BANANA HOLES: UNIQUE KARST FEATURES OF THE BAHAMAS

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ABSTRACT: Banana holes are circular to oval voids with diameters ranging from 2 meters to more than 10 meters, and with depths up to 5 meters, which are found throughout the Bahamas. They are named for a specialty crop sometimes grown in the thick moist soils that accumulate in them. They commonly have vertical or overhung walls, and exhibit phreatic dissolutional morphology. Occasionally, banana holes are found with complete or nearly complete roofs.

Banana holes are the result of shallow-phreatic dissolution in the top of a fresh-water lens supported by the last interglacial sea-level highstand (ca. 125,000 years ago). Their current surface expression is the result of the partial or total collapse of their thin roofs. They did not originate by progradational collapse from depth, or by vadose processes. Once expressed on the surface by roof collapse, however, banana hole floors are modified by vadose waters with elevated CO_2 concentrations derived from the organic material that collects within them.

Banana holes pose a significant land use hazard in the Bahamas, especially those with intact roofs. Geophysical techniques such as ground-penetrating radar are necessary to locate these cryptic banana holes.

INTRODUCTION

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. The Bahama islands consist of Late Quaternary carbonate rocks that were deposited during glacioeustatic highstands, when the bank tops were flooded. During those highstands, only a portion of the bank tops were subaerial islands, as is the case today. During the intervening glacioeustatic lowstands, the entire banks were subaerially exposed, and carbonate deposition effectively ceased. These Quaternary carbonates have been subjected to a variety of karst processes. For a review of the geology and karst geomorphology of the Bahamas, see Mylroie and Carew (1995b).

Regardless of sea-level position, the portion of the bank that is subaerially exposed collects meteoric precipitation, and dissolution of the carbonates occurs at the surface, in the vadose zone, and in the phreatic zone of the fresh-water lens. This dissolution has produced a variety of karst features, including karren and epikarst, blue holes, and caves. Karren and epikarst are surface karst features on a scale of centimeters to meters. Blue holes are deep water-filled shafts (see Mylroie et al. 1995b). Four cave types are found within the Pleistocene portion of the carbonate rocks: pit caves, flank margin caves, lake drain caves, and banana holes (Mylroie and Carew 1995a; 1995b; Mylroie et al. 1995a).

Pit caves are vertical vadose shafts found predominantly on eolianite ridges. They form from dissolution by descending meteoric water that is collected in the epikarst (Pace et al. 1993; Mylroie and Carew 1995b). Flank margin caves that are subaerial today formed in the distal margin of a past fresh-water lens, under the flank of Pleistocene eolianite ridges, where vadose fresh water, phreatic fresh water, and sea water combined to produce dissolutionally-aggressive mixed water (Mylroie and Carew 1990; Raeisi and Mylroie 1995). Lake drain caves are conduits that carry water into and out of lakes in a pattern related to ocean tides. Their presence results in lakes that maintain normal marine salinity despite climatic conditions which might otherwise create fresh-water or hypersaline conditions. The mode of origin for lake drain caves is poorly understood (Mylroie et al. 1995a). Banana holes are isolated voids that are generally circular to oval in plan, range from a few to over 10 m in diameter, and from a few to 5 m deep, that are found below seven meters elevation. Their origin has been the subject of debate (Pace et al. 1993; Mylroie and Carew 1995a; Mylroie et al. 1995a), which this discussion is designed to resolve.

BANANA HOLE DESCRIPTION

Caves and other dissolutional features of the Bahamas have long been recognized in the scientific community (Nelson 1853; Agassiz 1893; Shattuck and Miller 1905). Abundant circular and shallow cave-like features were noted to collect fresh water and organic material to produce a rich soil (Nelson 1853). These small depressions and open caverns were termed "pot-holes" by Nelson (1853), who commented on the variety of specialty crops grown in them, "...fruit-trees, pine-apples, Indian corn, sugarcane, &c. grow luxuriantly..." (Nelson 1853, p. 203). Shattuck and Miller (1905) called these features "banana-holes". The Glossary of Geology (Bates and Jackson 1987) defines banana holes as, "A term used in the Bahamas for a sinkhole, in which it is customary to cultivate bananas and sugar cane." The term is used in a similar sense in Sealey (1994). However, important reviews of early Bahamian geological studies (Sealey 1991) and early Bahamian cave exploration (Shaw 1993) fail to

