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Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

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PIT CAVE MORPHOLOGIES IN EOLIANITES: VARIABILITY IN PRIMARY STRUCTURE CONTROL

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ABSTRACT

The landforms of San Salvador, Bahamas, demonstrate extensive karst development, including epikarst features called pit caves. Studies on Hog Cay, an interior dune ridge located north of the San Salvador International Airport runway, indicate that some pit caves have morphologies controlled by bedding. These pit caves, initiating within the vadose zone, have a tendency to follow the foreset beds of the dune for some distance and are analogous to solution chimneys found in continental settings. These solution chimneys are distinguished from vertical shafts, which propagate vertically into the vadose zone of the subsurface with little, if any, horizontal offset.

Previous field observations have described how eolian deposits can be sorted by grain size into alternating coarse-grained and fine-grained strata. The alternating strata undergo selective cementation, where the coarse-grained strata become poorly-cemented and the fine-grained strata become well-cemented because of retention of pore waters. This is observed in weathered outcrops as poorly-cemented micro-recesses and well-cemented micro-ledges. In the subsurface, the coarse-grained, poorly-cemented strata are the preferred flow path for vadose water. This water is perched upon and flows laterally along the foreset beds on the well-cemented, fine-grained strata. Pit caves forming under these conditions are described as solution chimneys.

Also found on Hog Cay are pit caves that extend from the surface down to near sea level. These vertical shafts are generally found on the crests of dunes, with the deepest shaft being over 15 meters. They commonly display a near-perfect cylindrical shape and extend vertically with little or no horizontal offset. The walls of vertical shafts exhibit micro-ledge and micro-recess morphology; however, the vertical shafts have no indication of bedding control. This lack of bedding control may be due to localized, incomplete cementation of the fine-grained layers, facilitating vertical shaft development.

Preliminary XRD analysis of the pit caves shows that the top and bottom wall rocks of one pit is almost entirely calcite, but the wall rocks in the middle of the pit have a high aragonite content. These observations are consistent with long residence time of meteoric water in the epikarst at the top of the pits, and the presence of a paleo-freshwater lens at the 5e sea level highstand near the bottom, allowing for the inversion of aragonite to calcite. However, the rapid transit time of the vadose water along the pit walls allowed dissolution to enlarge the pit, but without inversion of the primary aragonite.

INTRODUCTION

In the past decade, many papers have been published describing the development of karst features in the Bahamas (Pace et al., 1993; Mylroie and Carew, 1995; 1997; Harris et al., 1995; Mylroie et al., 1995; Carew and Mylroie, 1997; Mylroie and Vacher, 1999). Cave development in small carbonate islands is a direct representation of fluid dynamics within the hydrologic sector of the island. The fluid dynamics at work in the phreatic zone, where fresh water and salt water mixing generates an increased dissolution potential, initiate the development of flank margin caves (Mylroie and Carew, 1990). At the top of the freshwater lens, phreatic pockets of dissolution are the antecedent conditions for the formation of banana holes (Harris et al., 1995). In the vadose zone, autogenic input of meteoric water into the epikarst initiates the development of pit caves, as described by Pace et al. (1993).

The genesis and geomorphology of phreatic dissolution features, such as flank margin caves and banana holes, have been given much attention in the past (Pace et al., 1993; Mylroie and Carew, 1995; 1997; Harris et al., 1995; Mylroie et al., 1995; Carew and Mylroie, 1997); while only a small percentage of field research has gone into discerning the origin and influence of pit cave evolution (Pace et al., 1993; Mylroie and Carew, 1995; Harris et al., 1995). Extensive field investigations during two separate trips to San Salvador (Dec 2000 and Dec 2001) were conducted to assess the nature of karst development, particularly pit cave development, on a middle Pleistocene eolian ridge, Hog Cay, which is located in the interior of San Salvador on the northwest side of the island.

SETTING

San Salvador

San Salvador Island, Bahamas, is one of many islands that make up the Bahamian Archipelago. The island is located at 24° North Latitude, 74.5° West Longitude, approximately 650 km southeast of Miami, Florida (Figure 1). San Salvador Island is approximately 11 km wide and 19 km long. The total area is 161 km^2 with a maximum elevation of 40 meters above mean sea level, although most of the eolian ridges on the island range from 10 to 20 meters in elevation. The island is composed mostly of eolian calcarenites, lakes, and low plains. All dunes currently above sea level are middle to late Quaternary in age. Those eolianites above 6m in elevation are above any past glacioeustatic sea-level highstand, and therefore above any previous elevated fresh-water lens position. Thus they have never experienced phreatic conditions. There are no surface streams on the island due to the high porosity (≤ 30%) of the limestone. Many inland lakes can be found, and an examination of water salinity versus location in relation to the ocean demonstrates the complex system of karst features hidden beneath present sea level (Crump, 2002).

