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INVESTIGATION AND REVIEW OF DISSOLUTION FEATURES ON SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

Subaerial dissolution cavities are found throughout The Bahamas. They can be placed into three categories: flank margin caves, pit caves, and banana holes. Flank margin caves are now understood, but the origin of pit caves and banana holes is still debatable. Pit caves are found at higher elevations along dune ridges and have a depth to width ratio >1. Banana holes are found at lower elevations and have a depth to width ratio <1. Three areas on San Salvador Island were chosen for study of these features: The Line Hole area represents a low lying plain that has been affected by past sea-level highstands and, hence, fresh-water lens position, and many banana holes are found in this area; Great Lake dune ridge is in the interior of the island, the bulk of the ridge is above any past sea-level highstand, and several pit caves are found on the ridge; Sandy Point dune ridge is in a coastal region also above any past sea-level highstand, previous surveys have documented pit caves in the area and additional pit caves were located and tied into the existing survey.

Petrologic analysis of wall rock samples has revealed that both pit caves and banana holes formed in öolitic rock. Two pits at Sandy Point penetrate from öolitic rock into a blower bioclastic unit. X-ray diffraction analysis of rock samples from the three areas showed that the wall rock of pit caves and banana holes is composed mainly of calcite with some remaining aragonite. Dolomite is absent.

Formation of pit caves is by concentration of meteoric water by surface and subcutaneous channelization. Banana holes are formed by roof collapse into small phreatic chambers formed at an ancient vadose-phreatic interface of the fresh-water lens during a past sea-level highstand.

INTRODUCTION

Caves are found throughout The Bahamas. The majority of caves on San Salvador Island can be placed into one of three categories: flank margin caves are found in the flanks of dune ridges and usually consist of a main chamber with smaller passages that lead into the dune only to end abruptly; pit caves are found at higher elevations along dune ridges and are deeper than they are wide; banana holes are found at lower elevations, are usually wider than they are deep and sometimes have an overhanging rim, thus producing some cave passage. (Mylroie, 1988; Pace and others, 1992).

In addition to those above, there are also cavities found along the coast of San Salvador in a variety of configurations, with blowholes and other voids consistent with coastal processes. Another type of cave is termed the "paleosol cave" (Mylroie, 1988). Paleosol caves are voids where resistant paleosols compose the roof of a cave excavated in the weaker underlying limestone, usually by coastal processes.

Many studies have centered on the correlation of fresh-water lens hydrology and dissolutional processes with respect to the genesis of horizontal caves (Carew and others, 1982, Palmer and Williams, 1984; Mylroie and Carew, 1988, 1990; Smart and others, 1988; Smart and Whitaker, 1989; Vogel and others, 1990; Mylroie and others, 1991). As these features are found in late Pleistocene rocks, the karst processes which produced them were necessarily rapid. The purpose of this investigation was to define, catalog, characterize, and determine the genetic history of pit caves and banana holes.

GEOLOGY OF SAN SALVADOR ISLAND

San Salvador Island is approximately 11 km wide and 19 km long. The island is fringed by a narrow shallow shelf which ranges from 0.2 km to 5.6 km in width and is covered by up to 15 m of water. The shelf edge breaks sharply to near vertical to water depths greater than 2000 m on the west and south, whereas the upper part of the slope is steep, but somewhat more ramp-like on the east side of the island.

Depositional events on San Salvador have been tied to sea-lèvel position (Carew and Mylroie, 1985). During times of sea-level highstands when portions of the bank are subaqueous, $CaCO_3$ precipitates and produces the sediment source for deposition. During sea-level lowstands, no sediment is produced, deposition ceases, and erosional processes dominate.

Several different rock types comprise the subaerial geology of San Salvador. They range from subtidal deposits, including fossil reef structures, to intertidal and supratidal facies including eolian dune ridges. The rocks are Pleistocene and Holocene in age. Paleosols are common on all Pleistocene rocks.

The topography of San Salvador Island is dominated by a series of Pleistocene eolian ridges. Holocene eolian ridges are common on the east coast. These dune ridges reach a maximum of 40 m in height; however, the majority are between 10 and 20 m. The composition of the ridges is variable. Using petrologic analysis, Schwabe and others (this volume) recognize four categories of Pleistocene dune ridges. They are: öolitic, bioclastic, lower bioclastic gradational to öolitic, and lower bioclastic unconformably overlain by öolitic. Basal portions of some Holocene ridges contain superficial öoids, but Holocene dunes are dominated by bioclastic material (Carew and Mylroie, 1985; Boardman and others, 1991). Shallow saline and hypersaline lakes occupy the low areas between many of the dune ridges. These lakes have no direct surface connection to the ocean, but many of them are connected to the ocean by karst conduits, and to each other by natural or man-made canals (Davis and Johnson, 1989; Winter, 1992). The ocean shoreline consists of rocky headlands and sandy beaches which often contain Holocene beachrock.

The stratigraphy of San Salvador has been extensively studied, and a current working stratigraphic column has been developed (Carew and Mylroie, 1985; 1991). The Owl's Hole formation is the lower of two Pleistocene formations and comprises the oldest subaerial rocks on San Salvador and, possibly, throughout The Bahamas. It is a bioclastic eolian deposit. Very few öoids are present in these rocks. The Owl's Hole Formation is currently thought to be about 220,000 years old or older (Carew and Mylroie, 1991). The Owl's Hole is capped by a paleosol that separates it from the overlying Grotto Beach Formation. The Grotto Beach is divided into two members. The French Bay Member is a fossiliferous öosparite deposited as transgressive beach, back beach and eolian deposits. The Cockburn Town Member consists of subtidal sands, coral reefs covered by regressional subtidal reef-fill, beach, back-beach and regressive eolianite deposits. Fossil corals from this formation yield U/Th ages of 131,000 to 119,000 years. (Chen and others, 1991) which is consistent with deposition during oxygen isotope substage 5e. All Grotto Beach rocks are capped by a paleosol. This paleosol marks the Pleistocene/Holocene boundary. The Holocene is represented by the Rice Bay Formation. The Rice Bay is also divided into two members. The North Point Member is a transgressive eolian pelsparite. The Hanna Bay Member includes all rocks deposited in association with present-day sea level and consists of beach and back-beach eolianites and modern beachrock. The Rice Bay formation is not covered by a paleosol. Whole rock ^{14}C dates indicate that the North Point sands formed about 5,300 years ago, and the Hanna Bay sands about 3,600 years ago, (Carew and Mylroie, 1987).

HYDROLOGY OF SAN SALVADOR ISLAND

In The Bahamas, the porous limestone which dominates the lithology of the islands also controls the type and size of the fresh-water lens. Fresh-water recharge quickly infiltrates through these porous rocks and is perched upon and displaces saline ground water below because of the difference in water densities. The result is a water table which generally obeys the principles of the Ghyben-Herzberg model. The fresh-water / salt-water interface is commonly referred to as the halocline or mixing zone. As the fresh/salt water boundary can be abrupt, with no mixing involved, the term halocline is used herein, as it properly identifies the change in salinity. The height of the fresh-water lens above sea-level is approximately 1/40th of the total thickness of the fresh-water lens, and reflects the 1 part in 40 density contrast of fresh and salt water. Any differences in porosity and permeability do not effect the 1 to 40 relationship.

