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FLANK MARGIN CAVE INVENTORY OF THE BAHAMAS

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ABSTRACT

Flank margin caves are hypogenic mixing chambers formed in the margin of the fresh-water lens on carbonate islands and coasts. They develop, by mixing dissolution, without turbulent flow, in a very short amount of geological time. The caves start as small elliptical chambers with irregular protrusions. As chambers increase in size, laterally adjacent chambers become connected. As this process continues, much larger caves develop parallel to the lens margin. There is only a limited amount of penetration toward the lens interior. Ultimate cave size is controlled by the amount of time the lens (and sea level) stays at a relatively constant elevation. The caves above today's sea level are believed to have formed during the last interglacial sea-level highstand (~6m above msl, oxygen isotope substage 5e), approximately 131,000 to 119,000 years ago. However, the large size of some of these caves requires a tremendous amount of dissolution within that 12,000-year time window. These large caves, found throughout the Bahamas, have been studied by a number of researchers on at least eight Bahamian island including Cat Island, Eleuthera, Great Inagua, Long Island, New Providence, North Andros, San Salvador, and South Andros. The current database contains 66 mapped flank margin caves, with 46 analyzed for length, width, area and perimeter. Due to the irregular shape of flank margin caves, with many interconnected chambers, length and width measurements do not truly express the cave dimensions. However, the area and perimeter measurements account for irregular cave shape, including bedrock columns in cave chambers. The cave size categories are small (100 m^2), medium (100-1000 m^2) and large (>1000 m^2).

INTRODUCTION

The research reported here was conducted to create a data base of flank margin caves in the Bahamian Archipelago, and to use that database to determine if patterns were present that would help explain how these caves developed. The production of macroscopic dissolution voids in the coastal carbonates of islands and continents has been recognized to be different from the way such voids are produced in inland carbonate settings. Over the last 15 years, the conditions that produce these caves have been described in a series of papers (e.g. Mylroie and Carew, 1988; 1990; 1995; Mylroie et al., 1995a; 2001). The general model that pulls together the unique features of coastal carbonate cave production is the Carbonate Island Karst Model, or CIKM (Mylroie et al., 2004). The central elements of the CIKM are:

1) Fresh water - salt water boundary conditions create mixing dissolution, and produces organic-trapping horizons at the boundaries of the fresh-water lens that enhance dissolution.

2) During the Quaternary, Glacioeustasy has moved the fresh-water lens up and down through a vertical range of over 100 m.

3) Local tectonics can overprint the glacio-eustatic sea level events, adding complexity to the record.

4) The karst is *eogenetic*, i.e., it has developed in carbonate rocks that are young and have never been buried below the range of meteoric diagenesis.

5) Carbonate islands can be divided into four categories based on basement/sea level relationships:

A) Simple carbonate islands (no non-carbonate rocks),
B) Carbonate cover islands (non-carbonate rocks beneath a carbonate veneer),
C) Composite islands (carbonate and non-carbonate rocks exposed at the surface),
D) Complex islands (faulting and facies interfingering create complex carbonate/non-carbonate relationships.

The largest, most complex, and also most unusual caves that develop under CIKM conditions are called *flank margin caves*. Their name reflects their development under the flank of the enclosing carbonate landmass at the distal margin of the fresh-water lens. They are the largest dissolutional features because their location at the edge of the lens allows superposition of the vadose/phreatic mixing zone on top of the fresh-water/sea water mixing zone. The mixing of waters at these two superimposed horizons creates dissolutional aggressivity, even if both waters are initially saturated with respect to $CaCO_3$. These two mixing horizons are also horizons of density contrast, so that organic material collects there. Oxidation of this organic material creates CO_2, which helps drive dissolution beyond the capabilities of mere mixing. If the organic loading is significant, anoxic conditions may develop that can produce additional acids, such as that created by oxidation of H_2S to H_2SO_4 (Bottrell et al., 1993).

