GEOLOGY AND KARST GEOMORPHOLOGY OF SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT: The exposed carbonates of the Bahamas consist of late Quaternary limestones that were deposited during glacio-eustatic highstands of sea level. Each highstand event produced transgressive-phase, stillstand-phase, and regressive-phase units. Because of slow platform subsidence, Pleistocene carbonates deposited on highstands prior to the last interglacial (oxygen isotope substage 5e, circa 125,000 years ago) are represented solely by eolianites. The Owl's Hole Formation comprises these eolianites, which are generally fossiliferous pelsparites. The deposits of the last interglacial form the Grotto Beach Formation, and contain a complete sequence of subtidal, intertidal, and eolian carbonates. These deposits are predominantly oolitic. Holocene deposits are represented by the Rice Bay Formation, which consists of intertidal and eolian pelsparites deposited during the transgressive-phase and stillstand-phase of the current sea-level highstand. The three formations are separated from one another by well-developed terra-rossa paleosols or other erosion surfaces that formed predominantly during intervening sea-level lowstands.

The karst landforms of San Salvador consist of karren, depressions, caves, and blue holes. Karren are small-scale dissolutional etchings on exposed and soil-covered bedrock that grade downward into the epikarst, the system of tubes and holes that drain the bedrock surface. Depressions are constructional features, such as swales between eolian ridges, but they have been dissolutionally maintained. Pit caves are vertical voids in the vadose zone that link the epikarst to the water table. Flank margin caves are horizontal voids that formed in the distal margin of a past fresh-water lens; whereas banana holes are horizontal voids that developed at the top of a past fresh-water lens, landward of the lens margin. Lake drains are conduits that connect some flooded depressions to the sea. Blue holes are flooded vertical shafts, of polygenetic origin, that may lead into caves systems at depth.

The paleokarst of San Salvador is represented by flank margin caves and banana holes formed in a past fresh-water lens elevated by the last interglacial sea-level highstand, and by epikarst buried under paleosols formed during sea-level lowstands. Both carbonate deposition and its subsequent karstification is controlled by glacio-eustatic sea-level position. On San Salvador, the geographic isolation of the island, its small size, and the rapidity of past sea level changes have placed major constraints on the production of the paleokarst.

INTRODUCTION

The Paleokarst Field Conference, sponsored by the Karst Waters Institute, was held February 17-21, 1995 at the Bahamian Field Station on San Salvador Island. The island was selected as the conference location because the isolated nature of the island, its small size, and the youthful age of its carbonates place strong constraints on any models used to explain the abundant paleokarst features present there. Carbonate deposition and karst processes have combined to yield the landforms seen today in carbonate islands like San Salvador. The purpose of this paper is to introduce the reader to the geology and karst geomorphology of San Salvador Island, Bahamas. This paper also provides background material for three other papers in this volume (Raeisi and Mylroie 1995; Harris et al. 1995; Mylroie et al. 1995) that deal with specific aspects of karst development on San Salvador Island and the Bahamas.

This paper is a synopsis of several major works on Bahamian geology and karst geomorphology that have been recently published or are currently in press (Carew and Mylroie 1995a; 1995b; Mylroie and Carew 1995; Mylroie et al. 1995). The reader is referred to those publications for a more detailed analysis of the themes and ideas brought forward here. In addition, Carew and Mylroie (1994a) and Mylroie and Carew (1994) are field guides to the geology and karst of San Salvador Island, with detailed descriptions of specific sites that illustrate the concepts presented in this paper.

REGIONAL SETTING

The Bahama Islands are a 1400 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, and Mouchoir, Silver, and Navidad banks, that are a separate political entity. The northwestern Bahama islands are isolated landmasses that project above sea level from two large carbonate platforms, Little Bahama Bank and Great Bahama Bank. To the southeast, beginning in the area of San Salvador Island, the Bahamas consist of small isolated platforms many of which are capped by islands that make up a majority of the available platform area. The Bahamian platforms have been sites of carbonate deposition since at least the Cretaceous, with a minimum thickness of 5.4 km (Meyerhoff and Hatten 1974) and perhaps as much as 10 km (Uchupi et al. 1971). The large platforms of the northwestern Bahamas are separated by deep channels or troughs, and the smaller isolated platforms of the southeastern Bahamas are surrounded by deep water. Water depth on the platforms is generally less than 10 meters. There is no evidence of active tectonics in the Bahamas (Carew and Mylroie 1995c).

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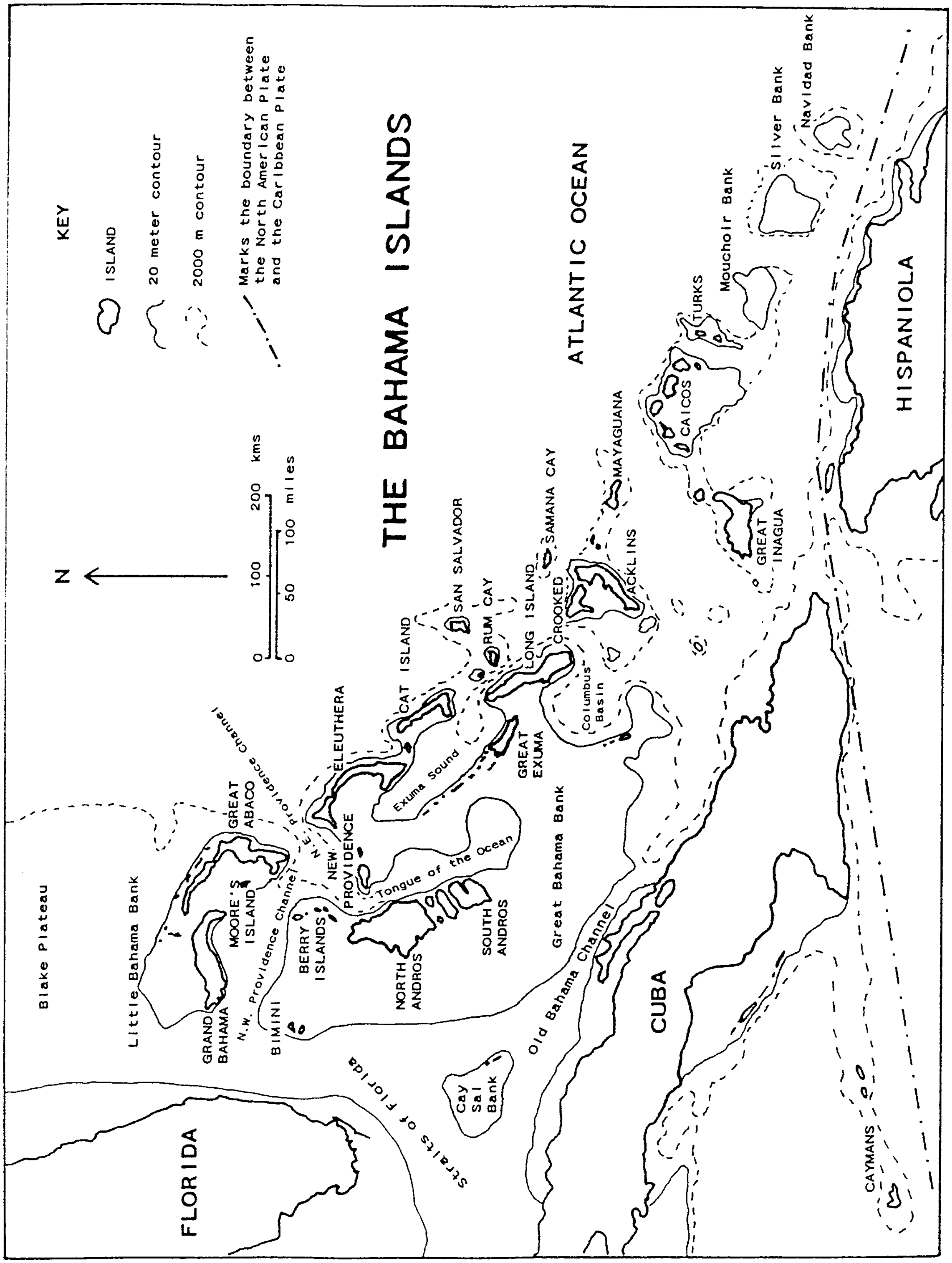