The Ghyben-Herzberg model is an idealized model that depicts an oversimplified description of the fresh-water lens in a carbonate environment. Many other factors such as porosity and permeability variations in the bedrock, karst features, amount of fresh-water input, lakes, coastline configuration, and dune structures control the actual size and geometry of any carbonate island fresh-water lens (Wheatcraft and Buddemeier, 1981; Ayers and Vacher, 1986; Davis and Johnson, 1989; Vacher and Bengtsson, 1989). The fresh-water lens on San Salvador is partitioned by interior saline and hypersaline lakes with the larger portions of the lens located under dune ridges (Davis and Johnson, 1989).

KARST OF SAN SALVADOR

The results of karstification processes are very prominent throughout The Bahamas. San Salvador Island has several types of karst features. Mylroie (1988) placed these into five different categories which are: coastal phytokarst, inland karst, horizontal solution conduits, blue holes, and depression karst. This study redefines the karst features into four categories which are: blue holes, karren, horizontal karst, and vertical karst.

Re-examination of Depression Karst

The Mylroie (1988) classification included the term "depression karst" which included closed contour depressions at various scales. Banana holes and pit caves were included in this category, but now have been reclassified into the categories of horizontal and vertical karst as outlined below. The other features included in this category were the depressions visible on topographic maps. These large-scale features of "depression karst" have been investigated and have been found to be constructional in origin. That is, they represent inter- and intra-dune swales and abandoned lagoons behind fossil reefs (Mylroie, 1990; Vacher and Mylroie, 1991). On San Salvador, such constructional depressions have not been affected much by dissolutional processes, unlike in Bermuda, because of the drier climate of the southeast Bahamas (Vacher and Mylroie, 1991). Hence, these large depressions are not considered karst and were not included in this investigation or classification.

Blue Holes

The Bahamas are famous for the blue holes that are found throughout the islands. They are usually characterized by pools, the level of which is controlled by tides, a depth to width ratio >1, and are found in the lagoons and in the interior of the islands (Burkeen and Mylroie, 1992). Salinities in the pools may be fresh, brackish, hypersaline, or marine. Some of the pools connect with complex cave systems while others end in sediment or collapse. The blue holes may result from upward stoping of deep dissolution conduits, fracture voids produced by incipient collapse of the bank margin, or pit caves formed during Pleistocene low sea levels that are flooded today (Mylroie, 1983; Burkeen and Mylroie, 1992). Blue holes were not included in this study as they are difficult to examine and represent the complex result of many sea-level changes.

Karren

The term karren describes a broad group of minor karst features (White, 1988). The karren on San Salvador can be divided into four categories: coastal, interior, paleosol, and Holocene. Much of the marine coastal shoreline of San Salvador possesses blackened, jagged, pitted pinnacles that are known as marine coastal phytokarst. These are found only in places where sea spray comes into contact with Pleistocene or Holocene limestone rock. It is thought that the genesis of these features is dependent upon the coexistence of chemical dissolution processes and the constructive and destructive processes of algae and other encrusting marine organisms and their predators (Viles, 1988). Many of the inland lake shorelines also posses a type of phytokarst known as lake shoreline phytokarst. This lake phytokarst, while not normally as well developed as marine phytokarst, is probably formed through similar processes. The variable salinities between the different lakes affect the genesis of these features.

Interior karst comprises those smaller karst features found in the interior portions of the island. This category includes small dissolution tubes and tube networks found along ridges and interior plains. It also encompasses small kaminitzas (small dissolution basins) and related rock etching. Some features are produced by rain fall directly on exposed rock surface, others by water flow through the patchy soil.

Paleosol karst is the remnants of a previous karst surface that has since been fossilized. As such, it is found associated with paleosols covering only the Pleistocene bedrock (Owl's Hole Formation and Grotto Beach Formation). Paleosols can be recognized by their light to dark - red colored, hard, micritic character. They also usually contain vegemorphs and burrows. The paleosol karst represents a fossilized interior karst surface, and dissolution features (karren) are draped and filled by paleosol material. Because paleosols represent past erosion surfaces, they are unconformities and play a key role in understanding island stratigraphy and history (Carew and Mylroie, 1985; 1991).

Holocene rocks (Rice Bay Formation) on San Salvador Island are easily identified by the lack of red micritic paleosol. Most outcrops of Holocene rocks are on the east and north sides of the island and show a karst development different from that on Pleistocene rocks. There are no obvious large karst features such as caves or dissolution cavities in Holocene rocks. Most outcrops are seen in sea cliffs and road cuts and show a macroscopic porosity that appears vuggy in some places and represents both chemical and mechanical removal of grains (Mylroie, 1988).

Horizontal Karst

Horizontal karst represents another type of karst found on San Salvador and is divided into two categories: flank margin caves and banana holes. Flank margin caves have been studied extensively (Mylroie, 1983; 1988; Mylroie and Carew, 1988; 1990; Vogel and others, 1990; Mylroie and others, 1991). Their origin is controlled by the placement of the fresh-water lens. The flank margin model (Mylroie and Carew, 1990) for the genesis of these caves suggests that the edge of the fresh-water lens is an area of intense dissolution. This is the result of the convergence of the two primary areas of dissolution in the fresh-water lens: the top of the lens and the halocline (Fig. 1). The upper portion of the fresh-water lens is where phreatic water from the lens mixes with vadose water. Even if both of these waters are individually saturated with $CaCO_3$, their mixing produces renewed chemical aggressivity for dissolution (Bogli, 1980). The second area of intense dissolution is the lower portion of the fresh-water or halocline. The halocline is the area where the $CaCO_3$ saturated fresh-water lens meets the $CaCO_3$ saturated salt water below. This boundary may be distinct or broad. Mixing of these waters produces a chemically complex brackish water that is capable of renewed aggressive dissolution (Plummer, 1975). These two areas of dissolution at the top and bottom of the lens meet at the margin of the lens, thus producing an environment with the highest rate of dissolution (Mylroie and Carew, 1990).

The resultant flank margin caves are found from 0 to +7 m above present sea level. They formed when sea level was higher than at present. They occur mostly in the flanks of Pleistocene dunes and are aligned with the dune axis (Fig. 2). Most contain a low elongate entrance that leads into a large central chamber or chambers. These voids are interpreted as the former position of the margin of the discharging fresh-water lens where dissolution was at a maximum (Mylroie and Carew, 1990). From this chamber(s), smaller passages lead into the dune only to suddenly end. Mylroie and Carew (1990) hypothesized that the passages leaving the back of the chambers represent sites of concentrated movement of water from the fresh-water lens toward the dune margin. The concentration of flow was produced by preferential movement along bedding planes and other heterogeneities in the dune. The dissolution front moved headward up these flow paths, but dissolution ended abruptly when sea level fell. Entrances to these caves formed after a lowering of sea-level and subsequent abandonment of the caves, by slope retreat which eventually breached the outer wall of the main cave chamber(s).

