

**PROCEEDINGS OF THE 14TH SYMPOSIUM
ON THE GEOLOGY OF THE BAHAMAS
AND OTHER CARBONATE REGIONS**

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**BELL HOLE ORIGIN:
CONSTRAINTS ON DEVELOPMENTAL MECHANISMS, CROOKED ISLAND, BAHAMAS**

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ABSTRACT

Bell holes are vertical, cylindrical voids, higher than they are wide, with circular cross sections and smooth walls found in the ceilings of dissolutional caves primarily from tropical and subtropical settings. They range in size from centimeter to meters in height and width. The origin of bell holes has been controversial, with two proposed categories: vadose mechanisms including bat activity, condensation corrosion, and vadose percolation; and phreatic mechanisms including degassing and density convection.

Crooked Island, Bahamas has a number of caves with bell holes of unusual morphology (up to 7 m high and 1.5 m in diameter), commonly in tight clusters, requiring significant bedrock removal in a small area. In many cases, numerous bell holes are open to the surface, which requires that up to a meter or more of surface denudation has occurred since the bell hole first formed. Surface intersection has little impact on the phreatic mechanisms, which were time limited to cave genesis from 119 to 131 ka ago, but greatly reduces the time window for later vadose mechanisms, which need to have been completed before bell hole intersection by surface denudation.

The Crooked Island observations suggest that bell hole development occurred syngenetically with flank margin cave development under phreatic conditions. Because flank margin caves develop under slow flow conditions, vertical con-

vection cell processes are not disrupted by turbulent lateral flow and bell holes formed as a vertical phreatic dissolution signature.

**INTRODUCTION
Bell Hole Morphology**

Bell holes are common in caves from tropical and subtropical environments. Bell holes can be described as cylindrical to conical, vertical voids in the ceilings of caves. Bell holes have the general appearance of the inside of a church bell with the clapper removed, hence the name. The vertical axes lengths of bell holes are much greater than their corresponding horizontal axes lengths, with heights up to 4 m or more, and widths up to 1 m or more (Figure 1).

Wilford (1966) first described bell holes in caves from Sarawak as cylindrical, elongate cavities with circular cross sections and near to completely vertical axes. He also noted that the bell holes seemed to have formed with no regard for variations of bedding dip and joint plane attitudes, or changes in the lithology of the limestone. Bell holes rarely appear as isolated features, but more commonly as groups that may cover an entire cave chamber ceiling. Bedrock floor features known as 'bell pits' (Lauritzen and Lundberg, 2000) are shallow depressions in bedrock commonly associated with the bell holes directly above them (when conditions allow the bedrock floors to be observed).



Figure 1. Typical bell holes from Hartford Annex Cave, Rum Cay, Bahamas. The view is straight up. Note the strong sense of verticality, and the cylindrical shape with the domed apex. The two bell holes at the top of the image are about 30 cm in diameter. Based on examples from San Salvador Island, the brown stain on the upper right bell hole is a remnant gypsum crust.

Bell pits are typically wider in diameter, and shallower, than the corresponding bell hole above. Bell holes are most often found in clusters as opposed to being isolated features.

The clusters can be very tight, less than a meter apart from one another, and sometimes individual bell holes have merged together (lower right side of Figure 1). Bell holes have been observed that have been intersected by the surface as surficial denudation cut down from above, and the apex has been completely removed such that cylinder walls and the flat land surface above are perpendicular (Figure 2). In other cases some bell holes open as a smaller hole adjacent to the apex of the cylinder because of intersection by a slope (Figure 3). Because of the ubiquity of bell holes, the mechanism or mechanisms responsible for bell hole formation are important for understanding the development of macroporosity in karst environments.

Dogwiler (1998) conducted a quantitative analysis of bell hole morphometry and distribu-

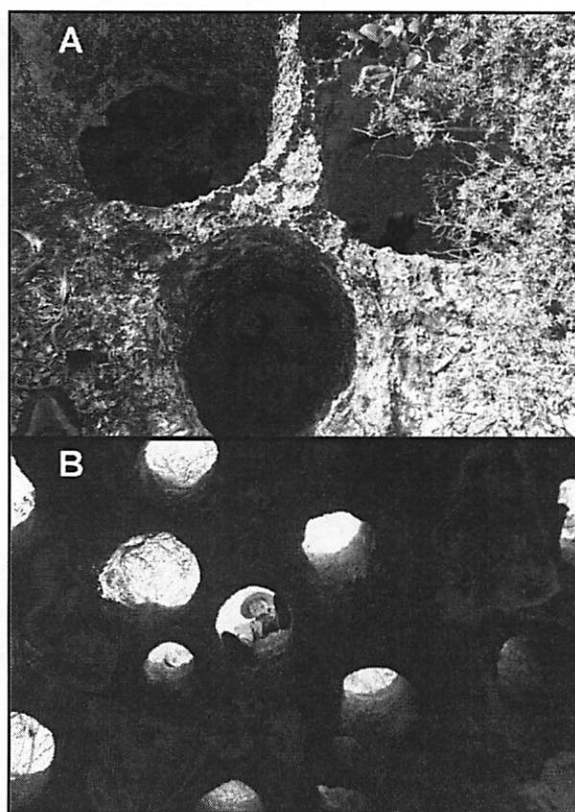


Figure 2. Fenestral Cave, Crooked Island, Bahamas. A) On top of the cave, looking down. Note that the holes are cylinders perpendicular to a flat land surface. Toe of shoe in lower left corner for scale; holes are about 30 to 40 cm across. B) Looking up at the same bell holes as in A. Note how thin the bedrock roof is.

