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LAND MANAGEMENT ISSUES OF CARBONATE ISLAND KARST

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ABSTRACT

It has been long recognized that karst landscapes (characterized by closed depressions, etched bedrock, caves, and springs) present land management issues different from those found on terrains developed on insoluble rocks. This recognition was formulated based on the type of karst commonly found in continental interiors called *telogenetic* karst, as the limestone is dense, recrystallized, and diagenetically mature. Carbonate islands, on the other hand, consist of *eogenetic* karst; that is, karst formed on very young, porous, and diagenetically-immature limestones. In addition, carbonate islands have a freshwater lens, and the lens boundary with the underlying marine water creates a potent geochemical environment for the development of caves. As the freshwater lens floats on the marine water, sea-level change due to island tectonics or glacial ice volume change cause the cave-forming geochemical environment to also change elevation. This environment is explained by the Carbonate Island Karst Model, or CIKM.

The land management issues centered on the CIKM fall into two categories. The first category is the physical condition of the surface (epikarst) and subsurface (caves) that help control plant and animal habitats, modern and ancient human use, and stored scientific information. Habitat examples include bats in caves, parrots nesting in dissolution pits, and plants in sinkholes. Important archeological material is found in caves, and modern construction requires understanding where cave chambers are. Caves are important sites for preservation of paleoclimate data in sediments and deposits such as stalagmites.

The second land management category is the hydrological behavior of freshwater resources, including water quantity and quality. The ideal freshwater lens of the textbooks is distorted by dissolutional pathways produced in island limestones by karst processes. Contaminants spread by both preferred dissolutional pathways and by diffuse flow, making plume flow direction and concentration difficult to model.

Whereas telogenetic karst produces discrete surface features and groundwater flow paths, the eogenetic karst of carbonate islands produces a continuum of landforms and subsurface groundwater flow paths that require a different approach to land use management. Successful land use for many activities requires that the underlying karst processes and their products be understood.

INTRODUCTION

Within the karst scientific community, it has long been recognized that karst landforms and flow systems create unique land management issues that require a different approach than for non-karst landscapes. Karst landscapes are defined as areas where the land surface and the underlying groundwater flow systems are dominated by dissolution of the bedrock. Bedrock types such as limestone, dolomite, gypsum, and rock salt all dissolve to varying degrees in natural surface waters and ground waters. Limestones and dolomites, collectively called carbonate rocks, are the most common karst-forming rock types. Sinking streams, underground rivers, springs, sinkholes, and etched rock surfaces are a result. The mainstream scientific community was slow to understand how karst areas differed from other landscapes. Beginning in the 1980s, a series of professional textbooks on karst processes (e.g., Jennings, 1985; White, 1988; Ford & Williams, 1989) set the intellectual framework for solid scientific application of karst science to land use issues. At the same time, two different symposia series dealing with land use and karst began a regular schedule of meetings that continues to this day. The "Sinkhole Conference" meetings are focussed on direct engineering applications to problems in karst areas, addressing both structural and hydrological problems primarily. This series has a strong business and industrial outlook, and has published symposia proceedings (e.g., Beck & Stephenson, 1997) that have become the benchmark volumes in the engineering of karst terranes. The second symposia series is the National Cave Management Symposia, which address issues of karst conservation. This second series has strong participation from federal and state as well as private stakeholders who own karst lands and wish to improve their ability to manage these unique landscapes. The Cave Management Symposium Proceedings series (e.g., Pate, 1995) have also become the benchmark volumes for management of cave and karst lands.

As the 1990s proceeded, successful management and use of karst landscapes, as practiced by government, private, and business entities, had become fairly sophisticated and widespread. Unlike the 1970s, when karst lands were more likely than not to be mismanaged, most karst areas today are properly managed. The database and subsequent paradigms on karst land management had been derived from experiences on karst formed in continental interiors on old and dense carbonate rocks. When these models were applied to young, porous carbonates, as found on many tropical islands, they did not work well. The purpose of this paper is to present why these young carbonates are different, and to suggest strategies that will allow successful land management in the carbonate island environment.

ISLAND KARST

Carbonate rocks form generally in warm, shallow waters where a variety of plants and animals use calcium carbonate, $CaCO_3$, as a structural material. Upon death, these skeletal remains accumulate and become compacted and cemented, forming porous carbonate rock. Tropical carbonate islands seen today exist in the environment of their carbonate rock's formation. The carbonate rocks found in continental interiors today were deposited long ago, underwent deep burial and recrystalization (or even metamorphosis to marble), and were brought back to the surface and exposed by uplift and erosion. These continental carbonates are dense and diagenetically mature. Plate tectonics has moved them thousands of kilometers away from their environment of deposition. These old, dense, and mature carbonate rocks are called *telogenetic* rocks (Chouquette & Pray, 1970), which reflects their long history of modification. The young, porous, and basically unaltered carbonate rocks found in or near their environment of deposition were labeled *eogenetic* rocks (Chouquette & Pray, 1970). Recognizing that these two rock types undergo dissolution and conduct ground water in very different ways, Vacher & Mylroie (2002) proposed the terms *telogenetic karst* and *eogenetic karst* for the karst landforms and ground-water flow systems formed, respectively, on the two rock types.

