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THE CAVES OF ABACO ISLAND, BAHAMAS: KEYS TO GEOLOGIC TIMELINES

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Abstract: Abaco Island, located on Little Bahama Bank, is the most northeastern island in the Bahamian archipelago. Abaco exhibits typical carbonate island karst features such as karren, blue holes, pit caves, banana holes and flank margin caves. Landforms that resemble tropical cone karst and pseudokarst tafoni caves are also present. The three cave types of Abaco—flank margin caves, pit caves, and tafoni caves—are abundant, but each forms by very different mechanisms. Flank margin caves are hypogenic in origin, forming due to mixing dissolution at the margin of the freshwater lens. Since the lens margin is concordant with sea level, flank margin caves record the position of sea level during their formation. Flank margin caves exhibit phreatic dissolutional features such as bell holes, dissolutional cusps and spongework. Pit caves form as vadose fast-flow routes to the freshwater lens and are common on the Pleistocene eolianite ridges of the Bahamas. Pit caves are characterized by their near-vertical or stair-step profiles. Because pit caves form in the vadose zone, their position is not tied to sea level. Tafoni caves are pseudokarst features that form when the soft interior of an eolianite ridge is exposed to subaerial erosion. Since tafoni caves form by mechanical processes, they do not exhibit phreatic dissolutional features. Tafoni caves may be mistaken as flank margin caves by the untrained observer, which may cause problems when using caves as sea-level indicators. Each of Abaco's unique cave types may preserve depositional and erosional features that are useful to the researcher in creating general geologic timelines. While these timelines may not give exact dates, they are useful in the field for understanding depositional boundaries and determining sequences of geologic events.

Introduction

The Commonwealth of the Bahamas (Fig. 1A), located southeast of Florida and northeast of Cuba, consists of 29 islands, numerous keys, shallow banks and rocks (Albury, 1975). The northwest-southeast trending archipelago extends 1400 km from the stable Florida peninsula to the tectonically active Caribbean Plate boundary near Hispaniola (Carew and Mylroie, 1995). The Turks and Caicos Islands make up the southeastern extent of the same archipelago, but are a separate political entity. The Bahamian portion of the archipelago is 300,000 km^2 in area, 11,400 km^2 of which is subaerial land (Meyerhoff and Hatten, 1974).

Abaco Island (Fig. 1), located on Little Bahama Bank, is the most northeastern island in the archipelago. It is bordered on the east by the deep waters of the Atlantic Ocean, on the south by the deep waters of N.W. Providence Channel and N.E. Providence Channel, and on the west by the shallow waters of the Little Bahama Bank (Fig. 1A). The landmass of Abaco consists of two main islands, Great Abaco Island and Little Abaco Island, and numerous outlying cays (Fig. 1B).

The Bahamas have long been the focus of geologic work on modern carbonates (Illing, 1954; Multer, 1977; Tucker and Wright, 1990; Carew and Mylroie, 1997 and references therein). The Bahama Platform has particular interest to geologists as it provides a modern analog for the dynamics of ancient carbonate depositional platforms, many of which are major petroleum reservoirs. The Bahama Platform (Fig. 1A) is composed of a series of thick, shallow-water, carbonate banks along the subsiding margin of North America (Mullins and Lynts, 1977). The current landscape of the Bahamas is largely constructional and is greatly influenced by glacioeustatic sea-level fluctuations (Carew and Mylroie, 1997). Carbonate deposition occurs on the flat bank tops during glacioeustatic sea-level highstands when shallow lagoons dominate. During sea-level lowstands, sea level drops below the bank margins. Carbonate sedimentation ceases and subaerial karst processes dominate on the exposed bank tops. Lowstands are recorded in the sedimentary record by the development of terra rossa paleosols. These fossil soil horizons are the result of the concentration of insoluble materials, such as atmospheric dust, due to pedogenic processes.

Background

Island karst is a result of the unique environments and associated processes that affect carbonates in small island settings (Mylroie et al., 2004; Jenson et al., 2006). Island karst is different from typical karst landscapes that develop in continental settings, and from karst on islands, which

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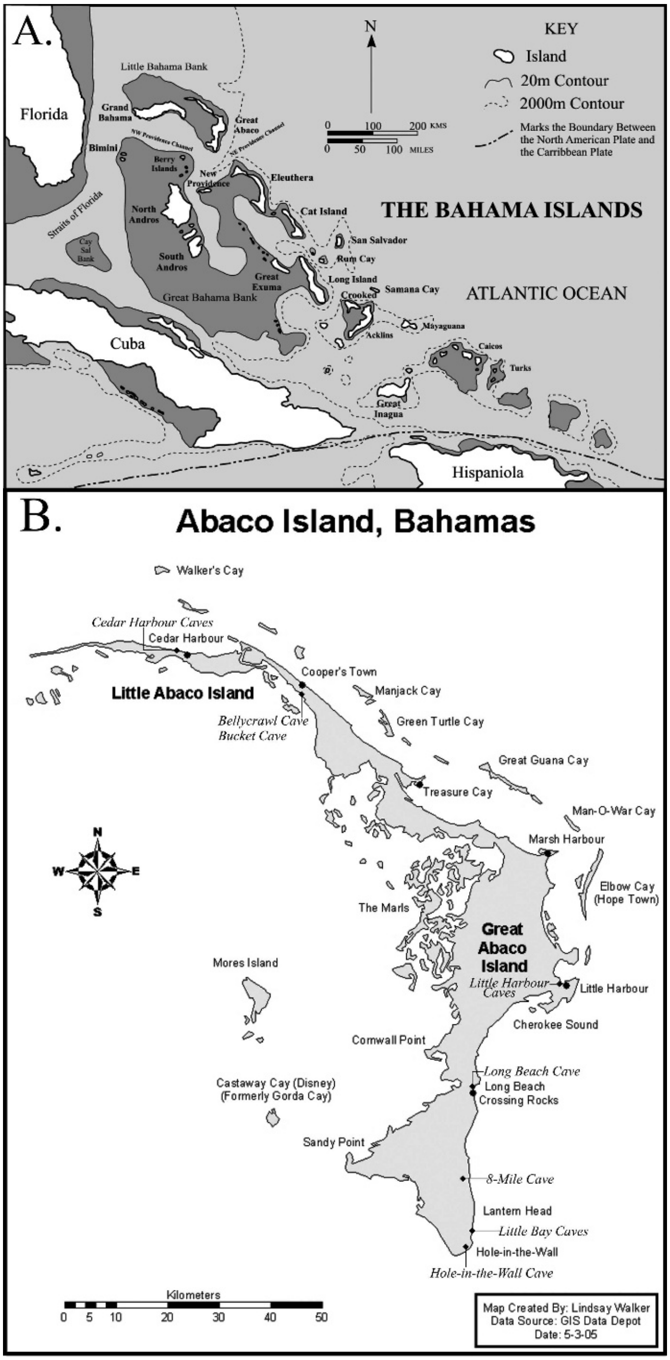

Figure 1. A: Map of the Commonwealth of the Bahamas (modified from Carew and Mylroie, 1995). B: Map of Abaco Island, Bahamas, showing cave locations. Town locations are labeled in normal font. Cave locations are shown in italics. When two or more caves are close together they are shown as one dot: Cedar Harbour Caves = Cedar Harbour Cave I–V; Little Harbour Caves = Azimuth Cave, Dripping Stones Cave, Hunter's Cave, Manchineal Cave, and Sitting Duck Cave; Little Bay Caves = Little Bay Cave I–III.