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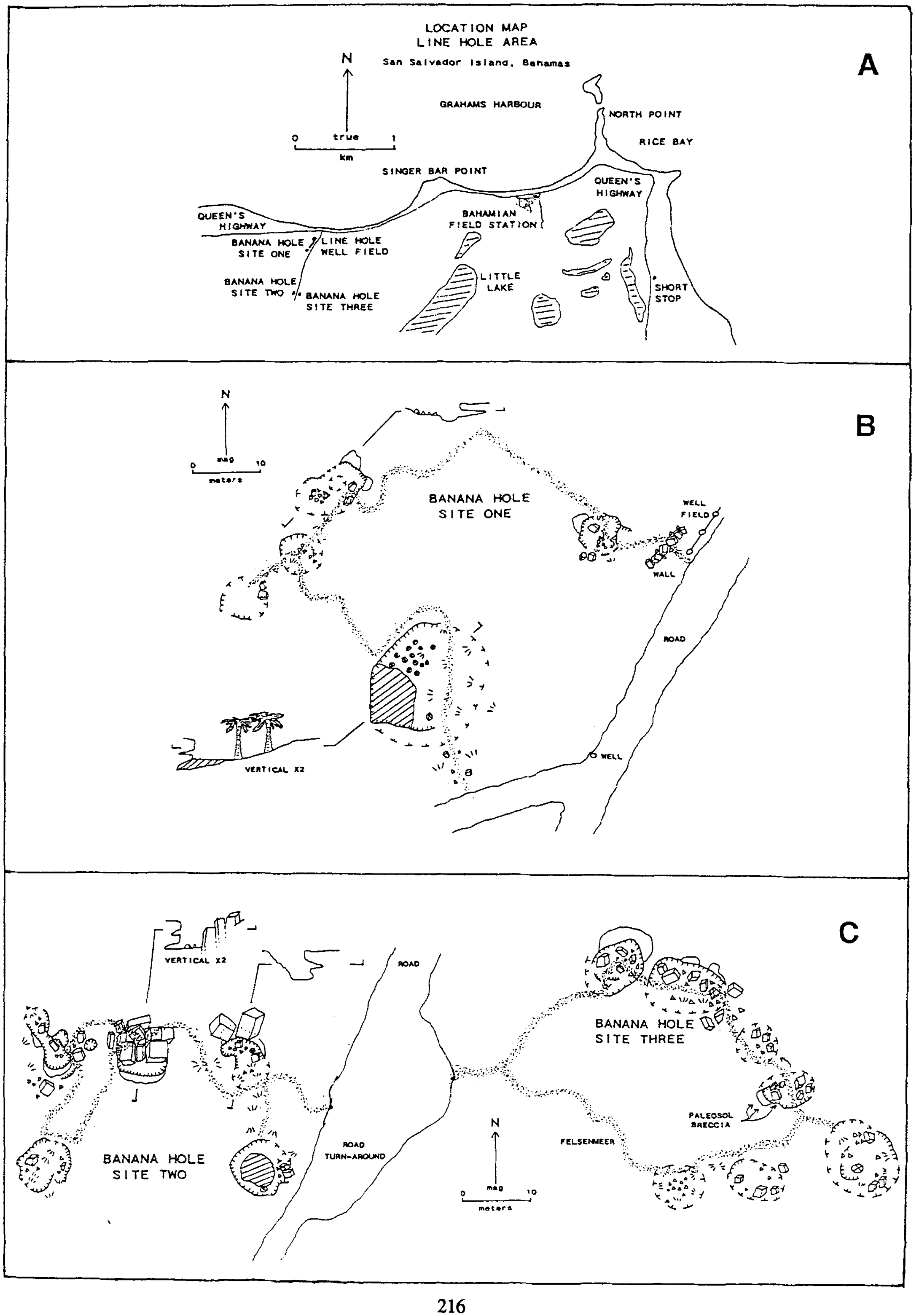

A
LOCATION MAP
LINE HOLE AREA
San Salvador Island, Bahamas
N
0 true 1
km
GRAHAMS HARBOUR
NORTH POINT
RICE BAY
SINGER BAR POINT
QUEEN'S HIGHWAY
QUEEN'S HIGHWAY
BAHAMIAN FIELD STATION
BANANA HOLE SITE ONE
LINE HOLE WELL FIELD
BANANA HOLE SITE TWO
BANANA HOLE SITE THREE
LITTLE LAKE
SHORT STOP
B
N
0 mag 10
meters
BANANA HOLE SITE ONE
WELL FIELD
WALL
ROAD
WELL
VERTICAL X2
C
VERTICAL X2
ROAD
BANANA HOLE SITE TWO
ROAD TURN-AROUND
N
0 mag 10
meters
BANANA HOLE SITE THREE
PALEOSOL BRECCIA
FELSENMEER

◄ *Figure 1. The Line Hole area, San Salvador Island, Bahamas, showing three banana hole sites (see also Fig. 5). A - Location map of the Line Hole area on San Salvador Island; B - Banana Hole Site One; C - Banana Hole Sites Two and Three. Linear dotted bands are the trails at the sites; three diverging lines indicates a slope down in the direction of divergence; collapse material shown diagrammatically as block shapes; sloping banana hole boundaries shown by dip symbols; vertical drops shown by solid line with hachures (on down side); thin lines joining hachured lines display partial cave chambers; diagonal ruling is water.*

mention banana holes. Banana hole is the name currently used by Bahamians for these commonly vertical-walled voids, therefore the term banana hole is adopted for this paper.

Banana holes are commonly ovoid in plan, and although their diameters are usually from 2 to 10 meters across, and they are from 2 to 5 meters deep, they consistently show a width to depth ratio >1. Banana hole configurations (Figs. 1-4) range from sloping depressions closely resembling classic sinkholes seen in continental settings (Fig. 1), to vertical-walled depressions (Fig. 2), to holes with an over-hanging lip or partial ceiling (Figs. 3 & 4), to voids with a complete ceiling (entered laterally from an adjacent banana hole, e.g. figure 2). Banana holes contain curvilinear dissolution surfaces, bedrock spans, thin wall-partitions, and wall pockets indicative of a phreatic origin. Usually, banana holes contain large blocks of rock and other debris, some of which has clearly fallen from the walls or ceilings.