Tropical islands and their karst differ from that found on continents by more than just the rock type. Islands contain a freshwater lens, which floats on underlying sea level (Figure 1). As a result, they are subject to the geochemical effects of the mixing of those waters. In turn, the placement of the freshwater lens depends on climate and on sea-level position. All these elements of rock type, environmental setting, and sea-level change have been combined into the *Carbonate Island Karst Model*, or the CIKM (Mylroie & Jenson, 2000; Mylroie, *et al.*, 2001; 2004). The CIKM has the following elements:

1) Freshwater-saltwater mixing occurs within the freshwater lens.

2) Glacioeustasy has moved the freshwater lens up and down through a vertical range of over 100 m.

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

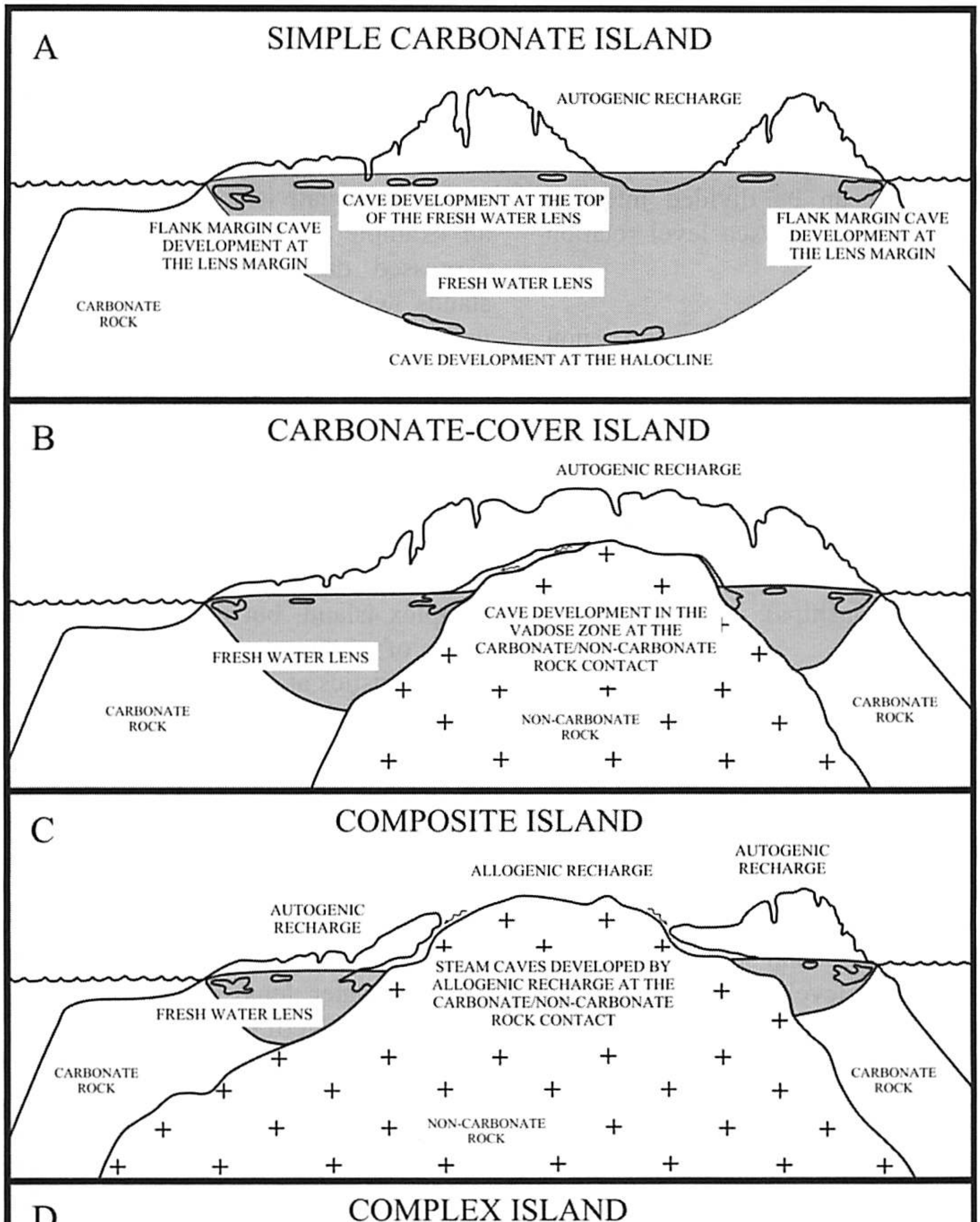

Figure 1. The island classification scheme for the Carbonate Island Karst Model (CIKM), showing simple carbonate island (A), carbonate-cover island (B), composite island (C), and complex island (D). The lens is drawn with vertical exaggeration.

4) The karst is *eogenetic*; 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 on the surface);
D) Complex islands (faulting and facies interfingering create complex carbonate/non-carbonate relationships).

