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FLANK MARGIN CAVE COLLAPSE IN THE BAHAMAS: PREDICTIVE METHODS

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ABSTRACT

The risk of sinkhole collapse in The Bahamas is almost entirely caused by failure of cave roofs. Cover-collapse sinkholes, common elsewhere (e.g. Florida) and caused by catastrophic sediment flow into underground voids, are almost non-existent in The Bahamas because soil cover is thin. On the large carbonate banks of The Bahamas, conduit flow at depth leads to large collapse features that under current sea-level conditions become blue holes. Predicting this collapse is difficult. On large and small banks, flank margin caves, formed in the distal margin of the fresh-water lens at a past sea-level highstand, are common, as is a subset of that cave type, the banana hole. Flank margin caves have three entrance types: dissolution pit, side breach, or ceiling collapse. The latter two are the result of mass erosional forces; pits form by focused vadose dissolution (and can be confused with breached bell holes). Banana holes typically result in roof collapse due to their location in Pleistocene strand plains which cause them to form with thin roofs predisposed to failure.

The use of surface slope as a proxy for controlling factors in Bahamian flank margin cave collapse was initiated. This study demonstrated that 7.5 minute topographic maps cannot resolve slopes in enough detail to predict potential collapse locations. Field surveys with 1 m contours allowed for a more concise slope range in which each entrance type preferentially occurred; collapse breaches and pits were common on gentle slopes and side breaches on steep slopes. The location of flank margin caves and banana holes can be simply found in a general sense, but the specific position of these voids within those localities cannot be determined. Further investigation into the location of subsurface voids and the collapse risk associated with such voids can be performed using various geophysical methods including GPR and gravity surveys, although these methods are labor intensive and time consuming.

INTRODUCTION

Sinkhole formation by sudden subsidence or collapse in soluble rocks results from failure of material overlying dissolutional voids (White, 1988). If the failure is in the bedrock roof of the void, it is called *cave collapse*. If the failure is in a soil arch formed by overlying sediment trickling through a hole in the bedrock into a void through time, it is called a *cover collapse*. Most catastrophic sinkhole collapse seen in news reports from areas like Florida are cover collapse events, as the unconsolidated sediment overlying the limestone there is commonly 10 to 30 m thick (Polk and Brinkman, 2013). In this setting, sediment loss down even small openings into a cave below can, given enough time, form large soil arches in the unconsolidated material, leading to eventual catastrophic failure. Such collapses can be triggered by large rainfall events (increasing soil weight and flushing sediment downward), drought (loss of soil cohesion and drop in the water table with buoyancy loss), or artificial actions (e.g. groundwater withdrawal, focusing of drainage, loading by building construction). In comparison, cave collapse is relatively rare. However, if the limestone surface has little or no sediment cover, then cover collapse events cannot occur, and sudden collapse events will be caused solely by failure of the bedrock roof of the cave.

Figure 1. Images of Bahamian flank margin caves showing characteristic entrances. A) Collapse entrance to Babylon Cave, Acklins Island, with collapse blocks visible in the background. B) Large collapse entrance in 1702 Cave, Crooked Island; Figure 13 shows a map of this cave, the collapse shown is the one on cross section line (c), the image was taken looking northeast into the collapse. C) Fenestral Cave, Crooked Island, showing a side breach entrance caused by storm wave erosion; note also the thin roof making roof collapse likely in the future. D) Duncan Pond Cliff Cave, Acklins Island, a large side breach entrance, with portions of the collapsed hillside visible in the background. The cave ceiling shows small pit entrances which are most likely breached bell holes.

Cave roof collapse is a land-use hazard that has long been of concern in the carbonate island setting, such as The Bahamas, but field reconnaissance costs and the logistical difficulties of field work have left much unanswered about cave roof collapse risk. Caves and karst landscapes are recognized as a geologic hazard (White, 1988), including the special issue of islands (Wilson et al., 1995). Flank margin caves (Figure 1), which form by dissolution at the margin of the freshwater lens, are a major type of cave in carbonate islands (Mylroie and Mylroie, 2007; Mylroie, 2013). Flank margin caves commonly have portions that have collapsed (Figure 1A and 1B), as well as areas where the roof is thin and prone to collapse (roof in Figure 1C). Side breaches caused by cliff or slope retreat can also occur (Figures 1C and 1D). Banana holes (Figure 2), typically found in late Pleistocene progradational strand plains throughout The Bahamas, are small, immature flank margin caves with thin roofs (Ho et al., 2013). Banana holes are thought to pose the greatest potential collapse hazard (in terms of frequency) due to their thin roofs. The roofs are thin because most banana holes are

Figure 2. Banana holes, San Salvador Island, The Bahamas. A) Banana hole showing the common circular shape and vertical walls caused by collapse. B) Another banana hole, showing a portion with an intact roof.

located just beneath the surface of low elevation (3-8 m), relatively level, late Pleistocene strand plain terraces (e.g. 49% of San Salvador Island is below 6 m elevation, Wilson et al., 1995). Because flank margin caves form near the flank of the enclosing landmass at the sea-water contact, and banana holes form in late Pleistocene progradational strand plains, their *general* locations are relatively easy to predict. However, *specific* location predictions remain elusive. Flank margin caves, as well as banana holes, form as entranceless caves that cannot be observed from the surface until they are breached by hill retreat, roof collapse, or a pit intersection (Figure 1D). Remote sensing and GIS technology provide venues by which spatial research on cave roof collapse can be conducted (e.g. Ho et al., 2013). The slope of the overlying topography is the only parameter that can be viewed remotely in efforts to infer what is happening beneath the surface. The slope would have an effect on roof thickness; steep slopes being more stable and gentle slopes leading to greater risk of collapse. The problem is that inexpensive highly accurate satellite data are not readily available for The Bahamas. The resolution of the topographic data will affect the ability to calculate roof thickness and in turn define the potential to predict flank margin cave collapse.

The Carbonate Island Karst Model (CIKM) was developed and validated via extensive fieldwork on numerous islands in The Bahamas and elsewhere. That fieldwork included surveying and mapping cave location and extended profile (Jenson et al., 2006; Mylroie and Mylroie, 2007; Mylroie, 2013). The CIKM describes island karst as being controlled by sea water and fresh water mixing, sea-level position (eustatic and/or tectonic), rock age (usually youthful, termed *eogenetic*), and island geology (from simple to complex). The Bahamas are classified in the Simple Carbonate Island category under the conditions of the CIKM (Mylroie and Mylroie, 2007), meaning only carbonate rocks form the land surface and the aquifer holding the fresh-water lens. The Bahamas provide a useful study area to develop a test model for cave roof collapse due to the islands' young age, relatively simple geology, and lack of tectonics (except for Mayaguana Island, see Kindler et al., 2010).