Figure 1. Map of the Bahama Islands and surrounding area, detailing islands, banks, and deep-water troughs.

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 Bahamas as the result of plate tectonic motion associated with the opening of the North Atlantic Ocean in the Mesozoic. The pattern of banks, troughs, and basins is seen as inherited 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 continuous Mesozoic carbonate platform. Recent work by Eberli and Ginsburg (1987) has demonstrated that the Bahama banks are undergoing depositional progradation. However, Mullins and Hine (1989; 1990) have demonstrated active erosional segmentation of the banks. It is possible that both original horst and graben topography, coupled with later bank progradation and segmentation, are responsible for the configuration of the modern Bahama Banks.

The geologic literature on the Bahamas is extensive, but the bulk of that literature deals with the carbonate banks and related deep water environments. Comparatively little work has been done on the subaerial geology of individual islands. The first modern geologic description of a Bahamian island was not published until Titus' work on San Salvador in 1980 (Titus 1980; 1983; 1984; 1987). Hutto and Carew (1984), Carew and Mylroie (1985; 1995a; 1995b), and Hearty and Kindler (1993) on San Salvador; Garrett and Gould (1984) on New Providence; Wilber (1987; 1991) on Little San Salvador and West Plana Cay; Mitchell et al. (1989) on Conception Island; and Carew and Mylroie (1989a) on South Andros represent some of the initial attempts to provide geologic descriptions of Bahamian islands.

SUBAERIAL GEOLOGY OF THE BAHAMAS

Depositional Model

The exposed rocks of the Bahamas are all Late Quaternary carbonates, dominated by Pleistocene subtidal facies at low elevations, and eolianites at elevations above 6 m. Paleosols occur at all elevations. The glacio-eustatic sea-level changes of the Quaternary have alternately flooded and exposed the Bahamian banks, subjecting them to cycles of carbonate deposition and dissolution, respectively. Significant carbonate deposition on the islands occurs only when the platform tops are partially or totally flooded. So, the carbonate rocks of the Bahamas consist of sedimentary packages deposited during sea-level highstands, that are separated by erosional unconformities (usually marked by paleosols) produced largely during sea-level lowstands (Carew and Mylroie 1985; 1995a; 1995b). Each depositional package consists of: a transgressive phase, a stillstand phase, and a regressive phase. These phases each contain a subtidal, intertidal and eolianite component. However, Holocene sea level is sufficiently high that the only marine deposits exposed on land today are those associated with the stillstand phase of oxygen isotope substage 5e (circa 125,000 years ago), which was about 6 m higher than present sea level. Even the transgressive-phase and regressive-phase marine deposits of substage 5e are below modern sea level. Assuming an isostatic subsidence rate of 1-2 m per 100,000 years (Mullins and Lynts 1977; Carew and Mylroie 1985; 1995c), earlier highstands were either not high enough (stage 7), or occurred too long ago (stage 9 and earlier) for subtidal deposits to exist above modern sea level (Carew and Mylroie, 1995c). In contrast, eolianites form topographic highs that extend well above past and modern sea levels, so eolianites from several Quaternary highstands are exposed on Bahamian islands.

The details of the following summary of the depositional model of the Bahamas are available in Carew and Mylroie (1994a; 1995a; 1995b). During each transgressive phase, carbonate sediments accumulate as the banktops begin to flood. As sea level rise continues, the beach sediments are continually re-mobilized by the shoreline advancing landward. In some areas, large dunes are formed, and they may be subsequently eroded 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 its acme. During the stillstand phase of the sea-level highstand, abundant subtidal and intertidal facies are deposited, but eolianite production is probably less than during the transgressive phase, because the system approaches equilibrium and reefs grow up to sea level. During the regressive phase, some of the stillstand-phase subtidal deposits are re-worked by coastal processes, and some substantial eolianites may be formed. These regressive-phase eolianites are abandoned as their source areas retreat seaward with falling sea level. As sea level descends below the platform tops, erosional processes become dominant on the platform, and soils that will eventually be preserved as paleosols are produced. The use of paleosols as stratigraphic markers is very helpful in sorting out suites of Quaternary carbonates. However, because of spatially-patchy distribution of carbonates during each depositional cycle, and the complexities of paleosols, there are many potential difficulties in the use of paleosols as stratigraphic markers (Carew and Mylroie 1991). A typical sequence of events for a depositional cycle in the Bahamas is shown in figure 2.

