DEVELOPMENT OF THE CARBONATE ISLAND KARST MODEL

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Abstract: The development of a comprehensive conceptual model for carbonate island karst began in the Bahamas in the 1970s. The use, initially, of cave and karst models created for the interior of continents, on rocks hundreds of millions of years old, was not successful. Models developed in the 1980s for the Bahamas, that recognized the youthfulness of the carbonate rock, the importance of fresh-water mixing with sea water, and the complications introduced by glacioeustatic sea-level change produced the first viable model, the flank margin cave model. This model explains the largest caves in carbonate islands as being the result of mixing zone dissolution in the distal margin of the fresh-water lens, under the flank of the enclosing land mass. The flank margin model, taken from the Bahamas to Isla de Mona, Puerto Rico, in the early 1990s, provided the first viable explanation for the very large caves there. Field work in the geologically-complex Mariana Islands in the late 1990s resulted in the development of the Carbonate Island Karst Model, or CIKM, which integrated the various components controlling cave and karst development on carbonate islands. These components are: 1) Mixing of fresh and salt water to create dissolutional aggressivity; 2) Movement of the fresh-water lens, and hence the mixing environments, by 100+ m as a result of Quaternary glacioeustasy; 3) The overprinting of glacioeustatic changes by local tectonic movements, where present; 4) The unique behavior of eogenetic (diagenetically immature) carbonate rocks; and 5) The classification of carbonate islands into simple, carbonate cover, composite, and complex categories. Current research involves the use of flank margin caves as predictors of past and present fresh-water lens configuration, the analysis of flank margin cave morphology as a measure of the processes that create them, and the CIKM as an indicator of paleokarst distribution.

Introduction

This paper is designed to present to the National Speleological Society reader an understanding of the unique and unusual types of caves and karst that form in tropical carbonate islands. It will also summarize how, for the last 35 years, we have pursued island caves around the world, and attempted to figure out why they are there, and how they formed. Given that it has been 40 years since the JCKS published an anniversary issue such as this one, the time frame is about right to present a review article that takes the reader through the development of ideas about caves and karst on islands, and what we understand today. The research began in the Bahamas, which as will be seen, was fortuitous as they represent some of the simplest carbonate islands that can be found anywhere. (We use the term carbonate island, instead of limestone island, to take note that the rocks we are dealing with contain three carbonate minerals: calcite and aragonite which are different forms (or polymorphs) of calcium carbonate, $CaCO_3$; and dolomite, a calcium-magnesium carbonate, $CaMg(CO_3)_2$.)

We explored and mapped (crudely) our first island cave, Hunt's Cave on New Providence Island, Bahamas, while on a tourist visit in 1971. As northeastern U.S. cavers, we found the heat of the caves and the ever-present biota, especially cockroaches, to be quite a shock (we came back in 1990 and mapped it properly). In 1974 we accompanied Art and Peg Palmer, of Oneonta State University, to Bermuda at the invitation of Mike Queen (then at the Bermuda Biological Station), to map caves and to examine the unusual karst processes in operation. As it turned out, Bermuda caves are somewhat unique, even among island caves, and the team could not agree on how the caves were forming. Beginning in 1976, we began making annual field trips with James Carew, now at the College of Charleston, and our students to the Bahamas, first to North Andros Island in 1976, then to San Salvador Island from 1977 to the present. The hook was set, and we have been captivated and intrigued by island caves ever since. The research began as a two steps forward, one step backward experience as our ignorance of island karst processes was slowly replaced by a growing appreciation for the specialized environment we were observing.

Early Research

For over a decade we applied the models and theories of cave development established by research on continental caves to the caves of the Bahamas, and we had little luck in

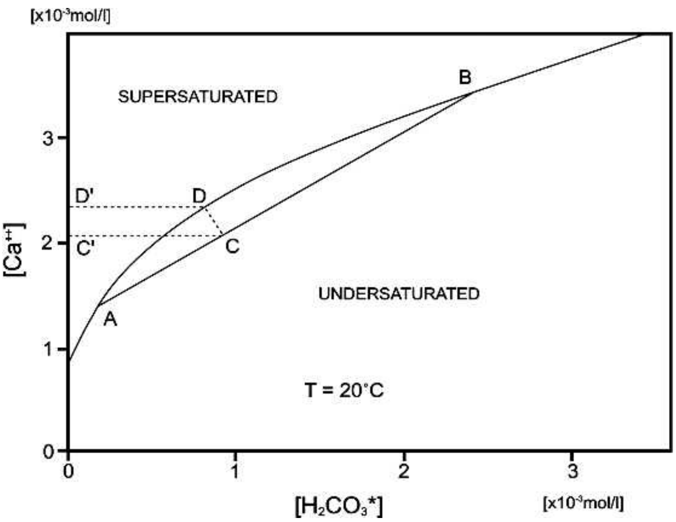

Figure 1. Equilibrium curve for $CaCO_3$, after Dreybrodt (2000). See text for explanation.

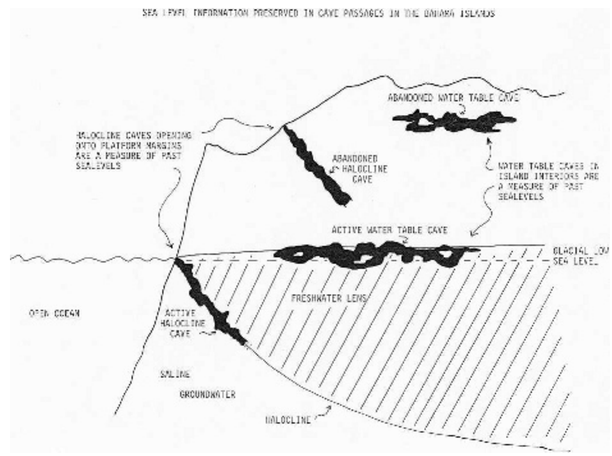

Figure 2. Figure 6 of Mylroie and Carew (1988b). This figure shows water table caves as mixing chambers and not true conduits. The halocline cave's apparent steep dip is a result of vertical exaggeration, and is shown as a conduit discharging directly to the sea. Sea level controls are also evident.

understanding what was going on. In 1991, Palmer (1991) described two major classifications of caves: epigenic caves that are coupled to the surface hydrology, and commonly have sinking streams, caves as turbulent flow conduits, and springs. The second classification was hypogenic, meaning that the cave formed by dissolution in the subsurface as a result of mixing of waters of different chemistry; these caves lack sinking stream inputs or conduits carrying turbulent flow to discrete springs because they are uncoupled from the surface hydrology. Our initial investigations treated the caves of the Bahamas as epigenic in type, although the term hadn't been published yet. We then began to consider what was unique about the island setting, and started to back away from continental theories. We recognized that sea level controlled the position of the fresh-water lens in islands, but we still were conceptually tied to the idea of continental stream caves (Carew et al., 1982; Mylroie, 1983; Mylroie and Carew, 1988a). Some of these ideas, in hindsight, are quite amusing. We also generated some papers, based on amino acid racemization (AAR) dating of rocks in the Bahamas, that attempted to portray cave development as occurring in very short time periods (Mylroie and Carew, 1986a, 1986b, 1987). It turns out that we were correct about the rapid cave development, we just had the wrong time window in the Quaternary because of the bad dates from the AAR work (see Carew and Mylroie, 1997, for a discussion of the AAR problem).

Palmer et al. (1977), drawing on the geochemical work of Bögli (1964, *in* Bögli 1980) and Plummer (1975), had advanced a theory that mixing of marine and fresh waters under carbonate islands could create an environment of enhanced dissolution, and so explain cave development on Bermuda. In the late 1970s and early to mid 1980s, Bill Back and his co-workers published a series of papers (Back et al., 1986 and references therein) that used the mixing of sea water and fresh water under carbonate coasts as a way of explaining porosity and permeability development, dolomitization, and coastline evolution in the Yucatan Peninsula. The essential geochemistry is presented in Figure 1 (Dreybrodt, 2000). Because the saturation curve for $CaCO_3$ is convex upward, waters saturated at two different initial conditions, as at A and B in the figure, when mixed create a water body, C, that is beneath the saturation curve, and so is unsaturated. This water body now has renewed dissolutional potential and will dissolve $CaCO_3$ until it again reaches the saturation curve at D. The amount of Ca^{2+} put in solution is shown by the step from C' to D'. Seawater, and the fresh-water lens in carbonate islands, are usually saturated with respect to $CaCO_3$, but they did so at different initial conditions. Therefore their mixing produces an unsaturated solution, and dissolution will create caves. It was also recognized that descending vadose water, upon reaching the top of the water table at the fresh-water lens, could also mix and create a site of renewed dissolutional aggressivity.

Examination of how these ideas could affect island karst were presented in a paper published in 1988 (Mylroie and Carew, 1988b), that focused on the migration of the fresh-water lens as sea level changed during the Quaternary (Fig. 2). An important misconception arose out of this figure. The fresh-water lens was drawn as commonly found in textbooks and research papers, that is, with vertical exaggeration that shows the halocline descending steeply downwards. However, a 1 km-wide island commonly has a fresh-water lens less than 10 m thick, so the aspect ratio is 10 m/1000 m, or 1 part in 100. The lens margin does not dip steeply. The idea of a steeply descending lens margin was reinforced by the report of cave divers Rob Palmer and Dennis Williams (Palmer and Williams, 1984), who reported that they were able to follow the halocline downwards in cave passages at a relatively steep angle. We now recognize that the existence of the cave passage distorted the flow pattern in the lens, causing the lens to utilize the cave passage as a short-cut to the sea. As sea level has migrated numerous times during the Quaternary, many dissolutional environments have been overprinted, creating a complex of dissolution voids and collapses, forming caves with a significant vertical component. It is these caves that appear to be distorting the modern fresh-water lens, as opposed to the modern lens creating the entire cave complex (the halocline cave of Fig. 2).