These caves originated during times of past high sea level; however, the exact means of formation seems to be rather complex. Studies of wall rock samples has revealed that marine phreatic, fresh-water phreatic, and vadose conditions have at one time or another, all existed within the caves (Vogel and others, 1990; Schwabe and others, this volume).

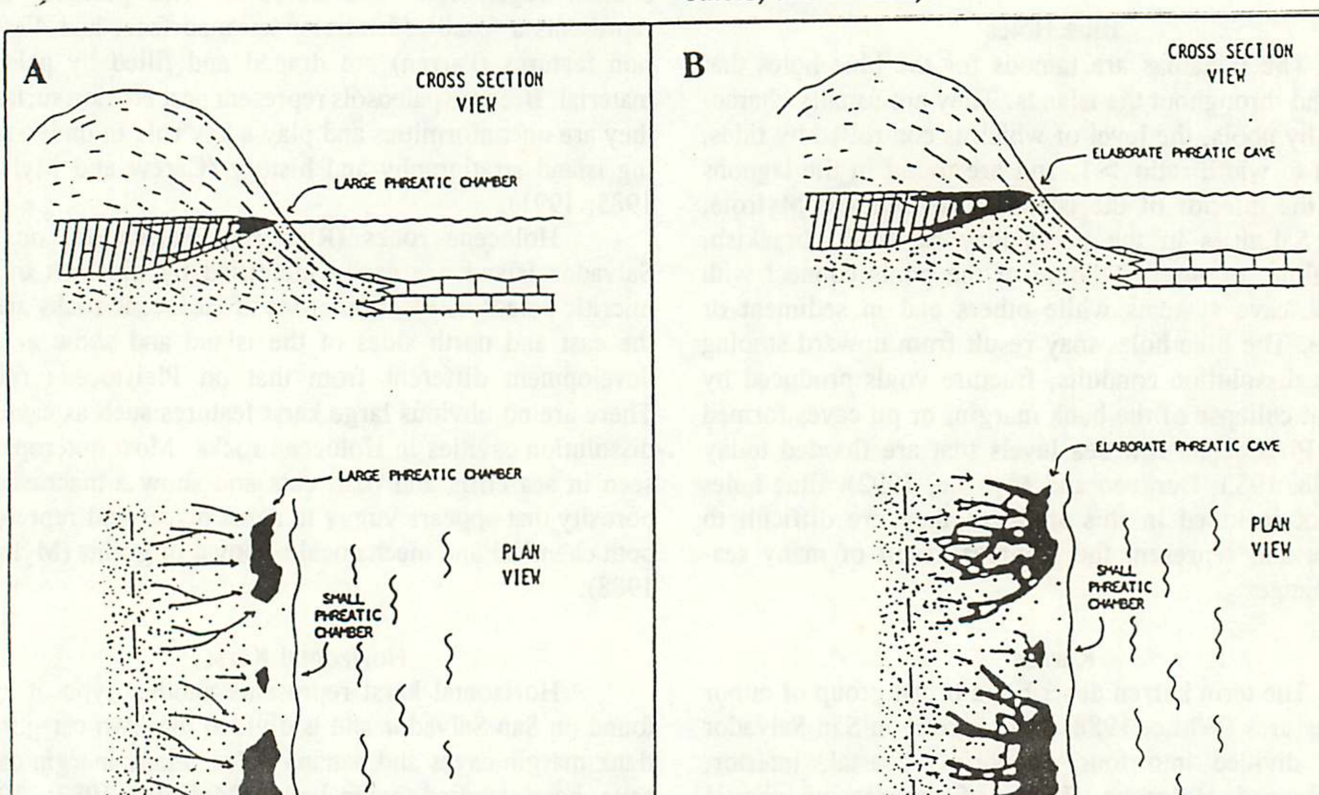

Figure 1 - A. Intense dissolution occurs at the discharging margins of the freshwater lens where the vadose/phreatic boundary and halocline converge. B. With time, the phreatic chambers enlarge and migrate into the dune along the incoming diffuse flow sources. (From Mylroie and Carew, 1990)

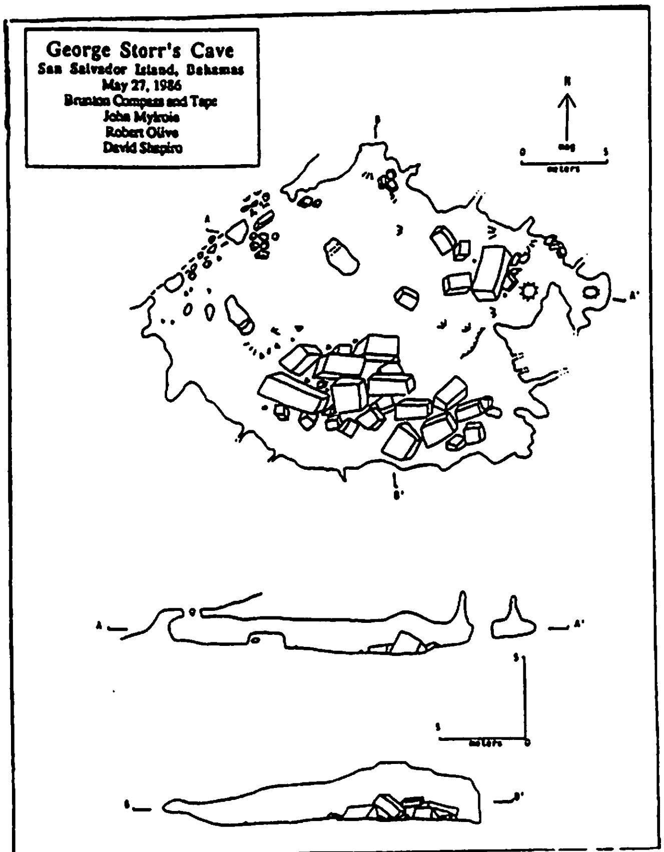

Figure 2 - A typical flank margin cave. Notice the thinness of the roof and potential to make a feature similar to a banana hole by collapse.

Dating of the rock in which these caves formed, by amino acid racemization of fossil *Cerion* sp. along with U/Th dates of subsequent speleothem formations, were used by Mylroie and Carew (1988) to estimate sea level position and duration during the Late Quaternary; however recent work (Mirecki and others, this volume) suggests that these amino acid data may be suspect. Rock samples from flank margin caves analyzed by XRD (Schwabe and others, this volume; Vogel and others, 1990), showed that 8 of 18 samples (44%) contained traces of dolomite, possibly reflecting the marine water and halocline influence on cave formation. The time window for cave formation appears limited to about 15,000 years centered on the oxygen isotope substage 5e highstand that occurred about 125,000 years ago (Mylroie and others, 1991; Carew and Mylroie, 1992). Recent work (Bottrell and others, this volume) suggests that biological factors may enhance cave dissolution.

Banana holes are found in areas below 7 m elevation, and are usually distant from the flanks of eolian ridges (Fig. 3). Their setting is, therefore, much different than that of flank margin caves. Banana holes often contain material collapsed into chambers. The collapse may be complete, producing a vertical-walled depression; or incomplete, leaving an overhung partial roof. The chambers are round to ovoid in plan and usually are no more than 12 m in diameter, with depths usually less than 4 m. They have a depth to width ratio less than 1. Small round dissolution pockets are often seen in the walls of banana holes. Banana Holes are named for the plant commonly cultivated in their rich soil bottoms.