tion in caves to provide a means for understanding the processes that may be responsible for bell hole genesis and other cave ceiling dissolutional features. However, as an unpublished MSc thesis, this work has not been readily available to the speleological community. Dogwiler (1998) noted that cave ceilings contain a wide variety of cusps, pockets, and other convex-upward forms in the centimeter to meter scale; bell holes are one such type of feature, albeit one with a very distinctive morphology. He collected ceiling concavity data from both continental caves in North America and flank-margin caves from San Salvador, Bahamas, and Isla de Mona, Puerto Rico, focusing on those

most like bell holes in shape. The bell holes were measured along their vertical axes at 20 cm intervals, and then along their horizontal axes. He found bell holes in Major's Cave on San Salvador, Bahamas to have an average diameter of 30.97 cm and an average height of 60.20 cm. Similar averages were also found in Lighthouse Cave on San Salvador. Data from continental caves such as Roppel Cave in Kentucky revealed ceiling pocket dimensions very different from those of the carbonate island karst, with ceiling pocket diameters almost twice that of the vertical axes. Dogwiler (1998) indicated these features are likely not true bell holes. Quantitative analysis has also been accomplished for Runaway Bay Caves, Jamaica (Lundberg and McFarlane, 2009), where bell holes with similar average width and depth values were reported (35 cm width, 62 cm height). Bell holes in caves in the Cayman Islands (Tarhule-Lips and Ford, 1998) have values that ranged into larger dimensions, as much as 1.3 m wide and 5.68 m high.

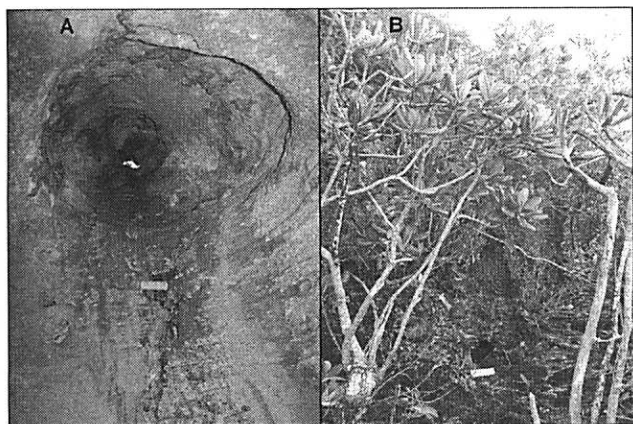


Figure 3. Osprey Cave, Crooked Island, Bahamas. A) Bell hole looking straight up, scale bar is 10 cm long. Note opening near the top of the bell hole, in the side, and not at the apex. B) Opening seen in A, as viewed from the outside. The bell hole continues upward in the higher ground to the left about 25 cm. Scale bar is 10 cm long.

Models of Bell Hole Genesis

Bell holes can be found all over the world in both continental and island karst environments. There have been two major dissolutional categories recognized that encompass possible mechanisms for bell hole origin: vadose and phreatic processes. Vadose mechanisms include bat activity (Miller, 2006; Lundberg and McFarlane, 2009), condensation corrosion (Tarhule-Lips and Ford, 1998), and vadose percolation (Ford and Williams, 1989). Phreatic processes include degassing and density convection (Ford and Williams, 1989; Dogwiler, 1998; Mylroie and Mylroie, 2009).

The bat activity model has a long history, which is reviewed in Lundberg and McFarlane (2009). Miller (1990; 2006) is a recent proponent of this idea, which was based in part on his observation that bell holes were not found in caves beyond obstacles such as breakdown chokes or sumps that precluded bat entry. He felt that bat feces and urine, as well as claw and wing activity, were the excavation mechanism. Lundberg and McFarlane (2009) examined the bat question more closely. They disagreed with Miller (2006) about the mechanism, stating that bat urine and feces are not sufficiently acidic to dissolve carbonate rock. Tarhule-Lips and Ford (1998) stated such activity would not focus dissolution at the bell hole apex, as is necessary for the vertical cylindrical shape, and noted the lack of claw marks on bell hole walls. However, Lundberg and McFarlane (2009) were able to show how small bat colonies occupying shallow roof concavities could create a unique environment from their own body heat, and their exhalations of CO₂ and H₂O. They measured rock temperatures in bell holes with bat colonies in them, noting that occupied bell holes were 1.1 C° hotter than unoccupied bell holes. In addition, the water vapor exhalations of bats is sufficient to create a film of moisture on the bell hole wall saturated with metabolic CO₂. The CO₂ plus H₂O mix would create carbonic acid, H₂CO₃, which would drive CaCO₃ dissolution. They estimated the rock

dissolution rate to be as much as 0.005 cm³/day. The bell hole temperature elevation was argued to keep the dissolutional focus at the bell hole apex, as the warm moist bat exhalations would rise, to produce the vertical cylindrical shape. This model was made for bell holes with an average height of 62 cm and an average width of 35 cm (Lundberg and McFarlane, 2009, their Table 1), which limited the volume of rock removed to approximately 0.07 m³. The Lundberg and McFarlane (2009) model is a biologic condensation corrosion model, where condensing water, carrying dissolved CO₂, attacks the limestone wall rock. The bats help create the environment where their metabolism provides the heat and gases necessary to create a dissolutionally-aggressive water condensate directed upward.

Tarhule-Lipps and Ford (1998) also argued for condensation corrosion, but without biological mediation as provided for by bats in the Lundberg and McFarlane (2009) model. Using examples from the Cayman Islands, Tarhule-Lipps and Ford (1998) felt that evening to daytime air exchanges would drive the necessary water condensation. As a result, bell hole size should reflect an entrance source of atmospheric moisture; the bell holes closer to entrance sites being larger. A problem with condensation corrosion models is that bell holes lack the vertical flow sculpturing common where descending vadose water causes dissolution. In response, it has been argued that condensation corrosion creates a thin film that dissolves CaCO₃, but then evaporates, leaving a powdery CaCO₃ crust behind that is easily dislodged.