On San Salvador Island, banana holes are found in the Sangamon terrace, a low bench 1 to 6 m above sea level. This terrace comprises 49% of San Salvador (Wilson et al. 1995). Banana holes can be extremely common, as in the Line Hole and Hard Bargain areas of San Salvador Island (Figs. 1 and 5). Initial studies of cave density on San Salvador Island indicate that there are 0.54 banana holes per km^2 (Wilson et al. 1995). These data, however, are based on information in published reports that were not specifically concerned with banana holes. Wilson et al. (1995) recognized that their data represented a minimum figure because the published data did not take into account known banana holes that had not been catalogued, or areas that had not as yet been explored for banana holes. Banana holes are common on most Bahamian islands (e.g. New Providence Island, Fig. 4).

As part of research in progress for the MSc thesis of one of the authors (Harris), detailed surveys on San Salvador, such as that of the Line Hole area (Figs. 1, 2 and 5), and the Hard Bargain area (Figs. 3 and 5) yielded a banana hole density of > $1{,}000/km^2$. Clearly, banana holes are important surface features in the Bahamas, and land use decisions should not be made without considering the risk represented by them. As some banana holes have complete roofs (Fig. 2), they can be a hidden or cryptic, as well as an obvious, hazard to land use. Accurate predictions concerning banana hole presence and density requires understanding how they formed, as some of the theories presented below underestimate true banana hole abundance.

BANANA HOLE ORIGIN

The origin of banana holes has been the subject of debate. Three processes have been proposed to account for them: 1) surface and vadose dissolution, 2) collapse of deep-seated voids, and 3) shallow phreatic dissolution. Shattuck and Miller (1905) felt that the holes developed by vadose dissolution processes, and that this dissolution occurred primarily during glacioeustatic lowstands. Smart and Whitaker (1989) suggested that banana holes develop as an outcome of weathering induced by vegetation and the resulting accumulation of organic-rich soils in them, which accelerated the dissolution process. Pace et al. (1993) argued for phreatic dissolution within a shallow fresh-water lens, followed by roof collapse, as the origin of banana holes.

Vadose Hypotheses

Pit caves are caves that form in the vadose zone by collection of meteoric water from the epikarst (Mylroie and Carew 1995a; 1995b; Mylroie et al. 1995a). Some of these pit caves can reach diameters of >5 m (Pace et al. 1993), a size similar to that of banana holes. Could pit caves become banana holes? To do so, pit caves that are characterized by a width to depth ratio 1<, the opposite of what is observed in banana holes, would have to be largely filled with debris to achieve the banana hole width to depth ratio of >1. Preliminary results from ground-penetrating radar show that banana holes have only a thin layer of debris on their floors (Fig. 6), therefore, they are not infilled pit caves.

Smart and Whitaker (1989) argued that banana holes were surface karst features similar to sinkholes in continental settings. Their model begins with an initial undulating bedrock surface with small depressions and hollows that preferentially collect meteoric water and organic debris. There would be more collected water available to drain downward from these small depressions, and the water would also have enhanced CO_2 partial pressures derived from biological activity in the organic-rich soil of these depressions. The extra CO_2 enhances dissolution, thereby enlarging the depression. With enlargement, a positive feedback effect leads to greater moisture and organic debris, and still more dissolution. The moisture and organic-rich soil available encourages colonization by rooting plants, which drives the production of CO_2 even higher. Over time, as envisioned by Smart and Whitaker (1989), the end result is a steep-walled depression, or a banana hole.