After a decade of fieldwork in the Bahamas, we began to see a pattern in the largest dry caves found on the islands (for a review of Bahamian geology, see Carew and Mylroie, 1995a; 1997). The large caves commonly were entered where a hillside had been breached by erosion or had collapsed. The caves were found at elevations of 1 to 7 m, which was in agreement with the position of at least one earlier sea level during the Quaternary, the last interglacial associated with Oxygen Isotope Substage 5e (OIS 5e), which lasted from 131 to 119 ka (Chen et al., 1991). This sea level reached 6 m higher than at present, as glacial ice melted back a bit more than it has today. Given that the Bahamas are tectonically stable, only a glacioeustatic sea-level highstand could have elevated the fresh-water lens above modern sea level, and so placed the fresh-water lens at, and slightly above, that elevation. Cave morphology was predictable and consistent: large chambers near the edge of the hill containing the cave, numerous ramifying passages near the back of the cave, and many cross-links and connections. Cave chambers were wider than they were high, with curvilinear and cuspate margins. Remnant bedrock pillars were common. Passages heading inland commonly ended in blank bedrock walls. As important as what the caves contained was what they did not contain: no turbulent flow markings such as wall scallops, no stream-laid sediments, no sinking stream or spring entrances. To explain these caves, we developed the *flank margin cave* model to interpret the size, shape, position and configuration of the caves (Mylroie and Carew, 1990). The name is derived from the interpretation that the caves develop in the distal *margin* of the fresh-water lens, just under the *flank* of the enclosing landmass (Fig. 3). At this location, the mixing environment of the vadose input to the water table is superimposed on the mixing environment of the fresh-water lens with underlying marine water, increasing dissolution beyond what either environment could do alone. Additionally, the lens cross section decreases at the lens margin, so flow velocities increase, transporting reactants in, and products out, faster than elsewhere in the lens (Raeisi and Mylroie, 1995). Finally, both the top of the lens, and the halocline, are density interfaces that can trap organic material. Oxidation of the organics creates CO_2 that can drive more dissolution; excess organics can create anoxic conditions and drive H_2S-mediated dissolution. The H_2S model appears supported by ^{34}S analysis of intergranular gypsum from some flank margin caves on San Salvador, which showed depletion values associated with biomediation of sulfur in anoxic zones (Bottrell et al., 1993).

Cave development by mixing dissolution in the margin of the lens, under the flank of the land mass, explained the features found in the caves (Fig. 4). The caves were not conduits, but mixing chambers, so the caves showed no evidence of turbulent flow. The greatest amount of mixing took place near the hillside, which, during an elevated sea level, was the shoreline. This action placed the largest chambers near the hillside. The ramifying and cross-linked passages represented migration of the dissolutional front inland. The large width to height ratio mimicked the shape of the distal margin of the lens. The wall morphology displayed dissolution by mixed waters, and mimicked wall and passage morphologies found in other mixed-water environments, such as the hypogenic caves of the Guadalupe Mountains of New Mexico (Palmer, 1991). Only a small amount of hillside erosion was necessary to breach into the caves, which formed initially without human-accessible entrances. It seemed that a significant puzzle regarding island cave development had been explained.

Flank margin caves were the largest, but not the only, type of cave found in the Bahamas. Two other types of dry caves were abundant. Pit caves are found all over the Bahamas, sometimes in very dense clusters, and occasionally at the top of hills. As the name suggests, these are vertical shafts that descend typically 5 to 10 m (Fig. 5). They rarely intersect flank margin caves. Their walls show classic vertical grooves formed by supercritical laminar flow of descending vadose water. During major rain events, they can be observed to efficiently collect water from the epikarst and conduct it downwards as vadose fast-flow routes. Their high density in places was initially thought, based on water budget considerations, to indicate much higher rainfall conditions at a past time. The high pit cave density is now understood to reflect competition and piracy among pit caves, such that some lose their recharge to upstream competitors (Harris et al., 1995). These caves can be complex as a result of this competition, which commonly leads to intersection of pit caves by one another. Pit caves form independently of sea level and fresh-water lens position, and can form in any exposed carbonate rock on an island.

The remaining major dry cave type is the banana hole. Banana holes are circular to oval chambers 5 to 10 m in diameter, and 1 to 3 m high, with phreatic morphologies but lacking the size and passage ramifications found in flank margin caves (Fig. 6). They are located in positions of 0 to 7 m above sea level, but laterally well away from where the lens margin would have been with sea level at

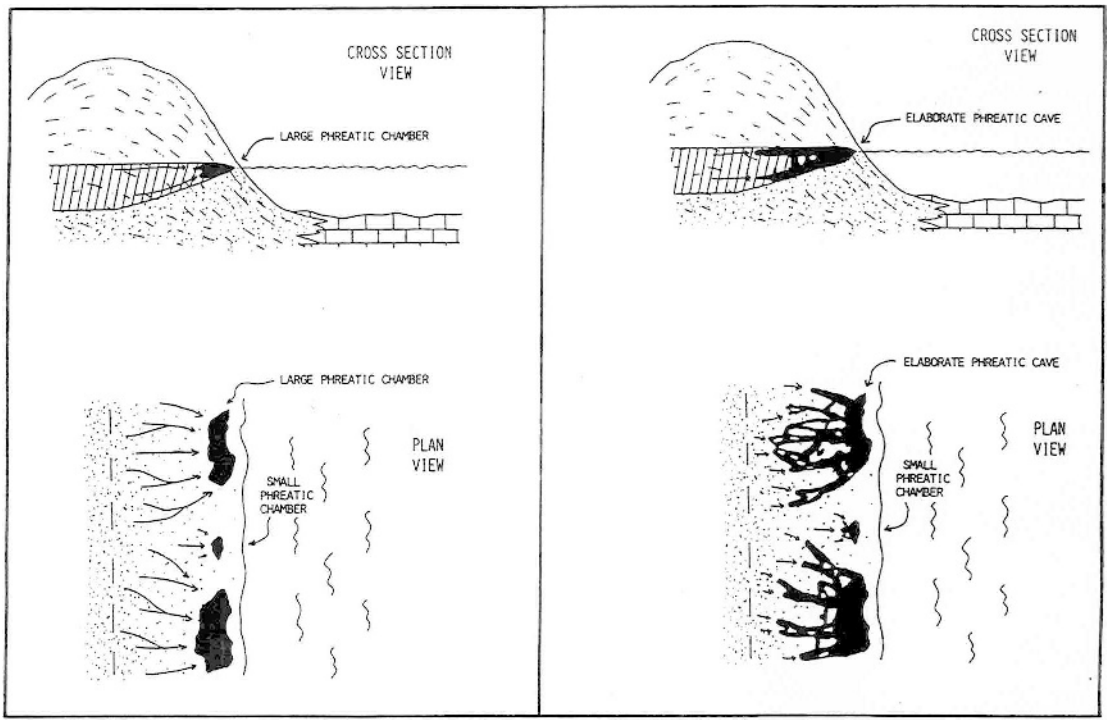

Figure 3. Figure 22 C&D of Mylroie, 1988 (reprinted in Mylroie and Carew, 1990). First display of the flank margin model, showing superposition of the mixing zones at the top and bottom of the fresh-water lens.

that elevation. They are entered where their ceilings have collapsed, or rarely where a pit cave has intersected them. They can be found in dense concentrations, up to 3000 per km^2 (Harris et al., 1995). Occasionally, a collapsed banana hole has a connection with an adjacent, uncollapsed banana hole. Their name is derived from their use to grow specialty crops, such as bananas. The collapses commonly collect soil, vegetative debris, and water, and so provide an excellent location for crop growth. Banana holes were initially thought to be vadose structures, formed by preferential dissolution in low spots on the ground surface (Smart and Whitaker, 1989). These low spots would collect extra water and organic debris, and generate CO_2 to drive dissolution at levels above what could be supported by simple meteoric water on adjacent, higher areas. The presence of wall morphologies of a phreatic nature, and the discovery that chambers with intact roofs existed, required that another explanation be considered. Downward-working vadose processes could not be invoked for roofed chambers showing phreatic morphology. Dissolution at the top of the fresh-water lens, by mixing of the lens water with descending vadose water, appears to be the mechanism (Harris et al., 1995). The dominant occurrence of banana holes has been in the Bahamas, which can be explained by considering the relief of those islands. Much of the Bahamas are a lowland plain 6 to 8 m above sea level. San Salvador, for example, is 49% such topography (Wilson et al., 1995). During the last interglacial, the fresh-water lens would have been very close to the land surface, such that the phreatic dissolutional voids formed by vadose water/fresh-water lens mixing would have had very thin roofs, in the order of 0.5 to 2 m thick. These voids would be prone to expression by collapse. Once drained by sea-level fall and open to the surface, they may have enlarged by the vadose organic-mat mechanism envisaged by Smart and Whitaker (1989). The lack of banana hole reports from carbonate islands other than the Bahamas may reflect the greater relief of those islands, such that banana hole voids are roofed by tens of meters of rock, and do not express by collapse. The occasional low and wide phreatic chambers found in deep quarries and high road cuts in the interior of islands such as Guam may represent banana holes.

