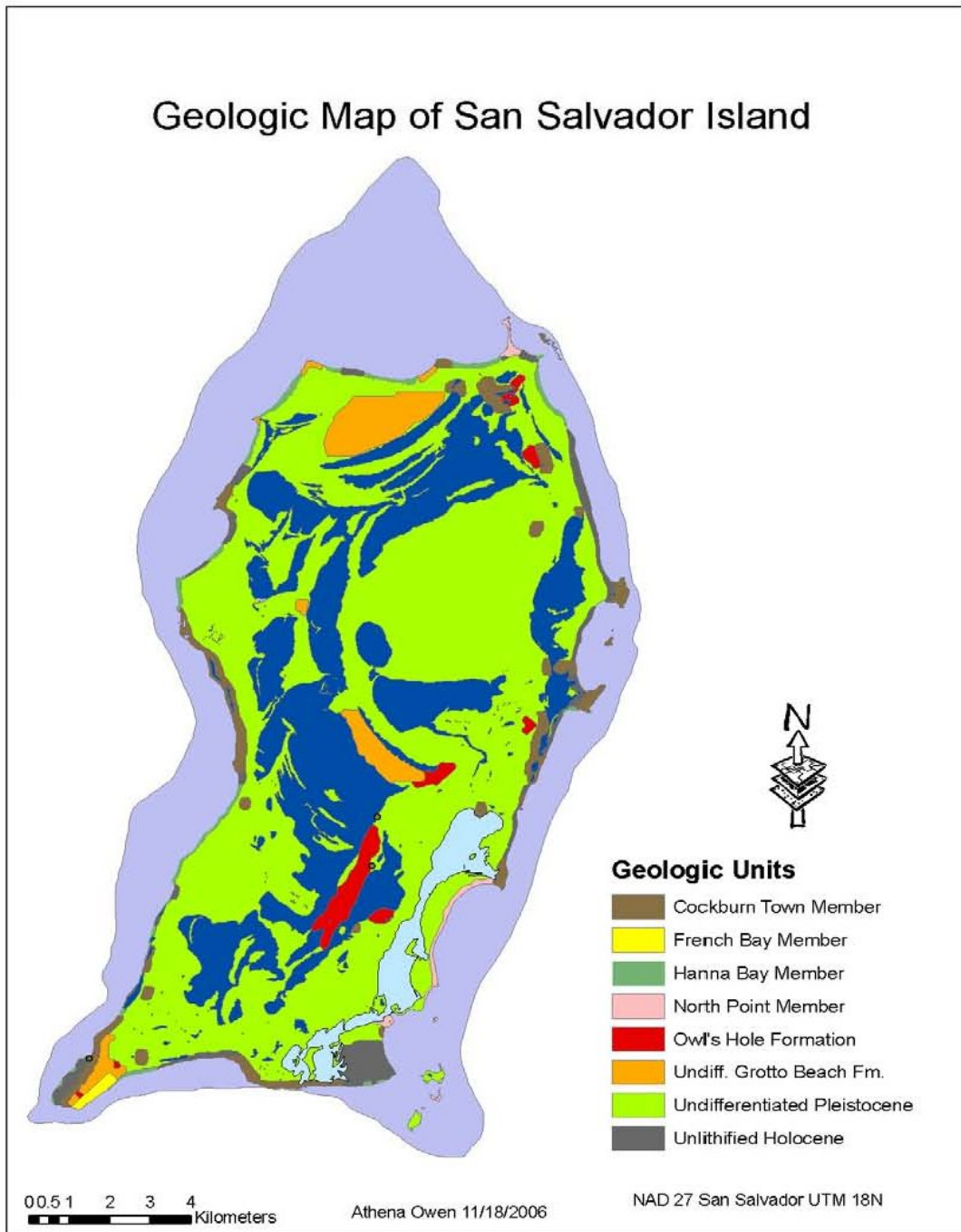
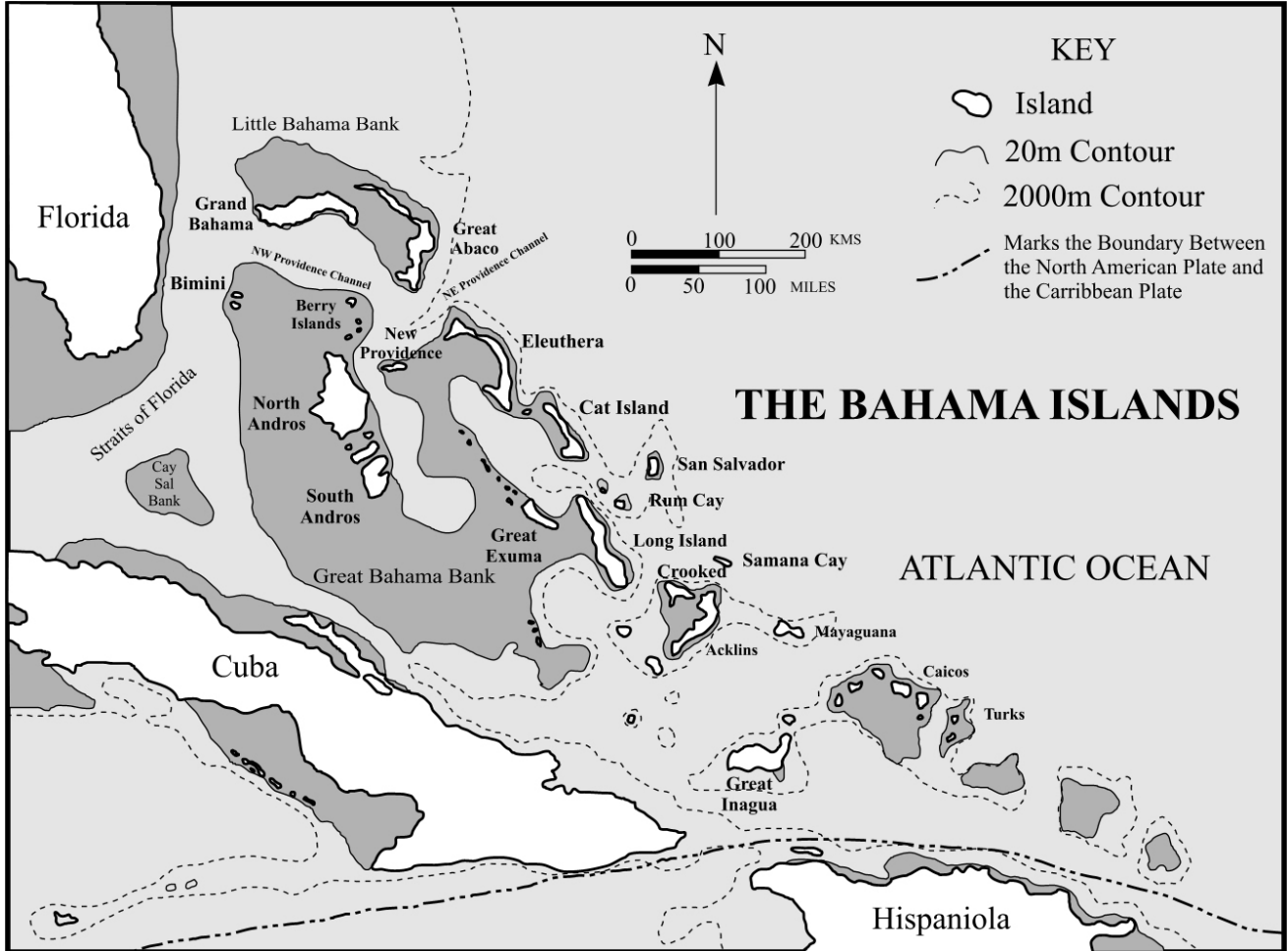


# FIELD GUIDE TO THE GEOLOGY AND KARST GEOMORPHOLOGY OF SAN SALVADOR ISLAND



John E. Mylroie and James L. Carew



**Figure 1. Map of the Bahamian Archipelago and surrounding environment. Modified from Carew and Mylroie, 2001**

**Cover image by Owen (2007), modified from Robinson and Davis (1999).**

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OF SAN SAL ISLAND**

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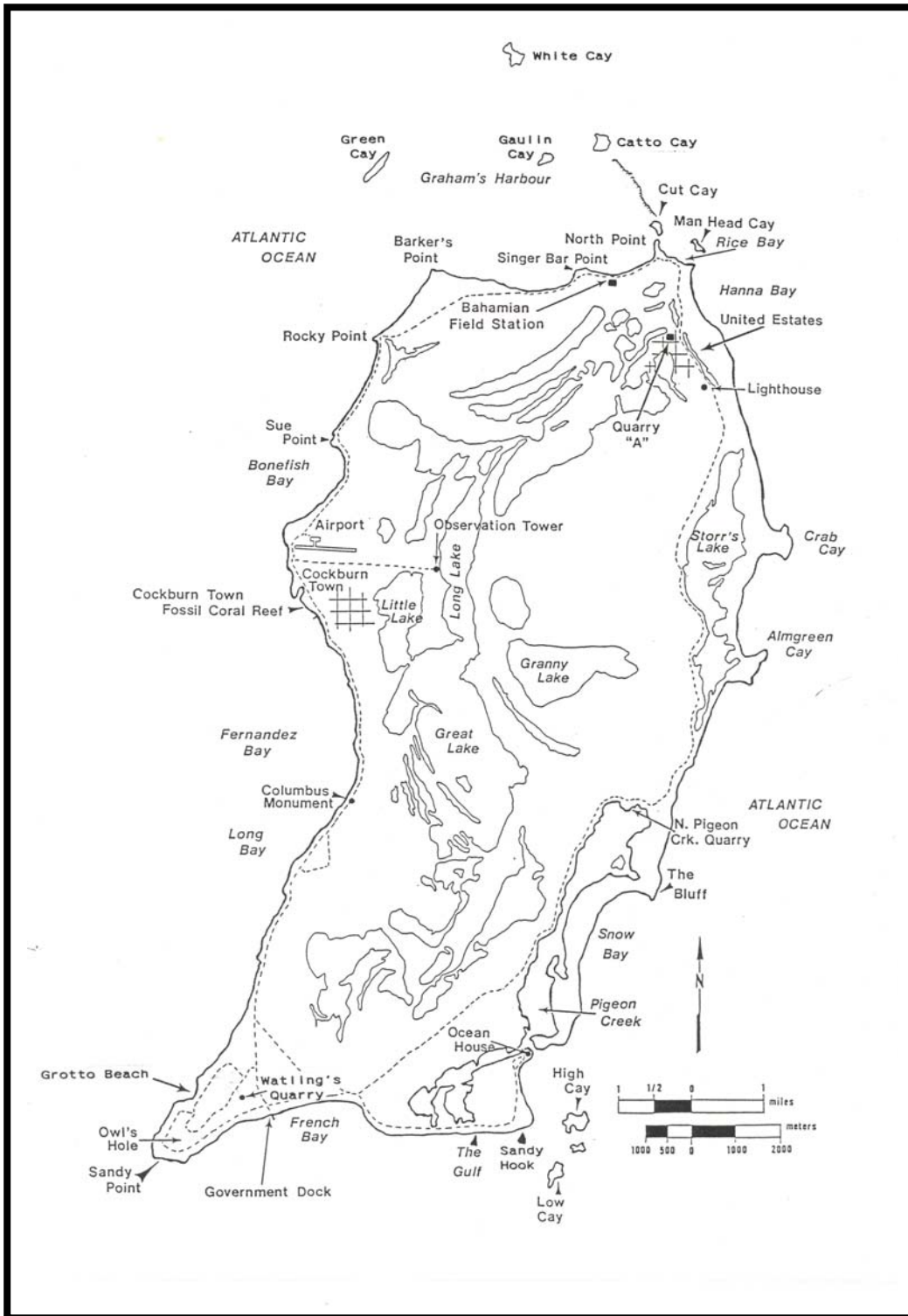


Figure 2. Map of San Salvador Island, Bahamas, with place names of important landmarks. From Carew and Mylroie, 1995a.

## INTRODUCTION

The purpose of this field guide is to introduce the participant to the geology and geomorphology of the Bahamas (Fig.1) as seen on San Salvador Island (Fig. 2), by visiting various localities exposed primarily along the perimeter of the island. The stratigraphy used in this guide (Fig. 3 and Table I) is that of Carew and Mylroie (1995a; 1997). This stratigraphic sequence comprises depositional units that were deposited as a result of sea level changes during the Quaternary. A general geologic map of San Salvador Island is shown in Figure 4.

Please do not hammer on rocks or collect samples without first checking with your trip leader, as many of the field trip stops to be visited are unusual and are designated as protected sites by the Bahamian Government. Some sites are located on private land, and all property, private or public, must be treated with the same respect you would expect on your own personal land.

The official name for the country we are in is “The Bahamas”, but “Bahamas” will be used in this field guide, as experience has taught us readers get confused when “The” is used; they assume a new sentence has begun. Despite recent discussions regarding the stratigraphic code, the term “Quaternary” will be used in this field guide. The depositional events of the Bahamas are tied to Quaternary sea-level position. As a result, the Marine Isotope Stage or MIS (formally the Oxygen Isotope Stage or OIS) designation for Quaternary sea-level events is utilized in this field guide. The term “carbonates” is used in the text to include the common mineralogies of calcite, aragonite, and dolomite. The Late Quaternary carbonate units of the Bahamas have significant aragonite, as their young age has preserved the original depositional mineralogy of the allochems, and inversion to calcite has not proceeded to a conclusion as in older rocks in continental settings. Dolomite is rare in the subaerially-exposed carbonate rocks.

The Gerace Research Centre has undergone a series of name changes since its founding in the early 1970’s. What began as the College Center of the Finger Lakes field station, or CCFL, became in the late 1980’s the Bahamian Field Station. A few older residents of San Salvador still refer to the field station as “Finger Lakes”. In 2002, in honor of its founder, Dr. Donald T. Gerace, the field station was renamed the Gerace Research Center as a 30<sup>th</sup> anniversary recognition. In 2007, as a result of closer oversight by the College of the Bahamas, the word “Center” in the title became “Centre”, the British spelling. Understanding the evolution of the field station name is important in sorting out publications from the field station found cited in the literature. The field station website is now [www.geraceresearchcentre.com](http://www.geraceresearchcentre.com). The Gerace Research Centre will be referred to in this guide as “the GRC” or “the field station”.

## REGIONAL SETTING

The Bahama Islands comprise a 1,000 km long portion of a NW-SE trending archipelago that extends from Little Bahama Bank off the coast of Florida to Great Inagua Island, just off the coast of Cuba (Fig. 1). The archipelago extends farther southeast as the Turks and Caicos Islands, a separate political entity (still a British colony by choice), and terminates with Silver Bank and Navidad Bank. The northwestern Bahama islands are isolated landmasses that project above sea level from two large carbonate platforms,

AGE	LITHOLOGY	MEMBER	FORMATION	MAGNETOTYPE
H O L O C E N E		HANNA BAY MEMBER	RICE BAY FORMATION	
		NORTH POINT MEMBER		
P L E I S T O C E N E		COCKBURN TOWN MEMBER	GROTTO BEACH FORMATION	FERNANDEZ BAY
		FRENCH BAY MEMBER		
		UPPER OWL'S HOLE FORMATION		GAULIN CAY
		LOWER OWL'S HOLE FORMATION		SANDY POINT PITS

**Figure 3. Stratigraphic column for San Salvador Island, and by extension, the Bahamian Archipelago. The Owl's Hole Formation subdivisions shown are not recognizable in the field on San Salvador Island, and are partitioned based on paleomagnetic evidence from laboratory analysis. Otherwise, all subdivisions can be determined by field observation. From Panuska et al., 1999.**

Little Bahama Bank and Great Bahama Bank. To the southeast, beginning in the area of San Salvador Island, the Bahamas comprise small isolated platforms capped by islands that cover a significant portion of the available platform area. The Bahamian platforms have been sites of carbonate deposition since at least Cretaceous time, resulting in a minimum sedimentary cover thickness of 5.4 km (Meyerhoff and Hatten, 1974) and perhaps as much as 10 km (Uchupi et al., 1971). The large platforms to the northwest are dissected by deep channels and troughs (Figure 1), whereas the isolated platforms

of the southeastern Bahamas are surrounded by deep water. Water depths on the platforms are generally less than 10 meters.

The origin of the Bahama platforms has been the subject of much debate, from which two main theories have evolved. Mullins and Lynts (1977) proposed a "graben" hypothesis, which explains the current configuration of the Bahama Archipelago as the result of plate tectonic motion that produced the opening of the Atlantic Ocean in the Mesozoic. The pattern of banks, troughs and basins is explained as resulting from an initial horst and graben pattern consistent with continental rifting. The competing theory is the "megabank" hypothesis (Meyerhoff and Hatten, 1974; Sheridan et al., 1981; Ladd and Sheridan, 1987), which holds that the modern Bahamas are a segmented remnant of a much larger and continuous Mesozoic carbonate platform. Recent work by Eberli and Ginsberg (1987), Mullins and Hine (1989; 1990), Melim and Masferro (1997), and Manfrino and Ginsberg (2001) has demonstrated that the Bahama banks are undergoing both depositional progradation and erosional segmentation.

The geologic literature on the Bahamas is extensive, but the bulk of that literature deals with the carbonate banks and related deep-water environments. With the exception of San Salvador, comparatively little work had been done on the subaerial geology of other Bahamian islands until recently. The first modern geologic map of a Bahamian island was not published until Titus' work on San Salvador in 1980 (Titus, 1980). Adams (1983) was an early compilation of geologic sites on San Salvador. Hutto and Carew (1984) on San Salvador, Garrett and Gould (1984) on New Providence, Carew and Mylroie (1985) on San Salvador, Wilbur (1987; 1991) on Little San Salvador and West Plana Cay, Carew and Mylroie (1989a) on South Andros, and Kindler (1995) on Lee Stocking Island, represent some of the initial attempts to provide geologic descriptions of whole islands or portions of whole islands. A series of field guides have been produced over the years by the GRC, where the stratigraphic column of Figure 3 has been utilized on New Providence Island (Carew et al., 1996), South Andros Island (Carew et al., 1998), Eleuthera Island (Panuska et al., 2002), Long Island (Curran et al., 2004), Cat Island (Mylroie et al., 2006) and Rum Cay (Mylroie et al., 2008). The model has also been used successfully on Abaco Island (Walker, et al., 2008). A thorough overview of Bahamian island geology can be found in Curran and White (1995), and in the three papers forming Chapter 3 of Vacher and Quinn (1997).

## **SUBAERIAL GEOLOGY OF THE BAHAMAS**

### **EOLIANITES**

Among the classic carbonate units of all ages from around the world, Quaternary carbonates are well known for their abundance of eolian calcarenites (or *eolianites* for short; the term *dune* will also be used). This abundance is especially prevalent in the Bahamas, which are dominated by eolian facies. For many years, the absence of such units in the rock record was not understood, in part because workers on the classic Mesozoic and Paleozoic carbonate units were unfamiliar with eolianites, and how they would appear in the ancient rock record. Recent work, as described in Abegg et al. (2001), has revealed how much more common eolian calcarenites are in the rock record than previously recognized. The Bahamas, and San Salvador Island in particular, offer a superb opportunity to examine eolianites, and study their relationship with more typical subtidal carbonate facies (Carew and Mylroie, 2001).

AGE	OXYGEN ISOTOPE STAGE	Titus 1980 <sup>1</sup>	Carew and Mylroie 1985	Titus 1987	Hearty and Kindler 1993	Carew and Mylroie this paper <sup>2</sup>
HOLOCENE	1	*Recent sand*	Rice Bay Formation Hanna Bay Mbr North Point Mbr	Unnamed Holocene	Rice Bay Formation East Bay Mbr <sup>2</sup> Hanna Bay Mbr North Point Mbr	Rice Bay Formation Hanna Bay Mbr <sup>4</sup> North Point Mbr
	3		no deposits recognized	Granny Lake Oolite	no deposits recognized	
	5a	Grahams Harbour Limestone	Grotto Beach Formation Dixon Hill Mbr <sup>2</sup> Cockburn Town Mbr	Dixon Hill Limestone <sup>2</sup> Grotto Beach Limestone	Almgreen Cay Formation <sup>2</sup> Upper Mbr Lower Mbr	(no positively identifiable deposits of these ages) Grotto Beach Formation Cockburn Town Mbr <sup>5</sup>
PLISTOCENE	5e	Grotto Beach Limestone	French Bay Mbr		French Bay Mbr	French Bay Mbr
	7, 9, 11, or earlier		Owl's Hole Formation	Unnamed Pre-Sangamian	Fortune Hill Formation <sup>2</sup> Owl's Hole Formation	Owl's Hole Formation <sup>6</sup>

Table 1. Comparison of stratigraphies for San Salvador Island, and the Bahamas. From Carew and Mylroie, 1994.

1 Thus recognized the Grahams Harbour and Grotto Beach limestones only as Pleistocene, and he considered them to lie on an unnamed pre-Pleistocene biomictic.  
2 units identifiable only through amino acid racemization data  
3 this physical stratigraphy can be applied throughout the Bahamas  
4 includes all material assigned to East Bay Mbr by Hearty and Kindler, 1993  
5 includes rocks assigned to Almgreen Cay Fm and Fernandez Bay Mbr by Hearty & Kindler, 1993  
6 includes rocks assigned to Fortune Hill Fm by Hearty & Kindler, 1993



Eolianites are relatively unique among carbonate units in being solely terrestrial deposits. While eolianite allochems were created in the subtidal environment, lagoon, beach and eolian processes resulted in the deposition of these allochems in the terrestrial environment. Eolianites deposited half a million years ago may have never been exposed to phreatic conditions, either marine or fresh water. The placement of eolianites today, with some in coastal settings, and some in interior settings, means that their bases may currently be in marine or fresh phreatic water, respectively, while their upper areas are solely in the vadose environment. The geochemical mobility of  $\text{CaCO}_3$  results in rapid surface cementation, which produces carbonate eolianites that are closely tied to their source areas, and which cannot migrate long distances, as siliciclastic dunes can. Once eolian grain deposition slackens, meteoric water quickly forms a calcrete crust on the dune surface, effectively locking the dune in place. Thus, eolianites found today in island interiors were deposited when a beach was once in close proximity. The various positions of Quaternary glacioeustatic sea-level highstands means that past beaches, and their derived eolianites, could have been at many different locations on a platform. In other words, morphostratigraphy does not work well in the Bahamas, as it is not a simple situation of the most interior dunes being the oldest. See Carew and Mylroie (1995a; 1997) for a complete discussion of the morphostratigraphy issue.

## **DEPOSITIONAL MODEL**

The exposed rocks of the Bahamas are all mid to late Quaternary carbonates, with one exception (Kindler et al., 2008), dominated by eolianites, intertidal facies, and subtidal facies at low elevations, and solely by eolianites at elevations above 8 m. Paleosols occur at all elevations. The glacio-eustatic sea-level changes during Quaternary time alternately have flooded and exposed the Bahamian platforms, subjecting them to cycles of carbonate deposition and dissolution, respectively. Significant carbonate deposition has occurred in the past only when the platforms are flooded, as they are today.

The carbonate sequences of the Bahamas can be viewed as individual packages deposited during each sea-level highstand, separated by erosional unconformities (usually marked by terra rossa paleosols) produced during each sea-level lowstand (Carew and Mylroie, 1995a; 1997). Figure 5 illustrates the sequence of events described below. Each depositional package consists of three parts: a transgressive phase, a stillstand phase, and a regressive phase. These phases each contain a subtidal, intertidal, and eolianite component. Because Holocene sea level is sufficiently high, the only marine deposits exposed on land today are those associated with the higher stillstand phase of marine isotope substage 5e (MIS 5e), about 131,000 to 119,000 years ago (Chen et al., 1991). At its maximum, the MIS 5e sea level was about 6 m higher than at present. The transgressive and regressive marine deposits of substage 5e are below modern sea level, and the stillstand subtidal deposits of sea-level highstands prior to those of substage 5e also are not visible. Given isostatic subsidence rates of 1-2 m per 100,000 years (Mullins and Lynts, 1977; Carew and Mylroie, 1995b), earlier highstands were either not high enough, as for stage 7, or if high enough, occurred too long ago, as for stage 9 and earlier, to have those subtidal deposits exposed above modern sea level. However, Kindler et al. (2007) have discussed a purported MIS stage 7 subtidal deposit above modern sea level on coastal Great Inagua, but has invoked tectonics as a result of proximity to the Caribbean-North American plate boundary as the cause. In contrast, eolianites form topographic highs that extend well

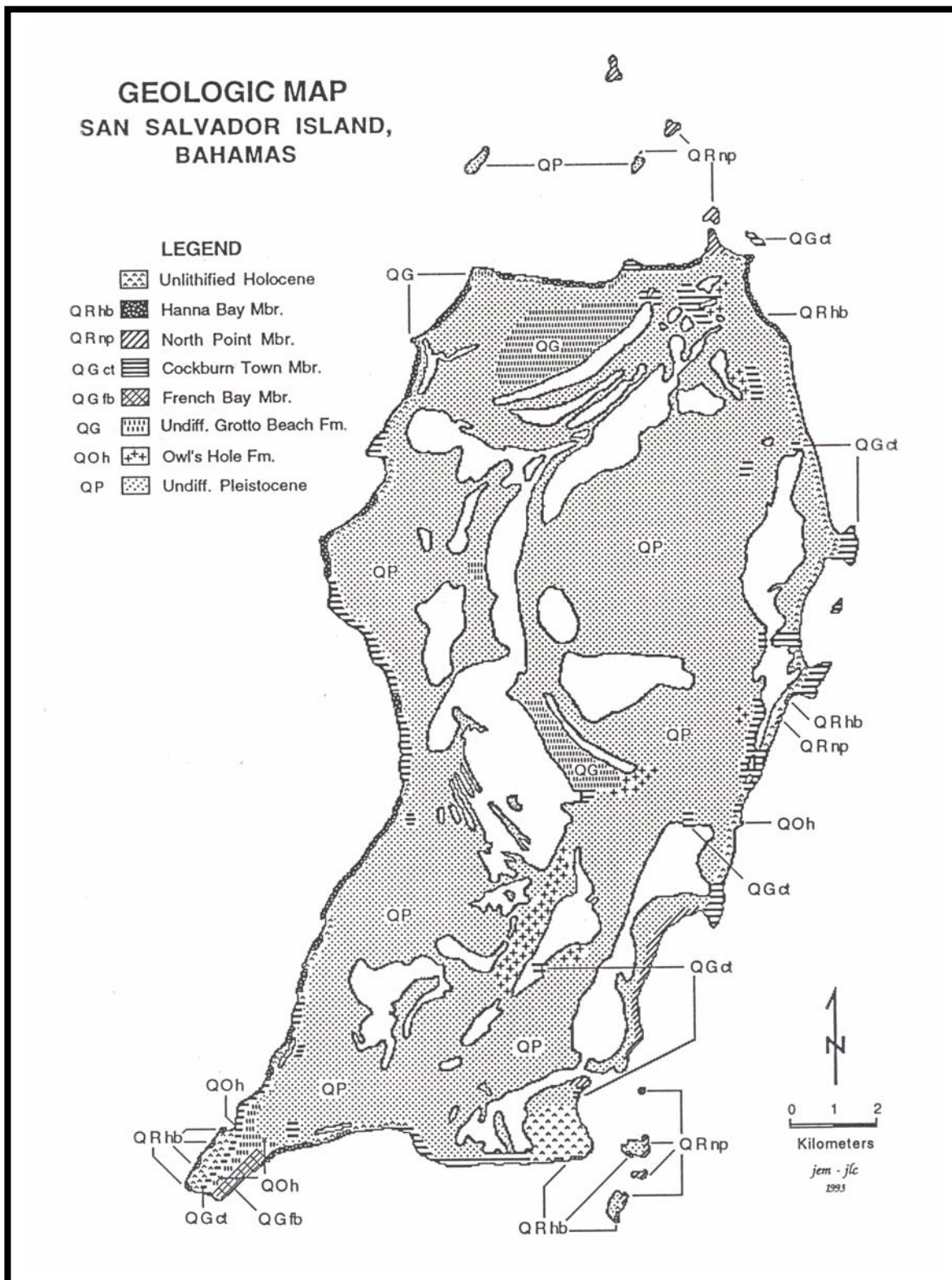
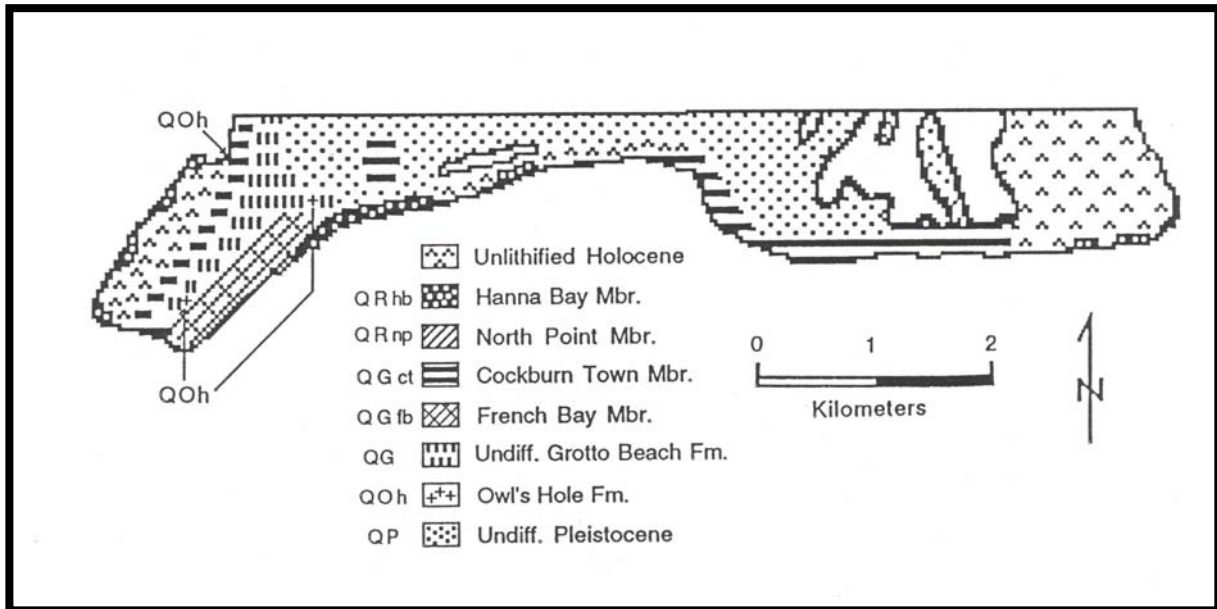


Figure 4A. Geologic map of San Salvador Island, Bahamas. Note that the bulk of the island is undifferentiated Pleistocene (QP), and that the greatest resolution is along the perimeter, where coastal outcrops, road cuts, and quarries are preferentially located. From Carew and Mylroie, 1995a.

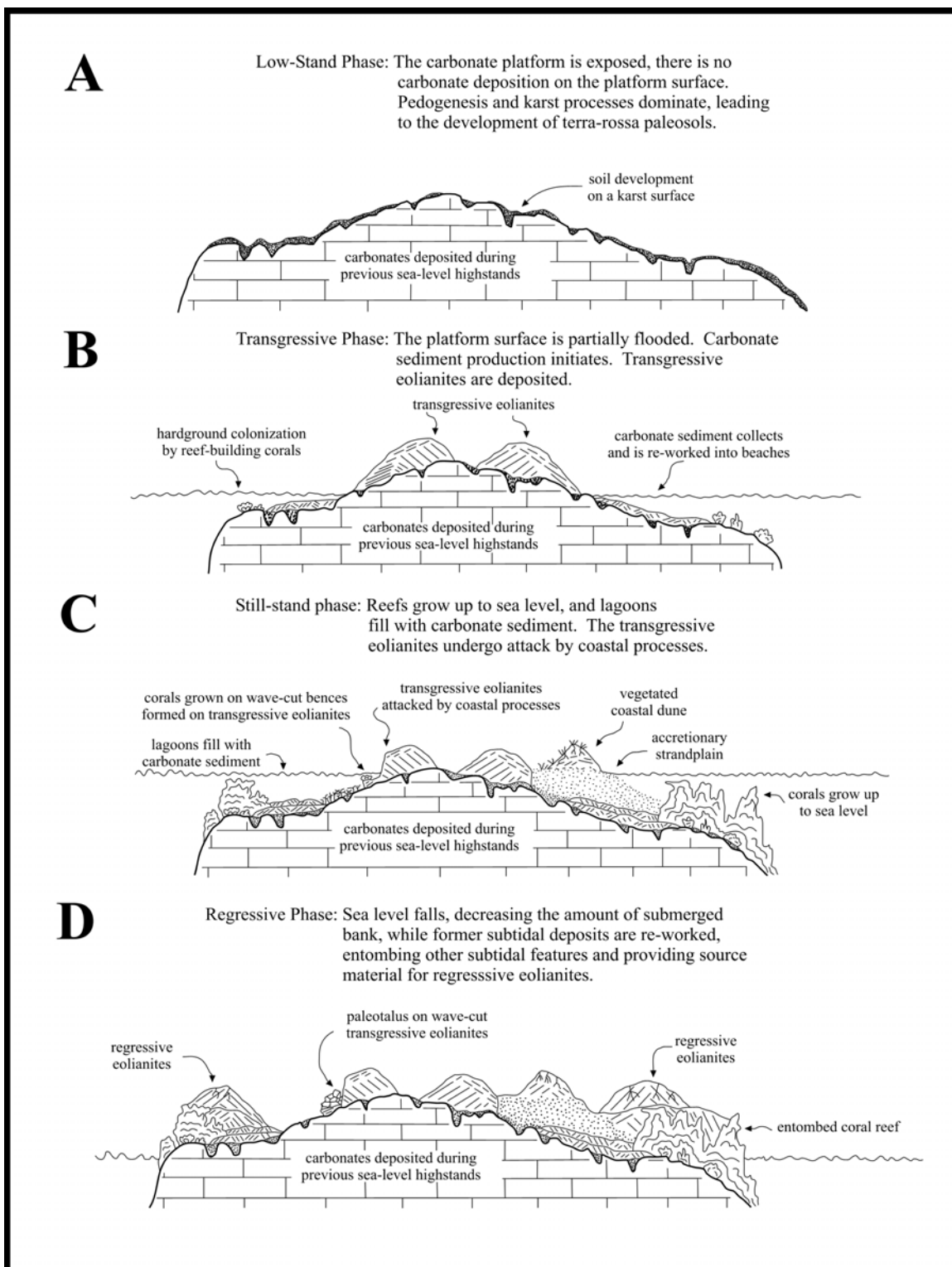


**Figure 4B. Expanded view of the south coast of San Salvador, highlighting the detail available because of the rocky coasts, many road cuts, and numerous pits and caves present. From Carew and Mylroie, 1995a**

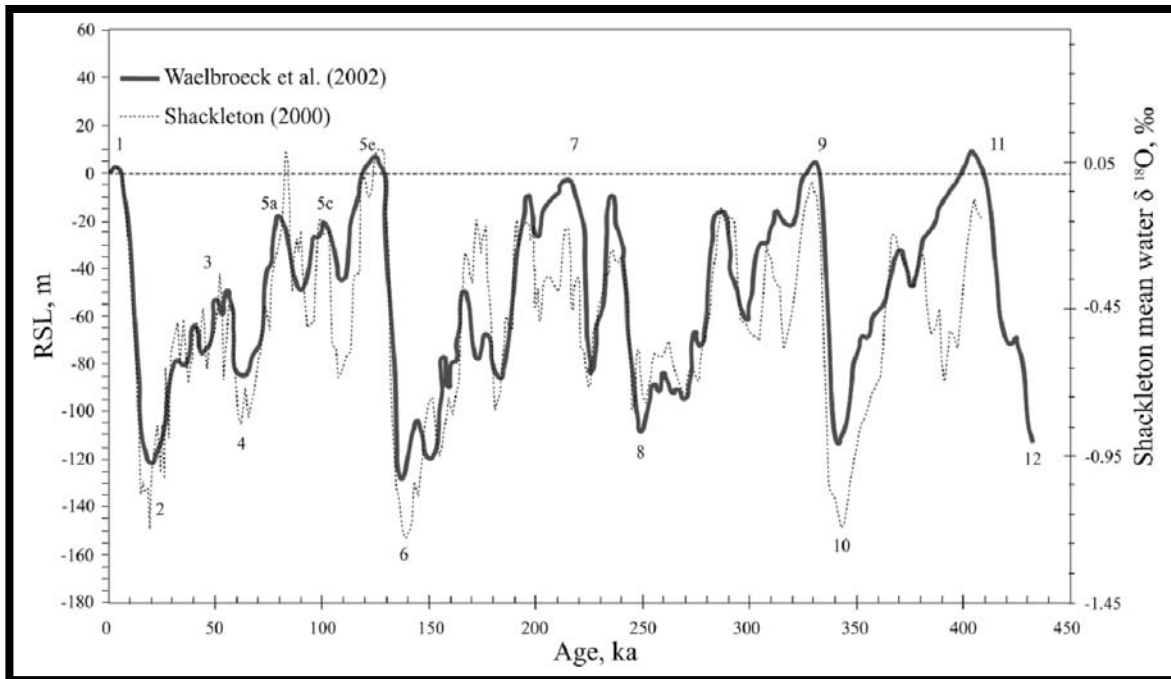
above past and modern sea levels, so eolianites from numerous highstands, from the mid Pleistocene to the Holocene, are widely exposed on Bahamian islands.