Hog Cay is an eolian ridge located north of the San Salvador International Airport runway (Figure 2). Petrographic analyses show the ridge rock is bioclastic (Beda, pers. comm.), placing it in the Owl's Hole Formation, which is the oldest stratigraphic unit (≥ 220 ka) exposed on the island (Carew and Mylroie, 1995; 1997). The ridge was chosen for exploration because of its potential

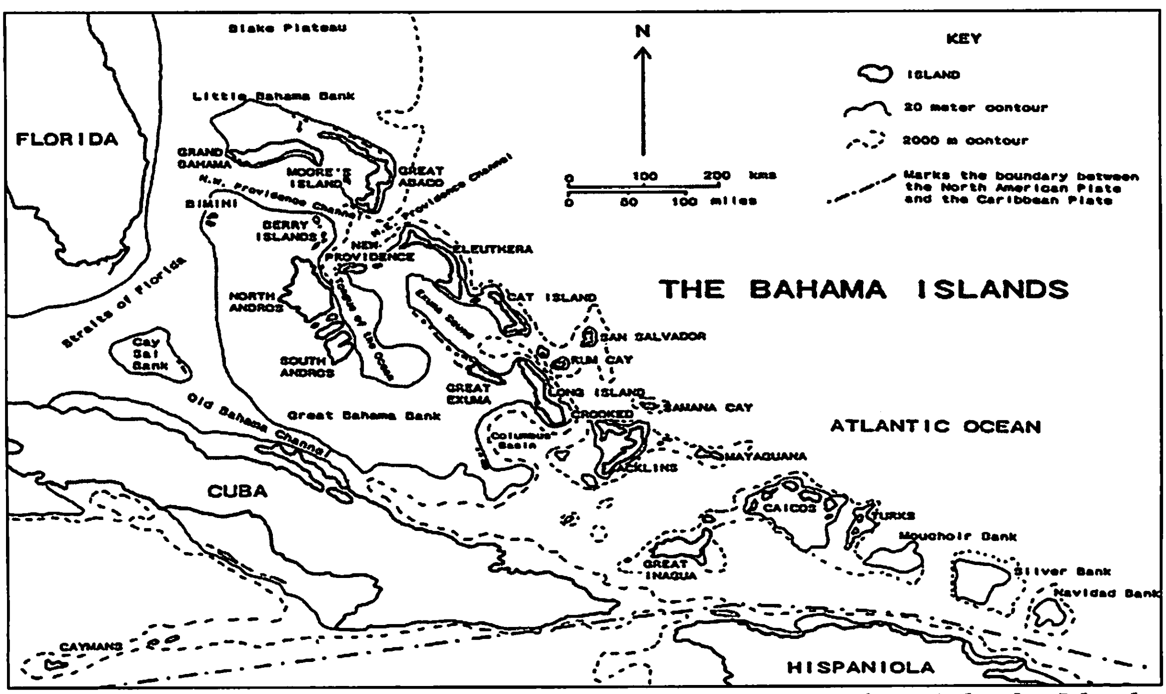

Figure 1. Map of Bahamian Archipelago showing the location of San Salvador Island (Mylroie and Carew, 1990).

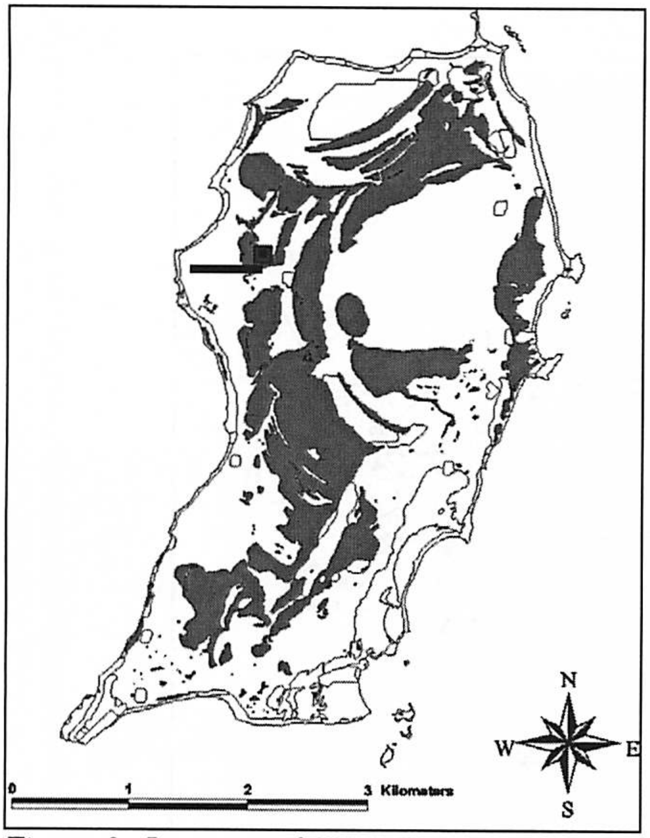

Figure 2. Location of Hog Cay (black square), north of the San Salvador International Airport (rectangle).

to possess advanced stages of karst development. At the beginning of the two-year project, the only significant karst feature known on the cay was Majors Cave, a flank margin cave (Figure 3). It was discovered on the ridge in 1997 and subsequent surveying showed it to be the second largest known cave on the island.

In order to put the present research into perspective, a brief summary of previously described cave types are reviewed below.