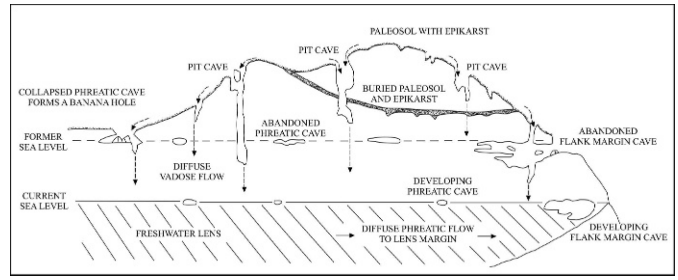

Figure 2. Schematic diagram of island karst processes on a simple carbonate island showing the fresh water lens (modified from Mylroie and Carew, 1995).

forms in the interiors of large islands such as Puerto Rico, Cuba, and Jamaica (Vacher and Mylroie, 2002). Karst on islands is more similar to continental karst than carbonate island karst. The principles of island karst are summarized by the Carbonate Island Karst Model, or CIKM, described by Mylroie, et al. (2004) and Jenson et al. (2006).

Most of the freshwater that exists on carbonate islands like the Bahamas is stored in the freshwater lens, which is an accumulation of meteoric water that floats on the underlying marine water due to the density contrast (Fig. 2). Surface streams are rare or completely absent. As a result, many typical karst processes, such as stream cave formation, do not take place. The karst features of carbonate islands can interact in complex ways forming a highly modified landscape (Fig. 2).

Karst features known to occur on Abaco include karren, blue holes, pit caves, banana holes, flank margin caves, and landforms that resemble tropical cone karst. Tafoni, pseudokarst voids formed by subaerial erosion, are also present. Only the three cave types—flank margin caves, pit caves, and tafoni caves—are discussed in this paper. Because these cave types form by very different mechanisms, each provides a unique understanding of island karst and geomorphic processes, as well as clues to the geologic history of Abaco. The purpose of this study is to describe the presence of these caves on Abaco and to demonstrate the importance of caves in constructing general geologic timelines.

Flank Margin Caves

Flank margin caves form from mixing dissolution at the margin of the freshwater lens under the flank of the enclosing landmass (Mylroie and Carew, 1990). Because the calcium carbonate saturation curve is convex upward, the mixing of two waters of varying concentrations creates a solution that is less saturated with respect to calcite (Dreybrodt, 2000). The interaction of waters of different chemistries at the boundaries of the freshwater lens, therefore, creates an environment of preferential carbonate dissolution (Mylroie and Carew, 1990).

Mixing dissolution occurs both at the top of the lens, where vadose freshwater mixes with phreatic freshwater, and at the bottom of the lens, where phreatic freshwater mixes with marine water (Mylroie et al., 2004). The top and bottom of the lens are also density interfaces, which allow for the collection of organic material. The oxidation of these organics produces CO_2 and thus increases dissolutional capability (Mylroie et al., 2004). Evidence suggests that the presence of sulfate-reducing bacteria in the mixing zone may have a significant role in the formation of mixing zone porosity (Bottrell et al., 1993). Thus, both organic and inorganic mixing are involved. The mixing zones at both the top and bottom of the lens meet at the lens margin (Fig. 2), forming a site that is most favorable for mixing zone dissolution. Because the margin of the freshwater lens is concordant with sea level (Fig. 2), flank margin caves mark the position of sea level during their formation (Carew and Mylroie, 1995).

Flank margin caves are hypogenic (*sensu* Palmer, 1991). They form as complex mixing chambers, not conduits for turbulent-flow underground drainage. As such, they commonly form with no surface openings, although entrances may later be created when erosional retreat of the island flank intersects the cave. Their shape is globular with an extended horizontal dimension and limited vertical development reflecting their origin along the thin lens margin. As dissolution continues over time, individual voids may intersect to create larger caves. The joining of the voids creates a characteristic cave pattern of a maze of larger chambers connected by smaller passages. These small passages often radiate outward from the main chambers but end abruptly in bedrock walls. The walls and ceilings exhibit large dissolutional cusps, bellholes, and spongework as evidence of their phreatic formation.

Though the dissolutional cusps that are common in flank margin caves have a similar appearance to the scallops found in many stream caves, they are different in several ways. Scallops form under turbulent flow conditions, are asymmetrical (providing a flow direction indicator), and their size is inversely proportional to velocity (Curl, 1966; Curl, 1974). In mixing zone caves, where flow is strictly laminar, scallops do not form. However, dissolution does act differentially on the bedrock surfaces within the cave to produce dissolutional pockets or cusps.

Flank margin caves were first recognized in the Bahamas (Mylroie and Carew, 1990) and have since been found on Bermuda (Mylroie et al., 1995), Isla de Mona (Frank et al., 1998), the Mariana Islands (Mylroie et al., 2001), the Yucatan Peninsula of Mexico (Kelly et al., 2004), and Cuba (Soto, et al., 2004; Downey and Walck, 2005). The tectonically stable Bahamian archipelago continues to be the ideal location to study flank margin caves and mixing-zone porosity. To date, flank margin caves have been described in the Bahamas on Cat Island (Mylroie et al., 2006), Crooked Island (Lascu, 2005), Eleuthera Island (Lascu, 2005), Great Inagua Island (Roth, 2004), Long Island (Mylroie et al., 1991), New Providence Island (Mylroie et al., 1991), North Andros Island (Roth, 2004), San Salvador Island (Vogel et al., 1990), and South Andros Island (Carew et al., 1998). This paper reports the first study of flank margin caves on Abaco Island (Walker, 2006).

The majority of flank margin caves that are currently exposed in the Bahamas have dissolutional ceilings between 1 m to 7 m above modern sea level, which is consistent with formation in a freshwater lens elevated by the +6 m Oxygen Isotope Substage (OIS) 5e highstand that occurred approximately 125 ka (Carew and Mylroie, 1995). This evidence, combined with a lack of speleothem age dates greater than 100,000 years, suggests that all flank margin caves currently exposed in the Bahamas were formed during the OIS 5e highstand, and agrees with reported isostatic subsidence of the archipelago of 1–2 m per 100,000 years (Carew and Mylroie, 1995).

Pit Caves

Pit caves are vadose shafts that result from the gathering of meteoric water into discrete inputs in the epikarst (Mylroie and Carew, 1995). Pit caves are characterized by their near vertical or stair-step profiles, vertical grooves on the walls, and the absence of curvilinear dissolution surfaces that are characteristic of phreatic conditions (Mylroie and Carew, 1995). Pit caves commonly have a well-developed system of feeder tubes within the epikarst that deliver water to the pit (Harris, et al., 1995). The active lifetime of a pit cave is relatively brief as its development is interrupted by the formation of newer pits upstream that pirate its recharge. The end members of this process are areas of high pit density called pit complexes, which represent the accumulated pit cave development and subsequent abandonment over time (Mylroie and Carew, 1995). Pit caves in these complexes can occur at densities of over 100 per km^2 (Harris et al., 1995; Seale et al., 2004).