Each depositional cycle initiates as a marine transgression begins to flood the bank tops and shallow-water carbonate deposition takes place. At the margin of the remaining land area, beach sediments are continually remobilized by the bulldozing action of the advancing sea. Large dunes are formed, which may be subsequently attacked by wave action as sea level continues to rise. Only the largest or most favorably positioned transgressive-phase eolianites survive the rise of sea level to a maximum. During the stillstand of a sea-level high, subtidal and intertidal facies are deposited, but as the system reaches equilibrium, eolianite production is apparently less than during transgression. This decrease in eolianite production may be a response to reefs growing to wave base, and lagoons becoming more quiescent, such that wave energy to drive sand supply to the beaches is reduced. During regression, stillstand subtidal lagoon deposits are reworked by waves as sea level falls and the surf zone passes through the former lagoonal sediments. As a result, substantial regressive-phase eolianite packages can be formed. These regressive-phase eolianites are ultimately abandoned as sea level falls below the bank tops. As the sea moves off the platform, terrestrial erosional forces take over and soils that will eventually be preserved as terra rossa paleosols are produced. It is important to recognize that during the Quaternary, the Bahamas have been in a sea-level lowstand condition as a result of glacio-eustasy for about 85 to 90% of the time (Fig. 6). The Quaternary carbonate units seen exposed in the Bahamas today represent deposition during that small fraction of the time when sea levels were high enough to flood the banks and turn on the carbonate sediment factory.

In the Bahamas, the most complete sequence of deposits representing a transgression, stillstand, and regression cycle is the depositional package formed during the MIS 5e



**Figure 5. Depositional model for San Salvador Island and the Bahamas overall. Carbonate deposition is restricted to transgressive, stillstand, and regressive phases of a glacioeustatic sea-level highstand. Surficial karst processes and pedogenesis dominate lowstands below about -20 m. See text for details. Modified from Carew and Mylroie, 1995a.**



**Figure 6. Quaternary sea level curve for the last 450 ka. Note how little time has been spent at sea levels at or above modern elevations. From Lascu, 2005.**

event. Older packages are incomplete, for the reasons given earlier, and the Holocene package does not, as yet, contain a true regressive phase (although it does include progradational regressive deposits). A general model for the development of the stratigraphy of Bahamian islands was first proposed by Carew and Mylroie in 1985. This model was developed using San Salvador Island as the specific example, but as noted earlier, it has been successfully used on other islands by Carew and Mylroie (1989a) and by other workers (Wilbur, 1987; 1991; Kindler, 1995), and in the series of field guides listed earlier. The model has been modified with the accumulation of new data (Carew and Mylroie, 1989b; 1991; 1995a; 1997). A stratigraphy developed from this model is presented in Figure 3, and it is the basis for the stratigraphic assignments and descriptions given in this field guide. This stratigraphy is based on field relationships, and does not require the use of geochronological tools, although it subsequently has been substantiated by a number of geochronologic methods (Carew and Mylroie, 1987a). A spirited debate developed in the 1990s about Bahamian stratigraphy (see Carew and Mylroie, 1997, and references therein) centered on the reliability of amino acid racemization (AAR) analyses for making stratigraphic subdivisions in the absence of evidence provided by field relationships.

The eolianite packages older than MIS 5e were initially lumped together as the Owl's Hole Formation, although it was recognized at the time that this unit probably contained eolianites from a number of pre-substage 5e sea-level events (Carew and Mylroie, 1985). AAR data were subsequently used to subdivide the Owl's Hole into multiple units on San Salvador Island (Hearty and Kindler, 1993). While AAR data were considered controversial, it was later established on Eleuthera Island that subdivisions of the Owl's Hole could be demonstrated in the field (Kindler and Hearty, 1995; Panuska et al., 2002). Paleomagnetic analysis of the secular variation in paleosols also indicated that

the Owl's Hole could be subdivided (Fig. 3) into at least an upper and lower unit on San Salvador Island (Panuska et al., 1999). The eolianites of the Owl's Hole Formation are predominantly bioclastic, and ooids are extremely rare. The Owl's Hole Formation is usually recognized in the field by its relationship to overlying deposits. Efforts to subdivide units in the Bahamas by petrologic methods have been attempted (e.g. Kindler and Hearty, 1996; 1997), but demonstrated petrologic variability among single Pleistocene units, as well as in Holocene units, indicates that this technique is not reliable (e.g. Sparkman et al., 2001). The various stratigraphies proposed for San Salvador are compared with the stratigraphy used here in Table 1.

## STRATIGRAPHY

The eolianite packages older than marine isotope substage 5e (MIS 5e) are combined as the *Owl's Hole Formation*, because separation of these eolianite packages cannot be reliably accomplished based on field criteria in most places (Carew and Mylroie, 1995a; 1997). As noted earlier, with the Kindler et al. (2007) exception, there are no subtidal units of this formation exposed above current sea level. The eolianites of this unit are predominantly bioclastic, and ooids are extremely rare. The Owl's Hole Formation is usually recognized in the field by its relationship to overlying deposits.

Overlying the Owl's Hole, and separated from it by a paleosol or other erosion surface, is the *Grotto Beach Formation*. This formation was deposited during MIS 5e. It consists of two members. The older unit is the *French Bay Member*, which comprises transgressive-phase eolianites (Carew and Mylroie, 1985; 1995a; 1997). In some localities, transgressive-phase eolianites are marked by an erosional platform on which later stillstand fossil corals are found (Carew and Mylroie, 1989a; 1995a; Halley et al., 1991). The younger unit is the *Cockburn Town Member*, a complex arrangement of stillstand subtidal and intertidal facies overlain by stillstand and regressive-phase eolianites. In earlier versions of our stratigraphic model (Carew and Mylroie, 1985; 1989b) the Grotto Beach Formation also contained the Dixon Hill Member, which was thought to represent an eolianite deposited during MIS 5a about 85,000 years ago. This member was incorrectly based solely on amino acid racemization data (Carew et al., 1984) and has therefore been eliminated from the stratigraphy (Carew et al., 1992; Carew and Mylroie, 1995a; 1997). During Grotto Beach time ooids were produced in great numbers, and the vast majority of eolianites in the Grotto Beach Formation are either oolitic (up to 80-90% ooids) or contain appreciable ooids.

Another lively debate about Bahamian geology concerns whether MIS 5a eolianites exist in the Bahamas (see Carew and Mylroie, 1997; Kindler and Hearty, 1997, and references therein). As noted above, AAR data were used to identify a possible MIS 5a eolian unit in 1985 (Carew and Mylroie, 1985), but that unit was dropped when field work demonstrated that the unit in question was older than MIS 5e (Carew and Mylroie, 1995a; 1997), and laboratory tests indicated use of the land snail *Cerion* for AAR work was extremely unreliable (Mirecki et al., 1993). However, some argued that use of whole rock AAR analysis avoided this problem and such AAR data were used to identify purported MIS 5a eolianites on a number of Bahamian islands (Kindler and Hearty, 1997, and references therein). Field evidence to demonstrate, one way or the other, that MIS 5a units exist in the Bahamas has been elusive. Convincing outcrops of MIS 5a eolianites on Eleuthera Island (Kindler and Hearty, 1995; 1997) indicate that eolian deposition took place in the Bahamas during MIS 5a. AAR data have been used to

identify MIS 5a eolian units on Bermuda (Vacher and Hearty, 1989). There is no reason why MIS 5a eolianites should not exist elsewhere in the Bahamas; the difficulty has been establishing conclusive field criteria to demonstrate their presence.

Overlying the Grotto Beach Formation, and separated from it by a paleosol or other erosion surface is the *Rice Bay Formation* that has been deposited during Holocene time (MIS 1). The Rice Bay Formation is divided into two members, based on their depositional history relative to Holocene sea level. The *North Point Member* consists entirely of eolianites, whose foreset beds can commonly be followed for at least 2 m below modern sea level. These drowned foreset beds indicate that the North Point Member comprises transgressive-phase eolianites. Whole rock  $^{14}\text{C}$  measurements from the North Point Member indicate particle ages centered around 5,300 yBP (Carew and Mylroie, 1987a). Laterally adjacent, but rarely in an overlying position, is the younger *Hanna Bay Member*. This unit consists of intertidal facies and eolianites deposited in equilibrium with modern sea level. This equilibrium indicates that the Hanna Bay Member is a stillstand-phase eolianite. The eolianite grains have radiocarbon ages that range from approximately 3,300 yBP to 400 yBP (Carew and Mylroie, 1987a; Boardman et al., 1989). While weakly-developed ooids have been reported from the early stages of North Point Member deposition (Carney and Boardman, 1991), the Rice Bay Formation is predominantly peloidal and bioclastic on San Salvador. On Cat Island, however, Hanna Bay Member eolianites are rich in ooids (Mylroie et al., 2006).

The North Point Member rocks around the Bahamas are currently being attacked by wave erosion. Sea caves, inland cliff-line talus, and coral-encrusted wave-cut benches of the North Point Member exist. Similar relationships can be seen preserved in the rock record in the transgressive-phase French Bay Member of the Grotto Beach Formation, as mentioned earlier.

## **FIELD RECOGNITION OF STRATIGRAPHIC UNITS**

The stratigraphy discussion reveals some of the difficulty in correctly identifying stratigraphic units in the field. The problem results from a number of sources. First, the rocks are all very young, and as a result, fossils by themselves do not give much of an age metric. Eolianites are notoriously fossil poor anyway, containing at best highly fragmented and polished bioclasts, and occasional land snail shells. Second, the eolianites are patchily distributed and are not laterally extensive, so that layer-cake geology is rarely applicable. As a result, outcrops where eolianites can be seen to be stacked are rare and highly prized. Third, the stable tectonic setting of the Bahamas results in exposure of subtidal units only if those units were deposited when sea level was higher than at present. As noted earlier, only the Cockburn Town Member of the Grotto Beach Formation, a MIS 5e deposit, meets this criterion. Fourth, outcrop exposures are poor. The best natural outcrops occur where coastal cliffing has taken place, or where caves, pits and blue holes have penetrated the bedrock mass. Artificial exposures, as found in road cuts and quarries, have proven, like most everywhere else, to be very valuable. The interiors of most Bahamian islands, which usually lack roads, quarries and coastal cliffs, are very much geologic terra incognita (see Fig. 4A).

Geochronological methods have proven useful, but they cannot be applied directly while in the field. Sampling and later laboratory analysis must be done, which removes the opportunity for immediate field interpretation. Analysis of  $^{14}\text{C}$  has been extremely useful in determining allochem ages, and by extension, rock deposition ages, but only for

Holocene deposits. Uranium age dating has worked extremely well for fossil corals, and for cave stalagmites. Fossil coral ages have shown to be, with the one exception mentioned for Great Inagua (Kindler et al., 2008), entirely within MIS 5e (Carew and Mylroie, 1995b). Paleomagnetism has been able to differentiate between terra rossa paleosols, but only by use of secular variation, as the rocks are not old enough to show reversals (Panuska et al., 1999). Amino acid racemization (AAR) has been used by a variety of workers, but as noted earlier, the results have been very controversial.

Some field methods that have proved unreliable in determining the stratigraphic unit to which a rock belongs are petrographic analysis, and degree of cementation. While certain units on San Salvador are known to have a general petrologic character, such as ooids being most common in the Grotto Beach Formation, that pattern does not hold everywhere on San Salvador, and most certainly does not hold on other Bahamian islands. Modern depositional environments in the Bahamas show large-scale changes in allochem production and deposition from place to place. While these deposits are all forming on the same sea-level highstand, in the rock record it would be tempting to separate them into different sea-level highstands, and therefore different stratigraphic units, based on their differing petrologies. Cementation is more a function of local environment than age of the rock. The terra rossa paleosols that blanket the Pleistocene rocks of the Bahamas are very good aquicludes, and they restrict vadose flow and subsequent cementation. As a result, some Owl's Hole Formation rocks are barely cemented, whereas in other localities these rocks are fully cemented. Conversely, in coastal areas, the effects of sea spray leads to unusually thorough cementation, even in young Holocene rocks.

### **The Field Problem**

So what can one do when in the field? Figure 7 displays a flow chart that allows rocks to be classified upon direct observation in the field. First, determine the facies of the outcrop. If the facies are subtidal, *in situ*, and the outcrop is above the modern high tide mark, then the rocks are from the last interglacial, (MIS substage 5e), and they are Cockburn Town Member rocks of the Grotto Beach Formation. Beware of modern storm lag deposits. Herringbone cross bedding, trace fossils such as *Ophiomorpha* sp, or *in situ* fossil corals, are clear and reliable indicators of fossil subtidal facies.

If the outcrop is eolian in character, then determine if it has a terra rossa paleosol on top. If it does, then the outcrop is Pleistocene in age. If not, then it is Holocene in age, as the outcrop has not existed long enough to capture the necessary aerosol dust that helps make a terra rossa paleosol. However, other processes, such as wave action, can remove a paleosol, so careful fieldwork is necessary to insure that a given outcrop never had a paleosol. The Holocene Rice Bay Formation is recognized by this lack of a well-developed terra rossa paleosol. The Rice Bay rocks may have a thin calcrete crust, and the crust may have a slight pink or tan stain, but it is not a true terra rossa paleosol.

Within the Rice Bay Formation, the position of the beds relative to modern sea level is crucial. The North Point Member was recognized as being deposited when sea level was slightly lower than today (but on the platform to produce carbonate allochems) because its eolian foreset beds dip below modern sea level by at least 2 m. The North Point Member consists solely of eolian facies. The Hanna Bay Member, which has beach and back beach facies as well as eolian facies, was deposited with its beach facies in equilibrium with modern sea level. Given a rising sea level in the Holocene, the



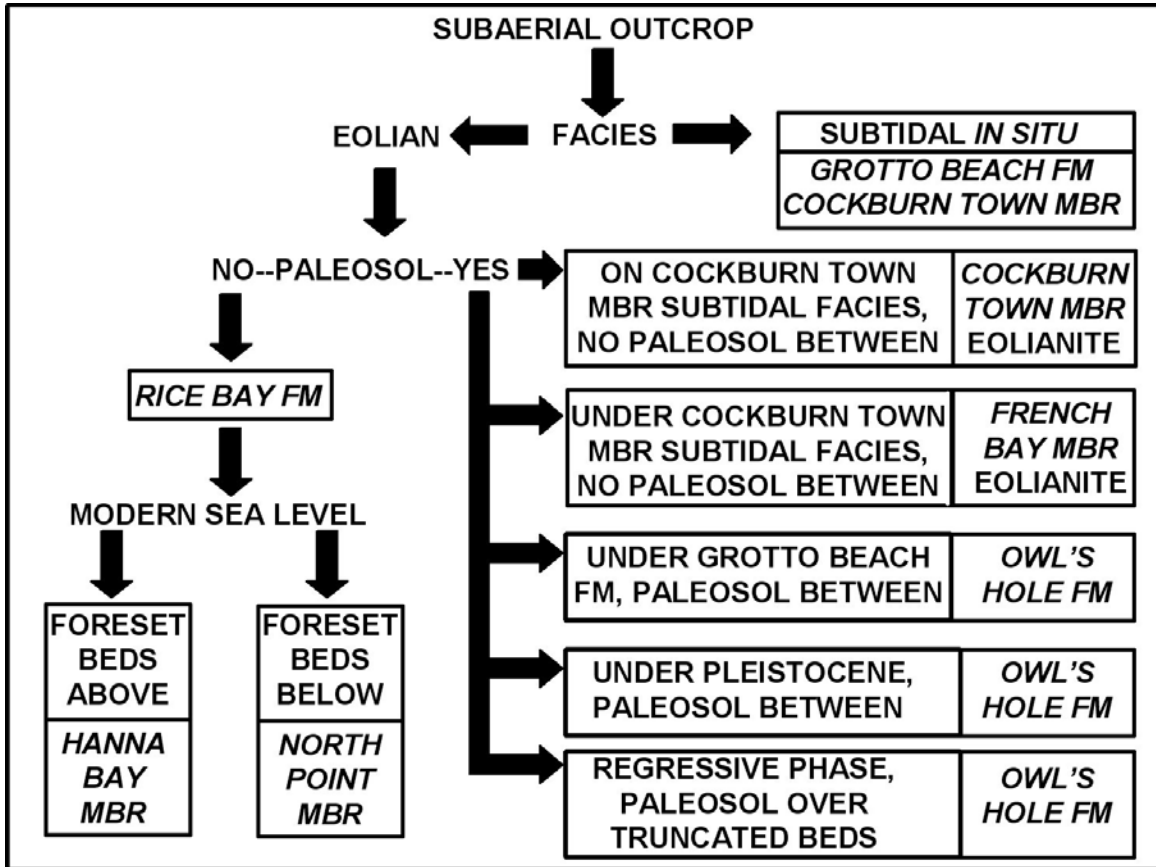


Figure 7. Flow chart to apply field evidence toward making a decision about placement of an outcrop into the San Salvador stratigraphy of Figure 3.

North Point Member rocks must be older than the Hanna Bay Member rocks. So field relationships show not only that these two members are Holocene (no terra rossa paleosol), but that they are of different age. After these interpretations were submitted for publication (Carew and Mylroie, 1985), <sup>14</sup>C dating demonstrated that the field-determined age relationship was correct. The second important outcome from the recognition of the Holocene age of the Rice Bay Formation was that it demonstrated that major eolianite production occurs on the transgression of sea level, whereas the traditional dogma was that eolianites formed only on the regression. The major reason for the regression interpretation was the belief that only after a long duration of sea-level highstand would there be enough carbonate allochem accumulation to provide a source for dune production. The transgressive nature of the Holocene eolianites demonstrated how quickly carbonate sediments form and accumulate once the platform has been flooded as a result of glacioeustatic sea-level rise. Dating of <sup>14</sup>C (Carew and Mylroie, 1987a) has shown that large accumulations of Holocene carbonate allochems are common on San Salvador (and by extension, elsewhere in the Bahamas).

### Transgressive Phase Versus Regressive Phase Eolianites

Eolianites in the Bahamian stratigraphy have been classified as *transgressive phase*, *stillstand phase*, and *regressive phase* (Carew and Mylroie, 1995a; 1997; 2001). Stillstand-phase eolianites tend to be less common, and less voluminous than the

transgressive and regressive-phase counterparts, for reasons given earlier. The deposition of an eolianite on a transgression produces features in the eolianite that are different than those of an eolianite deposited on a regression. These differences are listed in Table 2. The various criteria of Table 2 fall into two main categories: those that develop as a result of deposition and the immediate post-depositional setting, and those that develop after the dune is fully deposited.

Transgressive-phase eolianites usually have well preserved fine-scale bedding high in the section, right up to the calcrete crust or terra rossa paleosol. Plant trace fossils, or vegemorphs, are rare and incompletely developed. The terms rhizomorphs or rhizcretions, common in the literature, are not used here because plant stems, as well as roots, may be preserved; see Carew and Mylroie (1995a; 1997; 2001) for a discussion of this issue. On the converse, regressive-phase eolianites have disrupted bedding high in the section, and contain abundant and voluminous vegemorphs (which have caused the disruption of the original bedforms). The primary reason for this difference in plant trace fossils and their effects is that a transgressive-phase eolianite is deposited at the start of a transgressive episode, when the Bahamas have spent ~100 ka as high, vertical-walled islands. There is no beach and dune environment, and hence no beach and dune plant ecology. Fieldwork and <sup>14</sup>C dating of Holocene transgressive-phase eolianites indicates that they form very quickly. This rapid deposition means that the dunes are deposited and quickly derive a calcrete crust prior to the establishment of the typical beach and dune ecology found in the Bahamas today. Therefore they are not bioturbated by plant roots, and their bedforms are preserved in fine detail. However,

Characteristic	T	S	R
Eolian bedding preservation	fine scale	partially to highly disrupted	highly disrupted (esp. upper part)
Vegemorphs	few	abundant	extensive
Sea caves	penecontemporary	rare	none penecontemporary
Cliffing and boulder talus deposits	penecontemporary in beach and eolian facies	penecontemporary in back-beach to intertidal	no penecontemporary cliffing
Protosols	uncommon	common	common
Corals	on penecontemporary wave-eroded benches	not found on penecontemporary benches	no penecontemporary benches
Facies relationships	eolian facies dominant, overlapped by S and R deposits	marine facies abundant, shallowing-upward sequences	eolian facies dominant, often overstepping marine facies
Environments represented in exposed rocks	predominantly eolian, occasional beach facies	eolian, marine, strandplain, lacustrine, tidal deltas	predominantly eolian

**Table 2. Criteria for differentiating eolian calcarenites into transgressive phase (T), stillstand phase (S), or regressive phase (R). From Carew and Mylroie, 1997.**

regressive-phase eolianites form after sea level has been stable for ~10 ka, and the beach and dune ecology is fully established. As sea level falls, and regressive phase-eolianites are deposited, they are quickly colonized by plants adapted to nearby beach and stillstand dune environments, which will leave abundant plant trace fossils, or vegemorphs, in the subsequent rock record. This vegetation creates the high degree of bedform disruption found in regressive-phase eolianites.

For reasons that are not well understood, regressive-phase eolianites are more likely to have calcarenite protosols than transgressive-phase eolianites. Calcarenite protosols are immature, weakly developed paleosols lacking significant insoluble residue from dust fall. They are extremely similar to the young soils found on Holocene eolianites today. They are believed to represent immature soil development during pauses in the deposition of an eolianite package; a pause long enough to leave a weak soil character, but too short a time for a mature soil to form. Calcarenite protosols indicate that regressive phase-eolianites form in several discrete events, while transgressive-phase eolianites form rapidly and continuously (as the vegemorph data indicate).

The second group of criteria for classifying an eolianite as transgressive or regressive phase deals with what happens to the dune after it is fully formed. In the case of transgressive-phase eolianites, sea level is, by definition, still rising. As a result, the eolianite is impinged upon by wave action, which can cut a notch and wave-cut platform in the dune. Subsequently, this platform may become a subtidal hardground upon which corals can grow. Sea caves may also be carved into transgressive-phase eolianites. After sea level falls, the former coastal scarp becomes an inland scarp and can collect a talus deposit, which can then lithify. None of these features is found on true regressive-phase eolianites, as they form when sea level is dropping, and therefore do not undergo wave attack on the *same* sea level cycle.

These criteria lead to interesting field interpretations. Both the North Point Member of the Rice Bay Formation, and the French Bay Member of the Grotto Beach Formation show the transgressive-phase criteria. The North Point Member is a transgressive-phase eolianite, being Holocene with foreset beds dipping below modern sea level. North Point Member rocks contains all the criteria listed in Table 2 for a transgressive-phase eolianite. The presence of the same characteristics in French Bay Member rocks leads to their interpretation as transgressive-phase eolianites, and their classification as a separate member within the Grotto Beach Formation. The regressive-phase characteristics are found in Pleistocene eolianites that overstep MIS 5e fossil reefs. The lack of a terra rossa paleosol between the reef and the overlying eolianite, and the gradation from reef to beach to back beach to dune facies indicates the eolianite formed on the same sea-level highstand as the reef. Given that the fossil reef is above modern sea level, it must be Cockburn Town Member of the Grotto Beach Formation. Hence the overlying dune is also Cockburn Town Member and a regressive-phase eolianite.

There is more utility to these transgressive versus regressive phase criteria. If an eolianite has a terra rossa paleosol that overlies a truncated surface of a regressive phase eolianite, then the eolianite can be placed in the Owl's Hole Formation. The reasoning is as follows. The presence of the terra rossa paleosol indicates the eolianite is Pleistocene. If the eolianite has abundant vegemorphs, it is regressive phase (something easily observed, when present, if the dune has been wave cut). The eolianite shows a wave-cut platform, which could not have been cut on the same sea-level highstand that formed the eolianite, as the eolianite is regressive phase; the wave

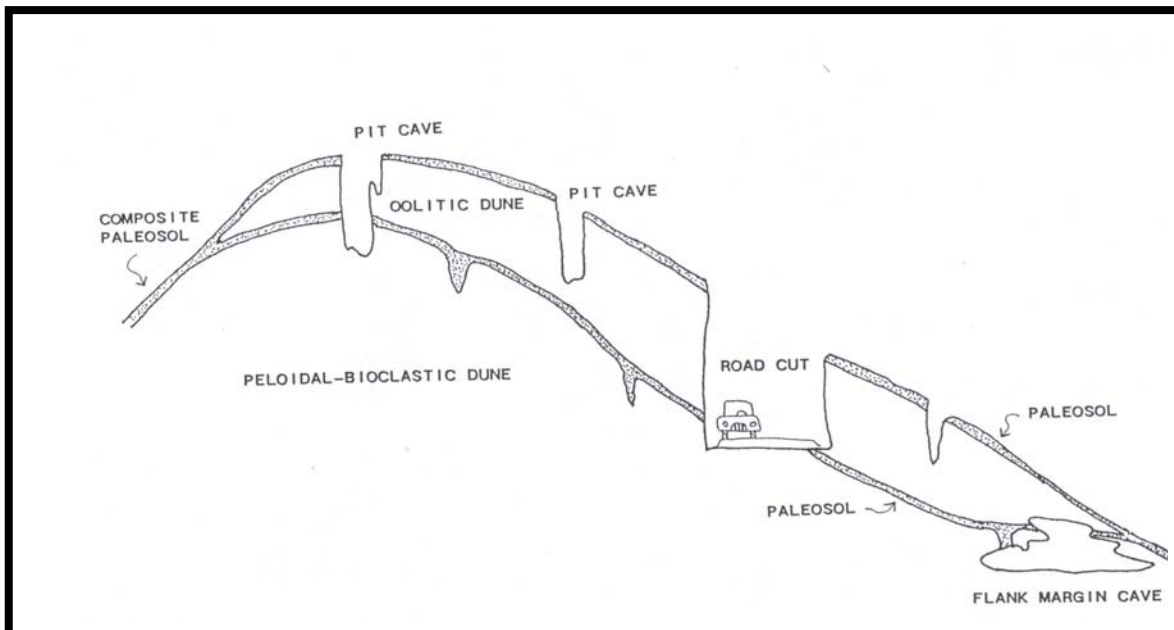
cutting must be from a later highstand. That later highstand must be from Grotto Beach Formation time (MIS 5e), as the wave-cut platform, an intertidal/subtidal feature, is above modern sea level. The paleosol drapes over this wave-cut platform, so it is the paleosol that covers the Grotto Beach Formation (the Fernandez Bay magnetotype of Panuska et al., 1999; Fig. 3). The eolianite therefore must be older than the Grotto Beach Formation, so it is part of the Owl's Hole Formation.

One of the classic conundrums in stratigraphy is differentiating true regression, due to a drop in sea level, from sediment progradation during a sea-level stillstand. The Holocene in the Bahamas shows many large strand plains of carbonate sediment that have prograded into lagoons. In the rock record, this relationship would appear as beach and eolian facies overlying subtidal facies without an intervening terra rossa paleosol, the classic indicator of regression. However, in a true regressive situation in the Pleistocene of the Bahamas, it is not uncommon to find a calcarenite protosol overlying the reef facies, indicating subaerial exposure of the reef prior to entombment in eolian sediments. Eolianite on a fossil reef without any beach or back beach facies is also evidence of a true regression.

### **Presence of a Terra Rossa Paleosol**

The presence of a terra rossa paleosol indicates that the rock outcrop is Pleistocene in age. Not all Pleistocene rocks have a paleosol on them. In coastal locations, wave action can strip off the resistant paleosol. Abaco Island, because of its high rainfall, has had broad inland areas of paleosol eroded away (Walker et al., 2008). Because paleosols represent the weathering and erosion front on top of the carbonate rock, and because karst processes have been active, the paleosol commonly drapes a surface with relief of up to 1 m or more. Dissolution pits and hollows contain paleosol material. While meteoric erosion, or wave action, can strip most of the paleosol surface, the material in dissolution pits and hollows is commonly preserved, such that examination of the outcrop on a wider scale will locate these features, allowing the outcrop to be properly interpreted. In some cases, such as on a few wave cut platforms, the terra rossa paleosol has been truncated, but the rocks of the platform show alveolar texture indicative of subaerial exposure (Carew and Mylroie, 1985). Paleosols are not all the same, and their successful interpretation depends on understanding their pedogenesis in a karst environment developed in young carbonates (Carew and Mylroie, 1991).

Because of the patchy distribution of eolianites, paleosols may cover an eolianite from a single sea-level highstand at one locality, while adjacent to that spot, the paleosol bifurcates to cover two eolianites, each produced on separate sea-level highstands (Fig. 8). Note that in the scenario provided earlier regarding identification of wave-cut platforms on Owl's Hole rocks, a terra rossa paleosol would have formed on the regressive phase Owl's Hole rocks prior to the MIS 5e wave-cutting event. That paleosol would have been stripped from the portion of the Owl's Hole eolianite cut into a platform by wave action. Elsewhere on that dune, however, the Owl's Hole rocks would still have had their original terra rossa paleosol. Those portions of the dune higher than the MIS 5e sea-level highstand would have a terra rossa paleosol that continued to develop from Owl's Hole time up through to the present, but the wave cut platform would have a terra rossa paleosol only from MIS 5e time to the present; i.e. a Grotto Beach Formation age paleosol.



**Figure 8. Cartoon showing various ways terra rossa paleosols may be viewed. The peloidal-bioclastic dune has been on-lapped by an oolitic dune; two paleosols exist in the center and right, but a single composite paleosol exists to the left. From Carew and Mylroie, 1995a.**

If the rock under the paleosol is a subtidal facies, it is, as previously noted, Cockburn Town Member of the Grotto Beach Formation. But if the rock is an eolianite, then its assignment to a formation, or a specific member of a formation, is problematic. In the absence of any other information, the rock is simply “undifferentiated Pleistocene”. While petrologic character of the rock is not a solid diagnostic tool for placing an eolianite in the stratigraphic column, on San Salvador the presence of abundant ooids has been a useful rule of thumb to say the rock is probably Grotto Beach Formation. The stratigraphic classification of Pleistocene eolianites depends on the relationship of a given eolianite to other units associated with it. The one exception is the paleosol drape over a wave-truncated, regressive-phase eolianite, described earlier. In that case, the single eolianite unit carries all the necessary information for stratigraphic classification.

Eolianites overlying subtidal facies without an intervening terra rossa paleosol are, as described earlier, Cockburn Town Member (Fig. 7). Eolianites underlying subtidal facies without an intervening terra rossa paleosol are French Bay Member (subtidal facies above modern sea level are obligatory Cockburn Town Member rocks). An eolianite separated by a terra rossa paleosol from an overlying eolianite which in turn has a terra rossa paleosol on top must be Owl’s Hole Formation. The overlying paleosol could be either a Grotto Beach Formation eolianite, or a later eolianite within the Owl’s Hole Formation. The information given would provide no unique interpretation. On San Salvador Island, if the overlying eolianite was ooid-rich, the best *guess* would be that the overlying eolianite was Grotto Beach Formation. As figure 8 demonstrates, the use of morphostratigraphy to determine the age of dune ridges is problematic and has not worked well in the Bahamas (Carew and Mylroie, 1995a; 1997; Schwabe et al., 1993; Sparkman et al., 2001).