In addition to the dry caves of the Bahamas, there are many caves that are under water and are accessible only by cave divers. The most spectacular of these are the famous blue holes, which can range from little more than ponds, to sensational deep shafts and kilometers-long cave systems (Fig. 7). Unlike flank margin caves and banana holes, which had to be generated in the relatively short time that sea level has been above modern levels, blue holes reflect the accumulated speleogenesis of many sea-level oscillations. During sea-level lowstands, vadose speleothems such as stalagmites and flowstone grew in what were air-filled shafts and caves. The U/Th dates of these formations range from 15 ka back to the limit of the U/Th technique at 350 ka (Carew and Mylroie, 1995b). The fresh-water lens and its mixing zones have passed up and down the section of rock containing the blue holes many times during the

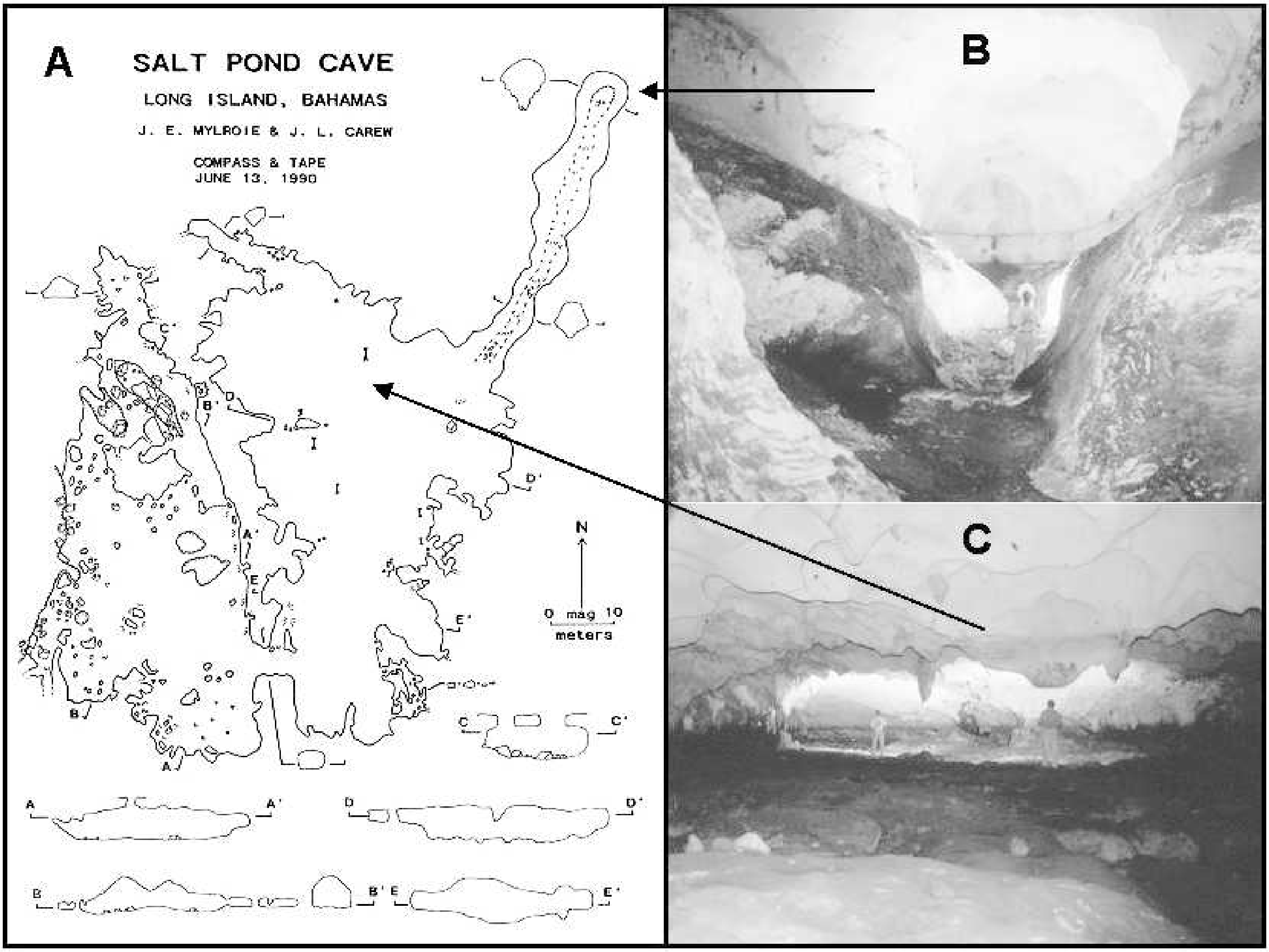

Figure 4. Salt Pond Cave, Long Island, Bahamas. A) Map of the cave, showing passage shape and configuration. B) Interior of Salt Pond Cave, showing a long, tubular passage ending in a blank bedrock wall; the site of the dissolution front when sea level fell at the end of the last interglacial sea-level highstand. C) Interior of Salt Pond Cave, demonstrating the great width relative to height in flank margin caves, indicative of their formation in the thin distal margin of the fresh-water lens.

Quaternary. The amount of over-printing by fresh-, mixed- and salt-water environments, vadose conditions, and collapse is immense. Because of the extensive use of blue holes by recreational divers, in the late 1980s there was confusion about what a blue hole was and how they should be defined. After consulting with Bahamian blue hole explorer Rob Palmer, cave scientist Pete Smart, and Bahamas geographer Neil Sealey, the following definition for blue holes was proposed (Mylroie et al., 1995a, p. 225): "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 submerged cave passages." As blue holes can be found in island interiors, or in lagoons, a further description was added: "ocean holes open directly into the present marine environment and contain marine water, usually with tidal flow; inland blue holes are isolated by present topography from marine conditions, and open directly onto the land surface or into an isolated pond or lake, and contain tidally-influenced water of a variety of chemistries from fresh to marine" (Mylroie et al., 1995a, p. 225). A different approach to defining and describing blue holes can be found in Schwabe and Carew (2006). Blue holes are polygenetic, forming by drowning of pit caves, flank margin caves and banana holes; by progradational collapse; by bank margin failure; and by marine flooding of paleoconduits (Fig. 8). Blue holes are known to react to tides, sometimes with strong currents, especially for ocean holes. Smaller holes, found on inland water bodies in the Bahamas, have been called lake drains (Mylroie et al., 1995b). These are very cryptic features that help regulate

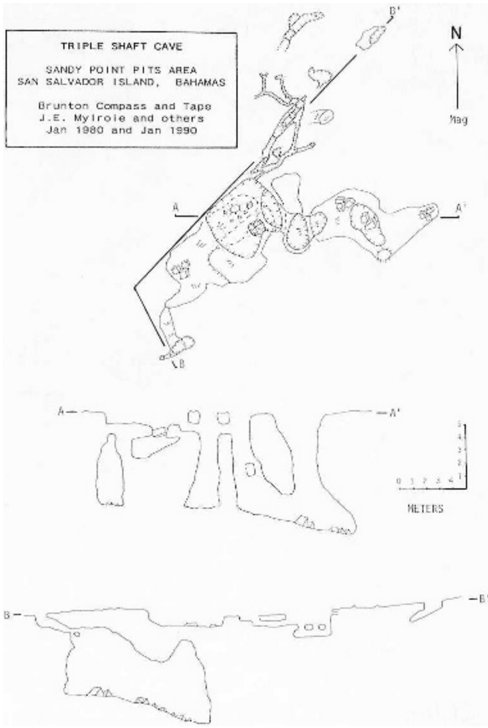

Figure 5. Triple Shaft Cave, a pit cave complex, San Salvador Island, Bahamas. Meteoric water collected in the top few meters of the epikarst passes downward through the vadose zone, forming pit caves, which compete and interact to produce complexes as shown here.

the salinity of inland water bodies by supplying normal salinity sea water, but their nature and configuration is unknown.

