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Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

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MODELING CARBONATE ISLAND KARST

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ABSTRACT

Carbonate islands have developed a karst hydrology different from that of continental settings, explained as the Carbonate Island Karst Model (CIKM). The principal aspects of this model are outlined below:

1) Mixing of fresh water and sea water occurs at the fresh-water lens boundaries.
2) Glacio-eustasy has moved the fresh-water lens up and down over 100 m.
3) Local tectonic movement can overprint the glacio-eustatic sea level effects, adding complexity to the record.
4) The karst is *eogenetic*, i.e., it has developed in carbonate rocks that are young and have never been buried below the range of meteoric diagenesis.
5) Carbonate islands can be divided into four categories based on basement/sea-level relationships:
   A) Simple carbonate islands (no non-carbonate rocks above sea level),
   B) Carbonate-cover islands (non-carbonate rocks above sea level, but beneath a carbonate veneer),
   C) Composite islands (carbonate and non-carbonate rocks exposed on the surface),
   D) Complex islands (faulting and interfingering of units creates complex carbonate/non-carbonate relationships).

Eogenetic carbonate rock enters the meteoric environment with uniform primary porosity and forms a fresh-water lens that approximates the Dupuit-Ghyben-Herzberg condition. Over time, preferred interconnected lateral permeability develops in the direction of the historical hydraulic gradient concurrently with cementation and occlusion of the pores not involved in the lateral flow route. This results in an anisotropic aquifer in which vertical hydraulic conductivity is diminished while lateral hydraulic conductivity is enhanced. Given a constant sea level and enough time, the lens would thin to vanishing. Quaternary glacio-eustatic cycles, and tectonic uplift and subsidence on islands in tectonically active environments, have generally precluded the development of such an end state on modern carbonate islands.

The CIKM can be visualized as a three-dimensional field, in which sea level follows the y-axis (vertical), island size follows the x-axis, and island composition follows the z-axis. Through time, carbonate deposition, tectonics, and glacio-eustasy interact to produce an island evolution trajectory. The CIKM is useful for systematic interpretation and description of island karst and aquifer evolution. For example, as sea level falls, island size increases, catchment increases, and island surface area increases relative to the island perimeter, which may cause groundwater flow in the aquifer to shift from diffuse to conduit flow. A drop in sea level may also bring the fresh-water lens into contact with the non-carbonate rocks, as in Bermuda. This partitions the lens and creates a subsurface catchment for vadose water, which funnels flow along the paleotopography of the non-carbonate rock.

INTRODUCTION

Water resource problems on carbonate islands are similar to those on all islands in that the available potable water is limited to what can be obtained by the island catchment and the local climatic conditions. Given the limited water resources on islands, degradation of water quality can have immediate and severe consequences.

Aquifers in young carbonate islands are unique. First of all, water flow through carbonate aquifers modifies the aquifer by dissolution, redistributing porosity such that flow conditions change (Vacher, 1988). The dissolution of the carbonate can also create landforms, such as caves and closed depressions, that further modify the path for aquifer recharge and transport, creating a karst environment. In continental settings, the modeling of karst aquifers requires different methods from those traditionally used in porous media flow (e.g., Palmer et al., 1999). Carbonate island aquifers in general, therefore, need to be modeled differently from aquifers on islands made of other rock types. Moreover, although karst models developed for continental settings work well on some older carbonate islands, or parts of them, such models are not appropriate for younger islands or parts of younger islands. The karst that develops in the young limestones typically found on small carbonate islands reflects dissolutional processes (e.g. mixing zone dissolution) that are different from the classical processes of karst evolution. The term "island karst", as it is generally used, therefore implies a commonality amongst carbonate islands that in reality does not exist.