Flank margin caves develop as mixing chambers, and are not true cave conduits in that they lack turbulent flow. The reactants enter the chambers by diffuse flow, fresh water from the landward side and sea water from the marine side. As the chambers enlarge, the mixing front shifts to the landward wall of the chamber. If fresh-water inflow occurs along any discrete pathways, the mixing front will advance up those pathways, creating a complex series of passages heading inland. As the chambers grow, they also interconnect. The end result is a complex series of chambers with a maze-like configuration. They commonly extend parallel to the coast, and have limited vertical extents, reflecting their origin in the thin distal margin of the fresh-water lens. Flank margin caves fall in the category of *hypogenic caves* (Palmer, 1991), that is, caves that have formed without a direct connection to surface hydrology, but by mixing of disparate waters in the subsurface. Their pattern fits the spongework and ramiform classifications of Palmer (1991).

Flank margin caves were first recognized in the Bahamas (Mylroie and Carew, 1990), and field work has subsequently identified them on Bermuda (Mylroie et al, 1995a), Isla de Mona (Frank et al, 1998), the Marianas (Mylroie, et al., 2001) and Yucatan, Mexico (Kelley et al., 2004). Because flank margin cave formation is tied to the fresh-water lens position, they are also tied to sea level position. The Bahamas represent a tectonically stable environment where all sea-level change is glacioeustatic. Flank margin cave development is limited by the stability time of the lens at any given elevation. As a result of their development prior to Quaternary glacioeustasy, the flank margin caves of Isla de Mona are extremely large (up to ~20 km of survey). Subsequent tectonic uplift placed the caves well above glacioeustatic sea level fluctuations, which preserved them. In the Marianas, tectonics have been active throughout the Quaternary, such that when combined with glacioeustasy, the fresh-water lens never persisted at any given elevation, and the caves, while numerous, are rarely as large as in the Bahamas. Work in the Yucatan has demonstrated that flank margin caves form on continental carbonate coasts, as well as on islands.

Of the settings described above, the Bahamas have the youngest carbonate rocks. The flank margin caves are developed in carbonate rocks, primarily eolianites that are most likely less than 500,000 years old. In some cases it has been demonstrated the rocks are only ~125,000 years old (Florea et al., 2004). These rocks were deposited during the oxygen isotope substage 5e sea-level highstand, and afterwards the fresh-water lens invaded these new rocks, creating flank margin caves in a syngenetic manner (Jennings, 1968).

The Bahamas, as noted previously, are tectonically stable. They are also islands whose water budgets are entirely derived from local precipitation. The rocks are very young by almost any geologic measure. Such a situation creates very tight time and space boundary conditions in which flank margin caves could have formed. So, while the investigation of flank margin caves has spread to many other locations around the globe, the Bahamas remain the key locality in which to study flank margin cave development.

THE PROJECT

The study of flank margin caves suffered in the early years from a lack of data on the caves themselves. Prior to the subdivisions of caves that eventually resulted in the CIKM, all cave types in carbonate islands were lumped together without regard for different mechanisms of formation (see Mylroie and Carew, 1995a). Some caves, like blue holes, are polygenetic in origin (Mylroie et al.,1995b). The vast majority of the caves in the Bahamas were unmapped when work by authors Jim Carew, Joan Mylroie and John Mylroie was initiated in 1976. The maps that did exist followed no standard cartographic conventions (see Dasher, 1994) and were difficult to interpret. All the caves in the current data base, with the exception of those mapped on Cat Island by Rob Palmer and colleagues (Palmer, et al.,1986), were mapped over the last 28 years under the leadership of authors Jim Carew, Joan Mylroie, and John Mylroie.

The caves were mapped using standard cave mapping techniques. Compass, tape and clinometer were used to establish the quantitative three-dimensional configuration of the cave passages, and on-site sketching was used to provide passage detail (see Dasher 1994 for a discussion of these procedures). Initial maps were drafted in traditional pen and ink after data reduction by hand calculator, but in recent years sophisticated computer programs have been utilized.