THE SECOND RESEARCH PHASE

As noted earlier, the Bahamas, with their youth, relatively simple geology, and lack of tectonics were a good starting point to figure out the complexities of cave and karst development in carbonate islands. The record of cave genesis for the dry caves of the Bahamas was well understood, but questions remained about what had happened during the sea-level oscillations of the Quaternary. The first opportunity to examine this question came in the early 1980s, when the Johnson SeaLink submarine was made available to researchers on San Salvador Island (Carew and Mylroie, 1987). Dives were made on the wall of the carbonate bank on which San Salvador rests, to a depth of 1000 feet (305 m; the depth gauge of the submarine was calibrated in feet, as are U.S. scuba diver depth gauges, so those units are reported first here). The purpose was to locate possible horizons of cave openings that might reflect past sea level, and hence fresh-water lens, positions. In the 1980s, studies from blue holes showed that they did not exceed 300 feet (~90 m) in depth. That depth value was taken in some quarters as an indication that the maximum sea-level lowstand was at −300 feet (~ −90 m), and hence blue holes did not penetrate any deeper. Subsequently (Wilson, 1994), Dean's Blue Hole on Long Island, Bahamas was found to be an astounding 660 feet (201 m) deep, indicating that there was no geologic floor to blue hole depth. Drilling records indicated large voids as deep as 4,082 m (Meyerhoff and Hatten, 1974). The submarine dives were another means of checking the blue hole data. The dives did not examine the wall of the island at depths above 200 feet (~60 m), as modern coral overgrowth obscured the bedrock wall. Caves were found 13 times at a depth of 343 feet (105 m), and twice more at 412 feet (126 m), but nowhere else between 200 feet and 1000 feet depth (Carew and Mylroie, 1987). These data suggest a sea-level lowstand at those depths. The 126 m depth agrees with the oxygen isotope sea-level curve, which indicates the maximum eustatic sea-level lowstand in the Quaternary to be about −125 m. The implication of these observations is that during Quaternary sea-level oscillations, sea level is rapidly changing, either rising or falling in response to ice volume change on the continents, and therefore the fresh-water lens is never in one spot long enough to develop large, observable flank margin caves. Only when sea level has reached a peak (as during the last interglacial, OIS 5e), or reached a trough, and sea level must then reverse its position to make the next oscillation, is the fresh-water lens at one position long enough to make flank margin caves. The trouble with the caves found by the submarine is that we don't know their ages. While the Bahamas are tectonically stable, they are slowly subsiding at a rate of 1 to 2 m per 100 ka (Carew and Mylroie, 1995b). It could be argued that the observed caves could have formed at shallower depths, and have subsided to their observed location. The caves cannot be too old, however, as the steep walls of the Bahama Banks commonly fracture and fail (Daugherty et al., 1987; Mullins and Hine, 1989), and flank margin caves would be preferentially removed. The two horizons, at 105 m depth, and 125 m depth, may indicate the sea-level lowstands associated with OIS 4 (~50 ka) and OIS 2 (~20 ka), respectively.

The Bermuda caves remained a concern, as they did not fit into the cave development model created for the Bahamas, despite having very similar geology (Mylroie et al., 1995b). Similar, however, is not identical. Bermuda has two main differences from the Bahamas. First, it is in a wetter climate, which means its surface rocks erode by meteoric dissolution faster than land surfaces do in the drier Bahamas (especially San Salvador Island, which has a negative water budget). Second, Bermuda sits on a volcanic pedestal that is mantled by the carbonates that make up Bermuda's land surface. In contrast the Bahamas carbonates extend continuously to a depth of 5 km or more (Meyerhoff and Hatten, 1974). Flank margin caves are rare in Bermuda, known only from a few locations. The reason is climatic. In the higher denudation environment of Bermuda, hillsides erode more rapidly than in the

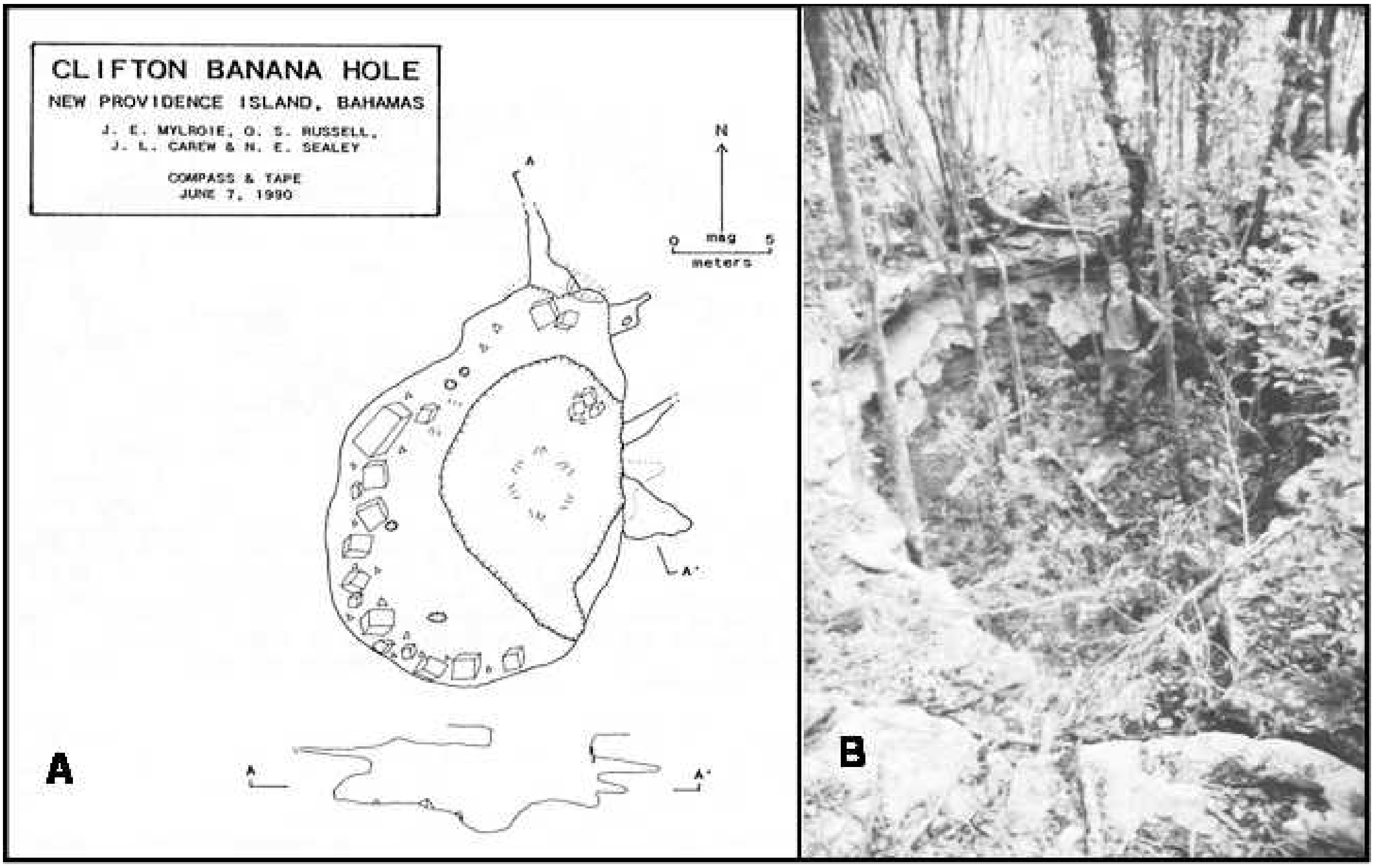

Figure 6. A) Map of Clifton Banana Hole, New Providence Island. Dissolution at the top of the fresh-water lens creates voids. B) Banana hole, unnamed, San Salvador Island; the proximity of the land surface to the top of the lens creates thin ceilings that are prone to failure by collapse.

Bahamas, and the flank margin caves formed during OIS 5e sea-level highstand, 125 ka, are now eroded away (Mylroie et al., 1995b). Their position of formation under the flank of the enclosing landmass made them vulnerable to surficial erosive processes. The famous caves of Bermuda are instead large collapse chambers, with extensive piles of breakdown that can be followed by scuba divers well below sea level. Rock surfaces showing phreatic dissolution are extremely rare in these caves. The mixing dissolution model proposed for Bermuda by Palmer et al. (1977), which proved to be the key to understanding flank margin cave development, does not seem to be the major cave-forming factor on Bermuda. The volcanic pedestal of Bermuda is now almost entirely below sea level, such that a fresh-water lens exists across the length and breadth of the island. However, during glacial ice maxima in the Quaternary, sea level would have been up to 125 m lower, and the volcanic pedestal, though mantled by carbonates, would have been above sea level, partitioning the fresh-water lens. Descending vadose water would have hit the carbonate/volcanic contact, and followed the topography of that interface downward to the fresh-water lens. Such aggregation of water as traditional stream passages would have created large chambers. It is the subsequent collapse of these chambers, and their progradation upward to the elevations seen today, that have created the unique caves of Bermuda (Mylroie, 1984; Mylroie et al., 1995b).

In 1992, at the invitation of Joe Troester of the U.S. Geologic Survey, research began on Isla de Mona, Puerto Rico, located in the Mona Passage halfway between Puerto Rico and the Dominican Republic. Mona is located very near the boundary between the North American plate and the Caribbean plate, and so is in a tectonically active area. The island itself has been uplifted such that it has vertical cliffs on three sides, which are up to 80 m high (Fig. 9). The island is entirely carbonate, as a limestone unit overlying a dolomite. Our initial interest in Mona was that it looked today, because of tectonic uplift, as San Salvador would have looked 20,000 years ago during the glacial ice maximum, when sea level was far below today's position. We knew from published reports that it had many large caves, and we thought the flank margin model might apply, as earlier reports had obviously been uncertain how the caves formed. Jim Quinlan (Quinlan, 1974) had described the caves as phantasmagorical, and reluctantly

Figure 7. Deans Blue Hole, Long Island, Bahamas. This blue hole is the deepest in the Bahamas at 200 m. Its position in a lagoon makes it an ocean hole, subject to direct marine influence. People on far cliff for scale.

