the vertical sequence of many Rice Bay Formation strata of Holocene age on San Salvador (Fig. 7A). These crusts and their associated thallo-ichnomorphs (Fig. 7B) formed on

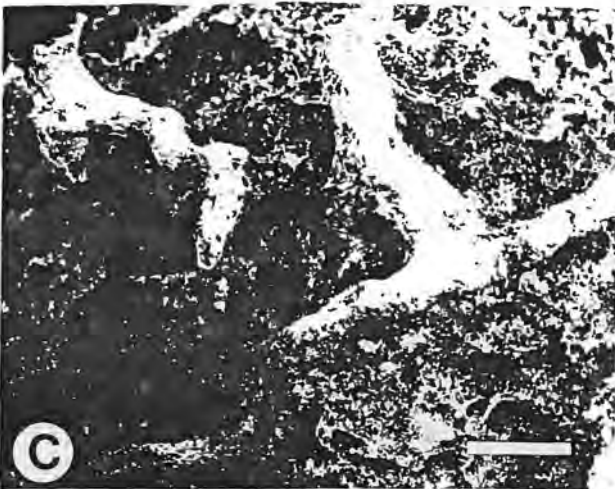
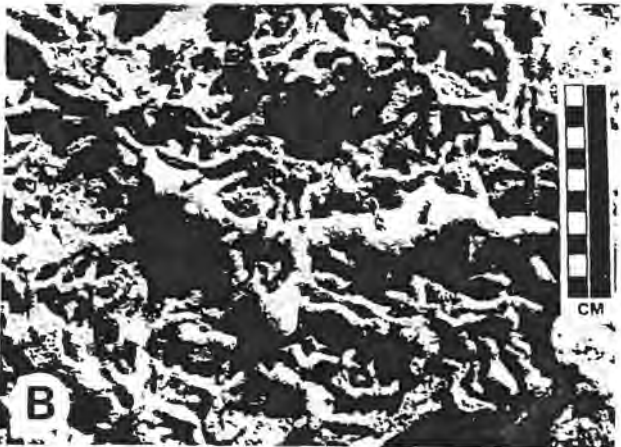


Fig. 2. A - Dense network of rhizo-ichnomorphs on the bedding surface of late Pleistocene eolianites. Great Inagua Island. B - Dense network of rhizo-ichnomorphs from the upper part of a late Pleistocene dune. Swollen parts of the structure may represent former nutrient storage areas modified by biogeochemical precipitation. The Gulf, San Salvador Island. C - Rhizo-ichnomorphs with tubular structure showing enlargement due to biogeochemical precipitation of micrite. Scale bar = 1.5 cm. Late Pleistocene, North Eleuthera.

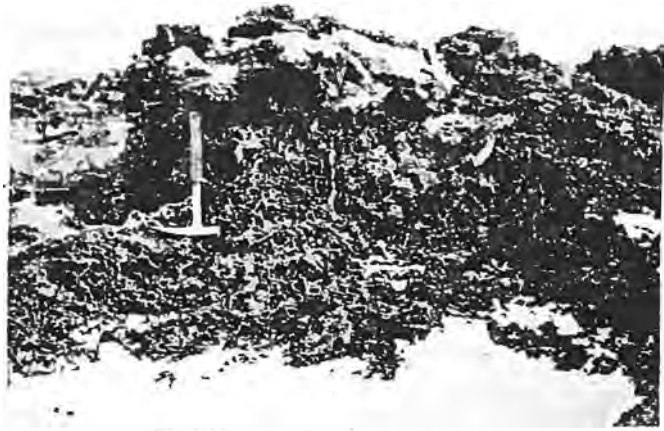


Fig. 3. Rhizo-ichnomorphs concentrated in the upper part of a late Pleistocene dune. Rocky Point, San Salvador Island. From Carew and Mylroie (1985).



Fig. 4. Rhizo-ichnomorph enlarged by micrite precipitation adjacent to plant root that penetrated deeply from the surface into a late Pleistocene dune. North Eleuthera.

