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UNUSUAL KARST PHENOMENA FROM CAT ISLAND, BAHAMAS

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ABSTRACT

Cat Island, Bahamas, contains some unusual island karst features. Cat's Cradle, a blue hole in the east-central Cat Island, is a progradational collapse structure that breached a large eolian calcarenite dune. The subaerial walls of the collapse are stepped at 3 m elevation, with the upper wall set back farther than the lower wall. This upper wall contains a complete ring of flank margin caves that open onto the bench above the blue hole. If the mixing model for flank margin speleogenesis is correct, then the blue hole was marine during the 6 m high MIS 5e sea-level highstand.

A 2 km long section of the east coast of Cat Island is a late Pleistocene back-beach breccia facies, indicating strand plain progradation, followed by wave erosion of that plain to create back-beach breccia, and subsequent continuing progradation of the strand plain. The fresh-water lens followed that progradation and created flank margin caves within the breccia facies, indicating the rapidity with which flank margin cave speleogenesis operates, as the entire sequence of rock deposition and dissolution had to be accomplished within the ~ 9 ka long MIS 5e event.

Big Cave, in central Cat Island, is located at 55 m elevation on a shoulder of Mount Alvernia, the highest point in The Bahamas at 62 m elevation. The cave has all the small- and large-scale bedrock morphologies found in flank margin caves, but cannot be a flank margin cave in the traditional sense given its elevation above any possible Quaternary sea-level highstand. Cave genesis within freshwater lens perched on a terra rossa paleosol has been previously offered as a possible explanation.

INTRODUCTION

A karst reconnaissance trip was made by the authors to Cat Island, Bahamas, from February 3 to February 18, 2016. The purpose of this expedition was to locate, survey, and catalogue cave and karst features as part of a project of the Coastal Cave Survey, an informal cave research group that specializes in coastal and island caves. This work built on reconnaissance done in February 2006 for the Cat Island field trip (Figure 1) to be run in June of that year by the Gerace Research Centre as part of the 13th Symposium of the Geology of The Bahamas and Other Carbonate Regions (Mylroie *et al*. 2006). The 2016 expedition also built on much earlier work by Rob Palmer and colleagues that had specialized on the caves of Cat Island (McHale 1986; Palmer 1986; Palmer *et al*. 1986). The geology of Cat Island has not been well studied, the manuscript by Lind (1969) on coastal landforms being one of the few pieces of geologic literature available before 2006. The 2006 field guide reconnaissance trip led to a return to Cat Island by several participants to study specific

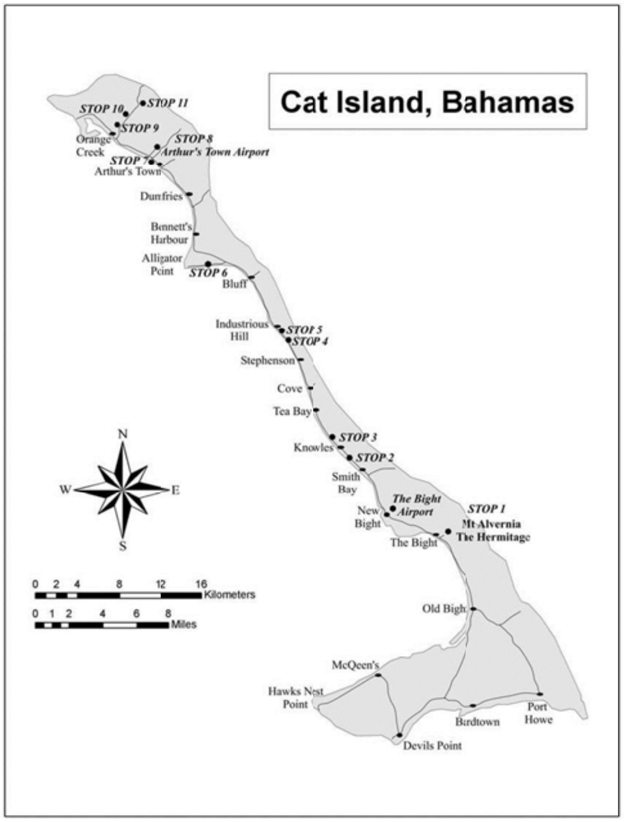


Figure 1. Map of Cat Island, showing the three areas reported in this paper. The map, adapted from Mylroie, et al., 2006, also shows the field trip stops for the June 2006 GRC field trip.

features of the island's geology (e.g. Curran *et al.* 2008; Glumac *et al.* 2011, 2012). The caves documented during the 2016 field season formed a critical component of a paper that has re-interpreted Quaternary sea-level in the Bahamian Archipelago (Mylroie *et al.* 2020). The 2006 field guide remains the most comprehensive assessment of the geology of Cat Island (Mylroie *et al.* 2006). The cave and karst results from both the 2006 and 2016 expeditions were presented at the National Speleological Society annual meeting in July of 2016 (Albury, et al. 2016) as well as at the Third Joint Symposium on the Natural History and Geology of the Bahamas (Albury *et al.* 2019). The purpose of this paper is to highlight three specific aspects of that work that have broad impact on our understanding of Bahamian geology, karst processes, and Quaternary sea-level.