## **GEOLOGY SUMMARY**

The identification of rock units in the Bahamas is tied to understanding the overall depositional model for carbonate deposition, and the recognition of the various criteria that place a rock unit within that model. The recognition of criteria depends on favorable outcrops. Coastal exposures, which provide sea cliffs that allow a view of the rock interior, are critical. As are caves, pits and the subaerial portions of blue holes, which do the same rock penetration. Quarries, road cuts and other excavations provide important access to the underlying geology. Experience counts as well, but the observer must be careful to have not “seen it because I believed it”.

### **KARST AND LANDFORM DEVELOPMENT IN THE BAHAMAS**

The Bahama Islands have landscapes that are dominated by original depositional features, and are only slightly modified by subsequent dissolutional (karst) processes. The high porosity of the limestones that form the islands results in rapid infiltration of meteoric water and the absence of surface streams and related erosional features such as valleys and channels. Classic surface karst landforms such as sinking fresh-water streams, blind valleys, and poljes are absent. The karst features of the Bahamas fall into four main categories: karren, depressions, caves, and blue holes.

The youthfulness of Bahamian carbonate rocks creates different water-flow dynamics than are found in the dense, diagenetically-mature carbonates of continental interiors. The Bahamas exemplify what has been described as *eogenetic karst*, defined by Vacher and Mylroie (2002, p. 183) as “the land surface evolving on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis.” The term “eogenetic” was taken from Choquette and Pray (1970, p. 215) who defined the three time-porosity stages of carbonate rock evolution: “the time of early burial as *eogenetic*, the time of deeper burial as *mesogenetic*, and the late stage associated with long-buried carbonates as *telogenetic*.” Eogenetic carbonate rocks have not been extensively compacted or cemented and retain much of their primary depositional porosity. Most carbonate islands, and almost all carbonate islands found in tropical or subtropical locations, are made up of eogenetic limestones (Late Cenozoic) that were deposited proximal to the setting in which they presently occur. The Bahamas, being Mid to Late Quaternary in age in a non-tectonic environment, display this eogenetic character extremely well.

### **THE FRESH-WATER LENS**

In any essentially homogeneous body of rock like that of the carbonates forming the Bahamian islands, the freshwater lens floats on underlying, denser seawater that permeates the subsurface. The model for the ideal behavior of such water masses is the Dupuit-Ghyben-Herzberg model. In reality, variations in rock permeability and other factors result in distortion of the ideal lens shape in the Bahamas (e.g. Vacher and Bengtsson, 1989). Nonetheless, the Dupuit-Ghyben-Herzberg model serves as a useful first approximation of the relationship between the freshwater and underlying marine groundwater in an island.

During past higher stands of the sea, the fresh groundwater lens in each island was as high or higher than it is today. Beneath the surface of those past freshwater lenses, within the limestone rock of the islands, caves were produced by dissolution. Each time

sea level fell, the caves became abandoned and dry. Under today's climatic conditions the Earth is warm and sea level is relatively high, but not quite as high as at some times in the past. We can therefore enter dry caves today throughout the Bahamas. In contrast, the blue holes of the Bahamas lead into caves that are flooded by seawater. These blue holes represent the cumulative dissolution and collapse that has occurred during many sea-level fluctuations. The complexity of cave passages found in blue holes is the result of overprinting of repeated marine, freshwater, and subaerial conditions throughout Quaternary time. Conversely, the presently dry caves of the Bahamas formed during the relatively short time periods of the Late Pleistocene when sea level was higher than at present. Bahamian caves that formed above modern sea-level elevation prior to MIS 5e time today lie below modern sea level owing to isostatic subsidence of the platforms (Carew and Mylroie, 1995b); however some data can be marshaled that call this interpretation into question (Lascu, 2005). Taking isostatic subsidence into account, sea level was high enough to produce the observed subaerial caves for a maximum of about 12,000 years of the MIS 5e time period. In addition, during that sea-level highstand, only the eolian ridges and a few beach and shoal deposits stood above sea level, and island size in the Bahamas was dramatically reduced compared to that of today's islands. As a consequence, freshwater lens volumes and discharges were comparably reduced. An end result of this scenario is recognition that dry Bahamian caves seen today represent development during a very short time period within small freshwater lenses and with minimal overprinting by later events. Any model that attempts to explain development of these dissolutional caves must operate under these tight constraints of time and space.

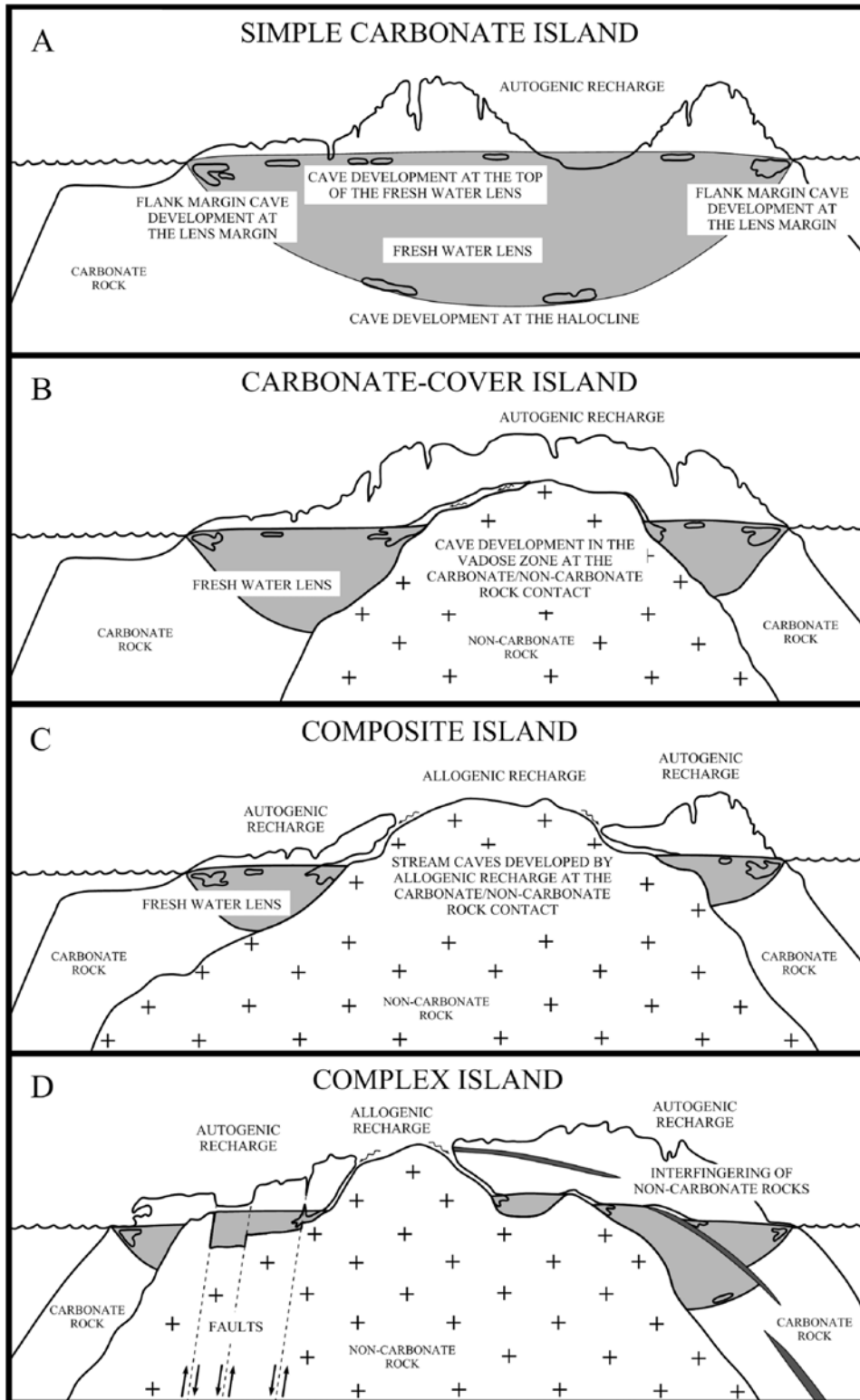
### **CARBONATE ISLAND KARST MODEL (CIKM)**

The Bahamas were the starting point for the development of what has become the Carbonate Island Karst Model (Jenson et al., 2006) or CIKM. The salient points of this model are shown in Figure 9 and Table 3. The key aspects are that cave and karst development in islands in eogenetic carbonate rocks is very different from that found in the telogenetic carbonate rocks of continental interiors, where most karst research has traditionally been done. Basically, karst development under the CIKM is controlled by the youthful age of the eogenetic rock involved (almost always Cenozoic, commonly Quaternary), the dissolutional aggressivity provided by mixing of freshwater and seawater, and the change in sea level created by glacio-eustasy and tectonics. Island configuration, especially as regards carbonate and non-carbonate rocks, is also crucial.

*Island karst* has been defined as that which forms under the constraints of the CIKM, whereas karst that develops in the interior of islands, removed from CIKM controls, is *karst on islands* (Vacher and Mylroie, 2002). For example, the caves and karst found in the Bahamas is island karst, but the cockpit karst of Jamaica, or the Mogote karst of Cuba and Puerto Rico, is karst on islands, as that karst differs little from what would be found in a tropical, continental interior such as Belize, or Vietnam. In the Bahamas, there are no tectonics or non-carbonate rocks, and application of the CIKM is simplified.

### **KARREN**

Karren are dissolutional sculpturing at the centimeter to meter scale found on exposed and soil-covered carbonate rocks of all ages and types. A variety of etched and fretted surfaces develop; on exposed surfaces this etching is sharp and jagged, whereas on



**Figure 9. The Carbonate Island Karst Model, or CIKM, catalogues islands into four forms. Many islands do not fall into strict categories, but may show different features in different areas. From Jenson et al., 2006.**



Distinct geomorphic types that distinguish carbonate islands from one another	Common attributes that distinguish island karst from karst of interior settings
<b>Simple Carbonate Islands:</b> Non-carbonate rocks remain below the zone of fresh-water influence, and recharge is exclusively autogenic. (Fig. 1A)	The karst is <b>eogenetic</b> , i.e., it has developed in carbonate rocks that are young and have not been buried beyond the range of meteoric diagenesis.
<b>Carbonate Cover Islands:</b> Non-carbonate basement rocks deflect percolating water and partition the fresh-water lens. (Fig. 1B)	<b>Dissolution is enhanced at the surface, bottom, and margin of the freshwater lens</b> by mixing of waters and trapping of organic materials at these boundaries.
<b>Composite Islands:</b> Non-carbonate basement exposed at the surface, and allogenic recharge is delivered to insurgences at the contacts. (Fig. 1C)	<b>Glacio-eustatic sea-level fluctuations</b> impose dissolutional and diagenetic diagenetic imprints reflecting the vertical migration of the lens.
<b>Complex Islands:</b> Interfingering of carbonate/non-carbonate facies and faulting combine to produce complex aquifer features. (Fig. 1D)	<b>Tectonic uplift and subsidence</b> overprints the glacio-eustatic imprints with additional dissolutional and diagenetic imprints, as well as structural modifications.

**Table 3. Components of the Carbonate Island Karst Model (Jenson et al., 2006)**

soil-mantled surfaces it tends to be smooth and curvilinear. Taborosi et al. (2004) reviewed the various terms and mechanisms proposed over the years to describe and explain karren on carbonate islands and coasts, and they provide updated interpretations. The term *eogenetic karren* has been applied by them to the unique etching and dissolution of surface carbonates on eogenetic carbonate islands and coasts. This term replaces the traditional “phytokarst” of Folk et al. (1973) or “biokarst” of Viles (1988). Eogenetic coastal karren is common in coastal areas wetted by sea spray. While biology plays an important part in this karren development, it is the eogenetic nature of the rock that leads to the spectacular morphology. The large amount of primary porosity, the differing character of the allochems, and the variability of the cements of eogenetic carbonate rocks create an environment that easily hosts endolithic boring algae. The biologic activity of those algae, coupled with invertebrate grazers and inorganic mixing dissolution, carve the eogenetic rock in jagged and irregular shapes, shapes reinforced by the pre-existing high variability of the allochem-dominated structure of the host rock.

In inland settings, karren are part of the epikarst, the weathered zone on the limestone surface. The epikarst consists of soil and loose blocks of limestone, which over a vertical distance of less than a meter grades into a dissolutionally etched and fretted surface containing numerous small holes and tubes. These holes and tubes in turn rapidly consolidate into widely-spaced discrete flow paths that transmit water downward into the rock mass (see pit caves below). On slopes, the soil and loose rock mantle is commonly removed, and the bedrock karren, tubes and holes are fully exposed.

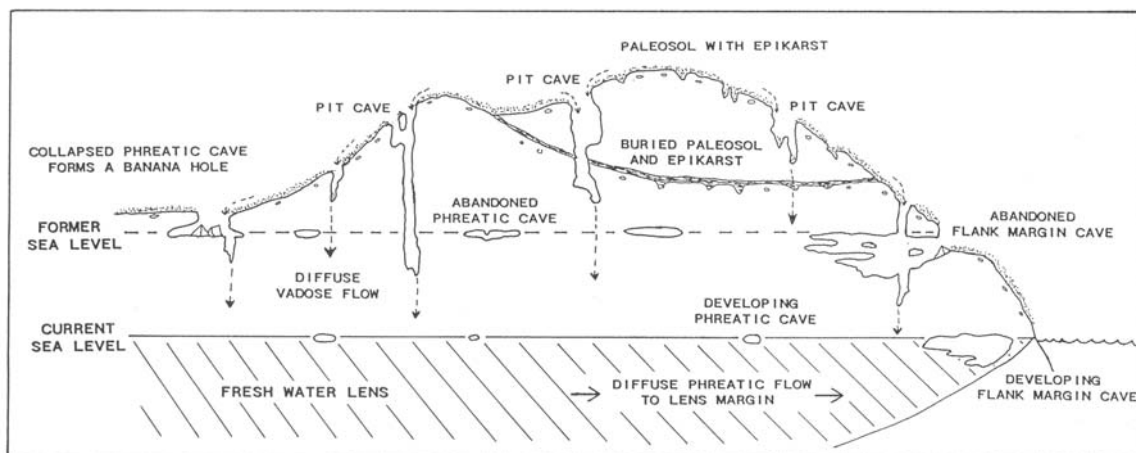
## DEPRESSIONS

Depressions are large basins completely enclosed by surrounding topography. In the Bahamas, large closed depressions, as viewed on topographic maps or on air photographs, represent constructional depressions maintained by subsequent dissolutional processes. These depressions have not been excavated by karst dissolution. The influence of climate on depression development in Atlantic Quaternary islands is reviewed by Mylroie et al. (1995a). These large constructional depressions originate as swales between eolianite ridges or as fossil lagoons. Depressions that extend below sea level contain lakes with salinities ranging from fresh to hypersaline, depending on the water budget of a given island, lake surface area, and subsurface hydrology. On San Salvador, yearly evapotranspiration exceeds precipitation and the

lakes suffer a net loss of water. This upcones marine water from depth, and further evaporative losses make the lakes hypersaline (Davis and Johnson, 1989). The fresh-water lens is consequently partitioned into smaller bodies underlying the remaining dry land. Some of these constructional depressions are linked to caves (lake drains, see below) that connect to the sea; tidal pumping causes exchange of waters that keeps some of these lakes at marine salinity. Lake margins are little modified by dissolutional processes when lake waters are hypersaline, as on San Salvador, but on wetter Quaternary eolian islands, such as Bermuda, depressions with fresh water enlarge laterally by dissolution (Myroie et al., 1995a).

## CAVES

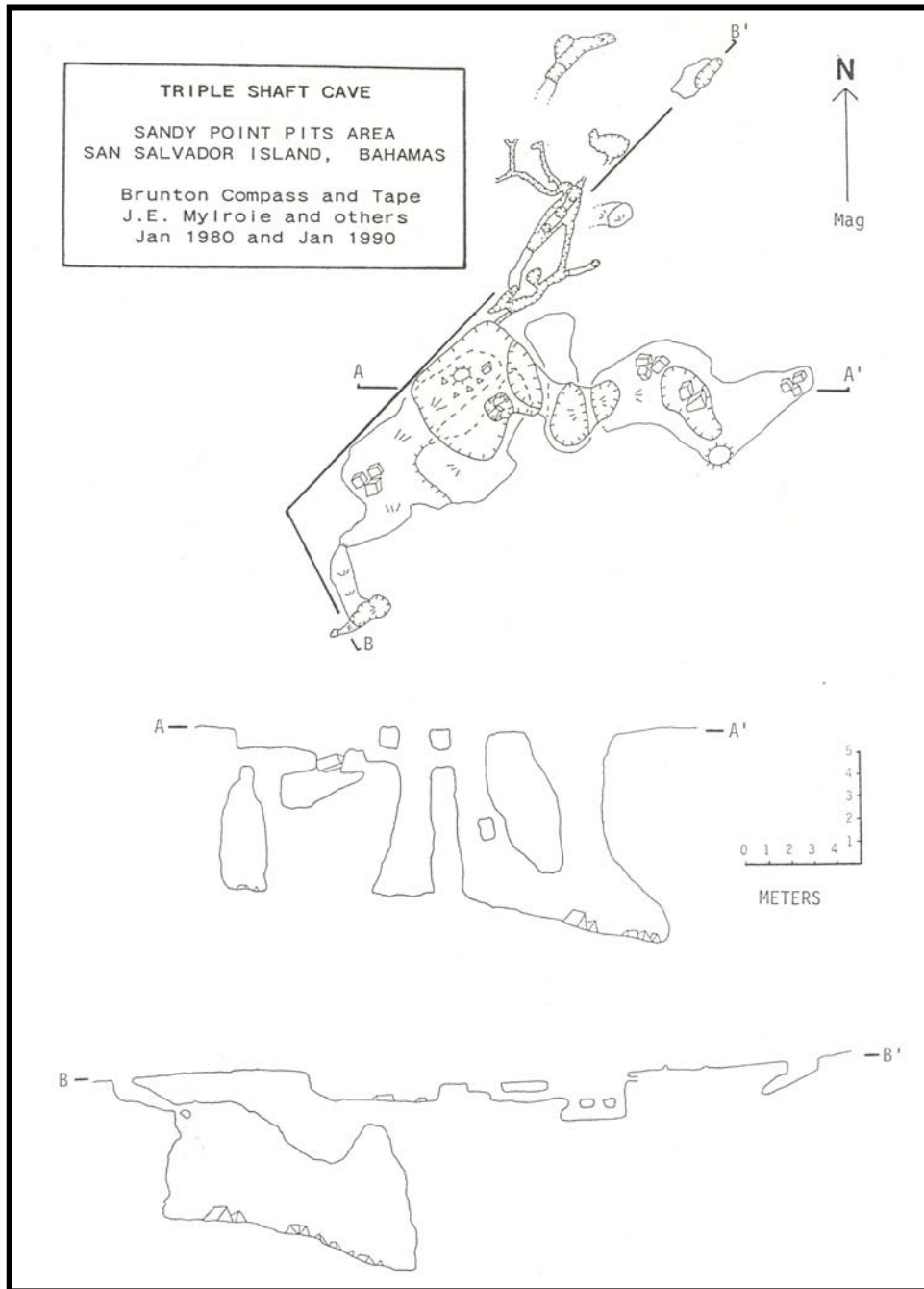
There are four main types of caves in the Bahamas: pit caves, flank margin caves, banana holes, and lake drains. The first three cave types are well understood, but lake drains remain something of a mystery. Figure 10 is an idealized representation of the major cave features found in the Bahamas, excepting lake drains.



**Figure 10. Cartoon representation of the three main cave types found on a simple carbonate island such as San Salvador: pit caves, flank margin caves, and banana holes. Changing sea level moves the fresh-water lens and its dissolutional environments. From Myroie and Carew, 1995.**

### Pit Caves

Pit caves are found all over the Bahamas, sometimes in very dense clusters, and occasionally at the top of hills. As the name suggests, these are vertical shafts that drop typically 5 to 10 m (Fig. 11), often descending in a stair-step fashion, with occasional small chambers. They rarely intersect other cave types, or penetrate to the fresh-water lens. Their walls show classic vertical grooves formed by supercritical laminar flow of descending vadose water. During major rain events, they can be observed to efficiently collect water from the epikarst and conduct it downwards as vadose fast-flow routes. Their high density in places was initially thought, based on water budget considerations, to indicate much higher rainfall conditions at a past time. The high pit cave density is now understood to reflect competition and piracy among pit caves, such that some lose their recharge to “upstream” competitors (Harris et al., 1995). These caves can be com-



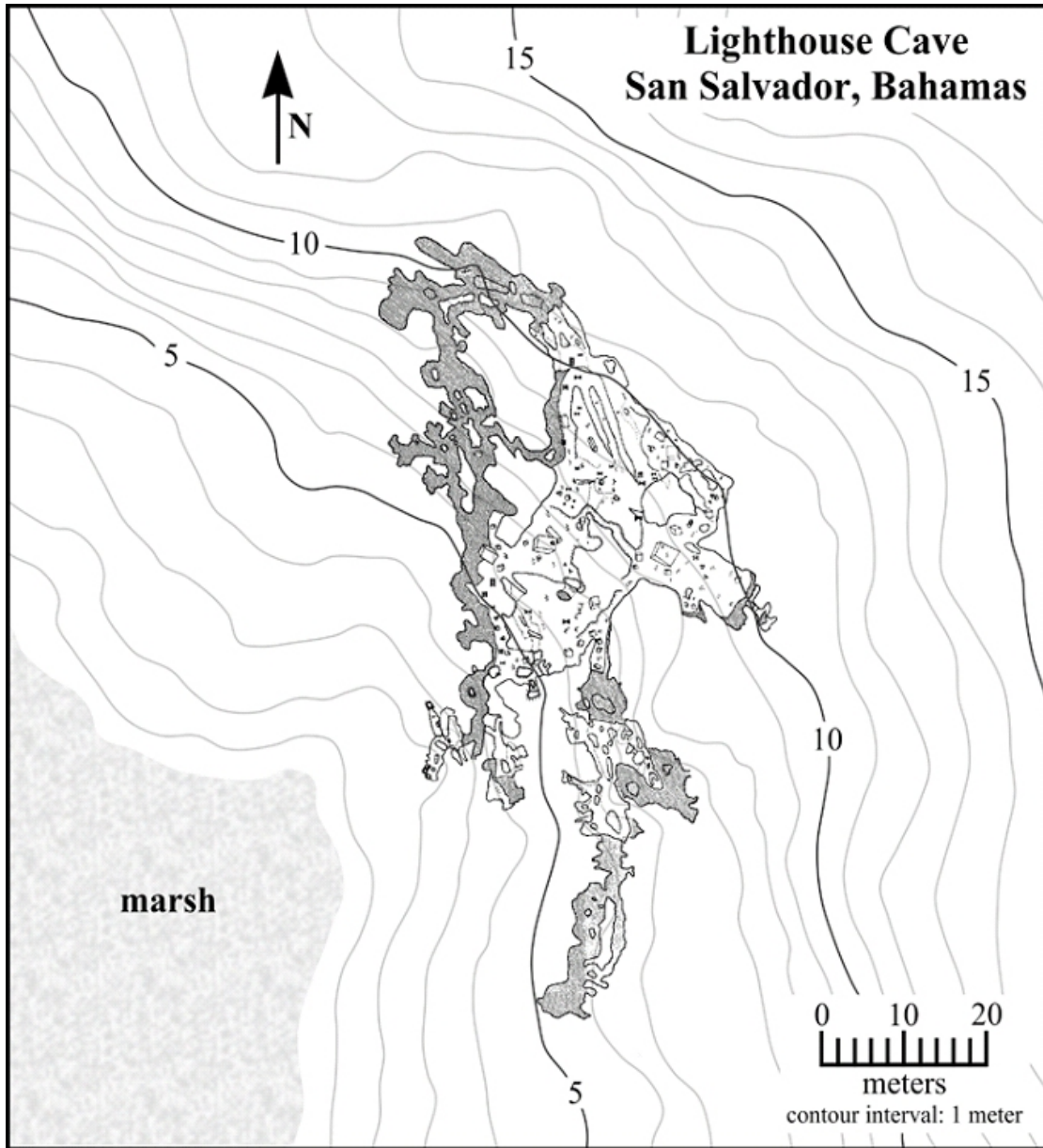
**Figure 11. Triple Shaft Cave, Sandy Point Pits, a typical Bahamian pit cave. Note the shallow epikarst water collection system, and the interconnected shaft system. From Harris et al., 1995.**

plex as a result of this competition, which commonly leads to intersection of pit caves by one another. Pit caves form independently of sea level and fresh-water lens position, and can form in any exposed carbonate rock on an island. They are absent from Holocene rocks, but penetrate a variety of Pleistocene eolianites.

## Flank Margin Caves

The largest of the caves that develop in simple carbonate islands form at the distal margin of the fresh water lens, under the flank of the enclosing landmass, so they are called *flank margin caves* (Myroie and Carew, 1990). These large caves are commonly entered where a hillside has been breached by erosion, or a portion of the cave roof has collapsed. The caves are found at elevations of 1 to 7 m elevation, which is in agreement with the position of at least one earlier sea level during the Quaternary, the last interglacial associated with MIS 5e, which lasted from 131 to 119 ka (Chen et al., 1991). This sea level reached 6 m higher than at present, as glacial ice melted back a bit more than it has today. The Bahamas are tectonically stable, so only a glacioeustatic sea-level highstand could have elevated the fresh-water lens above modern sea level, and so placed the fresh-water lens at, and slightly above, that +6 m elevation. Cave morphology is predictable and consistent: large chambers near the edge of the hill containing the cave, numerous ramifying passages at the back of the cave, and many cross-links and connections. Cave chambers are wider than they are high, with curvilinear and cusped margins. Remnant bedrock pillars are common. Passages heading inland commonly end in blank bedrock walls. The caves do not contain wall scallops or other turbulent flow markings, no stream-laid sediments, no sinking stream or spring entrances. The flank margin cave model was developed to interpret the size, shape, position and configuration of the caves (Myroie and Carew, 1990; 1995). The caves develop in the distal margin of the fresh-water lens, just under the flank of the enclosing landmass (Fig. 10). At this location, the mixing environment of the vadose input to the water table is superimposed on the mixing environment of the fresh-water lens with underlying marine water, increasing dissolution beyond what either environment could do alone. Additionally, the lens cross section decreases at the lens margin, so flow velocities increase, transporting reactants in, and products out, faster than elsewhere in the lens (Raeisi and Myroie, 1995). Finally, both the top of the lens, and the halocline, are density interfaces that can trap organic material. Oxidation of the organics creates CO<sub>2</sub> that can drive more dissolution; excess organics can create anoxic conditions and drive H<sub>2</sub>S-mediated dissolution. The H<sub>2</sub>S model appears supported by <sup>34</sup>S analysis of intergranular gypsum from flank margin caves on San Salvador, which showed depletion values associated with biomediation of sulfur in anoxic zones (Bottrell et al., 1993). There has been debate in the literature regarding the relative importance of the three mechanisms (e.g. Schwabe and Carew, 2006), but recently it has been suggested that the hydrologic condition of rapid lens-margin discharge alone, and not the geochemistry, is the critical factor (Moore et al., 2007).

Flank margin caves, as described earlier, have a variety of morphological features, all consistent with a non-turbulent, phreatic origin. The oval or globular chambers that are oriented parallel to the longitudinal trend of, and just under the flank of, the ridge in which they have formed, indicate the importance of the lens margin (Fig 12). Small radiating tubes extend from these large chambers into the ridge interior where they end abruptly or pinch out. These passages represent individual diffuse flow paths that delivered fresh water into the flank margin mixing area. The abrupt end of these passages reflects the position of the mixing front when sea level fell and the caves became subaerial. One final interesting aspect of flank margin caves is that they occur on scales from small chambers up to immense caves without loss of their general morphology or position with respect to the land surface. Size rank plots reveal that the caves self-select in three size groups based on growth of the initial voids, amalgamation of voids, and then amalgamation of clusters of voids (Roth et al., 2006). Computer



**Figure 12. Map of Lighthouse Cave, San Salvador. The cave has one large central chamber, adjacent smaller chambers, and ramifying dead-end passages. The cave follows the flank of the hill contour, the position of the distal margin of the fresh-water lens when the cave formed during MIS 5e. From Roth, 2004.**

modeling of void genesis creates the same plot, but adds a fourth group of tiny caves that were ignored by cave surveyors (Labourdette et al., 2007).

The general morphology of flank margin caves is similar to that of other caves formed under different mixed-water conditions (Mylroie and Carew, 1995), such as in the Guadalupe caves of New Mexico. This pattern of globular chambers, maze-like passage connections, thin wall partitions, and dead-end passages are called spongework or ramiform caves. Their development independent of surface conditions is termed

hypogenic (Palmer, 1991). More complete discussion of the freshwater lens, cave development, and the flank margin model can be found in Mylroie and Carew (1990; 1995), and Mylroie and Mylroie, 2007.

### **Banana Holes**

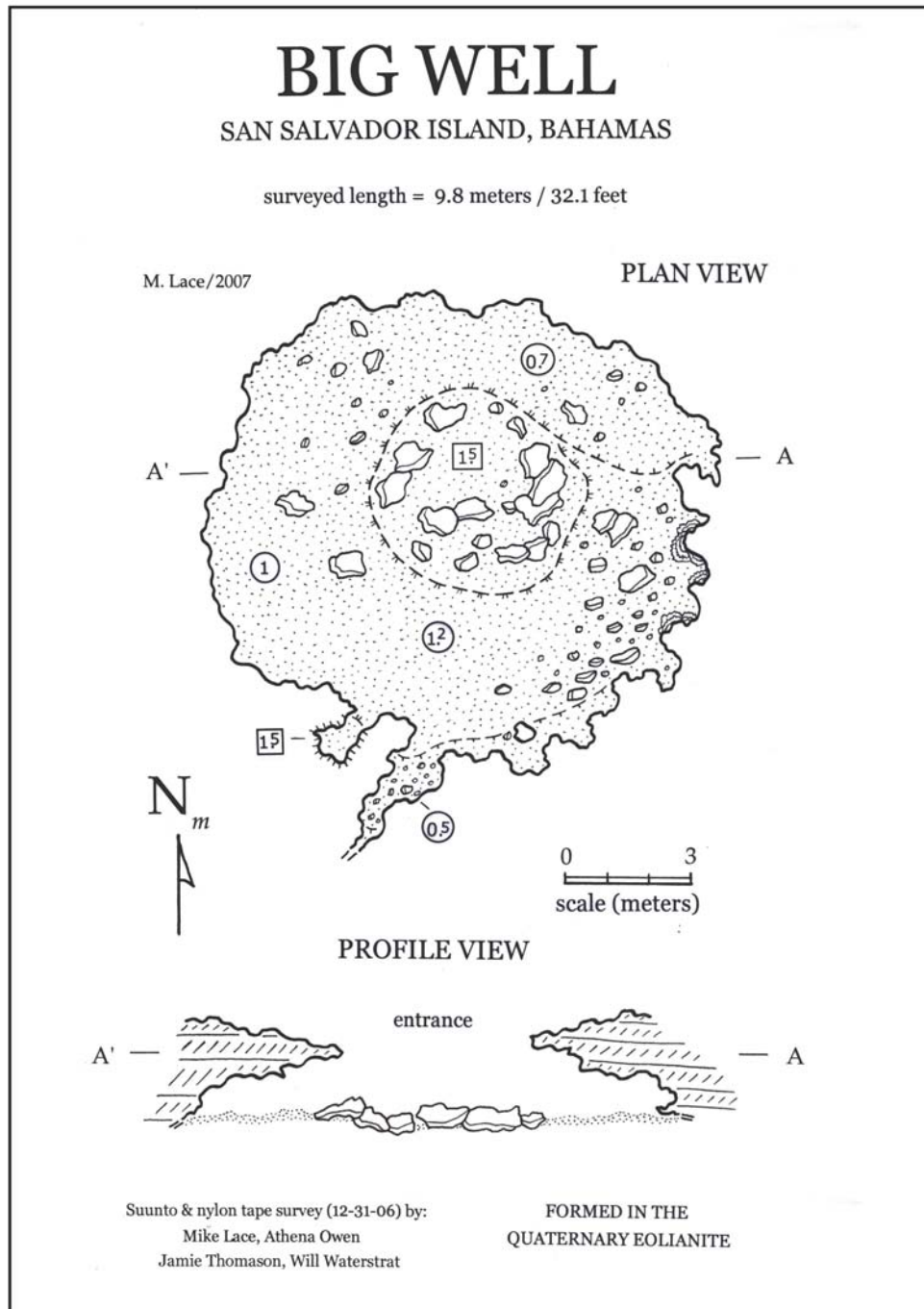
Abundant, but smaller caves develop at the top of the lens, away from the lens margin, called *banana holes*. Banana holes are circular to oval chambers 5 to 10 m in diameter, and 1 to 3 m high, with phreatic morphologies but lacking the size and passage ramifications found in flank margin caves (Fig. 13). They are located in positions of 1 to 7 m above sea level, recent research suggests the lens margin would have been nearby with sea level at that elevation. They are entered where their ceilings have collapsed, or rarely where a pit cave has intersected them. They can be found in dense concentrations, up to 3000/km<sup>2</sup> (Harris et al., 1995). Occasionally, a collapsed banana hole has a connection with an adjacent, uncollapsed banana hole. In the Bahamas, they commonly develop in the broad, low-elevation regions that make up significant parts of these islands. As a result, their roofs are thin and prone to collapse. Once collapsed, banana holes collect soil and vegetative debris, as well as water and are favored for the growing of specialty crops, such as bananas, which is how their name was derived (Harris et al., 1995). Their smaller size relative to flank margin caves is a result of their development in a lens margin following prograding sands into lagoons; as they form, the lens advances and abandons them. The result are chambers formed as *syndepositional caves*, i.e. formed as the rocks containing them formed. (Mylroie and Mylroie, 2009).

### **Lake Drains**

Lake drains are a contrived term used to describe small, un-enterable conduits that carry water into and out of lakes in a pattern related to tides. Their presence results in lakes that maintain marine salinity despite climatic conditions that might favor freshwater, such as in the northwestern Bahamas, or hypersaline water, such as in the more arid southeastern Bahamas. Some lakes are large, and their lake drains are small, such that the conduit flow from the sea is not sufficient to greatly modify the lake salinity. Unlike flank margin caves and banana holes, lake drains are true conduits. Their mode of origin and configuration are poorly understood, but their influence can be important on lake geochemistry and as a result, lake ecology (Davis and Johnson, 1989). They remain cryptic features.

