PROCEEDINGS OF THE 13th SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited By
Lisa E. Park and Deborah Freile

Production Editor
Lisa E. Park

Gerace Research Centre
San Salvador, Bahamas
2008

Front Cover: Rice Bay Formation, looking southwest along Grotto Beach. Photograph by Sandy Voegeli.

Back Cover: Dr. John Milliman, The College of William and Mary. Keynote Speaker for the 13th Symposium. Photograph by Sandy Voegeli.

Produced at
The Department of Geology and Environmental Sciences, The University of Akron

ISBN 0-935909-82-6

MAKING CAVES IN THE BAHAMAS: DIFFERENT RECIPES, SAME INGREDIENTS

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ABSTRACT

Caves in the Bahamas result from exposure to the same general ingredients, but with variations in the amounts, duration of exposure, and physical location. The ingredients that are known to influence cave development include: waters of differing chemistries, (fresh, brackish, marine), organics (DOC, POC, PIOC), metabolic by-products and end-products of microbial activity, and water flow. Different combinations of these variables generate dissolution at a variety of localities and at all scales. Dissolution occurs throughout the vadose zone, and in the phreatic zone, especially near the upper boundary of the fresh or brackish groundwater lens, and near the base of the fresh or brackish groundwater lens. The types and numbers of bacteria that occur on rock surfaces, within rock pores, and in the water in pores (including flooded dissolution voids) vary depending on the amount and geochemistry of the water, and the amount of organics available.

Data collected from caves currently below and above sea level have been integrated into a single comprehensive model of cave development in the Bahamas. The model recognizes that all dissolution caves result from exposure to a subset of common ingredients, but differ due to variations in the "cave formation recipe".

INTRODUCTION

Caves found on the Bahamian platforms range from small globular air-filled chambers to horizontally extensive flooded caverns, as well as near-vertical shafts that may be dry or flooded. Their openings are found high on eolianite ridges, on low coastal benches, among the mangroves in shallow creeks, in inland lakes, and on the shallow subtidal banks of the Bahamas. Caves within the Bahamian carbonate platforms range from several meters to several kilometers in lateral extent, and depths vary from less than a meter to several hundred meters. Mylroie and Carew (1995, p. 60) state that, "caves on carbonate platforms fall into three main categories: vadose, phreatic, and fracture caves". Recently, Schwabe and Carew (2006) suggested that Bahamian caves, whether currently above or below sea level, should be broadly classified into three general types (horizontal, vertical, and fracture-guided caves) based on their morphologies that result from their modes and locations of origin.

This classification reflects the idea that the horizontal caves currently above sea level, such as flank-margin caves and banana holes, are the result of the same phreatic dissolutional processes that have also formed or modified the horizontal caves that are currently flooded, many of which are commonly referred to as 'blue holes", a term which is of no scientific use (Schwabe and Carew, 2006). It is likely that the majority of the currently subaerial horizontal caves are younger, or less-developed, versions of the now-flooded caves. Likewise, many currently-flooded vertical caves, many of which are also referred to as "blue holes", likely had an origin that is similar to that of currently subaerial pit caves. Fracture-guided caves, whether exposed on land or currently on the flooded carbonate banks, all have their origins related to fractures that are aligned sub-parallel to steep bank margins adjacent to very deep water. Virtually all these fracture caves also have names that include the term "blue hole".

Regardless of the terms used to describe or classify caves in the Bahamas, it should be recognized that it requires the same basic ingredients to make voids in these carbonate rocks, no matter how big or small the features may be. The reason that these cave types differ from one another is that they result from different amounts of the ingredients needed to make voids, and variations in exposure times in the different dissolutional environments. The ingredients that are needed to make caves are limestone, water, organics, bacteria, and time.

VOID MAKING INGREDIENTS

Water

Obviously, water, is a prime ingredient necessary for cave formation in limestones. The supply of water in the vadose environment is temporally variable, and water movement is primarily downward under the influence of gravity. The generally accepted model for dissolution of limestone suggests that rainwater charged with CO_2 is responsible for dissolving near-surface epikarst features, as well as other voids formed between the land surface and the water table. The rainwater is assumed to be acidic, primarily as a result of incorporated atmospheric CO_2, but other acids (such as nitric acid which is commonly elevated in rain associated with thunderstorms) may also be present. In addition, the meteoric water may be further charged with CO_2 if it infiltrates through soil. That additional CO_2 in soils is generally regarded to be the product of soil microbes and respiration of other soil inhabitants (animals, fungi) (e.g., White, 1988).

We have discovered that rainwater collected in a sterile container before contact with the ground on San Salvador contained 10^3 bacterial cells/ml (Schwabe et al., 2006, 2007). So, the water starts its journey through the soil and rocks already charged with possible CO_2-producing bacteria and organics (bacteria that may be consumed by other bacteria). However, recent studies on San Salvador Island (Schwabe et al., 2006) have shown that rain water is buffered soon after it makes contact with the surface.