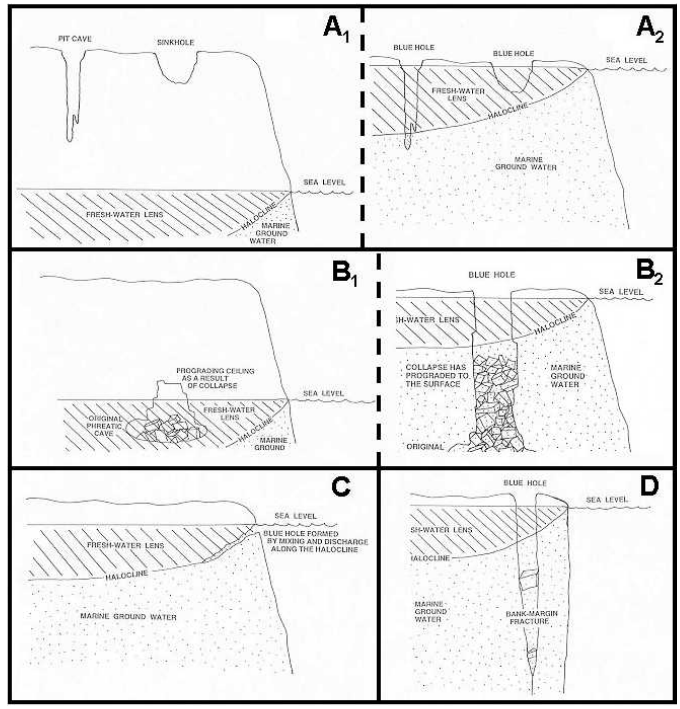

Figure 8. Four ways in which blue holes could form. A) By flooding of sinks and pits. B) By progradational collapse of deep voids. C) By bank margin failure. D) By flooding of conduit caves; note here the vertical lens exaggeration mentioned in Figure 2, still creating the incorrect impression. Adapted from Mylroie et al., 1995a.

placed them in the sea cave category, as he recognized that the caves were not traditional turbulent-flow conduits. Upon field examination, we determined the caves were clearly flank margin caves (Frank et al., 1998), but at an immense scale. The Lirio Cave System eventually mapped out at 20 km, and wrapped around the curving edge of the island (Fig. 10). The question then became why were the caves so large? Caves of over 1 km of linear survey are known in the Bahamas, but 20 km was astounding. The answer lay in the age of the caves. Working with Bruce Panuska, from our Geosciences Department (Panuska et al., 1998), we established, based on paleomagnetic reversal patterns in cave sediments and speleothems, that the caves were at least 1.8 million years old. The caves had developed in the Pliocene, before the onset of the high amplitude, short wavelength sea-level oscillations that characterize the Quaternary. Therefore sea level, and fresh-water lens position, had been stable at a given horizon for a much longer time than had been available in the younger rocks of the Bahamas. This longer time of lens stability had allowed extremely large flank margin caves to develop. Uplift then had placed the caves far above the influence of Quaternary sea-level change, effectively preserving the caves. The Bahamas demonstrated that significant flank margin caves could form in short time windows of approximately 10,000 years. Mona showed that once formed, such caves could survive for more than a million years. Flank margin caves are high-resolution, long-duration repositories of speleological information.

The work in Bermuda and the Bahamas was summarized in Mylroie et al. (1995b) and the Isla de Mona work was summarized in Mylroie & Carew (1995) and in Frank et al. (1998). One of the results of this early work was the recognition that closed contour depressions (commonly labeled in karst areas as sinkholes, uvalas, poljes, etc.) in these young islands were primarily constructional. That is, the depressions were the result of differential deposition of the carbonate rock to create closed contour depressions that drained by karst processes and therefore avoided becoming lakes and ponds. In the Bahamas, the swales between large carbonate eolian dunes had the appearance of very large closed depressions covering thousands of square meters. In other cases, the closed depression was a former lagoon, developed during the 6 m sea-level highstand of the last interglacial (OIS 5e), and now drained because sea level is not as high as it was at 125 ka. Most sinkholes in the 1 to 10 m diameter range found in the Bahamas are cave collapses, the majority a result of banana hole formation that was discussed earlier. The Bahamas differ from continental karst not only in the caves, but also in the depressions. Whereas most depressions, large and small, in continents are the result of dissolutional processes acting from the surface downward, in the Bahamas the large depressions are constructional and the small ones are collapse features from dissolution acting at a variety of depths, in a hypogenic mode.

Figure 9. Uplifted north side of Isla de Mona, Puerto Rico. Cliff is 70 m high, with flank margin caves visible at the top, along the limestone/dolomite contact.

The Current Research Phase

In 1997, John Mylroie was asked to present a keynote address on "Land Use and Carbonate Island Karst" at the *Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst* held in Springfield, Missouri in April of that year. The paper published from that conference (Mylroie and Carew, 1997) made the first attempt to view karst development on carbonate islands as a result of a predictable hierarchy (Fig. 11). The differences between some types of island cave and karst development could be attributed to interactions (or the lack thereof) of carbonate rocks with non-carbonate rocks that are commonly found on many islands. The announced presentation on carbonate island karst induced John Jenson, of the Water and Energy Resource Institute of the Western Pacific (now the Water and Environmental Research Institute, or WERI) at the University of Guam, to attend the conference to talk about his karst land use problems in Guam. From that meeting began a fruitful collaboration to investigate the tectonically active, geologically complex carbonate islands of the Mariana Archipelago.

Work in the Mariana Islands began on Guam in July of 1998. As with Isla de Mona, the carbonate rocks in the Marianas, while Cenozoic, were older than those of the Bahamas, and tectonic uplift played an important role. Unlike Isla de Mona, however, non-carbonate rocks outcropped on the surface. These outcrops created allogenic recharge, which upon reaching the contact with carbonate rocks, formed sinking streams, stream caves, and cave springs; typical epigenic caves. Guam provided field proof of the predicted third island category from Fig. 11C. In the vicinity of non-carbonate outcrops, allogenic water created caves similar to what can be found on continents. In the carbonate outcrop at a distance from those non-carbonate rocks, autogenic recharge controlled karst development. And in the carbonate coastal areas, classic flank margin cave development dominated. Isla de Mona, while tectonically uplifted, did not show any evidence of uplift in the last 125 ka (Frank et al., 1998). Guam and the other Mariana islands showed evidence of uplift throughout the Quaternary and up to the present day (Dickenson, 1999). The Mariana Islands presented an island karst environment of much greater complexity than had previously been studied. The field work, done in collaboration with John Jenson and his students, resulted in the first comprehensive interpretation of cave and karst development on Guam (Mylroie et al., 2001). The M.Sc. thesis from the Guam work by Danko Taboroši (Taboroši, 2000) instigated a series of publications addressing karren formation (Taboroši et al., 2004), cave development and distribution (Taboroši et al., 2005), and speleothem formation (Taboroši, 2006) as part of a Ph.D. program at Hokkaido University. The Marianas work continued on to Saipan (Wexel et al., 2001), Aquijan (Stafford et al., 2004), Tinian (Stafford et al., 2005), and Rota (Keel et al., 2006) islands, culminating in a review article of the caves and karst of the Marianas Archipelago (Jenson et al., 2006). The Saipan work (Jenson et al., 2002) resulted in a modification of the island category hierarchy to include a fourth category, the complex island, to represent situations in which complex faulting, and syndeposition of carbonates and volcaniclastics resulted in very complex compartmentalization of the fresh-water lens. One of the unusual outcomes of such compartmentalization is protection of water resources from upconing and saltwater intrusion during aquifer pumping. Another unexpected

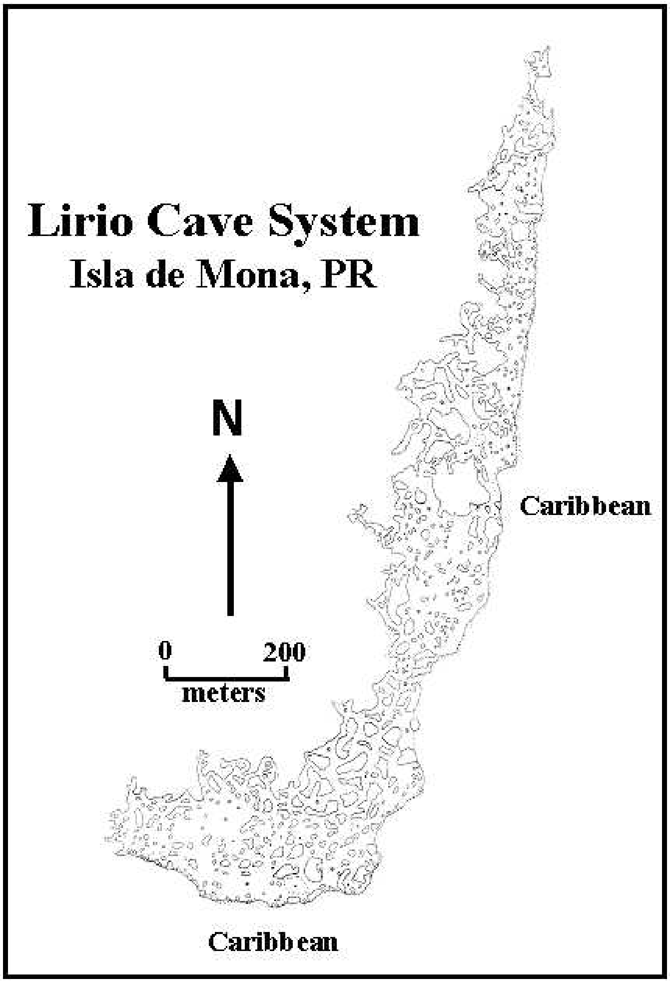

Figure 10. Map of the Lirio Cave Complex, Isla de Mona, Puerto Rico. Note that the cave is maze-like, with larger chambers towards the coast; that the cave does not penetrate very far inland but does wrap around the island coastline.

outcome was the development of confined aquifers, creating phreatic lift tubes to carry water out of the aquifer compartment, as in Kalabera Cave, Saipan (Jenson et al., 2006).