Cave maps with detailed surveys were created for caves on many islands throughout The Bahamas over the past four decades (Mylroie and Mylroie, 2013). Though the rationale behind the search for caves has not been to predict cave roof collapse, years of data from the development of the CIKM, funded primarily by petroleum companies as a paleokarst reservoir project (Labourdette et al., 2007), can now be used to assist in dealing with a potentially dangerous land-use hazard. The CIKM explains that the caves on many of these islands are not conduits, but rather mixing chambers, lacking evidence of turbulent flow (Mylroie and Mylroie, 2007). Vacher and Mylroie (2002, p. 183) differentiated "island karst" from "karst on islands" by explaining that "island karst" are those features which formed under the influence of the CIKM rather than the typical continental interior stream-cave model. The category "karst on islands" represents karst behavior similar to that seen on continents, commonly in large island interiors. The CIKM led to much advancement in karst related research that was previously difficult due to the lack of understanding of "island karst".

Another collapse feature found in The Bahamas and other carbonate platforms around the world is the blue hole. Blue holes are deep water-filled voids that form by a number of different mechanisms (Mylroie et al., 1995): 1) flooding of pit caves and deep sinkholes due to the rise of sea level during an interglacial; 2) failure of the bank margin, leading to development of deep fissures on platform perimeters; and 3) collapse of large, deep conduit caves well below current sea level in the carbonate platform. The last feature is a true cave collapse, but predicting them requires knowing were the conduits are, a difficult task given the rigors of cave diving, and the low number of such caves available to cave divers for exploration and survey. Because open blue holes are usually found only on islands or in nearby protected lagoons, the true number of blue holes is not known. Blue holes that have developed out on the open platform are currently filled with Holocene carbonate sediment. Extrapolation from island blue hole inventory counts suggests that in-filled, open platform blue holes exist in the thousands in The Bahamas (Larson and Mylroie, 2014). The conduits that collapse and form the blue holes result from lower sea-levels, when the carbonate platforms are exposed and the large catchment area drives traditional conduit flow development to discharge meteoric water from the fresh-water lens. The work reported here does not consider the blue hole collapse risk as surface topography has mimimal impact on blue hole expression.

Can cave location along with the slope of the overlying topography address cave roof collapse potential? The goal of this research is to establish a set of protocols to assess cave roof collapse risk for flank margin caves in The Bahamas. More specifically, the objective is to determine whether the Bahamas Lands and Surveys 7.5-minute topographic quadrangle map sheets from the early 1970s have the resolution necessary to predict flank margin cave collapse. Can the distal slope of the overlying dune be used to predict where bedrock is suspected to be the thinnest? Roof thickness and maximum chamber width are the two factors that cause collapse in caves (White, 1988). Neither of the two factors that lead to collapse are viewable from the surface. Since the slope of the topography can be remotely sensed and/or calculated, this project will test whether the slope can be used as a proxy for roof thickness. This research is important because up to this point, there is no way to predict flank margin cave roof collapse. Finding a way to predict flank margin cave collapse would be a significant step in land development practices in The Bahamas (as well as other carbonate islands and coastlines).

METHODOLOGY

Data collection

There were three types of data needed to conduct this research: 1) cave location data (GPS points, 15 m accuracy); 2) cave maps; and 3) topographic maps for the entire study area. The SRTM (Shuttle Radar Topography Mission) digital elevation maps (DEMs) available from the US government have 90 m accuracy. The STRM DEMs provide less accuracy than the Bahamas Lands and Surveys 7.5-minute topographic quadrangle maps, which have 20 ft (6 m) contours. For this reason, topographic maps from the Lands and Surveys Department of The Bahamas were used to obtain the slope overlying each cave. These topographic maps have 20-ft (6-m) contour lines and allow the location of the cave to be plotted on the surface, as well as calculation of the slope for that area. Some maps have a 10-ft (3-m) contour line placed

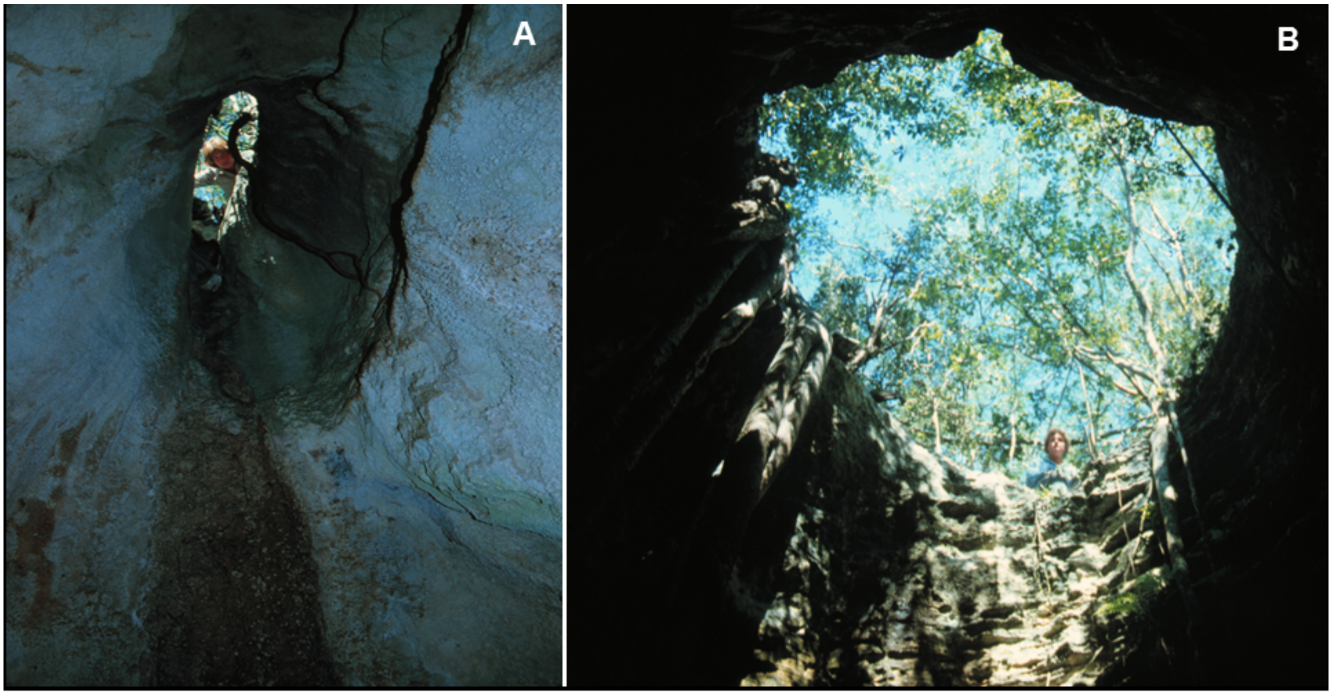

Figure 3. Pit caves, San Salvador Island, Bahamas. A) Pit cave with a small cross section but still deep. Note the elongated shape of the shaft. B) A large cross section pit cave. Both pits lead into the same cave, the aptly named Deep Hole Cave.

between the 20 ft (6 m) elevation and sea level in coastal areas, for better resolution of coasts and tidal position.