METHODS

The initial effort was to locate and map all currently subaerial caves on Cat Island. Submerged caves, such as those associated with blue holes, were not part of the study, although blue holes were noted when found. A few cave locations were already printed on the Bahamian government's Lands and Surveys topographic maps. Many were known to the local island residents, but this knowledge has deteriorated over the four decades the corresponding author has worked in the Bahamas, as the younger generation knows little about the interior of their own islands, and the older generation, who often did slash and burn agriculture in the interior of their islands, is dying off. Still, the local population remains the best source of information about cave locations. Commonly it is basic field reconnaissance of the islands by this research team that actually located the caves. Colleagues who work in the interior of islands for other research projects, such as animal or plant studies, share information on the caves that they find. Prior work was extremely useful (McHale 1986; Palmer 1986; Palmer et al. 1986). The interior of the Bahamian islands is commonly difficult to traverse; the expression used is that "the bush is too high to walk over and too low to walk under". Trail cutting is critical in these situations. High canopy forest is present in some island interiors, and fieldwork there is relatively easy, but for most areas on Cat Island, it is hard work. Aerial reconnaissance was useful, mostly for locating larger cave entrances, especially ceiling collapses and blue holes.

Caves located in the field were initially georeferenced in the field with Garmin Etrex series units, utilizing the WGS84 datum and with an average horizontal EPE (estimated projected error) of 2 to 3 meters. As elevation data from this method is of limited accuracy, cave elevation data were supplemented with orthographic surface surveys to apparent sea-level (where feasible) and cave surveys correlated to subterranean tidal pools to the nearest 0.1 meter and within modern microtidal environments (i.e., a tidal range of <1 meter). The data set was then correlated to satellite imagery, available DEM models and topographic maps.

Each flank margin cave was mapped by use of compass, inclinometer and tape (or laser range finder), with passage detail sketched to scale and annotated. The resulting cave map data are reduced and drafted using computer software Compass (www.fountainware.com) and Adobe Illustrator, respectively. The maps were then analyzed to provide additional morphometric parameters (NIH Image J software – www.NIH.gov) including the total aerial footprint of the cave. The maximum height of each phreatic dissolutional surface represents a minimum fresh-water lens position, and by extension, sea-level position at the time of cave origin. Cave length, the traditional measurement of cave size, is not an appropriate value for flank margin caves, which are connections of globular chambers and passages. The aerial footprint is a better measure of the cave size in this circumstance (Mylroie 2007; Waterstrat, *et al*. 2010). Flank margin caves form in the distal margin of the fresh-water lens where the lens is thin (Mylroie and Mylroie 2007; Mylroie 2013), therefore aerial footprint is a suitable proxy of cave volume as the vertical range of the cave is restricted.

The cave data were collected under permit from the Bahamian government, through the Bahamas Environment, Science and Technology Commission (BEST), who control release of such information. Cave location information is especially sensitive, given the vulnerability of caves and cave deposits to vandalism, desecration, and looting.

RESULTS

Breccia block facies

The first feature of interest was found while hiking northward along the east coast of Cat Island to cut a trail into a blue hole seen by a private airplane while flying into Cat Island with one of the authors aboard (Figure 1). The coast in this area is a bench about 3 to 8 m above sea-level. The bench is a mixture of beach, lagoonal, and breccia block facies (Figure 2). Because the breccia block facies is covered in part by terra rossa paleosol (Figure 2B), the initial interpretation was a solution collapse breccia similar to what is seen on the south coast of San Salvador Island at French Bay (Florea *et al.* 2001). Closer examination revealed that the blocks were covered by the terra rossa paleosol, but that the terra rossa material was not providing a matrix for supporting the blocks, the blocks instead rested in a clean, white sand (Figure 2C). Such breccia block facies are found all across the Bahamas, as first described in detail by Carew and Mylroie (1985; 1995) at Grotto Beach on San Salvador Island, where a Pleistocene example in the rock record is adjacent to a Holocene example currently in the process of formation. The terra rossa covering the breccia block facies, and the lagoonal facies adjacent to the blocks at 6 m elevation, demonstrate that the breccia block facies is Pleistocene in age, most likely from the last interglacial, MIS substage 5e. The MIS 5e highstand is believed to have lasted in The Bahamas from 124 to 115 ka (Thompson *et al.* 2011).

At numerous locations along this bench, flank margin caves of modest size are developed in the breccia block facies, the largest being Dragon Cave (Figures 3 and 4). This cave is entered from a roof collapse and contains numerous phreatic dissolutional features, indicating development within the MIS 5e fresh-water lens. The configuration of the cave does not favor a sea cave pseudokarst interpretation. Secondary calcite speleothems are present (Figure 4D). The cave meets all the requirements of a flank margin cave (Mylroie and Mylroie 2007, 2013; Waterstrat *et al.* 2010). A few other caves on the bench, of a similar nature, were also mapped.

Cat's Cradle blue hole

The second feature of interest is the blue hole located inland of the bench with the breccia block facies (Figure 1). This blue hole, Cat's Cradle, is a progradational collapse feature that has penetrated the side of an eolian calcarenite ridge, producing high walls that lead down to water (Figures 5 and 6). The high wall has a bench, or step in it 3 m above water level, and which contains numerous small caves of phreatic origin,