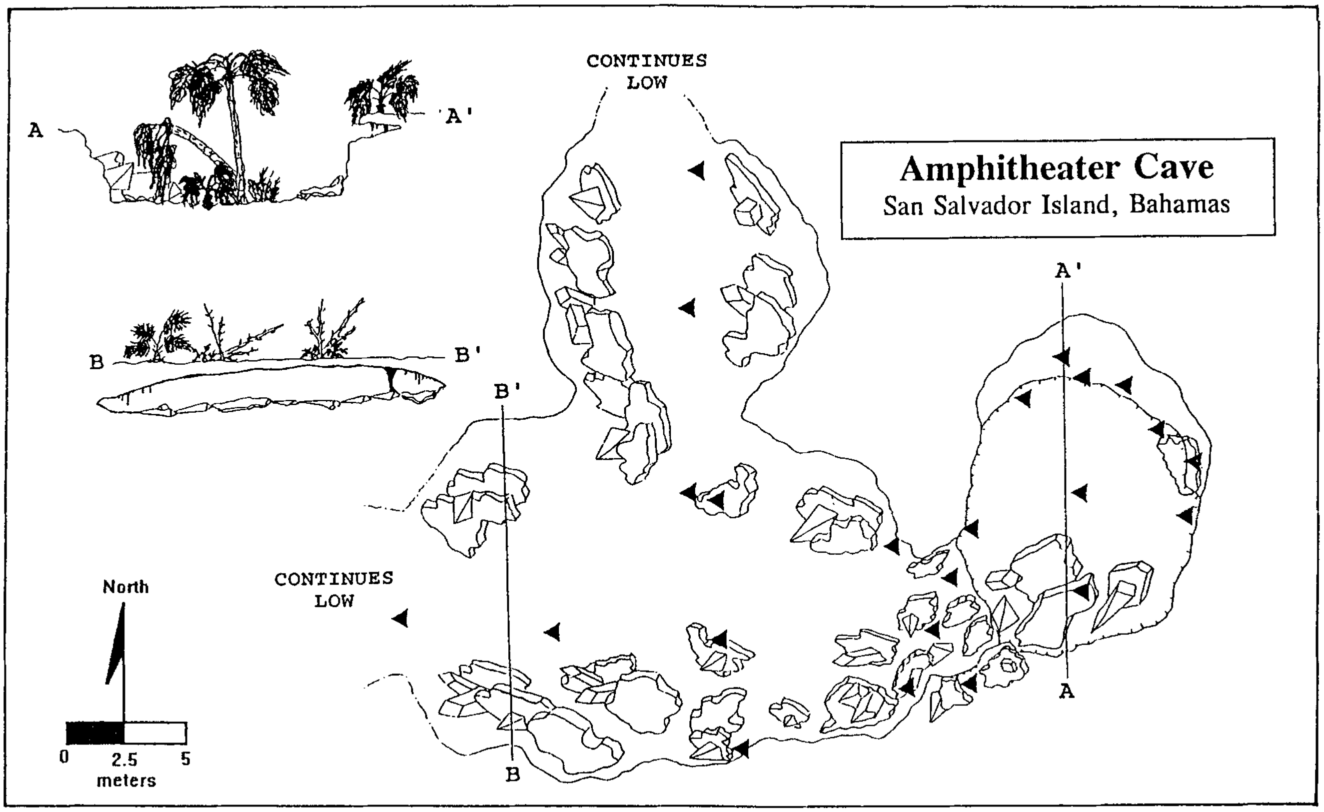


Figure 2. Amphitheater Cave, Line Hole area, San Salvador Island (located 800 m southwest of Banana Hole Site Three shown in figure 1). Symbols same as for figure 1; black triangles indicate stalactite and stalagmite deposits. The east side of Amphitheater Cave is an open banana hole, it leads west to several chambers with very thin roofs (see cross section B-B').

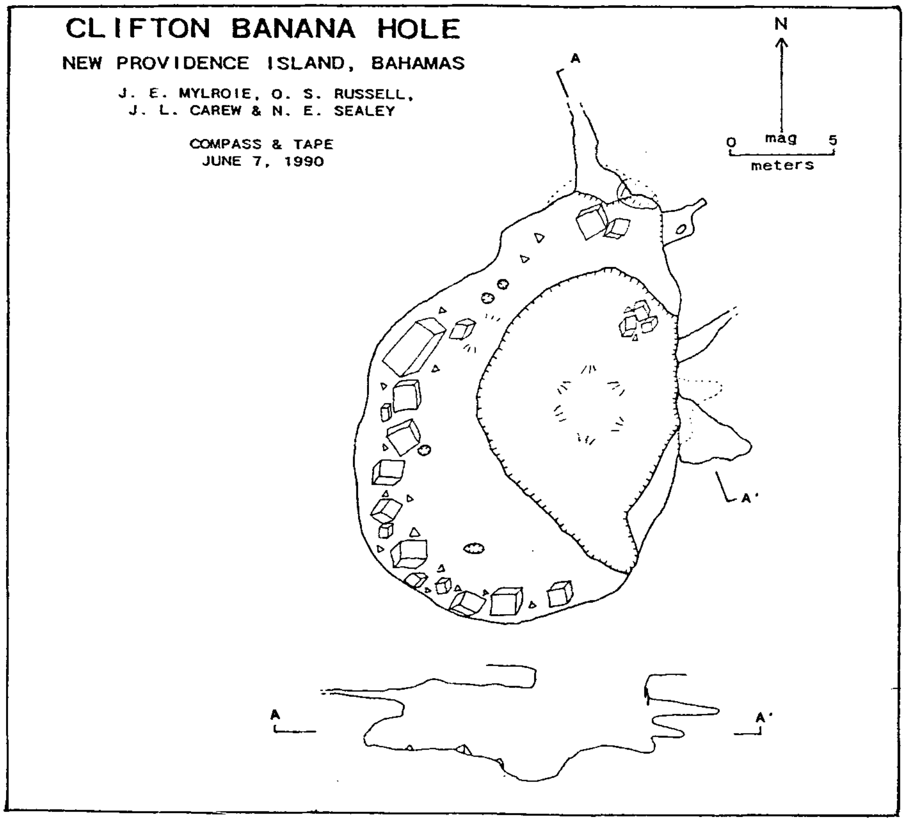


Figure 4. Clifton Banana Hole, New Providence Island, Bahamas, one of the larger banana holes in the Bahamas; symbols same as for figure 1 (from Mylroie et al. 1991).