Slope analysis

First, the caves were plotted on the associated 7.5-minute topographic map using GPS location data acquired from Coastal Cave Survey, directed by Michael Lace. This survey is a repository for island cave maps for islands from around the world (Lace and Mylroie, 2013). The location of each cave, given by x-y coordinates, was input into Google Earth and then manually plotted onto each island's topographic map. The topographic map set for each island consisted of 2 to 28 sheets to cover the entire island and various cays surrounding each island. Cave maps and/or topographic maps were not available for every cave that had a GPS point; only the caves with GPS location, a detailed cave map, and the corresponding topographic map sheet were used in the study. Each cave was located on the topographic map, and the slope inputs (rise/run) were manually measured using calipers and the map scale. The slope inputs were then recorded in Microsoft Excel to populate rise and run columns. Next, using functions offered in Excel, the slope was derived by using the following formula: Slope=DEGREES (ATAN (rise/run). By analyzing the slope of the flank of the dune, properly placing the cave and its vertical profile in relation to that slope, which sections demonstrate collapse and how thick the roof (overburden) is in those areas could be estimated.

Cave entrances

These analyses should aid in the prediction of potential cave collapse risk in regions with unknown caves using a slope/collapse relationship. Some caves have many entrances and areas with collapse, while others may have a single entry point with little to no evidence of collapse. When analyzing each cave map, each cave entrance was recorded in Excel and categorized by the following

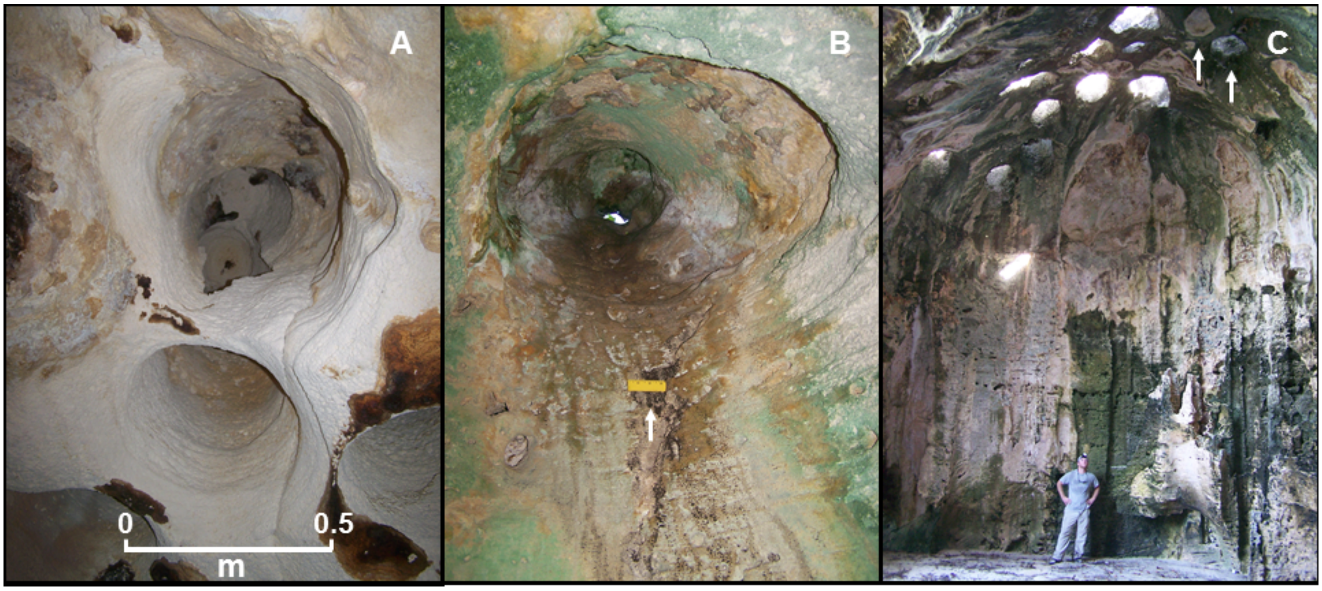

Figure 4. Bell holes from Bahamian Caves. A) Typical bell hole, showing the cylindrical shape, bell hole in upper center is 40 cm across and 2 m high (from the ceiling lip), Jumby Hole, Acklins Island. B) Bell hole from Osprey cave, Crooked Island, showing a small hole where surface denudation has just breached the bell hole to admit daylight. Scale bar (arrow) 8 cm long for scale. C) Breached bell holes from Fenestral Cave (see Figure 1C), Crooked Island; surface denudation has taken off the top of the domes in these bell holes, but others can be seen that are as yet un-breached (arrows).

entrance types: side breach from slope retreat (Figure 1C and 1D); roof collapse (Figure 1A and 1B); or pit intersection (Figure 3). The differentiation between collapse and pit intersection was subject to interpretation; if the hole in the roof was small and no collapse breccia was noted on the floor of the cave, the entrance classification was interpreted as pit intersection. The total number of entrances was also recorded. The slope of the overlying topography was plotted against each of the three categories of entrances, plus number of entrances, in an effort to determine if a relationship between slope and entrance type exists. Subsequently, during analysis, side and collapse entrances were treated as a single entrance type (mass wasting), to differentiate them from the simple downward dissolution formation mechanism of pit entrances.

After the entrance analyses work was completed, it was realized that entrances that had been classified as pit caves were actually two entrance types. The initial pit cave interpretation, and now what are understood to be the intersection of bell holes by the land surface. Bell holes are vertical, cylindrical tubes in the ceiling of many Bahamian caves (Figure 4A). Their origin has been highly controversial (Birmingham et al., 2010) with three separate speleogenetic mechanisms having been proposed. The mechanism supported by Birmingham et al. (2010), that the bell holes are dissolutional features formed by slow vertical convection when the cave initially developed, is the one used here. After cave development, the overlying land surface is slowly lowered by dissolutional surface erosion (i.e. denudation), by meteoric processes, such that the tops of the bell holes become opened, at first gradually (Figure 4B), and then entirely (Figure 4C). To casual observation, the difference between a breached bell hole and a vertical pit produced by downward vadose flow may not be obvious. It is critical to recognize that proper identification of breached bell holes indicates a significant amount of surface denudation. Such denudation thins the cave roof and makes subsequent cave roof collapse more likely. The results reported in this paper for pit cave entrances conflate two different processes. This issue will be dealt with further in the Results and Discussion sections.