The island categories (Fig. 11) established in Mylroie and Carew (1997), were modified in Mylroie et al. (2001) to reflect advice from H. Len Vacher at the University of South Florida (Mylroie and Vacher, 1999) that not all carbonate islands showing non-carbonate outcrops had the carbonate rocks as a rim, so the third category was modified from carbonate-rimmed island to composite island. That action, and the addition of the complex island category resulted in the creation of a new, four panel figure to express the island type hierarchy (Fig. 12).

Understanding of water flow dynamics in carbonate islands had been pioneered by H. Len Vacher (e.g., Vacher, 1988). The key to that work was the recognition that carbonate aquifers are unique in hydrology in that they are capable of extensive self-modification through dissolutional and depositional processes involving $CaCO_3$. This self-modification is extremely important in the young carbonate rocks that make up carbonate islands today. One of the unexpected outcomes of this work was that the longer a fresh-water lens sat in a given section of young carbonate rock, the more permeable the rock became. As shown in Figure 2, the fresh-water lens exists because a slope, or head, of water is needed to drive the meteoric water collected at the water table to the island perimeter. The less permeable the rock, the steeper the necessary slope (as an analogy, consider a car on a slope; if the axles are rusted, it takes a steep slope to move the car; if the axles are greased, the car moves on a gentler slope). As the fresh-water lens floats in a 1 to 40 ratio based on its density difference with sea water (1.000 versus 1.025 g cm^{-3}), the lens is 40 times as thick below sea level as it is above sea level as a result of buoyancy. Therefore, as the lens becomes more permeable by dissolution, its slope becomes less, its elevation above sea level becomes less, so its thickness becomes less. In the Bahamas, the thickest fresh water lenses are found in the recent Holocene sands (Wallis et al., 1991). While these sands have very high primary porosity, that porosity is not organized into high permeability, and the lens is relatively thick as water flow is not efficient. In the adjacent, older Pleistocene rocks, which may have seen two or more sea-level highstands and associated fresh-water lens events, the permeability is higher and the lens is thinner. Building on these studies, Vacher and Mylroie (2002, p. 183) defined the term eogenetic karst as "the land surface evolving on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis." The term eogenetic was derived from Choquette and Pray's (1970, p. 215) studies of rock age and diagenesis; they defined "the time of early burial as eogenetic, the time of deeper burial as mesogenetic, and the late stage of associated with erosion of long-buried carbonates as telogenetic." Most karst in continental settings is the result of dissolutional processes acting on telogenetic rocks, rocks that are diagenetically mature, recystallized, and lack significant primary porosity. In eogenetic karst, caves are created directly within the eogenetic rocks, bypassing diagenetic maturation, uplift, and telogenetic dissolution (Fig. 13).

The parameters that controlled the development of karst on islands were initially outlined by Mylroie and Vacher (1999) and codified as the Carbonate Island Karst Model, or CIKM, which first appeared by that name after the initial study of Guam (Mylroie and Jenson, 2000; Mylroie et al., 2001). The CIKM has been tweaked and modified over the years. The principles of the CIKM include:

1. Mixing of fresh and salt water at the boundaries of the fresh water lens results in a localized area of preferential porosity and permeability development. Collection of organics at these boundaries may also

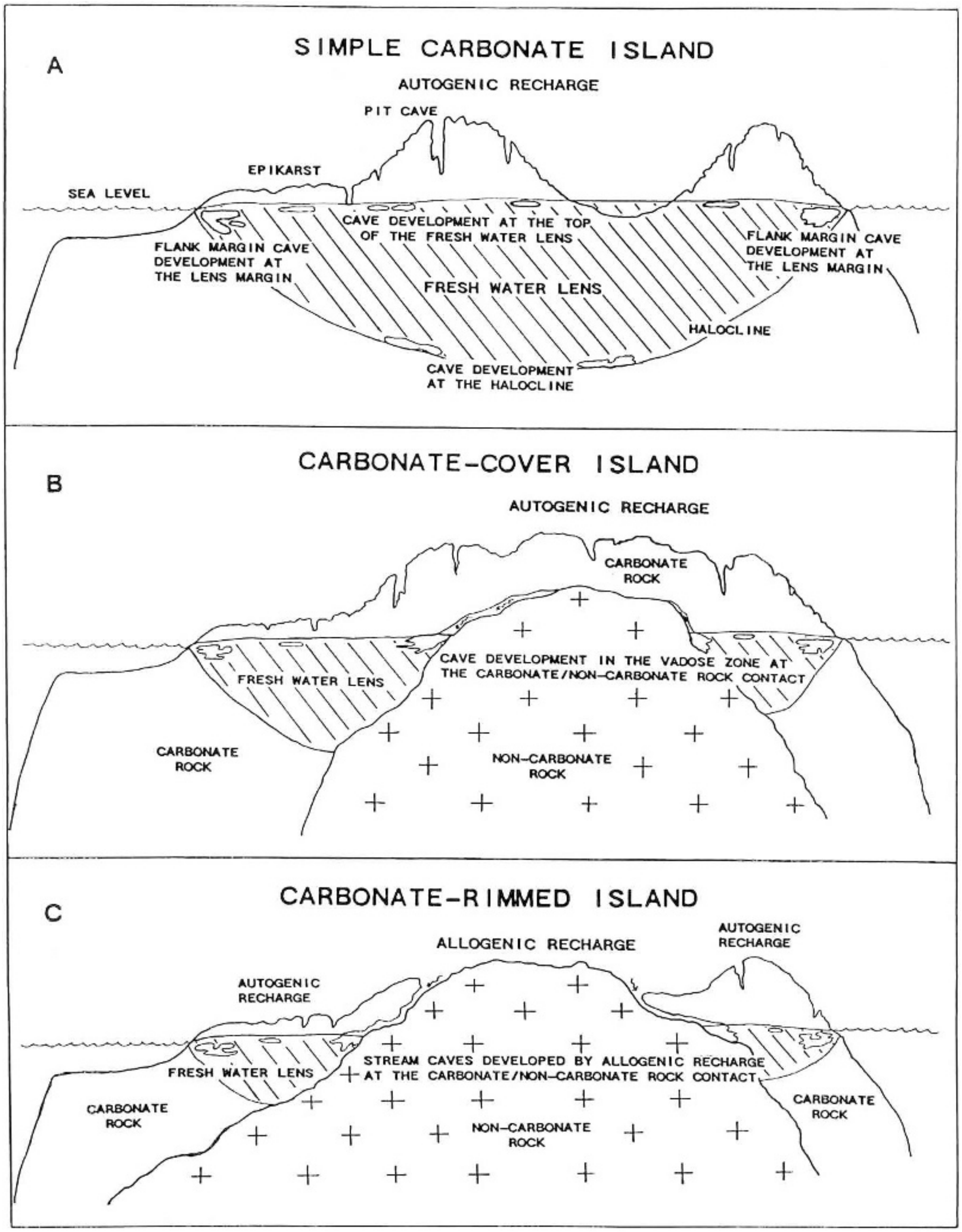

Figure 11. First presentation of a karst classification of carbonate islands, from Mylroie and Carew (1997). The Bahamas fit the (A) Category, Bermuda (at sea-level lowstands) fits the (B) Category, and Guam fits the (C) Category.

enhance dissolution. The maximum dissolution occurs at the lens margin, where the water table and halocline mixing zones are superimposed.

2. Glacioeustacy has moved sea level, and thus the fresh water lens position, up and down more than 100 m throughout the Quaternary.
3. Local tectonic movement can cause overprinting of dissolutional and diagenetic features developed during different glacioeustatic events.
4. The karst is eogenetic in that it has developed on rocks that are young and have never been buried below the zone of meteoric diagenesis.
5. Carbonate islands can be divided into four categories based on basement/sea level relationships (Figs. 11 and 12).

   A. Simple Carbonate Island—Only carbonate rocks are present (Fig. 11A). Meteoric catchment is

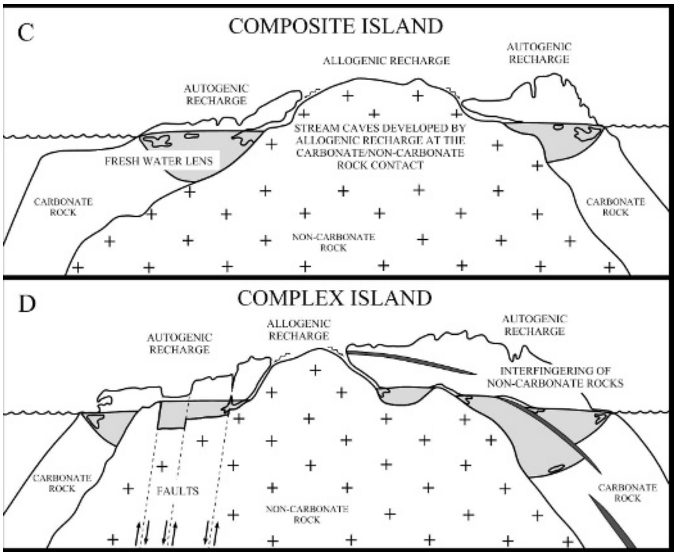

Figure 12. Updated karst classification of carbonate islands, changing Figure 11C from carbonate-rimmed island to composite island, and adding a new category, the complex island, best represented by Saipan.