The vadose models of Tarhule-Lipps and Ford (1998) and Lundberg and McFarlane (2009) have the advantage of working in cave environments that have left the phreatic realm of cave origin, and are now in the vadose realm of cave senescence. Such a setting provides a somewhat open-ended time window for the development of bell holes.

The phreatic models assume some sort of circulation in flooded chambers that localizes and

concentrates dissolution at selected sites in the ceiling. One argument against the vadose models is that they fail to explain bell pits, the shallow depressions found on bedrock floors under bell holes. Such pits appear unlikely to be due to dripping vadose water because bell holes show no evidence of dripping water during their formation. Many caves have thick guano deposits on their floors, which would require bell pits to either have formed prior to guano deposition, or subsequently under the guano layers (guano mining in the 1800s removed much of this guano from Bahamian caves, exposing the original dissolutional bedrock floor). The latest model to explain bell holes and bell pits assumes vertical convective flow under phreatic conditions, where the convective cell is bounded by both the floor and ceiling, such that dissolution takes place at each site (Mylroie and Mylroie, 2009). The convective model appears viable for non-turbulent flow regimes, such as found in flank margin caves, as well as in traditional turbulent conduits under stagnant flood conditions.

The Bahamian Situation

Subaerial Bahamian caves are abundant. The largest of these caves are flank margin caves, which develop in the distal margin of the fresh-water lens under the flank of the enclosing landmass (Mylroie and Carew, 1990). In the Bahamas, flank margin caves are developed in eolian calcarinites less than 500 ka in age. Due to the tectonic stability of the Bahamas, these dry caves could have formed only when a glacioeustatic sea level higher than today's had elevated the fresh-water lens above modern sea level. Only the last interglacial (MIS 5e) has been high enough (+6 m) and recent enough (131 to 119 ka) to have formed the caves as they are observed in the present, correcting for isostatic subsidence (Carew and Mylroie, 1995). The youthfulness of both the caves, and the limestones containing them, place important constraints on any bell hole model.

Bell holes are found in many Bahamian flank margin caves, which means they can form quickly (less than 131,000 years, the maximum age of the caves), in small hills on small islands, and without any significant burial or diagenesis. The phreatic mechanism requires that the bell holes are syngenetic with cave formation, for Bahamian flank margin caves developed by dissolution within an elevated fresh-water lens during the 12,000-year time window of the last interglacial sea-level highstand (MIS 5e) 131 to 119 ka (Carew and Mylroie, 1995). The vadose alternative would allow for a 119 ka time window after original cave formation; i.e. from the end of MIS 5e to the present, when vadose conditions existed within the caves. The short time windows for both proposed mechanisms of bell hole formation require that a very large amount of bedrock is removed in a very short period of time. The correct mechanism for formation would also remove bedrock vertically more rapidly than horizontally given the average measurements for bell hole morphology from Dogwiler (1998), Tarhule-Lips and Ford (1998) and Lundberg and McFarlane (2009). According to Wilford (1966), bell holes are unaffected by bedding and jointing attitudes and carbonate facies leading to the conclusion that bell holes must form uniformly upward from a horizontal plane producing the characteristic circular, cylindrical shape. The dissolutional mechanism must be powerful enough to ignore rock variations. It has been well established that dissolution in the distal margin of the fresh-water lens is both rapid and powerful (Mylroie and Mylroie, 2007).

The development of bell holes in very young Bahamian limestones has impact on another idea concerning bell holes. Ford and Williams (2007) argued that the development of bell holes is accelerated by the removal of calcite cement between carbonate grains, as the grains are less soluble. Cement removal would allow the grains to fall out of the bell hole, decreasing the volume of rock necessary to remove by dissolution. However, grainfall should accumulate on the bedrock

floor, but bell pits are found instead. In addition, in young Bahamian carbonates, the grains are still aragonite, which means the grains are more soluble than the calcite cement, so the grainfall idea cannot be supported for Bahamian bell holes.

On San Salvador Island, Bahamas, Lauritzen and Lundberg (2000) observed flowstone in bell holes that had been cut by dissolution so as to be smooth with the bell hole surface, indicating dissolution after vadose conditions had allowed calcite precipitation. This evidence was used to support the vadose model, as the phreatic origin of the cave preceded the subsequent vadose condition. It is recognized in the Bahamas, however, that the MIS 5e highstand had a short fall of a few meters for perhaps 1 ka before sea level rose back to its highstand position (Carew and Mylroie, 1999). The cave could have formed and the bell holes developed phreatically, then the vadose speleothems were deposited during the brief mid-MIS 5e sea-level fall. These speleothems would have been subject to phreatic conditions during the second highstand pulse, and partially dissolved. Therefore the speleothem material, unless dated as younger than 119 ka, cannot be used as proof of a vadose origin for bell holes in the Bahamas.

Miller (1990, 2006) reported bell holes on the underside of breakdown blocks, and argued such features attest to a bat (vadose) origin. This interpretation assumes that breakdown is a post-phreatic activity, which is not necessarily true. It also assumes that breakdown occurring in a vadose environment could not be subsequently returned to phreatic conditions. In the Bahamas, sea-level fluctuations such as occurred on the MIS 5e sea-level highstand provide such a phreatic-vadose-phreatic cycle situation.