Rainwater collected directly into sterile containers in January 2007 had a pH of 5.72 [with salinity = 0.25mg/l, chloride = 22.3mg/l, alkalinity = 14mg/l (all HCO_3^-), and Ca = 3.2mg/l]. In contrast, rainwater collected from profuse overflow from a rooftop at the Gerace Research Centre in 2006 had a pH of 8.5, and the pH of water collected from the 18-acre catchment at the Gerace Research Centre 18 hours after an intense rainstorm in June 2006 had a pH of 9.18 (pers. comm., Dr. Jon Martin, Univ. Florida). The reason that these latter two observations are significant is that they demonstrate that very brief contact with the surface is sufficient to change the pH of the water to non-acidic values. In the case of the rooftop rainwater, a few minutes contact with a thin film of carbonate dust and a few rock fragments on the roof was sufficient to buffer this profuse flow of water to alkaline pH values.

So, it appears that except at the immediate surface and just below soils (epikarst), it is unlikely that significant dissolution could occur in the vadose zone unless there is some other variable affecting the system. We have proposed (Schwabe et al., 2006, 2007) that the previously unidentified ingredient that makes it possible for vadose water to dissolve limestone is abundant populations of interstitial CO_2-producing bacteria living in the rocks of the vadose zone, as well as bacteria populations that live on exposed limestone surfaces, especially in karst voids (e.g., Laiz et al., 1999; Groth and Saiz-Jimenez, 1999). It is also likely that plant roots, with associated fungi and bacteria, which produce CO_2 (and other chemicals that form acids), also play a significant role in some void development.

Because the bacteria are not homogenous in the vadose rock (Ehrlich, 1990), meteoric waters that descend through the vadose zone will not always encounter CO_2 producers. It is reasonable to suppose that in areas where the downward-migrating water in the vadose zone is not acidified by bacteria (and perhaps other taxa), precipitation of cement is likely to occur. It is also likely that other taxa of bacteria may play a role in calcite precipitation. We suggest that bacterial 'hot spots' may explain why macroscopic voids of various sizes are dispersed throughout limestones in the vadose zone. In Holocene rocks in the Bahamas, which have been exposed only to vadose conditions, a wide range of macroscopic voids are already clearly visible.

Water in the phreatic zone comprises freshwater, brackish (mixed) water, and marine water. Study of water from open wells, cave drip water, brackish water in a cave and at a spring, and seawater on San Salvador Island has shown that they are all supersaturated with respect to calcite, and at least at equilibrium with aragonite (Moore and Martin, 2006). As reported by Moore and Martin at the symposium, their study has also shown that, contrary to the currently accepted model, mixing of these various water bodies (both open and closed to CO_2) does not produce sufficient undersaturation to explain the formation of significant sized voids such as flank margin caves and banana holes. Study of phreatic waters in flooded caves on Grand Bahama Island and Andros Island show that they are also saturated or supersaturated, except where there are large bacteria populations, mostly associated with density horizons associated with the zone of mixing between fresh to brackish groundwater and underlying marine groundwater (Schwabe, 1999; Schwabe and Herbert, 2004; Schwabe et al., 2006, 2007). Thus, it also appears likely that bacteria play a significant role in void development in the phreatic zone.

Interestingly, although bacteria occur throughout the water column in the phreatic zone in the Bahamas, they are concentrated in areas at the top of the groundwater lens (a density interface between air and water) and in association with the mixing zone (a density interface between fresh and marine groundwater). This is consistent with the earlier-reported preferential development of banana holes and flank margin caves at those locations (Mylroie and Carew, 1990; 1995)

In most portions of the phreatic zone, water movement as a result of groundwater-lens discharge is crucial for void enlargement (Mylroie and Carew, 1990; 1995). It has also been documented that the marine portion of the water column that flows into and out of the islands as a result of tides, waves, and storms also causes movement of the overlying groundwater (Schwabe, 1999). Water movement due to lens discharge, and entrainment due to oscillations of marine water, is important in the removal of solutes formed by the dissolution of rock. So, the large bacteria populations associated with the mixing zone (Schwabe, 1999; Schwabe et al., 2006, 2007), whose production of CO_2 maintains the dissolutional capacity of these phreatic waters (see further discussion in the Organics section), combined with high water-flow rates are probably responsible for the preferential location of most large karst voids (flank margin caves) in the Bahamas.

In contrast, in a few areas the lack of significant groundwater movement sets up conditions that permit the accumulation of huge bacterial populations which contribute to void development. The prime example of these conditions are the currently flooded vertical caves called "black holes" found on Andros (Figure 1.) and Grand Bahama islands (Schwabe and Herbert, 2004). In these settings there is little to no movement of the marine water beneath the sharp halocline and therefore there is no mixing zone. The lack of water flow allows very thick (>1m) microbial layers to form above the marine water, and vertical migration of such layers via sea level change may explain why these voids are primarily vertical features with no significant horizontal extension (see further discussion in the Organics section).