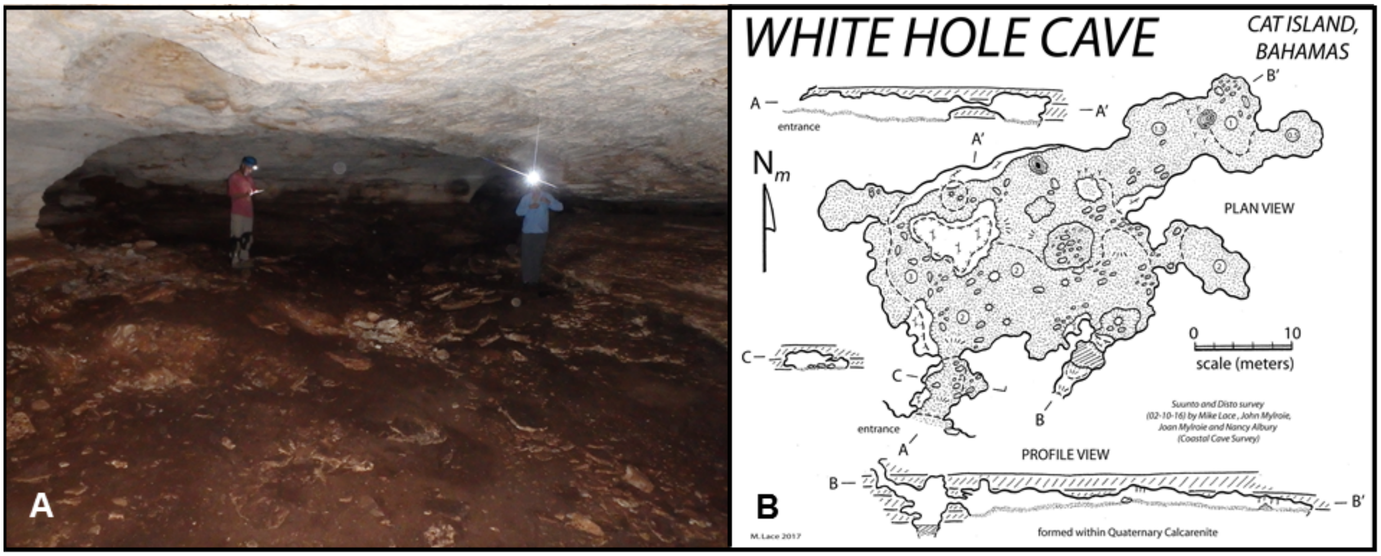

Figure 5. White Hole Cave, Cat Island, Bahamas. A) Central chamber of the cave, showing a wide, unsupported span. B) Map of the cave, which was used to determine span dimensions. The image in (A) was taken looking north through the largest room in the cave. The dark brown on the cave floor is bat guano, the host rock is white.

Unsupported span (maximum chamber width)

The maximum chamber width was recorded to help determine the relationship between roof span and roof collapse (Figure 5). By documenting the maximum unsupported span, along with the overlying slope, it could be further demonstrated what effect slope has on roof thickness, that in turn controls aspects of collapse. For example, a cave with maximum chamber size (x) and an overlying slope (z) does not demonstrate collapse, but another cave with equal chamber size (x) and a lesser overlying slope (y) does demonstrate collapse. This approach demonstrates how chamber size affects collapse potential when coupled with roof thickness. It is not believed that cave chamber size alone is the cause for collapse, as there are caves with very large chambers with very little to zero collapse. It has been proposed that slope has an effect on beam thickness; the cause for collapse is beam thickness coupled with the maximum unsupported span, neither of the two causes collapse by itself (White, 1988).

Data analysis

The data collected are not distributed normally. The data will be presented by histograms as a nonparametic display to determine if there is a relationship between the cave entrances and cave chambers, and the slopes that surround them.

RESULTS

A total of 107 caves across eight islands (consisting of over 70 topographic map sheets) were analyzed to determine if slopes calculated from topographic maps were predictive of the degree of flank margin cave collapse. Figure 6A shows the islands utilized in the research. Figure 6B shows Abaco Island cave locations, as a representative island, with the cave locations plotted into Google Earth using GPS data points. The full table of results for slope, entrance type/quantity, and maximum chamber width for each cave, as well as cave location maps for all islands displayed in Figure 6A, are shown in Lawrence (2014).

A summary of those results is as follows: There were a total of 408 cave entrances. Of the 408 total, there were 123 side breach entrances, 185 pit entrances, and 100 collapse entrances recorded. Signs of roof collapse were absent in 61 of the 107 caves analyzed. As previously stated, if the hole in the roof was small and no collapse breccia

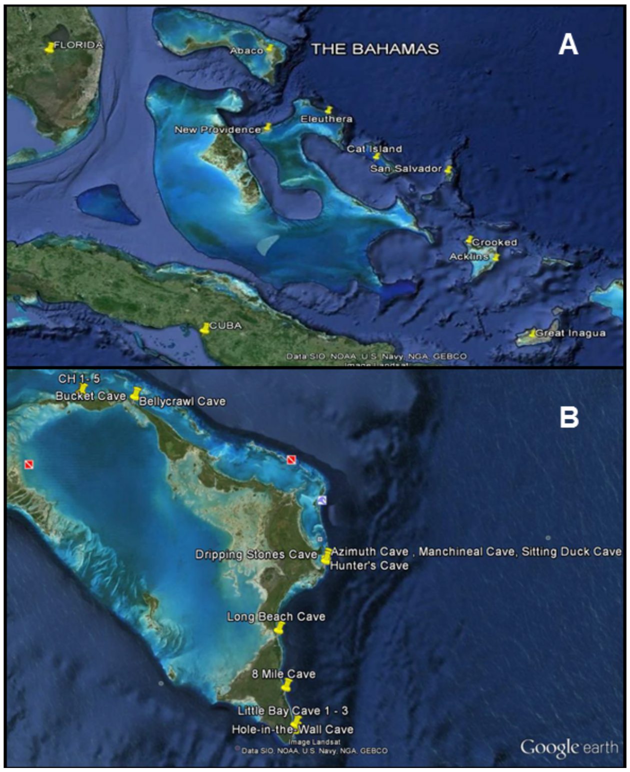

Figure 6. Location maps of caves in The Bahamas, from Google Earth. A) Map of The Bahamas, showing islands used (not including Florida and Cuba). B) Map of Abaco Island, showing cave locations; all islands included in the study had a similar map (see Lawrence 2014 for all maps).

was noted on the floor of the cave, the entrance classification was defaulted to pit intersection (it is now recognized that many of these pit entrances were bell holes intersected by surface denudation). Histograms of slope vs entrance type are shown in Figures 7. Rare slopes greater than 14 degrees are not included (all having side entrances). These steeper slopes range from 17 to 90 degrees, accounting for 12 slopes and 15 side entrances. The full data are in Lawrence (2014). The histograms of slope vs entrance type (total, side, collapse, and pit) do not indicate a relationship detectable between slope and any single type of entrance category (Figure 7B) from topographic data of 20 ft (6 m) resolution. The large number of pit cave entrances for slopes of 3 degrees or less may represent bell hole intersections by surface denudation. Each cave in the study had one slope measurement (Figure 8A). The total number of slope measure-