An extensive literature exists on the hydrology of carbonate islands (e.g., Vacher and Quinn, 1997, and references therein), but the concepts of karst processes on carbonate islands were first developed on Bermuda and in the Bahamas (e.g., Mylroie et al., 1995; Mylroie and Carew, 1995). These islands, composed of Quaternary carbonates on stable platforms, provided controlled models for studying karst development in island settings. One of the first distinctions made was that young island carbonates, while highly porous, lack directed permeability and have lower hydraulic conductivities than older island carbonates in which dissolution and cementation had lowered porosity, but created preferred permeability pathways (Vacher, 1988; Vacher and Wallis, 1992). Over time, preferred interconnected lateral permeability develops concurrently with cementation and occlusion of the pores not involved in the lateral flow route along the hydraulic gradient, resulting in an aquifer anisotropy in which vertical hydraulic conductivity is diminished while lateral hydraulic conductivity is enhanced in the direction of the historical gradient (Vacher and Mylroie, 2002). Given a constant sea level and enough time, the lens would become thinner and eventually vanish. Such a situation has not occurred in the Quaternary because glacio-eustatic cycles have precluded this process from reaching the end state. Uplift and subsidence of islands in tectonically active environments combines with sea-level eustasy to arrest this evolution even more frequently. Such re-arrangement of porosity and permeability is not possible in the dense, diagenetically mature carbonates that make up most karst systems in continental interiors.

The distinction between "island karst" and "karst on islands" can now be made (Vacher and Mylroie, 2002). In the former, the carbonates are young and associated with their environment of deposition. In the latter, the carbonates are older and, though on an island, have characteristics of continental karst. Two of the most famous islands traditionally associated with karst processes, Jamaica and Puerto Rico, are really islands with (classsical) karst on them, following continental models. Other famous islands, such as Bermuda and the Bahamas, exhibit true *island karst.*

ISLAND KARST

Island karst results from the unique environment and associated processes that carbonates experience in island settings. Beginning with work first in Bermuda and then in the Bahamas in the 1970's, the senior author (Mylroie) attempted to outline the criteria that create island karst. The junior author (Jenson), working independently in the Mariana Islands, had difficulty reconciling the models and ideas coming out of the Bahamas with what he was observing in the geologically more complex Mariana Islands in the western Pacific. In 1997, after both authors presented their work at a conference, they began collaborating to apply the ideas developed on simple carbonate islands to more geologically-complex carbonate islands. The first comprehensive conceptual model was developed by Mylroie and Carew (1997). The initial model accounted for the presence of fresh- water/sea-water mixing and the relationship of carbonate rocks to non-carbonate rocks on islands. Mylroie and Vacher (1999) and Vacher and Mylroie (2002) subsequently revisited the implications of karst processes for the evolution of aquifers on carbonate islands, focusing on rock modification. In the meantime, the initial Mylroie and Carew model (1997) has incorporated changes from work in the Pacific, developing into the Carbonate Island Karst Model (CIKM) in 2000 (Mylroie and Jenson, 2000a,b; 2001; Mylroie et al., 2001). The model now includes a number of factors that center on three main elements: fresh- water/sea-water mixing, sea level, and rock characteristics.

Fresh-Water/ Sea-Water Mixing

Because the calcium carbonate saturation curve is convex upward, mixing of two saturated waters at different initial conditions forms a new solution below the saturation curve, and hence with renewed dissolutional capability. While this had been applied to freshwaters as a mechanism to explain cave formation (e.g., Bogli, 1964), Plummer (1975) applied it to the mixing of sea water with fresh or brackish water. These ideas were applied to Bermuda to explain cave formation (Palmer, et al., 1977) and to the Yucatan, Mexico (e.g., Back et al., 1986) to explain not only large-scale porosity development, but carbonate diagenesis as well. Mixing dissolution was applied to the Bahamas shortly thereafter (Mylroie and Carew, 1988; Smart et al., 1988) to interpret cave development. In particular, it was later shown that the most favorable site for mixing dissolution in the fresh-water lens of a carbonate island or coast was at the lens margin, just under the flank of the enclosing land mass. At this location, water flow velocity is high, as the cross-sectional area of the lens is reduced by thinning of the lens, while discharge has been integrated for the entire island catchment. In addition, the top of the lens (where vadose fresh water mixes with phreatic fresh water) and the bottom of the lens (where phreatic fresh water mixes with phreatic sea water) converge at the lens margin, focusing their mixing-dissolution potentials in close proximity to one another in both space and time. The top and bottom of the lens are also density interfaces which collect organics, whose oxidation produces CO_2 and increases dissolution capability. The voids developed in this environment have been called *flank margin caves* (Mylroie and Carew, 1990) because of their development under the flank of the island, at the margin of the lens. They are the largest dissolution voids formed in islands made entirely of carbonate rocks. They are not true conduits, but complex mixing chambers.