### **Depressions Revisited**

In most telogenetic carbonate settings found in continental interiors, the smaller closed contour depressions, sinkholes (American terminology) or dolines (European terminology), form quite differently than those in eogenetic carbonate islands such as the Bahamas. Sinkholes form by three main methods: 1) carbonate dissolution by focused epikarst flow to create small, saucer-shaped depressions; 2) collapse and subsidence of a thick soft sediment or soil mantle into a small dissolutional opening; and 3) collapse of the bedrock roof of a dissolutional chamber. In telogenetic continental carbonates, the longer time span available results in both a thick residual soil mantle, and more time for bedrock dissolution. The telogenetic character of the bedrock results in epikarst flow focussing to joint intersections and related flow pathways. Sinkholes formed by dissolution and soil subsidence are very common. But cave passages are relatively rare (less than 1% of the porosity), so collapses into bedrock voids are also relatively rare. In



**Figure 13. Map of Big Well Cave, a typical banana hole with one low, wide oval chamber. Note the thin roof, which promotes collapse. Cartography by M. Lace.**

the Bahamas and related eogenetic environments, there are no thick soils to subside downwards, and dissolutional openings, even large ones like pit caves, open flush to the land surface. There has been little time since bedrock deposition for dissolution of saucer-shaped sinkholes. But because flank margin caves and banana holes are extremely common, often with relatively thin bedrock roofs, collapse sinkholes are common, and they are the dominant small depression type in the Bahamas. The rule of

thumb in the Bahamas for depressions is: large ones are constructional, and small ones are cave collapses.

## **BLUE HOLES**

A famous karst feature of the Bahamas is the blue hole. The term "blue hole" has been used in a variety of ways. A complete review of the history of blue hole studies, and the various uses of the term, can be found in Mylroie et al. (1995b). A different approach to defining and describing blue holes can be found in Schwabe and Carew (2006). Blue holes are defined here as: "subsurface voids that are developed in carbonate banks and islands; are open to the earth's surface; contain tidally-influenced waters of fresh, marine, or mixed chemistry; extend below sea level for a majority of their depth; and may provide access to submerged cave passages." (Mylroie et al., 1995b, p. 225). Blue holes are found in two settings: "ocean holes open directly into the present marine environment and contain marine water, usually with tidal flow; inland blue holes are isolated by present topography from marine conditions, and open directly onto the land surface or into an isolated pond or lake, and contain tidally-influenced water of a variety of chemistries from fresh to marine" (Mylroie et al., 1995b, p. 225). The most common alternative use of the term "blue hole" is to describe large and deep karst springs in continental interiors (Mylroie et al., 1995b).

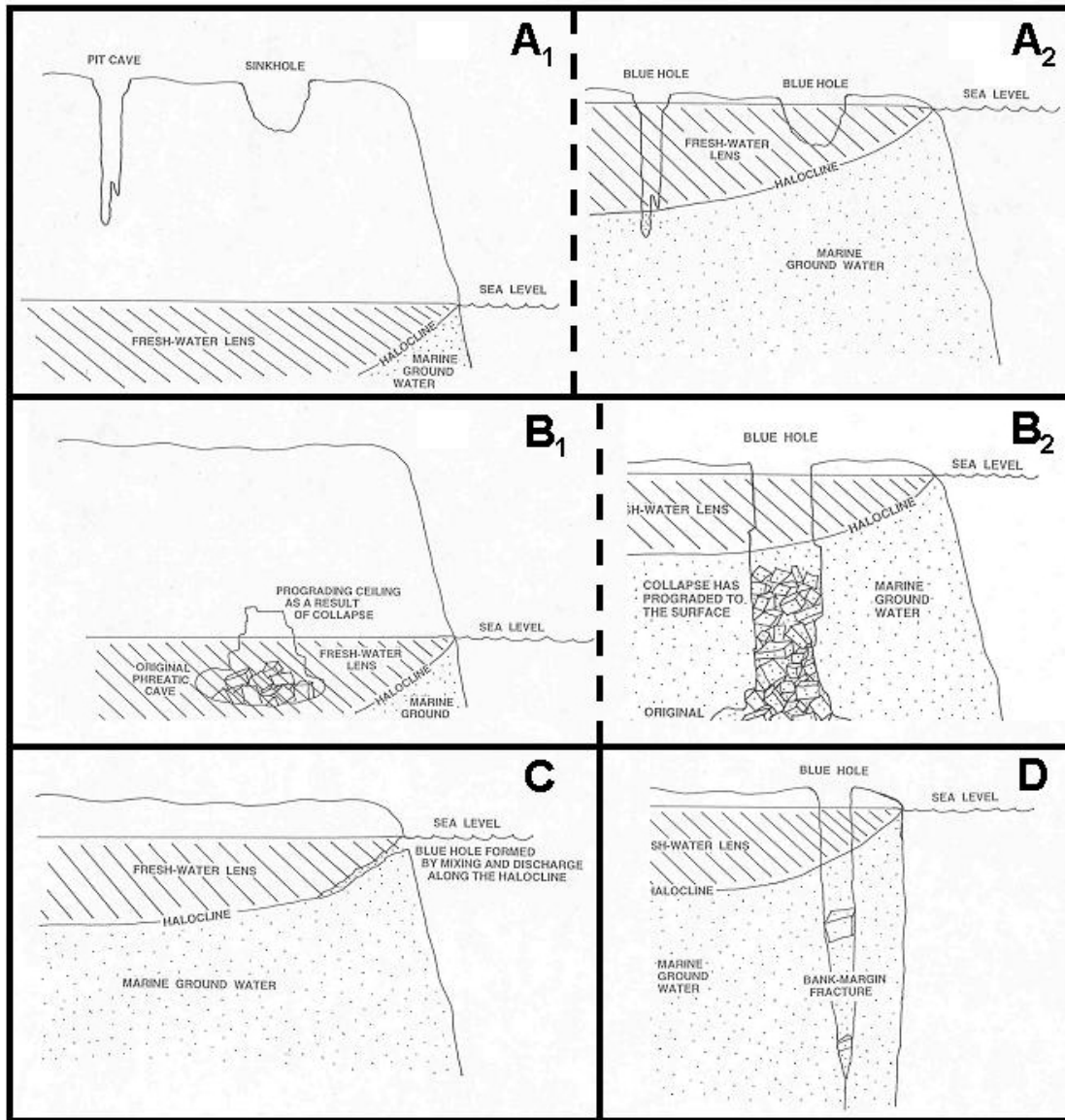
In the northwestern Bahamas, blue holes with depths in the 100-125 m range are common, and it was thought that their depth was limited by the position of the lowest glacial sea-level lowstand, which was about 125 m below present sea level. However, exploratory wells commonly intersect voids below that depth, e.g. depths of 21 to 4082 m; the deepest of these voids was large enough to accept 2,430 m of broken drill pipe (Meyerhoff and Hatten, 1974). Dean's Blue Hole on Long Island is known to be over 200 m deep, ending in a vast chamber (Wilson, 1994). Blue holes commonly lead into major horizontal cave systems, such as Lucayan Caverns on Grand Bahama Island, and Conch Blue Hole on North Andros Island (Palmer, 1985).

Blue holes are flooded karst features of polygenetic origin. They have developed in a variety of ways (Fig 14). 1) Pit caves that formed during sea-level lowstands flood during sea-level highstands to form some blue holes. 2) In places, failure of the steep margins of the Bahama banks produces bank-margin fractures. Wide gaps along these fractures can result in blue holes (Palmer, 1986; Carew and Mylroie, 1989a; Carew et al., 1992). 3) Collapse of large dissolutional voids at depth that were produced during sea-level lowstands or pre-Pleistocene highstands can prograde to the surface to form blue holes. Blue holes may open laterally into horizontal cave systems at a variety of depths. Some of these connections may be random intersection of caves formed by other means.

## **Pseudokarst**

Pseudokarst means literally "false karst". A good example would be kettle holes in glacial sediments, or lava tubes in volcanic terrain. In the Bahamas, with 100% carbonate outcrops, how does one get pseudokarst? There are actually two types of pseudokarst in the Bahamas: tafoni and sea caves. Tafoni are hollows and undercuts that form in rock cliffs as a result of a variety of subaerial weathering processes. They can resemble breached flank margin caves. The term has many definitions, and the reader is referred to Owen (2007) for a complete discussion of the term, its definition, and the processes that make tafoni in the Bahamas. Tafoni are abundant on cliffs in





**Figure 14. Cartoon of the polygenetic origin of blue holes: A<sub>1</sub> and A<sub>2</sub>, pit caves formed at low sea level are flooded by sea level rise; B<sub>1</sub> and B<sub>2</sub>, Dissolutional voids formed at lower sea levels prograde collapse upwards; C, dissolution along the halocline (note image is vertically exaggerated at least 10x); D, bank margin collapse creates water-filled fractures. From Mylroie et al., 1995b.**

eolianite facies, as cliffing exposes the poorly-cemented interior to subaerial processes such as wind and drying, while the vertical face limits meteoric cementation. Marine cliffs, because of cementation by sea spray, don't form tafoni unless the sea cliff is very high, or the result of episodic storm events, such that sea spray is a limited factor. Collapse of sides of an eolian ridge into a cave or blue hole creates a vertical cliff in which tafoni readily form. Tafoni are found in Holocene Rice Bay Formation eolianites, indicating that they can form quickly. Small tafoni are found in road cuts and quarries, even in sawn blocks of eolianite used in buildings, another indication of a rapid process. Tafoni in protected Holocene eolianite sea cliffs are the same size as those in protected coastal Pleistocene eolianites, indicating that it was Holocene sea level that created the

cliffing to form the tafoni. Descriptions of tafoni on San Salvador can be found in Owen (2007). Relict tafoni formed high in MIS 5e sea cliffs are described from Abaco (Walker, 2006; Walker et al., 2008).

Sea caves are the result of wave action on a rocky coast. Sea caves are found in all rock types, and most literature describes them as forming at major structural weaknesses such as faults, dikes, and lithologic contacts (Waterstrat, 2007). In the Bahamas, the Quaternary eolianites don't have faults, dikes or lithologic contacts, but sea caves are abundant, implicating wave energy patterns, and not rock characteristics, as the major control of the spacing and size of the resulting sea caves. Descriptions of sea caves on San Salvador can be found in Waterstrat (2007).

It is important to be able to differentiate tafoni from sea caves, and both from flank margin caves. Both sea caves and flank margin caves are a measure of sea level at their time of formation, but only flank margin caves provide information on the nature of the fresh-water lens that formed them. Sea caves and flank margin caves found in island interiors from a past, higher sea level event(s) provide information on denudation rates. If an open chamber is found at the base of an eolianite ridge, and it is identified as a sea cave, then erosive denudation has been minimal. If the chamber is a flank margin cave, then enough hillside has been eroded away to breach into the cave. Misidentifying sea caves as flank margin caves, or vice versa, can create problems in interpreting denudation rates and paleohydrology. Tafoni are not restricted to sea level, and so misidentifying a tafoni as a paleo sea cave or a breached flank margin cave will result in an incorrect sea level interpretation. Tafoni misidentified as breached flank margin caves also will lead to incorrect paleohydrology interpretations. Owen (2007) and Waterstrat (2007) provide a quantitative methodology using area to perimeter ratios of cave maps, and entrance width to maximum width ratios, to differentiate the three cave types.

### **Karst Summary**

Island karst is dominated by sea-level position, the fresh-water lens, and the eogenetic nature of the carbonate rocks. The caves and karst features that form on islands differ dramatically from similar features in continental interiors. Because island karst falls in or near the carbonate depositional environment, preservation of such karst as paleokarst is more likely than for continental situations. There is evidence that as island size increases, diffuse flow to the island margin becomes inefficient, and true conduit flow develops (Mylroie and Vacher, 1999). Cave divers in the Bahamas have discovered long conduit systems at depths of about 20 to 30 m (Palmer, 1986). A sea level at that depth would expose almost all the Bahamian carbonate platforms to create giant islands, and perhaps force a switch from flank margin cave development to conduit cave development.

### **ISLAND STRATIGRAPHY AND KARST GEOLOGY FIELD TRIP**

The field trip presented below is a combined island stratigraphy and karst geology exposition. The stops have been arranged in the order that allows the most efficient travel (Fig 15 A&B). As described, the field trip can be accomplished as three separate all-day trips, one on Island Stratigraphy, one on Island Karst Geology, and a half day each at Lighthouse Cave and the GRC lake trail. The Island Stratigraphy trip is

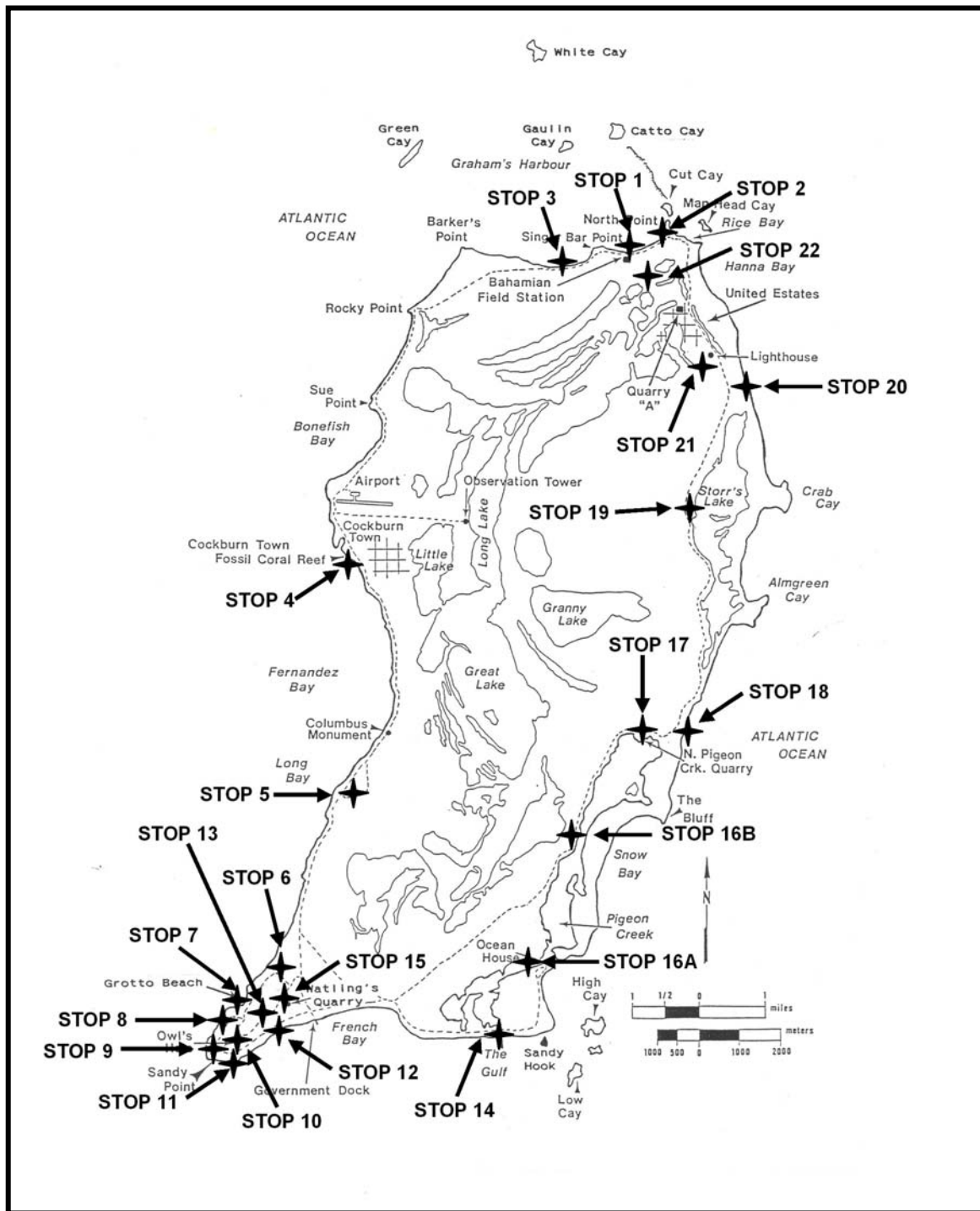
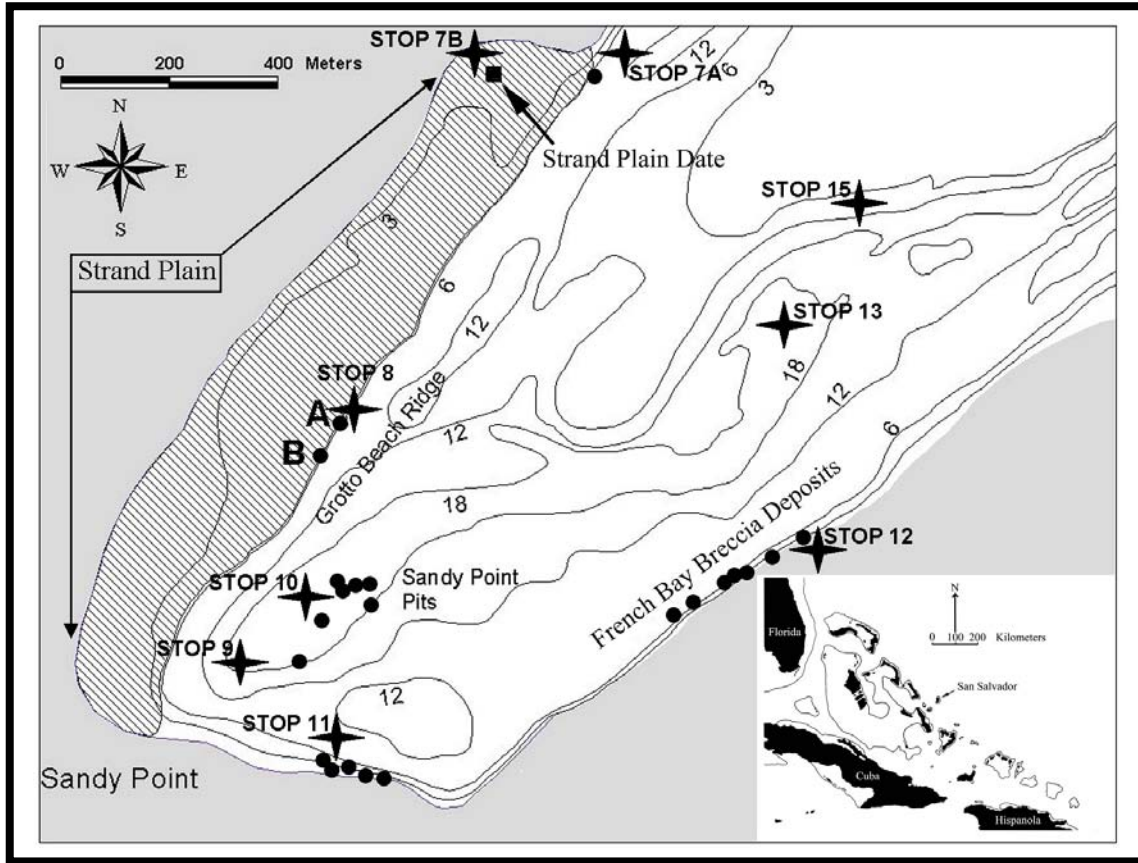


Figure 15A. Figure 2 reproduced with field trip stop locations. Figure 15B shows a close up of the Sandy Point area and its many stop locations. Modified from Carew and Mylroie, 1995a



**Figure 15B. Location of the field trip stops in the Sandy Point area. Solid circles mark significant cave and karst locations. A is Altar Cave, B is Dripping Rock Cave. The lowland area marked “strand plain” is all Holocene beach accretion. Modified from Florea et al., 2004.**

accomplished by visiting the following selected stops in proper order: Stop 1, Stop 2, Stop 3, Stop 4, Stop 7A, Stop 7B, Stop 12A, Stop 12 B, Stop 14, and Stop 15. If time allows, the order of Stop 14 and 15 can be reversed, and Stop 16A, Stop 16B, Stop 17, Stop 18, Stop 19, and Stop 20 can be done. Adding the east side Stops 16-20 on top of the earlier stops is ambitious for a single day. As the Pigeon Creek snorkel (Stop 16A) is a very interesting activity, but time consuming, and a hike down to The Bluff at Stop 18 also takes time, doing the east side stops as a separate day is more reasonable. Stop 14 then becomes an option to do near the end of the first day or start the second day. The Pigeon Creek snorkel is tide-dependent, so the order of doing the east side stops depends on when the tidal current will be at its maximum.

The Island Karst Geology trip can be similarly accomplished by taking selected stops in this order: Stop 5, Stop 6, Stop 8, Stop 9, Stop 10, Stop 11, Stop 12, and Stop 13. The Island Stratigraphy trip has a natural lunch stop at Grotto Beach (Stops 7A and 7B), but the Island Karst Geology trip does not. A good spot to take lunch is at Stop 13 with its nice vistas. The trip stop order can be adjusted to be at Stop 13 at lunch time, as the karst stops from Stop 8 to Stop 13 are all short drives apart (Fig. 15B). Any field trip schedule is somewhat dependent on group size; large groups move more slowly than small groups. The Island Karst Geology trip, with visits to a number of small caves,

exacerbates large group delays, and this potential time sink should be taken into account.

The Lighthouse Cave trip is easily done in a half day, as is the GRC Lake Trail trip. These two trips can be sandwiched around lunch at the GRC.

Many of the directions given are based on road patterns existing at the time of the fieldwork, some of which was done three decades ago. All around San Salvador, but especially in the Sandy Point area, where roads from a former housing development are being overgrown to an astonishing degree, directions may not work well. Therefore directions such as “take the 3<sup>rd</sup> left” may be hard to follow. It is strongly recommended that visitors check with the GRC Executive Director to be certain on how to find specific sites.

### **Stop 1: Hanna Bay Member of the Rice Bay Formation, Graham's Harbour**

Leave the main gate of the GRC field station and cross the road to the concrete ramp. At the base of the ramp turn to the west (left). Along this section of coast are Holocene rocks assigned to the Hanna Bay Member of the Rice Bay Formation. This unit comprises the youngest rocks on San Salvador, and in the Bahamas.

Along this cliff line, rocks assignable to beach face through back-beach dune lithofacies can be seen to have depositional dips congruent with current sea level. There is no terra rossa paleosol. These rocks are weakly cemented bioclastic and peloidal calcarenites. Cement, where present, is primarily meniscus style low-Mg calcite. Radiocarbon ages for whole rock samples from outcrops assigned to this unit range from 420 yBP to about 3,500 yBP (Carew and Mylroie, 1987a; Boardman et al., 1989). The cliffing of these deposits is not the result of a sea level change, but change of coastal dynamics during a stable sea level (over the last 3,000 years). Possible reasons for the change of coastal dynamics in this setting may include growth of the barrier reef to wave base, or alternatively, the erosion of the barrier represented by the eolianites of North Point, Cut Cay, Catto Cay and White Cay. To the east (right) are rocks that are very young. These flat slabs of beach rock have yielded a cannonball cemented into the rock (Adams, 1983) and even more recent objects such as bottle caps and glass.

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

About 750 m east from the field station, just before the road turns southeast at North Point, is the large concrete Government Dock. From the Government Dock, walk east along the beach onto the nearly flat rocky platform, with cliffs beyond. Notice the swirling, crosscutting patterns of variously truncated eolian bedding. The morphological form of North Point and the bedding style clearly indicate the eolian origin of this rock. There is no terra rossa paleosol. Petrographically, these rocks are similar to those seen at Stop 1, with the additional presence of superficial ooids low in the section. The rocks are assigned to the North Point Member of the Rice Bay Formation based upon the bedding relationships relative to sea level. At various places along this outcrop, it is quite evident that the bedding dips steeply (approx. 28°) below present sea level and can commonly be seen to continue at least 2 m below present sea level. It is clear that these dunes were formed at a time when sea level was at least 2 m below its present position. The rocks, then, are older than those rocks seen at Stop 1. Radiocarbon ages of whole rock samples from these outcrops average about 5,300 yBP (Carew and Mylroie,

1987a). Detailed studies of these rocks have been reported by White and Curran (1985; 1988). The Holocene age of these rocks, coupled with their deposition below current sea level, their lack of vegemorphs, and the well preserved bedding structures high in the section demonstrate that they are transgressive in origin.

The rocks of the Rice Bay Formation seen at Stops 1 and 2 are Holocene, and they characteristically lack a capping terra rossa paleosol. In addition, they generally are weakly cemented (except in the spray zone) and usually exhibit little karst development other than coastal eogenetic karren. The North Point rocks show numerous large tafoni on the relatively calm Grahams Harbour, or west side, of the point. On the more energetic Rice Bay, or east side of the point, wave energies are higher and more constant, such that sea spray cements the coastal cliffs and tafoni development is inhibited, but sea cave development is common. The wave cut platform on the Grahams Harbour side is above sea level, and reflects development only during major storm events. Those events have also cliffed the west side of North Point, but at rare times such that sea spray cementation has been minimal in the cliffs. As a result, the tafoni are abundant and large but sea caves rare.

### **Stop 3: Singer Bar Point, Pleistocene/Holocene Boundary**

West from the field station about 1,700 m, the road veers southwest away from the coast and traverses a low ridge, then meets the coast again. The rocky headland behind and to the northeast is Singer Bar Point. A little farther ahead, a small isolated outcrop is seen at the water's edge; stop here. At this stop a terra rossa paleosol marking the unconformity between the Holocene Rice Bay and the Pleistocene Grotto Beach Formation is well exposed. Note the color, hardness, and "undulatory" nature of the paleosol. Inspect the actual contact between the two formations; it is a thin (~1 cm) red line that could easily be missed by the casual observer. The overlying rock is a bioclastic and peloidal eolianite of the Hanna Bay Member of the Rice Bay Formation; the underlying unit is oolitic subtidal sands of the Cockburn Town Member of the Grotto Beach Formation.

### **Stop 4: Cockburn Town Fossil Reef**

Proceeding west and south along the main road, go past the airport and Club Med and into Cockburn Town, stopping in the coastal parking area to the west of the road just south of the power station and across the road from the post office and other government offices. Prior to the dredging of an enlarged marina to the north, the old dock here was the main landing point for island supplies. Walk north from the parking spot, between the power station fence and the coast, to where a pipeline comes in from the coast. Barges anchor offshore, and a flexible hose brings in gasoline and diesel fuel for the storage tanks inside the fence. Follow the pipeline west to the rocky coast, then turn right and head north. The fossil reef extends both north, as well as south past the old dock, but the best exposures are to the north. DO NOT SAMPLE AT THIS SITE. There is loose rubble in places, that with permission, may be sampled. This locality, as might be expected from the name, is the type section for the Cockburn Town Member of the Grotto Beach Formation.

The rocky outcrops here contain the famous Cockburn Town fossil reef. U/Th dating established the reef as developing during MIS 5e (Carew and Mylroie, 1987a), and one of the first TIMS U/Th dating of fossil corals was done here (Chen et al., 1991) which

refined the MIS 5e age structure. The reef has been well studied, and the leading source is the work by Curran and White (1985; 1989). San Salvador has many fossil reef sites (Egerton and Mylroie, 2006), and the Cockburn Town Fossil reef is the largest and best preserved on the island. Careful analysis by White et al. (1998) reveals that there are two episodes of coral deposition during MIS 5e, separated by a brief (~1000 ka) hiatus, suggesting that MIS 5e had two peaks separated by a small dip in sea level. This interpretation has received support from work in flank margin caves (Carew and Mylroie, 1999), which show two phreatic events separated by a vadose interval (lowering of the fresh-water lens) during MIS 5e.

The preservation of shell and coral material, as well as red algae, is superb. Sea biscuits have been found here, and trace fossils are abundant. The high degree of preservation has been interpreted (Curran and White, 1985; Carew and Mylroie, 1995a; 1997) as the result of a sudden burial of the reef by sands during a major storm event, perhaps a hurricane. Some corals are in growth position, and algal encrustations show some coral died in growth position prior to entombment. The species of coral here include the major Caribbean forms, dominated by *Diploria strigosa*, *D. labyrinthiformis*, *Monastrea annularis*, *M. cavernosa*, *Acropora cervicornis*, *A. palmata*, *Porites porites*, *P. furcata*, and *P. astreoides*. The molluscs are dominated by *Chione cancellata*, and by ark shells such as *Arca imbricata*, *Barbatia cancellaria*, and *B. domingensis*. Trace fossils include *Ophiomorpha* sp. produced by callianassid shrimp and an excellent subtidal indicator, and *Skolithos linearis*. The mollusc shells show a great deal of color, and it is not unusual for people to bend over to pick up what they think is a modern loose shell, only to find it is 125 ka old and cemented into the outcrop.

A brief description of some major features is offered here. A full day or more can be spent at this locality looking at the myriad of fossils and associated structures. The reader is referred to the excellent field guides by Curran and White (1985; 1989) for a detailed description of this amazing site.

A small but deep reentrant about 30 m north of the pipeline is called “*Ophiomorpha* Bay” because of the abundant and exquisitely preserved *Ophiomorpha* sp. present. The burrows overlap, and the degree of bioturbation is immense. *Skolithos linearis* is also present. In areas of major sand flow, subtidal sand beds can appear, incorrectly, to have eolian foresets. The presence of *Ophiomorpha* sp is a clear indication of a subtidal setting.

Starting just prior to *Ophiomorpha* Bay, and continuing down most of the length of the fossil reef and parallel to it on the inland side, are a series of fractures infilled with a red, micritic material that is identical to that found in a terra rossa paleosol. Because of wave action, the terra rossa paleosol at the fossil reef has been mostly stripped away, but can be found in hollows and small dissolution pits along the reef. The long, linear fracture is believed to be an unloading structure, formed by the drop of sea level at the end of MIS 5e, such that the reef lost buoyant support, leaned paleo-seaward, and cracked. This scenario explains the co-linearity of the reef and the fracture. Terra rossa material infiltrated the crack and lithified. In places, this resistant infilling weathers out in positive relief, a classic inversion of topography.

About 40 m past *Ophiomorpha* Bay, the fossil reef trends north as a 5 m wide ridge with the lagoon to the west and a sandy trough to the east. This trough is not natural, but is the result of excavation for rock material used in construction. The excavating process

has exposed the reef in vertical section, allowing the intricate details of its internal construction to be seen. Ahead and to the east (right) is a small hill with an old telephone pole on it. The rock there shows the transition from reef to beach to back beach and back beach dune, a classic regressive sequence, showing the subtidal to eolian complexity of the Cockburn Town Member of the Grotto Beach Formation.

West of the hill, in the east-facing cut into the fossil reef, *A. cervicornis* can be seen in the vertical face. The *A. cervicornis* stems have a red algal encrustation, also fossilized. What is interesting at this site is that the algal overgrowth is preferentially elongated on the upward, or sun-lit side of the stem, indicating that the *A. cervicornis* was dead, but not yet broken down, when the algae grew on it. The entire sequence was buried in sand in the hypothesized storm event and preserved. Farther north, large sand bodies containing *A. palmata* stems and trunks can be seen, another indication of a storm event entombment.

### **Stop 5: Big Well, A Banana Hole**

Proceeding south along the main road, go through Cockburn Town, and continue south past the Columbus Monument to the village of Sugar Loaf, which is reached just after a coast road departs the main road to the right (west). The road goes up a low hill, then turns sharply west and trends downhill towards the coast. About 300 m past the change in direction, on the south (left) side of the road only a few meters from the pavement is Big Well, a banana hole (Fig. 13). A circular opening about 3 m across is a collapse into a low, wide room. The roof is only a meter or two thick. The cave is an oval chamber between 1 and 2 m high, and the cave walls have phreatic dissolution features. To the south end of the cave is a low spot, that when excavated, reaches the fresh-water lens, hence the name for the cave. Watling's Banana Hole, down slope from Watling's Castle (seen at the hill crest on way from Stop 14 to Stop 15) has a fitted stone stairway in one corner, leading down to the fresh-water lens. Banana hole origin is discussed in Harris et al., (1995).

Big Well has some trash in it, a common problem for caves and sinkholes world wide. While banana holes have been used for water resources, at the Fortune Hill plantation on the island's east side, a privy was built over a deep pit cave, which returned human fecal material directly back to the fresh-water lens.

### **Stop 6: Ink Well, A Blue Hole That Is Not Blue**

From Stop 5, continue west a short distance. The coast road mentioned in the Stop 5 description joins the main road at this point, and the main road continues south along the west coast of the island. Approximately 4.5 km south of Stop 5, power lines along the main road make an abrupt turn to the west (right). Take the next right turn (also has power lines) and take the second overgrown road to the right, and follow it north a short distance, then sharp left (west), curving southwest a similar distance to a dead end. Immediately ahead, behind a house, is Ink Well. This area has seen much recent development, and roads and power lines may not be where stated in this description.

Ink Well is a shallow blue hole. It has a fresh/brackish water lens about 3 m thick floating on an underlying salt water body. The presence of the non-marine water at the surface promotes a luxuriant (for San Salvador) vegetation at the margin of the blue hole. The collection of organic matter in the upper water layer has stained the water dark with



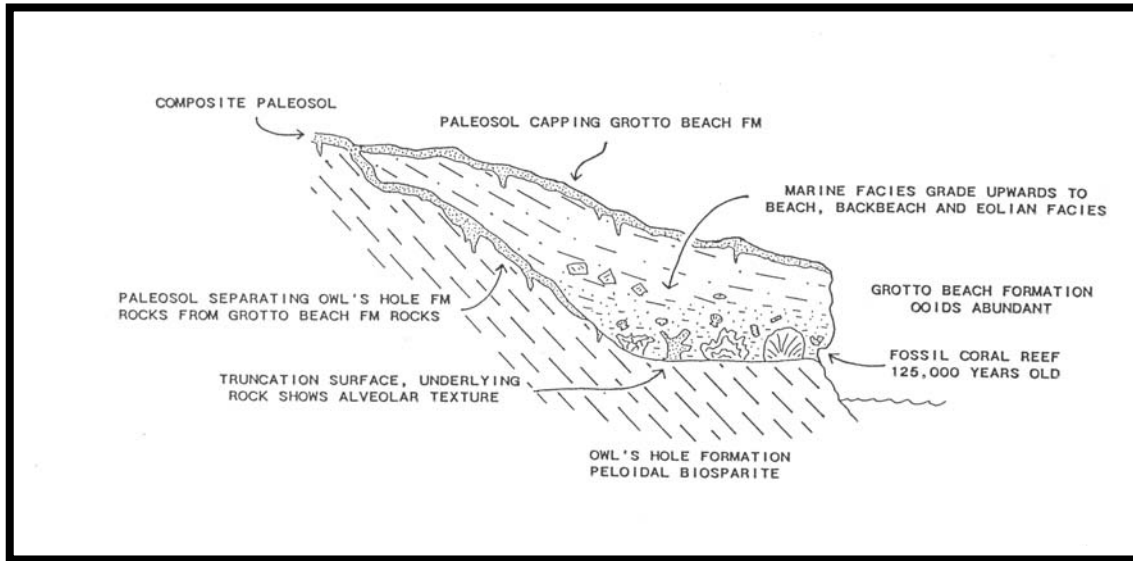
tannin, hence the name Ink Well and the lack of a blue color. Cave diver John Schweyen reported in 1986 that the upper layer has very poor visibility, but once the underlying marine layer is reached, the water was crystal clear. The halocline was very sharp. The depth of the blue hole is 8 m. While Ink Well shows minor tidal variation, no accessible conduit or cave was located by John Schweyen during his dive, and the bottom is sediment. Note the steep walls of the blue hole, suggestive of collapse, or undermining of the perimeter by chemical activity at the halocline. The relatively limited surface area of Ink Well helps prevent excessive evaporation and upconing of the underlying marine layer. The surface waters have a salinity of 5.20 ppt, indicating it is about 13.7% sea water (Moore et al., 2007).