Element 1, the mixing of fresh and saltwater, results in a mixture that is capable of dissolving $CaCO_3$, even if both waters were saturated with $CaCO_3$ prior to mixing (Mylroie & Carew, 1995). As a result, the boundary between the freshwater lens and the underlying sea water is an area of preferential dissolution and cave formation. This is a dissolutional mechanism not available in most inland continental settings. Elements 2 and 3 indicate that sea level can change, and if it does, the freshwater lens and the mixing zone between that lens and the underlying sea water will also move vertically. This will change the location of enhanced dissolution and cave formation. Element 4 has already been addressed, but some elaboration is useful. The old, dense, and mature carbonates of the continental interiors, the telogenetic carbonate rocks, have very low porosity. Initial water movement through such rocks is primarily along faults, joints, bedding planes, and other cracks in the rock, which are then enlarged by dissolution. In island environments, the eogenetic rock is itself quite porous, and water can move through these carbonate rocks somewhat uniformly and in large amounts. The opportunity for freshwater and seawater mixing, and subsequent dissolution, is enhanced on a broad areal scale. The type of caves and karst features that result will, therefore, be quite different than those for telogenetic rocks. Finally, element 5 describes the geologic setting of carbonate islands, in terms of a progression from simple to complex. Figure 1 presents this sequence diagrammatically.

The Bahamas are an excellent example of simple carbonate islands (Figure 1A). Bermuda is an example of a carbonate-cover island (better expressed during glacioeustatic sea-level lowstands, when the lens is lowered down onto the underlying volcanic edifice and the lens is partitioned as shown in Figure 1B). Barbados is an example of a composite island (Figure 1C), and Saipan is an example of a complex island (Figure 1D). While it is tempting to place entire islands into this four-part classification, it is best applied to parts of islands which are hydrologically distinct. For example, southern Guam behaves as a complex island, but northern Guam displays aspects of carbonate-cover and composite island characteristics at spatially distinct locations (Mylroie *et al.*, 2001).

The largest caves found in simple carbonate islands (Figure 1) are called flank margin caves, as they develop in the distal margin of the freshwater lens, under the flank of the enclosing landmass (Mylroie & Carew, 1990). They develop primarily from mixing dissolution, from both descending vadose freshwater mixing with the top of the freshwater lens, and with seawater mixing with the bottom of the freshwater lens. At the lens margin, these favorable dissolutional horizons are superimposed. The top and bottom of the freshwater lens are also density contrast horizons, and as such, they trap descending organic material. This organic matter produces CO_2 upon decay, which increases water acidity and helps further drive dissolution. If the organic loading is significant, the lens may go anoxic, and complex redox reactions and bacteriological activity may produce H_2S, which can oxidize to H_2SO_4 and drive dissolution still further (Bottrell *et al.*, 1993). The freshwater lens thins at its distal margin, decreasing the lens cross-sectional area and, as a result, increasing freshwater flow velocity. This rapid flow allows reactants and products to transit the system rapidly. As a result of all these factors, the distal margin of the freshwater lens produces the largest caves found in these island environments. The caves tend to be wide and low, indicative of their

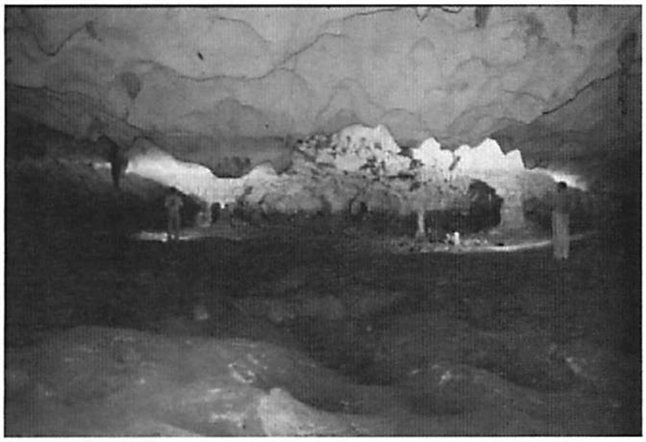

Figure 2. Salt Pond Cave, Long Island, The Bahamas. This cave developed in the distal margin of a freshwater lens perched on a sea-level highstand from the last interglacial, ~125,000 years ago. Note the breath of the cave chamber relative to its height. The dark line on the wall represents guano removed in the 1800s.

Figure 3. Cliff on Isla de Mona, in Mona Passage between Hispaniola and Puerto Rico. Tectonics has uplifted this island, draining flank margin caves that are now exposed in the cliff on a continuous horizon.

position within the distal margin of the freshwater lens (Figure 2). They also form continuous horizons that correspond to past sea-level highstands (either glacial or tectonic; Figure 3).

Caves that form by capture of surface water, transport of that water by conduit flow, and release back to the surface at springs, are known as *epigenic* caves (Palmer, 1991). Epigenic caves are directly coupled to the surface hydrology. The vast majority of caves found in continental interiors are epigenic caves. In contrast, caves that form by mixing of different waters inside an aquifer, away from surface hydrological influences, are known as *hypogenic* caves (Palmer, 1991). Some continental, telogenetic caves are hypogenic. The classic examples are the caves of the Guadalupe Mountains in New Mexico, including famous Carlsbad Caverns. In these cases, the mixing is between H_2S water rising up from nearby oil reservoirs, mixing with shallow O_2-rich phreatic water, and oxidizing to produce H_2SO_4, which then creates the caves (Hill, 2000). Flank margin caves are also hypogenic, mixing freshwater and saltwater within the carbonate aquifer to generate prodigious amounts of dissolution. Estimates are that flank margin cave chambers formed at a rate exceeding 1 m^3/yr (Mylroie & Carew, 1995). Epigenic caves can be found on carbonate islands, as Figures 1C and 1D demonstrate.