Pit caves in the Bahamas occur as both simple vertical shafts and complex features resembling solution chimneys (Seale et al., 2004). The more complex pits alternate between angled reaches developed along eolianite foresets and vertical reaches that cut through the depositional structure of the bedrock to form a stair-step profile. Pit caves rarely exceed 10 m in depth, but may connect with other pits to form horizontal extents of up to 50 m (Seale et al., 2004). On Abaco and other Bahamian Islands, pit caves are well developed in Pleistocene eolianite ridges, suggesting a relatively fast rate of formation.

Tafoni Caves

Cavernous weathering is the result of differential erosion on a rock surface that allows some areas of the rock to be preferentially removed while surrounding areas remain intact (Turkington and Phillips, 2004). The resulting pseudokarst voids or caverns are traditionally known as honeycombs, aveoli, and tafoni (McBride and Picard, 2000). Honeycombs and aveoli are centimeter to decimeter in size while tafoni (singular: tafone) are meterscale voids (McBride and Picard, 2000). Tafoni have been described from localities worldwide and a diverse range of climate regimes. They are especially common in arid and coastal environments (Sunamura, 1996). Tafoni are also known to form in a variety of rock types including sandstone, conglomerates, limestone, granite, and volcanic tuff (Campbell, 1999; McBride and Picard, 2000; Huinink et al., 2004 and references therein; Turkington and Phillips, 2004 and references therein).

The formation of tafoni is poorly understood and efforts to identify a single causative mechanism have been largely unsuccessful. Tafoni are most commonly attributed to salt weathering, although a variety of chemical weathering processes have also been described in tafoni formation (Sunamura, 1996; Campbell, 1999; Huinink et al., 2004; Turkington and Phillips, 2004 and references therein). Physical weathering may also be involved in tafoni formation, as many rock surfaces that are susceptible to cavernous weathering commonly exhibit a hardened outer crust over a weaker interior (Turkington and Phillips, 2004 and references therein). Removal of the outer crust allows for preferential erosion of the soft interior. It is likely that tafoni formation is controlled by complex conditions within the natural environment and that the dominant causative mechanism(s) will vary depending upon the conditions present in that environment. Tafoni in the Bahamas have recently been characterized by Owen (2007), who provides a comprehensive review of the relevant literature.

Methods

Preliminary fieldwork, focused on locating caves and important geologic outcrops, was conducted March 11 to 20, 2005. The remainder of the fieldwork, including mapping of all known caves, was completed from May 15 to June 15, 2005. The Friends of the Environment organization in Marsh Harbor, Abaco, assisted with local logistical support. A permit to conduct the research was secured through the Bahamian government.

Caves were surveyed using a compass, inclinometer, tape, and sketchbook, following the guidelines of the National Speleological Society (NSS) outlined in Dasher (1994). Survey data were entered into COMPASS software for reduction and line plot generation. Maps were drafted in Corel Xara × 1.0 using the line plots, field sketches, and the Association for Mexican Cave Studies (AMCS) Standard Cave Map Symbols (Sprouse, 1991). Since length is not an appropriate classification for flank margin caves or tafoni caves, the area and perimeter of each cave were computed using AutoCAD software. The area of internal bedrock pillars, columns, and bedrock bodies caught in passage loops was subtracted from the overall cave area. The perimeter of these features, however, was added to the overall cave perimeter, as these bedrock components were part of the water/rock interaction surface that formed the flank margin caves. When possible, the elevations of the caves were also measured relative to sea level. When caves were located too far inland to use sea level as a reference point, their approximate elevations were determined by plotting on topographic maps. Finally, the caves were classified as flank margin caves, pit caves, or tafoni based on their morphological characteristics.

Table 1. Areas and perimeters of mapped flank margin caves on Abaco Island, Bahamas.

Cave	Area (m^2)	Perimeter (m)
Bucket	21	38
Bellycrawl	23	29
Little Bay III	40	35
Cedar Harbour III	43	40
Cedar Harbour V	62	59
Cedar Harbour II	67	45
Little Bay I	68	58
Dripping Stones	71	51
Cedar Harbour I	133	67
Cedar Harbour IV	153	80
Little Bay II	156	60
Azimuth	164	73
Sitting Duck	185	83
Manchineal	186	71
Hunter's	214	316
Long Beach	428	386
8-Mile	919	692
Hole-in-the-Wall	3422	1941

Results and Discussion

Flank Margin Caves

Eighteen flank margin caves were explored and mapped on Abaco Island (Table 1), ranging in area from 21 m^2 (Bucket Cave; Fig. 3) to 3422 m^2 (Hole-in-the-Wall Cave; Fig. 4). Flank margin caves on Abaco fit the model of Mylroie and Carew (1990) in nearly every case and exhibit characteristic hypogenic features such as bell holes, dissolutional cusps, and spongework. They have limited vertical, and extensive horizontal dimensions (Figs. 3 and 4). Each cave that exhibited these characteristics, except one, was located between 1 and 7 meters above modern sea level.

Bellycrawl Cave near Cooper's Town, however, was located 10 m above modern sea level. This elevation was determined by surveying from the position of the cave entrance to sea level using a tape and a Suunto inclinometer. Bellycrawl Cave consisted solely of one low crawlway that quickly became too small for human exploration. The presence of other small phreatic voids along the same 10 m horizon implies that a freshwater lens may have reached an elevation of 10 m in this location. The absence of phreatic voids at this elevation on the rest

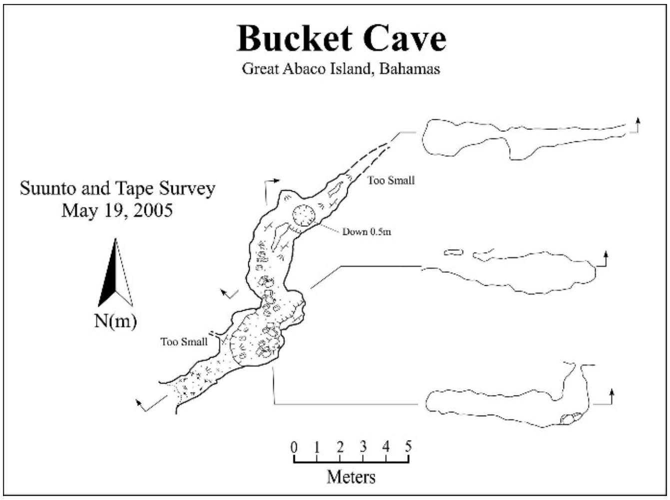

Figure 3. Map of Bucket Cave, Cooper's Town, Great Abaco Island, Bahamas.

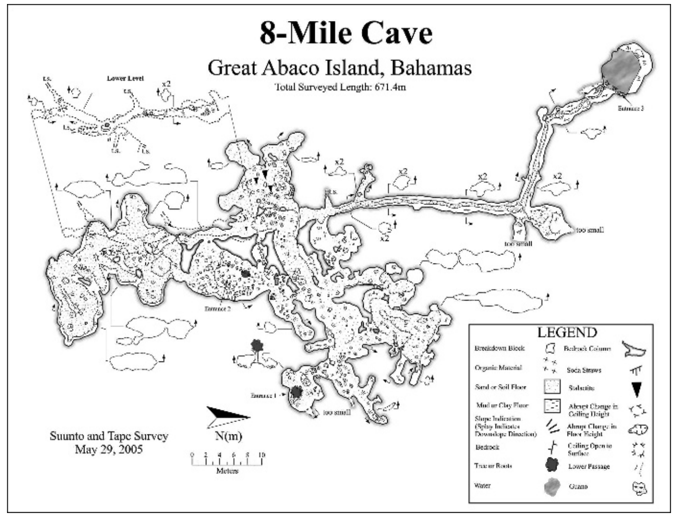

Figure 5. Map of 8-Mile Cave, Great Abaco Island.

of the island implies that this was most likely a local phenomenon. The small size of the voids could mean that the lens did not occupy that position for an extended period of time and may even have been episodic or the result of a small perched water table.