Back at the main road, and across it to the south, a short 30 m trail leads south to Church Blue Hole, a broad pond with a bedrock rim on all sides. It slopes down to a deeper section in the middle, but no cave passages are known. The water is saline to slightly hypersaline. Unlike many other Bahamian islands, San Salvador's blue holes have not yielded access to significant underwater caves. Why this is the case is not known. It could be simple chance, or it could relate to the small size of the San Salvador platform (see also the Stop 22 description)

### **Stop 7A: Grotto Beach Formation, Cockburn Town Member**

Return to the main road and follow the power lines west to the coast, then south to the cliffs above Grotto Beach. Stop the vehicles at the cairn along the road and proceed on foot down the slope to the top of a 5 m cliff overlooking the water. The rocks of these cliffs are Pleistocene in age, have a terra rossa paleosol, and are assigned to the Cockburn Town Member of the Grotto Beach Formation. Continuing on foot along the top of the cliffs to the south, towards Grotto Beach, strata with coarse shell hash and rounded beachrock pebbles can be seen. Also very prominently displayed are large- to moderate-sized, angular, erratic blocks entombed within the bedrock of the cliff. These blocks are laminar-bedded oosparites and oolitic biosparites and are distributed in all orientations relative to the surrounding, petrographically similar, sediments. These were contemporary back-beach rubble and cliff collapse features at the time of deposition (MIS 5e, ~125,000 years ago). Just before reaching the beach, the rocks of the cliffs comprise a fossil coral reef with capping patches of *Neogoniolithon* coralline algae that can be seen at eye or foot level (depending upon the volume of sand on the beach). U/Th ages of corals from these outcrops date to MIS 5e (Hattin and Warren, 1989). The reef facies are buried by subtidal sands and overtopped by beach to beach-dune facies (similar to the Cockburn Town Reef described by Curran and White, 1985). Petrographically, these rocks are a mixture of fossils, peloids, ooids, and intraclasts with a sparite cement. There is tendency for greater ooid content toward the top of the section. This sequence is capped by a paleosol that is preserved as patches and solution-pocket fills.

If the observer does not mind getting wet, enter the water where the beach and cliff meet. There, dune foreset beds that dip at about 28° to the southwest are truncated at the top, and upon that surface lies the reef and its associated facies. Those eolian deposits are either transgressive, MIS 5e dunes (French Bay Member of the Grotto Beach Formation), planed off by continued rise of sea level that ultimately led to marine flooding that permitted reef growth, or they are Owl's Hole Formation rocks that predate MIS 5e. Alveolar texture, commonly interpreted as evidence for subaerial exposure and

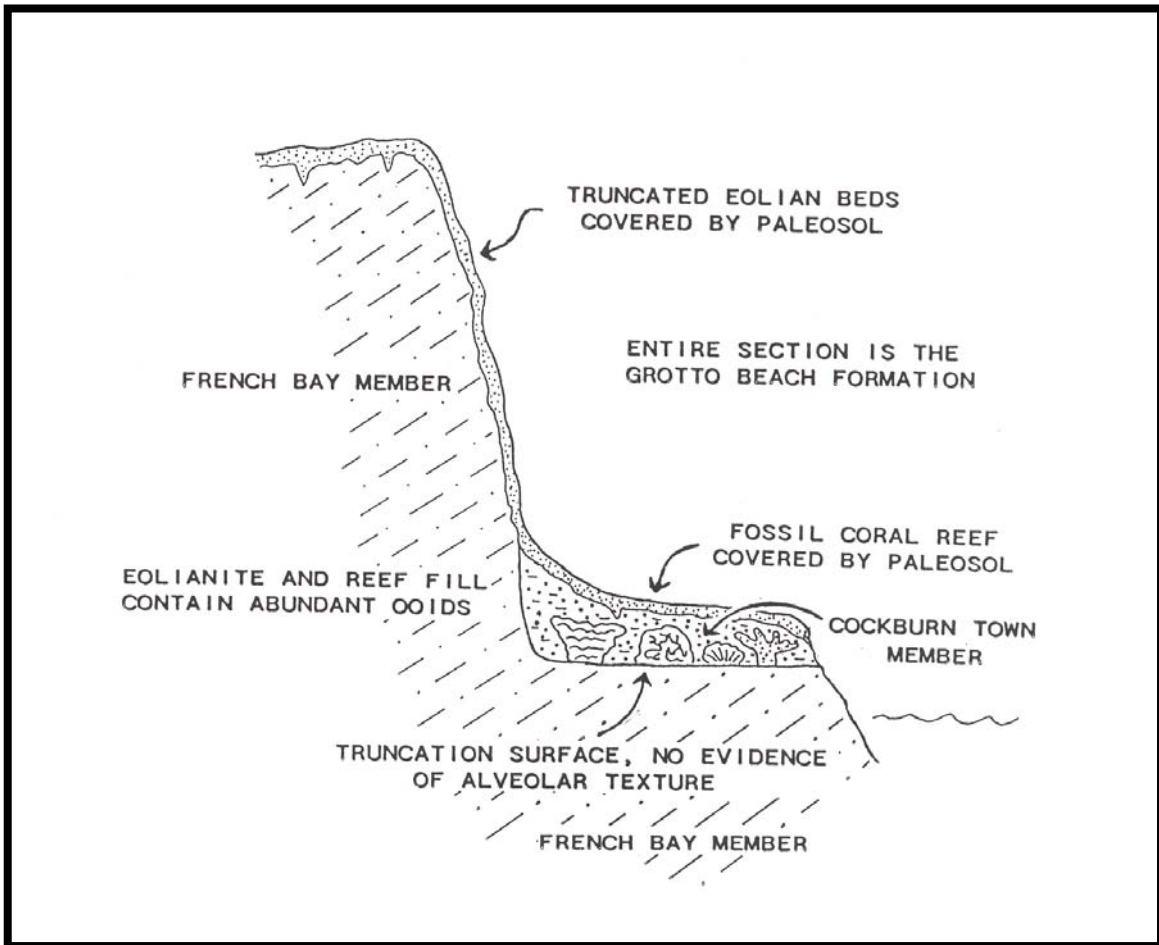


**Figure 16. The outcrop at Grotto Beach, Stop 7A, showing Cockburn Town Mbr, Grotto Beach Fm subtidal facies overlying truncated Owl's Hole Fm eolian facies. Alveolar texture, and the sharp petrologic change at the truncation surface are used to justify the Owl's Hole Fm assignment to the lower unit. From Carew and Mylroie, 1985.**

vegetative cover, can be seen in thin-sections of this bioclastic eolianite taken from just below the contact. This texture indicates a substantial period of subaerial exposure. These eolian rocks also have a complete lack of ooids (Stowers et al., 1989). Both of these observations support a pre-MIS 5e origin, thus making the rocks part of the Owl's Hole Formation. Figure 16 is a diagrammatic representation of the features seen at this stop. A similar, but significantly different sequence occurs when transgressive eolianites are cliffed by rise of sea level to a maximum, with subsequent coral growth on the truncated eolianite (Fig. 17). In that case, the petrological character of the rock is similar throughout the section, and there is no paleosol or alveolar texture associated with the truncation surface, as the eolianite is not significantly older than the overlying corals. The sequence shown in Figure 7B is commonly found in the Holocene on North Point Member rocks (Stop 2), except that the corals are actively growing today. The same sequence can be found in Grotto Beach Formation rocks at High Cay, South Andros (Carew and Mylroie, 1989a), and at Hole-In-The-Wall, Abaco (Walker, et al. 2008) where the underlying eolianite is part of the French Bay Member, and the overlying corals are part of the Cockburn Town Member. Because of this site's name and description in early San Salvador stratigraphies (Table 1), and because the visible contact with the underlying Owl's Hole Formation, this locality was selected as the type section of the Grotto Beach Formation, despite the absence of the French Bay Member.

### **Stop 7B: Holocene Analog for Pleistocene Back-Beach Rubble Facies**

At the western end of Grotto Beach are outcrops of Holocene (Hanna Bay Member, Rice Bay Formation) rocks. These rocks exhibit intertidal to back-beach facies and were deposited in equilibrium with current sea level. There is no terra rossa paleosol. Radiocarbon age of whole rock samples is about 3,200 yBP (Carew and Mylroie, 1987a).



**Figure 17. Cartoon of a transgressive-phase eolianite, truncated by wave action as sea level reaches a maximum, with the resulting hard ground hosting a coral reef. The similar petrologic character of the eolianite facies present, and the lack of alveolar texture at the truncation surface support the interpretation. The French Bay Mbr of the Grotto Beach Fm displays this sequence in the rock record, and the North Point Mbr of the Rice Bay Fm displays this sequence in the modern. From Carew and Mylroie, 1985.**

Note that these cliffs are breaking down, and large- to moderate-sized slump blocks are being entombed in modern sands. These outcrops serve as a modern analog for the Pleistocene erratic blocks seen at the cliffs described in Stop 7A at the other end of the beach. Coastal eogenetic karren are poorly developed here, compared to Stop 7A. This lack of karren indicates that these rocks, although 3,200 years old (allochem age), have only recently been uncovered from modern sands and exposed to sea spray.

The situation at Grotto Beach demonstrates some of the complexity that can occur in what appears to be a simple carbonate environment. The stop shows a Holocene progradational strand plain, that has accreted from the site of Pleistocene rocks at Stop 7A seaward to Stop 7B. These deposits would appear regressive in the rock record, as they are currently entombing Holocene corals in the lagoon, yet that entombment has occurred on a stable sea level. Examination of the Holocene corals being entombed demonstrates that they are dead and highly weathered prior to actual burial. The

detailed preservation of Pleistocene corals seen at Stop 4 would not have survived a gradual burial, and so indicates rapid burial must have occurred, most likely during a storm event.

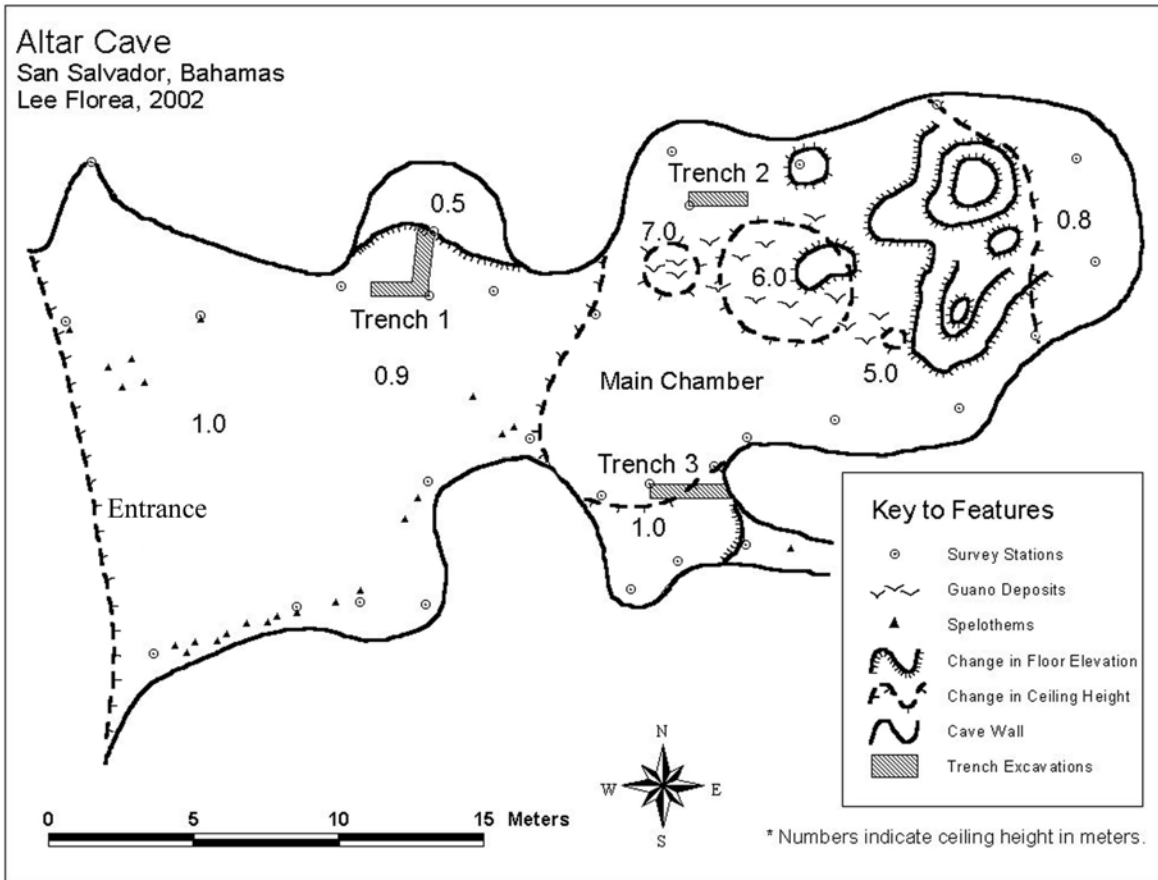
### **Stop 8: Dripping Rock Cave and Altar Cave**

From Grotto Beach, proceed south, following the road down from the Grotto Beach cliff line to the Holocene accretionary plain until a wide trail on the left (east) is reached. A sign with the words "Dripping Rock" may be visible here. The trail leads southeast across the Holocene strand plain seen at Stop 7 toward cliffs in the Grotto Beach Formation which are a continuation of the cliffs seen at Stop 7A. Where the trail meets the cliff, a large rock overhang protects an abandoned plantation well. The overhang is the roof of a breached flank margin cave, Dripping Rock Cave, the continuation of which can be seen to trend back into the hillside. Note the large algae-covered flowstone formations and stalactites at the rear of the overhang. These calcite speleothems do not form on exposed cliffs and outcrops, but only in the high-humidity of cave chambers. Their presence is evidence that the cave was once a completely sealed chamber, that was later opened by hillslope retreat (Myroie and Carew, 1991). For a complete discussion of exposed versus cave calcite speleothems, and their implications for identifying breached caves, see Taboroši et al. (2006).

Proceeding north along the outcrop, numerous small caves and reentrants are found. Many of these reentrants have the appearance of bioerosion notches that may have been formed during a past higher sea level, but the presence of subaerial calcite speleothems, the variable elevation of the reentrants, and their undulating floors indicate that they are the erosional remnants of flank margin caves, not fossil bioerosion notches (Myroie and Carew, 1991).

Continuing north, a large open area under an overhang, the Pink Grotto (named for pink algae on the ceiling) is encountered. Dessicated speleothems seen at the north end support, but do not prove, the interpretation that the chamber is a breached flank margin cave. The back wall of the chamber consists of rocks that represent the transition from subtidal shoals (herring bone cross bedding) at the base, up through a back-beach/shore-face boulder rubble, into an eolian facies. This is the same transition as seen at Stop 7A. Continuing along the trail (north) several hundred meters, the cliff begins to diminish into a hillslope. Just beyond a large banyan tree a low wide opening appears in the base of this slope. This opening is the entrance to Altar Cave (Fig. 18). The cave proceeds north 30 m as an easy crawl over sand into a large chamber which usually houses some bats. At the rear of this chamber, a mound of flowstone that looks like a ceremonial altar was the inspiration for the cave's name. Altar Cave is a flank margin cave, but unlike those seen previously at this stop, it is almost entirely intact. Here, a minimum of hillslope retreat has just intersected the edge of one of the cave passages, which has allowed access to the cave. From Altar Cave, a trail can be followed north and west back to the road, or the route in can be reversed to the south, then west to the road.

Altar Cave was the site of a study (Florea et al., 2004) that attempted to determine if the cave walls contained a geochemical signature of mixed water dissolution. Another goal was to determine the origin of the sand covering the cave floor; was it disarticulated from the walls and ceiling, or was it washed into the cave during construction of the Holocene strand plain? The latter question would help determine when the cave was breached to



**Figure 18. Map of Altar Cave, showing sample trenches. Trench 3 was the only trench to reach a bedrock floor. The rock there was partially de-cemented by leaching as a result of major storm vadose-flooding events. The cave is formed in the Cockburn Town Mbr of the Grotto Beach Fm. From Florea et al., 2004.**

the surface environment. Three trenches were dug into the cave floor up to a depth of 2 m. Only one trench conclusively hit bedrock, and that rock was soft and de-cemented. The bat guano was found only in the upper layers of sand. Dating by  $^{14}\text{C}$  gave a sand age of 4,700 yBP. The sand was similar to the sands of the Holocene strand plain outside the cave, but contained etched and partially-dissolved sand grain fragments that showed a cave wall and ceiling provenance; these grains concentrated to form a thin layer at the floor bedrock contact. The interpretation of the cave indicates that it formed during MIS 5e. From the end of MIS 5e until Rice Bay time, the cave was a sealed chamber isolated from the surface environment. When Holocene sea-level rise placed wave action at this location (as it still is today at Stop 7A), the cave was broken into and Holocene sands began to enter the cave. Wave dynamics changed, and the coastline receded as the Holocene strand plain accreted westward, making the Altar Cave sea cliff into an inland cliff (Fig 15B). At this time, bats began to inhabit the cave. During major rain events, the Holocene stand plain saturates and water flows into the cave to sink in the cave floor. It is believed that this sinking water helped to de-cement and leach the bedrock floor of the cave. The  $^{14}\text{C}$  date, the lack of guano at bedrock/sediment contact, and the Holocene stand plain support the interpretation of the cave entrance opening about 5,000 years ago.

A final point about Altar Cave. It is in the same rocks as seen at Stop 7A. Stop 7A indicates a progradational environment at Grotto Beach during MIS 5e similar to the progradational environment seen in the Holocene today at Stop 7B. The section seen at the Pink Grotto, where herring bone cross bedding, back-beach breccia facies, and dune material is seen in a vertical profile, indicate a progradation. As this progradation occurred, the fresh-water lens extended seaward as the eolian unit advanced seaward. Therefore Altar Cave did not develop at the start of the MIS 5e highstand, but part way through. Such rapid cave formation following immediately on the deposition of the carbonate sediment, results in *syndepositional cave* development (Myroie and Myroie, 2009), a subcategory of syngenetic caves.

Stops 7A, 7B, and 8 indicate how many geologic and hydrologic events are concentrated into the small time windows of platform flooding during the Quaternary.

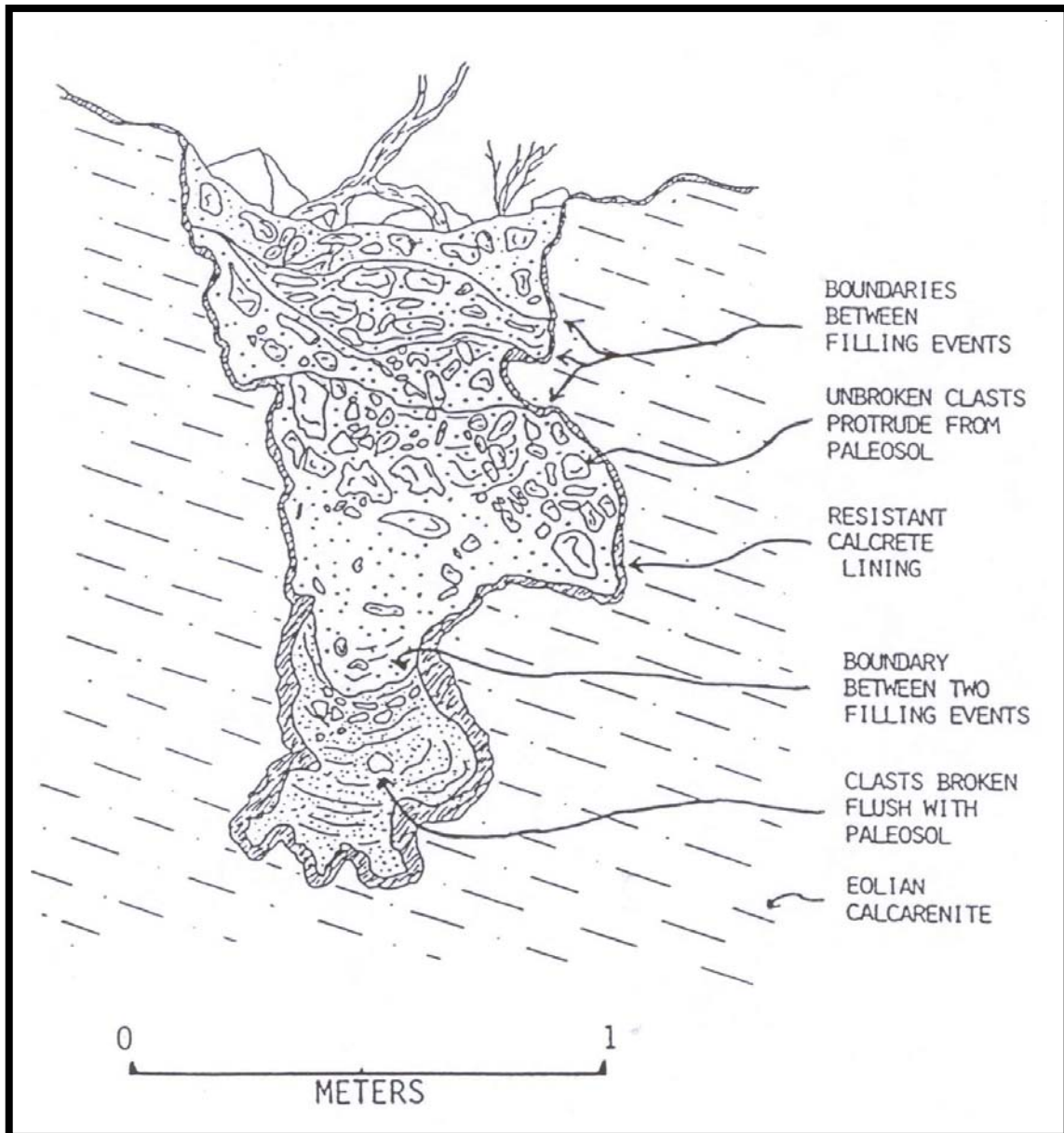
### **Stop 9: Infilled Dissolution Pit**

From Stop 8, Altar Cave, continue south to Sandy Point. From here, take the road to the left (east) up the hill to a prominent road cut. On the south wall of this road-cut in eolian calcarenite of the Grotto Beach Formation is a 2+ m deep dissolution pit that is almost entirely filled with eolianite clasts and palaeosol material (Fig. 19). The material at the bottom of the pit is a well-lithified micritic terra rossa paleosol with fractured clasts. Above that is a similar, but less lithified deposit in which the clasts are not fractured. More unindurated layers occur above. The pit wall has a resistant micritic lining. The well-cemented clasts and matrix at the bottom of the pit are both fractured smooth, but the clasts protrude from the less-well cemented material in the next layer higher up. The various layers are separated by thin micritic crusts that run subhorizontally across the pit infill. Is the cementation difference, and the micritic crusts, a result of different ages for discrete infilling events, or does the cementation difference and the micritic crusts represent progressively wetter, and therefore more diagenetic, conditions with depth in a continuous infilling situation?

### **Stop 10: Sandy Point Pits**

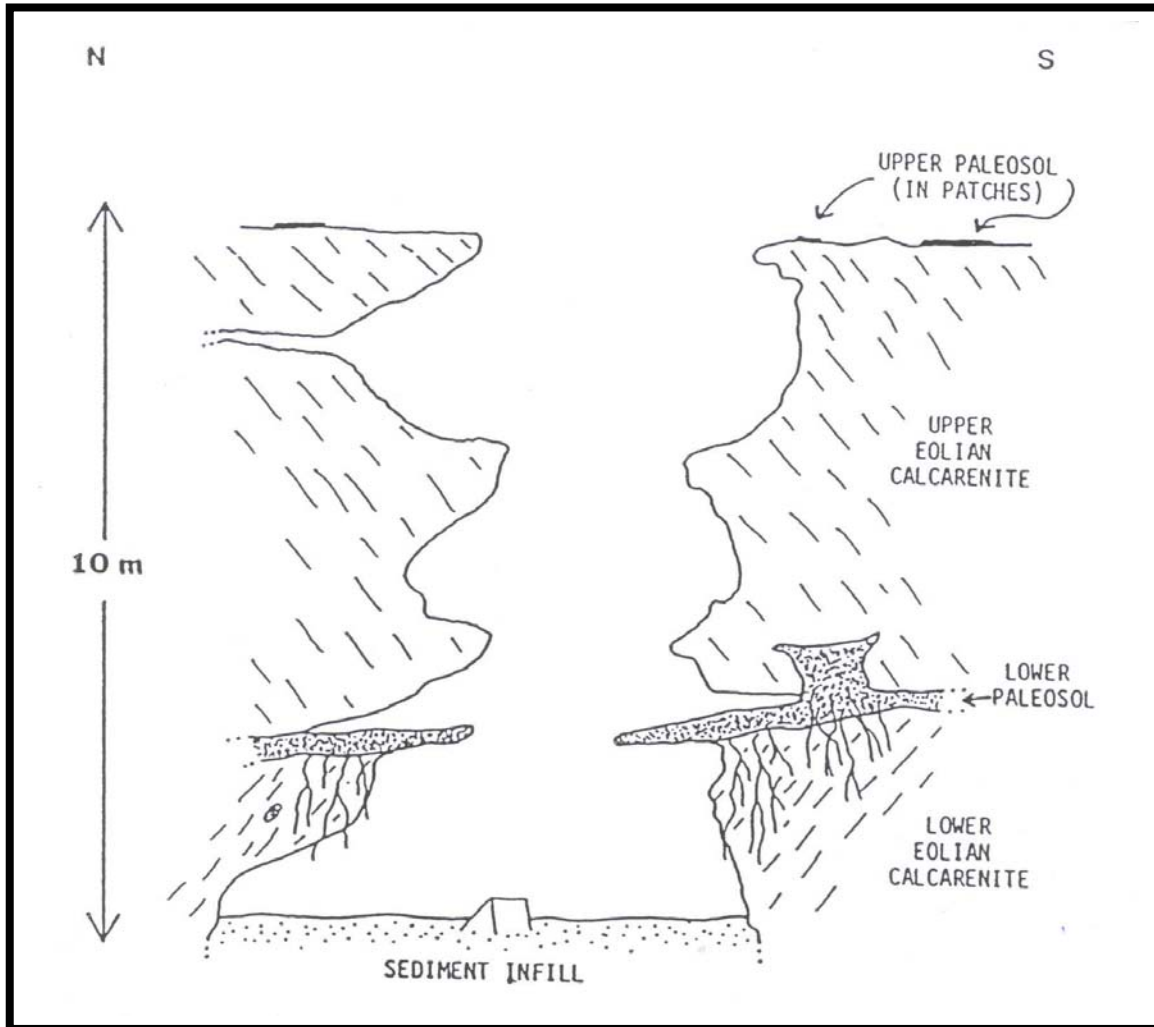
Immediately east of Stop 9, following the road left around the corner, is a flat area at the crest of the ridge, the Sandy Point Pits area (do not confuse this area with the Sandy Point Caves of Stop 11). This amazing area contains over 50 pit caves ranging from tubes 0.5 m in diameter that penetrate downward 2 to 3 m, to large shafts up to 8 m across and up to 10 m deep (Pace et al., 1993; Harris et al, 1995). The elevation where the truck is parked is + 18 m above sea level, and the entire terrain surface is well above any past sea level highstand. No pit is deep enough to reach current sea level, and all pits end in sediment fill. Many of the pits are complex, and some interconnect to provide a short but varied caving experience. Please exercise caution in walking around and exploring these pit caves. From the eastern cairn where the truck is parked, walk due east through the scattered brush and bare rock. Watch your footing, as many shafts are small and their openings are flush with the ground surface. The first large feature encountered is an 8 m shaft with an entrance diameter of about 1.5 m. The shaft leads to a small, dead-end chamber.

Just beyond is Owl's Hole, one of the largest pits in the area (Fig. 20). It is 10 m deep and was named for white snowy owls that are commonly seen here. Access into the pit can be accomplished by going down the far side of the shaft, following the slope until the



**Figure 19. Infilled dissolution pit at Stop 9. The infill has sub-horizontal micritic layers, and cementation increase down section. The pit wall has a very hard micritic lining. From Mylroie and Carew, 1995.**

final step down is done with help from the tree trunk and roots. The climb is not trivial. At the bottom, be alert for falling rocks. In the later 1980's a rock fell here and punctured a student's 2" thick notebook, barely missing several people. Be warned! At the bottom is a chamber with stalactites and a sediment floor. The top of the section within Owl's Hole consists of about 8 m of oolitic eolianite of the Grotto Beach Formation. The lack of vegemorphs indicates the rocks may be French Bay Member. Below that is a paleosol exposed about 1.5 to 2 m above the floor of the pit. This paleosol has been repeatedly analyzed for its paleomagnetic record. Original data (triplicate analyses) revealed that it is magnetically reversed, indicating that the paleosol formed during the last major paleomagnetic reversal episode (or earlier) about 780,000 years ago (Mylroie et al.,



**Figure 20. Owl's Hole Pit Cave, Sandy Point Pits. Based on petrography and few vegemorphs, the upper unit is assigned to the French Bay Mbr of the Grotto Beach Fm; the lower unit is assigned to the Owl's Hole Fm, as it is below two terra rossa paleosols. From Carew and Mylroie, 1985.**

1985). The bioclastic eolianite underlying the paleosol, assigned to the Owl's Hole Formation, was therefore interpreted to be that old or older. More recent paleomagnetic analyses of the paleosol in Owl's Hole has found no magnetic reversal in this paleosol, but it does have an unusual paleomagnetic signature that contains an anomalous positive SE component (Panuska et al., 1991). These bioclastic eolianites correlate with the lower eolianite at Grotto Beach (Stop 7A) and at Watling's Quarry (Stop 15). Based on the early, erroneous paleomagnetic reversal data, this outcrop was selected as the Owl's Hole type section, as it was thought at that time to be the oldest rock in the Bahamas, and likely older than the similar outcrops at Grotto Beach and Watling's Quarry.

About 50 to 60 m south-southeast of Owl's Hole, along a route marked by cairns, is a suite of interconnected pit caves, Triple Shaft Cave (Fig. 11). These pits can also be reached by walking back downhill a few meters from where the truck is parked, and going directly downslope southeast over relatively open terrain. These pits are

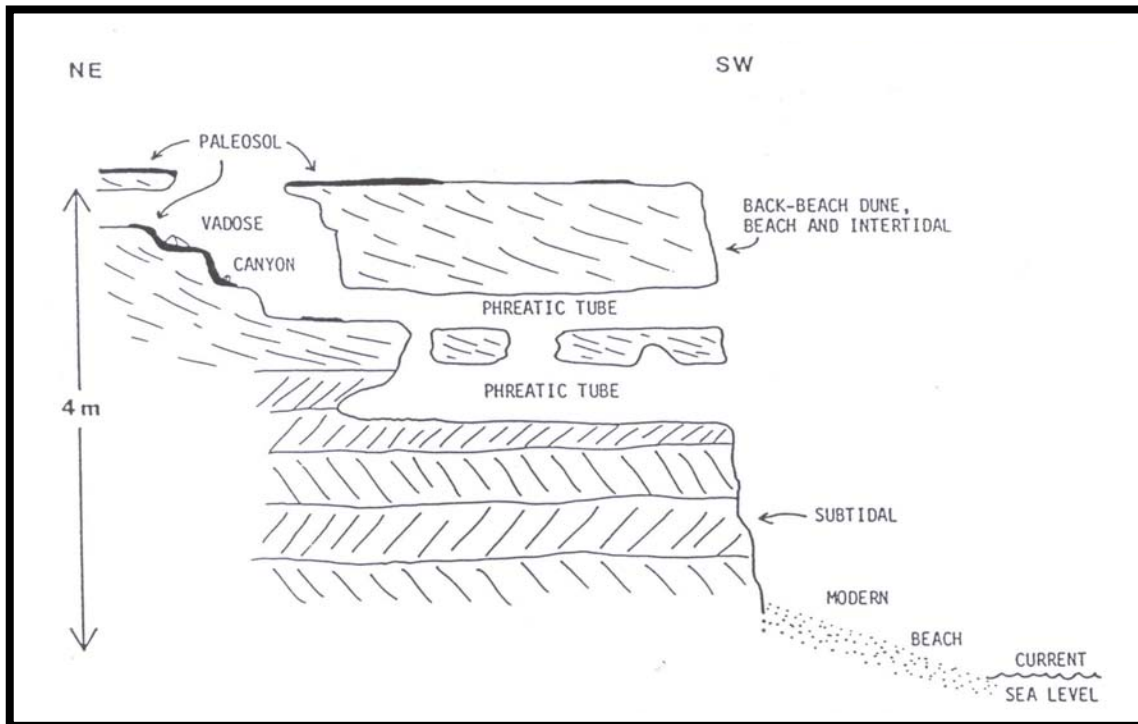


connected by passages at a number of levels. In the bottom chamber there are some palm-frond impressions in the eolianite. Just to the north-west is a sloping plain of bedrock with a number of surface-truncated cavelets and tubes, which converge on the larger pits (Fig. 11). This exposed section of the epikarst illustrates how it gathers meteoric water and focuses such flow into specific pit caves for transport to the freshwater lens. As new pit caves are developed beneath the epikarst flow path, older pit caves are abandoned. The result is more pit caves than would seem reasonable for a water budget based on catchment area (Harris et al., 1995). An accurate understanding of this pit cave system was obtained by visiting the area during intense rains, and watching where the water went.