It is important to differentiate between *island karst* and *karst on islands*. Island karst is karst developing under the conditions of the CIKM, the dominant aspects of which are freshwater-saltwater mixing and freshwater lens migration as a result of sea-level change. Karst found in older rocks in the interior of large islands, such as the mogote karst of Puerto Rico or the cockpit karst of Jamaica, is not island karst as defined here, but karst on islands. That is, the karst behaves much like karst found in the interior of continents because it is not influenced by freshwater-saltwater mixing or sea level change. The rocks, as they are in the island interior, are comonly older than coastal carbonates and have lost some or all of their eogenetic porosity. The situation can be complex, in that both Puerto Rico (northwest coast) and Jamaica (Jackson Bay) have coastal environments where the CIKM applies, and so the karst there can be considered island karst. The differentiation between island karst and karst on islands may appear to be trivial hair-splitting, but successful land management on carbonate islands can only be accomplished by recognizing the difference. As a metaphor, the casual observer might wish to classify bats, bees, and birds as very similar because they all fly, whereas from a biological perspective the differences are important and significant.

LAND MANAGEMENT ON CARBONATE ISLANDS

Caves and Karst as Physical Features

Karstlands have distinct physiographic features, such as etched bed rock surfaces, sinkholes, sinking streams, caves, and springs that make these landscapes unique. The situation on carbonate islands, especially those areas that fall under the CIKM, is even more unique. For example, consider the simple carbonate island (Figure 1). For islands such as The Bahamas, water catchment is considered autogenic, that is, all the drainage is collected on the carbonate rock surface, and quickly enters the subsurface by way of either primary porosity or by small dissolution pathways. True sinkholes are small, as rainwater is not focussed into a few widely-spaced points to descend into the rock as would happen in dense limestones of continental interiors, but easily en ters the eogenetic rock within centimeters of its impact point with the surface. The large closed contour depressions of The Bahamas are constructional, that is, they reflect primary depositional features in the bedrock, such as swales between eolianites, or lagoons formed behind reefs during the last interglacial (~125,000 years ago) when sea level was 6 m higher than today. Because of the eogenetic porosity of the rock, and the rapid development of many dissolutional pathways into the subsurface, these depressions are drained and do not become ponds or lakes unless they intersect sea level.

The most abundant sinkholes found in The Bahamas are banana holes (Figure 4), so named for the specialty crops that are commonly grown in them by islanders (Harris et al, 1995). They form as small mixing chambers at the top of the freshwater lens. During the last interglacial formed under low plains in The Bahamas. When sea level fell, these small caves were drained. Over time, their relatively thin roofs collapsed, to produce a circular feature commonly 2-10 m across and a few meters deep (Figure 4). Flank margin caves can also collapse to form sinkholes (Figure 5). Classic sinkholes and sinkhole plains, as found in continental interiors, are rare.

Figure 4. A banana hole on San Salvador Island, The Bahamas. While this banana hole has collapsed and is open to the surface, nearby are several banana hole caves with thin but complete roofs, entered laterally from an open adjacent banana hole.

Blue holes, a classic karst feature of The Bahamas (Figure 6), are polygenetic in origin, the result of a variety of geologic processes working during the Quaternary, including glacioeustatic sea-level change. They are defined as: *Blue holes are subsurface voids that are developed in carbonate banks and islands; are open to the earth's surface; contain tidally-influenced waters of fresh, marine, or mixed chemistry; extend below sea level for a majority of their depth; and may provide access to cave passages* (Mylroie *et al.*, 1995:231). The definition can be further expanded: *An ocean hole is a blue hole that opens directly into the present marine environment and usually contains marine water with tidal flow. An inland blue hole is a blue hole isolated by present topography from marine conditions, which opens*

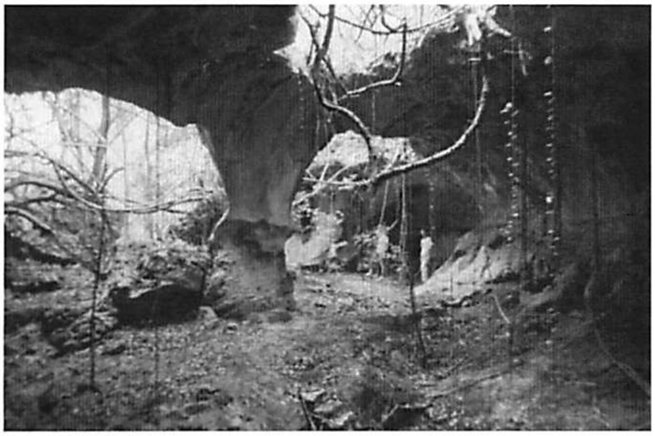

Figure 5. A flank margin cave on New Providence Island, The Bahamas, in which the outer wall is mostly collapsed. As these caves develop just under the enclosing flank of the land mass, they are vulnerable to exposure by minor erosion of the hillside, as shown here.

directly onto the land surface or into an isolated pond or lake, and which contains tidally-influenced water of a variety of chemistries from fresh to marine (Mylroie *et al.*, 1995:231). Blue holes, therefore, provide a very diverse habitat for biota (e.g., Palmer, 1986).