Cave size was measured by area, as opposed to survey length, as the caves are not linear cave stream passages, as in many continental settings, but globular mixing chambers. Their size was best measured by using their area, as taken from computer plots. Area determinations were made by measuring the outside perimeter and total area of the cave, and then subtracting out the area and adding the perimeter of any interior, isolated bedrock columns. Such compensation increased the total cave perimeter, but reduced total cave area, from what would have been determined by measuring only the outer wall footprint of the cave. Cave area is a good surrogate for cave

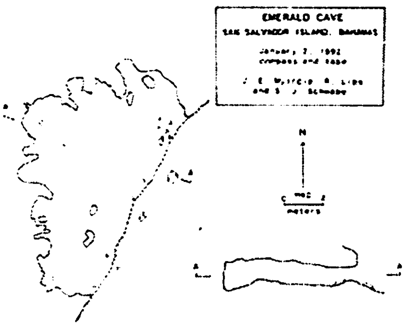

Figure 1. Emerald Cave, San Salvador Island, a typical small flank margin cave in the Bahamas.

volume, as the vertical dimension of the caves tends to be small relative to its area, and also relatively constant over the cave footprint.

The impetus for the current work has been a contract from private industry to determine the nature of void production in a fresh-water lens. These resources greatly expanded the scope of the project, and allowed caves on numerous islands to be mapped. Of particular interest are some very large caves located on Long Island and Eleuthera Island. These large caves stretch the envelope of the flank margin model, as they represent significant carbonate removal by dissolution under conditions of limited time for fresh-water lens position, and limited aerial extent of that lens.

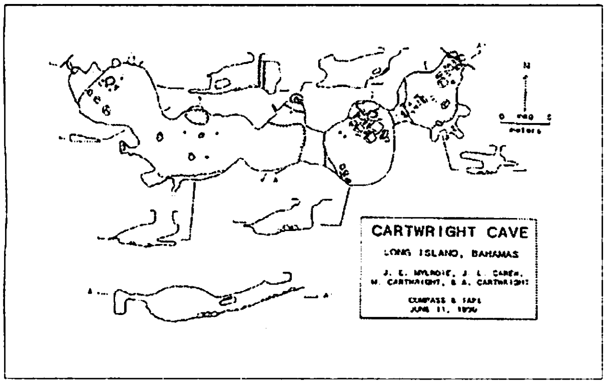

Figure 2. Cartwright Cave, Long Island, a typical flank margin cave of medium dimensions in the Bahamas.

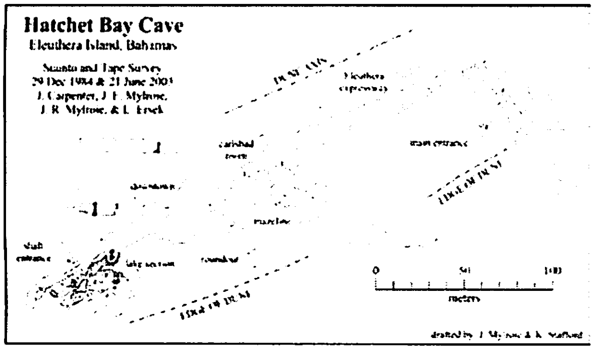

Figure 3. Hatchet Bay Cave, Eleuthera, a typical flank margin cave of large dimensions in the Bahamas.

RESULTS

The data base, as it currently exists, covers eight islands that run a traverse of the Bahamian archipelago. This traverse includes large islands (e.g. North Andros and Eleuthera) and small islands (e.g. New Providence and San Salvador), and it covers wet environments in the northwestern Bahamas to dry environments in the southeastern Bahamas. The data collected are summarized as follows:

Bahamas

- 66 Caves total (digitized & undigitized)
- 16 Caves are small, as digitized
- 24 Caves are medium, as digitized
- 6 Caves are large, as digitized
    - Cat Island
        - 9 caves total
        - 8 caves have been digitized
        - 1 cave is small in size
        - 5 caves are medium in size
        - 2 caves are large in size
    - Eleuthera
        - 6 caves total
        - 2 caves have been digitized
        - 2 caves are large in size
    - Great Inagua
        - 2 caves total
        - 1 cave has been digitized
        - 1 cave medium in size
    - Long Island
        - 6 caves
        - 3 caves are small in size
        - 2 caves are medium in size
        - 1 cave is large in size
    - New Providence
        - 8 caves
        - 2 caves are small in size
        - 6 caves are medium in size
    - North Andros
        - 1 cave total