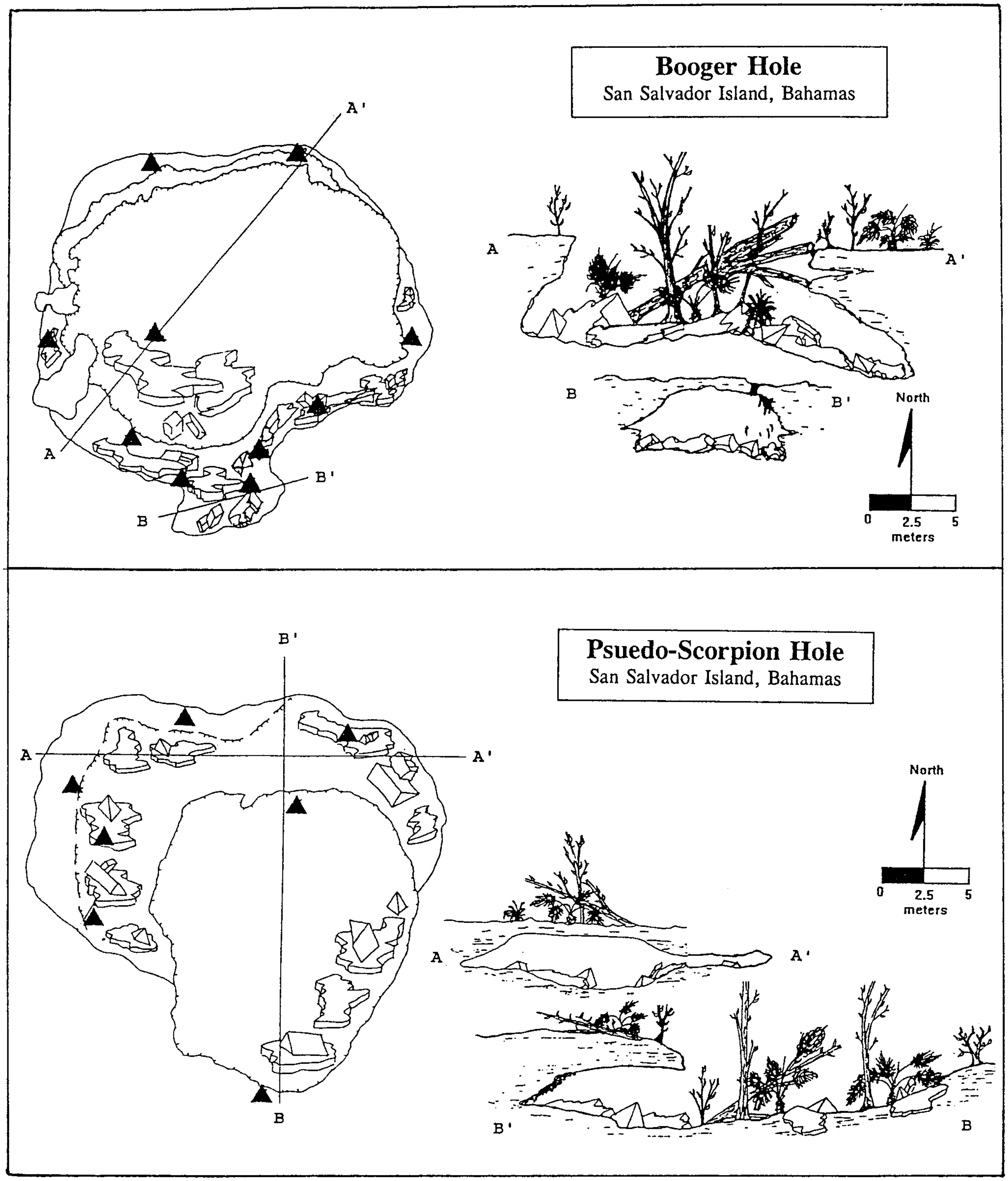


Figure 3. Two banana holes from the Hard Bargain area of east-central San Salvador Island (see Fig. 5); symbols same as for figures 1 and 2. Note collapse debris, overhung roofs, and side chambers. Typical vegetation types encountered in Bahamian banana holes has been represented in the cross sections.