TYPES OF CAVES ON SAN SALVADOR

Flank Margin Caves

The flank margin model of cave development, as defined by Mylroie and Carew (1990), demonstrates that phreatic voids form as a result of intense dissolution on carbonate coasts along the flank of eolian dunes and at the margin of the

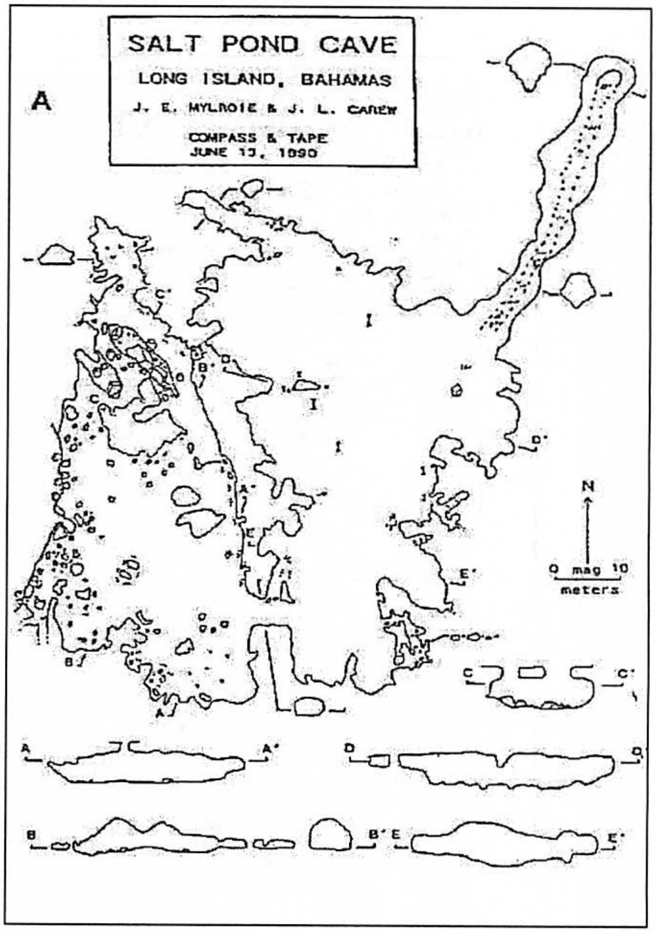

Figure 4. Flank margin caves are exemplified by blind pockets and dead-end passages, where horizontal extent far exceeds vertical relief (from Carew and Mylroie, 1994).

freshwater lens as a result of fresh water and salt water mixing. This dissolution creates a series of horizontal voids, parallel to the axis of the dune, which are characterized by blind pockets and dead-end tubular passages (Figure 4).

The dry flank margin caves of today formed during the last interglacial sea level highstand (Sangamon), which is associated with the deep-sea oxygen isotope substage 5e (~125 Ka). Sea level fluctuated between 4 and 6 meters above present sea level for about 10 to 15 k.y., marking the height of the transgression event (Carew and Mylroie, 1995). Flank margin cave entrances are formed when slope retreat intercepts the voids beneath the dune (Mylroie and Carew, 1990).