Gentry and Davis (2004) describe perching of wetland waters on San Salvador Island in association with low permeability paleosols. A +10 m dissolutional ceiling from Hatchet Bay Cave on Eleuthera Island in the Bahamas was also explained by storm loading of the lens and perching of the water table by a paleosol (Lascu, 2005). Terra rossa paleosols, due to their relative impermeability and common occurrence in the Bahamas, no doubt have at least local control over freshwater lens position, just as a lower-permeability layer would affect water-table position in a continental setting. A paleosol was visible along the shore fronting the voids. However, it was not possible to determine within the scope of this project if the paleosol may have had a role in the development of the 10 m horizon. Perching of the freshwater lens is certainly a phenomenon that needs further investigation throughout the Bahamas.

The keyhole passage in 8-Mile Cave is an unusual passage shape for a flank margin cave. It is located at the northeast extent of the cave and consists of a long passage trending approximately north-south, and makes a nearly 90° turn continuing to the west (Figs. 5 and 6). In epigenic (i.e., stream) caves, phreatic processes form tubular passages with ovoid cross-sections while vadose flow creates deep, narrow canyons with rectangular cross-sections (Palmer, 1991). Keyhole-shaped passages in

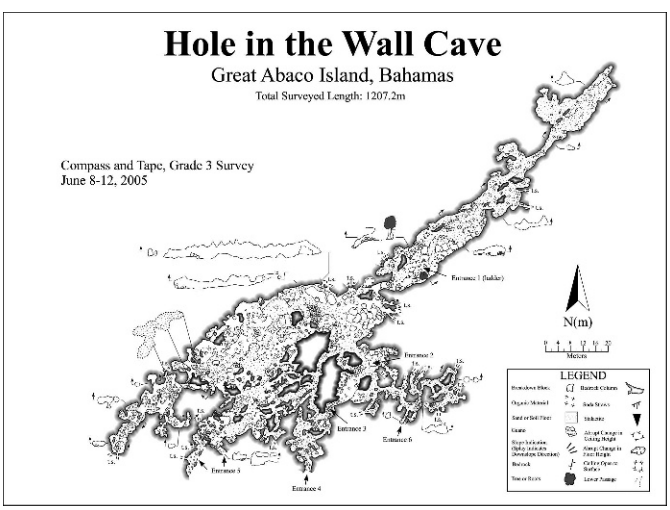

Figure 4. Map of Hole-in-the-Wall Cave, Great Abaco Island, Bahamas.

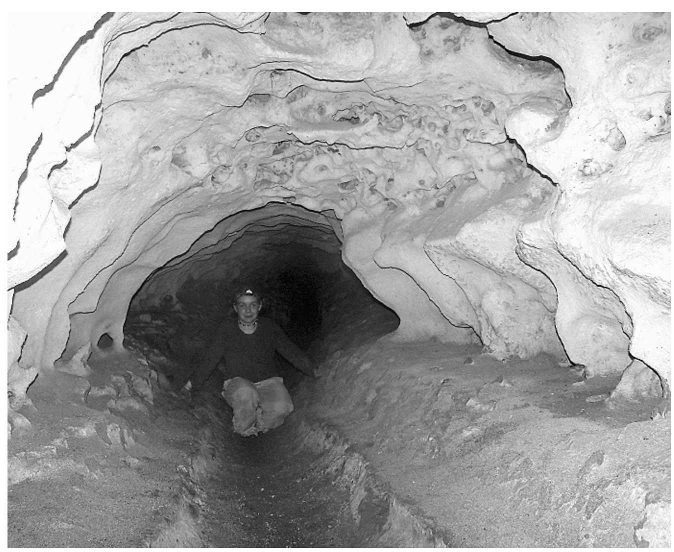

Figure 6. The Keyhole passage in 8-Mile Cave, Great Abaco Island.

stream caves are usually the result of modification of an originally phreatic passage by vadose flow (i.e., formation of a canyon in the floor of an ovoid tube). Because 8-Mile Cave was not formed by stream processes, but rather by mixing dissolution, this typical explanation does not apply. The keyhole passage has phreatic origins as indicated by dissolutional cusps on the walls, ceiling, and spongework (Fig. 6). The trench in the floor, which causes the keyhole-shaped cross-section, seems to have come later, as it does not exhibit the same phreatic features as the rest of the passage. The trench may be explained by water entering the cave during storm events through a large crack present throughout much of the passage ceiling. If this water were to pond on the floor of the passage, it may form a trench by dissolution of the floor. The deepest area of ponding occurs where the passage makes the 90° bend to the west (Fig. 5). A small pool of water was present in this location during the initial survey of the cave. If ponding of surface waters are allowing for continued dissolution of the cave floor, 8-Mile Cave shows an interesting interaction with current hydrologic processes on Abaco, which is not typical of flank margin caves. Beyond the pool at the bend the passage continues as a solely phreatic feature before intersecting a large vadose pit that has developed from the surface (Fig. 5).

Some flank margin caves on Abaco also were useful in helping to determine the geologic history of the area in which they are located and even the relative age of the dune deposits in which they are enclosed. This is especially true in Little Harbour and Cedar Harbour where coastal flank margin caves contain stalactiflats (Elliott, 2007), breccia facies, beach deposits, and paleosols. The importance of these features is described later as part of the discussion of using these caves as geologic timelines. In addition, the presence of flank margin caves in Little Harbour located on opposite sides of the same eolianite ridge, such as Dripping Stones Cave and Hunter's Cave, provides evidence that the margin of the freshwater lens was active on both sides of the ridge at the same time. This suggests that the ridge itself may have become a small island during the OIS 5e highstand as surrounding topographic lows were inundated by the rising sea.

Pit Caves

Pit caves and solution pits are extremely common on Abaco. Some locations have particularly high solution pit densities, although most of these are too small for human exploration. Pit caves, or solution pits large enough for human exploration, are numerous in several locations, which includes the Hole-in-the-Wall area on the south side of the island. Only one pit cave, Blowhole Cave (Fig. 7), was mapped as part of this study because pit caves have been thoroughly covered by other workers (Mylroie and Carew, 1995; Harris et al., 1995; Seale et al., 2004).

Blowhole Cave is located near Hole-in-the-Wall on the southern coast of Abaco Island (Fig. 1). The cave entrance is found on the same headland as the sea arch known as

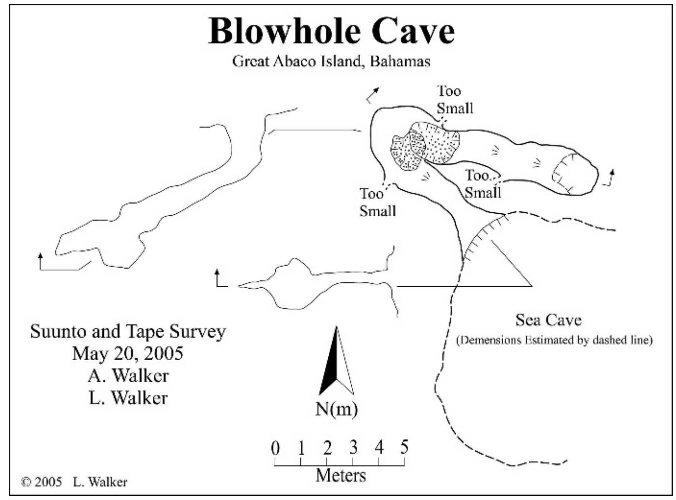

Figure 7. Map of Blowhole Cave, Great Abaco Island, Bahamas.