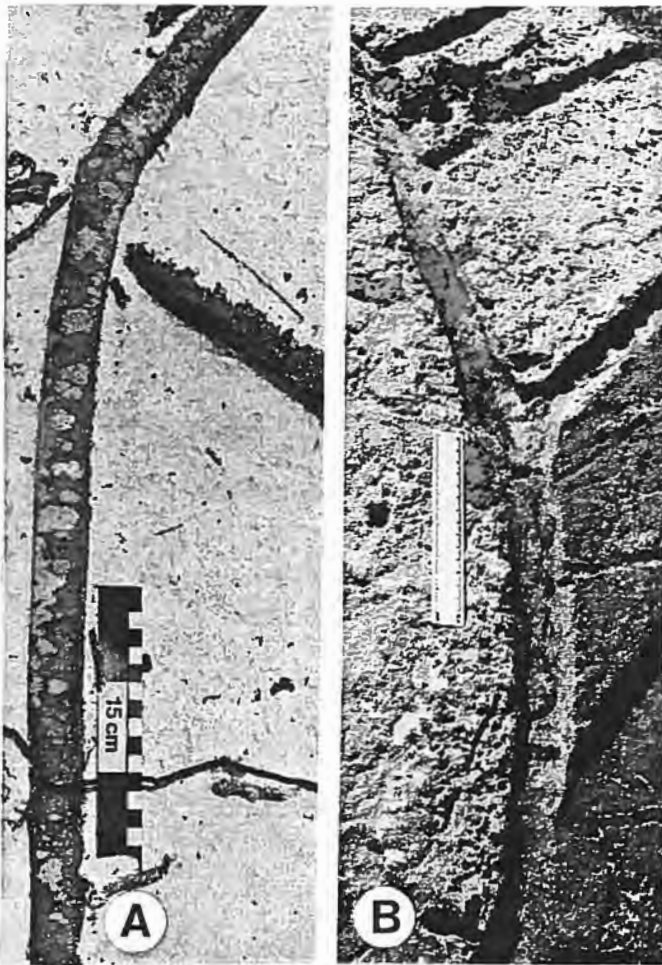


Fig. 5. A - Roots of living sea grape (*Coccoloba uvifera*). B. - Root mold probably of the sea grape (*Coccoloba uvifera*). Holocene, Hanna Bay, San Salvador Island.

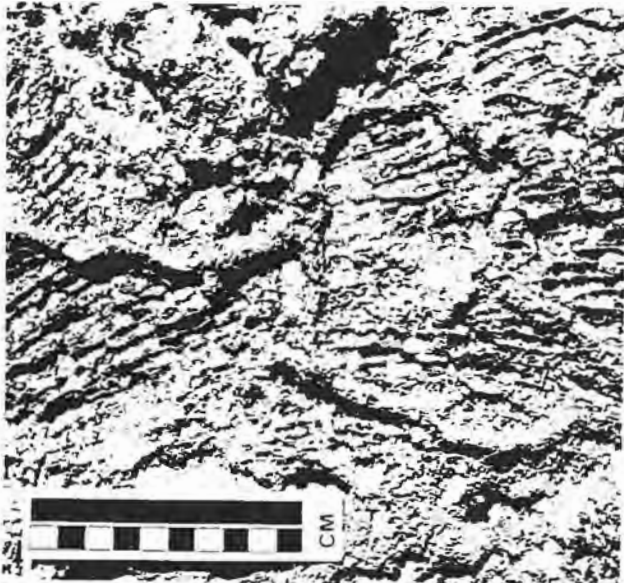


Fig. 6. Rhizo-ichnomorphs on the surface of coral fossilized in growth position. Devil's Point, Great Inagua Island.



Fig. 3. Polychaete borings along bedding in a carbonate eolianite exposed in the upper subtidal region off North Point. Magnification is 2X.

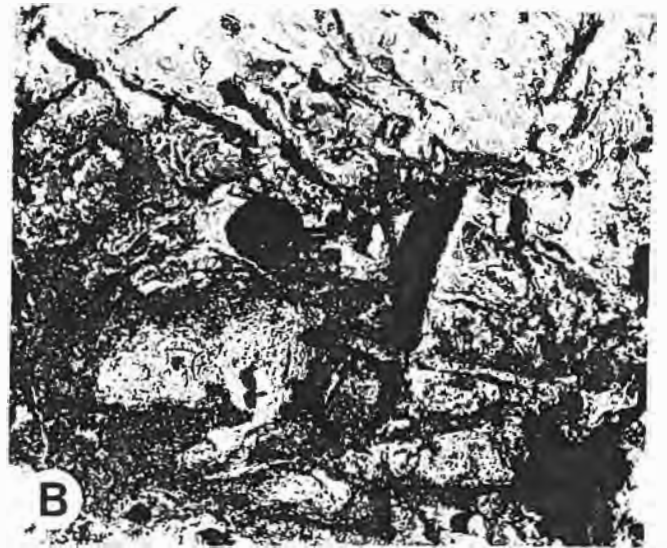


Fig. 7. A - Micritic crusts on bedding surfaces of a Holocene dune. Scale = 10 cm. North Point, San Salvador Island. B - Thallo-ichnomorphs on the surface of a micritic crust. Holocene dune. North Point, San Salvador Island. Lens cap = 5.5 cm.

the surface of sand dunes during relatively long intervals of non-deposition that were separated by periodic sedimentation events, probably related to severe wind storms. Such occurrences were regarded as a specific criterion for the recognition of eolianites in the rock record (White and Curran, 1988). The postulated mode of formation of these Holocene dunes differs significantly from the conditions under which the Pleistocene dunes formed as described by Caputo (1995) and much of the evidence for these interpretations is provided by phyto-ichnomorphs. In this example, the distribution and activities of plants probably were responding to differences in climate, especially rainfall.