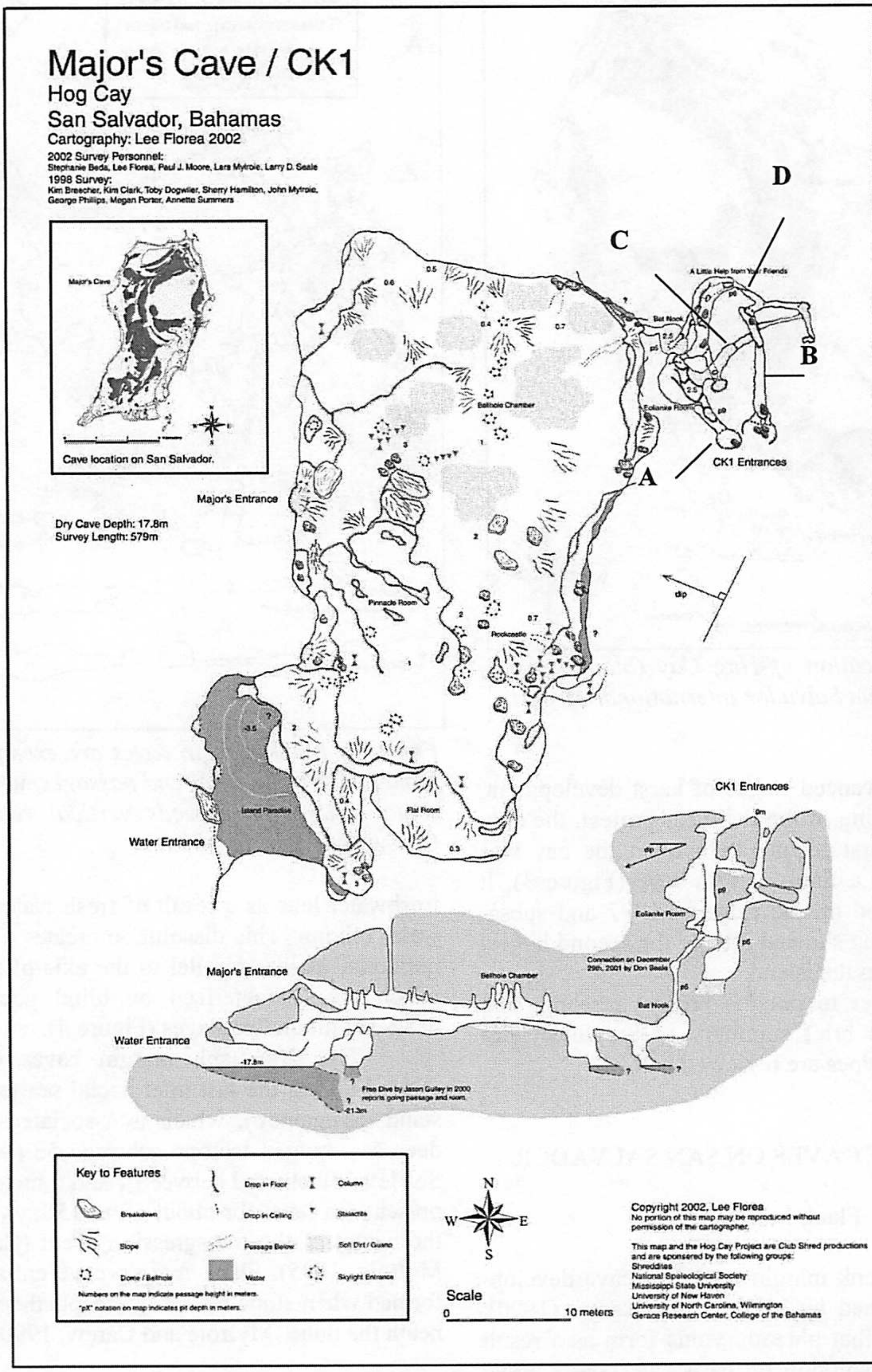

*Figure 3. Map of Majors Cave / CK1 system. Majors Cave, a flank margin cave, was intersected by CK1, a solution chimney, creating the deepest known dry cave in the Bahamas at 17.8m. Locations **A**, **B**, **C**, and **D** are collection sample points for XRD analysis.*

Banana Holes

Harris et al. (1995) describe banana holes as shallow phreatic voids that develop along the top of the freshwater lens, inland from the lens margin. In the Bahamas, this dissolution occurs in lowland plains, such that the voids are shallow. Collapse of the thin bedrock cap results in a depression with limited vertical depth and extended horizontal distances up 10 meters (Figure 5).

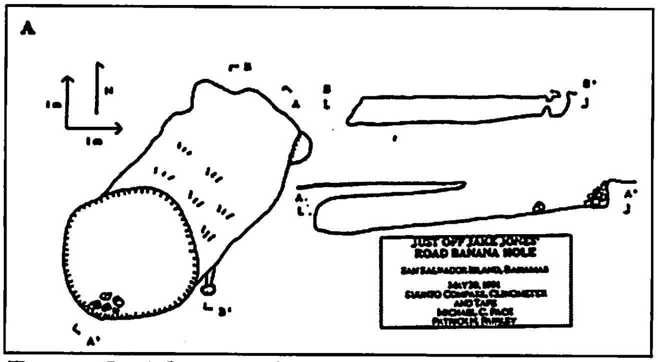

Figure 5. A banana hole commonly found on San Salvador. Entry is only possible after collapse of bedrock cap (from Pace et al., 1993).

As with flank margin caves, the dry banana holes of today formed during the last interglacial highstand; however, they are not as expansive as flank margin caves because of the less aggressive nature of the freshwater at the top of the lens, compared to conditions at the lens margin.

Smart and Whitaker (1989) argue that carbonic acid, formed by dissolution of carbon dioxide generated by micro-organisms and root respiration in the soil, provides the major chemical potential that drives dissolution in most karst areas. Their argument implies that soil P_{CO_2} increases with depth and density of the soil mat. They further their argument by describing the development of banana holes to be a result of the following:

1. A direct effect of soil depth on P_{CO_2}.
2. The persistence of decomposition at deeper, moister sites.
3. The tendency for organic material to erode from micro-topographic highs and accumulate in lows.
4. The tendency for vegetation to preferentially occupy these accumulation sites.

This model may apply to certain types of dissolution features found in the Bahamas; however, it does not address banana holes that are not yet open to the surface, or voids that have a nearly intact roof with a small entrance at the surface (Harris et al., 1995; Figure 5). The organic material located at the bottom of the banana holes may contribute to further enlargement of an exposed banana hole; however, this would be a secondary process, independent of initial development.

Pit Caves

Pit caves are dissolution features that transmit meteoric water from the epikarst to the top of the freshwater lens or water table (Mylroie and Carew, 1995). As pit caves are open channels, they deliver the water at a much faster rate than diffuse flow through the vadose zone. They have been referred to as vadose fast-flow routes (Jocson et al., 2002). The development of pit caves results from concentration of meteoric water in the epikarst, which exploits weak points in the carbonate rock to open a macroscopic pathway into the subsurface. Piracy of epikarst flow by new pit caves is common, creating more pit caves than the available water budget would appear to allow (Harris, et al., 1995). This paper will address the mechanisms responsible for pit cave morphology.

METHODS

In order to examine possible mechanisms controlling pit cave morphology, compass and tape surveys of karst features on Hog Cay were employed. Land surveys connecting the cave surveys, permitted spatial analysis of karst features on Hog Cay. This analysis resulted in the construction of a three-dimensional representation of Hog Cay using ArcView 3.2a. X-ray diffraction analyses of pit cave wall rock assessed mineralogical composition, and petrographic analysis of the eolianites determined the relative age of Hog Cay.

RESULTS AND DISCUSSION

The field work on Hog Cay has resulted in a distinction being made between vertical shafts and solution chimneys, which have been collectively referred to as pit caves in papers on Bahamian karst development. Vertical shafts propagate vertically into the vadose zone with little, if any, horizontal component. Solution chimneys have a tendency to follow the foreset beds of the dune for some distance and are morphologically analogous to solution chimneys found in continental settings as described by White (1988).

In continental settings, solution chimneys form by following tilted bedding planes, faults or fractures in the subsurface; however, on the seismically quiescent San Salvador platform, with its well-sorted carbonate eolian ridges, one would not expect to find extensive folding, faulting or fracturing. The field work on Hog Cay has revealed that solution chimneys do develop in young rocks on tropical islands and are not restricted to continental settings or regions of tectonic activity.