Hole-in-the-Wall. From the entrance the passage extends down a 35° slope, following the dip of the eolianite foreset beds. At the bottom of the slope a small horizontal crawlway continues to the southeast and ends in a steep drop into a sea cave where the waves can be seen breaking. It is not known if downward growth of the vadose pit penetrated the roof of the sea cave or if roof collapse in the sea cave intersected the vadose pit. However, most likely both mechanisms were at work. The interaction of the sea cave and the vadose pit creates a blowhole. Each time a wave breaks into the sea cave below, Blowhole Cave goes dark. The sound of the wave is funneled through the cave along with a strong burst of air, spray, and sand.

Tafoni Caves

During the initial reconnaissance for this study, a group of 14 caves, later named the PITA Caves (Table 2), was discovered high in an eolianite ridge along the beach west of Hole-in-the-Wall on the south end of the island. The PITA Caves were of interest at the onset of this study because they originally appeared to be located along a continuous horizon about 20 m above modern sea level (Fig. 8A). Their arrangement in a continuous horizon suggested that they were flank margin in origin. As discussed previously, current models of flank margin cave formation in the freshwater-saltwater mixing zone require that caves will be located between 1 and 7 m above modern sea level in agreement with the +6 m OIS 5e highstand (Mylroie and Carew, 1990). Given the tectonic stability of the Bahamas, a sea-level highstand of at least 20 m would be required to form flank margin caves at the elevation of the PITA Caves. A +20 m highstand has been proposed for OIS 11, but the data have been controversial, especially in the Bahamas (Lascu, 2005; Mylroie, 2008). The major problem with this argument is that no confirmed subtidal deposits dating from highstands prior to OIS 5e, including

Table 2. PITA cave elevations, Abaco Island, Bahamas. Elevations were measured from entrance ceiling to sea level.

PITA Cave	Elevation (m)
A	22.5
B	21.5
C	18.7
D	19.9
E	14.5
F	17.9
G	18.0
H	20.9
I	17.7
J	10.8
K	18.8
L	14.1
M	20.3
N	17.4

OIS 11, have been found in the Bahamas. If the PITA Caves were shown to be flank margin caves, they would have provided the first conclusive evidence of a sea-level highstand in the Bahamas higher than the +6 m OIS 5e that was still exposed above modern sea level despite subsidence.

Upon further investigation it became clear that the PITA Caves are not found in a continuous horizon. The large amount of vegetation in the area had initially made it impossible to see many of the caves. Once the vegetation around the caves had been removed and the elevations of the caves were measured it became clear that cave elevations were more random (Fig. 8B and Table 2). Also, individual investigation of each cave shows that they lack characteristic flank margin cave phreatic dissolutional features such as cusps and bell holes (Fig. 8C). The rough surfaces of the cave walls and ceilings are more typical of mechanical erosion (Fig. 8C). The combination of these observations demonstrates that the PITA Caves are not

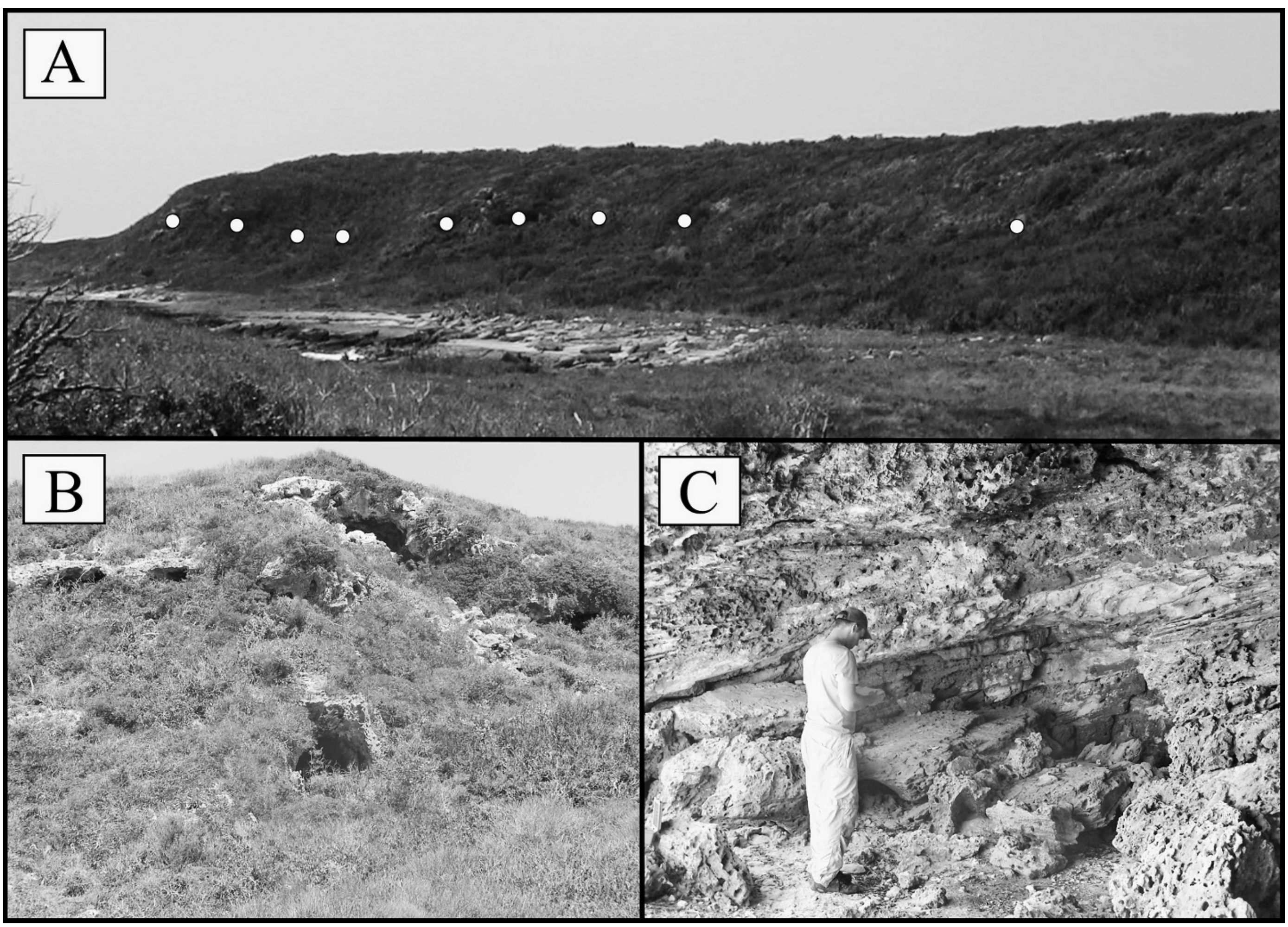

Figure 8. A: Apparent continuous horizon of the high PITA Caves as seen from the beach before vegetation was removed. White dots show cave entrances visible from the beach. B: Pita Caves F–J as seen from the beach. Notice the various elevations of the entrances. C: Interior of PITA Cave B showing evidence of mechanical erosion.