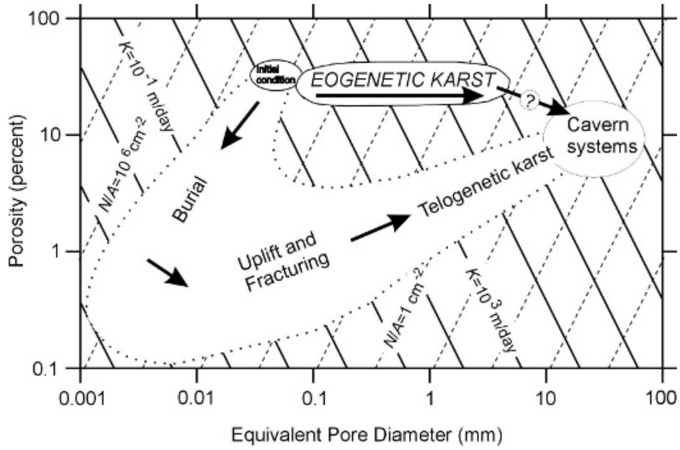

Figure 13. The evolution of eogenetic karst. Slanting solid lines are hydraulic conductivity, K, in m/day. Slanted dashed lines are tube density (number of tubes per unit area, or N/A), a measure of the degree of enlargement of the pore structure (with a consequent decrease in pore number). Eogenetic karst takes a short cut from the original depositional environment to cave development without going through burial, massive diagenesis, and uplift. After Vacher and Mylroie, 2002.

entirely autogenic and flow within the fresh water lens is controlled entirely by properties of the carbonate rock. The Bahamas are examples of simple carbonate islands.

B. Carbonate-Cover Island—Only carbonate rocks are exposed at the surface and the catchment is entirely autogenic (Fig. 11B). Non-carbonate rocks exist under carbonate rocks and may partition and influence flow within the lens, including conduit flow at the contact. Bermuda, at a sea-level lowstand, is an example of a carbonate-cover island.

C. Composite Island—Both carbonate and non-carbonate rocks are exposed at the surface (Fig. 12), allowing for allogenic and autogenic catchment. The lens is partitioned and conduit cave systems can develop at the contact of the carbonate and non-carbonate rocks. Barbados and Guam are examples of composite islands.

D. Complex Island—Carbonate and non-carbonate rocks are complexly interrelated by depositional relationships and/or faulting (Fig. 12). Perching, isolation, and confining of the fresh-water lens is possible. Saipan is an example.

Vacher and Mylroie (2002) also differentiated between island karst, and karst on islands. Island karst develops under the influence of the CIKM. Karst on islands develops in uplifted regions of island interiors, and behaves much the same way as karst on continents at the same latitude. The flank margin caves of Isla de Mona or the Bahamas are examples of island karst. The cockpits of Jamaica, or the mogotes of Puerto Rico, are examples of karst on islands, as they are isolated from glacioeustasy and fresh water/salt water mixing. They are similar to the karst landforms of Belize, a tropical but continental setting.

The karren (dissolutional sculpture at the centimeter to meter scale) of carbonate islands differ from those found in continental interiors of the mid to high latitudes, where most karren research has been done. The jagged, pitted and irregular karren of the coastal environment of tropical carbonate islands is well known, and the classic study is by Folk et al. (1973). That work, and many later works (e.g., Viles, 1988) ascribed the unique nature of this island karren to marine spray, boring endolithic algae, and grazing by gastropods, among other reasons. Folk et al. (1973) called it *phytokarst*, based on the large degree to which the endolithic algae had penetrated and permeated the rock surface. Taboroši et al. (2004) were able to demonstrate that the key factor was the eogenetic nature of the rock. The lack of diagenetic maturity made all weathering processes, organic and inorganic, responsive to the texture, composition, porosity, and cementation of the allochems (particles) that made up the young carbonates. Taboroši et al. (2004) called such karst etching eogenetic karren. Endolithic algae were able to colonize such weak and porous rock in high abundance, which initiated the entire organic aspect of karren development in the coastal carbonates of tropical islands. Endolithic algae do not colonize dense, recrystallized teleogenetic rocks to a similar extent. On southern Guam, in the interior away from CIKM effects, are limestone units ranging in age from

Oligocene to Pliocene. Analysis of these rocks and their karren showed that as diagenetic maturity increased, the karren became less distinctive as eogenetic karren, and resembled more closely the telogenetic karren of continental interiors (Taboroši et al., 2004).

Future Research

The current state of affairs regarding island karst is very promising. One of the interesting applied research areas is the potential for island karst to be preserved as paleokarst in the rock record, therefore becoming a host for mineralization or hydrocarbons. As eogenetic carbonate rocks are found proximal to their environment of deposition, all that needs to happen to preserve those rocks, and any included karst features, is for subsidence to lower them and continued carbonate deposition to bury them. To preserve an existing telogenetic conduit cave system in a continental interior setting would require major adjustment of plate tectonic motion, to depress the landmass and allow burial to occur. While all this plate adjustment was occurring over millions of years, the existing cave system would need to avoid destruction by erosion. It is clear that eogenetic karst is predisposed to preservation, and that paleokarst in the rock record is most likely former eogenetic karst.

To locate and assess paleokarst in the subsurface, it is important to determine what to search for. Imagine a large carbonate unit in the subsurface, a disk 100 m thick and 10 km in diameter, once exposed at the earth's surface and subjected to karst processes, and now buried. If one assumes telogenetic, conduit cave karst, then one looks for voids extending from the center of the disk to the margin in a few places, as conduit caves that drained the interior of the feature. If one assumes that eogenetic mixing zone karst was active, then one looks for dissolutional voids spaced around the perimeter of the feature. There is a 90° difference in search strategy depending on which model is chosen.

The unique pattern of flank margin caves has called attention to how they develop. Unlike teleogenetic conduit caves, for which a large and extensive data base exists, the eogenetic island cave data base has been built from scratch over the last three decades by a very small group of workers. As a result, until recently the patterns that drive eogenetic caves such as flank margin caves were not easily interpreted. A rank order plot of flank margin caves based on areal footprint (Fig. 14), from the Bahamas, shows that the caves self-select into three size categories (Roth et al., 2006). Areal footprint, or cave area, was selected as the size determiner because it is the best measure of how much dissolution has occurred. Given that flank margin caves form in the distal margin of the fresh-water lens, their vertical variation is minimal as the lens is so thin at that location. Calculating area using the outside perimeter, and removing the area of any inner bedrock pillars, creates

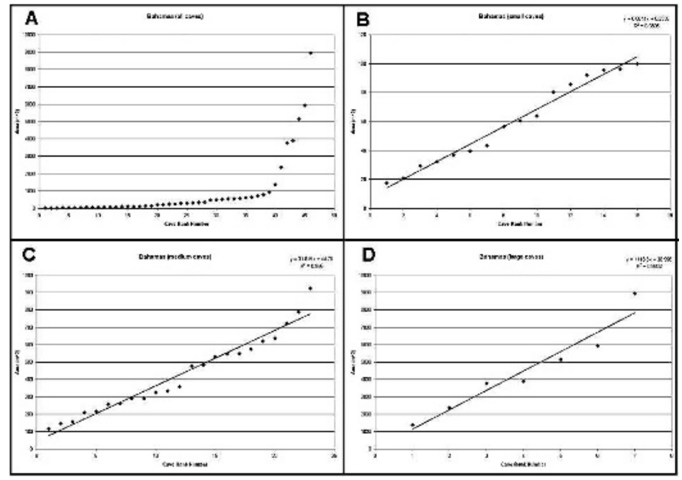

Figure 14. Rank order plots of flank margin cave size (as determined by areal footprint). A) Complete plot, which has 3 straight line segments, each reproduced in (B) small caves, 100 m^2, R^2 = 0.9805, slope = 6.024; (C) medium caves, 100–1000 m^2, R^2 = 0.956, slope = 31.815; and (D) large caves, over 1000 m^2, R^2 = 0.9302, slope = 1,113.3. The line slope changes indicate the point at which major cave chamber intersections occur, creating a jump in cave size. From Roth (2004).

a measure of the amount of dissolution. For stream caves in telogenetic settings, cave length is a good measure of the amount of dissolution, as those caves are very long compared to their widths.