Sea Level

Glacioeustasy

Glacio-eustasy has repeatedly moved sea level vertically at least 130 m during the Quaternary in tectonically stable setting of islands like Bermuda and the Bahamas. Therefore the fresh-water lens, and its dissolutional environments, has similarly migrated. Initial investigations of cave development in the Bahamas tied cave development to sea level, but failed to recognize the role of mixing dissolution (Carew et al., 1982). Those investigations applied the continental "shallow phreatic" model to cave development and suggested that the caves formed preferentially at the top of the lens as traditional conduits.

Subsequent work on the flank margin caves in the Bahamas, however, showed that they formed entirely during the last interglacial (oxygen isotope substage 5e). These caves developed by mixing dissolution in a fresh-water lens that was up to 6 m higher in elevation than present sea level (and hence present fresh-water lens level). Under current conditions, the flank margin caves formed during the last interglacial are drained and dry, allowing detailed exploration and examination. Explorations by submersibles have also shown caves below sea level that correlate with

Quaternary sea-level lowstands at depths of 105 and 125 m (Carew and Mylroie, 1987).

Tectonics

In tectonically active settings, independent vertical movement of the carbonate island through the fresh water lens can overprint the sea-level record of glacio-eustasy, complicating the development and expression of caves. Tectonic uplift, however, can create field conditions that assist in understanding island karst process. Caves formed at lower lens positions and now lifted above sea level can be studied without scuba or submarines. On Isla de Mona, Puerto Rico, for example, tectonic uplift has placed the flank margin caves at 20 to 80 m elevation, well above any possible Quaternary glacio-eustatic sea level fluctuation. Vertical carbonate cliffs rise out of the sea, with flank margin caves at discrete horizons representing former lens positions. This condition is analogous to that the Bahamas may have exhibited during glacio-eustatic sea-level lowstands, when their steep-sided platforms were partly exposed.

Tectonism also can fault, fold, and tilt carbonate islands to create preferred ground-water flow paths that follow structural features in both the vadose and phreatic zones. Tectonic activity may also be associated with volcanism, which can create even more complex carbonate/non-carbonate relationships that also influence groundwater flow (see below).

Rock Characteristics

The nature of the carbonate rock that supports the aquifer containing the fresh-water lens has important implications for groundwater recharge, transport, and discharge. Lagoon, reef, and eolian facies, for example, each exhibit different aquifer properties. Dolomite and limestone aquifers also behave differently. Such differences are well recognized in rocks from continental settings, but in carbonate islands, the youthfulness of the rocks has important consequences for expressing facies differences during aquifer development. For very young rocks, significant aragonite content may be present, creating a soluble phase not available in older rocks. In fact, it is the youthfulness of the carbonate rocks that creates one of the major differences between island karst and the karst of continental interiors (or "karst on islands").

Eogenetic Karst

Eogenetic karst is defined as "the land surface developing on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis" (Vacher and Mylroie, 2002, p. 183). The term *eogenetic* is used in the sense of Choquette and Pray (1970 p. 215), who subdivided the postdepositional evolution of carbonate porosity into three time-porosity stages conforming to the rock cycle: "the time of early burial as *eogenetic*, the time of deeper burial as *mesogenetic*, and the late stage associated with erosion of long-buried carbonates as *telogenetic*". Eogenetic carbonates are in the early stage of evolution, prior to (or escaping from) burial. The vast majority of karst publications address telogenetic karst, i.e., "the karst developed on and within ancient rocks that are exposed after the porosity reduction of burial diagenesis" (Vacher and Mylroie, 2002, p. 183). Eogenetic rocks retain many of their primary characteristics, and are undergoing meteoric diagenesis as a result of post-depositional, subaerial exposure. In most cases, eogenetic rocks are young rocks, and close to the site of original deposition, such as the exposed carbonates of Bermuda and the Bahamas. The well-karsted rocks of Florida and the Yucatan (see Martin et al., 2002), while older and more altered, are still eogenetic, and the karst on them is also considered to be eogenetic, as they are still in the range of meteoric diagensis (Mylroie and Vacher, 1999). Eogenetic karst responds quickly to the flow of fluids, reducing the porosity while simulaneously producing the directed, preferred permeability of the type previously mentioned for young rocks in Bermuda and the Bahamas.