The flank margin caves of the Bahamas, being young caves which developed rapidly in relatively youthful carbonate rock, offer constraints on bell hole formation that do not exist in other tropical and subtropical settings. The purpose of this paper is to report simple bell hole observations from Crooked Island, Bahamas and

comment on their impact on ideas regarding bell hole modeling.

OBSERVATIONS AND INTERPRETATIONS

During field work on Crooked Island (Figure 4) in May of 2004 and December of 2007, a total of 22 flank margin caves were entered and mapped (Birmingham et al., 2008). A visit to Acklins Island in December of 2008 provided additional data. Of particular note from these visits were the large number of bell holes found in the caves, their large size, and the interaction of some of those bell holes with the land surface above. The observations fall into four important categories.

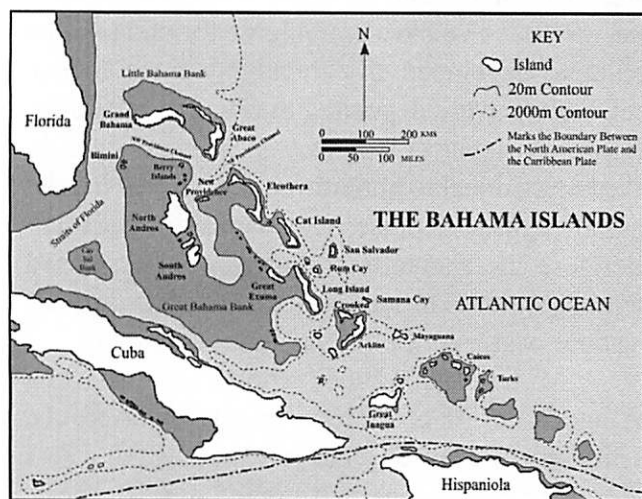


Figure 4. Map of the Bahamian Archipelago, showing islands discussed in the text.

Bell Hole Complexity

Despite the width and height data averages from Dogwiler (1998) and Lundberg and McFarlane (2009), bell holes are not always uniform in size as Tarhule-Lips and Ford (1998) demonstrated. On Crooked Island they can range from a few centimeters in height and width to almost a meter across and 4 meters high as seen in Figure 5, or larger. The broad range in sizes observed, and the

connection of some by lateral dissolution holes, argues against the bat origin theory. Additionally, some bell holes are smaller than the voids bats are known to roost in today, such as the smaller openings in Figure 5.

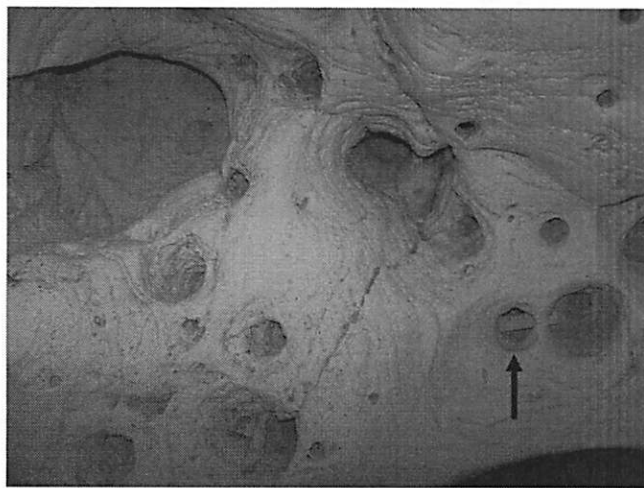


Figure 5. Bell holes in Cumulus Cave, Crooked Island, Bahamas, shown at an upward looking angle. Ruler stretching between two small bell holes in the lower right of the image is 10 cm long (black arrow). The bell holes shown range in diameter from 2 cm to 75 cm, and in height from 4 cm to ~400 cm.

Gypsum Crusts

Figure 6 (as well as Figure 1 from Rum Cay, Bahamas and Figure 7 from Acklins Island, Bahamas) shows that bell holes have crusts in them. On San Salvador Island, similar crusts were primarily gypsum (Onac et al., 2001; 2008). The presence of gypsum requires that the dissolutional process has stopped, and that the gypsum subsequently formed by evaporation of sulfate-containing water entering from above the cave as vadose flow contaminated by sea-spray. Isotopic studies indicate that the ³⁴S in the gypsum crusts is identical to marine sulfur (Bottrell et al., 1993), and has not been biomediated. Numerous cave minerals from San Salvador Island, including much of the

gypsum, show development as a result of interaction with either sea water ions or bat guano, or both (Onac et al., 2001; 2008). However the bat guano was not the source of the sulfur based on the Bottrell et al. (1993) stable isotope study. The gypsum crusts appear to be evaporative deposits formed by wicking of vadose water contaminated by sulfate-containing sea spray out onto the bell hole walls. Because the bell holes extend upwards into the cave ceiling, they preferentially intercepted the vadose flow, and gypsum deposition was localized there. Gypsum crusts are not only in bell holes, but also found on cave ceilings and walls (Figure 7), indicating the crusts form independently of bat activity.

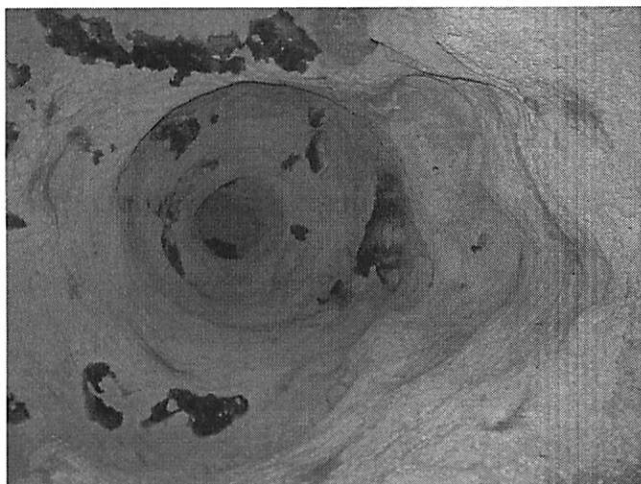


Figure 6. Bell hole in Crossbed Cave, Crooked Island, Bahamas. Dark patches are secondary mineral deposits, most likely gypsum. The central diameter of this bell hole, half way up, is ~90 cm, height ~4 m.