Kindler (1995) in his studies of Bahamian strata on Lee Stocking Island and elsewhere distinguished Pleistocene and Holocene limestones in part by differences in their contained rhizcretions (Klappā, 1980 terminology). He believed that root molds and tubules could be found in Holocene strata, but root casts are restricted to strata of Pleistocene age. This field method does not seem completely valid for the limestones on San Salvador.

Carew and Mylroie (1995) use the relative abundance of what they call vegemorphs to distinguish between dunes that formed during regressive versus transgressive phases. Their hypothesis is based on the assumption that following complete marine withdrawal from a platform it will take a long time for plants that are capable of colonizing dunes to be re-established as they must be imported from some refugia. Thus dunes formed during a subsequent transgression will be largely devoid of plants. Conversely, during regressive phases of dune formation dune-dwelling plants will be well established and such dunes will be well vegetated.

The Pleistocene dunes described from San Salvador by Caputo (1995) are regressive dunes according to the classification of Carew and Mylroie (1995), yet they were largely devoid of vegetation during their formation and only became vegetated when the climate became more humid. On the other hand, the dunes that have formed during the Holocene transgression appear to have been vegetated throughout most of their development (Curran and White, 1987, 1991; White and Curran, 1987, 1988). This suggests that the establishment of vegetation is more influenced by climatic factors than the slow migration of colonizing plants.

## CONCLUSIONS

Traces of the roots and shoots of terrestrial plants are common features found in Quaternary limestones of the Bahamas. Classifications of these features have been made that do not consider whether they are ichnofossils.

Plant traces have been used for a variety of interpretative purposes including amplifying evaluation of depositional sedimentary environments, clarification of stratigraphic relationships, confirmation of episodes of sea-level change, and illuminating the impact of climate change on the character and distribution of terrestrial vegetation.

We conclude that some plant traces are properly classed as ichnofossils and make a first proposal for their classification. We propose the term phyto-ichnomorphs as a general term for trace fossils produced by plants and divide this into rhizo-ichnomorphs and thallo-ichnomorphs for those traces produced by the roots and shoots of plants respectively.

## ACKNOWLEDGEMENTS

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# A *CONICHNUS CONICUS*-GENERATED ICHNOFABRIC IN LATE PLEISTOCENE LIMESTONES AT CLIFTON PIER, NEW PROVIDENCE ISLAND, BAHAMAS

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## INTRODUCTION

New Providence Island is the site of the city of Nassau, the capital of The Bahamas and its largest population center. Roads are well developed on the island, providing easy access to numerous sites of geologic interest. The western half of the island presents several highly instructive sites revealing late Quaternary carbonate geologic features and described in a recent guidebook by Carew et al. (1996).

Clifton Pier is an easily reached site at the southwest corner of the island and on the seaward side of South West Road (Fig. 1). Here sea cliff exposures and human-generated cuts in the rock present one of the best vantage points on New Providence Island for the examination of late Pleistocene subtidal to beach limestone facies. A stratigraphic section with a total thickness of over 7 m reveals much about the vertical facies sequence, bedding styles, and physical sedimentary structures typical of Bahamian subtidal to beach transition sequences. In addition, the calcarenites of this sequence contain numerous trace fossils, dominated by large, well-developed specimens of the vertically-oriented trace fossil *Conichnus conicus*. The purpose of this contribution is to describe briefly the principal facies of the Clifton Pier section; particular emphasis will be placed on the assemblage of trace fossils found in the subtidal facies and its significance and interpretation.

The steep and commonly sheer cliffs at Clifton Pier have been extensively modified by human activity. Because deep water lies immediately offshore, this reach of coast is a port area for oil tanker off-loading, power generation, and associated industrial activity. The area now is far from idyllic, as it is littered with all manner of debris, from trash to rusting pipes to abandoned concrete buildings. The result is that this site is hazardous, and visitors should use great caution in moving around the pier area and clambering along the cliffs while dodging pipes and concrete obstacles and moving through the various abandoned facilities. The good news is that some of the cuts made into the rocks to service the various facilities provide excellent vertical exposures for ichnologic study and photography.

The sea-level history of a set of closely spaced cores in the area and the stratigraphic section at Clifton Pier recently were studied by Aurell et al., 1995. The late Pleistocene facies of the Clifton Pier area were shown in a map by Garrett and Gould (1984, Fig. 8), and notes on Clifton Pier and the regional geology are given in the guidebook by Carew et al. (1996).