Organics

The amount of organics (including live bacteria), the type of organic material, and the amount of available moisture will dictate the type and the number of bacteria that will reside and be active within the vadose and phreatic rocks and waters. The organics that bacteria in carbonate rocks, and in the groundwater, may metabolize comprises a wide variety of materials. The rocks themselves contain an initial organic component in the form of: interstitial bacteria, particulate organic carbon (POC), particulate inorganic carbon (PIOC), dissolved organic carbon (DOC), buried vegetation in eolianites, subtidal grass/algal facies, coral reefs, subtidal hardgrounds, organics in paleosols, etc. Organics are also introduced to the rocks after deposition by infiltration from above (e.g., atmospheric outfall, infiltration of surface organics such as animal wastes and carcasses, dead vegetation, and organics produced by live vegetation and fungi). In addition, the movement of marine water inward into an island via tides and currents delivers organics to the phreatic system, especially when voids are present at the depths where shallow marine water and fresher groundwater are mixing. All these organic materials provide metabolizable material for a variety of bacteria with differing environmental preferences such as aerobic to anaerobic heterothrophs and chemautotrophs. These bacteria in turn produce by-products and end-products of their metabolism that form acids that drive void development and enlargement.

Figure 1. Aerial view of the Black Hole of South Andros Island, Bahamas. This nearly circular opening is 300 m in diameter, and is the largest found thus far in the Bahamas. The sparse vegetation surrounding the opening gives the impression that the opening is elevated above the surroundings; however, everything in this field of view is nearly at, or below, current sea level.

The role of bacteria in sulfuric acid speleogenesis (SAS) has become an accepted model for some cave development (e.g., Engel et al., 2004), and some work in the Bahamas has indicated a role for sulphur-mediating bacteria (Bottrell et al., 1991, 1993); however, it is our contention that in the Bahamas, and similar carbonate settings, even traditional carbonic acid dissolution is also largely the result of bacterial activity. Whitaker and Smart (2006) suggested that CO_2 must be added to the ground water in the northern Bahamas by oxidation of surface- and soil-derived organics in the lens, but they did not document the presence of abundant populations of bacteria living in the rocks and groundwater as the probable source of bacteriogenic CO_2.

Some of the bacteria that have been found within non-SAS cave wall rocks (e.g., Actinomycetales) prefer oligotrophic conditions; that is, they are well suited to live in organic-poor environments (e.g., Chapelle et al., 1987; Chapelle and Lovely, 1990; Plummer et al., 1990; Laiz et al., 1999; Groth and Saiz-Jimenez, 1999). Despite the variety of sources of organics in Bahamian rocks, after the initial depositional organic load is exhausted most of the vadose zone rocks in the Bahamas are oligotrophic environments, so it is not surprising that we have found abundant Actinomycetales in those rocks (Schwabe et al., 2006, 2007). We have also found that some of these bacteria prefer only small amounts of moisture. To culture and isolate these wall-rock bacteria proved to be very difficult, as they were slow growers, and in some cases, unresponsive to many of the media provided. In contrast, we have found that, with only a few exceptions, the bacteria collected from water samples tended to grow rapidly and be easily cultured on a much wider selection of host media.

Although the availability of organics and water in the vadose zone is generally limited, especially compared to the conditions in the phreatic zone, it is possible that some large voids may form in the vadose zone where there were initial large supplies of organics (such as buried vegetation and root masses), or abundant organic input from living vegetation (such as a large tree), and/or a substantial supply of water (such as a perched groundwater lens. In those cases bacterial activity that produced CO_2, or other acids, would result in sizable voids. Such conditions may explain the flank-margin-style cave that occurs at an elevation of about 175 feet asl at Mt. Alvernia on Cat Island (Mylroie et al., 2006), which is well above any possible sea level position that could have placed the freshwater lens there. It is also likely that bacterial populations in the vadose zone play a substantial role in the development of pit caves (such as Owl's Hole on San Salvador Island). In these situations the development may be partly driven by bacterial activity that occurs in the sediment/soil that accumulates in these depressions (Smart and Whitaker, 1989), partly by bacterial and fungal activity associated with vegetation that may be anchored in the features, and partly by bacteria that live on the wall surfaces and within the rock, in a fashion similar to that demonstrated for tombstone and building stone deterioration (Paine et al., 1933; Ehrlich, 1990).

Time and Setting

The remaining ingredients for void development are time and setting. That is, the sizes and shapes of dissolutional voids is also dependent on how long they have been subjected to conditions favorable for void development. For example, due to lesser amounts of water and bacteria, voids formed only in the vadose zone are likely to be of more limited extent than those that have spent a similar time in the freshwater and mixing zone phreatic environments. In addition, rocks exposed for short intervals of time in the vadose or phreatic zone are also likely to be less extensive than those subjected to those conditions for longer intervals of time. However, individual cases of abundant organics, bacteria, and water may result in large voids in either environment even in short intervals of time.

Voids formed in the phreatic environment, particularly in association with the mixing zone, or halocline/pycnocline, where bacteria and organics are most abundant, are more likely to develop to large size than those formed elsewhere in the phreatic zone or in the vadose zone. In addition, voids that have been submerged during multiple episodes of glacio-eustatic highstands of sea level are likely to be larger than those formed during a single episode of submergence. Based on observations in currently flooded caves in the Bahamas, even if the water filling a void consists of marine water, substantial dissolution is likely, because bacteria-rich sediment and biofilm commonly covers the floors, and often drapes the ceilings (Schwabe, 1999). However, again it should be noted that specific conditions that produce abundant supplies of organics and bacteria are likely to produce larger voids than in other settings in rocks of the same age. Although there is no scientific documentation about the effects of organic flushing into the Lucayan Caverns system on Grand Bahama Island, it may not be a coincidence that these largest known horizontal cave systems in the Bahamas have entrances located within mangrove habitats which produce abundant organics that are flushed into the caves (see later discussion).