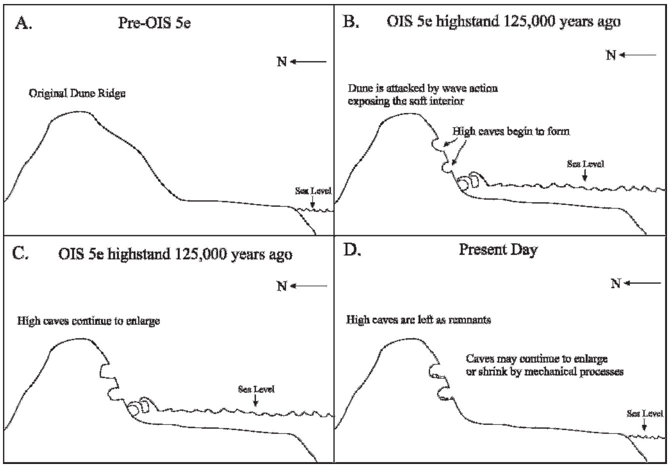

Figure 9. Proposed formation of high PITA Caves on Abaco Island, Bahamas.

flank margin caves and thus do not represent a +20 m sea-level highstand.

The PITA caves are most likely a form of tafoni: holes or depressions up to a few meters in dimension that form on cliffs and steep rock faces by cavernous weathering; a subaerial process (Ritter et al., 2002). As noted earlier, tafoni, as described in the literature, are extremely varied and no single agreed upon definition exists (Owen, 2007). The tafoni definition supplied by the Glossary of Geology (Neuendorf et al., 2005, p. 655) is only one of many, and the depth value given, 10 cm, is almost certainly an error because all literature sources reviewed by Owen (2007) show a depth value much greater than 10 cm. Ritter et al., (2002, p. 88) also discuss the terminology and literature concerning the definition and origin of tafoni, and conclude "The exact origin of tafoni, however, remains a mystery." As noted by Owen (2007) and Mylroie, et al. (2007), tafoni in Bahamian carbonates are only found in eolian calcarenite ridges where cave collapse, wave erosion, or anthropogenic activity such as road cuts and quarries has exposed the soft interior of the ridge to subaerial weathering. The PITA tafoni were probably formed during the +6 m OIS 5e highstand, when the ridge in which they are found was attacked by wave energy (Fig. 9). This erosion undercut the hillside, which then collapsed to form a cliff, resulting in removal of the calcrete crust of the dune. The soft interior of the dune was consequently exposed to attack by the coastal elements, allowing voids to be created at variable elevations (Figs. 9 and 10A).

Tafoni have also been identified on San Salvador Island, Bahamas on North Point (Fig. 10B) and in Watling's Quarry (Mylroie, et al., 2007; Owen, 2007). North Point is a modern sea cliff in Holocene eolianites with conditions similar to those that would have been present on Abaco during the formation of the high PITA Caves. Watling's Quarry is an inland exposure of Pleistocene eolianites. In both cases, the eolianite was carved into a cliff either by natural (North Point), or anthropogenic (Watling's Quarry) processes, which exposed the soft interior to erosion. Owen (2007) demonstrates that wind erosion is the primary cause of tafoni formation in Quaternary eolianites. It is important to note that because North Point is a Holocene deposit it could not have supported a past freshwater lens. Thus, the voids found in the North Point eolianite cannot be flank margin caves. This further supports the argument that the similar features on Abaco were formed in the same way as those on North Point and are not highly weathered flank margin caves.

The presence of tafoni in the Bahamas, first recognized in this study, is important because such pseudokarst voids can easily be mistaken for flank margin caves by the

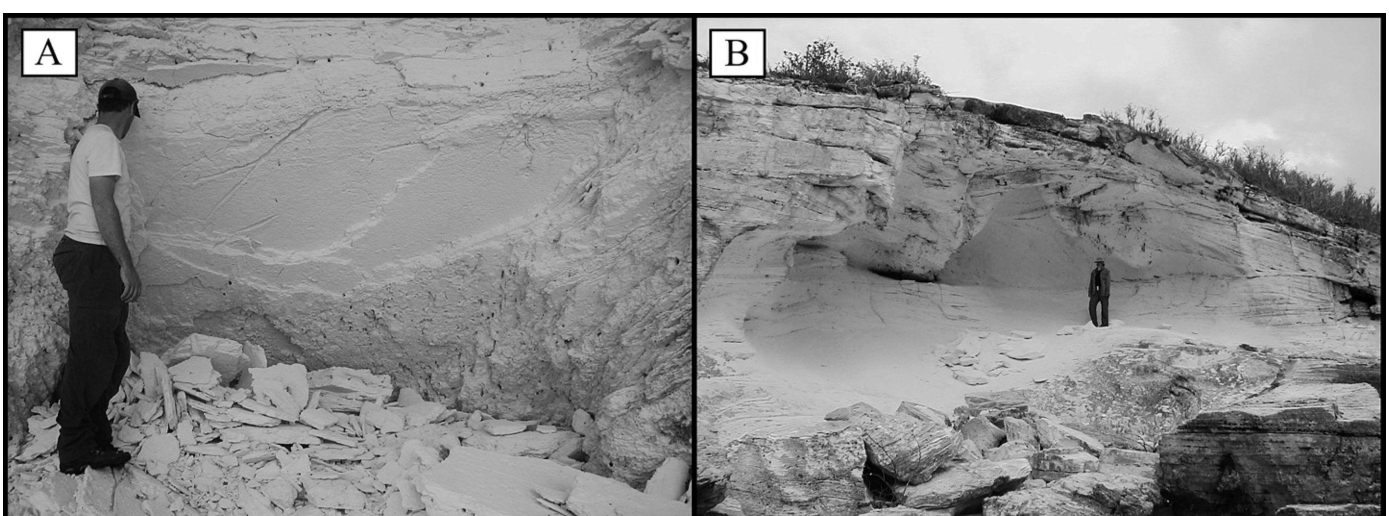

Figure 10. A. Exposed soft interior of a Pleistocene eolianite after removal of calcrete crust. B. Modern tafone-like feature in the Holocene eolianites of North Point, San Salvador Island, Bahamas.