## THE GEOLOGIC SETTING

Clifton Pier and Clifton Point are located at the southwestern end of New Providence Island (Fig. 1), at the physiographic edge of the island platform. The exposed rocks are carbonate grainstones (calcarenites) capped by a thin paleosol layer; a small coral head (? *in situ*) from this locality yielded a U/Th age of 146 +/- 9 ka (Neumann and Moore, 1975). Therefore, these rocks are of late Pleistocene age, and, based on stratigraphic position and rock type, they can be assigned to the Grotto Beach Formation of Carew and Mylroie (1995, and earlier references). Furthermore, the largely subtidal nature of these rocks suggests assignment to the Cockburn Town Member.

At Clifton Pier, we measured a well-exposed stratigraphic section that lies immediately to the east of the old concrete dock (left side of dock when facing seaward); this section is shown in Figure 2. The section has a thickness of 6.5 m and reveals a classic Bahamian shallowing-upward sequence (as described in White et al., 1984) consisting of fine to very coarse, shelly, peloidal grainstones, ranging from shallow subtidal beds, to swash zone deposits and overstepping beach beds with parting lineations and bubble porosity. The sequence is capped by a thin paleosol-caliche layer. Coarse and fine lamination couplets are prominent in these beds, particularly in the trough and tabular cross-bed sets, with the finer laminations showing preferential cementation.

The top of the yellow zone (intertidal algal zone) closely approximates the level of mean high water; we have found this level to be a convenient and reasonably consistent marker for the zero point of stratigraphic sections made throughout the Bahamas. The conical trace fossil *Conichnus conicus* is prominent in the lower part of this section.





Fig. 1. Location of Clifton Pier on New Providence Island (modified from Carew et al., 1996).

The upper part of the Clifton Pier section reveals a beach sequence and is nicely sketched in a figure recently published by Aurell et al. (1995, Fig. 5).

Interesting cliff exposures occur in both directions along this reach of coast. If time permits, move west along the coast, being careful to avoid the hazards mentioned earlier. Soon (about 100 m) one will come to an area where there is a large double cut in the rock normal to the coast. This is a part of the adjacent power station facility; the building areas are abandoned and now dangerous - move with care. On the northwest side of this cut area, a concrete staircase can be used for access to the base of the stratigraphic section shown in Figure 3. The rock exposures are clean and steep, and the section has a thickness of over 8 m and generally shows the same sequence of facies as in the previous section. Here *Conichnus conicus* is found to a level almost 3 m above the top of the yellow zone; its density of occurrence results in significant bioturbation and above this zone shallow-water physical sedimentary structures are well developed (Fig. 4).

Good exposures continue from this point along the coast. The climbing is a bit slow, but, if time permits, one should continue on to the entrance of a small sea cave (only easily accessible at low tide). The interior walls of the cave reveal excellent exposures of the subtidal beds that contain well-formed examples of *C. conicus*.

## THE TRACE FOSSIL ASSEMBLAGE

The shallow subtidal facies at Clifton Pier contain an ichnoassemblage dominated by *Conichnus* and *Ophiomorpha*, with minor *Skolithos linearis*, *Skolithos*-like forms, and horizontal, gently meandering burrows. The *Conichnus* specimens clearly belong to the ichnospecies *C. conicus* Myannil as defined by Pemberton et al. (1988). *C. conicus* is a large, conical, vertical burrow that exhibits nested, cone-in-cone laminations in longitudinal view and is circular to oval-shaped in horizontal cross-section (Fig. 5A,B). Burrows commonly exhibit a well lithified, exterior rim with