### **Stop 11: Sandy Point Caves**

From Stop 10, drive south through an over-grown traffic circle, to the coast, and slightly west to a prominent cairn. A trail leads from the cairn across a surface of Pleistocene bedrock to low sea cliffs. The coastline here is very dynamic, with large quantities of sand moving in and out depending on wave activity (e.g. Voegeli et al., 2006). When the sand is out, the waves break against the base of the cliff about 2.5 m below. If sand is in, one can step from the top of the cliff down onto a beach of variable width. How much can be seen of the karst features in the cliffs depends on how much sand is present. Following the trail straight to the cliffs a small rocky point will be seen immediately to the observer's right. There are a number of small vertical holes just a meter or two back from the cliff edge. The largest of these leads into a very short cave called Fire Drill Cave (Fig. 21). The cave can be entered from the small collapse entrance on top of the cliff. In the inland direction, the cave has the form of small vadose canyons that bifurcate and rise to small holes on the surface. In the paleo downstream portion, the floor of the cave changes from a vadose notch to a series of stacked phreatic tubes with numerous interconnections that eventually exit on the cliff face (unless there is too much sand). The point of transition from vadose to phreatic morphology is an indicator of the paleo-water table at the time of cave development. This indication of paleo-water table position is also a good measure of sea level at that time. The present position of the cave, and its truncated nature, suggests that there has been some scarp retreat since the cave developed. The cave is one of the few found anywhere in the Bahamas where such a vadose to phreatic transition can be observed.

Walking west a few meters to the small promontory on the right (west) and looking back at the cliff, one can see a truncated phreatic chamber in the cliff. This could be a relict continuation of the phreatic portion of Fire Drill Cave. The cliff rocks also record evidence of a past higher sea level, as shown by the excellent herring-bone cross bedding indicative of subtidal deposition (Fig. 21), overlain by back beach and dune facies. The rock is Cockburn Town Member of the Grotto Beach Formation, and as with the situation at Altar Cave at Stop 8, the rock and the cave formed on the same sea-level highstand. The cave formed immediately after the rock was deposited and exposed as sea level fell from the MIS 5e highstand. That interpretation would make the cave syndepositional (Mylroie and Mylroie, 2009). Alternatively, the rock was deposited, and the cave formed as a result of the previously discussed minor sea-level fluctuation during the MIS 5e highstand. Such a sea-level fluctuation on the MIS 5e highstand was suggested as the cause of phreatically dissolved flowstone in Hunt's Cave on New Providence Island (Carew and Mylroie, 1999).

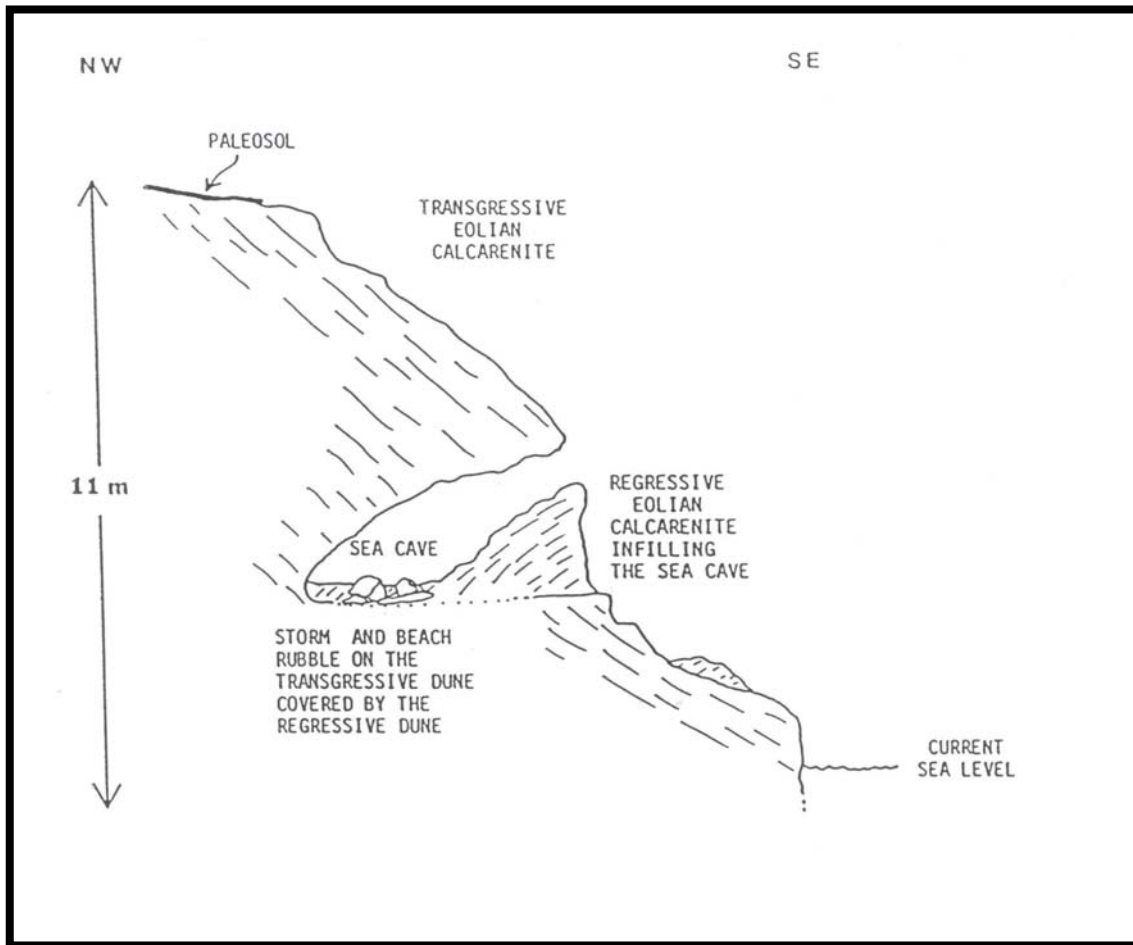


**Figure 21. Fire Drill Cave, Sandy Point Caves. There are two unique features to this small cave. First, it is developed in Cockburn Town Mbr subtidal facies of the Grotto Beach Fm, so it is a syndepositional cave, and second, it shows a classic vadose to phreatic transition passage morphology, very rarely seen in Bahamian caves. From Carew and Mylroie, 1985.**

Proceeding east along the cliff, about 75 m from Fire Drill Cave, Blowhole Cave can be seen. This short cave (even shorter if the sand is in) contains a terra rossa paleosol that drapes from the surface down into the cave. This paleosol drape indicates that the cave was present prior to the development of the paleosol. When the sand is entirely out, the cave leads east to another low entrance, and also down and west to another entrance at the base of the cliff face. The infilling paleosol contains a number of "black oolite" pebbles. Once thought to have come from a former island-wide deposit (Titus, 1983), it is now believed that the black color, which is more than just a coating, was caused by weathering in the soil, and/or along hypersaline lake margins. Fire also causes the blackening process. Study of the cave wall rock on this coast by gamma-ray spectrometry and magnetic susceptibility has been used to determine sediment cycle boundaries as well as subsurface microbial activity (Hladil et al., 2003a; 2003b; 2004). From here, reverse direction and return to the truck.

### **Stop 12A: Grotto Beach Formation, French Bay Member**

From the Stop 11, the Sandy Point Caves, continue northeast along the coastal road. About 1.5 km east of Sandy Point, stop the trucks where a prominent cairn marks a trail over the ridge to the sea cliffs. Follow the trail southeast approximately 100m to the cliffs overlooking French Bay. Go northeast about 25 m where a small cave is open on the sea cliff (Fig. 22). This sea cave was formed by wave action at a past higher stand of sea level, and it is analogous to the grottoes forming today at Grotto Beach, or more precisely, the sea caves on the Rice Bay side of North Point. At the back of this shallow cave, a lithified deposit of rounded cobbles and boulders is overlain in part by a set of



**Figure 22. Fossil sea cave in eolianite at Stop 12A. The cave formed in transgressive-phase eolianites of the French Bay Mbr, Grotto Beach Fm, was partially entombed by regressive-phase Cockburn Town Mbr eolianites, and has been breached by Holocene wave activity. From Carew and Mylroie, 1985.**

eolian deposits that presently choke off a portion of the cave, and which in the past probably entombed the cave. Petrographically, there is no dramatic difference between the host eolianite and the infilling eolianite. Both are oosparites, although the infilling eolianite contains somewhat larger ooids and is less well sorted. The rubble deposit is in a white sand matrix, and the clasts are rounded. These features make it unlikely that the rubble is a terra rossa infill. The very top of the rubble material and the adjacent secondary eolianite; however, have a terra rossa paleosol on top. These observations lead to the interpretation of an emplaced transgressive-phase eolianite, in which a sea cave formed during the subsequent MIS 5e sea-level highstand maximum (Fig. 23). The wave action created the rounded rubble deposit and white sand matrix. The cave was subsequently partially infilled by a dune deposit during the regression at the end of MIS 5e. During the following post-MIS 5e sea-level lowstand, terra rossa material infiltrated into the remaining void to overlay the rubble facies and regressive-phase dune material. Holocene sea-level rise has now placed wave energy back into this environment, but at a lower elevation than MIS 5e. None-the-less, wave energy has been sufficient to breach the enclosing secondary dune and expose the paleo sea cave. A paleo sea cave with evidence of a regressive eolian overlap, without an intervening terra rossa paleosol,

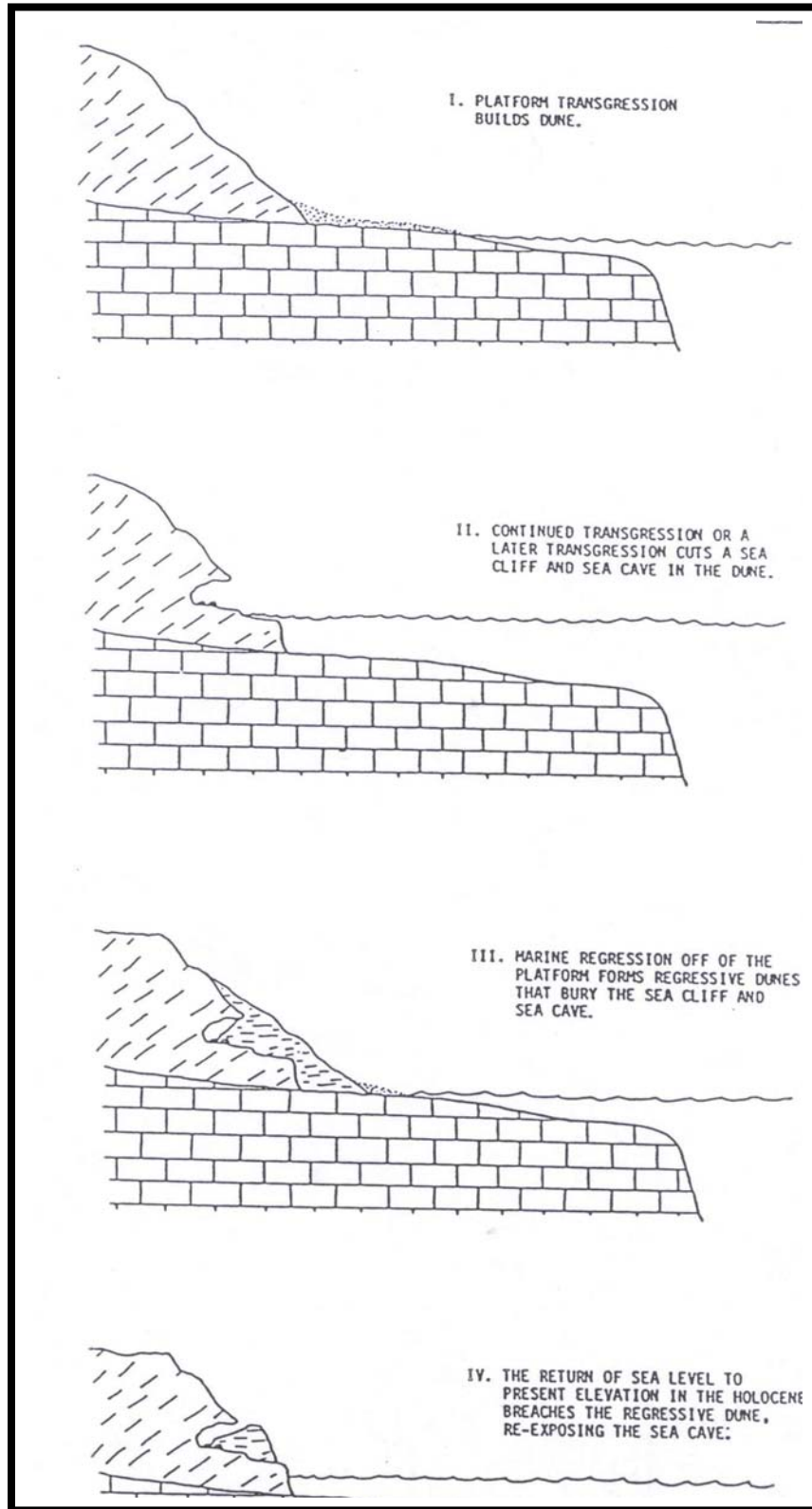


Figure 23. Cartoon showing a hypothesized sequence of events to produce a sea cave during MIS 5e in French Bay Mbr eolianite. From Carew and Mylroie, 1985.

is one of the indicators of a transgressive-phase eolianite. As noted earlier, the clearest modern analogue is the Rice Bay side of North Point.

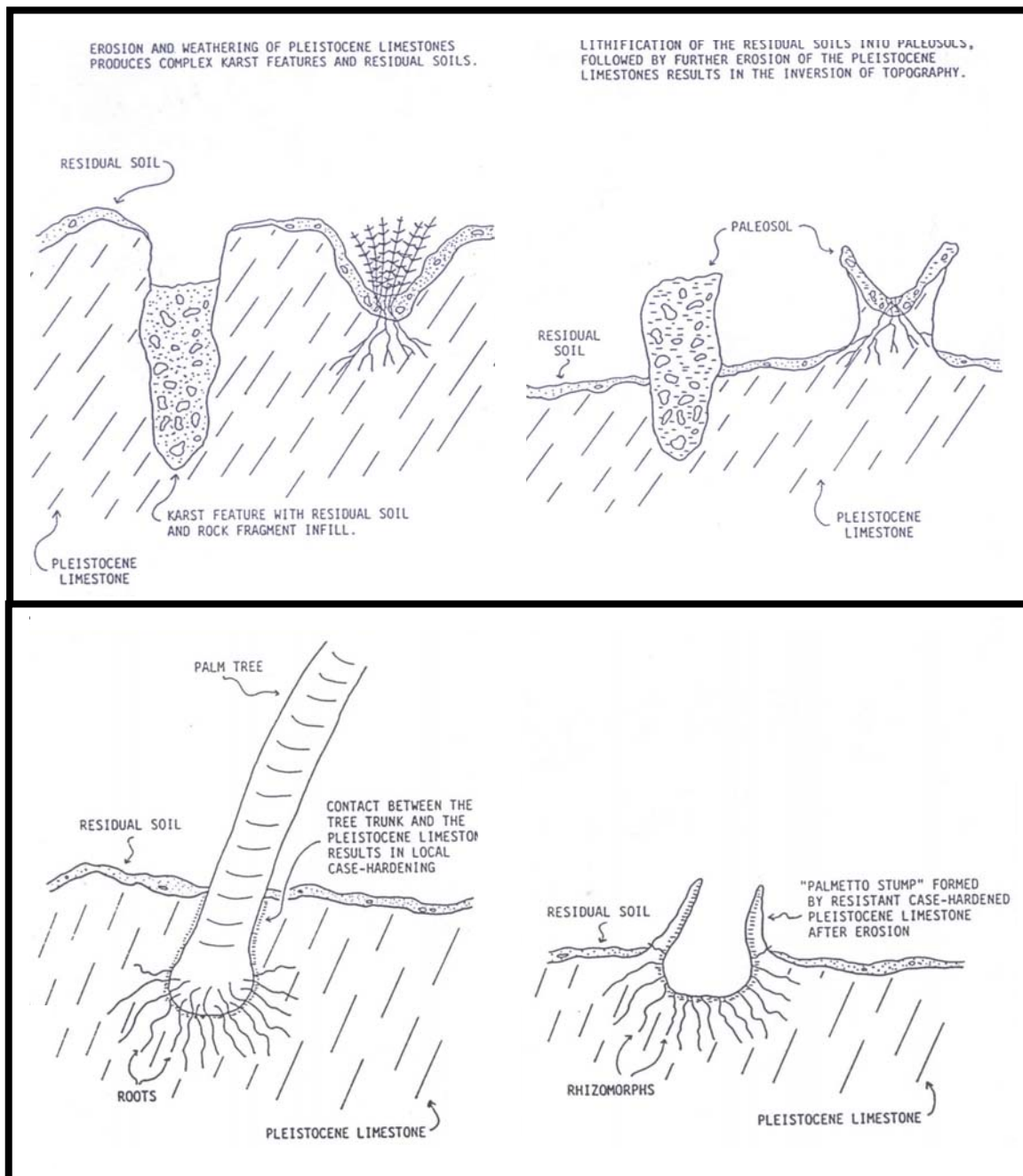
### **Stop I2B: French Bay Member**

Continuing northeast, the bedrock coast and cliff consist of a variety of eogenetic karren. Of particular note is the remnant terra rossa paleosol material in many dissolution pockets. In several cases, the terra rossa paleosol stands upright as a vertical pillar. The terms “dissolution pillars” and “palmetto stumps” has been used in the literature to describe these features, cylindrical rock bodies from 0.3 to 1 m in diameter, and 0.5 to 1.5 m high. Some have hollow interiors; some are curved. For a complete discussion of their origin see Mylroie (1988). Figure 24 presents the two competing ideas for the development of these cylindrical rock bodies. Field evidence from many Bahamian islands, and Bermuda, indicate that both mechanisms work and that these features are probably polygenetic. In the case of the features at this stop, they appear to fall into the “dissolution pillar” category, as the pit infill material was better cemented than the original enclosing eolianite. Coastal erosion has stripped the weaker eolianite away, and as with the terra rossa fissure fill at the Cockburn Town fossil reef (Stop 4), inverted the topography. In this case, the inversion is from dissolution pit to upstanding pillar.

Continuing northeast is an outcrop of angular blocks in a terra rossa paleosol matrix (Fig. 25). These blocks, ranging in size from a few centimeters to over one meter in across, are all laminar-bedded oosparites that are indistinguishable from the existing rock outcrops upslope of their present position. The deposit varies irregularly from grain to matrix supported. The contact of these deposits with the surrounding eolianites is marked by a reddish calcrete which extends downslope and seaward as a concave-up surface. The deposit is well lithified and weathers out in positive relief. There are over 30 of these outcrops along this coastline, and the resistant nature of the terra rossa paleosol matrix and breccias has created headland promontories along the coast.

The proposed origin of this deposit was first interpreted as follows (Fig. 26): a MIS 5e transgressive dune was eroded to produce a sea cliff during the MIS 5e sea-level maximum, as seen at North Point (Stop 2) in the Holocene. As a result of sea withdrawal at the end of MIS 5e, the sea cliff became an inland scarp. This inland scarp then underwent mass wasting to produce a cliff-base talus and associated soil, which subsequently became lithified into a paleotalus with a terra rossa paleosol matrix. Return of the sea to the current position during the Holocene has brought the eolianite and resistant paleotalus under renewed wave attack (Carew and Mylroie, 1985).

The “paleotalus” interpretation seemed reasonable, but the configuration of the deposits, sitting in smooth bowl-shaped indentations in the host rock, argued for a different interpretation. When first visited, these outcrops were thought to be solution collapse breccias. The problem with that interpretation is the 30+ outcrops along this coast. For these features to all be cave collapse structures would have required a large number of parallel caves to form along the coast perpendicular to it, or a single cave to run parallel to the coast such that it was segmented by collapse in many places. None of these explanations seemed likely, but the cave model being used at the time was one for continental, stream-flow conduit caves. An alternative explanation for the co-linearity of the deposits and the shoreline is that the deposits represent collapsed and in-filled flank margin caves, as flank margin caves tend to form parallel to the flank of eolianite ridges.

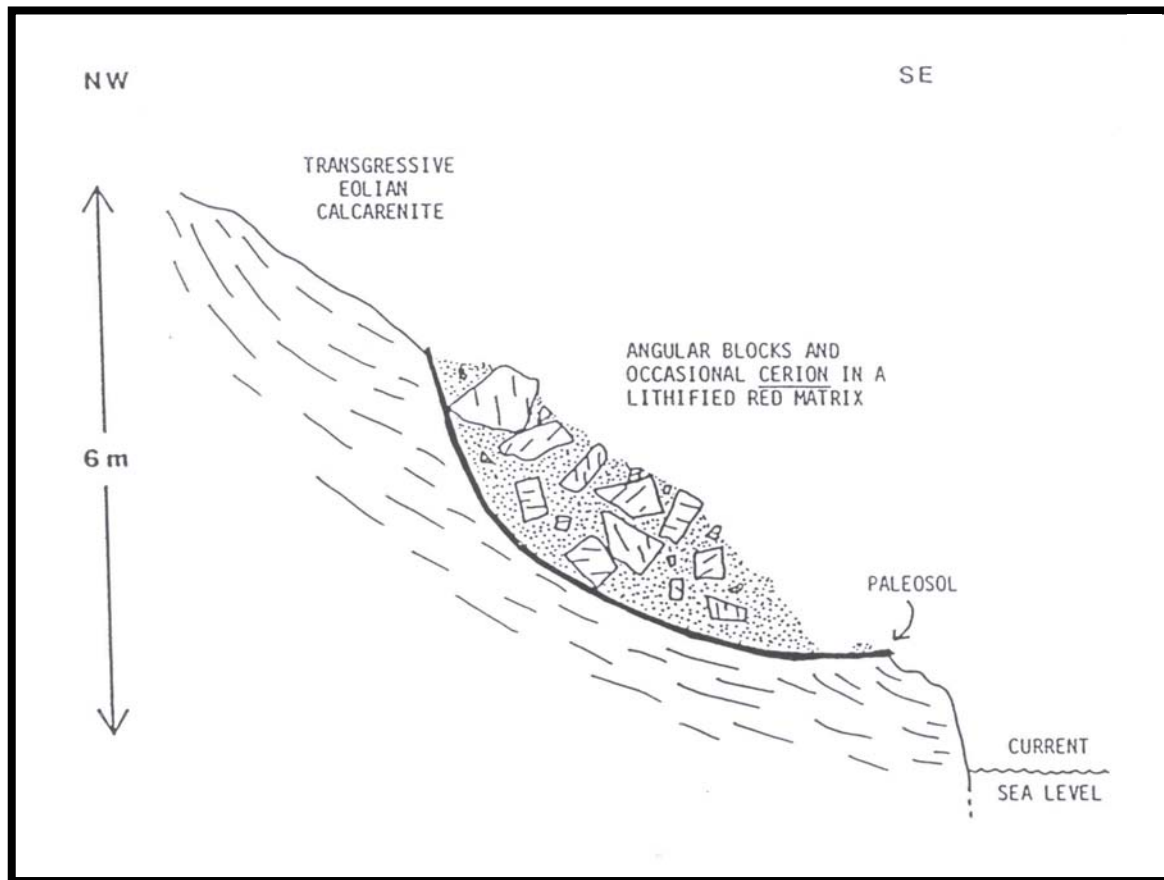


**Figure 24. Cartoon showing two possible origins for the hollow, or solid, positive-relief structures found in the Bahamas. Top panel, infill of dissolution pits and basins with terra rossa paleosol material, which resists later erosion to invert the topography. Bottom panel, micritization by water flow along tree trunks creates a hollow resistant feature. From Mylroie, 1988.**

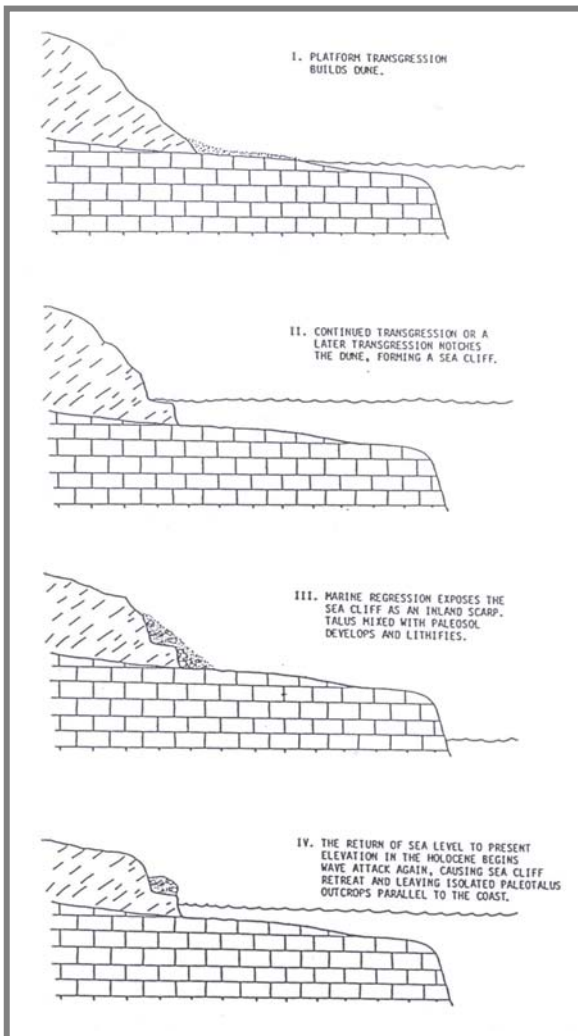
This alternate explanation of the deposits does not change the interpretation of these rocks as MIS 5e transgressive-phase eolianites, or French Bay Member. The eolianites had to be in place (i.e. transgressive) for the rise to the MIS 5e highstand to be able to place a fresh-water lens in the position to make the flank margin caves. Subsequent

regression from the MIS 5e highstand would have drained the caves, and erosive forces acting over the following 100,000 years could have breached the caves and filled them with soil and rock material (Florea et al., 2001), as shown in Figure 27. Such deposits are not known inland or on any other coast of the island, but there is not any other known French Bay Member outcrops, either. Similar solution-collapse breccias have been found at Hole-In-The-Wall, Abaco, where the unit containing them also has a wave-cut bench in which sit Cockburn Town Member fossil corals. Both these observations indicate the hosting eolianite as French Bay Member (Walker et al., 2008).

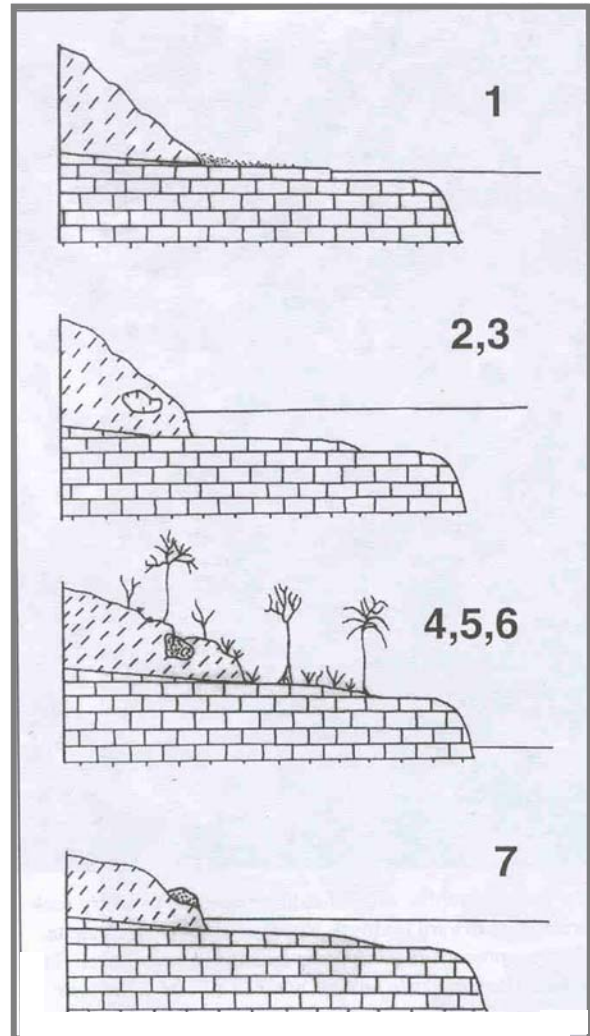
Stops I2A and I2B provide evidence for the interpretation of the eolianites of the French Bay coast as deposits formed during the transgressive-phase of the MIS 5e sea-level highstand. They are assigned to the French Bay Member of the Grotto Beach Formation, and they are the oldest known deposits of that formation. The North Point Member of the Rice Bay Formation is a Holocene analogue for these Pleistocene deposits.



**Figure 25. Cartoon of a typical breccia deposit as found along the French Bay coast on San Salvador. Angular blocks of sizes from centimeters to meters rest in a red, micritic matrix. Blocks are both grain supported and matrix supported. The deposit rests in a seaward tilted basin that has a resistant micritic lining. See text and Figures 26 and 27 for interpretations. From Carew and Mylroie, 1985.**



**Figure 26. Cartoon of the “paleotalus” hypothesis used initially to explain formation of the French Bay breccias on an abandoned sea cliff. From Carew and Mylroie, 1985.**



**Figure 27. Cartoon of the “solution collapse breccia” hypothesis that has replaced the “paleotalus” explanation for the French Bay breccias. From Florea et al., 2001.**

### Stop 13: Island Overview and Watling's Blue Hole

From Stop 12, continue east along the coast road, taking the next left turn north and then east past the octagonal house on the ridge to the observation platform above French Bay. From the top of the platform, the entire south end of the island can be viewed. Those with good eyesight will be able to look north and see Cockburn Town, which is identifiable by the radio mast and communications dish, and by the Casuarina trees on the west coast. To the northeast, the Dixon Hill lighthouse, site of Lighthouse Cave, may be seen. The lighthouse is one of the most distant spots from Stop 11 and gives the observer a feel for the size of the island. Note the uninhabited nature of the



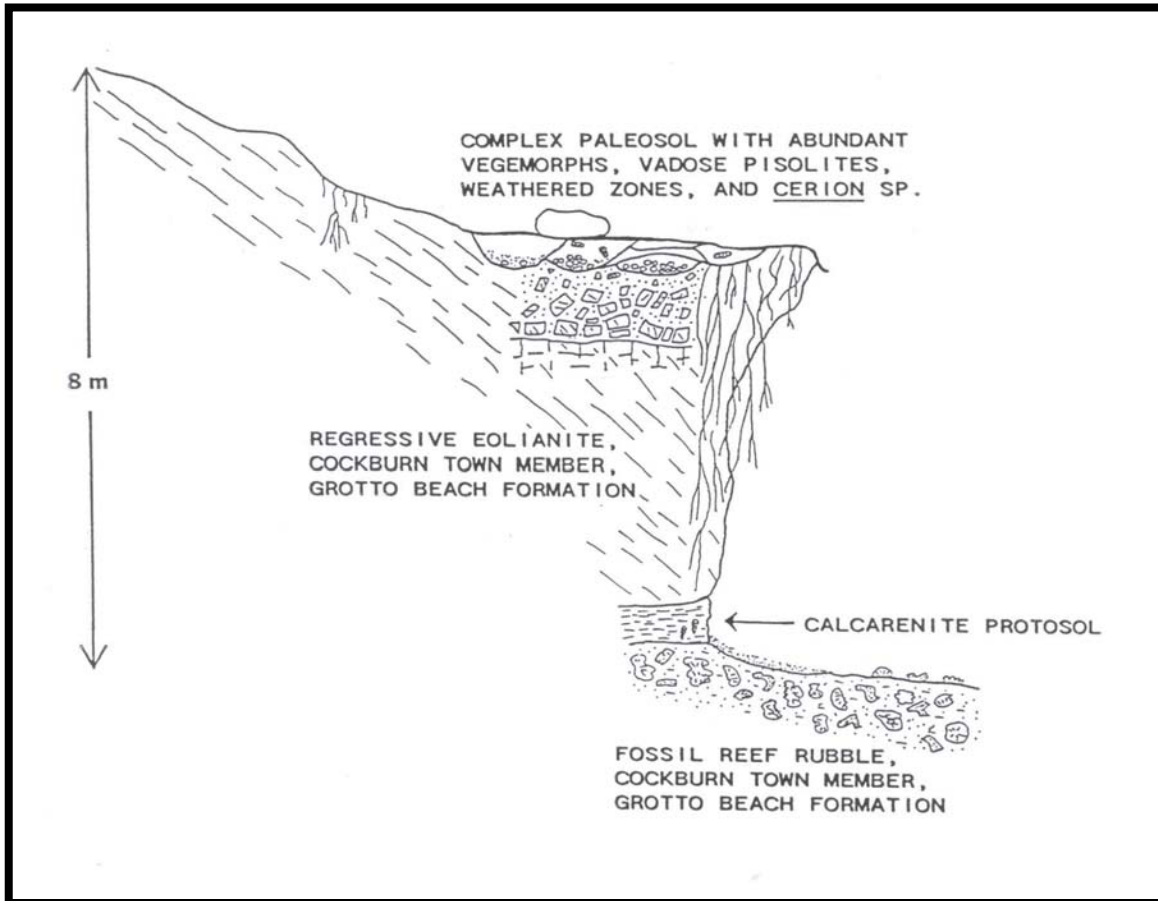
island's interior, with its long, high dune ridges and lakes that occupy the interdune swales.

Looking downslope north past the foot of the platform, the circular, light blue form of Watling's Blue Hole is visible. This blue hole has a tidal range (1 m) almost equal to that of the nearby ocean. It is a shallow bowl with a shaft in the center that leads to a horizontal cave passage at about 9 m depth. The cave conduit has a strong current when tide is rising or falling, and silt fills the conduit to within 15 cm of the ceiling. The initial chamber at the bottom of the blue hole is quite roomy, but becomes low as the actual conduit is entered. Because of the flow of marine water into and out of the blue hole, the geochemistry of the water is brackish (Crotty and Teeter, 1984). This water chemistry prevents the strong density layering seen at Ink Well (Stop 6), and limits adjacent vegetative growth, hence the collection of organics is minimal here and a light blue color is present. The deeper part of the blue hole does not reflect light from the bottom, and therefore has a darker color.