Vertical Karst

Vertical karst as exemplified by the pit cave is seen in several locations on San Salvador (Fig. 4). These pit caves are found primarily on the slopes and crests of eolian ridges, above 7m elevation. Their setting is different than that of either flank margin caves or banana holes. Pit caves are vertical holes with entrances that range from less than 1 meter to 7 meters in diameter. The depth of pit caves can reach 10 m. Pit caves have a depth to width ratio greater than 1. They are usually found in clusters along dune ridges at elevations above 7 m, although they can be found at all elevations. They exhibit many features of vadose origin such as vertical grooves and incised slots.

MATERIALS AND METHODS

Study areas were chosen to represent three main physiographic areas where banana holes and pit caves are found: 1) inland, lowlying plain; 2) interior dune; and 3) coastal dune. The Line Hole area, located on the north end of the island, represents a lowland area at or below 6 m elevation. During the last sea-level highstand, it would have been affected by the fresh-water lens and associated chemical processes. Great Lake dune ridge is located in the central portion of the island. It was chosen to represent interior environments above 6 m elevation. Portions of the ridge above 6 m elevation have never been affected by any past sea-level highstands. On the southern portion of the island, the Sandy Point coastal dune ridge was also studied. The portions of this coastal area above 6 m elevation, also have not been affected by past sea-level highstands.

For the study, known dissolution features at these sites were examined. Further exploration of the area revealed some new features. The research strategy included the use of existing maps and the production of maps from new surveys. Wall rock samples were taken from representative pits and/or banana holes from each area. Each feature was sampled at the top and bottom.

The rock samples were impregnated with blue epoxy, and 30 μm thin sections were prepared. Petrologic information was obtained by point counting using a Nikon petrographic microscope. Photomicrography was performed with a Nikon Fx 35WA camera. Some samples

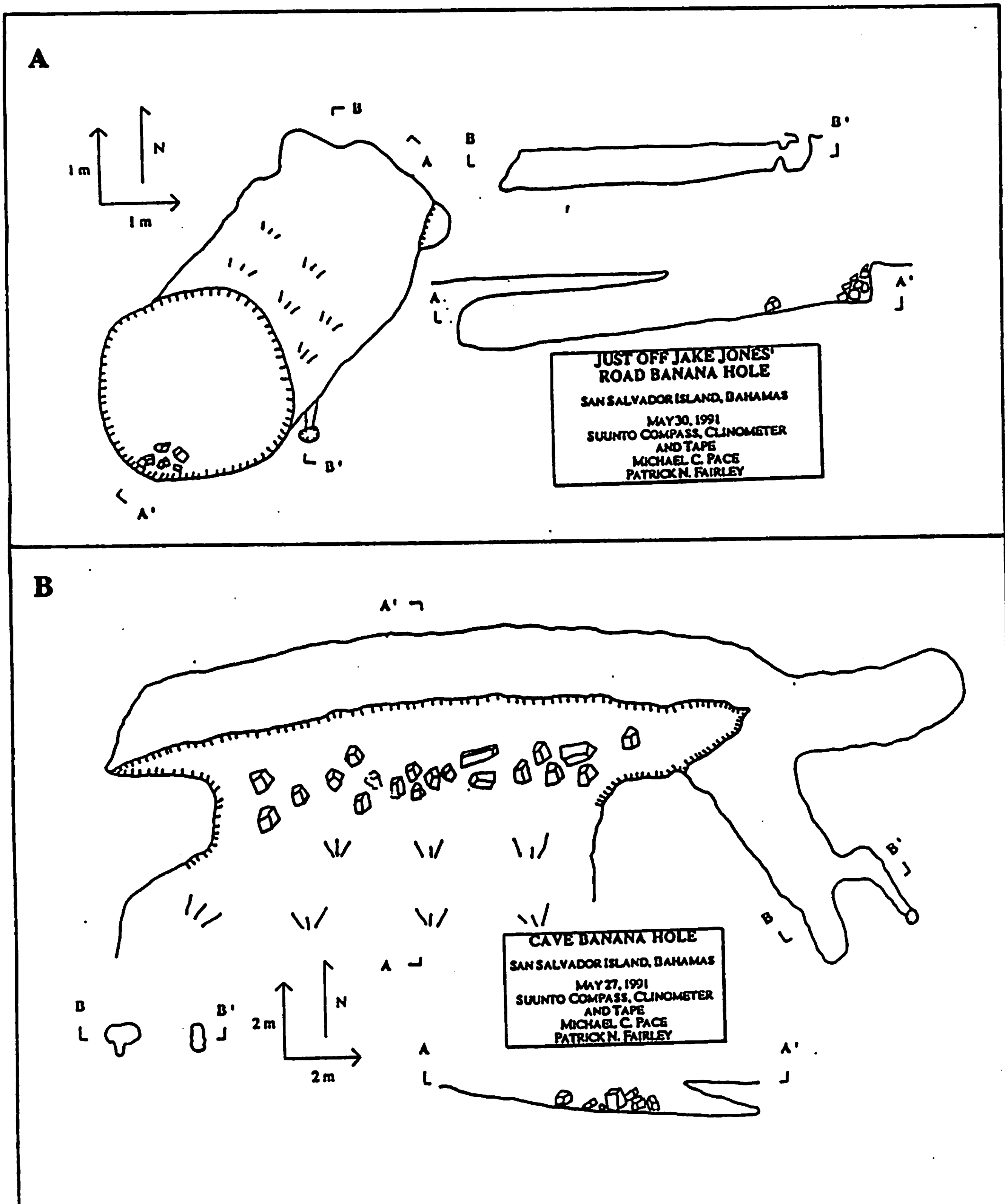

Figure 3 - Representative banana holes from the Line Hole area. A. Note the thin bedrock span that has partially collapsed. B. Note collapse is mostly complete, but phreatic elements still exist.