## CLIFTON PIER SECTION 1 New Providence Island, Bahamas

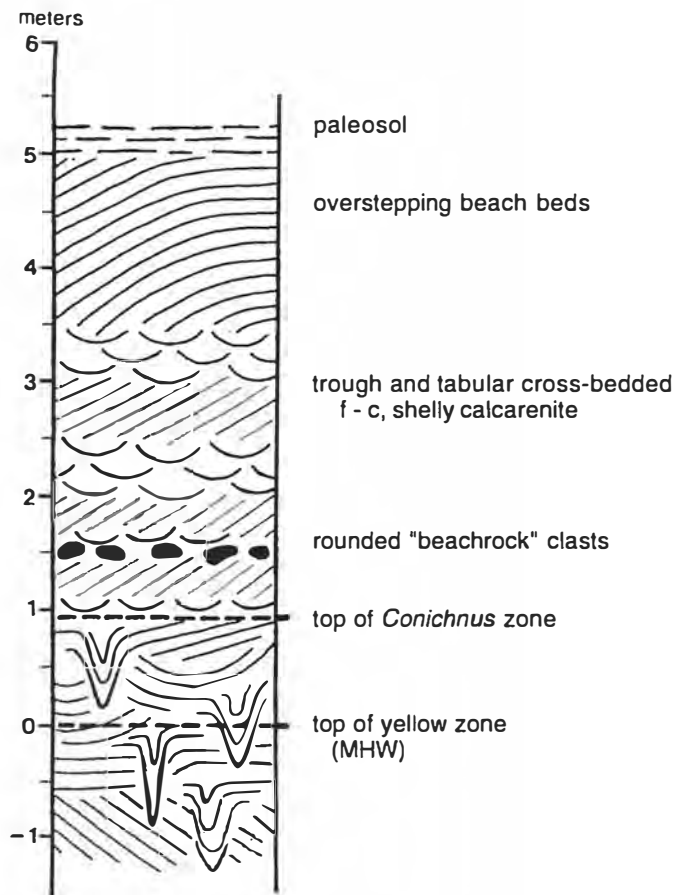


Fig. 2. Measured section showing shallowing-upward sequence immediately adjacent to the east side of the concrete dock at Clifton Pier.

the top of the conical form filled by coarse, poorly laminated sediment (Fig. 5B). In this tabular and trough cross-bedded sequence, *C. conicus* specimens are abundant and robust, averaging 9 to 10 cm in diameter (Fig. 6) and reaching 1.2 m in length. Most burrow lengths measured at Clifton Pier represent minimums because the full burrow length only rarely is revealed in outcrop.

In the sea cave exposure located a short distance beyond Section 2, specimens of *Conichnus conicus* are numerous and can be viewed in both vertical and horizontal section (Fig. 7A). The distinctive knobs found on the roof of the sea cave are the tops of *C. conicus* burrows! We were able to measure a 5.625 m<sup>2</sup> area of the cave roof; 30 burrow tops were counted within this area, for an average of 5.3 burrows/m<sup>2</sup>. Since all of these burrows are *in situ*, this is a measure of the density of tracemaker organisms that originally were present in these sediments. The nature of the tracemaker will be

CLIFTON PIER SECTION 2 (staircase)  
New Providence Island, Bahamas

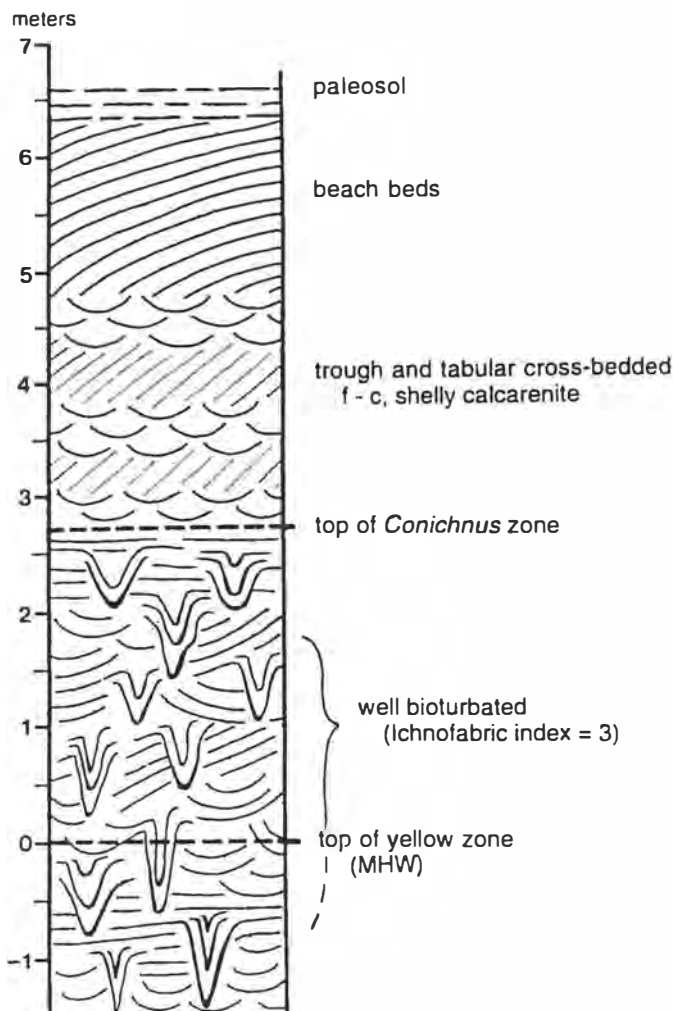


Fig. 3. Measured section at the power station facility cut, a short distance northwest of Section 1. Access to the base of the section is via the concrete staircase adjacent to the cut.

discussed further in the following section.