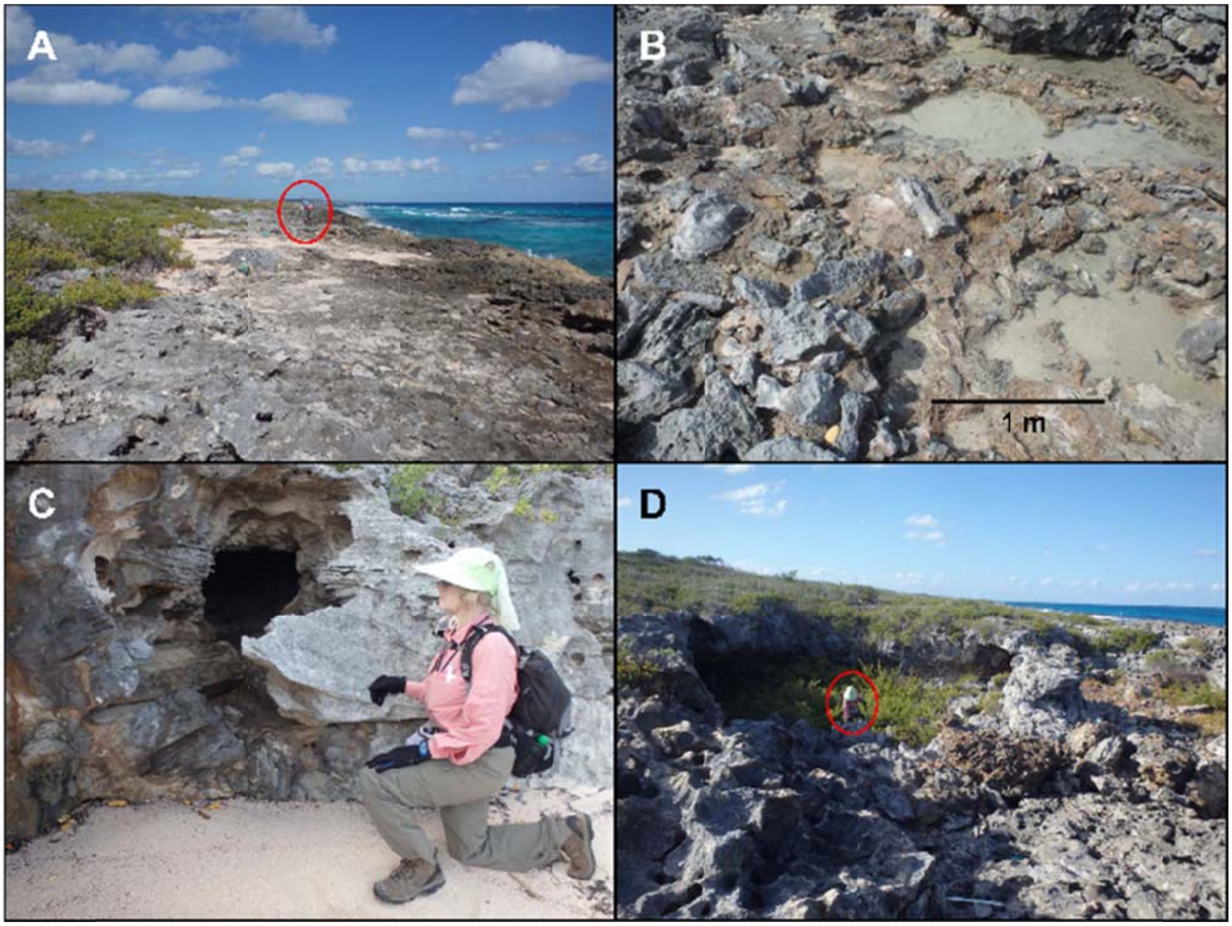
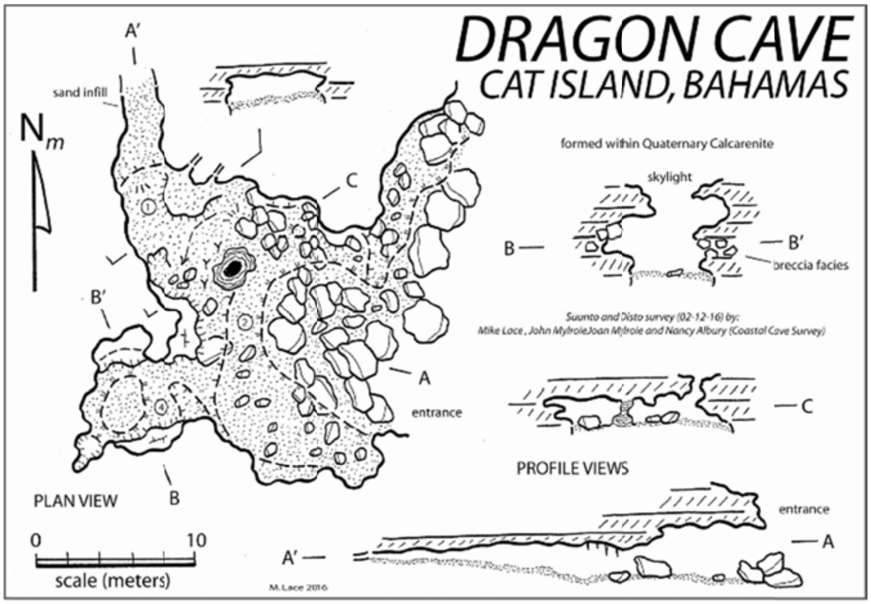


Figure 2. The coastal area from eastern Cat Island where the breccia block facies outcrops were found. A. General view of the bench, looking north, person in oval for scale. B. Surface outcrop of the breccia block facies, with overlying terra rossa paleosol that gives the appearance that the outcrop is a solution collapse breccia. C. Back beach cliff, showing the breccia block facies in vertical section, with a small dissolution cave. The terra rossa paleosol material is not present: a sand matrix partially supports the blocks. D. The collapse entrance to Dragon Cave, the largest of many flank margin caves found on the coastal bench, person in oval for scale.