Non-Carbonate Rocks

The relationship of carbonate to non-carbonate rock units has important implications for the development of karst features and groundwater recharge, transport, and discharge on carbonate islands. Four fundamentally different relationships (Figure 1) have been identified:

A. Simple Carbonate Island. – Only carbonate rocks are present (Figure 1A). Meteoric catchment is entirely autogenic, and flow within the fresh-water lens is controlled entirely by the properties of the carbonate rock, including fractures, joints, bedding features, and facies boundaries present. The fresh-water lens initially approximates the Dupuit-Ghyben-Herzberg model. Small, tectonically stable carbonate islands with no non-carbonate rocks present are end-member or ideal specimens for modeling the behavior of karst processes in eogenetic carbonate rocks. The Bahamas are all simple carbonate islands, which provide subjects for comparative study of karst development on large (Andros) versus small (San Salvador) islands. Because of their simplicity, the effect of island size on aquifer development can by studied in isolation from the effects of other variables.

B. Carbonate-Cover Island. – No non-carbonate rocks are present on the surface, and all meteoric catchment is autogenic (Figure 1B). Non-carbonate rocks are present beneath a veneer of carbonate rocks. In this case, the lens can be distorted or partitioned by the non-carbonate rocks. (In most carbonate island settings the non-carbonate rocks, whether volcanic or clastic sedimentary rocks, have hydraulic conductivities many orders of magnitude lower than the carbonates). Vadose flow is intercepted in the subsurface by the non-carbonate rock and is deflected by the paleotopography at the carbonate/non-carbonate contact to provide point recharge to the lens at various locations. This focused flow may create large cave passages, which are conduits along the contact but become mixing chambers upon reaching the lens. Where the lens abuts the non-carbonate rocks, the base of the lens is floored by those rocks. This creates what has been called "parabasal water" (Mink and Vacher, 1997), which is valued as it can be pumped without the risk of upconing seawater into the lens. Some islands, such as Bermuda (Mylroie et al., 1995), are a carbonate cap on a volcanic pedestal. Under current sea-level conditions, the fresh–water lens is positioned in the carbonates well above the volcanic contact, so that modern Bermuda is a simple carbonate island. During a glacio-eustatic sea-level lowstand, however, the lens moves downward so that the volcanic contact intercepts the lens, which partitions the lens and creates the subsurface concentration of vadose flow described above. The very large collapse caves of Bermuda are believed to be progradational features from large dissolution voids that developed at the volcanic contact (Mylroie et al., 1995).

C. Composite Island. – Non-carbonate rock is exposed at the surface, which creates an allogenic catchment for the adjacent carbonate rocks (Figure 1C). The fresh-water lens is partitioned, and water collected on the non-carbonate rock sinks at the contact with carbonate rock and follows the contact downward to the lens. Dissolutional retreat of the carbonate rocks at the surface contact can create large closed-contour depressions. Large conduit cave systems can develop on the contact above sea level (and hence above the fresh-water lens), and large chambers can form where the vadose flow enters the lens as a point recharge. Parabasal water is present. Barbados in the Atlantic and Guam in the Pacific are excellent examples of composite islands.