CAVE-MAKING RECIPES

Exploration of caves in the Bahamas for the past several decades has generated a plethora of data concerning caves currently above sea level and those currently flooded. Researchers studying one or the other of these cave environments have generated separate sets of observations, interpretations, and terminology (e.g., Mylroie and Carew, 1995; Schwabe, 1999; Schwabe and Herbert, 2004). Although it is clear that the currently dry flank margin caves and banana holes have had a submergence history, until now there has been no formal attempt to compare those voids to the currently flooded caves to determine the similarities and differences between them. Of course, over time, caves may experience a variety of different conditions due to changes in sea level, bank subsidence, and different climatic conditions, and thus can become polygenetic. The following discussion reports some of the significant features and aspects of some of the various cave types in the Bahamas.

Fracture-Guided Caves

Fracture-guided caves vary in the extent of their horizontal versus vertical development, but as the name suggests, they have clearly formed in association with significant fractures along some bank margins. These fractures are thought to result from bank margin failure along steep declivities during times of glacio-eustatic low sea level. Virtually all fracture-guided cave openings have been labeled as blue holes (e.g., Evelyn's Blue Hole, Stargate Blue Hole, etc.). However, aerial views (Figure 2.) of multiple openings in a linear sequence that parallels the coast, easily dispels any question as to their association with a linear feature. Fracture-guided caves have thus far been found only on Grand Bahama, New Providence, and Andros islands.

Figure 2. Aerial view of the south end of the fracture system on South Andros Island, Bahamas. Note the linear arrangement of the flooded cave openings.

A curiosity concerning these caves is why the openings to caves occur only at isolated locations along the fracture. Although it is only conjectural, one possible explanation is that it has to do with the type of limestone and possible organics 'hot spots'. It has been noticed (by Schwabe) that the rocks that compose many of the explored entrances are composed of fossil reefs commonly also associated with herring bone cross bedding.

Perhaps fossil reefs and associated subtidal deposits that happen to have been intersected by the fracture originally contained abundant organics that 'fed' large bacterial populations that resulted in significant dissolution in those areas, and ultimately collapse into those voids resulted in the development of cave openings at those sites.

The fracture systems extend from land onto the submerged platform, so even in the inland caves, tidal effects are very important. In the marine setting, fracture systems experience very dynamic tidal flux that generates a boil (dome) of out-flowing water at many cave entrances. This outflow is so powerful that entering the cave is nearly impossible and ill-advised. This condition occurs about three to four hours into the ebb tide. The reverse condition, a vortex of descending water that can prevent a diver from exiting from a cave forms at the entrance three to four hours into flood tide (Figure 3). Clear evidence that this phenomenon is related to hydraulic head produced by tidal rise and fall is provided by another phenomenon that has been repeatedly experienced by the researchers that have explored these flooded caves (e.g., Schwabe, R. Palmer). That is, outflow of water can change to inflow in less than a minute when storm waves push water up onto the submerged bank, thereby generating a higher hydrological head on the platform than what the current tide is generating. Once the storm abates and wind-driven water is no longer pushed on to the platform, the water flow returns to outflow.

These tidal and wind-driven water currents have a tremendous effect on many of these flooded caves, because they can pump large quantities of nutrients into the caves (Figure 3). These nutrients also permit encrustation of corals. and other marine life, on cave walls to 60 m depth, even though there may be no available light.

The walls of the flooded voids where this marine life exists, are very pitted and friable and the corrosion extends several centimeters into the wall rock. This bioerosion of the rocks is likely to enhance enlargement of the cave entrances. This phenomenon ceases at 60m depth. This depth limit appears to be associated with the dynamics of water movement within the caves. Observations made by Schwabe while monitoring the water chemistry at the entrance to Fourshark Cave over a 24hr period showed that only the top 60 m of water moves in and out of the cave during the semi diurnal tidal cycles. The water below 60 m in the cave, whose chemistry had been determined earlier, was never identified at the entrance of the cave, which suggests that those deep waters do not leave the cave (Schwabe, 1999). Thus, the water at depth in the caves becomes stagnant. Oxygen and nutrient content is low or non-existent, so the water is not suitable for marine growth (e.g., corals, sponges). This pronounced change in wall morphology at 60 m depth is also observed in the fracture-guided caves with entrances on land. Populations of bacteria that prefer anoxic conditions dominate the waters and cave wall rocks below 60 m depth (Schwabe, 1999). The top 30 to 40 m of cave passage in these settings tend to be the widest portions of the cave systems, and passages at depths > 60 m tend to conform to the shape of the fracture.