Vertical Shafts

Vertical Shafts show evidence of limited channeled surface flow that assists in the collection of autogenic water to a specific point of insurgence. Typically, points of insurgence on Hog Cay are attributed to micro-topographic lows that preferentially collect the meteoric water. Pohl (1955) and Merrill (1960), studying vertical shaft development in central Kentucky, describe that vertical shafts are of a vadose origin where seepage through a caprock allows for a point of attack on the limestone. Mylroie and Carew (1995) explain this for an island setting, stating that the epikarst, commonly with a calcrete crust, is the retardant factor allowing for discrete point inputs. Field observations on Hog Cay suggest that localized vadose flow is the primary controlling factor of pit cave development.

Vertical shafts form parallel to the effects of gravity and like their continental counterparts, show little if any morphological control by bedding structures (Figure 6). There is no correlation between elevation and the formation of vertical shafts; however, Pace et al. (1993) observed that most vertical shafts are located on dune ridges at elevations above 7 meters.

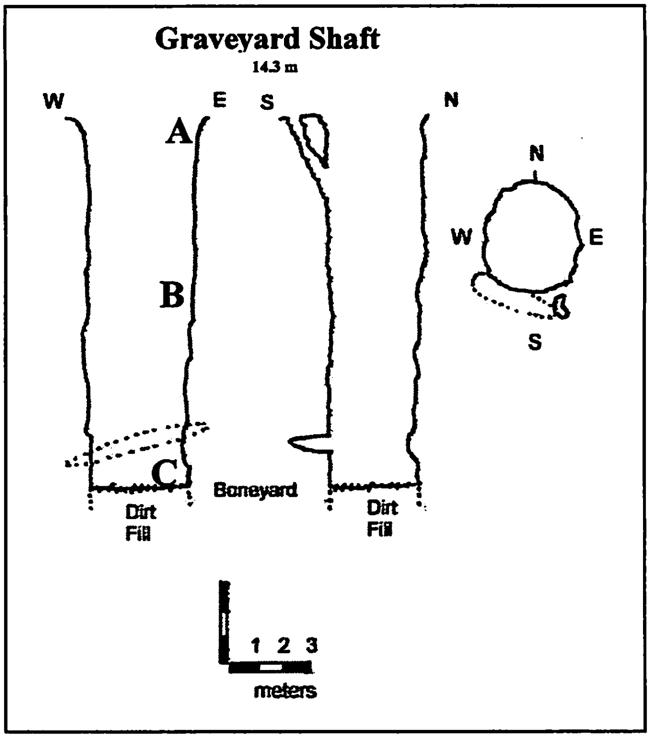

*Figure 6. Vertical shaft discovered on Hog Cay during the 2001 expedition. Deemed to be one of the deepest vertical shafts in the Bahamas, Graveyard Shaft extends well over 14m. Dotted line indicates an intercepted void in the subsurface. Locations **A**, **B**, & **C** indicate sample collection points for XRD analysis.*

Dune ridges described by Pace et al. (1993) were of an öolitic nature, and pit cave development rarely penetrated into lower bioclastic rock. However, current field investigations of the Owl's Hole Formation at Hog Cay, where no öolitic rock has been found, does show that extensive karst development can occur in bioclastic rock, and, in some cases, extend downward to near sea level.

Brucker et al. (1972) show that vertical shaft development is a result of complementary effects of geochemistry and flow dynamics, where meteoric water flows down the sides of the shaft, commonly as a supercritical-laminar flow. This flow is in the form of a film that is undersaturated with respect to calcite. Brucker et al. (1972) argue that the near-perfect cylindrical nature of vertical