D. Complex Island. – Non-carbonate and carbonate rock are complexly inter-related, either by faulting that brings the rocks into contact in non-depositional relationships or by syndeposition of carbonates with volcanic units or weathered non-carbonate rock, or both (Jenson et al., 2002) (Figure 1D). Faulting can isolate a carbonate unit, creating an independent, perched fresh-water lens. Faulting, by placing non-carbonate rocks against carbonate rocks, can also obstruct seaward flow of fresh water in the lens, creating long and circuitous discharge routes, confined aquifer conditions, or surface springs. The interfingering of carbonate facies with contemporaneous volcanic units and weathered non-carbonate rock can distort vadose recharge pathways, perch fresh-water, and create confined conditions within the lens. Saipan and Rota Islands in the Northern Mariana Islands of the western Pacific are excellent examples.

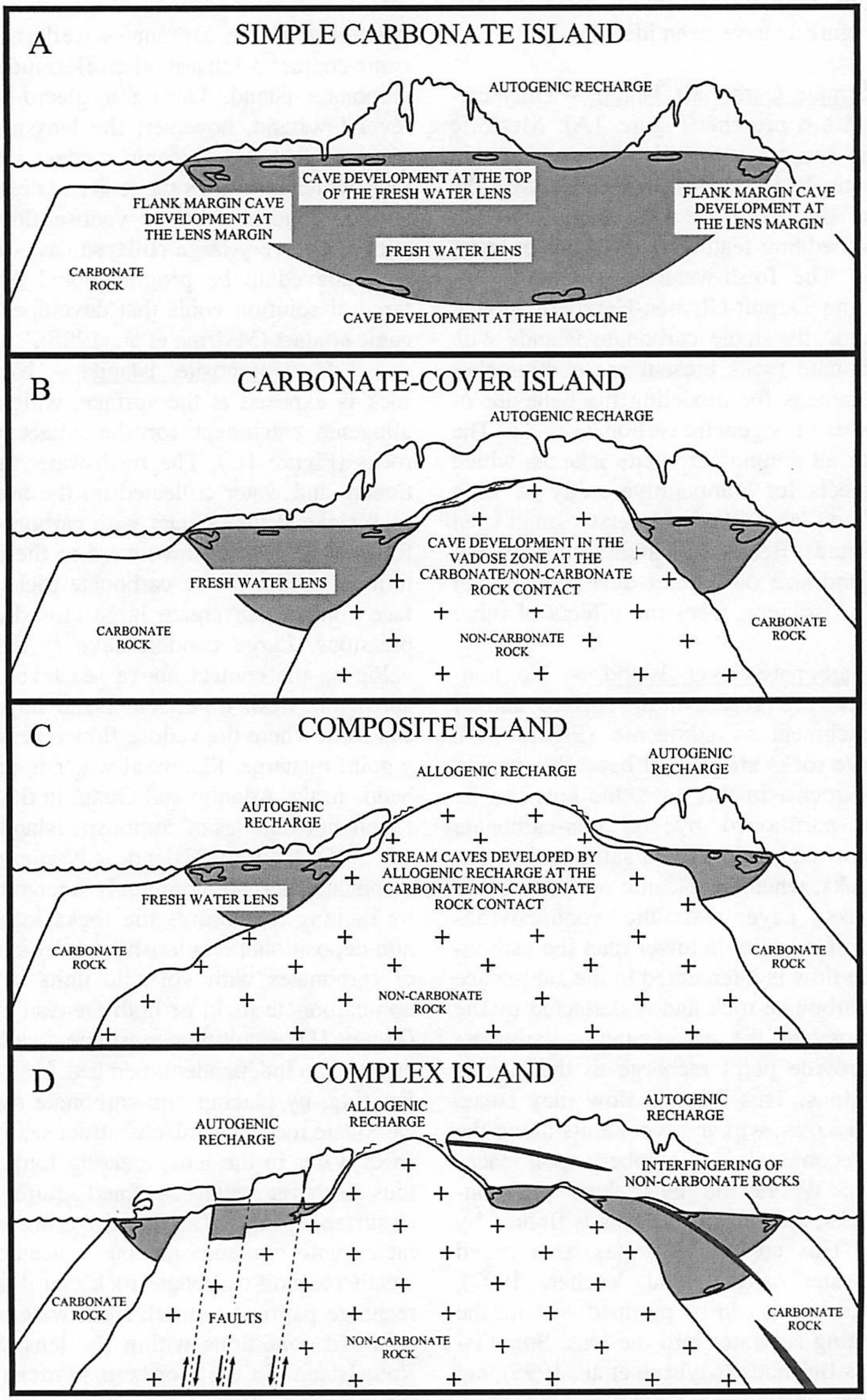

Figure 1. Diagrammatic representation of a Simple Carbonate Island (A), a Carbonate-Cover Island (B), a Composite Island (C), and a Complex Island (D). See text for a discussion of each island type.