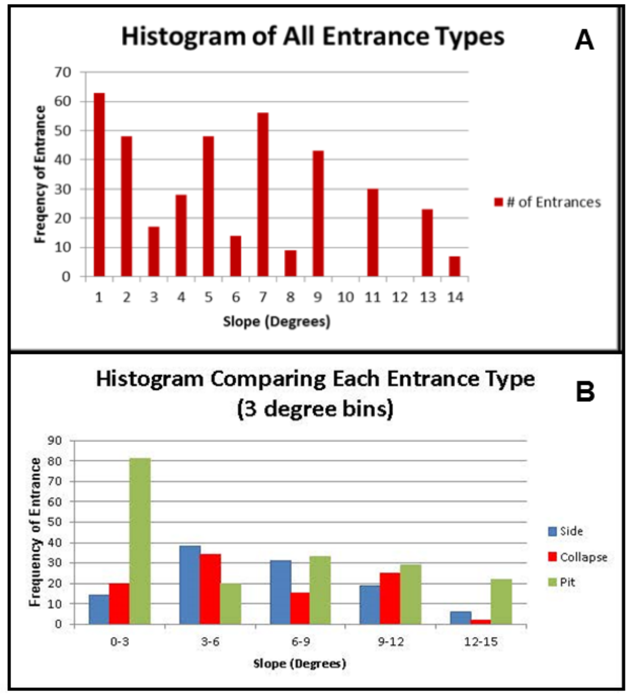

Figure 7. Histograms of overall slope and cave entrance data. A) Number of entrances for each slope measured from 7.5-minute topographic maps. B) Frequency of entrance type based on combining the slopes into 3 degree bins.

ments of each slope value was plotted to determine the slope abundance for each slope (14 degrees or below) used in the study (Figure 7). Both side and collapse breaches are a result of large-scale surface erosion, unlike pit entrances which form by focused dissolution or bell hole intersection. For this reason the number of surface erosion cave entrances (side and collapse) per cave were plotted along with slope abundance (Figure 8B); the number of cave entrances exceeds slope abundance. Therefore, most caves have more than one macroscopic entrance. Pit caves' distribution differed from that of side and collapse breach (Figure 7B).

Chamber size (maximum chamber width) was analyzed to see what effect it may play in collapse risk. The slope or each cave, along with the chamber size was plotted on a histogram for each of the caves in the study (Figure 9). This plot allows the variance in chamber size to be observed, and helps the user realize how unpredictable chamber size is. Since chamber size and roof thickness are coupled as the causes for collapse, this unpredictability of chamber size further complicates using slope as a predictor of collapse.

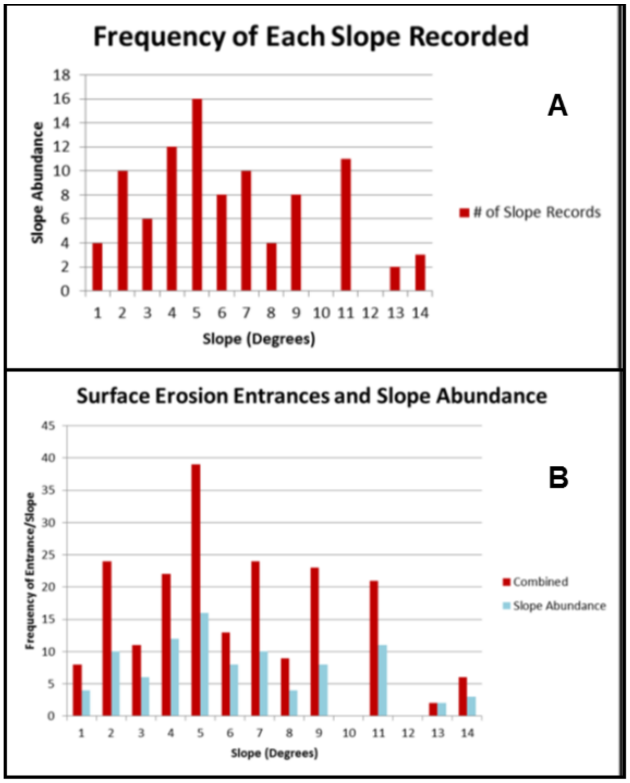

Figure 8. Histograms of slope frequency and surface erosion abundance. A) Frequency of each slope recorded in the database from 7.5-minute topographic maps. B) Combination of side breach and collapse entrance abundances with slope abundance (by degree of slope); the data show most caves have approximately two entrances of this type.

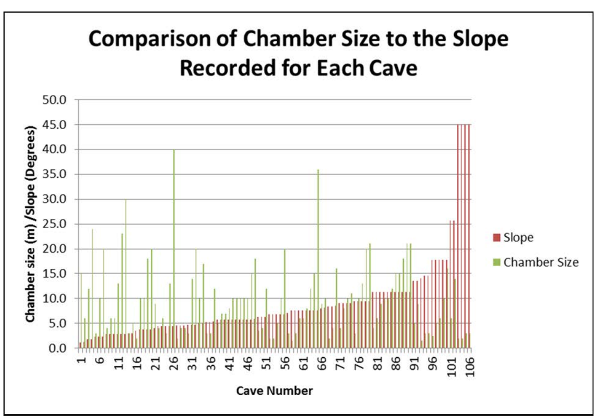

Figure 9. Comparison of chamber size to the degree of slope. There is no recognizable pattern.

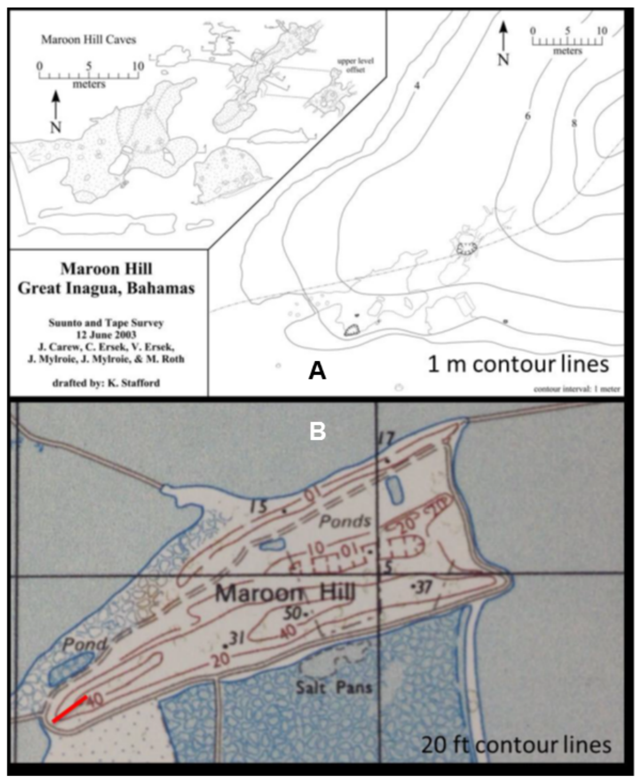

Figure 10. Maroon Hill Cave, Bahamas. A) One meter contour map surveyed over the caves of Maroon Hill. B) Compare with A, 7.5-minute topographic map segment showing Maroon Hill. The caves and survey of (A) shown by the short line at the southeast tip of the hill. Maroon Hill Cave was one of six caves for which high resolution contours were surveyed, see Lawrence (2014) for all cave maps and overlying contour surveys.