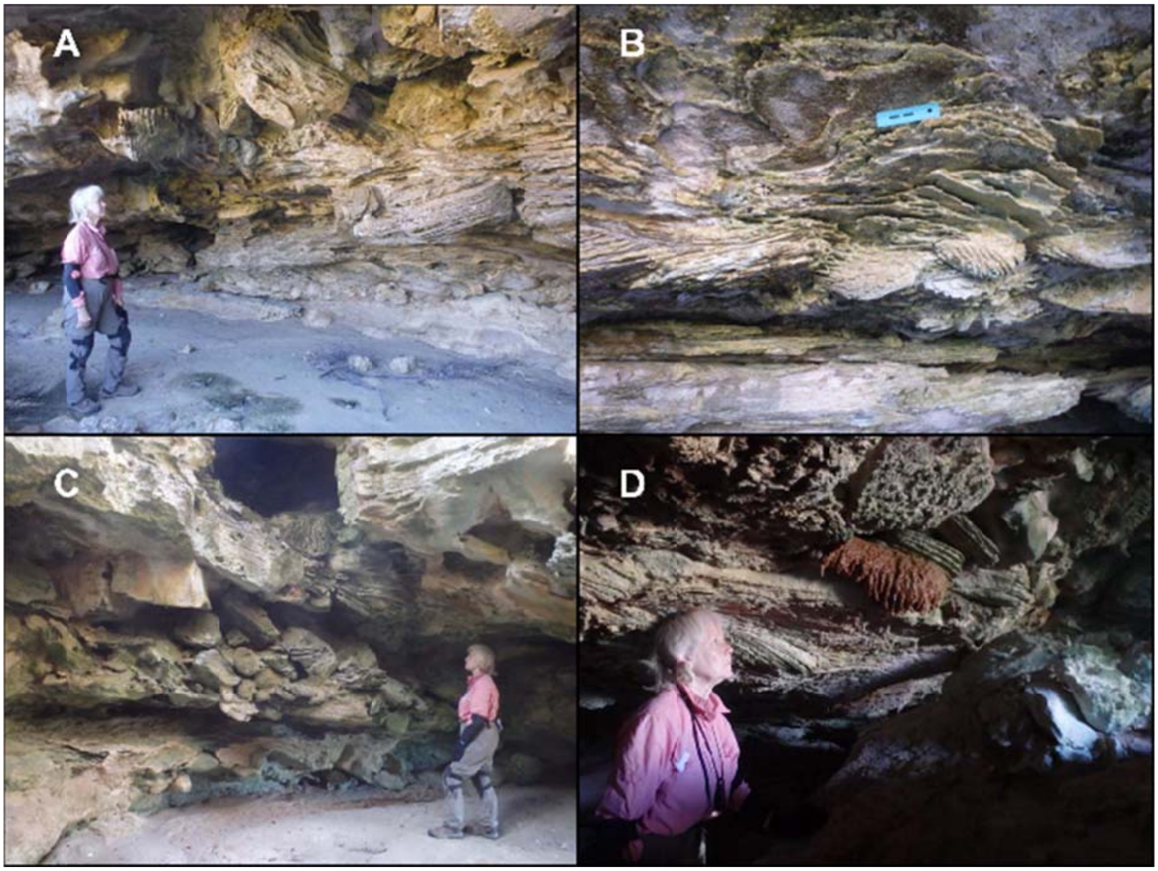


Figure 4. Inside Dragon Cave. A. Entrance room, showing chaotic breccia blocks in a sand matrix. B. Close up of the breccia block facies, showing cross-bedded lagoonal sands between the blocks; small ruler 4 cm long for scale. C. Phreatic dissolutional features cutting through the breccia block facies. D. Calcite flowstone in cave wall of breccia blocks.

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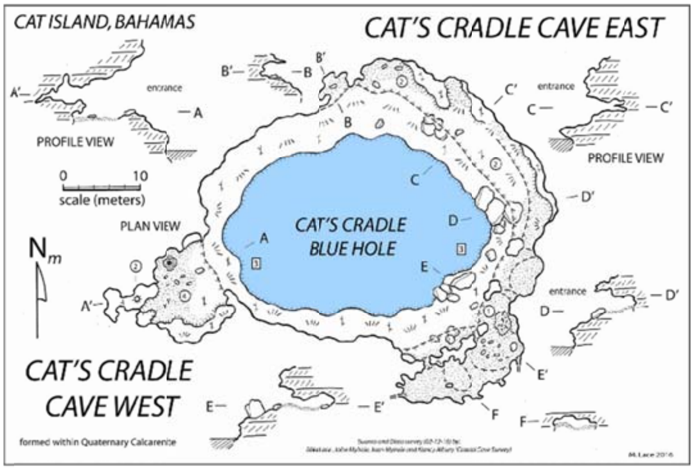