Vertical Caves

Vertical caves are generally developed in association with descending water in the vadose zone, by dissolution horizons that migrate up and down in response to sea level changes, or by upward propagation by collapse into a void at depth. Vertical caves may inadvertently intersect horizontal caves, but the horizontal passages are not directly associated with the development of the vertical caves. Vertical caves include subaerial pit caves, and many flooded features called "blue holes" and "black holes". These caves typically have no horizontal passages, or only limited horizontal development. A few known exceptions exist, such as CK1 and John Winter's Cave (Hog Cay Cave), on San Salvador Island, Bahamas. Some of these features have voids that extend along foreset bedding (solution chimneys), and CK1 intersects a large flank margin cave (Major's Cave) (Moore et al., 2004).

At a few places on the flooded Bahama Banks some vertical voids have a deep black color when seen from the air. These 'black holes' (Figure 1) have a dark color because they harbor an unique microbial population that probably plays a significant role in the formation of those voids.

The cause of the black color is a meter-thick layer of dark-pigmented purple sulfur bacteria that occurs about 17.8m below the water surface (Schwabe and Herbert, 2004). These large vertical caves seem to require very specific environments and conditions to form and have to date been found at only a few locations in the Bahamas (Table 1). It appears that the main reason that these black colored microbial layers form in these systems is that there is no significant (measurable) horizontal flow of water at those locations.

Figure 3. Vortex formed on a flood tide, in the entrance to a cave named 'Luscas Breath'. This is the entrance to a fracture-guided cave located on the eastern bank margin of South Andros near Deep Creek.

Lack of horizontal flow allows these loosely floating populations of mostly purple bacteria to generate dense (bacterial counts $>10^7$ cells/ml), undisturbed, well-defined layers within the water column. These floating bacterial masses are so dense that they appear inky-black, and they have thus far always been found at 17.8 meters depth, and are each about one meter thick. This consistent thickness is most likely due to some light-limited requirement for these bacteria. These bacterial masses are at a consistent depth because they are located on the density interface where brackish water meets the underlying marine water. Any horizontal flow within the marine water beneath the microbial layer would prevent such sharp biological boundaries from forming, and the bacterial masses would be dispersed. Lack of flow and tidal influence appears to dictate where black holes are likely to be found (Table 2).

It has been observed that the walls of these "black holes" are severely undercut where the bacterial layer is located (Schwabe and Herbert, 2004). This is likely the result of dissolution enhanced by the end-products and byproducts of the metabolism of these mostly anaerobic bacteria. So, it is possible that movement of this environment vertically with glacio-eustatic changes in sea level may have carved these vertical caves, or it may have enlarged pre-existing pit-cave-type voids.

Table 1. Some geochemical, physical and biological observations of flooded caves.

	Horizontal Caves	Fracture Caves	Vertical Caves
Current	√+++	√	Not detected
Microbial layer	√++	√+	√+++
Fresh Water	√+++	√ to none	√ to none
Brackish Water	Not detected	√+++	√+++
Marine Water	√+++	√+++	√+++
Organics	√+++	√+	√+++
Mixing Zone	√+++	√	none
Pycnocline	√	√	√+++
Measurable tidal changes	√+++	√+++	none

√ very low; √+ low; √++ moderate; √+++ very prevalent

So, a location deep in the interior of a large platform, where tidal flow is diminished, seems to be a major non-biological ingredient necessary for development of 'black hole' voids. Initiation of these vertical voids may be the result of their insular locations, where large amounts of micrite mud tend to accumulate. It has been noted that this carbonate mud tends to result in ponding of meteoric water (Figure 4).

These ponds of water are colonized by photosynthetic bacteria. However, as such ponds get deeper, less light is available at depth, which may eventually establish an environment better suited for dark-pigmented bacteria. The larger these populations become, the greater their influence is on the chemistry of the water-column, especially the pH. The water column above and below the bacterial masses is well buffered, with a pH of 8.5; however, in the bacterial layer pH ranges from 4 to 6. Because the walls at these locations are being aggressively dissolved away and there is little or no water movement, one would expect the water to become buffered. However, what we observe (Schwabe and Herbert, 2004) is that the huge bacterial population at these locations is able to maintain an acidic environment, despite lack of water flow.

Table 2. Types of flooded caves found to date on different Bahamian Islands

Islands	Horizontal Caves	Fracture Caves	Vertical Caves
Andros	√	√+++	√+++
Grand Bahama	√+++	√+++	√
San Salvador	√	none	√
New Providence	√	√	√
Cat Island	√+	none	√
Long Island	√+	none	√
Eleuthera	√	none	√
Acklins	√+	none	√
Exuma	√	none	√
Abaco	√	none	√

√ very low; √+ low; √++ moderate; √+++ very prevalent

Energy, to maintain such a large population of bacteria in these vertical caves (i.e., 5 tons dry weight, Schwabe and Herbert, 2004) seems to come from a well-established algal population growing in the water above the toxic water at 17.8 m depth. These algae produce a degradation product of dimethylsulfonium propionate (DMSP), a major osmoregulatory solute in marine algae (Madigan et al., 1997). DMSP can be used as a carbon and energy source by microorganisms and is catabolized to dimethyl sulfide and acrylate. The latter compound, a derivative of the fatty acid propionate, is used to support microbial growth (Madigan et al., 1997). Considering that there is limited vegetation growing outside the holes it seems reasonable that the algae within the hole produce a major energy source for the heterotrophic bacteria.