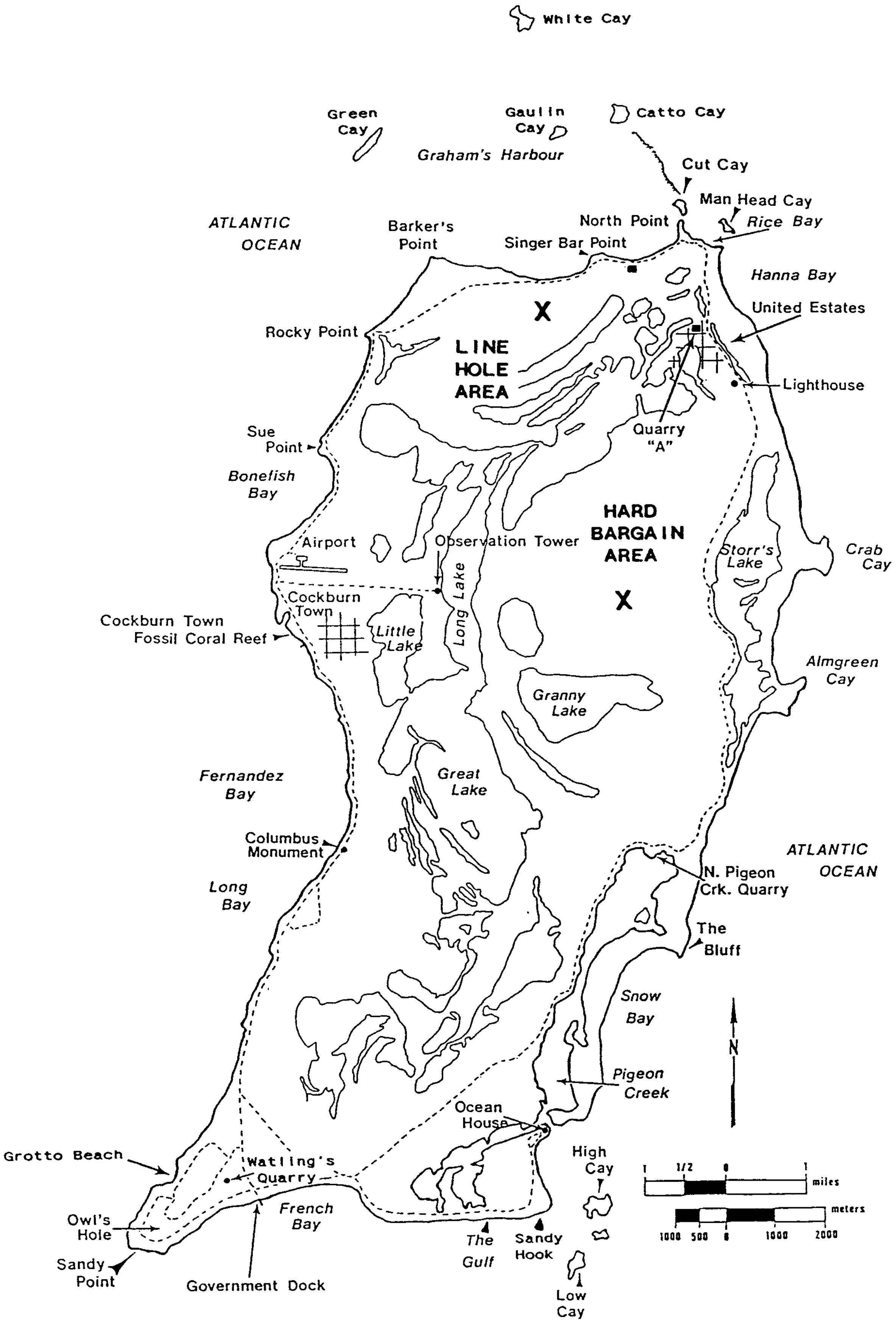


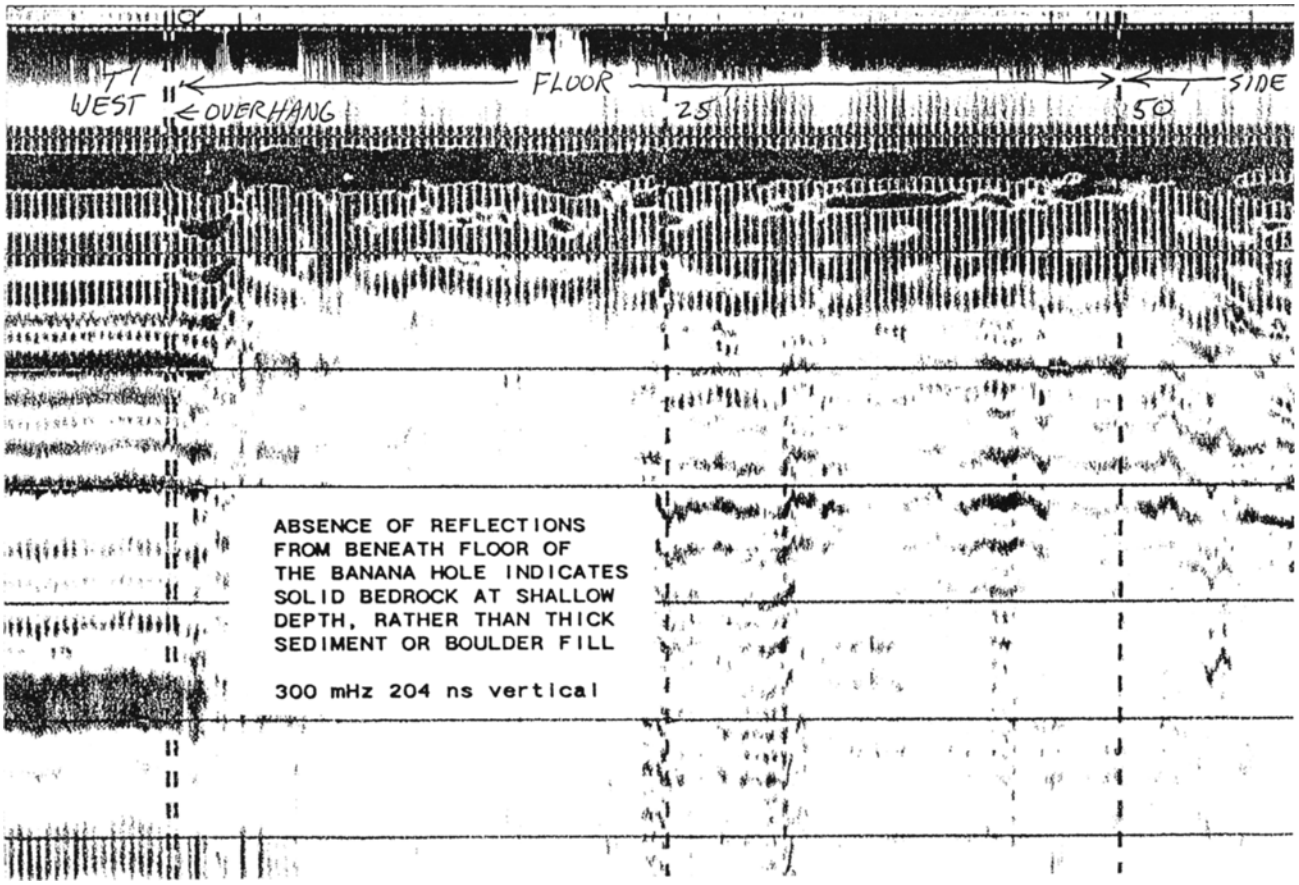
Figure 5. Map of San Salvador Island, Bahamas, showing location of the Line Hole and Hard Bargain areas.