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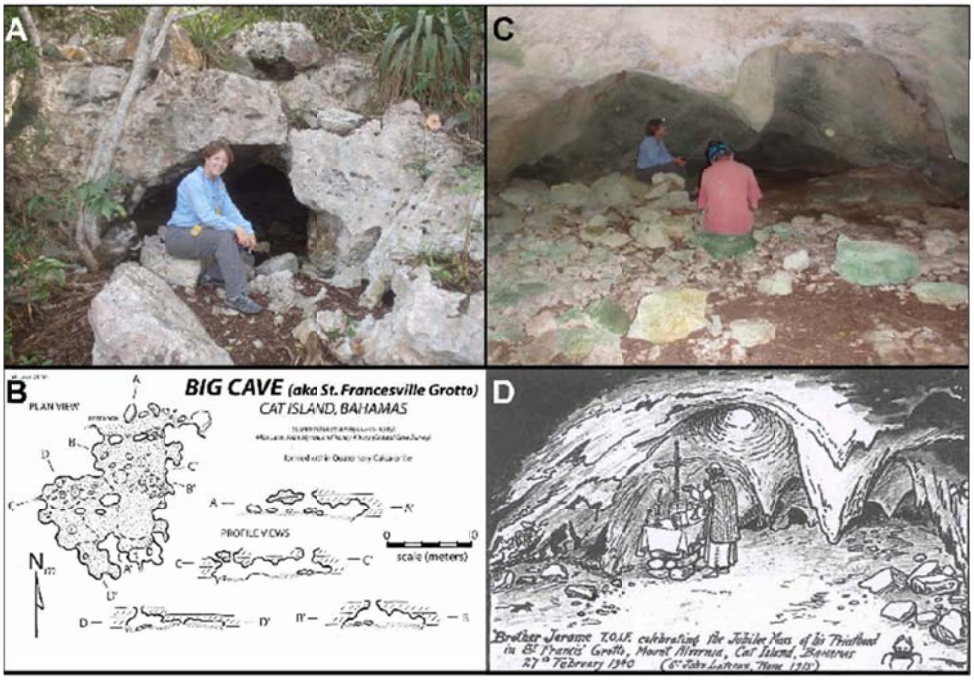
which ring the blue hole and all open inward toward the blue hole (Figure 7). The blue hole currently contains water of marine salinity (~35 ppt).

Big Cave

The third feature is located on a hilltop immediately adjacent to the Hermitage monastery at Mount Alvernia (Figure 1), the highest location in The Bahamas at 206 feet (62 m). A small cave, incongruously named Big Cave, is located here (Evans 1984; Taylor 2000). It has an entrance leading inward from the side of the hill, as well as some breached bell holes that open to the surface above the cave (Figure 8). The cave has dissolutional surfaces of apparent phreatic origin, a few calcite speleothems, and chambers large enough to stand upright in. The cave was used as a church to hold mass by a Father Jerome while the monastery was being built (Evans 1984; Mylroie *et al.* 2006; Taylor 2000). The cave is at an elevation of 180 feet (55 m), well above the position of any past Quaternary sea-level. On the west side of Mt Alvernia, just below the hill crest and in front to the monastery is a feature called Burial Cave (Taylor 2000). Taylor (2000) refers to this feature as a "natural arch" but site investigation in 2006 could not determine if the feature is natural or artificial. A slatted gate allows one to peer inside, and a stone wall divides the chamber, with Father Jerome's body allegedly behind the wall (Taylor 2000).

Figure 7. Flank margin cave passages associated with the southeastern side of Cat's Cradle blue hole. A. Oval tube leading inward from the blue hole bench. B. Interior room with smooth phreatic surfaces.



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DISCUSSION

Breccia block facies

The breccia block facies provide two important contributions. First, this is the most extensive outcrop of such facies as has been observed by the authors on the 15 Bahamian islands (and four similar islands in the Turks and Caicos) where we have conducted field work. The breccia block facies indicates how rapidly deposition and lithification events occur in young carbonates. The production of carbonate allochems for this facies, their emplacement as beach rock, and the subsequent disarticulation of that beach rock by wave energy, with entombment in lagoonal sands and prograding beach sands, all occurred during the first part of MIS 5e, which was only 9,000 years long in the Bahamas (Thompson *et al.* 2011). Syngenetically, the fresh-water lens invaded the prograding beach that began to infill parts of the lagoon, and flank margin caves developed within that breccia block facies before the end of MIS 5e ~115 ka, as outlined by Figure 9. Such syngenetic cave development in young carbonates has been part of a recent description and classification of how fast dissolutional caves can form in young carbonates (White *et al.* 2018).

Second, the development of flank margin caves in the breccia block facies is also an indication of how ground water dissolution occurs in eogenetic carbonates when water and solute transport is by diffuse flow. The essential outcome is that the facies characteristics have little impact on cave development, and the morphology of the cave thus produced, regardless of whether the facies are lagoonal sands, framework reefs, eolianites, or as in this case, breccia block facies. Because most cave and karst studies, until recently, have been done in carbonate telogenetic rocks in continental settings, where turbulent flow in fractures, bedding planes, joints and faults governs ground water flow and the subsequent cave morphology, the differences contrast with cave development in locations such as The Bahamas was long unrecognized (Mylroie and Mylroie 2007, 2017, 2019). The breccia block facies on Cat Island is an outstanding example of the rapidity of flank margin cave development, and the unique morphologies produced in eogenetic carbonates by diffuse flow regardless of facies type.

Cat’s Cradle blue hole

Cat’s Cradle blue hole is a classic blue hole that appears to be the result of progradational collapse of a large dissolution void at depth. The models for blue hole origin are reviewed by Mylroie, et al., 1995; the most common type of blue hole, and the ones that produce large, circular pipes leading deeply downwards, are thought to be formed by progradational collapse. Larson and Mylroie (2018) demonstrated that the large voids at depth that cause the collapse, and accommodate the collapse material, develop from large conduit systems that form on the Bahama Banks when sea-level is below the bank top and as a result these banks become very large islands. Such conditions support production of turbulent flow conduits, which are senescent at today’s high sea-level but can still be explored by cave divers.

Cat’s Cradle is somewhat unusual in that the collapse has prograded up through the side of an eolianite ridge, to produce there 8 to 10 meters of vertical wall between the land surface and the water in the blue hole, which is at current sea-level (Figure 5). Most blue holes of the progradational type open onto lowland plains in The Bahamas, and the amount of relief between the land surface and the blue hole water is only one or two meters. This aspect makes Cat’s Cradle look a bit like a cenote from the Yucatan of Mexico (e.g. Mylroie *et al*. 1995) as opposed to a typical Bahamian blue hole.