- San Salvador
  - 28 caves total
  - 20 caves have been digitized
  - 9 caves are small in size
  - 10 caves are medium in size
  - 1 cave is large in size
- South Andros
  - 6 caves total
  - 1 cave has been digitized
  - 1 cave small in size

The classification of the caves in small, medium, and large categories (Figures 1, 2 and 3) was made based on a rank-order plot of cave size (Figure 4), smallest at rank 1, and so on. At the scale of a single plot, it may be difficult to observe that there are three straight-line segments. When reproduced individually, the three segments are readily seen, and the fit of the data is quite good (Figures 5a, 5b and 5 c). Based on the break points in Figure 4, the dividing point for cave size classification is under 100 m^2 for small caves, between 100 m^2 and 1000 m^2 for medium caves, and over 1000 m^2 for large caves. This classification is not arbitrary, but self-selected by the caves as distinct line slopes.

DISCUSSION

The development of flank margin caves by mixing zone dissolution in the distal margin of the fresh-water lens of carbonate islands and coasts results in a predictable pattern. In the distal lens environment (in a stable sea-level situation) caves will form parallel to the lens margin, such that they have a large horizontal extent but a limited vertical dimension (as seen in the plan and cross-section views of Figures 1-3). The horizontal dimension can be extensive parallel to the lens margin, but will be limited in its inland extent as cave development is controlled by mixing of fresh and marine waters at the lens margin.

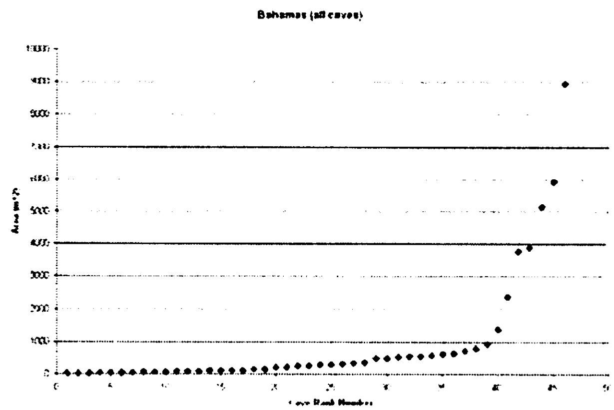

Figure 4. Plot of Bahamian caves as a plot of area versus rank number. Three straight-line segments exist (see Figure 5).

The data show that there are three categories of cave development: small (Figures 1 and 5a), medium (Figures 2 and 5b), and large (Figures 3 and 5c). These size classifications represent the consequences of void development through time. Initial dissolution begins as isolated chambers just under the enclosing flank of the landmass housing the fresh-water lens. These chambers commonly have areas of less than 100 m^2. As time passes, and the chambers grow larger, they transition from simple oval chambers into irregular chambers as mixing dissolution attacks discrete fresh-water inputs to the lens margin. Size continues to increase, and adjacent chambers intersect. These intersections result in a jump in cave size (as measured by area) to create the medium cave classification category.

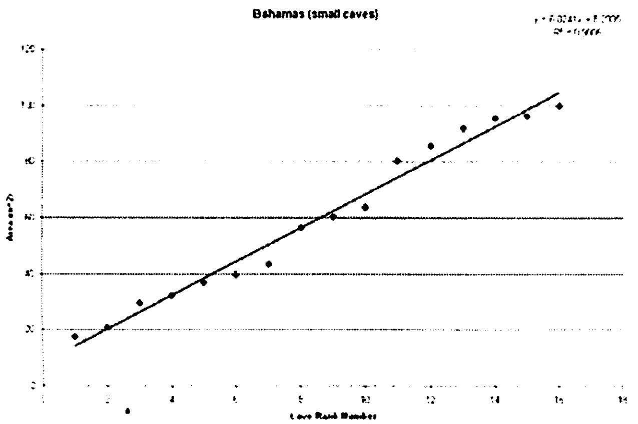

Figure 5a. Plots of cave area versus rank number for small caves in the Bahamas.