The low resolution of the topographic maps made much of the results inconclusive. Some caves had been mapped with surface topography included. Data were extracted from cave maps with the field surveyed (1 or 2 meter) contours overlaid for six caves (e.g. Figure 10). The higher resolution of spatial data leads to a more detailed analysis; these data allowed the slope to be calculated over the entire cave as well as the slope over the sections that showed collapse. A visual comparison of the two data types helps to clarify the limitations of this study. Figure 11 does show some trends. Side entrances fall towards the high slope angle end of the plot, collapse entrances towards the low slope angle end of the plot. Pit caves are strongly biased to the lower slope angles.

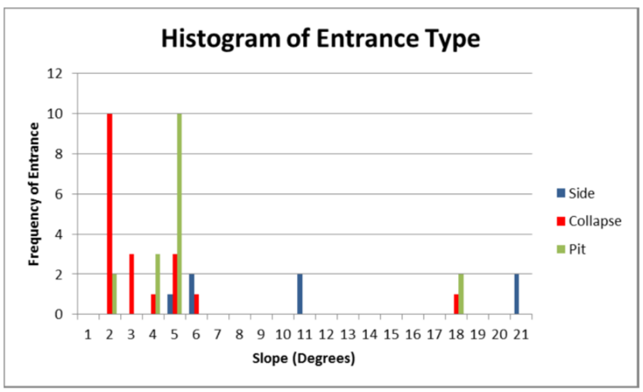

Figure 11. Histogram for the six caves with high resolution contour surveys

At this point, a realization was made that the accuracy of the calculated slope was not good enough to estimate roof thickness from the cave map data. The original methodology included a few steps that incorporated the estimation of roof thickness for areas of collapse using the calculated slope from the topographic maps, but due to the limitations of the data accuracy, these methods were not performed.

DISCUSSION

Topographic map analysis

This project focused on whether or not 7.5-minute topographic map sheets could be used to predict cave roof collapse; the resolution of the topographic maps does not allow such predictions to be produced. Using the calculated slope of 107 caves from data extracted from the topographic map sheets is based on the idea that slope can be used as a proxy for roof thickness (roof thickness being one of the critical components that initiates collapse). The resolution of the currently available topographic data allows the roof overhead to be crudely estimated using the slope derived from the topographic maps, but this slope is not accurate enough to determine roof thickness as the spatial data limitations are simply transferred. The variations in the hillslope, which are not noticeable from the topographic maps, can lead to an inaccurate roof thickness reading. With many areas having terraced slopes (Figure 12), the roof thickness can vary much over what appears to be a steady slope on the topographic maps but is not so in the real world. The map of 1702 Cave on Crooked Island (Figure 13, (c) and (d) cross-section lines) is an excellent example of how the flat areas (wider contour spacing) allows for collapse.

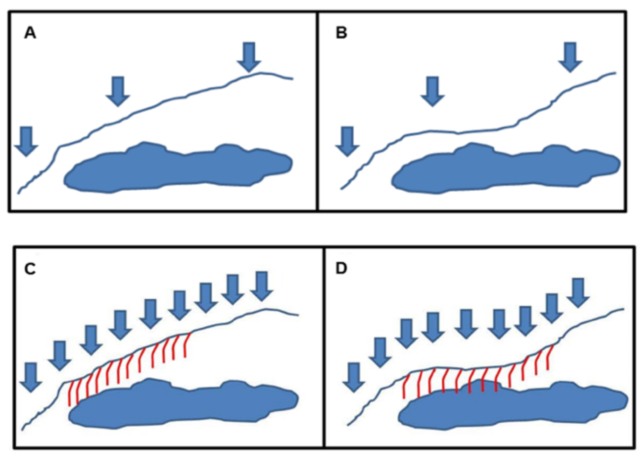

Figure 12. Consequences of slope contour resolution. A) Hypothetical slope based on extrapolation of a 20m ft (6 m) contour interval, with a cave underneath. B) A lessoning of slope with a concurrent of rock thinning over a cave roof would also fit the 20 ft (6 m) data. C) Same as in (A) showing how pit caves (vertical kinked lines) of a uniform shallow depth hit the cave only a few times. D) Same as in (B), showing how a lessoning of slope produces far more pit cave intersections with the underlying cave.

Figure 12 demonstrates the problem with this approach because of the resolution of topographic map sheets. If a prediction model was made, it would be misleading. In turn, the model could overlook a collapse risk (e.g. say that it is safe to build) by assuming a steady slope when in reality the landscape may have a varying slope (introducing flat areas with potentially thin roofs), as Figure 13 demonstrates. If this model was constructed using inadequate spatial resolution, it could result in someone building in a location that is actually prone to collapse (an accident). The worst-case scenario of this development would be a collapse event resulting in loss of life, time, and/or investment capital.

Flank margin cave entrances are interesting due to the fact that flank margin caves form as entranceless voids beneath the surface. The caves remain entranceless until the cave is breached by cliff retreat (side entrance), roof collapse (overhead entrance due to roof thickness and unsupported span), or pit intersection (overhead entrance occurs by localized active dissolution) and bell hole breaching. The 408 cave entrances consisted mostly of pit entrances (185); pits are typically the smallest type of entrance. Side breach entrances were the next most common entrance type (123) and are the largest entrance type, typically allowing one to walk/crawl into the cave from the side. Collapse breaches (100) are the most dangerous entrance type and often have a large area of collapse over gentle slopes. Side breach entrances are common near the coastline or where cliff retreat has occurred, commonly a steeper slope (e.g. Figure 13, the two smaller caves to the northwest on the map). Pit entrances are non-selective to their location of formation; pit entrances occur by the downward dissolution of rock as explained by epigenic karst processes (meteoric water). Side breach and collapse entrances are the result of processes that occurred after the hypogenic (decoupled from surface hydrology) speleogenesis of the cave was complete; pit entrances form by active epigenic (coupled to surface hydrology) speleogenesis. Bell hole entrances are the result of the chemical lowering of the landscape, which intersects these features. In that way they are the result of unfocused surface dissolution, whereas true pit caves are focused surface dissolution.