As exhibited particularly well in the exposures in the vicinity of Section 2 ("staircase"), *Conichnus conicus* can be a dominant burrow capable of bioturbating the sediment to the extent that a distinctive ichnofabric results (Fig. 7B). These exposures are ideal for measuring ichnofabric using the Droser/Bottjer Ichnofabric Index scale, and ichnofabric index values of 3 to 4 were obtained on a 5 point scale. At the high end of the scale, no new burrows could be added without directly impinging on a previously formed burrow.

*Ophiomorpha* also is present in the subtidal beds at Clifton Pier, but it is clearly and always subordinate in abundance to *Conichnus conicus*.



Fig. 4. View of mid-part of Section 2 showing trough and tabular cross-beds with lamination couplets well-bioturbated by *Conichnus conicus* and *Ophiomorpha*. A transition occurs at the upper part of the section to gently seaward dipping beach beds.

These *Ophiomorpha* are morphologically very similar to *Ophiomorpha* previously described by Curran and White (1991) from other areas in the Bahamas, except that they tend to be less robust (outside burrow diameters of 1.5 cm or less as opposed to 2 to 3 cm diameter average elsewhere). Figure 7C shows a well-developed, branching *Ophiomorpha* burrow system with shafts and tunnels. The burrows are well-lined and have the pelleted exterior and smooth interior surfaces characteristic of this ichnotaxon. As will be discussed in the next section, these tabular and trough cross-bedded sediments were deposited in an energetic environment, and the relatively mobile bottom likely suppressed dense burrowing by the *Ophiomorpha* tracemaker callianassid shrimp.

Vertical, lined and unlined, unbranched burrows 2 to 4 mm in diameter that represent the ichnospecies *Skolithos linearis* are present but rare in these subtidal deposits. With some searching, examples can be found. These burrows likely were formed by polychaetes (Curran and White, 1991). In the exposures at Section 2, we observed some