Flank margin caves begin as tiny voids that grow through time. As the dissolutional environment is restricted to the edge of the lens, this dissolution occurs in a band that runs from the coastline of the island inland just a few tens or hundreds of meters. In such a setting, the growth of small voids can continue, but at some stage, adjacent voids, of various sizes, will intersect. When they do, cave size then makes an immediate jump in size. As these cave clusters continue to grow, they then intersect other clusters, and there is again a large jump in cave size. Fig. 14 shows three straight line segments, with slopes that are approximately the square of the previous slope, that represent small (100 m^2 or less), medium (100–1000 m^2) and large caves (over 1000 m^2). The data indicate that as small dissolutional voids grow at random in the thin lens margin, their amalgamation occurs as discrete steps, even though within each size category there is a wide range of sizes depending on the initial size of the individual chambers, and how many became connected. Dissolution continues after chamber amalgamation, and such amalgamations have a greater chance of adding to chambers by connection than the smaller size class does. Computer modeling of this cave generation procedure generates line slopes that are identical to the empirical database (Labourdette et al., 2006), but include a 4th set at 1–2 m^2 in area. This 4th small

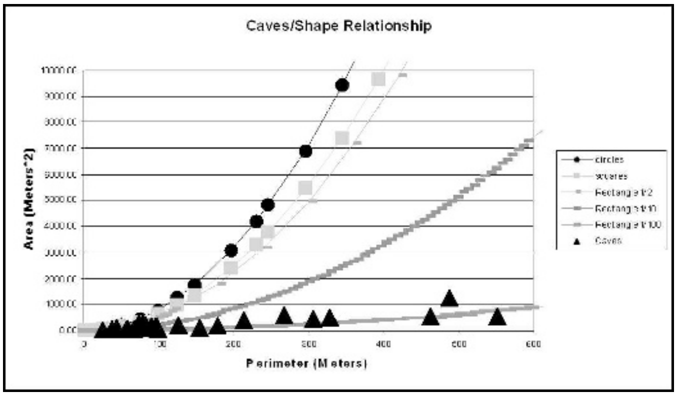

Figure 15. Plot of flank margin cave perimeter versus area, compared to standard geometrical objects. Globular dissolution chambers would expect to plot as a curve, much like circles and squares do. The high degree of perimeter complexity, produced by intersection of dissolutional voids, creates a linear plot instead, approximating a rectangle with a 1 to 100 aspect (width to length) ratio. From Roth (2004).

area group does not appear in the island data base as voids that small are not mapped as caves.

A further test of cave growth by aggregation of smaller caves can be done by plotting cave area versus cave perimeter. For these data, the internal area of bedrock columns and "islands" was removed from the areal footprint, but the perimeter of such internal features was retained, as it was a water-rock contact during cave development. As the perimeter grows linearly (m), but area by the square (m^2), simple geometric shapes produce an exponential curve as they get larger (Fig. 15). Flank margin caves, however, plot as an approximate straight line, which indicates their perimeters must be progressively more complex as the caves increase in size, compensating for the increase in area by the square. The easiest way to create this perimeter complexity is to aggregate smaller cave clusters to create a ramiform pattern, supporting the data created by the rank-order versus area plot (Fig. 14). Flank margin cave growth by cave aggregation is much different than conduit cave growth by surface water capture, further reinforcing how different island karst is from continental karst.

Area issues work not only at the cave level, but also at the island level. As islands get bigger, their perimeter becomes less relative to the island area. Or, in hydrological terms, the recharge area increases exponentially, but the discharge region increases only linearly. As islands get bigger, ever larger amounts of meteoric water must exit through the perimeter. For example, in an island with a radius of 1 km, its area (A) is 3.14 km^2, and its perimeter (P) is 6.28 km, for an A/P ratio of 0.5 km. If the island has a 100 km radius, A is 31,416 km^2, P is 628 km for an A/P ratio of 50 km. Mylroie and Vacher (1999) hypothesized that at some perimeter/area relationship, diffuse flow in the fresh-water lens must become inefficient, and conduit flow will initiate. Evidence of such a relationship can be seen today in the Bahamas and Bermuda. The dry flank margin caves seen today formed in hills that at a past +6 m sea level, were islands with linear dimensions of a few km. However, if sea level dropped 20 m below today's level, the broad, shallow Bahama Banks would become very large islands, with linear dimensions of hundreds of km. The same is true for Bermuda. Did this larger size cross a threshold and generate conduit flow systems? Cave divers have found long, linear conduit caves at depths of 20 to 30 m on Great Bahama Bank (Farr and Palmer, 1984), and at a similar depth on the Bermuda Platform (Vacher and Harmon, 1987). These depths are less than 60 m, and so were not observed during the submarine work on San Salvador Island. The field evidence would suggest that island size controls water flow from islands, favoring conduit flow at large island sizes.

As noted earlier, some of the most classic work on fresh water/salt water mixing and dissolution was done in the Yucatan area (Back et al., 1986). The large, complex cave systems of Quintana Roo State are known as intricate conduit systems discharging water from the interior to the sea (Smart et al., 2006). The Yucatan Peninsula can be considered a very large island, which would be expected to generate conduit flow. One question is: Does that conduit flow negate the development of flank margin caves in the areas along the perimeter where conduits are not present? Field work in the Akumal area of Quintana Roo has demonstrated that the Pleistocene coastal eolianites there contain flank margin caves (Kelley et al., 2006). During the last interglacial (OIS 5e), while the interior of the Yucatan Peninsula was discharging fresh water to the sea at depths of 10 to 20 m, an entirely different sort of cave was developing under hypogenic conditions in the distal margin of the fresh-water lens. Epigenic conduit flow caves and hypogenic flank margin caves can form and function in the same locality and at the same time.

Recent work has taken us to Fais Island, 220 km east of Yap, Federated States of Micronesia, in the far western Pacific. The island is an uplifted carbonate platform 1.2 km by 2.9 km, with elevations up to 28 m. The island obtains its fresh water from rainfall catchment, and following droughts or typhoons, suffers from water-supply problems. Research was undertaken to determine if the CIKM could assist in determining how to exploit the island's ground-water resources. The island beaches are underlain by a tightly-cemented reef flat that extends seaward, and that acts as an aquitard, restricting fresh-water lens discharge to the sea. Flank margin caves were not found in high ground behind the beaches, but only where headlands crossed the reef flat towards the open ocean. These observations indicated that fresh-water discharge in the past was directed through these headlands to bypass the low-permeability reef flats. Analysis of uplifted flank margin caves could be used as a proxy to locate preferred discharges for fresh water today. Using the lowest negative tides of the year, it was found (Mylroie et al., 2005) that ancient flank margin cave positions above modern sea level identified existing fresh-water discharge sites. It was also found that what was believed to be a blue hole or a large cave collapse feature was actually a sand-filled embayment, and a dug well from the Japanese occupation prior to WWII. As with the Holocene sand aquifers of the Bahamas discussed earlier, this sand-filled embayment had the largest amount of fresh water. In this latter case, it was the ability of the CIKM to successfully interpret a pseudokarst feature that helped address the water problem.

Summary

The development of the Carbonate Island Karst Model, or CIKM, required four major accomplishments:

1) Intellectual separation from cave and karst development models that had been produced in continental settings, in telogenetic rocks assuming conduit (or epigenic) flow.
2) Understanding the unique flow systems and geochemistry of isolated carbonate island aquifers, and applying those understandings to cave and karst development.
3) Collection of a sufficiently large data base within each island type to allow patterns to be expressed. In other words, find, explore, and map a lot of caves.
4) Study of a wide variety of carbonate island types to allow compare and contrast studies to be made. In other words, go to a lot of islands, and find, explore, and map a lot of caves.

The progression of the fieldwork from the simplest environment, in the Bahamas, to progressively more complex environments in Bermuda, Isla de Mona and the Marianas allowed the CIKM to be built modularly, expanding in a logical progression to accommodate each successive complication. If we had started our work in the Marianas, we may have well floundered for decades before piecing the puzzle together.

Cave and karst science is like any other science: discovery comes at unexpected times as a result of persistence, preparation, an open mind, and a little bit of luck. For the last 35 years we have traveled widely and sought out islands and their caves. Initially it was enough to find the caves. Then it was enough to map them. But finally, it wasn't enough until we understood why they were there. We didn't set out to become island cave and karst experts, but it sure has been fun.

Acknowldgments

Over more than three decades, our lives and our science have been uplifted by the many people who worked with us in all the many islands. Art and Peg Palmer took us on our first scientific island trip and for many years have provided friendship and scientific insight that has helped us with our work. Jim Carew has been the ultimate island partner and buddy, working with us to construct geological and karst models in the Bahamas that led to the foundation of ideas that now guide our research. Joe Troester initiated the Isla de Mona work, and was a champion of island karst. Len Vacher has been a source of solid scientific expertise and intellectual companionship that has kept us on task, aware of reality, and full of the fun of doing science. John Jenson swept us away to the Pacific, showed us what true complexity can be in islands, and been a steadfast friend and source of inspiration. Others who showed us how to think about islands in scientific terms have been great friends and colleagues: Mike Queen, Neil Sealey, Pete Smart, Fiona Whitaker, and the late Rob Palmer. We thank all the many students, graduate and undergraduate, who labored and struggled to do the field work and explore ideas about islands. We must thank Don Gerace, founder of the Gerace Research Center (GRC) on San Salvador Island (formally the Bahamian Field Station), who provided encouragement, resources, friendship, and occasional discipline and catapulted our career forward, along with Dan Suchy, Kenny Buchan, and Vince Voegeli, GRC Executive Directors. Murray State University and Mississippi State University provided us with an academic home, resources, and intellectual support to accommodate our research in distant areas. Carol Wicks and an anonymous reviewer provided helpful input. Finally, we thank the many government agencies (domestic and foreign), public workers, and private landowners in many countries and islands, who assisted us with access, permits, resources, and encouragement. The authors would also like to thank Marc Ohms for the cartography that appears in Figure 10.

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