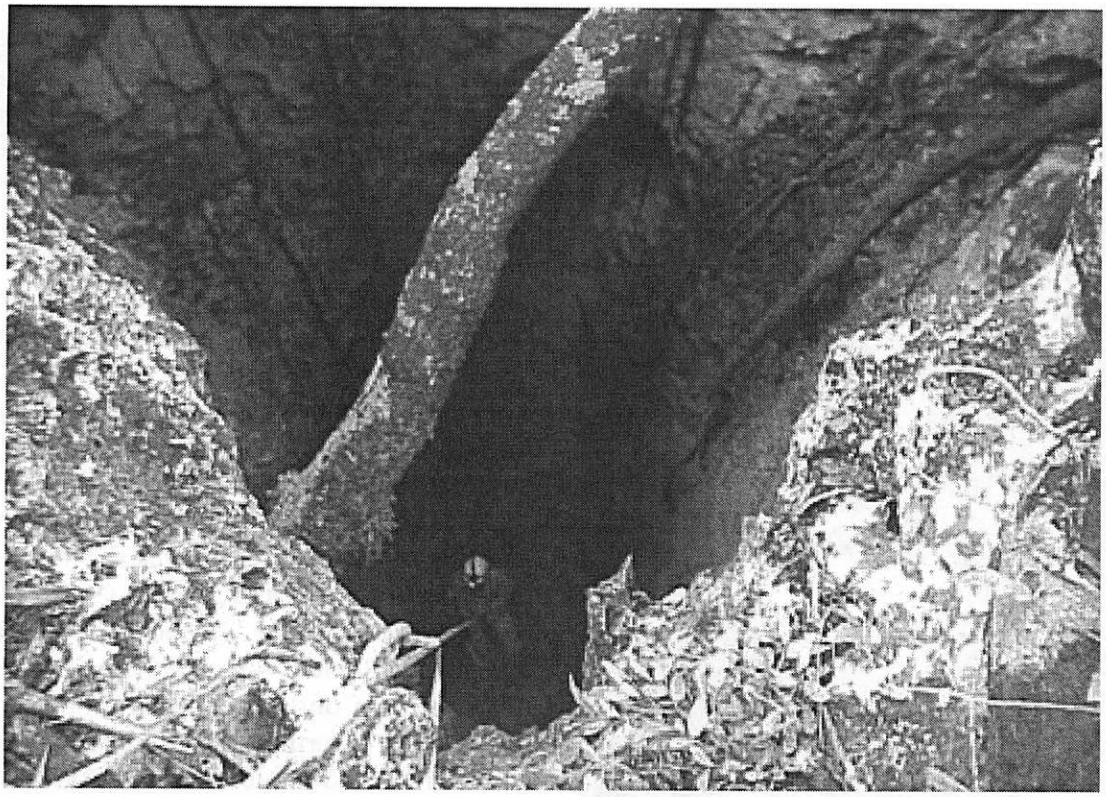

Figure 7. Image of Graveyard Shaft. Rappeller is only halfway down shaft.

shafts may be due to this supercritical-laminar flow. They infer that any projections and/or ledges on the vertical wall will reduce the velocity of film flow, which will create a hydraulic jump from a laminar flow to a turbulent flow condition. As a result, the erosion rate at the protuberance will be accelerated until only the vertical wall remains and the flow goes back to a laminar state The morphology of vertical shafts observed on Hog Cay, and elsewhere on San Salvador, appears to correspond to this hypothesis of vertical shaft development (Figure 7), and supports the process of vertical dissolution as observed by Pohl (1955), Merrill (1960), Pace et al., (1993) and Mylroie and Carew (1995).

Solution Chimneys

Unlike vertical shafts, solution chimneys show some appreciable morphological control due to bedding structure (Figure 11D). White (1988) states that the distinction between vertical shafts and solution chimneys is based on the balance between hydrologic control and structural control of shaft morphology. In White's study area Kentucky and Pennsylvania, he was able to show that certain vadose-origin caves are controlled by faults and fractures, thus displaying an offset vertical incision into the subsurface. However on San of Salvador, a tectonically stable platform, there are no apparent faults or fractures.

Caputo (1995) described how eolian deposits can be sorted by grain size into alternating coarse-grained and fine-grained strata. Coarse-grained strata are often poorly-cemented appear as micro-recesses in weathered outcrops. Conversely, fine-grained strata tend to be well-cemented and stand out as micro-ledges when exposed in weathered outcrops (Figure 8). It is postulated that in the subsurface, the coarse-grained, poorly-cemented strata are the preferred flow path for vadose water. This water is perched on the fine-grained, well-cemented strata and is forced to flow laterally along the foreset beds. In this case, cave passages tend to follow the dip of the foreset beds for some distances (Figure 9).

Exploration shows that solution chimneys on Hog Cay regularly end in a soil mat. In one exception, CK1, the solution chimney has been connected to an underlying flank margin cave (Majors Cave) and exploration is possible through the entire system (Figure 3).

It is hypothesized that once the connection between CK1 and Majors cave was attained, the soil plug that was in CK1 washed out, thus revealing the entire solution chimney. The connection between CK1 and Majors cave is an exciting discovery, especially since the cave survey indicates that it is the deepest known dry cave (17.8 m) in the Bahamas. This connection, however, may be fortuitous as synchronicity or order of cave genesis has not been determined.

The connection between CK1 and Majors Cave was further addressed by using the constructed three dimensional map of observed karst features on Hog Cay (Figure 10). The spatial analysis of the observed caves show that, with the exception of CK1 and Majors Cave, each of the caves are completely independent of each other, and no available evidence shows connections to other caves. Continued field investigations are in order to draw further constraints on possible cave connections and sequence of cave development

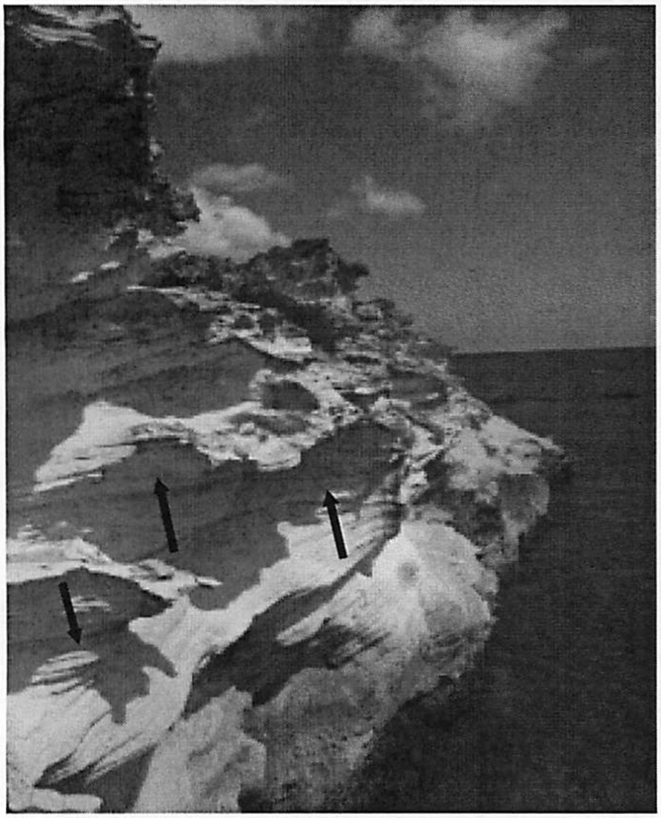

Figure 8. Exposed weathered outcrop displaying coarse-grain and fine-grain strata, as indicated by black arrows.