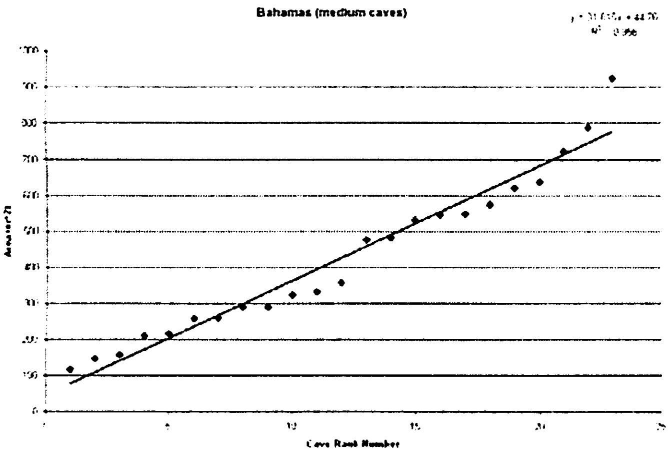

Figure 5b. Plots of cave area versus rank number of medium-sized caves in the Bahamas.

The transition from medium to large cave size classification occurs when the medium-sized caves enlarge and then connect with other medium-size caves. This creates another jump in cave size. This growth behavior can be seen in the configuration of the cave maps shown in Figures 1 – 3, and as an idealized presentation in Figure 6. This step-wise growth in size requires the lens be in a stable position for a long enough amount of time for the dissolutional process to mature. In the Mariana Islands, where tectonic uplift has overprinted glacioeustatic sea level change, lens stability times at a specific elevation are less

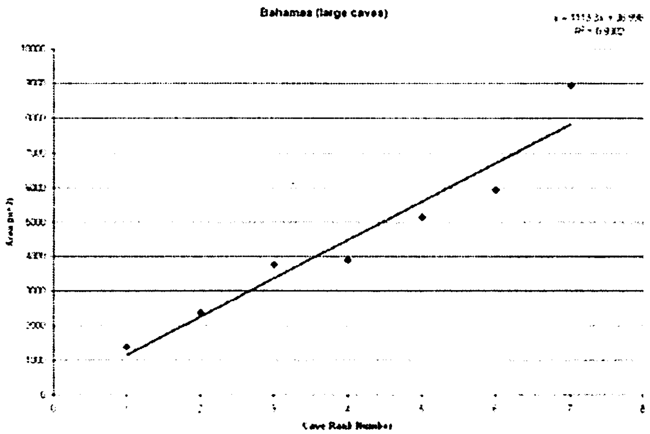

Figure 5c. Plots of cave area versus rank number of large-sized caves in the Bahamas.

than in the Bahamas, and the caves tend to fall only into the small and medium size classification categories.

As shown by the list of Bahamian flank margin caves, not all known caves have been digitized, and there is a disproportionate amount of cave data from San Salvador Island (a result of the Gerace Research Center on the island supporting long term, detailed field work). Nonetheless, the data have been collected from many islands across a broad geographic span, and the R^2 values for the Figure 5 graphs are quite high, above 0.9 in all three sub-plots, indicating that the correlation is indeed quite good.

The *epigenic caves* of Palmer (1991) in continental settings rarely undergo such step-wise growth. They enlarge by gradual extension of tributary cave passages in a process that is a continuum. On rare occasions, one cave may encroach on another conduit to pirate the latter's flow and make a large instantaneous jump in size. For flank margin caves, the juncture of two small or medium caves to produce a larger cave is a routine and expected occurrence, given the dissolutional environment at the distal margin of a fresh-water lens. The single biggest determining factor of flank margin cave size is stability time for the fresh-water lens.