Bell Hole Size.

Miller (2006) reported bell hole sizes in Puerto Rico to be 30 cm in diameter and approximately 1 meter in height, in general agreement with Dogwiler's (1998) Majors Cave data on San Salvador Island, Bahamas. Lundberg & McFarlane (2009), as noted earlier, report bell hole sizes in Runaway

Bay Caves, Jamaica to be similar to the Puerto Rico and San Salvador data. Tarhule-Lipps and Ford (1998) reported larger bell holes, up to 5.7 m high, but most below 3 m in height, with basal diameters ranging from 0.25 m to 1.3 m.

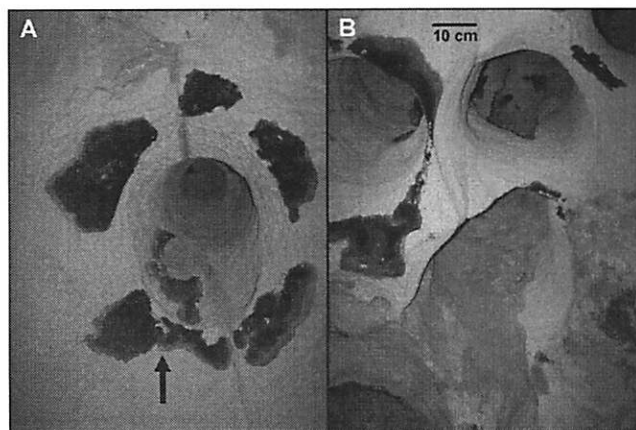


Figure 7. Bell holes and gypsum crusts from Jumbej Hole, Acklins Island, Bahamas, adjacent to Crooked Island (see Figure 4). A) Looking up into a bell hole with gypsum crusts inside and continuing out on to the flat ceiling. Arrow points to 10 cm long ruler for scale. B) Cluster of bell holes with gypsum crusts both inside the bell holes, and on the flat ceiling areas between bell holes. Notice that the middle two bell holes have a dissolved window joining them.

On Crooked Island, bell holes are commonly very high, up to 7 m high (Figure 8), with widths commonly over 1 m. These large bell holes are commonly open on one side, a difficult aspect to explain by the bat model, where dissolution is continually focussed at the bell hole apex.

Bell Hole Intersections.

Crooked Island has bell holes that intersect the land surface above, as seen in Figures 2, 3, 8, 9 and 10. Some of these intersections are circular holes flush on the bedrock surface (Figure 2). Both the phreatic and the vadose bat models require that bell holes form with a sealed apex. Therefore the

breaching of the bell holes by surface denudation must postdate the formation of the bell holes.



Figure 8. Bell holes in Generator Cave, Crooked Island, Bahamas. The bell holes are up to 7 m high, some have been subsequently intersected by the ground surface above. Many of the bell holes have their sides missing as a result of coalescence, a phenomena not compatible with the bat model.

The denudation necessary to intercept these bell holes, and reduce their domed apex to a simple exposed cylinder, reduces the available time to make the bell hole inside the cave. In some cases, as shown in Figure 3, the intersection has been from the side, further indicating the independence of bell hole formation from outside surface effects. Within a cave, missing side walls of bell holes, as seen in Figure 8, is also problematic. As noted earlier, the bat model offers no explanation for the dissolution of a partial side of a bell hole as the dissolutional focus in that model is solely on the apex. While it may be possible for a bell hole to open to the surface because of actions within the bell hole, no model offered so far can convert a bell hole from a small apex opening into a circular right cylinder without an apex cone. As all gradations of slight apex cone opening to fully denuded apex cone are observed in the field, it has been assumed that the opening of the bell hole to the

surface is a result of surface denudation.

DISCUSSION

The bell holes of Crooked Island demonstrate how simple observation without sophisticated measurements can assist in constraining model development and execution. The general setting of the Bahamas provides tight time constraints on any model of bell hole development. If phreatic, the bell holes formed in 12,000 years or less. If vadose, they formed in 119,000 years or less.