SAMPLE	Ooids	Peloids	Forams	Algae	Other Bioclasts	Other Clasts	Intraclasts	Porosity	Intergr.	Intragr.	Cement	Name	Average Grain Size	Sorting	Comments
Sandy Point															
SS-MJ91-OWLU	28%	27%					2%	10%	+	+	33%	Oopelosparite	.25 mm	well	poorly cemented
SS-MJ91-OWLL	†	6%	3%	2%	1%	51%		11%	+		26%	Pelbiosparite	.20 mm	poor	poorly cemented
SS-MJ91-TSPU	27%	27%				1%		5%			46%	Oopelosparite	.25 mm	poor	Small inclusions in matrix
SS-MJ91-TSPL	25%	27%					7%	7%	+	+	34%	Oopelosparite	.10 mm	well	
SS-DJ91-E20U	15%	34%						11%		+	46%	Oopelosparite	.25 mm	poor	well cemented
SS-DJ91-E20L	33%	16%		1%		2%	1%	10%	+	+	37%	Peloosparite	.25 mm	poor	moderately cemented, partially micritized
SS-DJ91-E29U	19%	34%				1%		11%	+	+	35%	Peloosparite	.30 mm	poor	well cemented
SS-DJ91-E29L		2%	6%	9%	2%	4%		29%	+		48%	Pelobiomicrite	.20 mm	poor	poorly cemented, highly altered to micrite cement
SS-MJ91-DSPU	38%	16%				1%		16%	+	+	29%	Peloosparite	.20 mm	poor	poorly cemented
SS-MJ91-DSPL	20%	31%				1%		14%	+	+	34%	Oopelosparite	.25 mm	poor	moderately cemented
SS-DJ91-DSPB	23%	39%			3%	1%		4%	+	+	31%	Oopelosparite	.25 mm	poor	well cemented, some ostracodes present
SS-MJ91-LOHU	31%	26%				1%	1%	4%	+	+	37%	Peloosparite	.20 mm	poor	
SS-MJ91-LOHL	36%	18%					3%	8%		+	35%	Peloosparite	.20 mm	poor	
SS-MJ91-LOHG	43%	19%						8%	+	+	30%	Peloosparite	.17 mm	poor	moderately cemented
Ghost tubes															
SS-DJ91-UGT1	11%	48%				2%		4%	+		36%	Oopelosparite	.20 mm	poor	well cemented
SS-DJ91-UGT2	14%	32%			1%	3%	1%	27%	+		23%	Oopelosparite	.35 mm	poor	poorly cemented, unconsolidated, ostracodes present
SS-DJ91-UGT3	12%	41%						13%	+	+	34%	Oopelosparite	.25 mm	poor	moderately cemented
SS-DJ91-LGT1	6%	50%	†			5%		14%	+		25%	Oopelosparite	.25 mm		majority of matrix dissolved, poorly cemented,
SS-DJ91-LGT2	2%	43%				6%	2%	9%	+		39%	Pelosparite	.30 mm	poor	poorly cemented
SS-DJ91-LGT4	1%	52%				1%		19%	+	+	19%	Pelosparite	.25 mm	poor	poorly cemented
Line Hole															
SS-MJ91-OWPU											0%				Sample micritized
SS-MJ91-OWPL	30%	30%				1%	5%	6%	+	+	28%	Oopelosparite	.30 mm	poor	poorly cemented
SS-MJ91-H20U	16%	30%			1%	6%	1%	4%	+		42%	Oopelosparite	.17 mm	poor	well cemented, partially micritized, one ostracod counted
SS-MJ91-H20L											0%				Sample micritized
SS-MJ91-JJRU	8%	43%				4%	1%	14%		+	30%	Oopelosparite	.35 mm	Poor	well cemented
SS-MJ91-JJRL	10%	43%	1%	†		3%	1%	12%	+	+	30%	Oopelosparite	.25 mm	Poor	med -> well cemented, ostracodes observed
SS-MJ91-2DCU	4%	42%	†	†		7%	4%	10%		+	33%	Oopelosparite	.40 mm	Poor	well cemented
SS-MJ91-2DCL	17%	33%					1%	10%	+	+	39%	Oopelosparite	.17 mm	Poor	well cemented
SS-MJ91-CAVU	27%	34%						7%	+		32%	Oopelosparite	.25 mm	Poor	portion of sample micritized
SS-MJ91-CAVL											0%				Sample micritized
SS-MJ91-CAVP											0%				Sample micritized
Great Lake															
SS-MJ91-RHLU											0%				Sample micritized
SS-MJ91-RHLL	15%	37%				6%		2%	+		40%	Oopelosparite	.20 mm	Well	well cemented
SS-MJ91-WHLU	29%	16%		1%				3%		+	53%	Peloosparite	.25 mm	Well	well cemented
SS-MJ91-WHLL	25%	13%	†	1%		5%		13%			43%	Peloosparite	.25 mm	Poor	well cemented
SS-MJ91-SSPU											0%				Sample micritized
SS-MJ91-SSPL											0%				Sample micritized
SS-MJ91-BWCU	48%	17%				1%					34%	Oosparite	.20 mm	Poor	Some intragranular porosity present

TABLE 1 - - Petrologic classification summary of rock samples from wall rock samples. († indicates features present but not counted, + indicates type of porosity present)

were crushed, powdered, and sifted to 250 μm. X-ray diffraction analyses were then performed using a Phillips Compact X-ray Diffractometer System PW 1840.

RESULTS

Line Hole

The vertical dissolution features of the Line Hole area fit the definition for banana holes. Most banana holes were located in the field by observing the tall trees that grow in many of the holes. The growth of these trees as well as other tropical vegetation is the result of closer proximity to the fresh-water lens, and the tendency of these holes to collect thick organic-rich soils. One hole had a fresh-water pool in the bottom. Figure 3 shows representative banana holes from the Line Hole area. Petrologic analysis of wall rock samples from this area revealed that these holes are located in ŏolitic rocks with a sparry cement (Table 1). Subsequent x-ray diffraction analysis showed the majority of the rock was calcite with the remainder composed of aragonite; no dolomite was found (Table 2).

SAMPLE	CALCITE	ARAGONITE	DOLOMITE
Sandy Point Pits			
SS-MJ91-OWLU	73.58%	26.42%	0.00%
SS-MJ91-OWLL	84.20%	15.80%	0.00%
SS-MJ91-TSPU	77.56%	22.44%	0.00%
SS-MJ91-DSPU	81.86%	18.14%	0.00%
SS-MJ91-DSPL	78.13%	21.87%	0.00%
SS-MJ91-LOHU	83.94%	16.06%	0.00%
SS-MJ91-LOHL	76.38%	23.62%	0.00%
SS-DJ91-UGT1	73.15%	26.85%	0.00%
SS-DJ91-UGT2	56.43%	43.57%	0.00%
SS-DJ91-UGT3	70.35%	29.65%	0.00%
Sandy Point Caves			
SSSP-51	76.10%	11.03%	8.68%
SSSP-53	61.61%	18.00%	20.39%
Line Hole			
SS-MJ91-OWPL	60.49%	39.51%	0.00%
SS-MJ91-JJRU	81.69%	18.31%	0.00%
SS-MJ91-JJRL	80.79%	19.21%	0.00%
SS-MJ91-2DCU	74.42%	25.58%	0.00%
SS-MJ91-2DCL	78.30%	21.70%	0.00%
Great Lake			
SS-MJ91-WHLL	92.33%	7.67%	0.00%
SS-MJ91-BWCU	86.69%	13.31%	0.00%

- Summary of X-ray diffraction analyses on selected samples from the study areas. No dolomite was found in any pit caves or banana holes. Only samples from a flank margin cave in the Sandy Point area contained dolomite.

TABLE 2

Great Lake Dune Ridge

This location contains karst features conforming to the parameters for pit caves. Most of the pits are located near the crest of the ridge, and they reach depths up to 5 m. Dissolution of some of the shafts of these pits seemed to preferentially occur at an angle of about 30°, along foreset beds, with subsequent vertical incision. Figure 4 illustrates a series of pits found along Great Lake dune ridge. Petrologic analysis of the wall rock samples from these pits showed they were located in ŏolitic rock with sparry cements (Table 1). X-ray diffraction analysis showed that the composition is primarily calcite with some remaining original aragonite. No dolomite was found (Table 2).