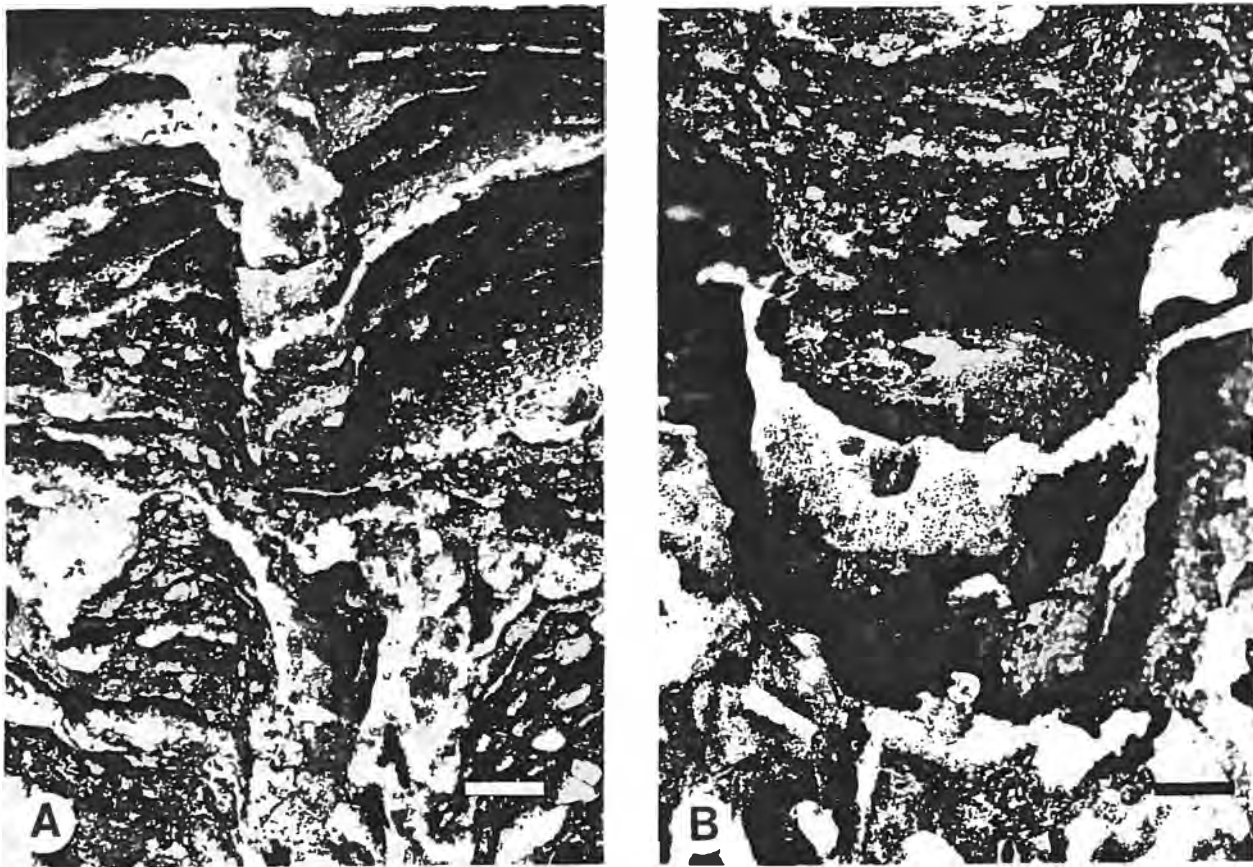


Fig. 5. A - longitudinal section of a typical *Conichnus conicus* specimen at Clifton Pier. Note nested cone-in-cone structure and well-laminated sediment couplets. Bar scale = 4 cm. B - Cross-sectional view of a *C. conicus* specimen. Note the well-lithified rim surrounding the burrow and the coarse, poorly laminated sediment infilling the top of the burrow. Bar scale = 2 cm.

DIAMETERS OF *CONICHNUS CONICUS*  
Clifton Pier, New Providence Island, Bahamas

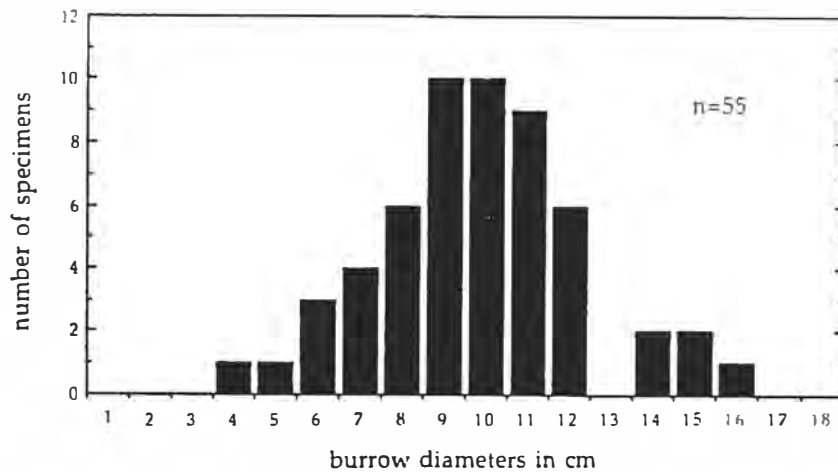


Fig. 6. Histogram showing the distribution of burrow diameters of 55 specimens of *Conichnus conicus* measured at Clifton Pier.

*Skolithos*-like burrows. They differ from typical *Skolithos linearis* by having a larger diameter (up to 0.8 cm) and a bulbous base. Also present but rare in this area are horizontal, gently meandering burrows that might reasonably be assigned to *Planolites*. As discussed below, similar burrows have been found with this ichnoassemblage in the Exumas. Both the *Skolithos*-like burrows and the horizontal, gently meandering burrows probably were formed by marine worms, although not necessarily polychaetes.

## INTERPRETATION AND SIGNIFICANCE

This *Conichnus conicus*-dominated ichnoassemblage or ichnocoenosis (since these trace fossils had a temporal origin) that characterizes the subtidal beds at Clifton Pier is known elsewhere from similar late Pleistocene beds in the Bahamas, namely from Little Exuma Island (Curran, 1990, 1994) and from a recently discovered occurrence at the north end of the Cockburn Town fossil reef complex on San Salvador. Beyond the Bahamas, the ichnocoenosis has been reported from similar settings in two other late Pleistocene units, the Miami Limestone in southern Florida (Shinn, 1968; Halley and Evans, 1983) and the Ironshore Formation on Grand Cayman Island (Pemberton and Jones, 1988; Jones and Pemberton, 1989).

In all cases, this ichnocoenosis occurs in carbonate grainstones characterized by tabular and trough cross-beds and representing shallow subtidal, shoaling conditions, likely deposited under the influence of nearshore or tidal currents in what are interpreted to be protected coastal bay to lagoonal conditions. At Clifton Pier, Aurell et al. (1995) interpreted the subtidal beds to have been deposited as part of a tidally influenced sand flat on a semi-protected bank, possibly behind a reefal complex.

*Conichnus* previously has been interpreted as the dwelling burrow or resting trace of an anemone-like organism (Pemberton et al., 1988), and Shinn (1968) made a convincing case for origin by the burrowing activities of a sea anemone by observing burrowing activity of the modern anemone *Phyllactis conguilegia*. Based on this analogy, we interpret the nested, cone-in-cone structures at Clifton Pier as representing the dwelling burrows and escape

structures of sea anemones attempting to keep pace with pulses of rapid sedimentation under at least somewhat protected, possibly lagoonal, and shoaling conditions. Likewise, *Ophiomorpha* and *Skolithos linearis* were subordinate in occurrence to *Conichnus conicus* owing to the actively shoaling conditions.