These four categories are not exclusive of one another and can coexist on a given island. For example, Tinian Island in the Northern Mariana Islands has a surface that is more than 95% carbonate, the rest being weathered volcanics. It fits the simple carbonate island model around its periphery, and the carbonate-cover island model in the interior, except at a few locations where small outcrops of weathered volcanics peek through. At these locations it fits the composite island model. Each category is thus an idealized end-member that assists in understanding and explaining the different evolutionary pathways in island karst development.

CARBONATE ISLAND KARST MODEL

The Carbonate Island Karst Model, or CIKM, integrates the concepts presented above into a systematic framework. The initial approach is to create a diagram that shows the relationships of the fundamental variables in graphic form. The CIKM can thus be visualized as a three-dimensional field, in which sea level follows the y-axis (vertical), island size follows the x-axis, and island composition follows the z-axis (Figure 2). Through time, carbonate deposition, tectonism, and glacio-eustasy interact to produce an island evolution trajectory. For example, as sea level falls, island size increases, catchment increases, and island surface area increases relative to the island perimeter. These changes may cause the aquifer to shift from diffuse to conduit flow (Mylroie and Vacher, 1999). Additionally, a drop in sea level may bring the carbonate/non-carbonate contact into the range of the fresh-water lens, as in Bermuda, partitioning the lens and creating a subsurface catchment for vadose water which funnels flow along the paleotopography of the non-carbonate rock. A sea-level fall may also expose carbonate lagoons on a composite island, increasing the ratio of carbonate rock exposed relative to the non-carbonate rock. The fresh-water lens can enlarge into this newly exposed carbonate rock, decreasing the influence of the non-carbonate portion of the island. The CIKM thus provides a fundamental departure point for systematic interpretation and description of island karst and aquifer evolution.

Eogenetic carbonate rocks on a simple carbonate island may host three different types of porosity: matrix, vugular, and conduit. Very young islands, such as Holocene sand shoals, may exhibit only matrix porosity. Islands of older Pleistocene rock may have lost some matrix porosity through cementation, but vugular porosity (as touching vugs) may have come to dominate the fresh water flow. If the island is large, conduit flow may develop because the perimeter-to-surface area ratio becomes insufficient to support discharge exclusively by diffuse flow (even when touching vugs are utilized). In simple carbonate islands, storage of water occurs primarily in the matrix, but flow is primarily in the touching vugs or conduits. In contrast, on continents in dense, telogenetic carbonate rocks, matrix porosity is commonly negligible, and vugular porosity unimportant. Flow is primarily by dissolution conduits although fractures can be important. In telogenetic karst, storage is negligible because matrix porosity is very small and conduit porosity is generally less than 1% (Worthington,1999).

Contaminant transport in karst aquifers has long been known to be very different than that in classic porous-media aquifers. In telogenetic karst, conduit flow is rapid and can traverse long distances with negligible filtration or dilution of water-borne contaminants. In island karst, the participation of matrix- and touching-vug porosity makes prediction of contaminant transport extremely difficult. The aquifer may have been overprinted by the various fresh-water lens positions caused by glacio-eustasy and tectonics, thus flow paths from previous conditions can be inherited. Studies that acknowledge only current conditions may therefore not explain inherited flow paths developed under very different conditions in the past. Only by incorporating past conditions can accurate and reliable aquifer conceptual models be developed.