The most complete sequence of deposits seen in the Bahamas today formed during the transgression, stillstand, and regression of the oxygen isotope substage 5e highstand event. Older packages are incomplete, for reasons given earlier, and the Holocene package does not, as yet, contain a true regressive phase (although it does contain progradationally regressive deposits). A general model for the deposition and stratigraphy of Bahamian islands was first proposed by Carew and Mylroie (1985). The model was developed on San Salvador Island, but it has been successfully utilized on numerous other islands (e.g. Carew and Mylroie 1989a; Carew et al. 1992; Wilber 1987; 1991; Kindler 1991). The model has

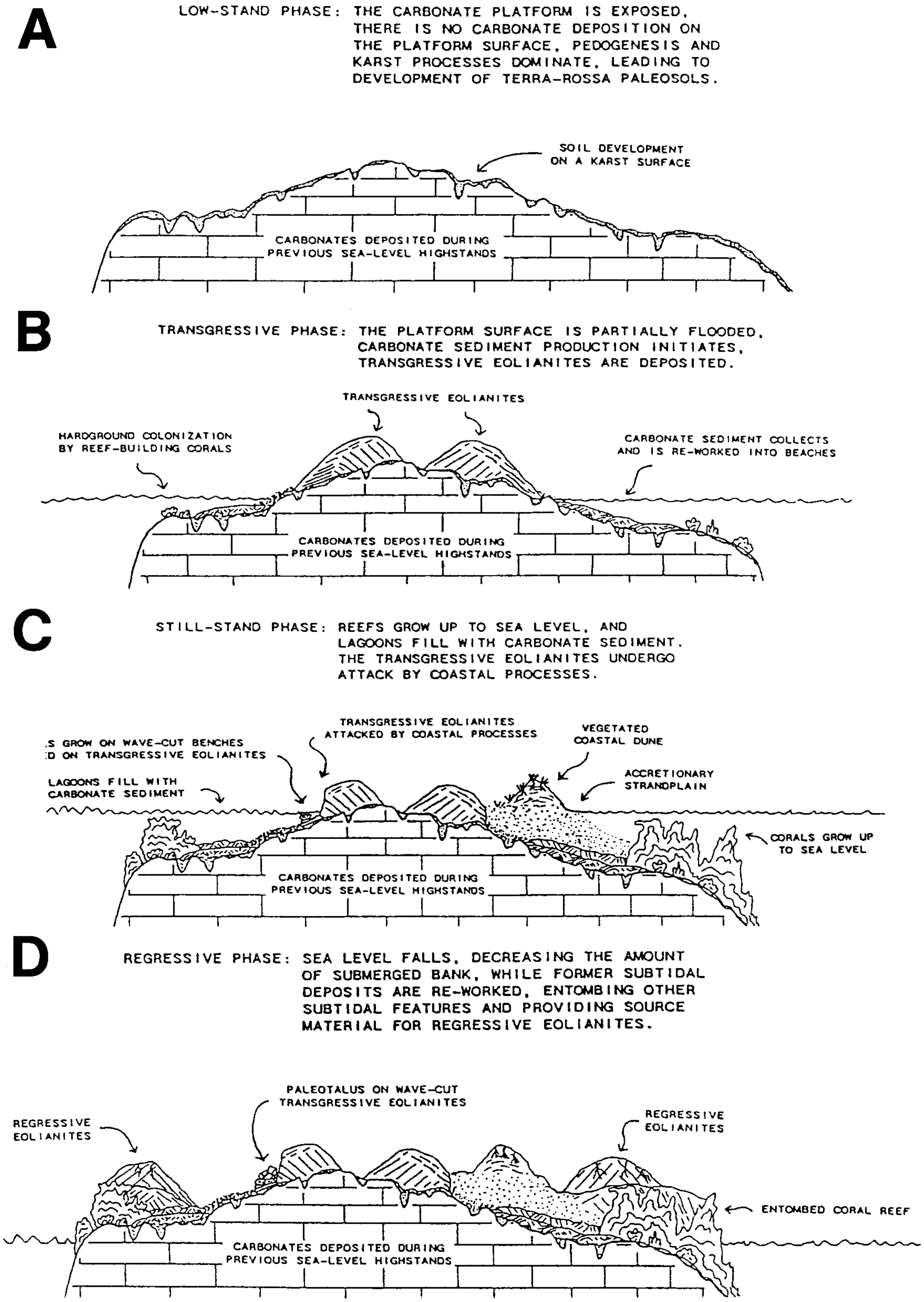

Figure 2. Illustration of the four stages of depositional development of Bahamian islands during each glacial/interglacial sea-level fluctuation. During highstands, the islands are the highest portions of steep-walled platforms with quasi-flat tops that are not inundated. During lowstands (below -10 m), the entire platforms are islands. Part A, lowstand phase, sea level >10 m below present sea level. Part B, transgressive phase, sea level is above -10 m and the platform tops are being progressively inundated by the sea as it rises to its acme. Part C, stillstand phase, sea level hovers around its maximum elevation (usually for 10,000 to 15,000 years). Part D, regressive phase, sea level falls and eventually descends below the platform top (from Carew and Mylroie 1995a).

Table 1. Comparison of stratigraphies proposed for San Salvador Island, and the Bahamas

AGE	OXYGEN ISOTOPE STAGE	Titus 1980[1]	Carew and Mylroie 1985	Titus 1987	Hearty and Kindler 1993	Carew and Mylroie 1995a[3]
HOLOCENE	1	"Recent sand"	**Rice Bay Formation** Hanna Bay Mbr North Point Mbr	Unnamed Holocene	**Rice Bay Formation** East Bay Mbr[2] Hanna Bay Mbr North Point Mbr	**Rice Bay Formation** Hanna Bay Mbr[4] North Point Mbr
PLEISTOCENE	3	**Grahams Harbour Limestone**	no deposits recognized	'Granny Lake' Oolite	no deposits recognized	(no positively identifiable deposits of these ages)
	5a		**Grotto Beach Formation** Dixon Hill Mbr[2]	**Dixon Hill Limestone**[2]	**Almgreen Cay Formation**[2] Upper Mbr Lower Mbr	
	5e	**Grotto Beach Limestone**	Cockburn Town Mbr French Bay Mbr	**Grotto Beach Limestone**	**Grotto Beach Formation** Fermandez Bay Mbr[2] Cockburn Town Mbr French Bay Mbr	**Grotto Beach Formation** Cockburn Town Mbr[5] French Bay Mbr
	7, 9, 11, or earlier		**Owl's Hole Formation**	Unnamed Pre-Sangamonian	**Fortune Hill Formation**[2] **Owl's Hole Formation**	**Owl's Hole Formation**[6]

[1] Titus recognized the Grahams Harbour and Grotto Beach limestones only as Pleistocene, and he considered them to lie on an unnamed pre-Pleistocene biomicrite.
[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 Femandez Bay Mbr by Hearty & Kindler, 1993
[6] Includes rocks assigned to Fortune Hill Fm by Hearty & Kindler, 1993

been modified with the accumulation of new data (Carew and Mylroie 1989b; 1994a; 1995a; 1995b; Carew et al. 1992), and possible refinement of the stratigraphy was provided by Hearty and Kindler (1993) using morphostratigraphy and amino acid racemization (AAR) geochronology. In our opinion, Hearty and Kindler's (1993) suggested modifications suffered from an inadequate sampling regime and questions about the validity of the AAR analyses and morphostratigraphy (Carew and Mylroie 1994b; 1995d). The stratigraphy of Bahamian surficial geology (Carew and Mylroie 1985; 1995a; 1995b) is based on field relationships, and does not require the use of geochronological information (Fig. 3). However, this stratigraphy has been subsequently substantiated by a number of geochronologic methods (e.g., Carew and Mylroie 1987a; Boardman et al. 1987). The various stratigraphies developed for San Salvador and the Bahamas are compared in table 1. Our geologic map of San Salvador is presented in figure 4.