## ACKNOWLEDGMENTS

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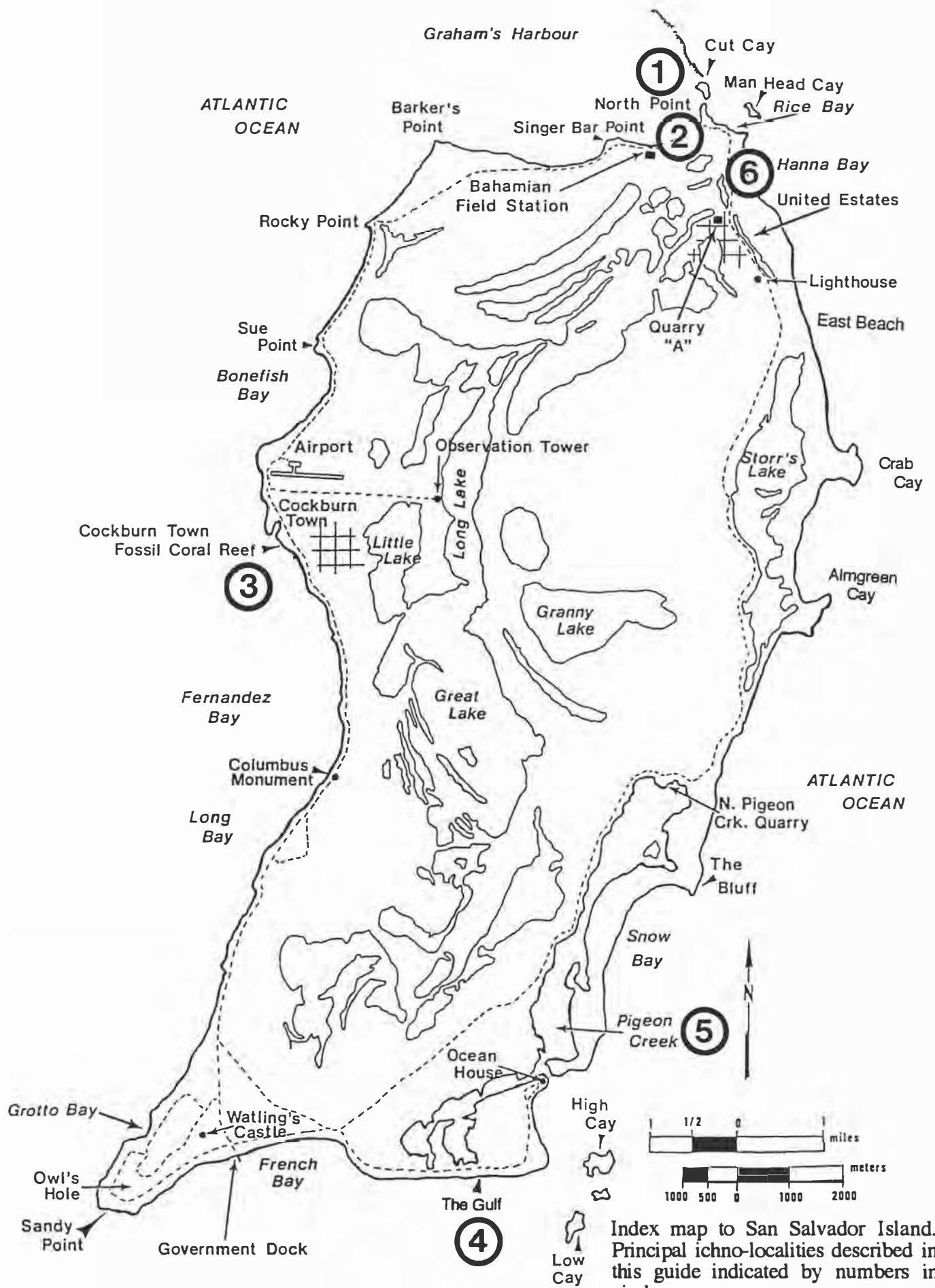
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Fig. 7. A - Well defined *Conichnus conicus* burrows exposed in a small sea cave just above mean high water-level and located a short distance northwest of Section 2. Note that the tops of several burrows (burrow infill sediment) are preserved on the roof of the cave. Rock hammer = 28 cm in length. B - Subtidal tabular and trough cross-bedded sequence well-bioturbated by *C. conicus*. Some *Ophiomorpha* also present. Scale = 15 cm. C - *Ophiomorpha* shaft and tunnel burrow system in well-laminated tabular cross-bedded sequence near Section 2. Bar scale = 3 cm.



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## Notes



Index map to San Salvador Island. Principal ichno-localities described in this guide indicated by numbers in circles.





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