The idea of a "downward-drilling" organic mat is very attractive, and to a certain extent it does explain some banana hole morphology. However, this method fails to account for banana holes that are not yet open to the surface, or which have a nearly-intact roof with only a small opening to the surface. In addition, as noted in the description of banana holes, they contain curvilinear dissolution surfaces, bedrock spans, thin wall partitions, and wall pockets. These morphological features are typical of phreatic dissolution, and are inconsistent with the vadose environment required for the organic mat hypothesis. Organic-rich soil and increased moisture does play a role in enlarging banana holes that are already open to the surface; however, the Smart and Whitaker (1989) model cannot explain the initial development of banana holes as enclosed voids.

Progradational Collapse Hypothesis

Could banana holes be progradational collapse structures that are the surface expression of deep-seated voids that have stoped upward to the surface? Such a mechanism has been proposed as one method of forming blue holes (Mylroie et al. 1995b), which tend to be many tens of meters in diameter, on average an order of magnitude larger than banana holes. If progradational collapse explained the origin of banana holes, they would have a thick collapse-breccia infill that extends deep below present sea level. As mentioned previously, preliminary ground-penetrating radar study has shown that banana holes on San Salvador Island have bedrock floors with a thin veneer of debris (Fig. 6). In addition, if banana holes are the top of breccia-pipe type collapse, they would be expected to extend to a variety of depths; however, banana holes are less than 5 m deep, and only rarely do they extend below sea level for a meter or two.

The mechanics of collapse into voids has been well studied (White 1988), and banana hole diameters are too small to consistently represent collapse prograding upward from depth. The thickness of the overburden, the span of the void, and the rock properties control collapse of the ceiling of voids (White 1988). Deep voids can support a larger ceiling span than shallow voids because of their greater overburden. As deep voids collapse, their ceilings prograde upward in an arch of ever-decreasing span until a stable configuration relative to overburden is achieved. Sometimes this occurs just as the collapse reaches the surface, producing a small diameter surface opening that reflects a far deeper, breccia-filled void below. It is extremely unlikely that all such deep-seated voids would propagate to the surface in a manner that consistently (>1000/km^2 on San Salvador) produced small-diameter sur-



ABSENCE OF REFLECTIONS FROM BENEATH FLOOR OF THE BANANA HOLE INDICATES SOLID BEDROCK AT SHALLOW DEPTH, RATHER THAN THICK SEDIMENT OR BOULDER FILL

300 mHz 204 ns vertical

Figure 6. Portion of a ground penetrating radar traverse over a banana hole at Site One, Line Hole area, San Salvador Island, Bahamas. The traverse ran east from an overhang across a flat bottom and up a sloping side (see notes at top of figure). The floor was free of the reflections associated with thick collapse or sediment deposits, supporting a shallow phreatic mode of development for the banana hole.

face openings, or banana holes. It is much more likely that the voids originated in very shallow setting, with very thin roofs. Over time, these roofs readily collapse to form banana holes with sizes from 2 to 10 m, with the collapse debris from a thin roof forming a minor layer on the solid bedrock floor of the banana hole. Progradational collapse of deep-seated voids is a viable mechanism for the development of large-diameter features like blue holes, but it is not a viable mechanism for formation of small-diameter features such as banana holes.

Shallow-Phreatic Hypothesis

Pace et al. (1993) examined and compared pit caves and banana holes. They concluded that banana holes are shallow-phreatic caves whose roofs had collapsed to create a surface opening. They emphasized the phreatic nature of the dissolutional morphology of banana holes, and noted that many banana holes had partial roofs. The large blocks and rubble found in many banana holes are consistent with this roof-collapse.

Some banana holes contain secondary subaerial calcite deposits (speleothems) such as stalactites, stalagmites, dripstone, and flowstone. The precipitation of these calcite deposits indicates that the chambers containing them were air-filled, and were isolated from the drying effects of the atmosphere, because CO_2 diffusion from drip water into air of nearly 100% humidity dominates $CaCO_3$ precipitation as speleothems. In a similar fashion, secondary calcite evidence has also been used to identify the notch-like remnants of flank margin caves, where the outer walls of these caves have been completely eroded away after calcite speleothem deposition (Mylroie and Carew 1991). Secondary subaerial calcite in banana holes is consistent with phreatic development of sealed cave chambers, followed by lowering of the fresh-water lens, and development of vadose conditions within banana holes with little or no direct communication to the surface atmosphere. Finally, partial or complete collapse of the banana hole roof produced the open holes commonly seen today.