The location of the eolianite ridge in the pathway of the progradational collapse means that during MIS 5e, when sea-level was 6 m higher than at present, there would have been mixing between the waters of the blue hole (likely to be sea water) and the fresh-water lens in the surrounding ridge. This mixing, and other associated chemical reactions involving organics and their decay, formed flank margin caves in a ring around the blue hole (Figures 6 and 7). These caves promoted instability in the high wall surrounding the blue hole, and after the end of MIS 5e; their partial collapse resulted in a bench being developed in the high wall at the elevation

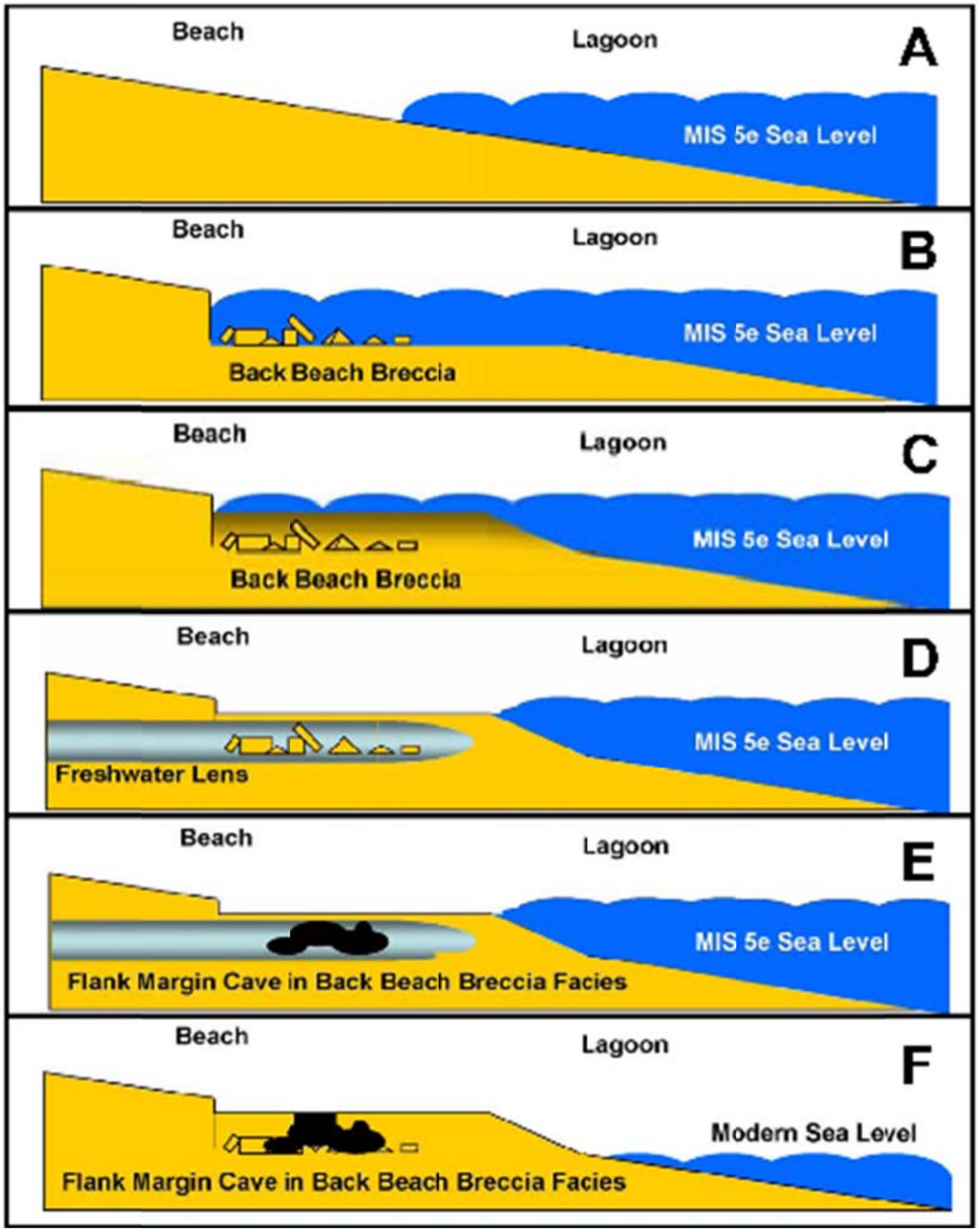


Figure 9. Development of the breccia block facies and subsequent flank margin caves. A. During the MIS 5e sea-level highstand, with sea-level 6 m higher than present, a prograding beach is formed. B. Beachrock formation, and wave attack create breccia blocks. C. Continued sand deposition entombs the breccia blocks to create the breccia block facies. D. Because new land has been created by sand progradation, the fresh-water lens advances into the breccia block facies. E. Flank margin caves form in the lens margin. F. Modern sea-level conditions; a terra rossa paleosol has developed on the breccia block facies, and many of the flank margin caves have breached to the surface.

of the caves; Figure 10 details a diagrammatic model of the evolution of Cat's Cradle blue hole. The presence of the flank margin caves also means the blue hole formed during or prior to the MIS 5e sea-level highstand, so as to bring two different water bodies in contact with each other during that highstand.