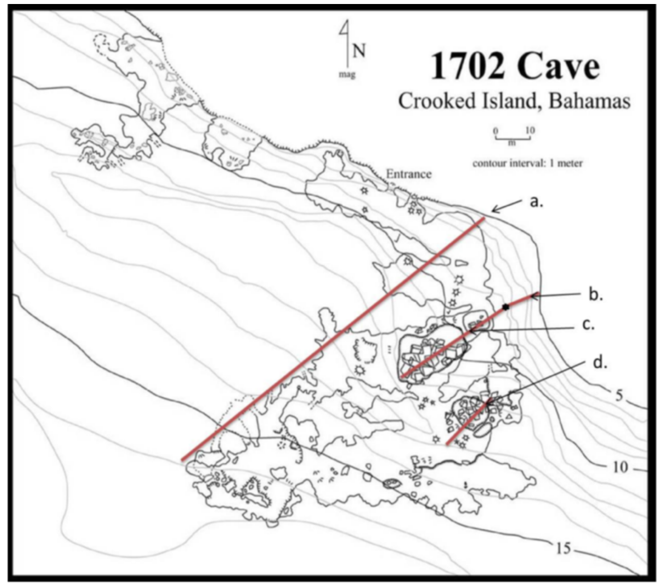

Figure 13. 1702 Cave, Crooked Island, The Bahamas, showing the value of high-resolution contour plots. Cross section (a), using only its endpoints, produces the same data as from a 7.5- minute topographic map with 20 ft (6 m) contours. Cross sections (b), (c), and (d) show how the slope actually varies in steepness. Note that the two large collapse entrances to the cave (circular structures outlined in bold on cross sections (c) and (d)) occur where the slope is both gentle and low elevation, creating a thin bedrock roof condition. Collapse at (c) shown in Figure 1B.

Many caves with the same overlying slope had a different entrance type, supporting the idea that it is more than just roof thickness that effect collapse; chamber width coupled with roof thickness controls the initiation of collapse. Chamber size and the slope for each cave were plotted together in a histogram, and as expected, there is no relationship between these two variables (Figure 9). Flank margin caves are de-coupled from surface processes, and their formation is controlled by the geochemistry and flow dynamics of the fresh-water lens margin. Therefore, as Figure 9 demonstrates, chamber size has no relationship to slope.

On the data plots for the 7.5 minute topographic maps, pit entrances show a relationship with low angle or gentle slopes (Figure 7B). That relationship persists when the slope is calculated from a 1-m-contour survey (Figure 11). Side and collapse entrances seem to show a relationship to gentle to moderate slopes (Figure 7B), but that apparent relationship is an artifact of slope abundance. Figure 8B demonstrates when side and collapse entrances are combined as a single mass wasting entrance type, the ratio of those entrances to slope abundance stays around 2. When the more detailed slope analysis using 1 m contours is displayed (Figure 11), collapse and pit entrances clustered near the low slope end of the plot and side entrances at the middle or high end of the plot.

The distribution of entrances as to slope angle is based on entrance origin. Pit entrances result from localized vadose flow dissolving its way downward. These pits are commonly only a few meters deep, but they can be as much as 10 m deep on rare occasions (Figure 2). When the slope is low, the amount of rock over the cave is less than when the slope is steep (Figure 12). As a result, a dissolution pit only a few meters deep is more likely to enter a cave when the slope is low and the roof is thin, regardless of the chamber size below and the amount of unsupported room span. Pits can have a variety of depths, but small depths are more common. While pit entrances are found on all slopes, they predominate at low slopes where the cave roof *must* be thin (under a steep slope, the cave roof can be thick or thin, depending on chamber size). Bell holes are phreatic dissolutional features formed in the roofs of caves (Figure 3). As surface lowering occurs over time, these will be the first cave features intersected. Their presence actually decreases the total mass of the roof, allowing roofs to stay stable when denudation has made the roofs thin, as in Figures 1C and 3C.

Collapse entrances result from roof failure. The thinner the roof (low beam thickness), or the wider the chamber (high unsupported span value), or both, the more likely is roof collapse. However, chamber width has no relation to slope (Figure 9), so collapse can occur at any slope but does seem to occur mostly at lower slopes which would create a thinner bedrock roof (Figure 12). This slope preference is hinted at in Figure 7B, but is better displayed in Figure 11 when higher slope resolution data are available.

Side entrances result from mass wasting and erosion of hillslopes. Because flank margin caves form under the flank of the land, at the distal margin of the fresh-water lens, to become exposed by surface erosion (as opposed to collapse or pit development) requires that the hillslopes retreat laterally so that the cave is intersected. The key is lateral retreat. The margin of a fresh-water lens during the last interglacial was at about 6 m elevation. A gentle slope starts out at an elevation below 6 m, and to reach that elevation must retreat significantly. A steep slope will reach the 6 m point after less slope retreat; a gentle slope must retreat farther to intersect a cave than a steep slope (Figure 14). While the data in Figure 7A are ambiguous regarding slope, the data in Figure 11 are much more convincing, with side entrances preferentially found at higher slope angles. Figure 11 again demonstrates the necessity of high-resolution slope analysis.

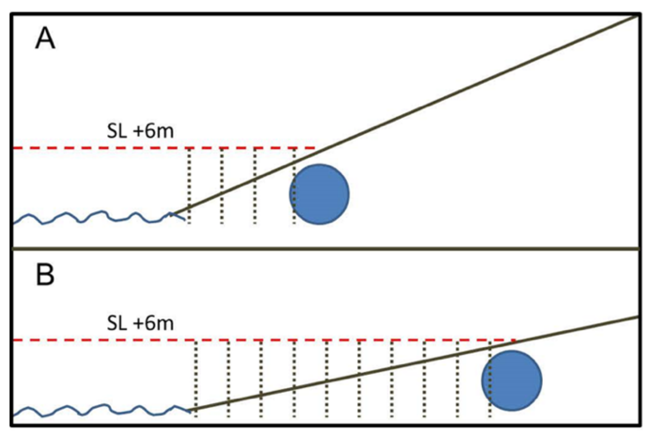

Figure 14. Cartoon showing how slope retreat intersects flank margin caves formed by a +6m sea-level highstand. A) On a steep slope, minor slope retreat is required to breach the cave wall. B) A gentle slope requires a greater degree of slope retreat to achieve cave wall intersection. Note that cave roof thickness is greater upslope for (A) as opposed to (B), providing more roof stability. This cartoon may explain the cave entrance distribution pattern in Figure 11.

Geophysical methods

Gravity surveys have been a successful tool used to locate flank margin caves and banana holes in The Bahamas (Kunze and Mylroie, 1991). GPR (ground penetrating radar) was used to locate voids when the San Salvador airport runway was extended from 4000 to 8000 feet in length. Over 25 voids were located and infilled during this project (most likely banana holes) (William Wilson, personal communication). Gravity, while successful, was labor intensive and not amenable to broad reconnaissance (Kunze and Mylroie 1991). The GPR was very successful, but the work was carried out on level, cleared land. In the vegetated, irregular areas, GPR would likely be less successful. Kunze and Mylroie (1991) state that the dense brush of The Bahamas make GPR impractical. Both GPR and gravity are promising methods for determining the location and size of voids, and void depth, but the use of such tools must be site specific and preferably the site be cleared of the native bush. When an area is predicted to be at risk for collapse due to the slope of the landscape and the assumption of a large span at depth, it is then that geophysical methods could be used to check for voids beneath the surface.