Sandy Point

Mylroie (1988) presented a description of many of the features in this area. During field work conducted in January 1991, an additional karst field was located north of the area mapped earlier by Mylroie and his students. It is thought that the two karst fields were originally one, but construction of a now-defunct golf course fairway covered the features between the two areas. Surficial karstification is very prevalent in this area. Here, as opposed to the thick vegetation found on the Great Lake dune ridge, failed commercial development has left much of the surface bare. Kaminitzas as well as various drainage features are commonly observed. Many of these surface drainage systems end at pits. Figure 5 shows two examples of the larger pits found in the Sandy Point area. Figure 6 shows another pit and associated surface features. Petrology of samples from this area revealed that the pits are in ŏolitic rock; however, one pit, Owl's Hole, penetrates through a paleosol into a lower unit. A sample was taken from under the paleosol and was shown to be bioclastic, as demonstrated in an earlier investigation (Stowers and others, 1989). This paleosol represents the Grotto Beach/Owl's Hole Formation contact, and the pit is the type section for the Owl's Hole Formation. Another pit in the area had bioclastic rock in the lower portion of the pit, but no paleosol was observed.

X-ray diffraction of the rock samples showed primarily calcite with some remaining original aragonite (Table 2). No dolomite was found in these pit caves. Two samples taken from a flank margin cave near the sea cliff area at the base of the dune at +3 m showed small amounts of dolomite (Table 2).

DISCUSSION

Initial Ideas

Both banana holes and pit caves are found in

Pleistocene öolitic rock. The öolitic rock in which they are formed was deposited during a Pleistocene sea-level highstand when the platform was flooded and sediment production was occurring. Geochronological studies by Carew and Mylroie (1987) indicate that large volume Pleistocene öoid deposition was restricted to the substage 5e sea-level highstand (125,000 years ago). Foos and Muhs (1991) have suggested that some öolitic dune ridges on San Salvador represent stage 7 deposition (220,000 years ago), but this information has not been corroborated.

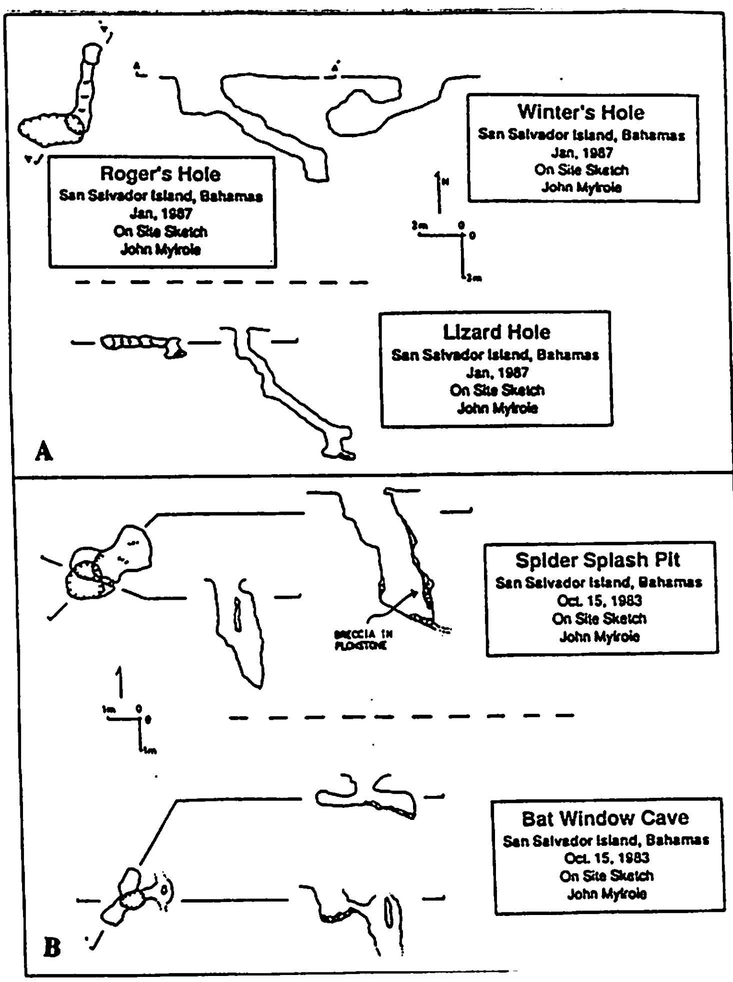

Figure 4 - Representative caves from the Great Lake Dune Ridge. Note the verticality, slanted sections of the pits are passage sections developed alone forest beds.

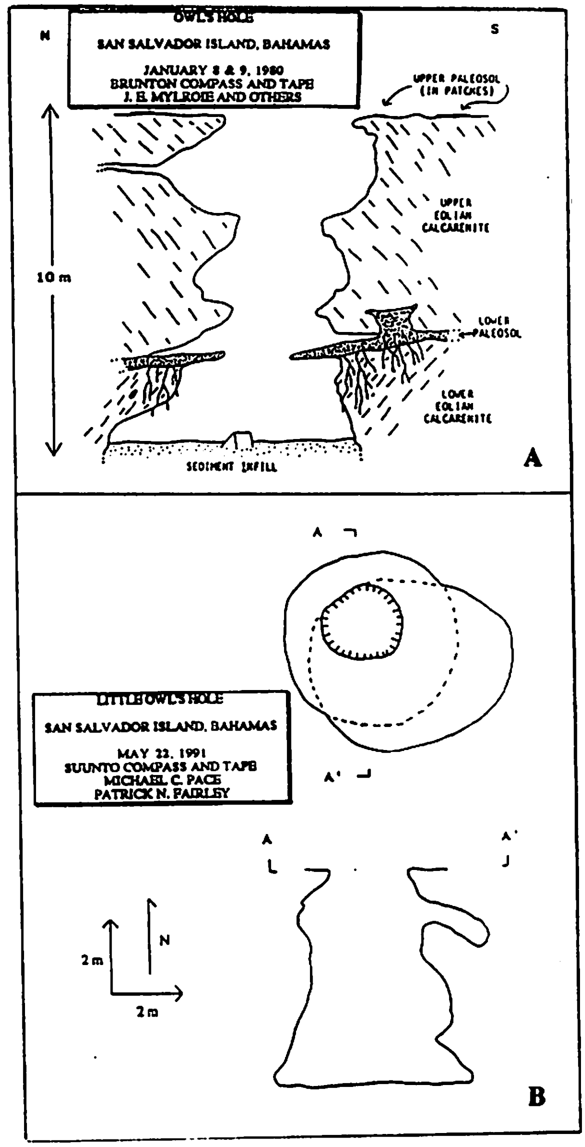

Figure 5 - Large pit caves found in the Sandy Point area. A. Owl's Hole, type section for the Owl's Hole Formation which is the paleosol and the underlying eolian calcarenite. B. Little Owl's Hole, several hundred meters northeast of Owl's Hole.

Therefore, banana hole and pit cave development had to be syngenetic with öolitic rock deposition, or subsequent to the rock's deposition. This observation means the pit caves and banana holes are approximately 125,000 years old or younger, and developed in the Grotto Beach Formation.