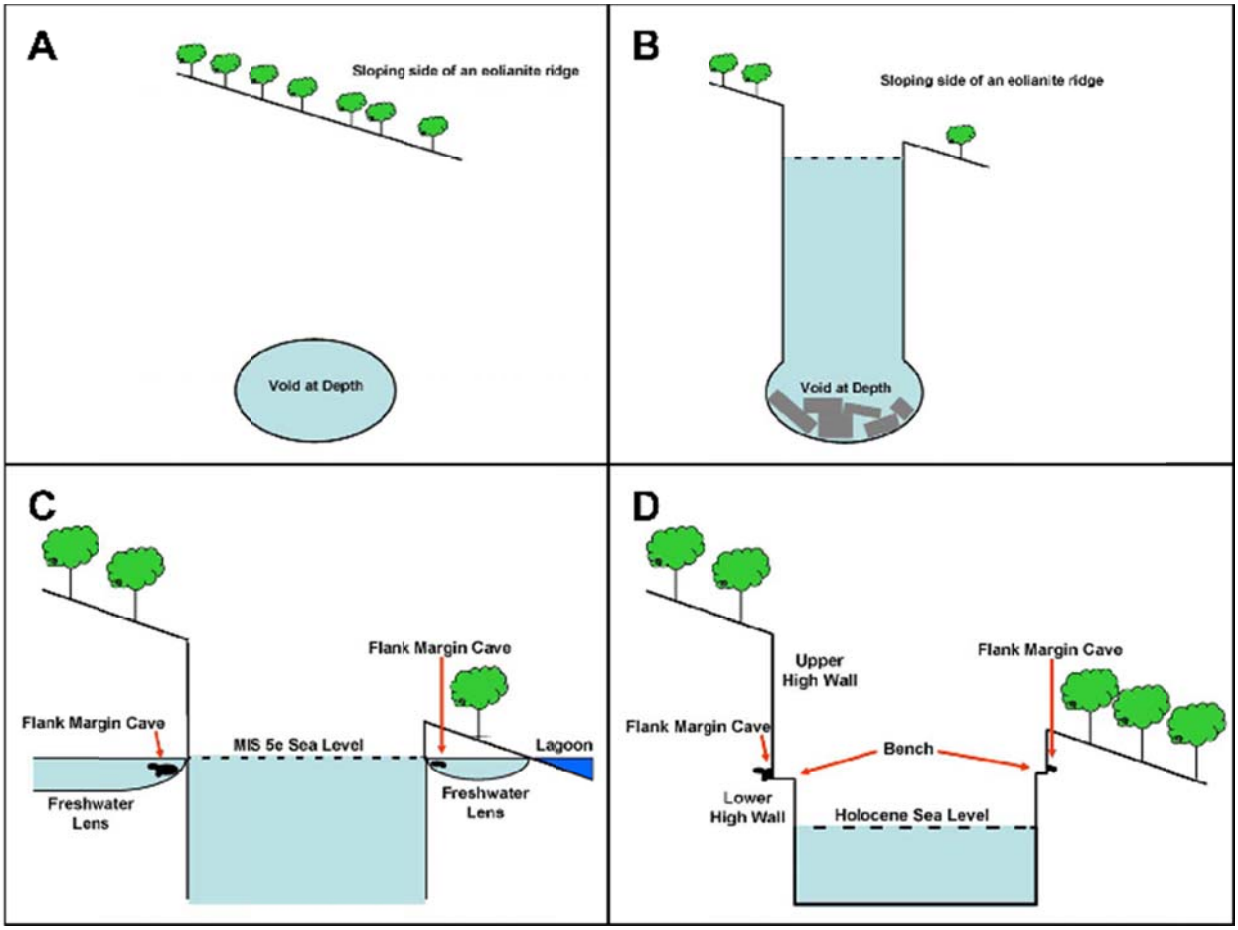


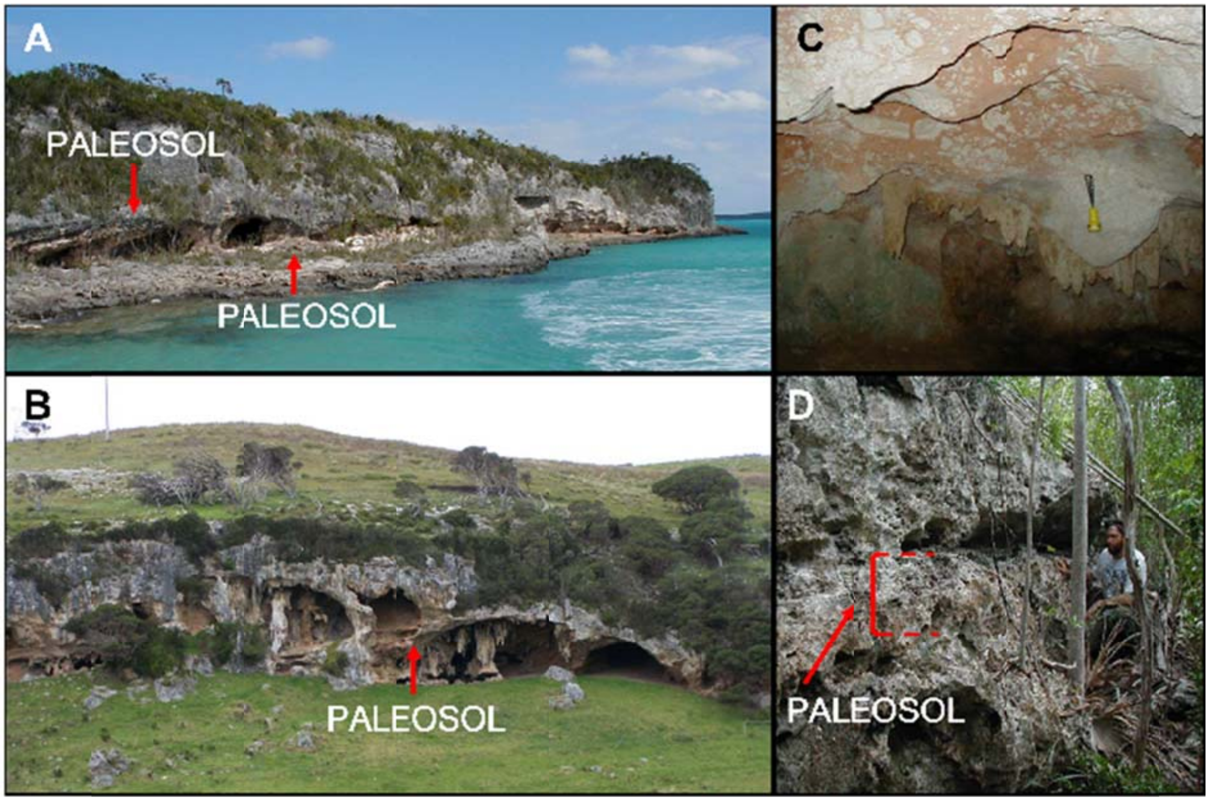
Figure 10. Evolution of the Cat's Cradle blue hole. A. During a glacioeustatic sea-level lowstand, the Great Bahama Bank is completely subaerially exposed and a large conduit is formed. B. Progradational collapse of a portion of that conduit before or during MIS 5e breaches the surface. During MIS 5e, the water level in the blue hole is 6 m above present. C. The freshwater lens surrounding the blue hole is different in chemistry than the water in the blue hole, and flank margin caves develop on the blue hole perimeter by mixing dissolution. D. After sea-level fall, partial collapse of the caves creates the bench seen today.