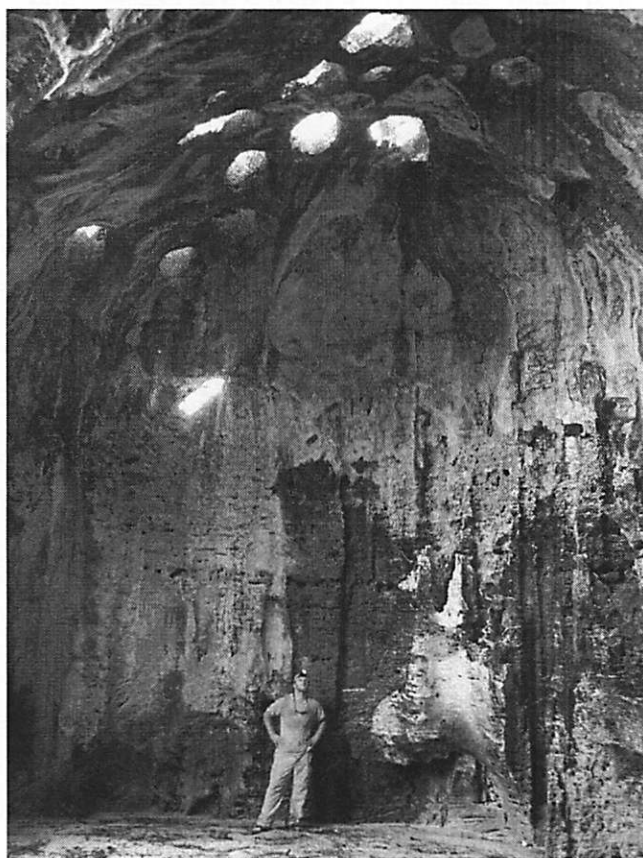


Figure 9. Bell holes in the ceiling of Fenestral Cave, Crooked Island, Bahamas. Note that many have been breached by downward erosion of the land surface above. Note as well that the wall scars of several bell holes can be seen to run from the ceiling to the sediment floor.

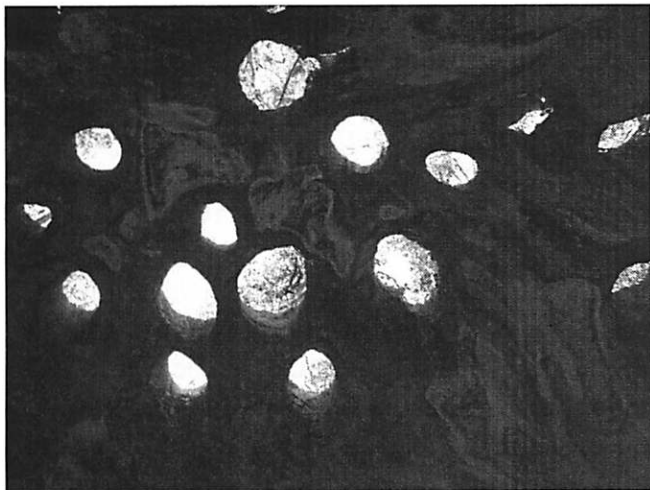


Figure 10. Fenetral Cave, Crooked Island, Bahamas, looking straight up. Most, but not all, bell holes at this site are open to the surface as a result of denudation of the landscape above.

The time window can be further constrained for the two leading vadose models of bat activity and condensation corrosion. If it is assumed that the bell holes formed inside the caves, growing upward, then they must predate any intersection of the bell holes by the land surface. Denudation rates in eogenetic island limestones are about 70 mm/ka (Jennings, 1985). To reduce a bell hole domed apex entirely, such that only a right cylinder remained, would require at least 50 cm of rock loss at the top of the bell hole. As soon as the apex is penetrated, the internal bell hole conditions for the vadose models disappear. At least a minimum of 7,000 years (500 mm/70 mm/ka) is required to remove a bell hole apex (once a bell hole apex is gone, there is no way to determine how much of the lower cylinder has also been lost). That 7,000 years must be taken away from the bell hole time window. This calculation assumes the bell hole apex was just below (and tangent to) the surface when bell hole development ceased. If any extra rock was overhead, that too would have to be removed in order for the bell hole apex to be intersected by surface denudation (see Figure 3B). Therefore the 7,000 years is a

minimum, and unlikely, estimate. A meter of extra rock would take an additional 14,000 years. A more reasonable estimate would be ~20,000 years (1 m surface denudation, ½ m of bell hole intersection) to create a bell hole exposed to the surface as a simple cylinder with no apex, as in Figure 2.

The vadose models require that the flank margin cave, which forms as a sealed chamber (Myroie and Carew, 1990), must be broken into by surface denudation to create an entrance for either macro-organism entry (bat model), or air flow (abiotic condensation model) to occur. Such entrances commonly form from hill slope retreat on the side of the cave, and are therefore independent of the previous vertical denudation argument. Based on existing Bahamian caves, such denudation must be several meters to penetrate the cave wall, and given the denudation rate for these limestones, would take on the order of 30,000 years to occur. Denudation affects both the initiation (lateral intersection to allow bat and air entry) and the termination (vertical denudation to cause bell hole intersection) of the vadose model time window. Therefore the vadose models do not have close to 120,000 years to act to make bell holes, but perhaps only 70,000 years, (120,000 minus the 30,000 years of lateral denudation to create a cave entrance to start bell hole formation, minus another 20,000m years for vertical intersection to stop bell hole development) or 60% of that time window.

Lundberg and McFarlane (2009) estimate that their bat model can make a 1 m high bell hole in 43,489 years (at 5% CO₂). They estimate this time drops to ~23,000 years if 30% porosity is assumed for the host rock, very similar for Bahamian eolian calcarenite porosity values. For bell holes over 5 m in height, or significantly over 35 cm in width, however, the post-MIS 5e time window is insufficient for vadose models to have produced the observed bell holes on Crooked Island. For example, a 5 m high, 1 m diameter bell hole requires removal of 0.8 m³ of rock material, or ten

times more than for the bell holes described by Lundberg and McFarlane (2009); given the dissolution rates calculated, the age of the bell holes would exceed the age of cave formation for a cave developed on the MIS 5e sea-level highstand (and, in some cases, exceed the age of the enclosing rock). Taller bell holes also create a problem for disposal of dissolved CaCO_3 in the bat model. If dissolution is taking place at the bell hole apex at the top of a 5 m long bell hole, then the fluid containing the dissolved CaCO_3 must flow all the way to the bottom of the hole without any CO_2 degassing to avoid re-precipitating the CaCO_3 on the bell hole wall. When bell pits are considered, the solution must drip from the bell hole to the floor with sufficient dissolutional aggressivity to make the bell pit. The walls of bell holes do not show the vertical grooving that such aggressive solutions would necessarily create. The bat model does not successfully scale up to the observed larger bell holes; given the bat model rate proposed by Lundberg and McFarlane (2009), there isn't time in 70,000 years to make a 4 to 5 m high bell hole.