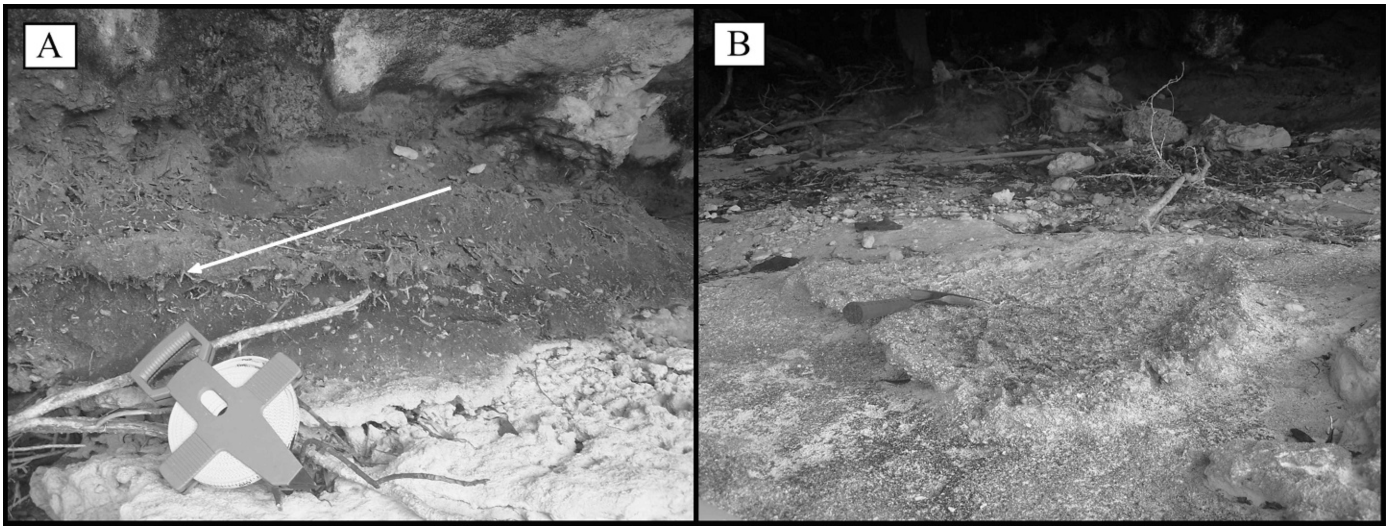

Figure 11. A. Paleosol in the wall of Cedar Harbour Cave II. Vegemorphs appear to be modern but are, in fact, calcified. Arrow indicates a vegemorph. Tape for scale. B. Patch of paleosol on the floor of Cedar Harbour Cave II. Rock hammer for scale.

untrained observer. Because flank margin cave elevations provide an estimate of sea-level height during their formation, identifying pseudokarst voids as flank margin caves can lead to incorrect estimates of past sea-level positions.

Caves as Keys to Geologic Timelines

In many locations on Abaco, the presence of caves can be used to create a timeline of past events; and thus, help to unravel the complex geologic history of an area. While these timelines may not allow the researcher to discern the exact ages of deposits, they are helpful in understanding depositional boundaries that are visible in the field. For example, the rock containing the cave must be older than the cave, but the cave deposits must be younger than the cave. If cave deposits can be tied to a specific geologic activity, such as breaching of the cave by wave activity, then the relative age of geologic events may be tied to geologic deposits, and the deposit becomes the marker for the event.

Near Cedar Harbour (Fig. 1B) on the northern coast of Little Abaco Island, both pit caves and flank margin caves preserve important geologic information. Here, the coastline is dominated by a consolidated eolianite with few vegemorphs (calcified remains of plant matter) overlain by a terra rossa paleosol and containing flank margin caves (the Cedar Harbour Caves I through V, Table 2). Within several of the Cedar Harbour caves, remnants of a paleosol with extensive vegemorph development are present along the cave walls and in patches on the floors (Fig. 11). This paleosol is only found within the caves and does not extend into the cliffs along the beach. Speleothems developed on a previous cave sediment floor now hang suspended above the original bedrock floor as stalactiflats (Fig. 12A). Beach facies containing eolianite breccia blocks are also commonly observed along the cave walls (Fig. 12B). The sum of these observations allows for a geologic timeline to be interpreted.

The elevation of the Cedar Harbour Caves above modern sea level suggests that they were developed ~125,000 years ago during the +6 m OIS 5e highstand in an eolianite ridge that was already present. The 5e highstand offered a 12,000-year time window, 131 ka to 119 ka (Chen et al., 1991). The eolianite formed either on the transgression of the OIS 5e highstand or during a previous highstand event. As sea level reached its maximum height, the stable position allowed for the development of flank margin caves within the eolianite ridge. The developing caves were breached by wave action as the 5e highstand continued. Beach sands were deposited in the caves, entombing breccia blocks from the eroding eolianite cliffs (Fig. 12B). As sea level fell at the end of the 5e highstand, the beach environment moved seaward and away from the caves. Speleothems grew as the caves were abandoned by marine waters. Vegetation colonized the area, including the beach deposits within the Cedar Harbour Caves, as the moist cave environment provided a favorable place for vegetative roots. A sandy soil eventually developed on the beach deposits. Stalactitic material and flowstone covered some of this new sediment floor.

As sea level rose with the present day highstand, the beach environment once again began to affect the caves and much of the vegetation was removed. Despite sea level being 6 m lower today than during OIS 5e, storm wave energy still reaches into the caves as is evident by modern beach deposits and organic matter in the caves. This wave action removed much of the soil that had developed during

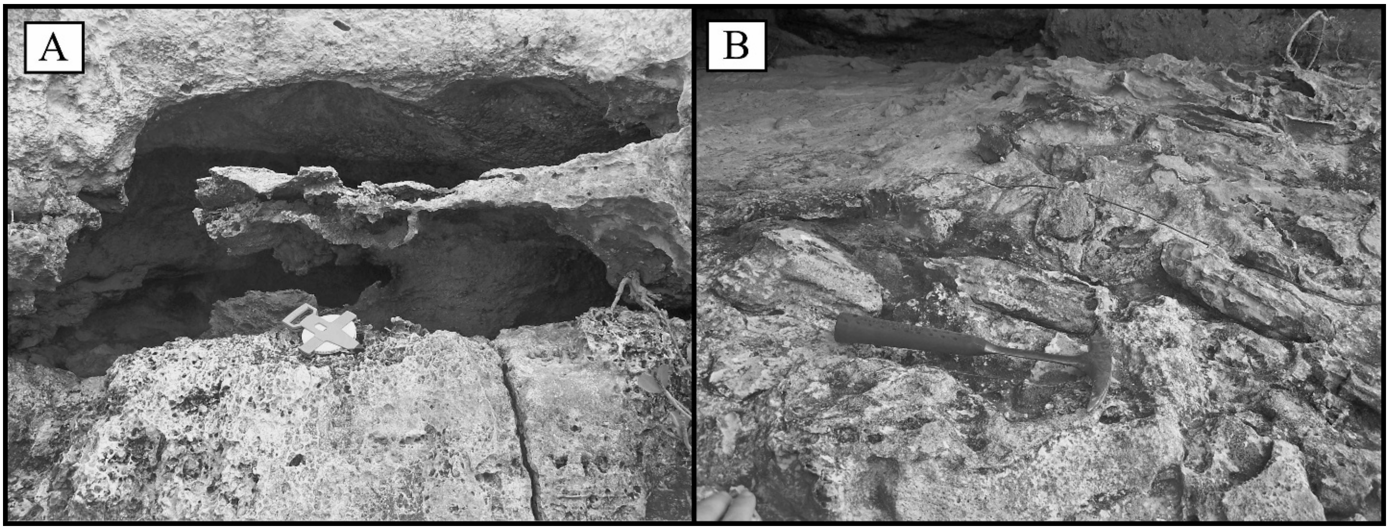

Figure 12. A: Well-developed stalactiflat in the western entrance of Cedar Harbour Cave III. Tape for scale. B: Breccia facies in Cedar Harbour Cave II. Rock hammer for scale.

the post OIS 5e lowstand. Today, only remnants are present as a paleosol along the walls of the caves and in small patches on the floors (Fig. 11). The excavation of this soil under speleothems allowed for the formation of stalactiflats as the speleothems were left suspended above the new floor level (Fig. 12A).