The rock wall around the blue hole (squares of rock represent former turtle holding pens) consists of an unusual collection of rocks, among which are blocks of rock that have been informally referred to as "lake facies" (Titus, 1987; Hagey and Mylroie, 1995). This rock contains abundant shells of the euryhaline mollusks *Batillaria*, *Pseudocyrena*, and *Anomalocardia*, which are indicative of brackish or moderate hypersaline conditions. Rocks of this facies are found as a veneer over older Pleistocene rocks, but rarely in place, they are usually encountered as float. The presence of such deposits, which formed during the MIS 5e highstand, indicates that restricted conditions existed in the lagoons in these locations at that time; therefore a pre-existing topography made up of Owl's Hole Formation and/or French Bay Member rocks must have been abundant. These "lake facies" rocks are part of the Cockburn Town Member of the Grotto Beach Formation (Hagey and Mylroie, 1995).

#### **Stop 14: The Gulf Exposures**

From Stop 13, take the coast road east, past the stop sign and the Government Dock at French Bay, 2.5 km to a side road leading right and east. This road passes old quarries to the north, and to the south a small pond has a series of coral rubble washover lobes on its far (southern) bank. These lobes date by  $^{14}\text{C}$  to about 3800 yBP (Pace et al., 1989). Continue on past a rocky shore to a road cut 2 km before Sandy Hook (the last road cut before reaching the Holocene strand plain of Sandy Hook). This site is called The Gulf. Examine the north wall of the road cut. It is an oolitic eolian calcarenite capped by a thin paleosol. Isolated vegemorphs and perhaps burrows can be seen in the face of the cut. Step back (watch for vehicles) and note that there is a well developed set of joints in the road cut that often form a classic "X" pattern. Examination of the joints reveals a calcrete layering along them, indicating that they predate the excavation of road cut and did not form as a result of the stress produced by bulldozing. Rocks this young and poorly lithified, which were never deeply buried, would not be expected to have joints. The joint orientation and pattern does not support a platform-edge subsidence model for their formation. Although their origin is unclear, these joints may have implications for mass wasting and cave and karst development. Cross the road (south) and proceed around the west end of the road cut onto the flat platform above the sea. Walk to the coast and look back at the large re-entrant that lies behind the south wall of the road cut (Fig. 28). The paleosol here is well developed, with many layers and



**Figure 28. Cartoon of the section at The Gulf, San Salvador. A fossil coral reef rubble facies is overlain by a calcarenite protosol, which in turn is overlain by an eolianite with abundant vegemorphs. The sequence indicates a true regression, and not a progradation at a constant sea level. All rock units are assigned to the Cockburn Town Mbr of the Grotto Beach Fm. From Carew and Mylroie, 1985.**

hollows, a form called intrapaleosol bifurcation (Carew and Mylroie, 1991) or a penetrative calcrete (Wanless and Dravis, 1989). Very large vegemorphs dangle from the paleosol surface and extend downward more than 3 m. The paleosol surface is essentially a fossilized epikarst. Examine the paleosol closely; it contains abundant *Cerion* sp. fossils and vadose pisolites. The route down to the beach passes by a large block of rock which clearly shows a characteristic soil profile including progressive disruption of bedrock. Large vegemorph structures such as seen here are known only from dune suites that are interpreted as regressive-phase.

If the tide is low, the bedrock flat between the cliffs and the outlying stack can be seen to consist of a coral reef rubble facies, which dates to the MIS 5e sea-level highstand approximately 125,000 years ago, which makes these rocks Cockburn Town Member of the Grotto Beach Formation (Carew and Mylroie, 1987a). The section is regressive (in the sea-level and depositional sense) as the dune oversteps the reef facies. Unlike the fossil reefs seen at Stops 4 and 7A, the reef here was preserved in a worn, rubble state, indicating it probably gradually passed through the surf zone and was buried as sea level fell.

At the contact between the reef and the eolianite, a calcarenite protosol can be seen. As noted earlier, these structureless, often fossiliferous paleosols represent brief pauses in deposition, as opposed to broad periods of exposure that formed the terra rossa paleosol that caps the entire outcrop. The calcarenite protosol between the reef and the dune is important. It indicates a period of subaerial exposure of the reef, prior to entombment by the dune. Therefore this setting is a true regression, and not a progradation on a sea-level stillstand at MIS 5e.

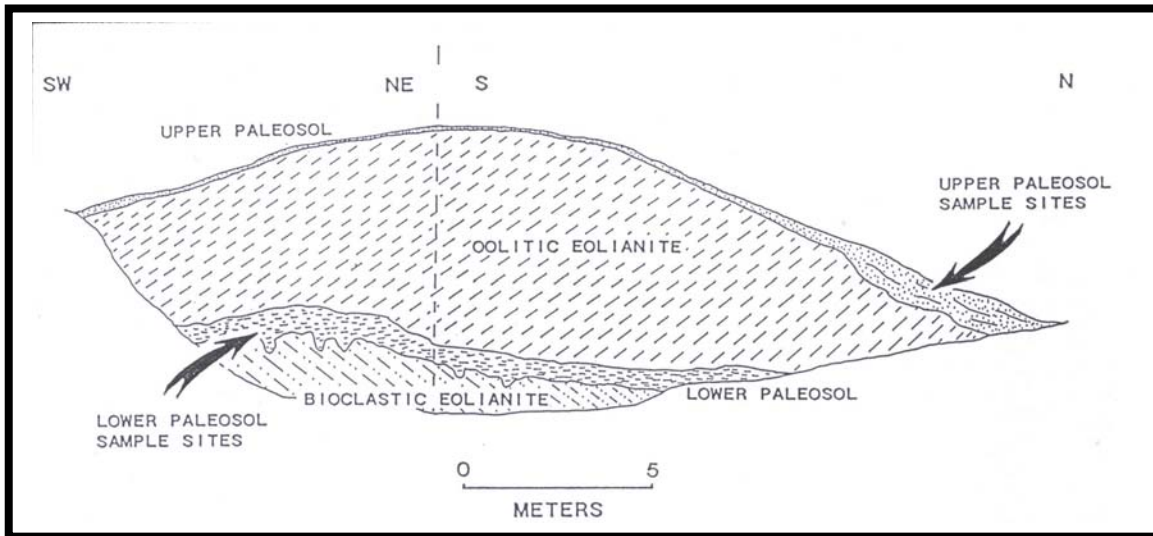
To the west, 100 m along the sea cliff, a prominent blow-hole is often active if the tide is high.

### **Stop 15. Watling's Quarry - Pre-Grotto Beach Rock**

From Stop 14 take the coastal road back to the west along the French Bay coast until the main road is encountered at the stop sign passed on the way out to Stop 14. Turn left (north) and proceed up and over the hill about 1 km. Take a left (west then southwest) onto the road that leads to Grotto Beach, first taken on the way to Stop 5 (follow the power lines). Take the third left (southeast) and drive to the end; just before the end is a small gravel pile and trail which extends about 250 m into Watling's Quarry. This quarry is one of the very few localities on San Salvador, and elsewhere in the Bahamas where two terra rossa paleosols occur in one outcrop (Fig. 29). Exposed on the west face of the quarry is an upper oolitic eolianite up to 7 m thick overlying a prominent, extraordinarily hard, red terra rossa paleosol overlying a lower eolianite. The upper, oolitic, eolianite contains occasional fragments of crabs, and near the upper paleosol, fossil *Cerion* sp. The lower eolianite, underlying the terra rossa paleosol within the outcrop, is approximately 1 m of exposed bioclastic eolianite. A relatively thin, but well developed calcrete caps the entire hill and appears to merge with the lower paleosol on the northwest side of the cliff face. Note how this upper terra rossa paleosol thickens and becomes more complex as the dune swale is approached.

The sequence here is most likely Grotto Beach Formation eolianites overlying Owl's Hole Formation eolianites. Despite the greater age of the Owl's Hole rocks, note the friability and poor cementation of much of the Owl's Hole outcrop. The paleosol surface has apparently prevented these sediments from becoming well-cemented, although there has been micritization of grains (Stowers et al., 1989). The degree of rock cementation has proven to be a very poor indicator of rock age on San Salvador Island and elsewhere in the Bahamas. The outcrop also demonstrates the patchiness of eolian deposition, in that the upper oolitic eolianite can be seen to end to the north, as the overlying and underlying paleosols merge to form a composite paleosol (Carew and Mylroie, 1991). Without the exposed quarry face, the true sequence could not have been determined from surface reconnaissance. The lack of abundant vegemorph structures high in the upper section suggest that it is a transgressive-phase eolianite, and could be classified as the French Bay Member. While it is possible that both units could be Owl's Hole Formation rocks, the paleomagnetic signature of the upper terra rossa paleosol also suggests the upper unit is French Bay Member (Panuska et al., 1999).

The quarry walls show evidence of many small pockets, which are tafoni. The quarry was cut in the early 1970's and the tafoni have increased in number and size in the 30 years that serious geologic observation has taken place in the quarry. The tafoni here,



**Figure 29. Composite section of the Watling's Quarry exposures. The presence of two terra rossa paleosols in the section obligates that the lower unit be assigned to the Owl's Hole Fm. The abundant ooids, and few vegemorphs of the upper unit suggest assignment of the French Bay Mbr of the Grotto Beach Fm. The two paleosols merge to the right (north) of the figure. From Carew and Mylroie, 2001.**

and in a nearby road cut, were measured by Owen (2007) as part of a statistical study to determine how fast, and by what mechanism, these tafoni were forming.

To complete the field trip, reverse back to the main road and proceed north to Cockburn Town and the GRC. As an alternative, for this or a later trip, the vehicle can be taken south to the intersection at the French Bay dock. From here, the main road continues east past the turnoff to Stop 14, and then north up the east side of San Salvador to see more field trip stops. These sites can also be reached by leaving the field station, going east past North Point then south down the east side of the island.

### **Stop 16A: Mouth of Pigeon Creek**

From Stop 14, continue driving east out on to the Holocene strand plain of Sandy Hook. The islands visible to the east and southeast are both Holocene and Pleistocene; the latter being the lower, darker terra rossa paleosol covered islands to the southeast. The road will swing north, and after a km will go uphill and end at a "T". Take the right (east) side of the "T" and then the first left turn to the north. This short road leads to a small parking area and a crude dock. To the left or west is the southern arm of Pigeon Creek; ahead and north is the northern arm; to the east, hard right, is the Pigeon Creek inlet. The crude stone structure to the northeast is a plantation-era supply building that held goods brought in by sea until the locals could come and get them. The low cliffs at the dock area are Rice Bay Formation. A trail leads west from the dock area and downward to near the water, where the Rice Bay Formation rocks can be observed to sit on a terra rossa paleosol. The underlying rocks are undifferentiated Pleistocene.

Pigeon Creek is not a true "creek" in the sense of flowing fresh water, but a tidal inlet. The term creek is applied in the British sense of a tidal marine water body longer than it is wide, that extends deeper into the land than a cove (Neuendorf et al., 2005, p. 149); it

is synonymous with “tidal creek”. Pigeon Creek has a north-south orientation, with an overall length of 9 km (Fig. 2). Its single opening to the sea is about 1/3 of the way north from its southern end. The creek is restricted in its flow, such that salinities in the summer can reach well above 40 ppt at its most remote point at the northern end. A tidal channel can be followed into both its southern and northern arms, and at the actual inlet area, tidal currents are very strong. The mouth of the inlet has a large ebb-tidal delta that can be observed to advance in real time across the lagoon north of Sandy Hook. The strong tidal current allows snorkelers to catch the ebb tide, strongest about halfway from the high to low tide stage. Enter the water at the dock area, but be extremely careful of boards, nails, and the eroded sheet metal boat ramp. The concrete boat ramp is very slippery, and numerous conch shells are present. Once safely past these hazards, the current will swiftly take the snorkeler out the tidal inlet, and on to the ebb tidal delta. The advancing front of this ebb tidal delta can be seen, encroaching over the thalassia meadow of the lagoon.

The snorkel will reveal sand waves in the tidal channel and coarse shell lag deposits. The mangrove on the channel sides is a nursery for a variety of fish and invertebrates. Hydroids commonly colonize the mangrove roots, and mild stings can occur. Out in the lagoon, isolated small coral heads, fish, invertebrates, and coralline algae are common. Do not exit the water onto private property; the best route is to snorkel on past the house, and exit up onto the rocky area, and follow it south to the beach and a road back to the main highway. An excellent alternative is to have the truck moved to this beach side road.

### **Stop 16B: Pigeon Creek Overview**

Reversing back across Sandy Hook, and past Stop 14, reaches the main road. Turn right (north), and approximately 6 km north of that junction, the coastal highway rises up a small hill, and a good view can be had of the north arm of Pigeon Creek. The tidal channel is clearly visible, and if the tide is low, thousands of mounds, built by callianassid shrimp, dot the estuary. These shrimp are the model for the organisms that create the trace fossil *Ophiomorpha* sp. The estuary is also a model for the restricted lagoon environments that may have produced the previously discussed “lake facies” deposits found elsewhere on San Salvador (Hagey and Mylroie, 1995). The low bedrock outcrops on the east side of Pigeon Creek are Pleistocene, but the ridge on the skyline farther east is Holocene Hanna Bay Member. The apparent cave opening seen on the east bank at water level is only an overhang of resistant terra rossa paleosol.

### **Stop 17: Pigeon Creek Fossil Ebb Tidal Delta (Quarry E)**

Continue north on the main road for 3 km to the abandoned settlement of South Victoria Hill, a scenic but forlorn place. The road turns due east just past the hamlet, and goes up a slight rise. At the crest of the rise, park the vehicle and look south into an abandoned quarry. This quarry, known as “Quarry E” or “North Pigeon Creek Quarry”, was once a spectacular site. Road widening in the early 1990’s pushed rubble over the north face of the quarry, obscuring what was a beautiful exposure of a MIS 5e fossil ebb tidal delta. The exposure had steeply dipping sand beds that to the casual observer would appear to be eolian foreset beds. The presence of large shell fragments, and *Ophiomorpha* sp trace fossils, indicate that the deposit was subtidal in origin. Teeter (1985a) was able to demonstrate that during MIS 5e, the estuary now occupied by Pigeon Creek was an open lagoon, but the basin known as Granny Lake, 3 km north,

was a restricted tidal creek. A channel connection, which can still be walked in the bush today, ran from the Granny Lake tidal creek to an inlet at the site of Stop 17, at the north end of modern Pigeon Creek. That channel built an ebb tidal delta during MIS 5e.

While the quarry has been degraded by the rubble infill, portions of the fossil ebb tidal delta can still be seen. In addition, the floor of the quarry is a terra rossa paleosol, which runs both under the ebb tidal delta facies at the north quarry wall, but also trends up the sides of the quarry and over the top of the quarry. This over-and-under-all-at-once appearance was commented upon by an early observer to be a “Klein bottle phenomena”. In other words, the ebb tidal delta facies were deposited in a topographic low point of pre-existing Owl’s Hole Formation rocks during MIS 5e. The terra rossa paleosol overlying the Owl’s Hole was buried in the topographic low, but was not buried on the high ground to either side. After sea level went down at the end of MIS 5e, pedogenic processes continued on the existing, unburied Owl’s Hole Formation terra rossa paleosol, while a younger terra rossa paleosol was developed on top of the ebb tidal deposit. That post-MIS 5e terra rossa paleosol merged with the Owl’s Hole terra rossa paleosol to either side of the ebb tidal delta deposit. In the quarry floor, the terra rossa paleosol surface, especially the dissolution pit infills in the paleosol, show many marine shells, most notably *Chione cancellata*. The marine shells show the initial transgression of the MIS 5e marine waters over the Owl’s Hole Formation rock and its terra rossa paleosol. The ebb tidal delta facies were deposited over the marine shells later in MIS 5e time. Therefore the marine shells, and ebb tidal delta facies, being subtidal units above modern sea level, are assigned to the Cockburn Town Member of the Grotto Beach Formation. On the south side the quarry, along the coast, are numerous fossil corals that grew during MIS 5e time on the hard ground provided by the terra rossa paleosol covering the Owl’s Hole Formation rocks. As these fossil corals are above modern sea level, they are also Cockburn Town Member rocks (Egerton and Mylroie, 2006). Stop 17 provides an interesting presentation of transgression across a terra rossa paleosol hardground, such that marine shells infill the subaerial dissolution pits, while later corals grew on that hardground. As the coastal situation matured on the MIS 5e highstand, an ebb tidal delta developed and prograded back across the hardground. After MIS 5e time, subaerial pedogenic processes entombed the marine deposits in a terra rossa paleosol, which merged with, and is indistinguishable from, the terra rossa paleosol covering the adjacent Owl’s Hole Formation rocks. This merging of terra rossa paleosols was seen earlier at Stop 15, Watling’s Quarry, where the overlying and underlying terra rossa paleosols are seen to merge.

During excavation of the quarry to provide fill material for the first road in the post WWII era, the bulldozer was able to penetrate the post-MIS 5e terra rossa paleosol to get at the ebb tidal sands underneath. The bulldozer could not easily penetrate the longer-duration terra rossa paleosol covering the Owl’s Hole Formation rocks under and adjacent to the sands, so excavation stopped at that boundary. Road widening in the 1990’s, as noted earlier, created the current setting. This site for years has been known as a place to see small scorpions, so be alert if moving rocks around by hand.

Pigeon Creek is notable for having a modern, active ebb tidal delta at one end, and a fossil, MIS 5e ebb tidal delta at the other end. Process and product are easily observed.

## Stop 18: The Thumb and The Bluff

Leaving Stop 17, the road trends east and then swings north again. A few hundred meters after the swing to the north, an unpaved bush road leads east up a dune. Park here and follow on foot the bush road a few tens of meters up to the dune crest. The dune is uncemented Holocene sands, but a core of cemented Holocene or Pleistocene rock could lie underneath. Downslope east to the beach is a single rock outcrop that angles out into the water, a feature called The Thumb. The Thumb is an eolianite assigned to the Owl's Hole Formation, as will be explained later. To the north along the coast, are a few more low-lying rock outcrops in the surf. These outcrops have an unusual facies that contain large numbers of the snail, *Cittarium pica*. A fossil reef, the Holiday Tract fossil reef (McGee, 2006) is a bit farther north as a low outcrop that from a distance appears, incorrectly, to be beachrock. These units are assigned to the Cockburn Town Member of the Grotto Beach Formation (McGee, 2006). In the far distance to the north, a large eolianite ridge, Almgreen Cay, extends out into the ocean. It has been assigned to the Cockburn Town Member (Carew and Mylroie, 1995a; 1997). To the south, about 1.5 km along the beach, a large eolianite body called The Bluff extends to the sea. It has geology identical to that at Almgreen Cay, and has been assigned to the Cockburn Town Member (Carew and Mylroie, 1995a; 1997).

The Thumb is interesting for a variety of reasons. It has a superb bioerosion notch along its south side. It is almost an island, linked to the land by a short tombolo. It is an eolianite, as demonstrated by its excellent foreset beds and other dune structures. Large numbers of vegemorphs occur associated with a well-developed terra rossa paleosol, indicating a regressive-phase origin for the eolianite. Examination of the north side of the outcrop shows that the foreset beds there are truncated, and that the terra rossa paleosol lies across those truncations. These features, as described earlier regarding interpretation of Pleistocene eolianites, indicate that the rock is Owl's Hole Formation. The unit was deposited on a regression, which allowed colonization by an established beach and dune plant community to create the abundant vegemorphs. The following transgression and stillstand cliffed the eolianite, and truncated the foreset beds. After sea-level later regressed, a terra rossa paleosol formed over the truncated foreset beds. The Holocene transgression followed. Evidence of three sea-level highstands (make the dune, cut the dune, and today) obligates an interpretation that The Thumb is part of the Owl's Hole Formation.

An easy walk of 1.5 km south along the beach reaches The Bluff. The Bluff is extremely similar in characteristics to the eolianite seen at The Gulf, Stop 14. A well-developed terra rossa paleosol caps the unit, which has abundant vegemorphs high in the section. These observations alone indicate a regressive-phase eolianite. Given the similarity to The Gulf outcrop, which can be seen to overstep a MIS 5e reef, The Bluff is assigned to the Cockburn Town Member. The northern few hundred meters of the outcrop cliff face reveal a classic calcarenite protosol running through the outcrop. The protosol is unstructured, white, and fossiliferous, as well as containing vadose pisolites. The fossils are primarily *Cerion* sp, with some crab parts, mostly chela. Occasional marine snail shells, such as *Cittarium pica*, are found, either from hermit crabs or from birds who drop shells to break them and eat the contents. These occasional marine shells are a warning against investing too much interpretation on an isolated fossil in the Bahamas. Hearty and Kindler (1993) assigned The Bluff a MIS 5a age, based solely on AAR data. Because of the setting at The Gulf, where similar units overstep a MIS 5e fossil reef, Carew and Mylroie (1995a; 1997) assign The Bluff to the Cockburn Town Member.

There is not much time between the end of MIS 5e at ~119 ka, and the peak of MIS 5a at 85 ka. If The Bluff were younger than Cockburn Town Member, it would have to be a MIS 5a deposit. The ~35 ka between MIS 5e and MIS 5a should be long enough that the paleosol between the eolianite and the fossil reef at The Gulf should show characteristics of a mature terra rossa paleosol. However, that paleosol is white, unstructured, and rich in *Cerion* sp fossils. It is a calcarenite protosol, and not mature enough to represent 35 ka of time. So while The Bluff could be MIS 5a, the field evidence at The Gulf supports a MIS 5e interpretation. The foreset beds of the eolianites at The Bluff dip below modern sea level, and have been truncated by the Holocene transgression.

### **Stop 19: Storrs Lake and Stromatolites**

From Stop 18, continue north on the main road. After a few km, a body of water will appear to the east. This is Storrs Lake. About 5 km north of Stop 18, the east shore of the lake comes close to the west shore, a place called the Storrs Lake Narrows. A fossil reef outcrops exists here, not as visible as it was prior to the early 1990's road widening. The fossil reef has been dated to MIS 5e (Carew and Mylroie, 1987a), providing evidence that some of the rocks present, while obviously Pleistocene because of their terra rossa paleosol, are actually Cockburn Town Member of the Grotto Beach Formation (Egerton and Mylroie, 2006). Continuing north another 3 km, the road begins to swing a bit west from Storrs Lake, and a quarry sits on the west side of the road. At this spot, modern, living stromatolites have been described from Storrs Lake (Neumann et al., 1989; Zabielski and Neumann, 1990). Storrs Lake is a long linear water body, similar in shape to Pigeon Creek. Unlike Pigeon Creek, it has no modern connection to the sea, and it has become hypersaline. Salinities of 80 ppt are common, high enough that eucaryotic life does not survive, but procaryotic cyanobacteria thrive. These cyanobacteria have no invertebrate grazers or fish to diminish their growth. Because of over visitation and over collection, casual wandering about to see the stromatolites is discouraged.

Storrs Lake has a tidal channel that can be followed down its length and into the unconsolidated Holocene coastal dunes that make up much of the east side of the lake. Teeter (1985b) suggested that based on the salinity history, and the presence of the tidal channel, that Storrs Lake, after Holocene marine flooding of its basin, had once behaved as Pigeon Creek does today. Long shore transport of sand eventually blocked the tidal inlet, and Storrs Lake switched over to its current hypersaline condition. The paleosalinities of the inland lakes of San Salvador, as determined by ostracode species assemblages, and ostracode carapace geochemistry, have allowed the changes in salinity during the last 3000 years to be determined (Teeter, 1995).

### **Stop 20: East Beach**

North from Stop 19 about 1.5 km, and well before the position of the Dixon Hill lighthouse, a paved road leads east to the coast at what is called East Beach (the beach can also be reached farther north by an unpaved road across from the lighthouse). Far to the south, a headland can be seen, Crab Cay. It has the same geology as seen at The Gulf, The Bluff, and Almgreen Cay. It has been therefore assigned to the Cockburn Town Member of the Grotto Beach Formation. To the north several km, sea cliffs formed in the Holocene Hanna Bay Member of the Rice Bay Formation can be observed.



San Salvador Island sits on a small platform that juts out into the North Atlantic Gyre. As a result, the east side of the island collects a tremendous amount of sea-born debris. The beach at Stop 20 is sometimes called “Trash Beach” because of all the litter. A project on beach litter revealed interesting data on debris provenance, categories, and durability (White and Curran, 2006). A piece of the space shuttle Challenger was found here in the early 1990’s, most likely having traveled completely around the North Atlantic from Florida. Beach studies have monitored the profile of San Salvador beaches (e.g. Voegeli et al., 2006), which can shift dramatically after major storm events. Analysis of beaches from around San Salvador demonstrated the east coast beaches were finer grained, and better sorted, than west coast beaches (Clark et al., 1989). These results were a bit of a surprise, considering the steady trade winds from the east, but the episodic winter storms from the North American continent create greater variability for west coast beaches.

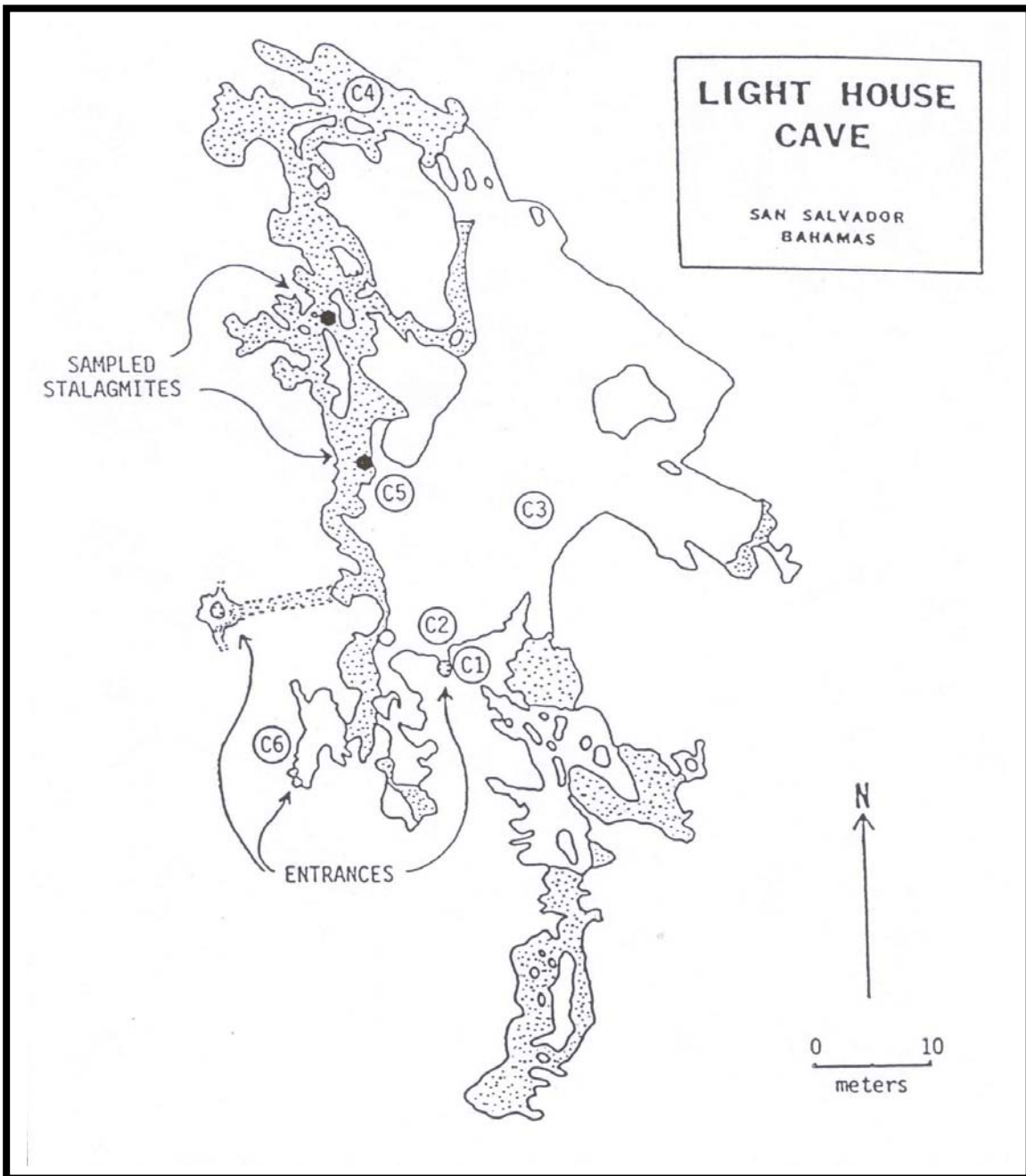
### **Stop 21: Lighthouse Cave**

From Stop 20, continue north into the village of United Estates until the Dixon Hill lighthouse is visible directly uphill to the west. Alternatively, to reach the cave from the GRC, drive east along the north coast on the main road, past North Point, and on south to the United Estates settlement. At the place where the causeway leads east across Fresh Lake to the beach, park the vehicle and on foot follow the concrete road uphill to the west. At the top of the hill is the Dixon Hill lighthouse, one of the few kerosene-fired lighthouses left in the world. It is usually possible to tour the lighthouse and view the island from the top. If this is planned, please do it on the way to the cave, as the keeper of the lighthouse does not appreciate cave mud being tracked through the lighthouse. The top of the lighthouse offers a panoramic view of San Salvador. Looking southwest, Cockburn Town is visible. Close examination of the inland lakes reveals jetties, canals, and docks. The inland lakes were the highway used by settlers to move about San Salvador, and to avoid the bush of the interior and the rough seas of the coast.

Facing east from the lighthouse, walk due east to the small gate in the wall that surrounds the lighthouse grounds (be careful of the various food crops and flowers that may have been planted in this area). Go through the gate and turn sharply to the right, onto a trail that heads south. While on this trail be careful. Cactus is often abundant, and other nasty plants with thorns and stickers overhang the trail. Proceed south down a steep hill over rocky outcrops (eolianite) to the floor of a small valley. The trail will continue over soft sediment then climb up slightly into more rocky ground with abundant small dissolution tubes, karren, and other karst features. The trail will eventually break out into a clearing with a deep red soil. Cross the clearing following the trail and turn right as the trail goes into the bush again, and bends slightly left and heads downhill. Soon a sharp right and short straight stretch reaches the cave entrance. A simplified map of the cave is shown in Figure 30 which displays the locations of various stops on the tour. Stops within the cave are labeled by the letter C. A topographic overlay for the cave is shown in Figure 12. A more detailed map of the cave is in Figures 31 A&B.

### **STOP C-I**

The Main Entrance to the cave is a collapse-modified pit cave that has intersected a phreatic chamber. Facing this entrance, the Cactus Entrance, a small hole flush with the surface, is to left (southwest) and downslope about 20 meters. Directly left (west) about



**Figure 30. Simplified map of Lighthouse Cave, showing the six in-cave field trip stops. See Figures 31 A & B for details of the cave. From Mylroie, 1988.**

30 meters is another hole that leads down to a small chamber and a few low passageways, one of which is water-filled. This water-filled passage was shown to connect to Lighthouse Cave in January 1987 by John Schweyen during a cave dive. Continuing on the surface downhill past these two minor entrances leads to the base of the dune at a mangrove swamp. Peering through the mangrove, an inland lake can be seen.

## **STOP C-2**

Climb down the Main Entrance, using the available ladder, or free climb by using a hole adjacent to the main pit. Collect the group in the room at the base of the drop. From this vantage point, a number of significant observations can be made. Directly ahead, to the north, is Aeolian Chamber, the main room of the cave. The rock floor in the Main Entrance area is modified by vadose flow, and the ceiling in this region has numerous small phreatic pockets called bell holes. Down to the left (west), water can be seen. The cave walls are white, but near the water they are stained dark brown. The top of the brown stain is the high tide mark. If the water level is near the high tide mark, some of the cave will not be easily accessible. Tidal range in the cave is nearly 1 meter, sometimes more during spring tides. The water is slightly hypersaline (38 ppt), and can be seen to enter and leave the cave by a choked passage at the southwest end of the cave (down and to the left from C-2). This spot is only a few tens of meters from the inland lake mentioned at Stop C-1. The water flow, as with the inland lakes in general, is tidal. The implication of this is that the cave does not connect in any other direct (conduit) manner to the internal plumbing of the island, which is consistent with a flank-margin mode of cave origin. Also consistent with the flank margin model is the lack of a natural entrance to the cave during its origin and growth. The three entrances are all later-forming vadose pit caves superimposed upon a series of sealed phreatic chambers.

To begin the actual tour of the cave, proceed right and upslope, around the east side of Aeolian Chamber. Climb to the top of the slope, where the terrain levels out.

## **STOP C-3**

From this vantage point, a number of observations can be made. Ahead, continuing to the north, is the rest of Aeolian Chamber. The broad, unsupported span of the ceiling in such young, porous rock is impressive. The floor of the chamber has numerous holes in it that lead to a warren of smaller passages under the room. Note that the room does not contain much breakdown. The absence of breakdown is not unusual in Bahamian caves, although breakdown is common in related areas like Bermuda (Myroie, 1984; Myroie et al., 1995a). Most of the large loose blocks can be shown to have disarticulated in place as a result of dissolution. The wall rock of this region shows the eolian sedimentary structures, especially the steep, large-scale foreset beds. Downslope to the south-southeast of Stop C-3 is a crevice in the wall that leads to Hydrology Hall, a three-dimensional maze that leads to the south (back under the trail on the surface). It ends abruptly in a blank wall. A room to the side of Hydrology Hall leads into Bat Series, a roosting spot for the bat colony that lives in the cave. Visitation to this area is discouraged to preserve the biological and geological aspects of this part of Lighthouse Cave. Ten meters north of the crevice leading to Hydrology Hall is a large opening into Bug Passage. This passage leads straight east and down to water and a termination, but by swinging to the north a loop through a guano crawl can be made back to the north end of Aeolian Chamber.