X-ray Diffraction Analysis

X-ray Diffraction (XRD) analysis shows that the predominant mineral present in the wall rock of pit caves is aragonite with an appreciable amount of calcite (Tables 1 and 2). The aragonite was found in a sample taken from the midpoint of the shaft (Figure 6, B), where it is bounded top and bottom by regions of ~100% calcite (Figure 6, A & C). While aragonite-rich bedrock appears to be the dominant rock type found on Hog Cay, the existence of ~100% calcite found in Graveyard Shaft indicates that there are zones in which complete inversion of primary aragonite takes place. At Graveyard Shaft, this is attributed to two formerly saturated regions in the present vadose zone – capillary water in the epikarst and a paleo-freshwater lens at the 5e sea level highstand – which allowed for inversion of primary aragonite to calcite at the pit top and bottom, respectively. The lack of significant inversion of aragonite to

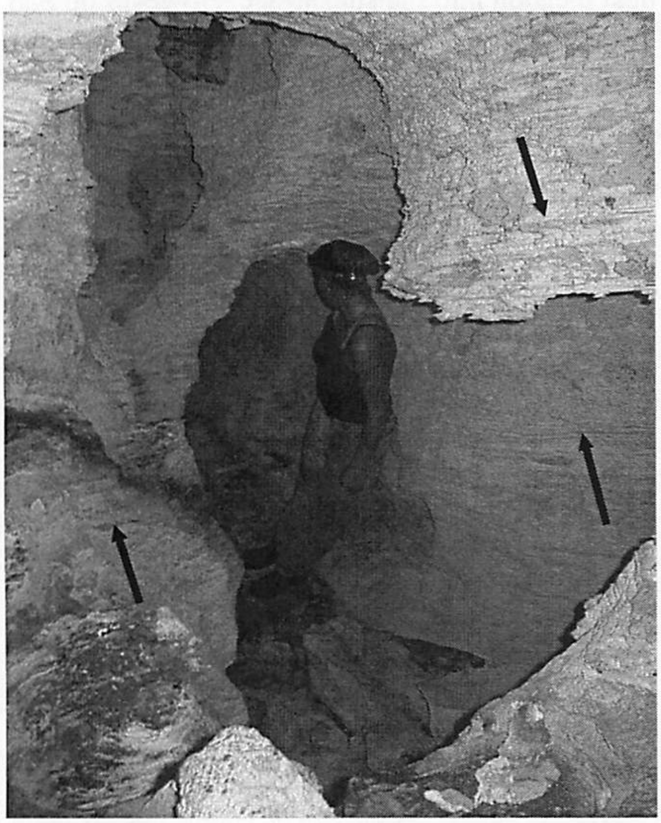

Figure 9. Passage in CK1, a solution chimney. Development is contingent on water flow being directed by strata within calcarenite.

Sample ID	Location	Relative Abundance*
GY-1	Figure 6, A	Ca>>Ar
GY-2	Figure 6, B	Ar>Ca
GY-3	Figure 6, C	Ca>>Ar
CK1-1	Figure 3, A	Ar>Ca
CK1-2	Figure 3, B	Ar>Ca
CK1-3	Figure 3, C	Ar>Ca
CK1-4	Figure 3, D	Ar>Ca
* Relative abundances based on curve area estimates		

Table 1. XRD analysis of samples collected from a vertical shaft (Graveyard Shaft) and a solution chimney (CK1) on Hog Cay.

Sample ID	Cave Name	Sample Location	Relative Abundance*
3HD-1	3 Holes Down	Inside Entrance	Ar>Ca
3HD-2	3 Holes Down	~4m inside pit	Ar>Ca
3HD-3	3 Holes Down	Near base of pit	Ar>Ca
RS-1	Rock Slide	Inside Entrance	Ar>Ca
RS-2	Rock Slide	Near base of pit	Ar>Ca
LB-1	Lone Bat	Inside Entrance	Ar>Ca
LB-2	Lone Bat	Near base of pit	Ar>Ca
* relative abundances based on curve area estimates			

Table 2. XRD analysis of collected samples from various solution chimneys on Hog Cay

calcite along the shaft walls is due to the rapid transit time of vadose water, which does not allow for the necessary residence time of meteoric water needed for the inversion.

SUMMARY

Pit caves found on Hog Cay are in the form of vertical shafts and solution chimneys. The micro-recesses and micro-ledges as described by Caputo (1995) are ubiquitous in both the vertical shafts and solution chimneys. However, the vertical shafts have no indication of bedding control, which may be due to cementation in the fine-grained layers being less complete in areas of vertical shaft development. This is in spite of the fact that bedding orientation is the same as nearby solution chimneys, which show passage development along the foreset beds.

The primary controlling factor in solution chimney morphology appears to be directly related to selective cementation of the eolian calcarenites, as defined by Caputo (1995). The preferred flow path for vadose water is the poorly cemented, coarse-grained strata within the eolian calcarenites. This water is perched on the well-cemented, fine-grained strata. In this case, water is controlled by the well-cemented, fine-grained strata and follows the dip of the foreset beds for some distance (Figure 11).