Stratigraphy

All Pleistocene eolianites older than oxygen isotope substage 5e comprise the Owl's Hole Formation, because these eolianite packages cannot be separated based on field criteria (Carew and Mylroie 1994b; 1995a; 1995b). As noted earlier, there are no subtidal units of this formation exposed above current sea level. Generally the eolianites of this unit are predominantly peloidal or bioclastic, and ooids are absent or 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 late Pleistocene Grotto Beach Formation. This formation was deposited during the oxygen isotope substage 5e highstand (circa 125,000 years ago). Locally it can be divided into two members. The French Bay Member consists of transgressive-phase eolianites (Carew and Mylroie 1985; 1989b; 1995a). In some places, these transgressive-phase eolianites are marked by a coeval erosional platform on which stillstand-phase fossil corals are found (Carew and Mylroie 1989a; 1995a; 1995b; Halley et al. 1991). The Cockburn Town Member is a complex arrangement of stillstand-phase subtidal and intertidal facies sometimes over-

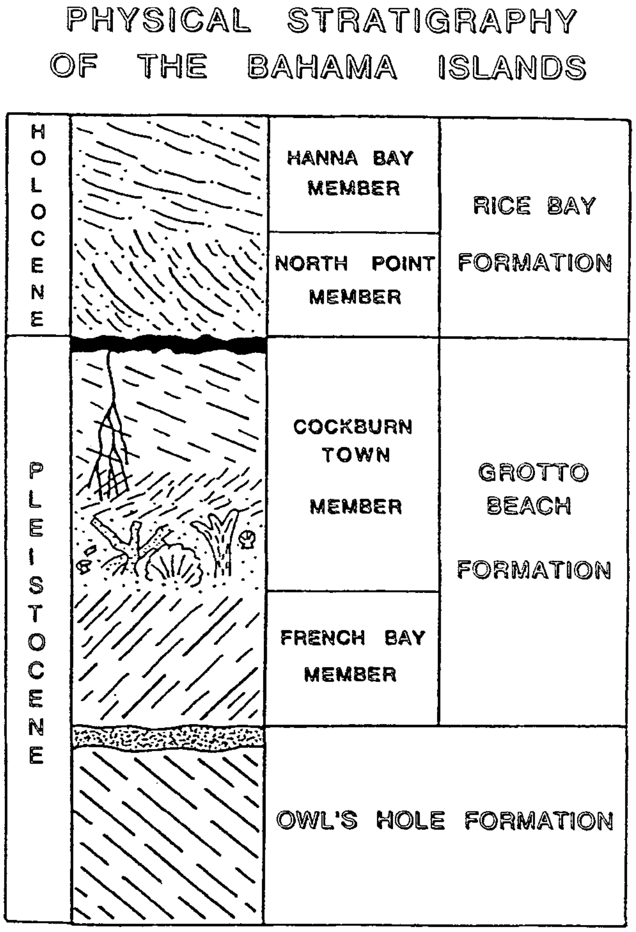

Figure 3. Physical stratigraphic column illustrating the temporal relationship between defined stratigraphic units. In the field, individual units are not necessarily seen stacked atop one another, but are often lateral to one another. The thin stippled and black layers are terra rossa paleosols, and they separate deposits formed during separate glacio-eustatic sea-level highstands.