The roof of Aeolian Chamber contains many vertical holes that are 25 to 50 cm in diameter, and up to a meter or more in height. They are characterized by very straight walls with a dome on top. Because of their shape, which looks like the inside of a bell with the clapper removed, they have been called bell holes. A review of bell holes is available in Dogwiler (1998). The reason to single out these features for discussion is

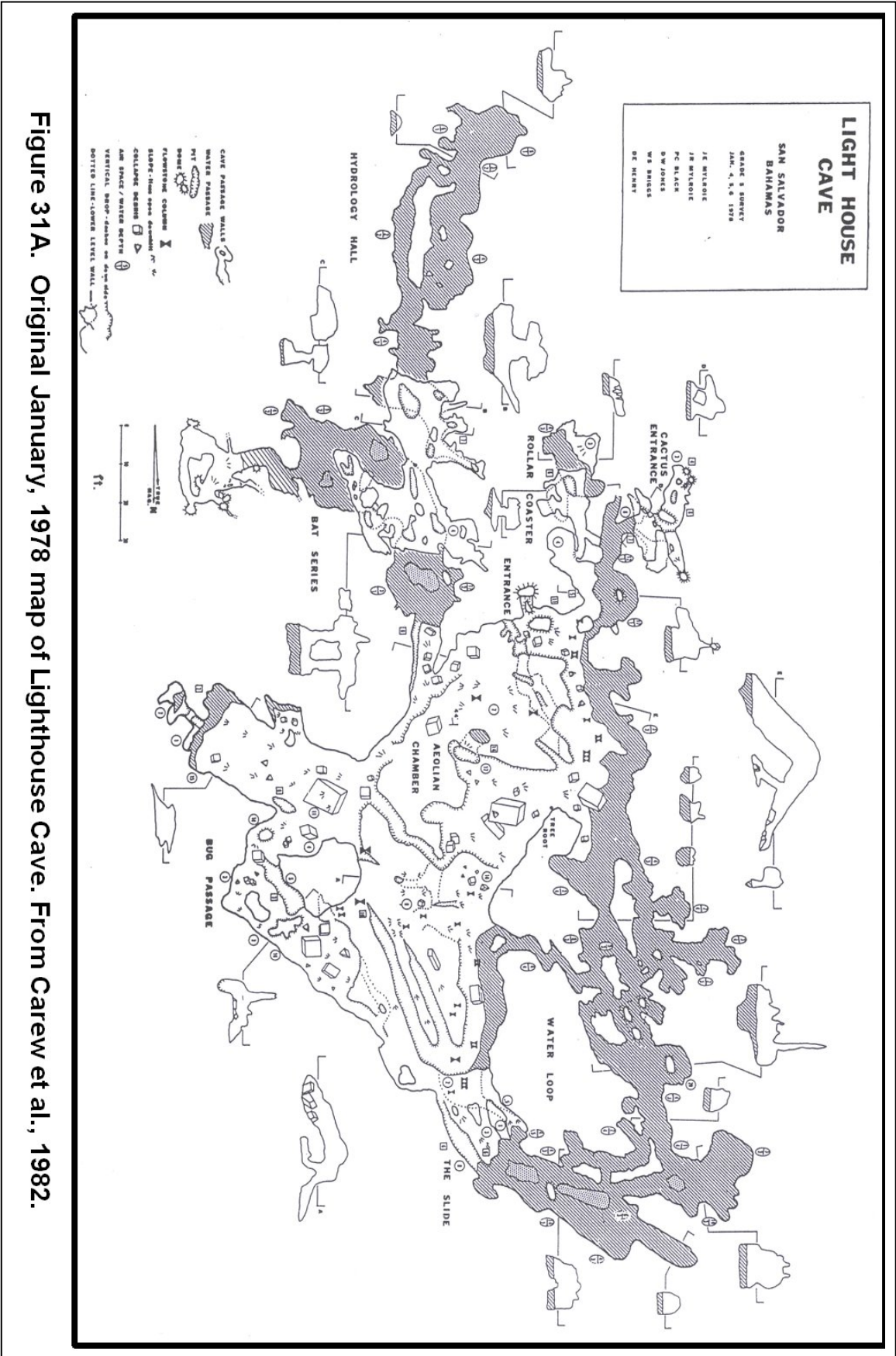


Figure 31A. Original January, 1978 map of Lighthouse Cave. From Carew et al., 1982.



the wide variety of theories that have been proposed to explain them. Some feel they are vadose in origin, a result of condensation corrosion (Tarhule-Lips and Ford, 1998), where water condenses on the cave roof, and uses atmospheric CO<sub>2</sub> to drive dissolution. The water then falls to the floor, where it re-evaporates, minus its dissolved solute load, to condense on the cave roof again and repeat the process. The other vadose theory states that bats and their metabolic activities form the bell holes (Miller, 1990). The rationale behind this argument is that when water-filled passages are explored to dry chambers, or collapse is dug away to enter new chambers, chambers that bats could not reach, bell holes are not seen. The implication is that no bats, no bell holes. The other theories involve phreatic conditions, such as the establishment of vertical convection cells where water sinks after becoming denser by dissolving the ceiling and gaining a solute load. Unsaturated water would then move to continue the dissolution process (Birmingham et al., in press).

At this time, the group should work its way to the north end of Aeolian Chamber, where the chamber wall bends to the northwest, and the room ends in a crevice that also heads northwest. Before heading off into the low crawls that empty into the Water Loop, look back across the top of Aeolian Chamber toward the Main Entrance, which is visible in the distance. This is the largest room in the largest cave on San Salvador, but even bigger chambers can be seen on other Bahamian islands (e.g. Salt Pond Cave, Long Island; Mylroie et al., 1991). The group now will work its way to the northwest down some sloping low crawlways, called The Slide, ending up in the water at Stop C-4. The key to successfully reaching Stop C-4 is to stay high in the crawls, avoiding the lower-elevation alternatives.

#### **STOP C-4**

This wet chamber marks the start of the Water Loop, a series of passages that will eventually lead back to the Main Entrance. The initial report on Lighthouse Cave (Carew et al., 1982) suggested that the cave developed during the MIS 5e highstand 125,000 years ago, and therefore the rock was that old or older. In the walls of this room note the fossil land snails, *Cerion* sp. Some *Cerion* from this location were removed for amino acid racemization (AAR) analysis, along with those from many other locations on San Salvador. That study suggested that the wall rock of the cave was approximately 85,000 years old (Carew et al., 1984; Carew and Mylroie, 1986; 1987a). As such, the rock was surmised to be correlative with the Southampton Formation of Bermuda (Vacher and Hearty, 1989). The Dixon Hill Member of the Grotto Beach Formation was thus created to deal with these results, although there was no other independent data to support the AAR geochronological results (Carew and Mylroie, 1985; 1989). These data led to a series of published reports suggesting that the eolianite and cave formed syngenetically on the MIS 5a highstand that occurred about 85,000 years ago (Mylroie and Carew, 1986; 1988). However, the MIS 5a highstand has not been well documented, and even the most optimistic interpretations of that highstand do not place it above today's sea level, which would be necessary to produce the cave's phreatic ceiling surfaces at their current elevation. A re-evaluation of the amino acid data (Mirecki et al., 1993) indicates that the 85,000 year age is most likely incorrect, and work by Schwabe et al. (1993) indicates that the rock is part of the Owl's Hole Formation. Therefore, the original interpretation of Carew et al. (1982) appears to have been correct (Carew and Mylroie, 1995a; 1997). As a result, the Dixon Hill Member has been deleted from the physical stratigraphy of the Bahamas.

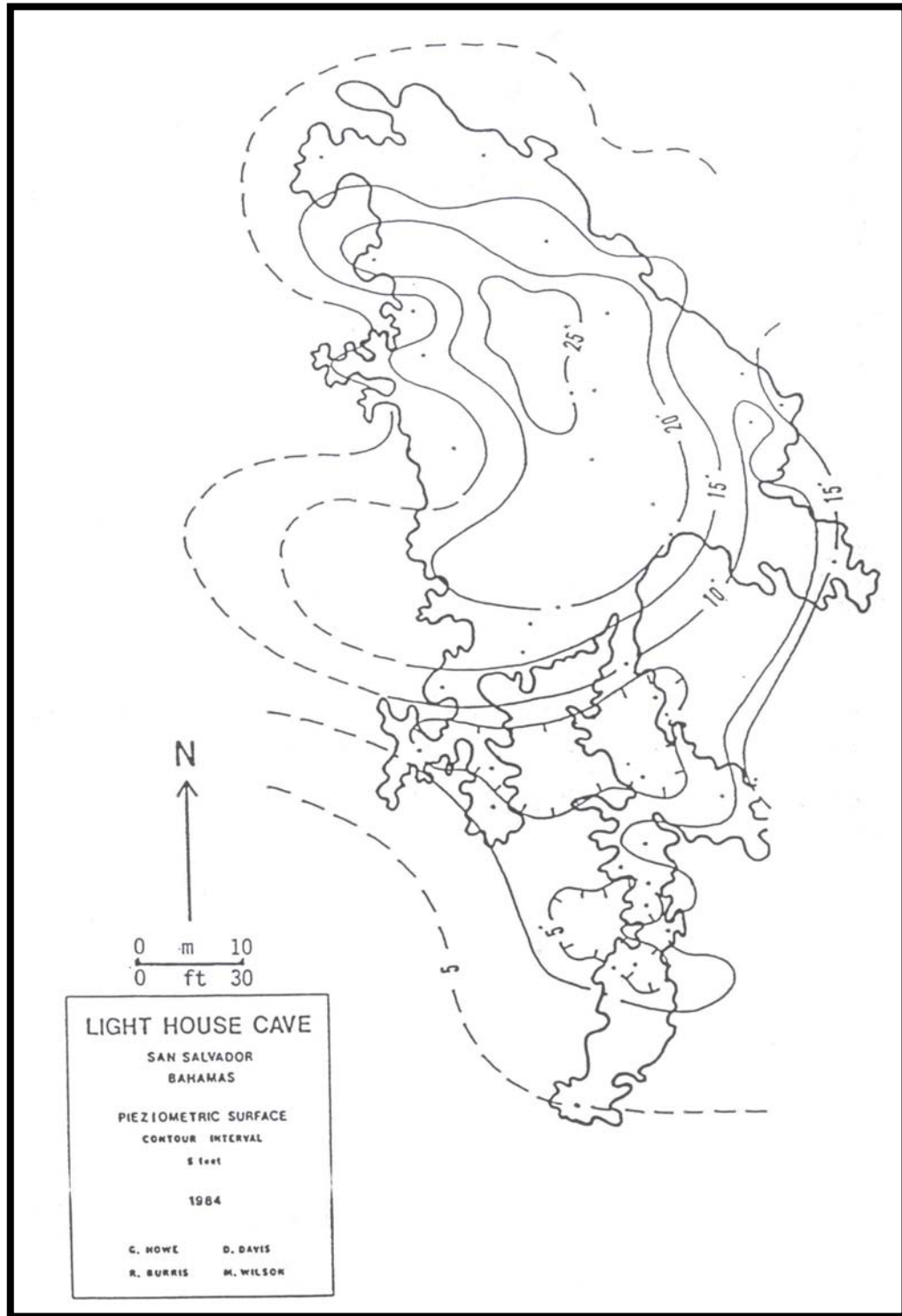


Figure 32. Map of the height above sea level of the highest phreatic dissolutional surfaces in Lighthouse Cave, a proxy for the potentiometric surface. From Mylroie, 1988.

The existence of the Water Loop offers the opportunity to engage in some speculation about flank margin cave origin in the Bahamas. Lighthouse Cave is one of the few flank margin caves in the Bahamas that extends below sea level; Hatchet Bay Cave on Eleuthera is another example (Mylroie, 1988). Most Bahamian flank margin caves are dry, that is, their bedrock floors are above modern sea level. The accepted argument for these floors is that the floor to ceiling distance (using dissolutional and not collapse surfaces) represents a minimum freshwater lens thickness when the cave developed. So, the existence of the Water Loop in Lighthouse Cave could indicate that there was a thicker lens in existence under Dixon Hill during MIS 5e than in most other Bahamian cave sites. Alternatively, Lighthouse Cave could be an over-printed cave, with the lower levels of the Water Loop having formed during a sea level highstand that preceded MIS 5e, and the dry area of Aeolian Chamber having formed during MIS 5e. The partially flooded aspect of the Water Loop could indicate either: 1) isostatic subsidence of the San Salvador platform since a pre-MIS 5e highstand that was significantly above modern sea level; or 2) a stable San Salvador with a pre-MIS 5e highstand just a little above modern sea level. Diligent investigation by cave divers has failed to find any route downward out of Lighthouse Cave; the bedrock floor of the Water Loop is at about -2 m maximum depth. This observation is consistent with the model for flank margin cave development: that is, the glacio-eustatic rises and falls of sea level are too rapid for stable lens position to occur long enough for cave formation. Only the still stands (at high and low sea levels, see Carew and Mylroie, 1987b; Mylroie and Mylroie, 2007) provide the time necessary for significant flank margin cave development.

Continuing on with the tour, straight ahead to the northwest is an example of a tubular passage that abruptly ends. According to the flank margin model, the end of the tube indicates the position of the mixing of diffuse freshwater flow coming into this dissolutional chamber from the ridge interior with sea water intruding from the coast. When sea level fell at the end of MIS 5e, the cave passage was abandoned and dissolution stopped. From Stop C-4, take the opening ahead and to the left, into a high, domed chamber. The way on is sharply to the left (south), through a low arch at water level (notice that the high tide mark reaches the ceiling of this arch), and requires getting partially wet. On the other side of the arch, the ceiling rises and there is a central tunnel heading south with a variety of maze passages on both sides. The bedrock floor is full of potholes, and the unwary can step in up to their neck or deeper (depending on stature). Persistent searching of the right (west) wall will reveal leads into low, mazy areas with no continuing passage except to the south to link up with the main passage. Persistent searching along the left (east) wall will eventually lead to discovery of a passage up into Aeolian Chamber. From this junction with Aeolian Chamber, routes lead left (north) back to the route into the Water Loop at The Slide, right (east) back to the Main Entrance, or straight ahead into a warren of small passages beneath Aeolian Chamber. By continuing straight through the Water Loop, some interesting domes can be seen overhead. These lead up and may connect with each other, but no substantial upper level is present. Some domes look entirely phreatic in nature, others have some vadose modification. Eventually, after a short stretch of deep water, another low arch with its ceiling below the high tide mark is reached. On the other side, the Main Entrance can be seen up and to the left (southeast).



## **STOP C-5**

Between the exit from the Water Loop, and the Main Entrance, are a series of stalagmites, one of which was collected in 1980 and dated by U/Th methods. The results of that dating are presented in Mylroie and Carew (1988). The stalagmite in question had two growth episodes, one centered at 49,000 years ago and one centered at 37,000 years ago. Between these two growth episodes the stalagmite contains an overgrowth of the marine serpulid worm *Filograna* sp. Carew and Mylroie (1988) interpreted this observation to indicate that the stalagmite, and hence the cave and the island, had experienced a brief marine flooding event between 37,000 and 49,000 years ago, which coincided with MIS 3. While most other sea-level records agree with a sea-level highstand at this time, few support a sea level that reached near or above modern sea level, and the data remain controversial. A second stalagmite, collected underwater in the Water Loop, had a basal date of 71,000 years (see Fig. 30 for stalagmite locations). These values are in agreement with the current interpretation of the cave as having developed during oxygen isotope substage 5e, 125,000 years ago. Stalagmite data from elsewhere in the Bahamas also supports an interpretation of flank margin cave development as having occurred during MIS 5e (Carew and Mylroie, 1995b), there being no known stalagmites older than 125,000 years in subaerial flank margin caves. Recent work (Lascau, 2005) suggests that this simplistic explanation may not be totally correct, and that prior sea-level highstands may have participated in the development of flank margin caves above sea level today in the Bahamas. MIS 11 seems the most likely culprit. As noted earlier, Lighthouse Cave itself could be the result of such an overprint.

Following the trend of the cave wall on the right (west) from Stop C-5, a low undercut in the wall leads west to a submerged passage that John Schweyen (in January 1987) connected to the third entrance mentioned at Stop C-1 (DON'T try to free dive this passage!). Continuing ahead in the water leads to a domed chamber as the main entrance passes from view over to the left. Ahead and to the left (southeast) the passage leads up to an alcove with a small opening through a thin partition and into a small set of passages called the Rollar [sic] Coaster. Immediately on the right is a window into the domed chamber, but continuing ahead leads into a nasty, bat-filled area and into a short lower level. No further way on has been found here. Straight ahead from the domed chamber, and up an incline, daylight can be seen in the roof.

## **STOP C-6**

From this spot, a short climb leads to the Cactus Entrance. At the base of the climb, in the low and rubble choked crawls, is the water entry/exit point for the cave. If the tide is either rising or falling, a significant flow of water can be observed here. It has not been possible to negotiate this passage for any distance. This water flow seems to be an artifact of current sea level, and the lateral breaching of the cave to the saline lake.

From this locality, members of the group may exit the Cactus Entrance and follow a short trail through a cactus forest (now mostly dead) back to the Main Entrance, or people may double back inside the cave to the Main Entrance and leave the cave there.

## SUMMARY OF LIGHTHOUSE CAVE

Lighthouse Cave meets the morphological criteria for flank margin caves. It is on the flank of a dune, and it has a large, central chamber with passages that radiate outward and end abruptly. A potentiometric map of the cave was made in 1984 (Mylroie, 1988), using the high tide mark as a baseline for measurements to the top of all phreatic domes and chambers around the cave. The results are shown as the contour plot seen in Figure 32. The contouring is not exact, but the data show greatest phreatic height above current high tide to be in Aeolian Chamber and nearby adjacent areas. Phreatic ceiling height drops off sharply in the radiating cave passages that trend to the south and east. If the cave developed during a single, stable sea-level highstand, the map provides a means to estimate the minimum thickness for the freshwater lens at that time (9 m). The upper limit of phreatic surfaces in the cave are an indication of the maximum height of the lens above current sea level when the cave developed. The data here indicate that the water table was slightly in excess of +7 m above sea level, in agreement with a freshwater lens floating on a +6 m sea-level highstand 125,000 years ago. Given some minor isostatic subsidence (Carew and Mylroie, 1995b), these phreatic surfaces reflect not just the stable lens configuration, but slight excess mounding of the lens in response to major storm events. Lighthouse Cave has no definite phreatic flow marks on the walls, no scallops or other horizontal flow markings, which suggests that there was no turbulent phreatic flow involved in cave formation. Vadose grooves can be found in some domes, and vadose notches are incised into the floor of Aeolian Chamber near the Main Entrance. The cave does not penetrate more than 2 m below current sea level, and the entire cave is contained within a layer about 9 meters thick.

The history of the interpretation of research on Lighthouse Cave shows that the geochronology of the cave has been the source of most debate. The stalagmite data from Lighthouse Cave agrees with other data sets worldwide as to the timing of the MIS 3 high sea level event, but suggests a higher amplitude to this sea-level highstand than is postulated by these data sets. The stalagmite data also support a Late Pleistocene age for the development of the cave, as none are older than 71,000 years. The age of the rock enclosing Lighthouse Cave is now recognized to be more than 125,000 years (Owl's Hole Formation). Based on the glacio-eustatic sea-level curves of the late Pleistocene, coupled with the tectonic stability of the Bahamas, it is clear that Lighthouse Cave was largely created in the 12,000 year time window of the MIS 5e sea-level highstand, centered approximately 125,000 years ago. The possibility that the lowest level of the cave is a relict of an MIS event before MIS 5e remains.

Dixon Hill is a small irregular ridge. At a sea level of +6 m it would have been a very small island, and the freshwater lens must have been small as well. Whatever mechanism is invoked to make the cave must also be capable of removing a volume of rock equal to the volume of the cave in a very short time in a very small freshwater lens. Mechanical transport is not an option. The potent dissolution capability of mixed fresh and marine waters, coupled with biologically induced oxidation/reduction reactions in the rapid flow regime of the lens margin, is currently the best explanation for the cave's origin (Mylroie and Mylroie, 2007; Moore et al., 2007). The flank margin model supports all the available observations and interpretations regarding the development of Lighthouse Cave.

## Stop 22: The Gerace Research Center Trail

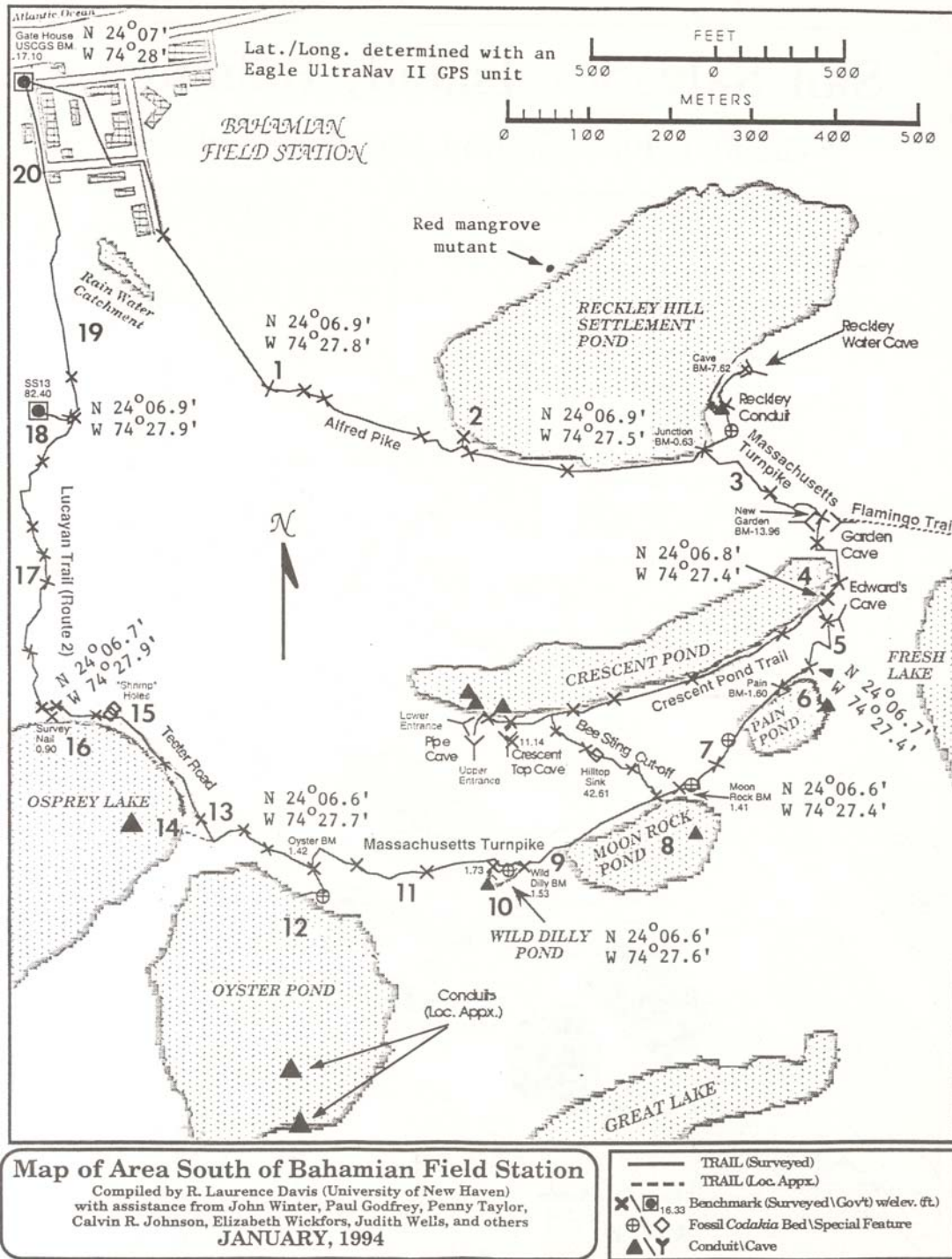
Behind the Gerace Research Center is a trail system that was cut in the late 1980's to provide access to a number of caves, ponds, blue holes, lakes, and outcrops. A field guide to those features has been written by Godfrey et al. (1994), and will be briefly summarized here. Figure 33 shows the trail system. At the southern end of the GRC, a trail leads past the catchment pond to an old quarry filled with debris from the time when the GRC was a navy base. The trail exits the quarry to the east and eventually follows along the shore of Reckley Hill Settlement Pond. At the southeast corner of the pond, a trail junction is reached. To the northeast, the trail continues for several hundred meters, to pass by a lake drain for the pond, and by a number of small caves: Midget Horror Hole, Reckley Hill Pond Water Cave, and Reckley Hill Pond Maze Cave. Reckley Hill Pond Water Cave is interesting in that it contains tidal water, which has been dye traced from the lake drain at Reckley Hill Settlement Pond, the only successful dye trace ever done on San Salvador. A small fossil reef has been located right on the trail, a few tens of meters south of the lake drain (McGee, 2006; Egerton and Mylroie, 2006).

At the trail junction, continuing southeast, over a low ridge, reaches Garden Cave, a partially-collapsed remnant of a once larger cave (Fig. 34). The remaining passages are interesting, and demonstrate how flank margin caves form just inside the ridge flank that encloses them. The trail passes to the west of the cave, goes down the ridge flank, and skirts the edge of Crescent Pond, so named for its conformity to the swale it occupies between two curving Pleistocene dune ridges. The trail splits again; to the south it goes by Pain Pond to Moon Rock Pond. The alternative trail goes west along the south shore of Crescent Pond to reach Crescent Top Cave and Pipe Cave. Pipe Cave is a very small cave, but Crescent Top is larger, with a pit in the back that reaches down to water, which fluctuates with the tides (Fig 35). East of Crescent Top Cave a few tens of meters, a trail leads up and over the ridge to the south, to join up with the Pain Pond trail at Moon Rock Pond.

Moon Rock Pond is named for the incredibly jagged and etched rock that surrounds the pond. Both the rock and its remnant terra rossa paleosol are highly partitioned by dissolution holes. The name "moon rock" was applied as the surface looks like it is covered in thousands of tiny craters. The rock's unusual appearance is the result of the bedrock platform being only a meter or less above the pond surface. In other words, the epikarst is directly coupled to the saline ground water. Mixing dissolution between meteoric water traversing a thin epikarst, with the marine water below has allowed dissolution to proceed to a degree rarely seen. If the bedrock platform were thicker, the epikarst would be de-coupled from the ground water. Vadose water would have less dissolutorial potential when it reached the ground water as a result of a longer residence time in the vadose zone, and the longer transit path downward.

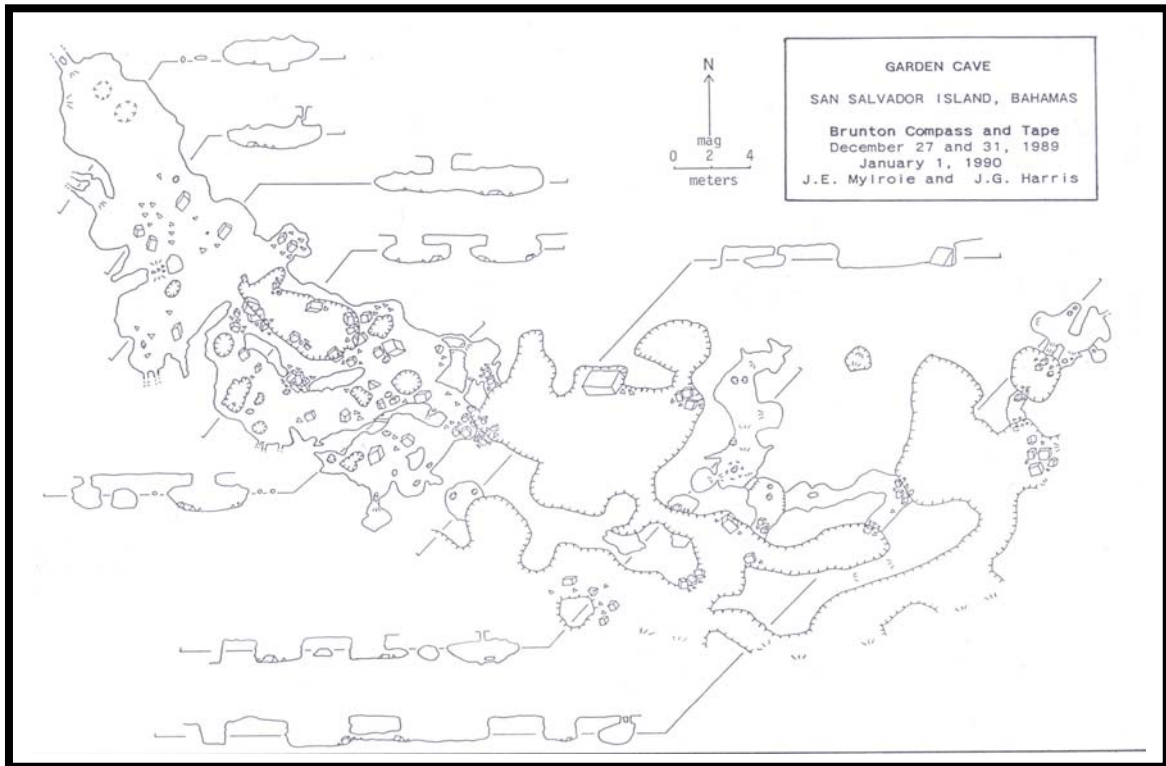
From Moon Rock Pond the trail continues west past Wild Dilly Pond to Oyster Pond. Along the rugged trail are outcrops of marine molluscs, primarily *Codakia* sp. These outcrops, along with the small fossil reef at Reckley Hill Settlement Pond indicate that the low areas are primarily Cockburn Town Member of the Grotto Beach Formation. The eolianites have not been assigned because of a lack of definitive criteria, and so are labeled as undifferentiated Pleistocene.

From Oyster Pond the trail heads northwest past Osprey Lake then due north up an eolianite ridge. Oyster Pond contains an opening that has a strong tidal flow, and is

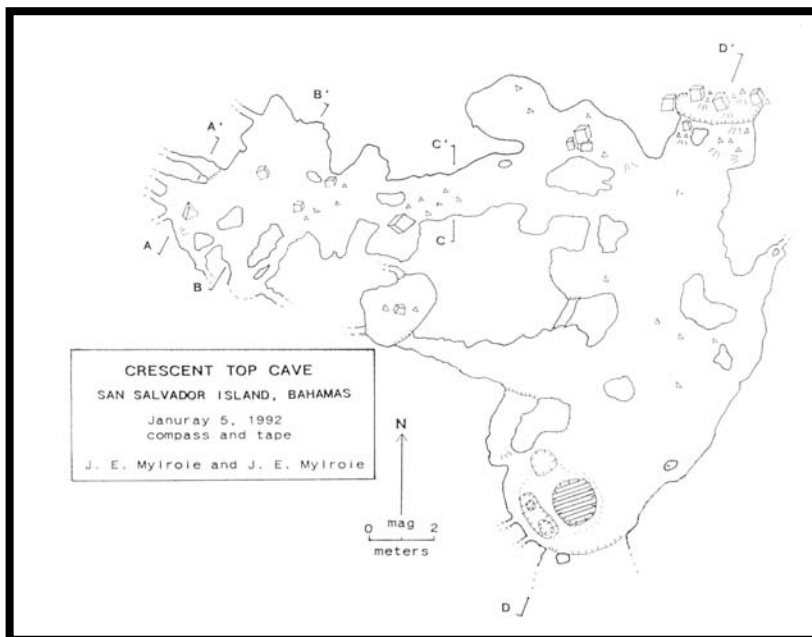


**Figure 33. Map of the trail system and associated features to the south of the Gerace Research Centre, all part of Stop 22. From Godfrey et al., 1994.**

initially large enough to enter by divers. It is the best opportunity on San Salvador for access to a significant underwater cave. The trail past Osprey Lake opens out, at the ridge crest, onto the water catchment of the GRC, providing a spectacular view over the field station, Grahams Harbour, and North Point. Following the west side of the catchment, a trail leads back on to the field station grounds.



**Figure 34. Map of Garden Cave.** The cave is reasonably intact to the west, but only fragments remain to the east. The cave is tucked just inside the flank of a low, broad eolianite ridge.



**Figure 35. Map of Crescent Top Cave.** The cave has a restricted entrance which maintains high humidity and a hole to marine water, at sea level, at the back.

## **FIELD TRIP SUMMARY**

The oldest rocks on San Salvador were seen at Grotto Beach, Owl's Hole, Watling's Quarry and The Thumb. In the first three of these localities there is a basal eolian calcarenite which is composed primarily of bioclastic grains and peloids. These calcarenites are either erosionally truncated with subtidal facies resting unconformably on them as seen at Stop 7A, or covered by a paleosol that is overlain by oolitic eolianites as seen at Stops 10 and 15. The Thumb provided a means to recognize Owl's Hole Formation rocks in the absence of overlying units. These rocks are assigned to the Owl's Hole Formation; and they are all pre-MIS 5e in age (>125,000 years old). They may have formed during an earlier sea-level highstand of oxygen isotope stage 7 (circa 220,000 years ago), 9 (circa 320,000 years ago), or 11 (circa 410,000 years ago), or perhaps even older sea-level highstands. Overlying the Owl's Hole Formation is the Grotto Beach Formation. Rocks assigned to this unit and consisting of a variety of facies from subtidal to eolian were seen at Stops 3 (under the paleosol), 4, 7A, I2A, I2B, 14, 15, 17, and 18, as well as at many of the karst stops. These rocks differ from both older and younger rocks in that the eolian facies are usually primarily oolitic (> 80% ooids) rather than bioclastic. Even subtidal facies contain numerous ooids. The Grotto Beach Formation rocks were deposited during MIS 5e (circa 125,000 years) highstand of sea level. Grotto Beach Formation rocks are capped by a calcrete/paleosol that marks the Pleistocene/Holocene boundary. This was illustrated at Stop 3.

The youngest (Holocene) rocks on the island are assigned to the Rice Bay Formation, and were seen at Stops 1, 2, 3, and 7B. These rocks yield radiocarbon ages of 5,500 yBP to 480 yBP. Eolian facies of these rocks are usually bioclastic and peloidal.

Stops 8, 9, 10, and 11 illustrated karst features developed in Grotto Beach Formation rocks (extending downward into Owl's Hole rocks at Stop 10). These features provide information about past sea level and climate. While the pit caves and associated epikarst may have been forming for the entire time since deposition of the Grotto Beach rocks, the flank margin caves had only the brief time window of the MIS 5e sea-level highstand (approximately 12,000 years) in which to form.

San Salvador Island, as a small, isolated island on an isolated platform, is an excellent demonstration of how complex carbonate depositional and erosional events can be despite limitations in island size. In addition, San Salvador indicates how fast some of these processes can operate, especially those limited to the relatively brief periods of platform flooding during the Quaternary.

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