Future work

Slope varies depending on where the transect is drawn. Using Lidar or advanced satellite data (both capable of sub-meter accuracy) in this type of study would open up other opportunities to address the cave collapse problem on carbonate islands. The cost for Lidar or advanced satellite data far exceeded the budget of this research project. The satellite data that were available had worse resolution than the topographic maps (90 m vs 6 m, respectively). Using GIS, the slope could be calculated for an entire study area using the slope tool in spatial analyst. Instead of the slope being calculated over chosen transects, each cell within the raster would have a slope value. The slope calculation in spatial analyst assigns each cell a slope value by taking the maximum change in elevation and dividing it by the distance between the cell and its eight neighbors. The consistency of the GIS slope calculation process removes human error and human bias from the process of slope calculation. With a full sample size of caves, cave maps, and high accuracy elevation data (e.g. Lidar), along with the computing potential of GIS, it is possible that a correlation between slope and collapse risk may be found.

CONCLUSION

The purpose of this study was to test the hypothesis that topographic maps produced by the Bahamas Lands and Surveys Department are insufficient in resolution to be used as a predictor of flank margin cave collapse risk in The Bahamas.

Analysis of 107 caves using over 70 topographic map sheets on eight islands shows no clear relationship between derived slopes and cave collapse. The topographic maps were not of sufficient resolution to create a cave collapse prediction model. Even use of slopes derived from six caves with 1-m contour survey produced only a moderate predictive pattern. There is a visually recognizable pattern using the higher accuracy data, especially for pit entrances, but an accurate prediction of collapse cannot be guaranteed. Cave collapse is not only dependent on slope as a proxy for roof thickness but on the configuration of the underlying cave. Flank margin caves are a series of globular chambers with widely varying chamber sizes and roof heights. This cave configuration makes it difficult to determine when any given slope has created a thin roof condition, which would be prone to collapse. Only banana holes, found in low-lying late Pleistocene stand plains, are guaranteed thin roofs; however specific prediction of the location of the next collapse event is not possible. Geophysical techniques have promise but are labor intensive, especially in remote island settings. Flank margin cave collapse is a very complicated problem. It was illustrated in previous literature that flank margin cave collapse was a fairly straightforward issue, but the use of slope as an indicator for roof collapse is not effective. Slope does demonstrate a relationship with entrance types that are the result of large-scale surface erosion (side breach and collapse breach). However, the prediction of those entrances is not possible due to the complexities of the initiation of an entrance. Many things must be taken into account to predict collapse (roof thickness, chamber size, and chamber configuration). Flank margin caves and banana holes are easy to localize; flank margin caves are under the edges of dune ridges, and banana holes are in late Pleistocene strandplains. However, the specific location of these voids within those localities eludes easy analysis. This study should be used as a guide to evaluate the landscape and consider if geophysical methods are needed for a particular area before development.

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REFERENCES

Birmingham, A.N., Lace, M.J., Mylroie, J.R., and Mylroie, J.E. 2010. Bell hole origin: Constraints on developmental mechanisms, Crooked Island, Bahamas. Pp. 18-30. In J.B. Martin and F.D. Siewers (Eds.). *Proceedings of the 14th Symposium on the Geology of the Bahamas and Other Carbonate Regions.* Gerace Research Centre, San Salvador Bahamas.

Ho, C.H., Mylroie, J.E., Infante, L R., and Rodgers, J.R. III. 2013. Fuzzy-based spatial modeling approach to predict island karst distribution: a conceptual model. *Environmental Earth Science* 71: 1369-1377. DOI 10.1007/s12665-013-2543-4.

Jenson, J.W., Keel, T.M., Mylroie, J.R., Mylroie, J.E., Stafford, K.W., Taborosi, D., and Wexel, C. 2006. Karst of the Mariana Islands: The interaction of tectonics, glacioeustasy and freshwater/sea-water mixing in island carbonates. *Geological Society of America Special Paper* 404: 129-138.

Kindler, P., Mylroie J.E., Curran, H.A., Carew, J.L., Gamble, D.W., Rothfus, T.A., Savarese, M., and Sealey, N.E. 2010. *Geology of Central Eleuthera, Bahamas: A Field Trip Guide*. Gerace Research Centre, San Salvador Bahamas, 74 p.

Kunze, A.W.G. and Mylroie, J.E. 1991. Use of gravity techniques to detect shallow caves on San Salvador Island, Bahamas. Pp 139-149. In R.J. Bain, (Ed.). *Proceedings of the 5th Symposium on the Geology of the Bahamas*. Bahamian Field Station, Port Charlotte, FL.

Labourdette, R., Lascu, I., Mylroie, J., and Roth, M. 2007. Process-like modeling of flank margin caves: From genesis to burial evolution. *Journal of Sedimentary Research* 77: 965-979.

Lace, M.J., and Mylroie, J.E. (Eds.). 2013. *Coastal Karst Landforms*. Coastal Research Library 5, Springer, Dordrecht, 429 p.

Larson, E.B., and Mylroie, J.E. 2014. A review of whiting formation in the Bahamas and new models. *Carbonates and Evaporites* 29: 337-347. DOI 10.1007/s13146-014-0212-7.

Lawrence, O.P. 2014. Predicting flank margin cave collapse in The Bahamas. MSc. Thesis. Mississippi State University, Mississippi State, MS, USA. 83 p. http://sun.library.msstate.edu/ETD-db/theses/available/etd-04042014-132659/

Mylroie, J.E., Carew, J.L., and Moore, A.I. 1995. Blue holes: Definition and genesis. *Carbonates and Evaporites* 10: 225-233.

Mylroie, J. E. and Mylroie J.R. 2007. Development of the carbonate island karst model: *Journal of Cave and Karst Studies* 69(5): 9-75.

Mylroie, J.E. 2013. Coastal karst development in carbonate rocks. Pp. 77-109. In M.J. Lace and J.E. Mylroie. (Eds.). *Coastal Karst Landforms.* Coastal Research Library 5, Springer, Dordrecht.

Mylroie, J.E., and Mylroie, J.R. 2013. Caves and karst of the Bahama Islands. Pp. 147-176. In M.J. Lace and J.E. Mylroie. (Eds.). *Coastal Karst Landforms.* Coastal Research Library 5, Springer, Dordrecht.

Polk, J.S., and Brinkman, R. 2013. Climatic influences on coastal cave and karst development in Florida. Pp. 317-345. In M.J. Lace and J.E. Mylroie. (Eds.). *Coastal Karst Landforms*. Coastal Research Library 5, Springer, Dordrecht.

Vacher, H.L., and Mylroie, J.E. 2002. Eogenetic karst from the perspective of an equivalent porous medium. *Carbonates and Evaporites* 17: 182-196.

White, W.B., 1988. *Geomorphology and hydrology of karst terrains*. Oxford University Press, New York, 464 p.

Wilson, W.L., Mylroie, J.E., and Carew, J.L. 1995. Quantitative analysis of caves as a geologic hazard on San Salvador Island, Bahamas. Pp. 103–121. In M. Boardman (Ed.). *Proceedings of the 7th Symposium on the Geology of the Bahamas.* San Salvador Island, Bahamian Field Station.