Figure 4. Ponded meteoric water in the interior west of South Andros Island, Bahamas. These shallow ponds are light green in color suggesting the presence of photosynthesizing bacteria. Note the different sizes of these depressions.

Thus far, only one mature black hole has been found on the partially submerged fringe of the platform on the north side of Grand Bahama Island. One mature flooded vertical cave (Rob's Blue Hole), without the purple microbial layer, has been explored off Nassau's north shore. However, the entrance to this vertical cave is now below sea level, and the languid environment necessary for the purple bacteria mass to develop is absent because the water column is stirred by tides and wave action. The nature of the water column aside, the wall morphology and the growth of abundant algae, is identical to that seen in other black holes. Several such systems on Andros have suffered a fate similar to Rob's Blue Hole, although they still maintain an abundant microbial population (though it is very different from those in the South Andros Black Hole) as well as a significant pycnocline. In those settings, these vertical caves are still relatively sheltered and have only a minor breach open to the sea, thus limiting water column mixing to the top 10 m. It appears that the most important ingredients required for these vertical caves to develop is a large platform, a very stable water column, and a large organic source.

Vertical pit caves are found throughout the Bahamas on high ground in eolianites. All of these vertical voids above 6 meters elevation have never been submerged. So, they are of vadose origin. Development of pit caves may also have have a microbial component. Endolithic cyanobacteria, hetertrophic bacteria, and fungi have been found to cause local dissolution of limestone through production of oxalic and gluconic acids (Ehrlich, 1990). Cyanobacteria and fungi dissolve tubular passages in which they can grow (Golubic et al., 1975).

Because of their need for light cyanobacteria can bore only a short distance into the rock; however, fungi and heterotrophic bacteria are not light limited. In addition, fungi and cyanobacteria can form a symbiotic relationship in the form of lichens (Ehrlich, 1990). In lichens the cyanobacteria share the carbon they fix with the fungi while the fungi share minerals that they mobilize with the cyanobacteria. The lichens and other bacteria that reside in surface depressions, and the rock beneath, produce by- and end-products that form acids that probably contribute to pit cave development. In addition, organics produced by the roots of many plants serve as nutrient sources for many bacteria; so plant growth in vertical voids may enhance void enlargement. Smart and Whitaker (1989) have proposed an "organic drill" hypothesis for development of banana holes. Although that hypothesis is not valid for the origin of banana holes, which are of phreatic origin, organic-bacterial-mediated dissolution may result in downward enlargement of breached banana holes and pit caves. In addition, bacteria and fungi in the pit walls are also likely to enhance pit development.

In coastal settings lichens and endolithic algae and bacteria provide a food source for snails and other invertebrates that scrape the surface of limestone to feed. This type of bioerosion has been noted on some reef structures in Bermuda (Golubic and Schneider, 1979), as well as in the Negev Desert where this erosion removes 0.7 to 1.1 metric tons of rock per hectare per year (Shachak et al., 1987). In the Bahamas, this mechanism of biological erosion is likely to result in pits in the limestone along the coasts. Formation of such depressions along the coast, which can later become catchments for moisture and organics when sea level falls, can lead to the genesis of pit caves during glacioeustatic sea-level lowstands.

Glacioeustatic sea level changes and island subsidence may eventually flood such pits. In that case, they might become black holes if they are in the right setting; or they may simply become flooded vertical caves, like some of the current marine "blue holes'.

Horizontal Caves

Currently-exposed subaerial horizontal caves, such as the flank margin caves and banana holes, originate from conditions similar to those found in the currently submerged horizontal caves that are found on Grand Bahama and a few other islands (Table 2). The caves, which are currently above sea level, most likely have only been submerged once or twice in their history, whereas the caves that are currently below sea level may have been submerged in the phreatic zone multiple times, and for that reason some are quite large and complex. However, being submerged in the phreatic zone is not by itself enough to make caves larger. There must be water movement, a mixing zone with density interfaces, and numerous active bacteria that generate sufficient chemical byproducts/end-products to keep the water acidified. Lucayan Caverns and Owl's Hole on Grand Bahama Island, Bahamas, are two of the largest known horizontal caves in the Bahamas. At this time there are ~10.5 km of mapped passage in these only partially explored systems. Although these caves are open to the surface, which may not have generally been the case for the development of flank margin caves, they are currently the only locales that provide us with some information about the conditions that might exist in phreatic voids generally.

These currently flooded caves are similar in many ways to subaerial flank margin caves and banana holes. For example, as one enters Lucayan Caverns from the national park side (Figure 5), one passes through the fresh-water lens into a passage with a smooth curvilinear ceiling that rises dramatically over a distance of about 20m then plunges toward the floor at the back of the chamber. The floor of the passage remains relatively level except where there is a pile of collapsed ceiling materials. This room is morphologically similar to the globular outermost chambers characteristic of flank margin caves. At this location in the cave, the top half of the water column is fresh and the lower half is marine. At the back of this chamber the descending smooth ceiling forms a partial wall as it reaches into the marine section of the water column. Once under this wall, the ceiling again rises into the freshwater lens over a distance of about 10m, it remains high until the back of the chamber where the ceiling again descends into the marine section of the water column. This is another globular chamber that is somewhat smaller than the entrance chamber. This morphology is again consistent with what is seen in subaerial flank margin caves, where the chambers behind the entrance chambers are similar in morphology but are typically smaller. Throughout the rest of the explored cave the chambers are within the marine water, and the mixing zone is at the ceiling. Except for the numerous speleothems, this section of the cave passage looks like a planar section of bedding has been removed. A diver in this passage finds the ceiling and floor a bit close. The passage remains this way for about 2000 m into the cave, where there is a small chamber created where a smooth curvilinear ceiling rises a few meters and then descends again to the depth of the earlier passage.