Big Cave

Big Cave is very problematic, as has been noted since its modern documentation (Mylroie *et al*. 2006; Mylroie 2013; Mylroie *et al*. 2020). The cave contains all the dissolutional signatures found in flank margin caves, but cannot have been produced by mixing of fresh water and sea water as it is located tens of meters higher than any known Quaternary sea-level in The Bahamas, or globally for other similar non-tectonic stable carbonate platforms. Because of the very uniform nature of flank margin caves around the world (*e.g.* Mylroie 2013), this cave type has become associated with any cave development by diffuse flow in an eogenetic carbonate rock. In other words, all flank margin caves have diffuse flow regimes during speleogenesis, but not all caves formed by diffuse flow are flank margin caves.

So how did Big Cave form? As noted earlier, organics have been implicated as one of the possible driving mechanisms for the speleogenesis of flank margin caves (e.g. Mylroie and Mylroie 2007), and was used to explain the development of banana holes in The Bahamas (Harris *et al.* 1995), although additional mechanisms now seem applicable (Mylroie 2013). Recently, organics have again been promoted as a major driver of dissolution in eogenetic carbonates (*e.g.* Gully *et al.* 2016). As noted in Harris *et al*. (1995), mixing dissolution can occur between descending vadose water and the phreatic fresh water of the freshwater lens as well as by classic sea water/fresh water mixing. Coupled with the oxidation of organics, vadose mixing may be enough to form dissolutional caves in a perched freshwater body totally separated from any direct marine water influence. Eolian calcarenites, or simply eolianites, are about as homogenous and isotropic as any sand-sized sedimentary rock. In The Bahamas, the eogenetic nature of the eolianites means that they have very high primary porosity, and that porosity has not yet been lost to burial and diagenesis (the mesogenetic realm), so the accompanying permeability is also high. These characteristics allow fluids to move through the rock and to interact with it in three dimensions. Mixing, combined with oxidation of organics in such porous and permeable material, even in fresh water, can produce voids large enough for human exploration.

The key to explaining Big Cave is to identify a mechanism for perching of fresh water other than by its density contrast with sea water. A possible candidate is a terra rossa paleosol, which can be very cemented and micritic, capable of retarding downward vadose flow and allowing it to accumulate as a perched water body. The influence of terra rossa paleosols in the development of caves in Quaternary eolianites has been described (Mylroie *et al.* 2020) as a way to perch a water table (Figure 11).



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Field work in the Big Cave area has been minimal. The effort so far has been to map the cave (Figure 8), but the supposed terra rossa paleosol has not yet been detected. In weathered outcrops, such paleosols are notoriously hard to document (*e.g.* Figure 11C versus 11D). If Burial Cave were truly natural, a similar speleogenesis mechanism would need to be proposed for its development.

If the paleosol argument cannot be proven, then there is a conundrum as to how to form a feature like Big Cave. As Mylroie (2013) and Mylroie *et al*. (2018) have discussed, Big Cave represents a challenge to the flank margin cave model. It is not so much a challenge to that model, which works very well in sea-level environments, as it is a question about how caves form in eogenetic eolian calcarenites that are not flank margin caves but show clear evidence of development in a diffuse flow hydrologic setting.

CONCLUSIONS

The three features from Cat Island discussed in this paper: breccia block facies, Cat's Cradle blue hole, and Big Cave, all present interesting phenomena that relate both to cave formation in eogenetic carbonate rocks, and also implications for sea-level magnitude and position in the Quaternary in The Bahamas. Both the breccia block facies and Cat's Cradle blue hole demonstrate the rapidity with which flank margin caves can form, and their subsequent influence on the landscape immediately around them. Big Cave is a clear anomaly: is that its true status or does it represent something that is more common than we have previously recognized? In any case, field work is planned to examine the Big Cave area thoroughly to see if a terra rossa paleosol or some other factor can explain its unusual position in the topography of Cat Island.

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