Similar features (breccia facies, beach deposits, stalactiflats, paleosols) found in the coastal flank margin caves of Little Harbour (Azimuth Cave, Manchineal Cave and Sitting Duck Cave) on the east coast of Great Abaco Island (Fig. 1B) suggest that the timeline that occurred at Cedar Harbour was not unique to one part of the island. This confirms our position that flank margin caves can preserve geologic information that can be used to discern the depositional and erosional history of carbonate islands, as well as providing vital evidence of past sea-level positions.

The rocky shore of Cedar Harbour contains numerous vertical structures that stand in relief to the surrounding surface of the eolianite bedrock (Fig. 13). Such vertical structures are common on other Bahamian islands and have been identified by previous workers as relict vadose solution pits (Carew and Mylroie, 1994). These pits formed during

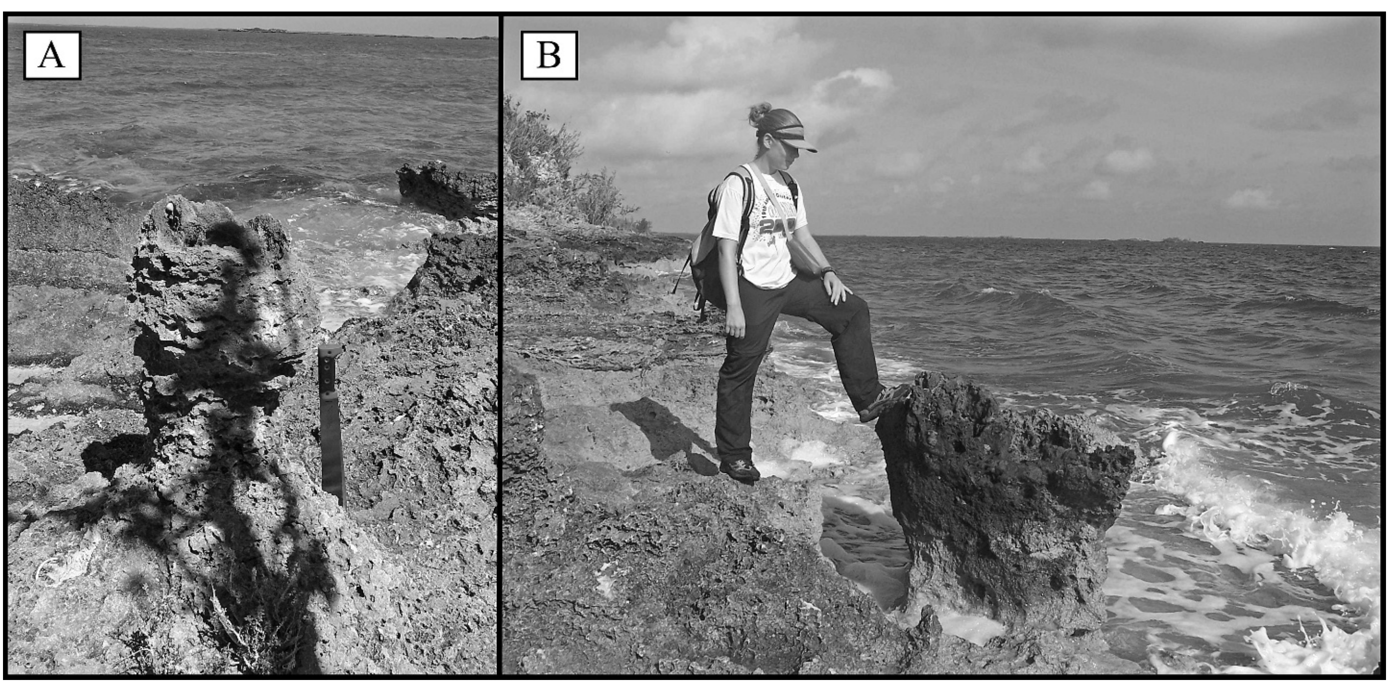

Figure 13. A–B: Vertical features on the coast near Cedar Harbour that represent relict solution pits. Machete for scale in A.

the original karstification of the eolianite bedrock surface, which took place during the lowstand following deposition of the eolianite. During this lowstand, the insides of the pits became coated with insoluble soil material, mostly aerosol derived, from the surrounding karst surface. This soil eventually hardened into a paleosol. During subsequent highstand events, the majority of the paleosol was removed from the surface of the bedrock due to marine processes. However, the paleosol in the pits was somewhat protected from the waves. The removal of the paleosol from the surrounding surface made that surface more susceptible to erosion by both dissolutional and mechanical processes. The pits interiors, however, were protected by the hard paleosol coating and eroded out in positive relief. They now remain as an example of inverted topography.

The eolianite exposed along the coast likely formed, at the earliest, during the last interglacial highstand (OIS 5e) approximately 125,000 ka. If it were deposited during this highstand, the paleosol would have developed during the following lowstand, and the removal of the paleosol by wave action and subsequent lowering of the bedrock surface would have occurred during the present highstand. Thus, the presence of the paleosol-coated pits demonstrates that the eolianite bedrock here is at least 125,000 years old.

Pseudokarst voids such as tafoni may also be helpful in clarifying geologic timelines. The tafoni found at North Point on San Salvador Island are modern features still forming in a recent eolianite deposited on the transgression of the current highstand (Fig. 10B). This eolianite has not been subjected to multiple sea-level events or extensive karstification. The tafoni found on Abaco, however, are relict features from a previous highstand event. The Abaco tafoni (or PITA Caves) were likely formed during the OIS 5e highstand on an eolianite that was already present. This eolianite may have been deposited on the transgression of the 5e highstand or during a previous highstand. As this eolianite was eroded by wave energy, the poorly-cemented interior was exposed to the extensive coastal weathering processes to form pseudokarst tafoni voids. Because the current highstand is not as high as the +6 m OIS 5e, the voids on Abaco today are not subject to continued wave energy and remain as evidence of past geologic processes.

Summary and Conclusions

Three types of caves: flank margin caves, pit caves, and tafoni caves, are identified on Abaco Island, Bahamas. Because each cave type forms by different mechanisms, they provide unique information about the geologic history of Abaco. Flank margin caves form due to mixing dissolution at the margin of the freshwater lens. And because the lens margin is concordant with sea level, flank margin caves mark the position of sea level during their formation. Pit caves and solution pits form as vadose flow routes to the freshwater lens. On Abaco and other Bahamian Islands, pit caves and solution pits are well developed in Pleistocene eolianite ridges, suggesting a relatively rapid rate of formation. Relict solution pits can provide clues to the age of the eolianite (Pleistocene versus Holocene) in which they have formed. Tafoni are pseudokarst voids that form by a variety of mechanisms. Bahamian tafoni form when the hard calcrete crust of an eolianite is removed, usually by wave action, exposing the soft interior to attack by erosional processes. While tafoni often form in coastal areas, their elevations cannot be tied to past sea levels. Mistaking tafoni for flank margin caves will result in incorrect estimates of past sea levels.

The effects of continuing erosional and depositional processes that occur subsequent to cave formation on carbonate islands may often be preserved within and around the cave in many forms. This information, when assembled correctly, can be used by the researcher to develop a general geologic timeline for the area. These timelines, while not absolute, are useful in the field for understanding boundaries for deposition and determining the sequence of geologic events. When compared with timelines for other areas, the researcher can begin to discern the geologic history of the entire island.

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