The etched and dissolutionally-modified bedrock of the land surface is called the epikarst. It is a geochemical weathering front migrating downward into the carbonate bedrock. The top surface is commonly very jagged, and loose disarticulated blocks of bedrock may rest on firmer material below. As chaotic as the land surface looks, within a couple of vertical meters the incoming meteoric water flow has been organized into a few selected pathways that conduct the water rapidly to depth in the bedrock mass, which is solid and coherent. Shallow caves under the epikarst commonly show broad ceilings penetrated in only a few locations by dissolutional tubes, whereas on the surface above, it appears that the rock is perforated like swiss cheese. This "swiss cheese" appearance is in part an outcome of the eogenetic nature of the bedrock, where high porosity and diagenetic immaturity result in a fretted and jagged appearance (Taborosi *et al.*, 2004). The epikarst represents a perched aquifer with a high amount of capillary storage. The consolidation of the water flow into selected vertical pathways results in pit cave formation (Harris *et al.*, 1995), which act as vadose fast-flow routes to quickly conduct the meteoric water flow to the water table (top of the lens). Studies in Guam indicate that at least 30% of the meteoric water reaches the lens in this fast flow manner (Jocson, *et al.*, 2002). These pit caves can be small and closely spaced, such that they are soil pipes a few meters deep and a few tens of centimeters across, or they may be more widely spaced to create vertical shafts tens of meters deep and meters across (Figure 7).

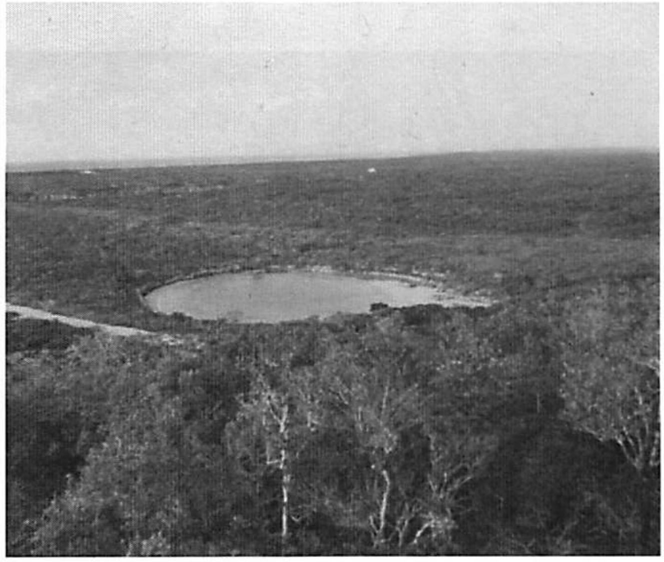

Figure 6. Watlings Blue Hole, San Salvador Island, The Bahamas, an inland blue hole with tidal movement and brackish water on the surface. The stone structures on the extreme right hand shoreline are turtle pens from the plantation period of European colonization (early 1800s).

In composite and complex islands of the CIKM (Figure 1C and 1D), non-carbonate rock is exposed at the surface and acts as an allogenic catchment for meteoric water, meaning that the water collected there will contact the limestone after being gathered elsewhere. The focussing of stream flow onto carbonate outcrops results in sinking streams similar to that found in continental interiors. In these islands, as well as in carbonate cover islands, water flow in the subsurface may be channeled by topography on the non-carbonate rock, creating large voids that prograde by roof failure to the surface, to produce large collapse sinkholes. Large surface depressions can be

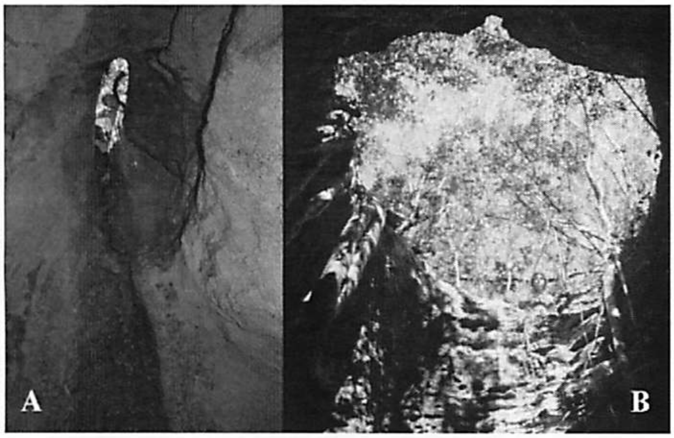

Figure 7. Two pit caves, one small (A) and one large (B), San Salvador Island, The Bahamas. Same person in each image for scale. These pit caves provide a vadose fast-flow route to carry meteoric precipitation directly to the freshwater lens.

excavated at the sinkpoint of surface streams at the carbonate/non-carbonate rock contact. This allogenic water is acting in an epigenic manner, coupling the surface hydrology to the subsurface hydrology directly.

What does this all mean for land use? For the flora, the degree of surface karst development can control access to water and nutrients. For example, banana holes, as they collect washed-in organic matter and soil, and because they provide a pathway for roots to get closer to the freshwater lens, have a flora distinct from that on the surrounding epikarst (Lenhert *et al.*, 1997). The epikarst is also home to a variety of organisms, where, analogous to a coral reef, there are nooks and crannies in abundance to provide escape from predation or climatic extremes. For example, the Bahama Parrot on Abaco nests in small epikarst dissolution features (Keith & Gnam, 2000). Caves are major bat roosts in The Bahamas (e.g., Hall *et al.*, 1998), and may utilize caves differentially based on gender (Fleming & Murray, 2005).