The vadose models fail to explain the bell pits associated with bell holes. Bell hole like structures are reported by Klimchouk (2007) as having formed in deep confined settings, which eliminates all vadose models. The vadose models are also inadequate to explain why bell holes form regardless of carbonate bedrock structure and facies. The vadose models are admittedly slow compared to phreatic models, and bell hole dissolution would be expected to be sensitive to subtle differences of rock structure and composition. Finally, for bell holes to form by either vadose method, there has to be an initiation point. Neither bat metabolic production nor condensation corrosion would create a domed structure from a flat roof. There must be irregularities in the cave roof sufficient to allow unique micro-environments to form and persist. Lundberg and McFarlane (2009) argue that most cave roofs have a cusped nature from initial phreatic speleogenesis, so that incipi-

ent hollows already exist for bat groups to occupy. Once a cylindrical hole has been formed, the proposed models have mechanisms that may work. But there must be a significant time lag to get past that initial condition (much like the activation energy required for certain chemical reactions to occur).

The presence of bats in bell holes with gypsum crusts on the walls and apex argues against bats being a major contributor to bell hole formation; their exhalation, and its subsequent H_2O condensation on the bell hole surfaces, should strip out the gypsum crust by the same dissolution argued to create the bell hole. Gypsum is more soluble than CaCO_3 , and is dissolved by simple ionic dissolution, requiring no special acidic pH effects as required for CaCO_3 dissolution. The bell hole surfaces cannot be precipitating highly soluble gypsum while at the same time dissolving less soluble CaCO_3 .

The phreatic model also operates under severe time constraints. The Bahamian flank margin caves have a 12,000 year time window to develop by phreatic dissolution, as their development is tied to an elevated fresh-water lens floating on an elevated sea level. Mylroie and Mylroie (2007) demonstrated that the dissolution in the distal margin of the fresh-water lens is extremely potent. These caves have chambers that cut across variations in rock type (eolian versus subtidal in the Bahamas), primary structure (dipping fore reef beds on Isla de Mona), flowstone (Bahamas and Isla de Mona) and terra rossa paleosols and pit infills (Bahamas and Isla de Mona). For the Bahamian examples, this dissolution was complete in a short period of time (12,000 years) to form extremely large chambers (tens of thousands of meters in volume).

The water flow in flank margin caves is non-turbulent, which allows vertical flow caused by density variations to occur. Mylroie and Mylroie (2009) have demonstrated that density variations can occur in such a hydraulic setting by thermal, evolved gas, or solute mechanisms. The

flank margin cave setting can be considered somewhat isothermal, and so thermal convection is not likely. However, the distal margin of the fresh-water lens encompasses three water types: marine water below the lens, the fresh-water lens itself, and descending vadose water reaching the lens from the land surface above. The entry of vadose fresh water as diffuse matrix flow through the eolian calcarenite roof of a flank margin cave would mix with the phreatic fresh water of the lens resulting in a mixing environment. Both waters could be saturated with respect to CaCO_3 , but if they had done so at different initial conditions, the mixing would create an aggressive solution that would drive additional CaCO_3 dissolution. This dissolution would be localized wherever vadose water was slightly concentrated to create cupolas in the cave ceiling. Such mixed water would contain more solute than either parent water, and so would be denser than either water. That solute-laden mixture would sink by density flow to the bottom of the chamber, where mixing with marine water, and further renewed aggressivity, would be possible. Such downward flow would force water upward. Dissolution would form a cupola on the cave chamber ceiling; as that cupola grew upward to form the bell hole cylinder and apex, it would trap the density convection cell. The quick saturation of the water at the top of the bell hole would prevent further dissolution along the bell hole sides as the solute-heavy water descended, maintaining the uniform cylindrical nature of the bell hole. The return flow at the base of the chamber would create the bell pit, as further mixing dissolution would be available there as a result of mixing sea water with fresh water. The aspect ratio of the bell hole and bell pits as seen today would be the aspect ratio of the convection cell when it was last functioning.

Alternatively, Mylroie and Mylroie (2009) have proposed gas production as a result of oxidation of organics, to create a buoyant water package. Water pressure in a fresh-water lens margin is minimal (less than 2 atm), so gas evolution is

possible. The base of the fresh-water lens is a density interface known to collect organic material and create dissolutional potential by CO_2 production, and under anoxic conditions, H_2S (Bottrell et al., 1991). Rising gases would create a convection cell that would localize at the cave ceiling in any indentation already present. The ceiling rock would be dissolutionally attacked by the CO_2 (or H_2S) rich water to create a bell hole, which would lock in the convection cell position. Bell pits are also explicable by this method. Gas-driven convection removes the need for any specific vadose flow entry into the cave from above.

The phreatic models require bell hole development when sea level was high, and the fresh-water lens had invaded the space now occupied by dry Bahamian flank margin caves. In the ~120 ka since that time, the land surface above the caves as well as the climate have changed. The absence of drip water entering bell holes today does not indicate what vadose water was doing ~125 ka above a developing flank margin cave.

The role of bacteria in the production of bell holes has not been addressed by any studies. Based on ^{34}S studies, bacteria have not participated in the gypsum crust production. However, bacteria might have at some stage been important for original bell hole dissolution, for either the vadose or the phreatic model, or even a combination of them.