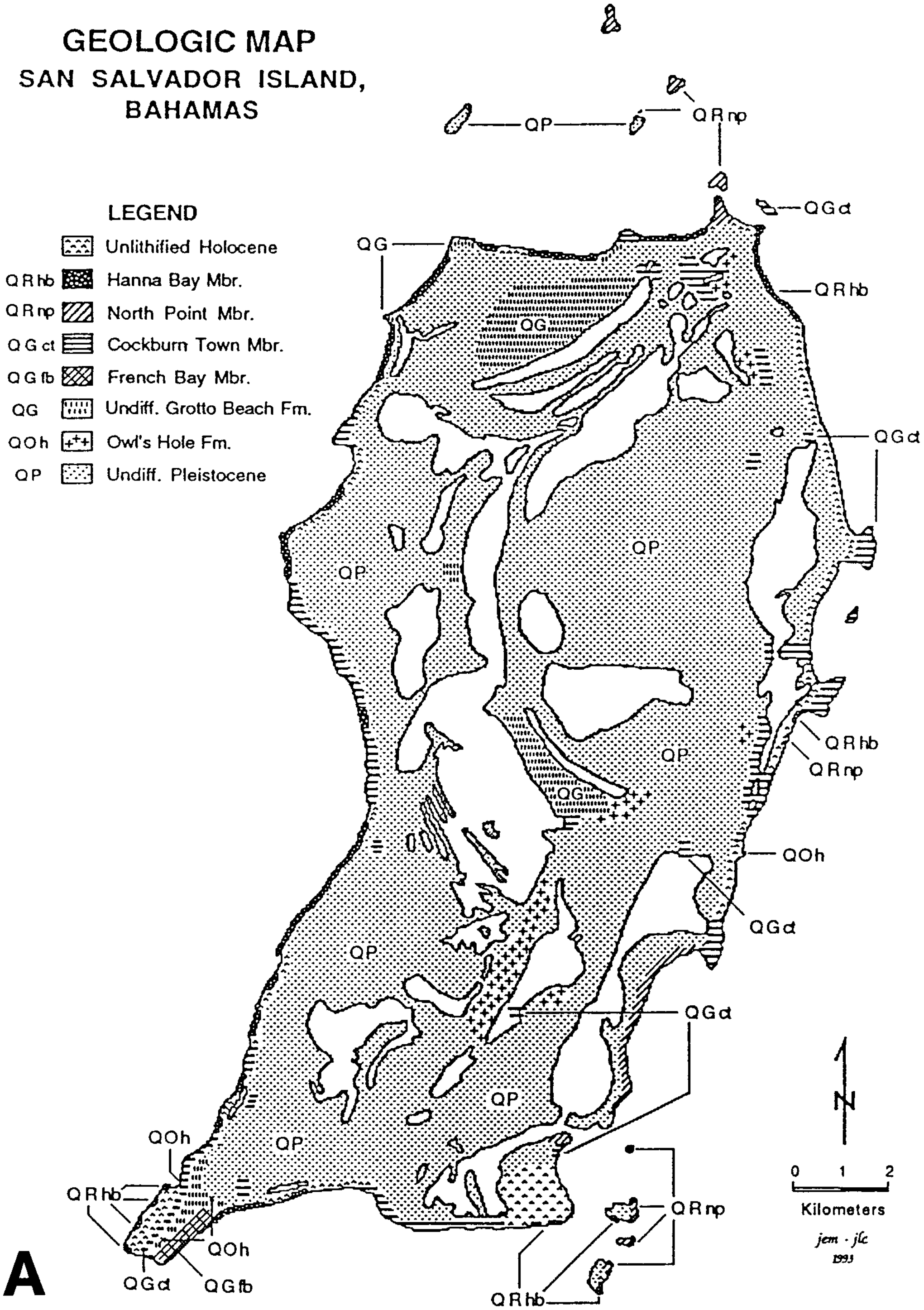

Figure 4. Part A, Geologic map of San Salvador Island, Bahamas. The patterns shown along the coast of the island represents the rock units exposed along that portion of the shore. The width of the pattern is necessary to depict the distribution of the various rock units, but it does not necessarily reflect the actual distributive width of those rocks. For example, in many places Pleistocene deposits are found immediately inland of Holocene rocks that form a thin outcrop along the shore. This map depicts only information that the authors actually have seen and where the unit assignment is supported by field and petrologic relationships. Because of the complexities that exist among paleosols and various deposits, there is no extension of the data into areas where the authors have not, or cannot, definitively determine the appropriate stratigraphic unit. Thus, much of the island is mapped as undifferentiated Pleistocene. Those rocks may belong to either the Owl's Hole Formation, or Grotto Beach Formation. See Carew and Mylroie (1995a; 1995b) for a review of the complexities of geologic mapping in this setting.

lain by regressive-phase eolianites. During "Grotto Beach time" throughout the Bahamas 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.

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 eolianites deposited during oxygen isotope substage 5a about 85,000 years ago. This member was incorrectly based solely on amino acid racemization (AAR) data (Carew et al. 1984), since brought into question (Mirecki et al. 1993). No field relationships establish this unit as a substage 5a unit, and the Dixon Hill has therefore been eliminated from the stratigraphy (Carew et al. 1992; Carew and Mylroie 1995a). We now recognize that the rocks of Dixon Hill consist of Owl's Hole Formation eolianites mantled by younger Grotto Beach Formation eolianites (Schwabe et al. 1993). Hearty and Kindler (1993) report AAR values for some deposits on San Salvador that suggest a substage 5a age, but these data are not as yet substantiated by field relationships (Carew and Mylroie 1994b; 1995d).

Overlying the Grotto Beach Formation, and separated from it by a paleosol or other erosion surface is the Holocene Rice Bay Formation. In places, the Rice Bay Formation can be divided into two members based on their depositional history relative to Holocene sea level. The North Point Member consists entirely of eolianites with foreset beds that commonly extend at least 2 m below modern sea level. Whole-rock ^{14}C measurements from the North Point Member indicate allochem ages centered around 5,000 yBP (Carew and Mylroie 1987a; 1995a). These data indicate that by 5,000 years ago, the platform top was partially flooded, in order to produce the carbonate sediment, but sea level had not yet reached its modern elevation. Laterally adjacent, but rarely in an overlying position, is the younger Hanna Bay Member. This unit consists of intertidal through eolian facies deposited in equilibrium with modern sea level. Whole-rock radiocarbon ages for the Hanna Bay Member range from approximately 3,300 yBP to 400 yBP, with an average age less than 2,500 yBP (Carew and Mylroie 1987a; 1995a; Boardman et al. 1987). While weakly-developed ooids have been reported from the early stages of North Point Member deposition (Hutto and Carew 1984; Carney and Boardman 1991; White and White 1991), the Rice Bay Formation is predominantly peloidal and bioclastic on San Salvador (Holocene ooids are common in some locales in the Bahamas, e.g. Joulter Cays). The North Point Member rocks have been or currently are being attacked by wave erosion, and sea caves, inland cliff-line talus, and coral-encrusted wave-cut benches of the North Point Member exist. Similar relationships can be seen in the transgressive-phase French Bay Member of the late Pleistocene Grotto Beach Formation, as mentioned above. The age of the allochems in the North Point and Hanna Bay members, in conjunction with the bedform relationships to modern sea level, indicate that sea level reached its modern elevation sometime between 5,000 and 3,000 years ago or later.

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. Surface karst landforms such as sinking streams, blind valleys, and tower karst are absent. The karst features of the Bahamas fall into four main categories: karren, depressions, caves, and blue holes.

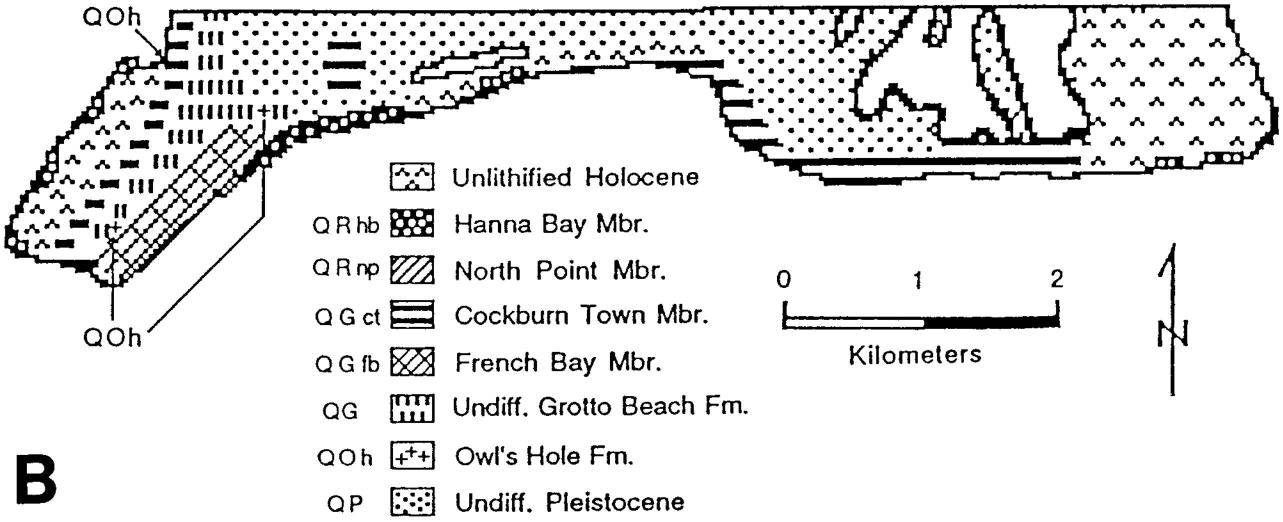

Figure 4. Part B, enlargement of the south coast of San Salvador illustrating the complexity of the geology there, which may be hard to discern on Part A (Carew and Mylroie, 1995a).