The presence of dolomite in the wall rock of flank margin caves has been associated with the complex mixing of marine and fresh water that occurs in the distal margin of the fresh-water lens where flank margin caves develop (Vogel et al. 1990; Schwabe et al. 1993). Wall rock from banana holes of the Line Hole region of San Salvador Island have been analyzed using x-ray diffraction (Pace et al. 1993). Those samples consist of low Mg-calcite, small amounts of aragonite, and no dolomite. So, the lack of dolomite in banana hole samples may indicate a lack of marine influence in banana hole development.

We suggest that banana holes developed in a shallow-phreatic setting near the top of the fresh-water lens away from the lens margin. Dissolution in the top of the fresh-water lens is enhanced, because there, vadose and phreatic fresh-water mixing occurs, which renews water aggressivity with respect to $CaCO_3$. This mixing model is consistent with the location of banana holes on the Sangamon terrace, away from the margin of any past fresh-water lens. In addition, if organic loading of descending vadose water is sufficient, the organics collect at the density interface represented by the top of the lens. The top of the lens may become anoxic with time, thereby allowing complex oxidation and reduction (redox) reactions that enhance $CaCO_3$ dissolution to occur. These reactions have been documented to occur at density interfaces in blue holes (Bottrell et al. 1991) and has been implicated in the development of flank margin caves on San Salvador Island (Bottrell et al. 1993). Such redox reactions greatly increase the dissolutional potential of the top of a fresh-water lens, and may they have played a similar role in the production of banana holes of the shape and abundance seen today in the Bahamas.

The following support the shallow phreatic hypothesis for the origin of banana holes. Preliminary ground-penetrating radar study indicates that the floors of banana holes are solid bedrock and are mantled with only a thin layer of soil and rock debris. The low, wide chambers of banana holes are consistent with development in a thin vadose-phreatic mixing zone at the top of a fresh-water lens. The occurrence of banana holes with intact and nearly intact roofs (Fig. 2), and the presence of subaerial calcite speleothems in banana holes also supports their origin as enclosed cave chambers. The lack of dolomite in the wall rock of banana holes, and its common presence in flank margin caves, may indicate that dissolution did not occur at the margin or base of the fresh-water lens, where mixing with sea water is common. The location of banana holes at shallow depths on low-lying interior plains in the Bahamas also argues for dissolution at the top of the lens away from the lens margin.

In this shallow-phreatic model, banana holes must have formed during a past sea-level highstand, most likely during the last interglacial (Sangamon; oxygen isotope substage 5e, circa 125,000 years ago). Earlier sea level highstands were either not high enough, or as a result of isostatic subsidence of the Bahamas, occurred too long ago to leave features such as banana holes above modern sea level (Carew and Mylroie 1995). In this scenario, as sea-level fell on the substage 5e regression, the Sangamon terrace rocks became exposed, a fresh-water lens developed within them, and phreatic caves (banana holes) formed along the top of the lens. Subsequently, sea-level fell farther, the void drained, subaerial calcite deposits formed in some of them, and the lack of buoyant support eventually contributed to roof collapse, which continues to the present. The breaching of the roof has allowed organic matter and surface water to enter the banana hole. This influx of organics and surface water may contribute to further deepening and enlargement of the void in a manner similar to that suggested by Smart and Whitaker (1989).

Banana holes are an abundant landform in the Bahamas. That abundance may be the result of the relationship of the land elevation to the fresh-water lens elevation at the time of banana hole formation. Banana holes are found almost entirely in the low-lying areas of the Bahamas at 4 to 7 m elevation, which has been labeled the Sangamon Terrace (Wilson et al. 1995). The Sangamon Terrace is a depositional feature, made up primarily of carbonates laid down during the last interglacial or Sangamon, circa 125,000 years ago (Mylroie and Carew 1995b). As previously noted, banana holes formed as sea level fell in response to glaciation that ended the Sangamon, and a fresh-water lens became established at very shallow depths in the Terrace. The result was a large number of very shallow voids. With a thicker overburden, as occurs where eolianite ridges are present, the voids are rarely large enough to express themselves as collapse structures. The Sangamon Terrace provides such a thin overburden that the banana holes routinely have a surface expression as a result of collapse. The absence of banana holes in some other carbonate island settings, such as Isla de Mona, Puerto Rico, has been attributed to the greater thickness of overburden compared to the Bahamas (Mylroie et al. 1995c).

SUMMARY

Banana holes are cave chambers that resulted from dissolution near the top of past fresh-water lenses that underlay low, flat terraces on Bahamian islands during later portions of the last interglacial sea-level highstand. The current expression of banana holes as circular, vertical-walled depressions results from a combination of roof collapse, and later vadose dissolution driven by the collection of organic-rich soil and moisture within the breached banana holes. Banana holes are neither the result of vadose dissolution alone, nor are they partially-infilled pit caves, or the result of progradational collapse from deep-seated voids. Their wide-spread expression in the Bahamas is in part a result of their development under conditions that left a very thin overburden above these phreatically-developed voids.

Banana holes are a land use hazard. This hazard is especially acute for banana holes with intact roofs, because these roofs are thin, and vulnerable to collapse. It is likely that many banana holes with entirely intact roofs exist, which makes them a cryptic or "invisible" cave-collapse hazard. Only the shallow phreatic hypothesis for banana hole development provides a prediction of abundant uncollapsed banana holes; the other hypotheses require all banana holes to be currently open to the surface. Geophysical techniques such as ground-penetrating radar are necessary to discover the location of banana holes with intact roofs.

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