At this time, it is unclear why vertical shafts, are able to form near solution chimneys. It is possible that selective cementation is not continuous throughout Hog Cay. It is also possible that the organic mat in the bottom of the shaft provides increased CO_2 and therefore increased dissolution potential at the shaft's base. More extensive surveys of the karst features on Hog Cay may provide further insight into the primary controlling factors in pit cave development.

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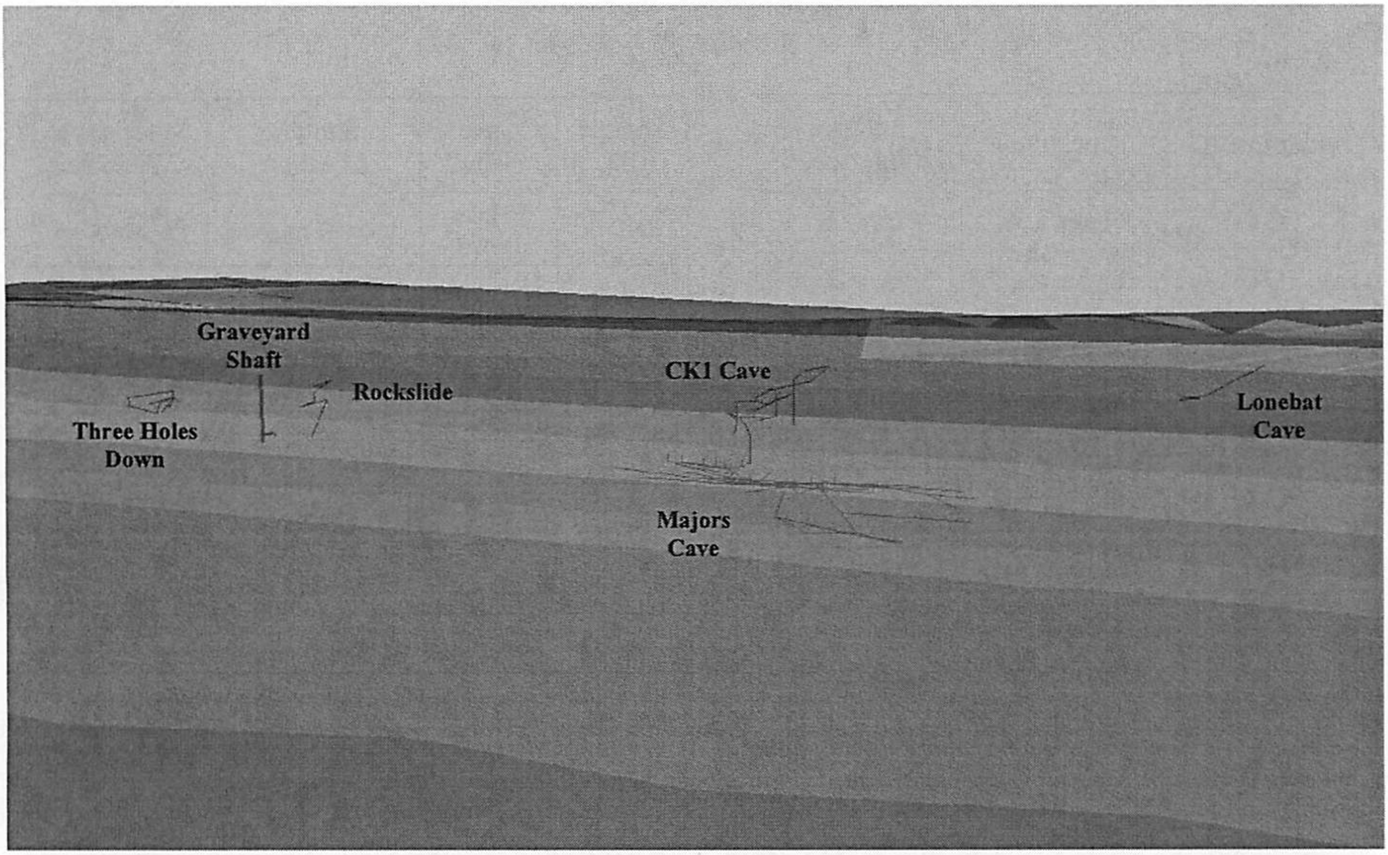

Figure 10. Three-dimensional representation of sampled karst features on Hog Cay.

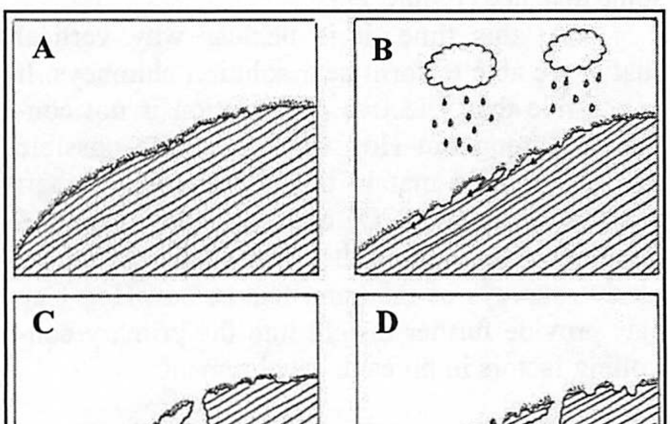

*Figure 11. Genesis of solution chimney development. **A** represents the initial state of an eolian dune; **B** is the development of an epikarst; **C** shows how a solution chimney develops along the dipping foreset beds; and **D** is the final stage of the solution chimney, where piracy of the chimney is caused by the development of a secondary vertical shaft.*

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