During a tidal cycle in Lucayan Caverns and Owl's Hole caves, water flows through the passages in the front 300 m of the caves at about two meters per minute (Schwabe, 1999). Approximately 320 m deep into the cave, the flow is greatly diminished and the mixing zone is only pencil-line thin. There is just enough flow to keep the boundary between freshwater and marine water intact. In this environment deep in the caves there are abundant microbial mats. Bacterial mats with morphologies similar to those on the floor in the Black Hole of South Andros cling to the ceilings of the cave. If they become detached they drift downward and form large masses on the cave floors.

At the front of the cave the 2 m/min flow, keeps the water crystal-clear. The cave walls and ceilings that are bathed in freshwater are snow white and only fine carbonate mud is dislodged by scuba exhaust. Within 24 hours dislodged carbonate mud from the ceiling settles out on the density interfaces in the mixing zone and is carried away by flow created by the current in the underlying marine water.

In contrast, the cave walls, ceilings, and floors that are in marine water are covered in orange, brown, and black bacterial biofilm (Schwabe, 1999). As mentioned above, the floors of the caves are buried in some places by several meters of this material giving the impression of a brown fluffy carpet. The bacteria in these microbial curtains and mats produce exopolymeric substances (EPS) that allows them to maintain reducing or dysoxic environments behind them, even though the water within the rest of the chamber or passage is oxidizing. As a result, the ceilings and floors of the caves may be preferred sites of dissolution, including SAS, despite the fact that the water may be marine.

In locations in the caves where there is a mixing zone several meters thick, it is created by dilution of marine water, that results from friction and turbulence created as the relatively denser marine water moves under the less dense freshwater lens. This nearly horizontal body of diluted marine water (mixed water) also harbors a large number of bacteria (Schwabe, 1999), which are caught, along with other organics, in this zone because of the pronounced density interfaces. This environment is very conducive for abundant living heterotrophic bacteria because they are provided ample material that they can metabolize.

The major source of the organic material in Lucayan Caverns comes from the semi-diurnal tidal flow through a 2-mile creek. This water collects large amounts of organic material before entering three known entrances that are located within a mangrove habitat. Large globs of organic material have been observed floating into the entrances during flood tide. Water, darkly stained by tannins and lignins, most likely from the mangrove roots, contain large populations of bacteria and diatoms commonly found in sunlit environments. This organic material is carried into the cave system twice a day, along with a fresh supply of oxygen and organic and inorganic compounds used by the autotrophs, chemolithotrophs, and heterotrophs (Schwabe, 1999).

Not only does the geochemical and microbial environment change vertically through the water column, it changes horizontally as well. At short (~10 m) distances into the cave, dissolved oxygen values are slightly higher than they are at the entrances of the cave. This may be explained by the fact that very large amounts of organics (tree limbs, berries, leaves, etc.) fall into the entrances, and as a result the abundant bacterial populations there consume the oxygen as they metabolize the organics. About 100 m farther into the cave, the environment becomes dysoxic to reducing, and as a result, microbial populations that are better suited for living in low to no oxygen environments prevail there (Schwabe, 1999).

Deep in some of the very extensive horizontal passages, the water is moving so slowly that its movement is nearly impossible to measure. In these settings oxygen concentration is very low, and hydrogen sulfide accumulates. When H_2S is oxidized it produces sulfuric acid.