Karren

Karren comprise dissolutional sculpturing at the centimeter to meter scale that are part of the epikarst, the surface weathered zone on limestones. The epikarst consists of soil and loose blocks of limestone, which over a vertical distance of usually less than a meter grade into solid rock that is dissolutionally etched, and fretted with numerous small holes and tubes. Within a few meters, these holes and tubes in turn consolidate into widely-spaced discrete flow paths that transmit water downward into the rock mass.

Karren include a variety of etched and fretted surfaces; on exposed surfaces this etching is sharp and jagged, whereas on soil-mantled surfaces it tends to be smooth and curvilinear. Coastal karren, improperly called phytokarst, commonly occurs in coastal areas that are wetted by sea spray. While biological activity plays an important part in coastal karren development, its role has been overstated (Viles 1988).

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 dissolution. The influence of climate on depression development on carbonate islands is reviewed by Vacher and Mylroie (1991). In the Bahamas, these large constructional depressions originated as swales between eolianite (dune) ridges or other deposits. Depressions that extend below sea level contain lakes with salinities ranging from fresh to hypersaline. Lake water salinity depends on the water budget of a given island, lake surface area, and subsurface hydrology. On San Salvador, yearly evapotranspiration exceeds precipitation, so the lakes suffer an annual net loss of water. This negative water budget causes the underlying marine water to upcone, and further evaporative losses make the lakes hypersaline (Vacher and Mylroie 1991; Mylroie et al. 1995). Some of these water-filled constructional depressions are linked to caves that connect to the sea (Davis and Johnson 1989). In those lakes, tidal pumping causes exchange of waters that keeps some of these lakes at or near normal marine salinity ($35^{\circ}/_{oo}$). Lake margins are little modified by dissolutional processes when lake waters are hypersaline, or fluctuate from marine to hypersaline.

Caves

There are four main types of caves in the Bahamas: pit caves, flank margin caves, banana holes, and lake drains. The relationships between pit caves, flank margin caves, and banana holes are shown in figure 5. Pit caves are formed as a result of dissolution by descending meteoric water collected in the epikarst (Pace et al. 1993; Mylroie and Carew 1995; Mylroie et al. 1995). Pit caves are vertical shafts with a width to depth ratio less than one that often descend in a stair-step fashion, with occasional small lateral chambers. They are rarely open all the way to the fresh-water lens. Pit caves are located preferentially on Pleistocene eolianite ridges, and are not found in Holocene rocks.

Flank margin caves are formed in the distal margin of a fresh-water lens located under the flank of an eolianite ridge. At that location fresh water and sea water mix to produce dissolutionally-aggressive brackish water. Flank margin caves are found primarily in rocks of pre-Grotto Beach age (Schwabe et al. 1993), and are absent from Holocene rocks. These caves are discussed more completely in the up-coming section on fresh-water lens hydrology and karst processes.

Banana holes are isolated globular chambers that dissolved at the top of a past fresh-water lens. Many of those with thin roofs have collapsed to produce small depressions that collect soil and provide excellent conditions for growing specialty crops such as bananas, hence the name given to them by Bahamians. Banana holes have a width to depth ratio greater than one, and are found primarily on lowland plains at elevations of 2 to 7 m, in a variety of Pleistocene facies (eolianites, lagoonal deposits, etc.). A thorough discussion of banana hole development is included in this volume (Harris et al. 1995).

Lake drains are 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 would otherwise favor either fresh-water lakes, such as in the northwestern Bahamas, or hypersaline lakes, such as in the more arid southeastern Bahamas (including San Salvador). Unlike flank margin caves and banana holes, lake drains are true conduits. Their mode of origin is not well understood, but their influence is important (Davis and Johnson 1989). Pleistocene lagoon and lacustrine deposits indicate that lake drains may have been active during the oxygen isotope substage 5e sea-level highstand (Hagey and Mylroie 1995).

Blue Holes

Blue holes are flooded karst features of polygenetic origin. They are vertical shafts that extend below sea level for a majority of their depth and have a width to depth ratio less than one. The name is derived from the distinctive dark blue color of these water-filled features. Blue holes are divided into two types (Burkeen and Mylroie 1992): 1) ocean holes that open directly into a lagoon or the ocean, are tidally influenced, and contain only marine water; and 2) inland blue holes which open onto the land surface or isolated pond or lake, may be tidally influenced, and exhibit surface water chemistries from fresh to marine. Inland blue holes commonly contain surface fresh water (especially in the northwest Bahamas) overlying marine water. The transition from fresh to marine water may be a sharp or gradational halocline.

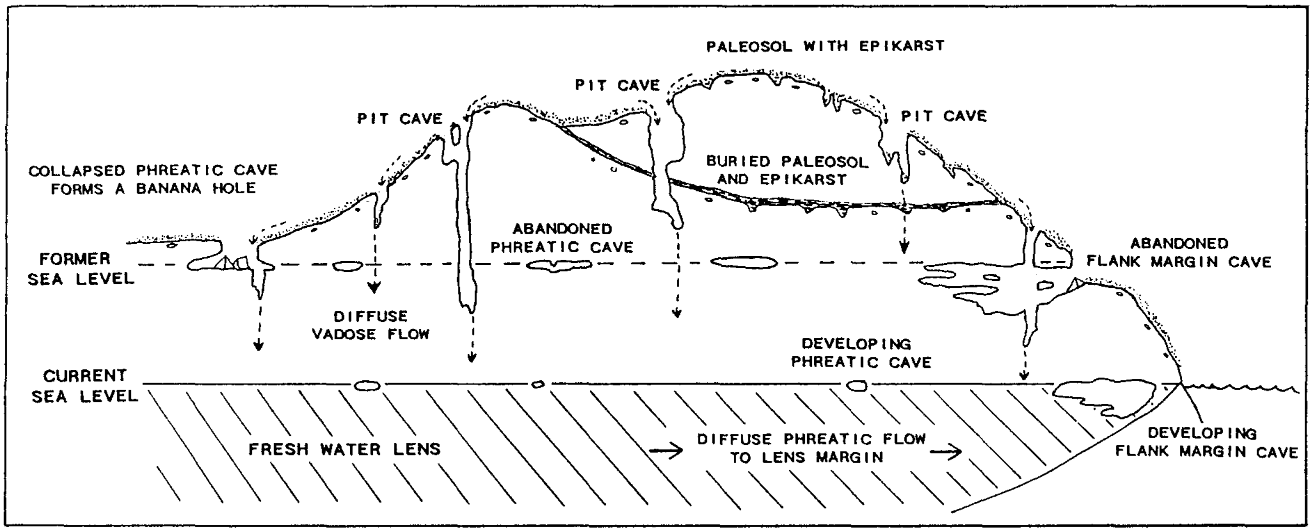

Figure 5. Diagrammatic representation of the freshwater lens within a Quaternary carbonate island, showing epikarst, pit caves, banana holes, and flank margin caves. Former versus current sea level positions, and the resultant products, shown (from Mylroie et al. 1995)