From the human viewpoint, land use on island karst creates a number of issues. The very name "banana hole" is a result of the recognition by Bahamians of the higher productivity of soils in the bottoms of those features, such that specialty crops (e.g., bananas) were preferentially grown there (Jackson, 1997). Planting crops in the epikarst commonly means that plants (corn or melons, for example) are planted individually in small, soil-filled dissolution pits and pockets where plowing is impossible.

Construction projects must deal with the unique aspects of a land surface that is commonly made of disarticulated rock rubble, and which may contain caves at shallow depths that are prone to collapse. During consideration of a new airport on San Salvador Island, an area at the north end was examined. Harris *et al.* (1995) had determined that the region contained banana holes in abundance, up to 3,000/km^2, and that many more probably were not yet expressed by collapse. A bulldozer was brought in to clear survey lines, and after the third event in which it broke through and fell into a newly breached banana hole, the effort was abandoned. The existing runway was extended at Cockburn Town after extensive geophysical work to find and fill karst features in the extension's path. Wilson *et al.* (1995) created the first risk assessment study of karst in The Bahamas, providing a statistical analysis of the cave and karst inventory to date. This study drew the first conclusions regarding evaluation of risk in the eogenetic, CIKM tropical carbonate island environment.

Caves are refuges for living biota and repositories for biotic remains. The youth of the carbonate rock on tropical islands means that the rock itself may contain significant exposures of fossil material that lived in the shallow seas which produced the limestone. Once formed, the caves can act as a habitat and preserve remains of that which once lived there. Caves on tropical islands can be a hazard for organisms that enter and cannot escape, primarily pit caves or ceiling collapse areas of other cave types that act as pitfall traps (Olson, 1982). Caves are an important source of paleontological information. A significant aspect of cave and human interaction, especially among primitive peoples, is the preservation of archeological material. Such preservation is common on carbonate islands such as The Bahamas (e.g., Granberry, 1980). Caves on tropical islands have long been used as a source of guano for fertilizer (Figure 2) and gun powder production (e.g., Frank *et al.*, 1998). Cave locations are common on topographic maps of The Bahamas, and caves act today as a recreational resource, with cave tours being offered on an occasional basis to Hamiltons Cave, Long Island; Hatchet Bay Cave, Eleuthera; and Lighthouse Cave, San Salvador. Such recreational visitation brings with it the risk of cave desecration by removal or vandalism of mineral deposits as well as paleontological, biological, and cultural materials (Figure 8).

Cave deposits such as guano, or paleontological and archeological remains, are an obvious resource. Less obvious are the data preserved in cave mineral deposits. Gypsum ($CaSO_4{\cdot}2H_2O$) deposits have been shown to be bimodal in origin. In pit caves, the gypsum indicates a sulfate source from sea spray, while in some flank margin caves, the gypsum indicates a biologically-mediated sulfur source (Bottrell *et al.*, 1993), as it is isotopically light ($\delta^{34}S$ = -22). Calcite speleothems, especially stalagmites, have been very useful in determining when flank margin caves were air-filled, such that stalagmites could grow from drip water (Carew & Mylroie, 1995). Analysis of marine overgrowths within stalagmites has also allowed sea-level highstand events to be resolved (Mylroie & Carew, 1988). Such measurements have helped determine which sea-level highstand event was responsible for flank margin cave development in The Bahamas.

Caves and Karst as Hydrological Pathways

As was noted earlier, the water flow paths in eogenetic karst are different than those found in teleogenetic karst. The pathways can be diffuse as well as conduit, and hypogenic as well as epigenic. The result is that water quantity and quality issues require a full understanding of aquifer behavior in carbonate islands. Regardless of geology, islands have major water issues, primarily because as isolated land masses, they must satisfy all water needs on-site. The freshwater lens is vulnerable to many misuses that will limit the total amount of water available. Contamination of a lens can further limit the amount of accessible water (Figures 9 and 10).

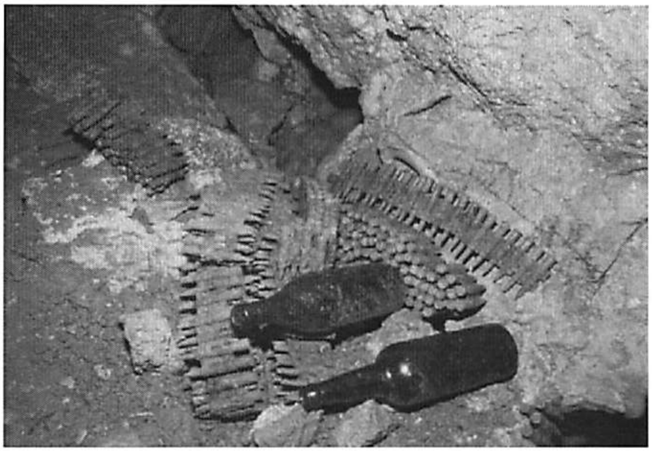

Figure 8. Ammunition and saki bottles from World War II in a cave on Guam in the western Pacific. The development of numerous caves at past sea level horizons on carbonate islands in the Pacific provided the Japanese with ready-made fortifications for island defense.