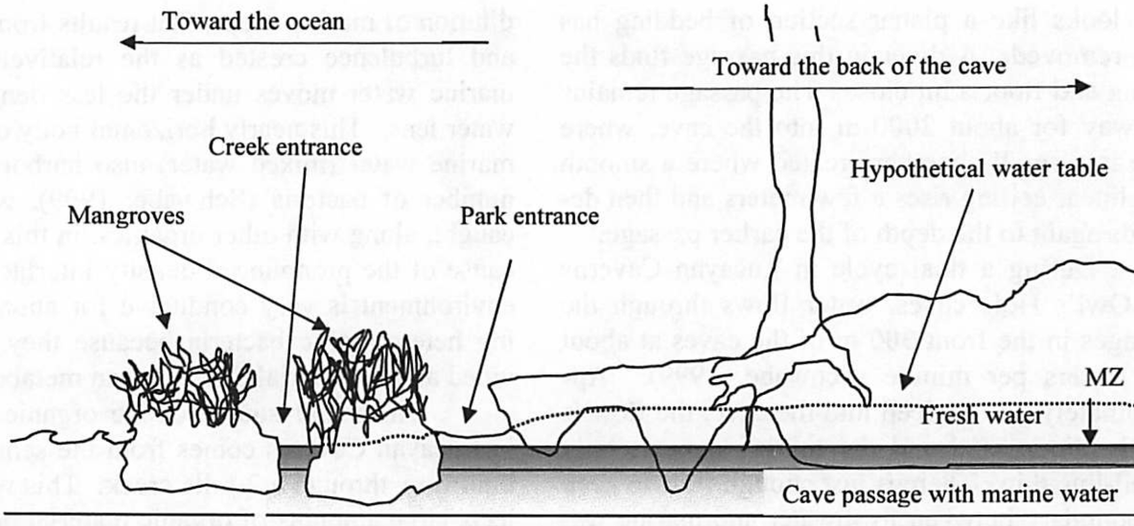

Figure 5. Typical horizontal cave morphology of Lucayan Caverns, Grand Bahama. The mixing zone (MZ) is the darker banding in the water column. The top of the freshwater body is at the dotted line which marks the water table.

While the generation of secondary porosity in the fronts of the caves is mostly driven by heterotrophic CO_2-producing bacteria, especially associated with the mixing zone, toward the back of the caves, in the nearly still environments, the numbers of anaerobic bacteria are higher, as are the concentrations of H_2S and H_2SO_4, so SAS may be the main dissolutional mechanism.

The presence of these various bacterial populations within the currently flooded caves provides us with a probable scenario for the conditions that also created the currently subaerial flank margin caves and banana holes. That once a void has been initiated, whether it is open or sealed, varying bacterial populations will thrive in the different sub-environments that develop based on differences in water movement, densities, and available organics.

CONCLUSIONS

In the Bahamas, horizontal caves, fracture-guided caves and vertical caves are found both above and below current sea level, suggesting that they share similar origins. The currently-flooded caves have probably experienced multiple submergence intervals, whereas the currently subaerial caves may have experienced as few as one (flank margin caves and banana holes) or no (pit caves) episodes of submergence. Study of the flooded caves has provided an opportunity to identify some of the processes that form, enlarge, and reshape caves in the Bahamas.

The variety of cave morphologies and the differences in size are a result of differences in the exposure time and amount of the various ingredients needed to generate secondary porosity. The key components necessary for secondary porosity development in limestones in the Bahamas, and also likely in other regions of the world, are moving or still fresh to marine waters, organics in all forms, various bacterial populations, and time. It appears that moving groundwater tends to result in the development of caves that have greater horizontal extent than their vertical development. The water movement results from groundwater lens discharge, and tidal and wind-driven currents which help generate a mixing zone and entrain the overlying less dense water. However, it is not the mere presence of a mixing zone that is sufficient to form and enlarge caves, as the undersaturation of the mixed water is not sufficient to result in substantial dissolution (Moore and Martin, 2006). Rather, due to density interfaces, the mixing zone physically supports concentrations of organic materials and bacteria which leads to acidification of these waters. In addition, the physical mixing and groundwater discharge also dilutes carbonate-saturated water, and enhances removal of solutes.

Bacteria in the rock pores of the vadose and phreatic zones, as well as those living in the waters in flooded voids, generate CO_2, H_2S, H_2SO_4, gluconic acid, and oxalic acid depending on the local environmental conditions. These various acids are all likely to cause dissolution.

In phreatic environments open to the surface, where there is little water movement, conditions that favor the accumulation of massive bacterial populations ($>10^7$/ml water) can develop. Such conditions may result in formation of large vertical caves, as the favored site of dissolution, marked by the pycnocline and the dense bacteria, migrates vertically with sea level changes. On the other hand, in the vadose zone large amounts of organics are not necessary to support abundant heterotrophic bacteria that prefer oligotrophic conditions. Thus pit caves, as well as a variety of other voids, may develop wherever there is sufficient water, perhaps episodically available, to "turn on" interstitial bacterial populations and bacteria on the void walls; and, in open pits, bacteria and other organisms in sediment at the bottoms of the pits may promote downward carving of the void. Some of the dissolution may also be happening from the inside out via interstitial bacterial activity, not just from the void surfaces inward.

A wide variety of bacteria living in the rocks and in the water in flooded caves are able to consume a wide variety of organics, providing opportunities for different bacteria with different environmental requirements to be active when appropriate conditions exist within the voids and rocks. Based on observations in currently flooded caves, the ecology, and therefore the geochemistry, may be very different in the outer portions of caves versus deeper into the caves.

We, and others (e.g., Paine et al., 1933), have documented that limestones harbor a variety of different types of bacteria, some active, and some in limbo at any given time. The appropriate bacteria will become active whenever the proper conditions for them arise. When they are active, they produce byproducts and end-products of their metabolisms that acidify the water they live in. As a result, secondary porosity, including caves, will develop, or be enlarged, where the bacteria are active. Abundant populations of active bacteria will result in the greatest dissolution.

ACKNOWLEDGMENTS

We thank many students and colleagues for numerous discussions that have helped us congeal our ideas. We also thank the College of Charleston Geology Department, and Dr. Donald T. Gerace, CEO, and Vincent Voegeli, Executive Director, of the Gerace Research Centre, for financial and logistical support. Lastly we thank Dr. Lisa Park and two anonymous reviewers for their comments on earlier versions of this manuscript. Their comments helped us improve this paper.

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