One interesting outcome of rapidly changing sea level, as in the Mariana Islands, is that the lens may adjust downward (actually, the island is adjusting upward) in small steps, such that the dissolutional void produced at each sea-level stage overlaps with the void produced at the previous stage. The caves produced are then flank margin caves stacked on top of each other, much like a stack of pancakes. While no single void is very big, by maintaining communication with voids above and below, large caves can result. The end result is a vertically elongated cave of small lateral dimension. In the field, these caves have been called "elevator caves", as the caves have developed by holding the lens in one place and having the island rise up through that position, leaving a trail of dissolutional voids behind. This discussion demonstrates the importance of knowing the tectonic setting of flank margin cave development.

As a final example, the very large flank margin caves of Isla de Mona, Puerto Rico exist today not only because they formed in a stable setting prior to the onset of high amplitude, short wavelength glacioeustasy in the Quaternary, but also because subsequent tectonics rapidly brought them up above any further sea level and fresh-water lens position.

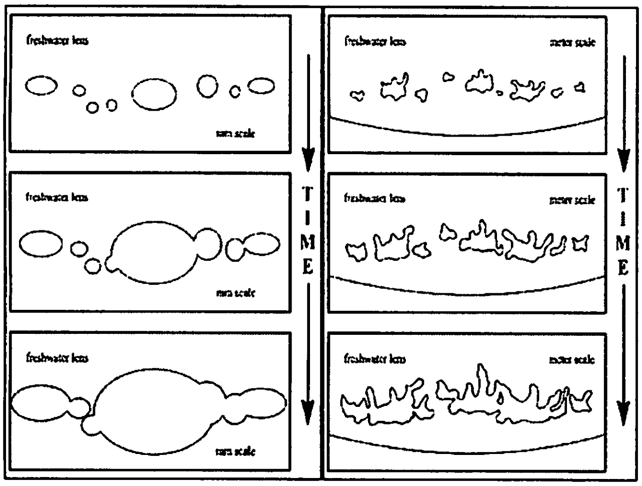

Figure 6. Idealized model of how flank margin caves form in the distal margin of the fresh-water lens. Left side shows microscopic scale, right side macroscopic scale. The connection of chambers to multiple chambers, and multiple chamber caves to each other (right side) create the step-wise jump in flank margin cave size.

Subsequent modification and overprinting of the caves was minimized. In the Bahamas today, large flank margin caves may exist well below modern sea level, formed in the same pre-Quaternary time of sea level stability that produced the caves of Isla de Mona. But unlike Isla de Mona, no subsequent tectonics has uplifted these caves to preserve them. In such, isostatic subsidence will have carried their sites of development well below modern sea level (and that is assuming the lens that formed them was at or near modern sea-level position, and not lower). It is also possible that failure of the bank margin, a common occurrence in the Quaternary in the Bahamas, has removed the caves entirely. Large flank margin caves were not observed at depths down to 200 m during submersible examination of the wall of San Salvador Island (Carew and Mylroie, 1987).

Climate is a key control of cave development on carbonate islands and coasts, as glacioeustasy is in the end an expression of climatic fluctuation. But other aspects of climate can be crucial as well. Bermuda is a carbonate island very similar to the Bahamas. Flank margin caves there are relatively rare, and are remnants of small size. Bermuda has a humid, positive water-budget environment, so that hillsides erode quickly. Such hillside erosion has removed the flank margin caves, which, because of their position under the flank of the landmass enclosing a past fresh-water lens, are vulnerable to even minimal hillslope erosional retreat (Mylroie, et al., 1995a).

CONCLUSIONS

Flank margin caves develop in a manner different from caves found in epigenic, continental settings. They increase in size incrementally by mixed-water dissolution, a hypogenic condition. That development occurs simultaneously at many spots along the distal margin of the fresh-water lens, so that, eventually, enlarging chambers intersect, and cave size jumps immediately. These connected cave chambers then intersect other groups of connected cave chambers, and overall cave size then again jumps instantaneously. While the work reported here is preliminary, indications are that the thresholds for each jump can be predicted based on the lens geometry, or in the converse, paleo-lens geometry can be determined by the nature of flank margin cave chamber interconnection.

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