On carbonate islands, the situation becomes even more difficult. The freshwater lens of a carbonate island does what other aquifers cannot—it self-modifies. As the freshwater lens persists through time, flow within the lens results in the development of dissolution pathways that increase the aquifer permeability, even as overall bulk porosity may be decreasing by cementation of pores not in the direct flow pathways (Vacher & Mylroie, 2002). As a result, the carbonate rock becomes more permeable with time. This higher permeability, commonly made up of linked pores called *touching vugs* with a centimeter-size scale (Vacher & Mylroie, 2002), results in a decrease in lens volume, and a final end-point is the disappearance of the lens. Because glacioeustasy in the Quaternary has moved sea level, and hence the freshwater lens, over a variety of positions, this end state has not been observed in the real world. However, a distinct inverse correlation between lens thickness and rock age has been demonstrated in Bermuda (Vacher, 1988) and in The Bahamas (Wallis *et al.*, 1991). The best aquifers in The Bahamas, for example, tend to be in Holocene sand deposits that are commonly less than 3,000 years old. While these units are very porous, their extreme young age means that they have undergone minimal dissolutional reorgani-

Figure 9. A banana hole that intersects the modern water table, New Providence Island, The Bahamas. Note both the macroscopic debris, and the abundant algae, indicative of both physical and chemical pollution of the aquifer at this location.

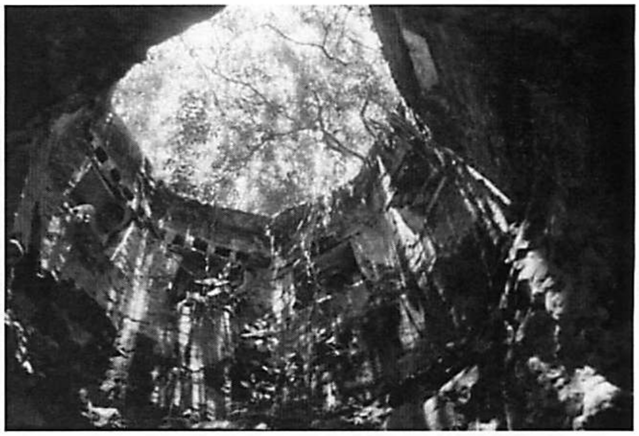

Figure 10. A pit cave on San Salvador Island, The Bahamas, converted during the plantation period (early 1800s) into an outhouse, sending human waste directly to the freshwater lens.

zation and their permeability, while high, can still support a thick lens. Pleistocene bedrock, on the other hand, has had a longer residence time for freshwater dissolution, and commonly has lower porosity but higher permeability, and the freshwaster lens is thin as a result.

Superimposed on top of this touching vug permeability, large dissolutional features, such as developing banana holes and flank margin caves, are superimposed. It is not well understood at this time how these voids, at the top and edge of the lens, respectively, influence lens flow. Also superimposed on the carbonate rock are joints and faults, which can influence flow. Some of these joints are the result of bank-margin failure, a passive, non-tectonic fracturing parallel to the edge of the island. These fractures can intercept lens flow and distort it (Whitaker & Smart, 1997; Shaw, 2003). Tectonic fracturing, common in islands such as those in the Mariana Island Arc of the western Pacific, can also distort the freshwater lens and create fast flow patterns that are superimposed on the slower touching-vug flow of the lens mass (Moran & Jenson, 2004). The alternate flow routes have confounded attempts to track water movement in the freshwater lens (Jocson *et al.*, 2002; Moran & Jenson, 2004). Understanding the duality of water flow in carbonate islands has led to better water management of both water amounts, and contaminant flow (Jocson *et al.*, 2002). Such lens contamination risk is not new to carbonate islands, as shown in Figure 10.

CONCLUSION

The development of karst on tropical carbonate islands involves processes and products unique to these islands. While many workers recognize the need to apply karst models to these islands, many have failed to recognize that the majority of the karst literature addresses karst formed on the telogenetic limestones of continental interiors. Such models do not work well in carbonate islands, and may actually be counter productive. The eogenetic limestones of tropical carbonate islands require the understanding of new approaches, such as the Carbonate Island Karst Model (CIKM), to successfully address issues as diverse as location and preservation cultural remains, cave deposits, flora and fauna habitats, engineering and construction, and water quantity and quality.

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REFERENCES

Beck, B. F., and J. B. Stephenson. 1997. *The Engineering Geology and Hydrogeology of Karst Terrains*. A. A. Balkema, Brookfield, Vermont.

Bottrell, S. H., J. L. Carew, and J. E. Mylroie. 1993. Bacterial sulphate reduction in flank margin environments: evidence from sulphur isotopes. Pp. 17-21 *in* B. White, ed., *Proceedings of the 6th Symposium on the Geology of the Bahamas*. Bahamian Field Station, Port Charlotte, Florida.

Carew, J. L., and J. E. Mylroie. 1995. Quaternary tectonic stability of the Bahamian archipelago: evidence from fossil coral reefs and flank margin caves. Quaternary Science Reviews 14:144-153.

Choquette, P. W., and L. C. Pray. 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. American Assoc. Petroleum Geologists Bull. 54(2): 207-250.

Fleming, T. H., and K. L. Murray. 2005. Phylogeography of three species of West Indian phyllostomid bats: preliminary observations. Pg. 8 in *Abstracts and Programs for the 11th Symposium on the Natural History of the Bahamas*. Gerace Research Center, San Salvador Island, Bahamas.

Ford, D. C., and P. W. Williams. 1989. *Karst Geomorphology and Hydrology*. Unwin Hyman, London.

Granberry, J. 1980. A brief history of Bahamian archeology. The Florida Anthropologist 33(3):83-93.