Several theories have been presented for the genesis of banana holes and pit caves (Smart and Whittaker, 1989; Mylroie, 1990). Mylroie (1990) hypothesized that pit caves and banana holes are polygenetic features that are formed by a combination of phreatic dissolution with subsequent roof collapse, concentration of surface water flow, and CO_2 production by decomposing organic material.

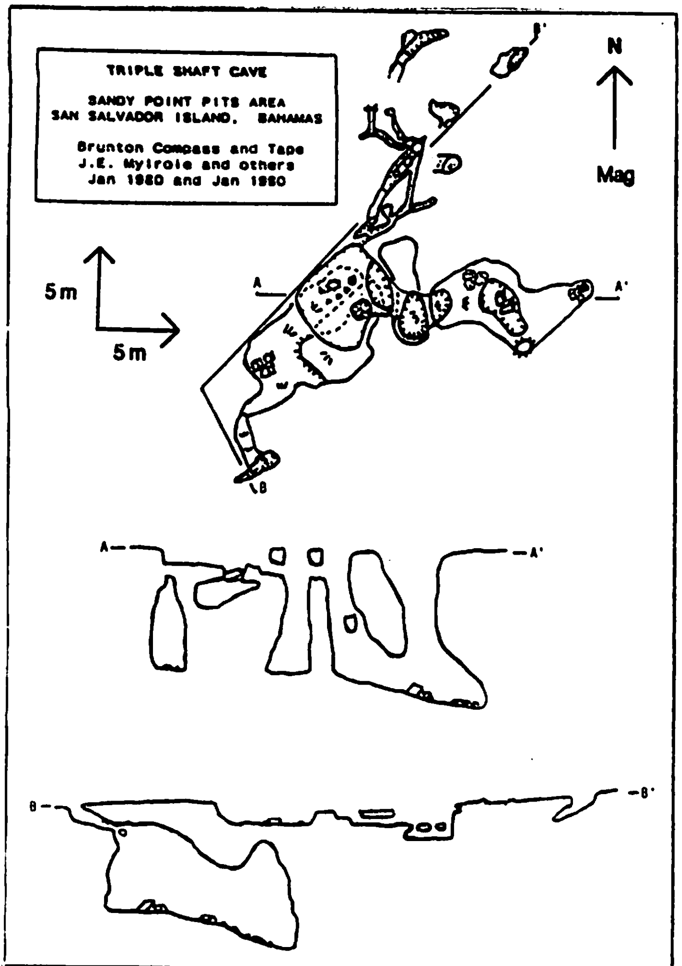

Figure 6 - Pit cave from Sandy Point area showing complex drainage system in the subcutaneous zone channeling water towards the pit.

Collapse is clearly a viable mechanism, and some pits and banana holes can be followed downward into horizontal phreatic caves with associated breakdown. Many pits, however, are narrow tubes less than 1 m in diameter extending downward in an undulatory manner for more than 5 meters, such a structure is not consistent with a collapse origin. Banana holes show various stages of collapse. Some banana holes have rims that cover a significant part of the dissolution void, while others have degraded to the point that the circular feature is almost entirely exposed to the surface. Collapse also occurs in flank margin caves on the margin of ridges, leading to features of similar appearance to banana holes.

The current resistant paleosol surface on the Pleistocene carbonates has been suggested as a mechanism to focus surface flow into pit caves and banana holes (Mylroie, 1988). Paleosol surfaces do focus modern water flow; however, in many pits this paleosol surface can be followed down pit walls, indicating that the pit was present before the paleosol formed. Localized vadose flow is evident in many pits in the form of vertical wall grooves and flutes. This evidence of localized vadose flow, however, appears at odds with the available catchment for the pits. Many pits are located at the crests of the ridges or adjacent to many other pits, apparently limiting their available recharge for pit formation (Mylroie, 1988).

Smart and Whittaker (1989) proposed a single mechanism for the formation of banana holes and pit caves (Fig. 7). They suggested that small, low areas collect organic material and water. CO_2 produced by the decaying organic material decreases pH and facilitates limestone dissolution. As the depression is enlarged through dissolution, it collects greater amounts of water and organic mater which, in turn, produces more CO_2 to aid in continued dissolution. Under this model, the depression widens and deepens. Roots from vegetation that may grow in the bottom of the pit can give water preferred routes to enter the rock, again, enhancing dissolution. Unfortunately, the downward-corrosion of organic matter as the mechanism to drill the pits cannot explain pits that locally step laterally. Some small banana hole entrances open into much larger chambers. This, again, is problematic for the organic mat hypothesis. Also, in banana hole areas, no surface flow network for the collection of water is observed.

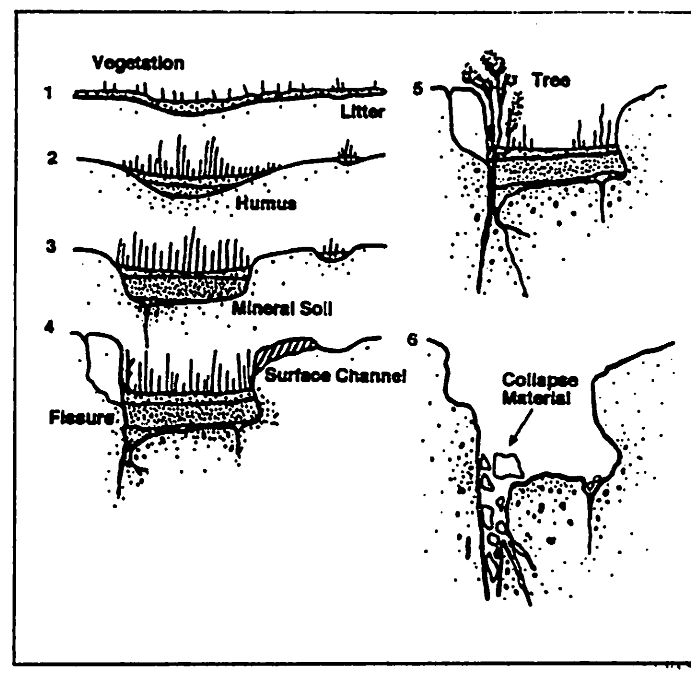

Figure 7 - Contribution of biogenic CO_2 from vegetative organic mats was thought to be a primary mechanism of formation for pit caves and banana holes. See text for details of this sequence. The morphology of pit caves and banana holes makes this unlikely as a primary mechanism, but it can effect enlargement of these features. (Modified from Smart and Whittaker, 1989).