Blue holes have developed in a variety of ways. Some are pit caves that formed during sea-level lowstands and which are flooded during sea-level highstands like at present. Others occur where failure of the steep margins of the Bahama banks produces bank-margin fractures. Along these fractures enlarged gaps can result in blue holes (Palmer 1986; Carew and Mylroie 1989a; Carew et al. 1992). Still others result by stoping from large dissolutional voids at depth that were produced during sea-level lowstands, or voids produced during pre-Pleistocene highstands that are now at depth as a result of platform subsidence. Some blue holes open laterally into horizontal cave systems at a variety of depths. Some of these blue hole-to-cave connections appear to be the result of random intersection of pre-existing caves by the blue hole. The history of the term "blue hole", and its application to various subaqueous karst features, is reviewed in another paper in this volume (Mylroie et al. 1995).

Sea Level and Landform
Origin: Construction Versus Dissolution

The landforms of the islands of the Bahamas have origins that are dependent on the position of sea level at their time of formation. During sea-level highstands, abundant carbonate sediments are formed. Some of those sediments are deposited as eolian dunes, and the intervening swales form the constructional depressions. Banana holes and flank margin caves develop in the fresh-water lens, the position of which is tied to sea level (Fig. 5). When sea level falls, carbonate deposition stops, and phreatic caves above sea level are drained. Banana holes and flank margin caves that are dry today formed during the last interglacial, circa 125,000 years ago, when sea level and the fresh-water lens were about 6 m higher than today. Far below modern sea level, blue holes often connect to banana holes and flank margin caves that formed when sea level was much lower than today (Carew and Mylroie 1987b). Pit caves, karren, and epikarst form on the subaerially exposed portions of the platforms during sea-level highstands, and on the entire platform surface when sea level is low and the platforms are completely exposed.

Freshwater Lens Hydrology and Karst Processes

In any essentially homogeneous body of rock like that of the Bahama islands, the fresh-water lens floats on underlying denser sea water that permeates the subsurface. The model for the ideal behavior of these water masses is the Ghyben-Herzberg model. In reality, however, variable rock permeability and other factors result in distortion of that ideal lens shape (Vacher and Bengtsson 1989). None-the-less the Ghyben-Herzberg model serves as a useful first approximation of the relationship between the fresh water and the underlying marine groundwater in an island. A diagrammatic representation of a fresh-water lens and relevant karst features is shown in figure 5.

During past higher stands of sea level, the fresh groundwater lens in each island was as high or higher than it is today. Beneath the surface of those past fresh-water lenses, in the phreatic zone, flank margin caves and banana holes were produced by dissolution. Because of a past sea level higher than at present, we can enter dry phreatic caves today in the Bahamas. In contrast, the blue holes of the Bahamas commonly lead into caves that are now flooded, both represent the cumulative dissolution 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, fresh-water, and subaerial conditions during the Quaternary or longer.

Conversely, the currently dry flank margin caves and banana holes of the Bahamas formed during the relatively short times of the late Pleistocene when sea level was higher than at present. Any flank margin caves that formed above modern sea level elevation before oxygen isotope substage 5e have, by today, isostatically subsided below modern sea level (Mylroie et al. 1991; Carew and Mylroie 1995c; Mylroie et al. 1995). Taking isostatic subsidence into account, sea level was high enough to produce the observed subaerial caves for a maximum of about 15,000 years of the oxygen isotope substage 5e highstand (Mylroie et al. 1991; Carew and Mylroie 1995c). In addition, in the Bahamas during that sea-level highstand, only the eolian ridges and a few beach and shoal deposits stood above sea level, and island size was dramatically reduced compared to today's islands. As a consequence, fresh-water lens volumes and discharges were comparably reduced. Thus, the dry flank margin caves and banana holes represent development during a very short time period within small fresh-water lenses, and they have been affected by minimal overprinting from later dissolutional events. Any model that attempts to explain development of these caves must operate under these severe constraints of time, water budget, and space.

Even though the marine groundwater and the fresh-water (or brackish-water) lens may both be saturated with $CaCO_3$, where they mix, the resultant chemistry often permits more $CaCO_3$ to be dissolved (Plummer 1975). The potency of this dissolution mechanism has been demonstrated in the Bahamas (Smart et al. 1988). Therefore, it is evident that caves should develop preferentially at the bottom of the fresh-water lens, in the mixing zone or halocline. Small caves may also form at the top of the fresh-water lens (or water table) where vadose water percolating down from the surface