CONCLUSIONS

The bat model is compelling because one commonly sees bell holes with bats in them; however, to assume cause and effect is incorrect. Bats clearly like bell holes, but their presence is merely opportunistic. Condensation corrosion is compelling, because the evaporation, condensation and dripping of such water from a cave roof is a simple concept; however, it requires an energy sink to absorb the 539 cal/g required to effect condensation, a difficult task in an isothermal tropical environment. The vadose model of bell

hole dissolution requires that those dissolutional conditions cease so that gypsum crusts can subsequently line the bell holes. Many bell holes today contain both a gypsum crust and a bat population, which implies the bats have utilized an existing hole. The vadose models cannot explain bell pits. The phreatic convection cell model presented here is purely speculative, but it has none of the many separate and unrelated problems that face the vadose models. In conclusion, the phreatic model is offered to the reader as a testable hypothesis for future work. The unique bell holes of Crooked Island, Bahamas provided the impetus to examine the bell hole problem once again.

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REFERENCES

- Birmingham, A. N., Lacey, M. J., Mylroie, J. R., and Mylroie, J. E., 2008 (abstract), Cave reconnaissance, Crooked and Acklins Islands, Bahamas. Program, National Speleological Society Annual Convention, p. 115.
- Bottrell, S. H., Smart, P. L., Whitaker, F., and Raiswell, R., 1991, Geochemistry and isotope systematics of sulphur in the mixing zone of Bahamian blue holes: Applied Geochemistry, v. 6, p. 99-103.
- Bottrell, S. H., Carew, J. L., and Mylroie, J. E., 1993, Bacterial sulphate reduction in flank margin environments: Evidence from sulphur isotopes, in White, B. ed., Proceedings of the 6th Symposium on the Geology of the Bahamas, Port Charlotte, Florida, Bahamian Field Station, p. 17-21.
- Carew, J. L., and Mylroie, J. E., 1995, Quaternary tectonic stability of the Bahamian Archipelago: Evidence from fossil coral reefs and flank margin caves: Quaternary Science Reviews, v. 14, p. 144-153.
- Carew, J. L., and Mylroie, J. E., 1999, A review of the last interglacial sea-level highstand (oxygen isotope substage 5e): Duration, magnitude and variability from Bahamian Data, in Curran, H. A. and Mylroie, J. E., eds., Proceedings of the Ninth Symposium on the Geology of the Bahamas and other carbonate regions, Bahamian Field Station, San Salvador Island, Bahamas, p.14-21.
- Dogwiler, T. J., 1998, Analysis of bell hole morphology and distribution: a tool for evaluating formational processes. Unpublished MSc thesis, Mississippi State University, 106 p.
- Ford, D. C., and Williams, P. W., 1989, Karst Geomorphology and Hydrology. Chapman and Hall, New York, 601 p.
- Ford, D. C., and Williams, P. W., 2007, Karst Hydrogeology and Geomorphology. John Wiley & Sons, London, 562 p.
- Jennings, J. M., 1985, Karst Geomorphology. Blackwell, New York, 293 p.
- Klimchouk, A., 2007, Hypogene speleogenesis: Hydrogeological and morphological perspective: Special Paper No 1, National Cave and Karst Research Institute, Carlsbad, NM, 106 p.

- Lauritzen, S.-E., and Lundberg, J., 2000, Solutional and erosional morphology, in Klimchouk, A. B., Ford, D. C., Palmer, A. N., and Dreybrodt, W., eds., *Speleogenesis: Evolution of Karst Aquifers*. National Speleological Society, Huntsville, Alabama, p. 408-426.
- Lundberg, J., and McFarlane, D. A., 2009, Bats and bell holes: The microclimatic impact of bat roosting, using a case study from Runaway Bay Caves, Jamaica: *Geomorphology*, v. 106, p. 78-85.
- Miller, T., 1990 (abstract), Bellholes: Biogenic (bat) erosion features of tropical caves: *Geo2 Occasional Paper No. 4*, v. 17, no. 2-3, p. 76.
- Miller, T., 2006 (abstract), Bellholes and bellbasins: Biogenic (bat) features of Caribbean caves: *Geological Society of America Abstracts with Programs*, v.38, no. 7, p. 63.
- Myroie, J. E. and Carew, J. L., 1990, The Flank Margin Model for Dissolution Cave Development in Carbonate Platforms: *Earth Surface Processes and Landforms*, v. 15, p. 413-424.
- Myroie, J. E. and Myroie J. R., 2007, Development of the Carbonate Island Karst Model: *Journal of Cave and Karst Studies*, v. 69, p. 59-75.
- Myroie, J. E. and Myroie, J. R., 2009, Unique dissolutional morphologies in caves: A result of convective flow regimes? in White, W. B., ed., *Proceedings of the 15th International Congress of Speleology*, National Speleological Society, Huntsville, Alabama, v. 2, p. 916-922.
- Onac, B. P., Myroie, J. E., and White, W. B., 2001, Mineralogy of cave deposits on San Salvador Island, Bahamas: *Carbonates and Evaporites*, v. 16, no. 1, p. 8-16.
- Onac, B. P., Sumrall, J., Myroie, J. E., and Kearns, J., 2008, *Cave Minerals of San Salvador Island, Bahamas*. The University of South Florida Karst Study Series, 70 p.
- Tarhule-Lipps, R. F. A., and Ford, D. C., 1998, Morphometric studies of bell hole development on Cayman Brac: *Cave and Karst Science*, v. 25, no. 3, p. 19-30.
- Wilford, C. E., 1966, "Bell Holes" in Sarawak Caves. *Bulletin of the National Speleological Society*, v. 28, p. 179-182.