Banana Holes

Prior to this study, banana hole origin was not well understood (Mylroie, 1988). The rocks in which they form must have been deposited during one sea level highstand with subsequent dissolution on that highstand or during a second sea-level highstand. The elevation of the stage 7 and earlier sea-level highstands (Mylroie and others, 1991) along with the 1-2 m/100,000 yr. subsidence rate for The Bahamas makes it unlikely that any phreatic dissolution features formed prior to substage 5e would be subaerial today as subsidence would have taken them below modern sea level (Carew and Mylroie, 1992). No other sea-level highstand event has surpassed modern sea level since substage 5e. This sea level interpretation is supported by the lack of any subaerially exposed subtidal facies in The Bahamas other than those from substage 5e (Carew and Mylroie, 1992). If the substage 5e highstand consisted of two sea level highstands separated by a minor low as proposed by Mylroie and others (1991), then dissolution could have been syngenetic with the early substage 5e highstand deposits, and/or dissolution during the later substage 5e highstand. Banana holes contain morphologies (curvilinear dissolution surfaces, bedrock spans, thin wall partitions, and wall pockets) consistent with phreatic development. The wall rock samples analyzed from the banana holes in the study lack dolomite, which suggests the absence of marine influence. Therefore, it appears that the banana holes formed at the top of the fresh-water lens where only vadose-phreatic mixing existed. In this scenario, öolites were formed on the initial substage 5e transgression, creating broad sand sheets. If sea level were to fall, then these sand sheets would become subaerial and subsequently contain a fresh-water lens. Once the caves had developed in that lens, further fall in sea level would drain the void, promoting roof collapse into the chamber. This collapse would allow organic matter to accumulate and surface water to enter the chamber. Contrary to Smart and Whittaker (1989), the water along with CO_2 produced by decomposing organic material may have enlarged and deepened the void, but did not significantly contribute to the morphology seen today until collapse of the chamber ceiling became nearly complete.

Pit Caves

As with banana holes, pit cave origin was not well understood prior to this study. Pit caves have a depth to width ratio greater than one and are found usually in clusters along the tops of dune ridges above +7 m. All initiate in öolitic rock, but may penetrate into lower bioclastic rock. Their morphology, including vertical grooves, suggests a primarily vadose origin. The role of a CO_2-producing organic mat in pit formation is, as for banana holes, questionable. Today, kaminitzas (shallow dissolution pans) seen in the Sandy Point area collect water and organic matter which would lead to favorable conditions for the production of biogenic CO_2. These small features are lined by a hard crust and are growing horizontally much faster than vertically as indicated by depth to width ratios much less than 1. It is unlikely, as for banana holes, that the downward drilling of an organic mat could produce all the features seen in pit caves.

The water budgets necessary for pit cave formation were initially thought to be a problem (Mylroie, 1988); however, field observations during rainstorm events demonstrate that, even near the crests of ridges, there is significant surface and subcutaneous flow (or epikarst, see Williams, 1985) to feed pits on the perimeter of the pit fields. The clustering of pits may reflect nothing more than the sequential piracy of water into new pits on the margin of the pit field, so that older abandoned pits are toward the center. This is analogous to what is seen in classical vadose shaft development in continental karst.

Pit caves usually end in loose sediment, but in some instances pit caves penetrate into flank margin caves lower in the dune, often continuing through the rock of the bottom of the cave passage, indicating penetration of the phreatic flank margin cave after sea level fell and placement of the flank margin cave in the vadose zone (Mylroie, 1988). This is a random phenomenon and no evidence has been discovered to indicate a connection between pit cave development and flank margin cave development. Their genetic history is completely independent.

During rainfall events when collected water reaches the bottom of the pit, the flow changes from conduit to diffuse as the water migrates through the dune rock. This diffuse flow produce a de-coupled system between the surface and the fresh-water lens. Under high discharge events the diffuse flow system is unable to drain the pit. This may explain some of the more unusual morphologies that resemble phreatic features of the pit caves near their bases which are still well above +6m.

Age of Development

As pit caves form in the same rock type as banana holes it is possible that their formation is syngenetic with formation of the rock. Such a phenomenon has been discussed by Jennings (1968) in Australian eolianites. As previously stated, banana holes must be formed during a sea level highstand(s). A highstand is necessary to both deposit the rocks and to form the phreatic void. Hence, their formation is constrained to a limited time period. Only the substage 5e sea level highstand(s) meets the criteria. Pit cave formation is independent of the sea level control for banana hole formation, but could have initiated in the same time frame as banana hole formation. While the primary dissolution of banana holes ceased when sea level fell, pit cave formation could continue and probably still continues today. It is equally possible, that pit cave formation began well after the highstand of substage 5e and that they formed in a completely different time frame from the banana holes. The intersection of flank margin caves by pits supports this view. The drape of paleosol into some pit caves indicates that they were initiated prior to the end of the Pleistocene.

Ghost tubes

Interesting features seen in one roadcut in the Sandy Point area appear to be infilled pits. These have been referred to as ghost tubes (Mylroie, 1988). Closer examination shows that the primary bedding structures of the surrounding dune continue through what is initially perceived to be infill material. The infill material is very soft and is easily excavated. Petrologic analysis of samples show that porosity within the "fill" area is much higher than the adjacent dune. It is evident that much of the cement has been removed from the rock and the grains have also been subjected to dissolution. We hypothesize that these ghost tubes may represent the early stages of pit formation by localized concentration of descending vadose water.

Differentiating Flank Margin Caves, Banana Holes, and Pit Caves

Banana holes and pit caves can be differentiated from flank margin caves by location, morphology, and rock chemistry. Flank margin caves are located in the flanks of dunes. Banana holes are found in inland plains. Usually pit caves are found in ridges. Some pit caves can be found at lower elevations. These pit caves appear like small banana holes, and probably developed during the last glacial sea level lowstand when the fresh-water lens was much lower and the inland plains were high in the vadose zone. The wall rock in flank margin caves is primarily bioclastic (Vogel and other, 1990; Schwabe and others, this volume). Banana holes and pit caves have been described, to date, only entirely in ŏolitic rock and only rarely do pit caves penetrate into lower bioclastic rock. Some flank margin caves contain dissolved flowstone indicating two separate dissolutional periods during substage 5e (Mylroie and others, 1991). No evidence of two-stage dissolution was found in banana holes and pit caves. Flank margin caves initially formed during the substage 5e highstand in pre-existing eolianites produced during the stage 7 highstand or an earlier highstand (Schwabe and others, this volume). Banana holes and pit caves clearly are developed in substage 5e rocks. The wall rock from flank margin caves often contains dolomite, whereas samples from banana holes and pit caves do not contain dolomite. The dolomite probably reflects marine involvement in flank margin cave genesis.

SUMMARY AND CONCLUSIONS

Banana holes are features formed by collapse into phreatic chambers formed in a fresh-water lens during a past sea-level highstand. The absence of dolomite in wall rocks of these features may result from the lack of a marine influence during the development these features. This suggests formation of these phreatic chambers at the vadose-phreatic interface at the top of the fresh-water lens. Once abandoned as a result of a fall in sea level, collapse of the thin roof into a chamber and late surface modification creates a banana hole. Their position and petrology of wall rock indicates development of the phreatic void approximately 125,000 years ago during the last interglacial.

Pit caves form by the concentration of meteoric water by surface and subcutaneous channelization. Once water penetrates the dune as a localized flow, dissolution of underlying, softer dune material proceeds rapidly, often preferentially along forest beds in the eolianite, with later vertical incision. These pit caves formed in the time window between eolianite deposition 125,000 years ago and the end of the Pleistocene.

The formation of flank margin caves, banana holes, and pit caves appears to have occurred in different environments; however, because of collapse, vadose enlargement and introduction of organic material in the caves (which enhances cave dissolution), they form a broad continuum with significant overlap.

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