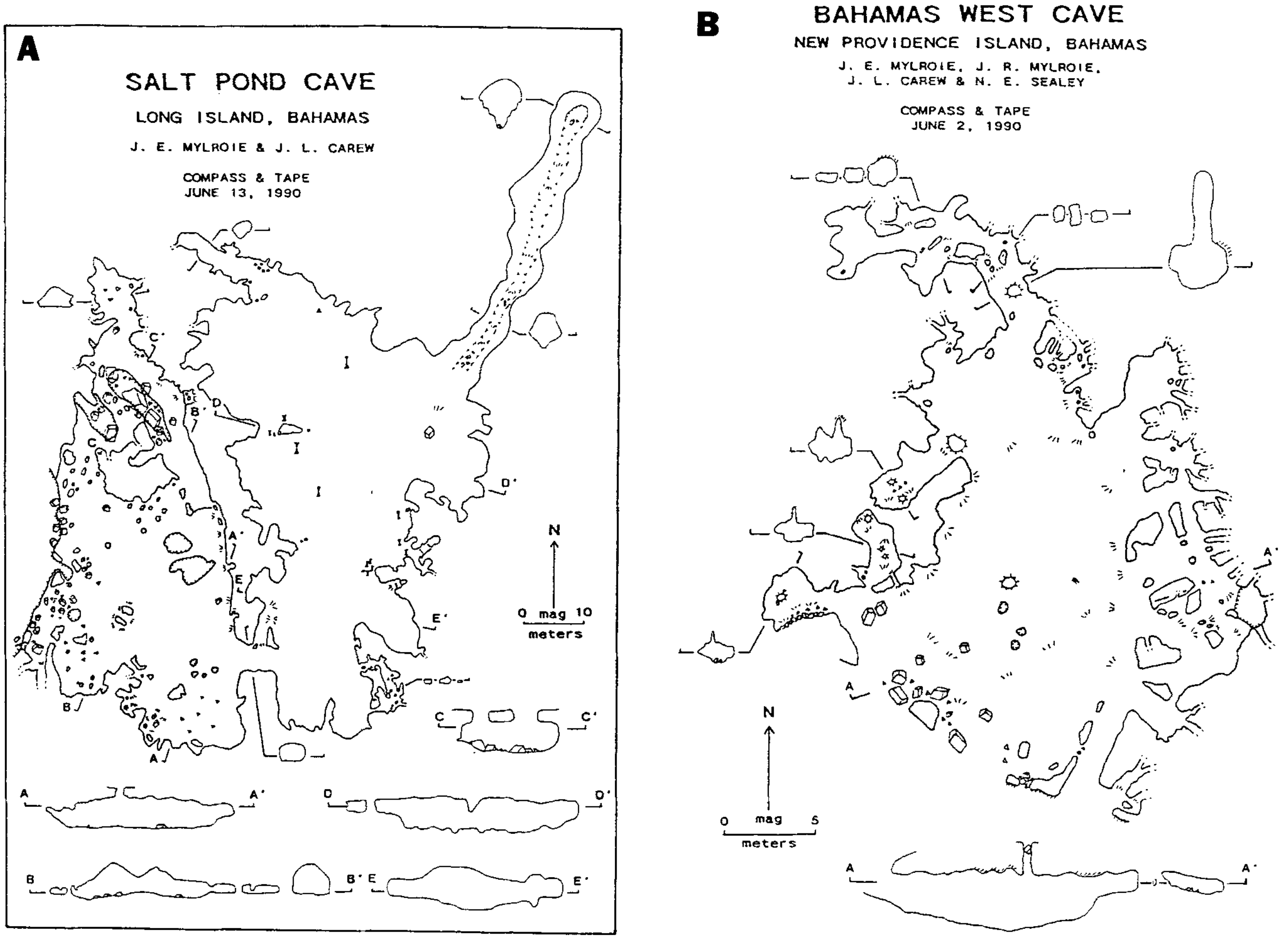

Figure 6. Maps with cross sections of Bahamian flank margin caves. Part A, Salt Pond Cave, Long Island, and Part B, Bahamas West Cave, New Providence Island, Bahamas. The maps show typical flank margin cave development which includes a large central chamber, or chambers, with maze-like passage development toward the interior of the ridge containing them. Surficial erosion and collapse provide entry into the caves. Note the many isolated bedrock pillars and thin rock partitions separating some passages and chambers, and the abrupt termination of some passages that trend into the ridge. Hachured lines indicate connections of the caves to the surface; rectangular blocks and open triangles indicate areas of collapse debris; solid triangles joined at their apex indicate stalactites and stalagmites; sets of three short diverging lines indicate a slope, downward in the direction of divergence (from Mylroie et al. 1991).

mixes with the fresh-water lens (Mylroie and Carew 1988; Mylroie et al. 1995).

At the distal margin of the lens, near the shoreline of an island, the vadose/phreatic mixing zone and the marine/fresh-water mixing zone are superimposed (Fig. 5). It is in this setting, at the distal margin of past fresh-water lenses, just under the flank of the eolian ridges, that were at that time individual islands, that the largest subaerial caves of the Bahamas were formed. These caves are referred to as flank margin caves (Mylroie and Carew 1990). Kinetic dissolution models (Sanford and Konikow 1989) indicate that in small islands like San Salvador it should not be possible to produce large dissolution voids in the short time frame (15,000 years) and limited water budgets mentioned above. Recently, microbial activity has been suggested as a means to help overcome these constraints (Mylroie and Balcerzak 1992; Bottrell et al. 1993). The collection of organic matter on density interfaces at the top of the fresh-water lens, and at the halocline, provides the substrate necessary for bacteriological processes that create anoxia and subsequent redox reactions. These reactions result in increased dissolution (Bottrell et al. 1991).

Flank margin caves have a limited variety of morphologies. They consist of 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. Small radiating tubes extend from these large chambers into the ridge interior where they end abruptly. Many cave passages loop back into one another or into the main chamber, and isolated bedrock pillars and thin wall-partitions are common (Fig. 6). The radiating passages represent individual diffuse flow paths that delivered fresh water into the mixing area. The abrupt end of these passages reflects the position of the mixing front when sea level fell and the caves became subaerial (Mylroie and Carew 1990; 1995). An 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. Erosion of these flank margin caves can leave reentrants on hillsides that may appear to be abandoned bioerosion notches (Mylroie and Carew 1991).

The general morphology of flank margin caves is similar to that of other caves formed under different mixed-water conditions (Mylroie 1991), such as that of 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 fresh-water lens, cave development, and the flank margin model can be found in Mylroie (1988), Mylroie and Carew (1988), Mylroie and Carew (1990; 1995), Vogel et al. (1990), Mylroie (1991), and Mylroie et al. (1991; 1995).

PALEOKARST AND QUATERNARY CARBONATE ISLANDS

All the Bahama islands are composed of late Quaternary carbonates. The bulk of those carbonates consist of the Grotto Beach Formation, which was deposited during the last interglacial circa 125,000 years ago (the Sangamon interglacial, correlated with oxygen isotope substage 5e), and the older Owl's Hole Formation rocks that almost certainly were formed less than 500,000 years ago. Despite the extremely young age of the rocks, there is a well-developed paleokarst landscape. All flank margin caves and banana holes above sea level today are paleokarst; the banana holes especially are abundant. Many of the pit caves are also abandoned and represent paleokarst (Pace et al. 1993). The blue holes are paleokarst, although today they may play an important role in island hydrology. The paleosols are fossil soils; so the epikarst they overly is also fossil, or paleokarst.

The abundant paleokarst of diverse origin that is found on today's young carbonate islands, such as San Salvador, indicate that karst forms quickly over wide areas. Therefore we should expect it to be present in the rock record, providing that conditions for preservation, such as subsidence and burial, exist. Mylroie and Carew (1995) present arguments that paleokarst produced early in carbonate deposition may be responsible for a significant portion of the paleokarst seen in the rock record today in many continental settings. We do not suggest, however, that this "early" paleokarst is the sole, or even the majority, of the paleokarst in the continental record. The purpose of this paper, and of the Paleokarst Field Conference itself, was to point out one end member of paleokarst development.

Paleokarst is important as a potential hydrocarbon reservoir, such as seen in the Yates field in Texas (Craig 1988). Paleokarst is also implicated in the formation of ore bodies in carbonates (Ford and Williams 1989). Paleokarst may be reactivitated as part of modern hydrologic regimes, especially in terms of hypogenic paleokarst. By examining what can happen in very young carbonates in a very short period of time, the studies from San Salvador Island and the Bahamas may help in understanding paleokarst in a variety of settings.

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