Hall, J. S., C. W. Stihler, and P. L. Dougherty. 1998. Bat populations on San Salvador and New Providence Islands. Bahamas Journal of Science 5(3):22-27.

Harris, J. G., J. E. Mylroie, and J. L. Carew. 1995. Banana holes: unique karst features of the Bahamas. Carbonates and Evaporites 10(2):215-224.

Hill, C. A. 2000. Overview of the geologic history of cave development in the Guadalupe Mountains, New Mexico. Journal of Cave and Karst Studies 62(2):60-71.

Jackson, J. A., ed. 1997. *Glossary of Geology*. American Geological Institute, Alexandria, Virginia.

Jennings, J. N. 1985. *Karst Geomorphology*. Basil Blackwell, Ltd., New York, New York.

Jocson, J. M. U., J. W. Jenson, and D. N. Contractor. 2002. Recharge and aquifer responses: Northern Guam Lens Aquifer, Guam, Mariana Islands. Journal of Hydrology 260:231-254.

Keith, J. O., and R. Gnam. 2000. Bahama parrots and feral cats on Abaco. Bahamas Journal of Science 7(2):20-26.

Lehnert, M. K., J. E. Mylroie, and D. A. Arnold. 1997. Vegetation diversity on carbonate island karst - the record from San Salvador Island, Bahamas. Pp. 33-37 *in* Karst Waters Institute Special Publication 3: *Conservation and the Protection of the Biota of Karst*. Karst Waters Institute, Charles Town, West Virginia.

Moran, D. C., and J. W. Jenson. 2004. Dye trace of groundwater flow from Guam International Airport and Harmon Sink to Agana

Bay and Tumon Bay, Guam. Technical Report No. 97, Water and Environmental Research Institute of the Western Pacific, University of Guam.

Mylroie, J. E., and J. L. Carew. 1988. Solution conduits as indicators of late quaternary sea level position. Quaternary Science Reviews 7:55-64.

Mylroie, J. E., and J. L. Carew. 1990. The flank margin model for dissolution cave development in carbonate platforms. Earth Surface Processes and Landforms 15:413-424.

Mylroie, J. E., and J. L. Carew. 1995. Karst development on carbonate islands. Pp. 55-76 *in* D. A. Budd, P. M. Harris, and A. Saller, eds., *Unconformities and Porosity in Carbonate Strata*. American Association of Petroleum Geologists Memoir 63.

Mylroie, J. E., J. L. Carew, and A. I. Moore. 1995. Blue holes: definition and genesis. Carbonates and Evaporites 10(2):225-233.

Mylroie, J., and J. Jenson. 2000. Guam and the carbonate island karst model. Pp. 82-86 *in* B. P. Onac and T. Tamas, eds., *Karst Studies and Problems: 2000 and Beyond*. Proceedings of the Joint Meeting of the Friends of Karst, Theoretical and Applied Karstology, and IGCP 448. Cluj-Napoca, Romania.

Mylroie, J. E., J. W. Jenson, D. Taborosi, J. M. U. Jocson, D. T. Vann, and C. Wexel. 2001. Karst features of Guam in terms of a general model of carbonate island karst. Journal of Cave and Karst Studies 63(1):9-22.

Mylroie, J. E., J. R. Mylroie, and J. W. Jenson. 2004. Modeling carbonate island karst. Pp. 135-144 *in* R. Martin and B. Panuska, eds., *Proceedings of the 11th Symposium on the Geology of the Bahamas and other Carbonate Regions*. Gerace Research Center, San Salvador Island, Bahamas.

Olson, S. L. 1982. Biological archeology in the West Indies. The Florida Anthropologist 35(4):162-168.

Palmer, R. J. 1986. The blue holes of South Andros, Bahamas. Cave Science 13:3-6.

Palmer, A. N. 1991. Origin and morphology of limestone caves. Geological Society of America Bull. 103:1-21.

Pate, D. L., ed. 1995. *Proceedings of the 1993 National Cave Management Symposium*. National Speleological Society, Huntsville, Alabama.

Shaw, C. E. 2003. Controls on the movement of ground water in the northeastern Yucatan Peninsula: examples from Yal Ku Lagoon and North Akumal. Pp. 23-32 *in Field Trip to the Caribbean Coast of the Yucatan Peninsula*. Salt Water Intrusion Conference.

Taborosi, D., J. W. Jenson, and J. E. Mylroie. 2004. Karren features in island karst: Guam, Mariana Islands. Zeitschrift fur Geomorphologie. N.F. 48:369-389.

Vacher, H. L. 1988. Dupuit-Ghyben-Herzberg analysis of strip-island lenses. Geological Society of America Bull. 100:223-232.

Vacher, H. L., and J. E. Mylroie. 2002. Eogenetic karst from the perspective of an equivalent porous medium. Carbonates and Evaporites 17(2):182-196.

Wallis, T. N., H. L. Vacher, and M. T. Stewart. 1991. Hydrogeology of the freshwater lens beneath a holocene strandplain, Great Exuma, Bahamas. Journal of Hydrology 125:93-100.

Whitaker, F. F., and P. L. Smart. 1997. Hydrogeology of the Bahamian archipelago. Pp. 183-216 *in* H. L. Vacher and T. M. Quinn, eds., *Geology and Hydrogeology of Carbonate Islands*. Elsevier, Amsterdam.

White, W. B. 1998. *Geomorphology and Hydrology of Karst Terrains*. Oxford University Press, New York, New York.

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