Eogenetic carbonate island karst aquifers exhibit more variation than do their telogenetic continental karst relatives. The rock itself, being eogenetic, undergoes rapid re-arrangement of porosity and permeability. Glacio-eustasy moves the fresh-water lens more often and more rapidly

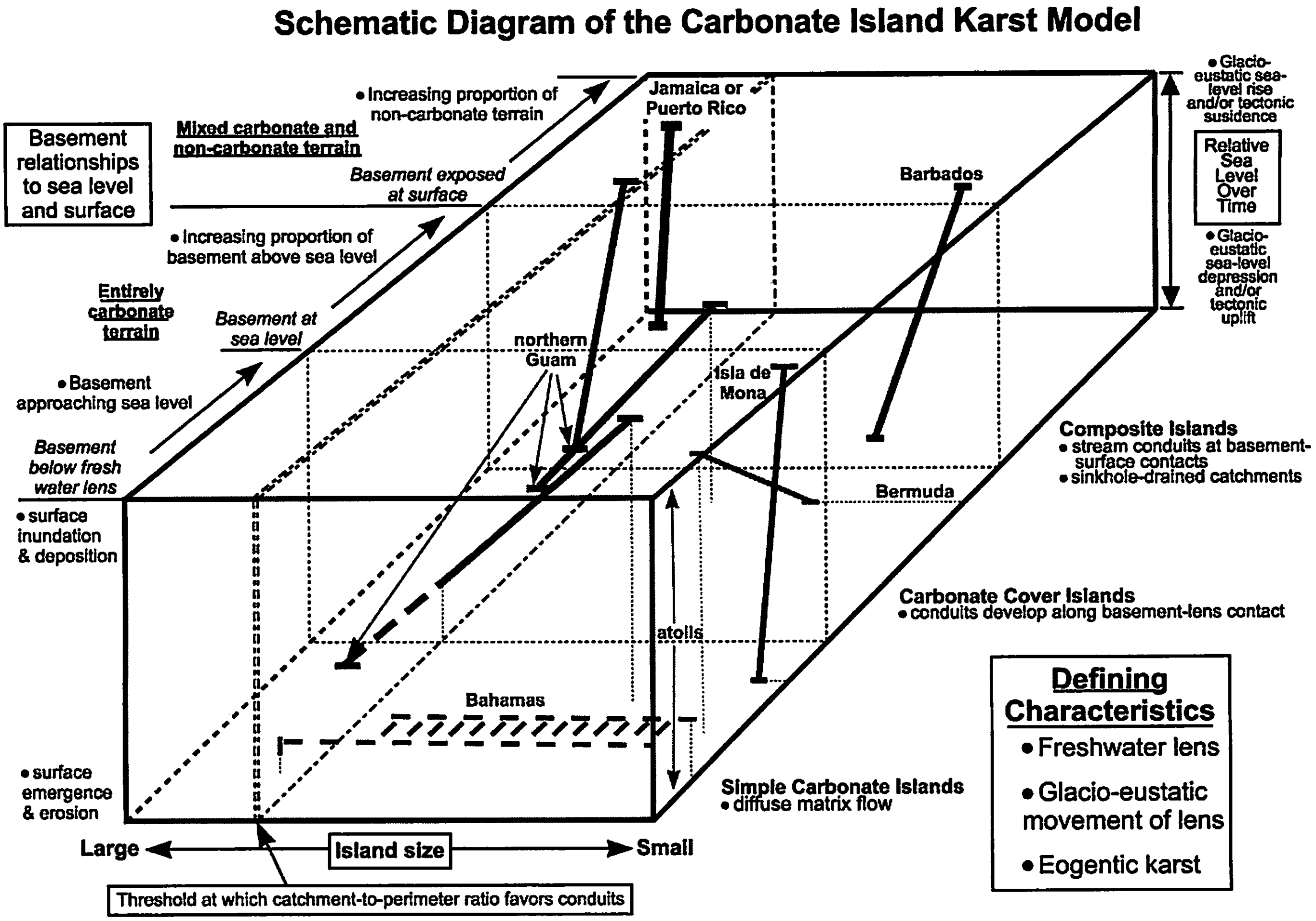

Figure 2. A schematic diagram of the Carbonate Island Karst Model, showing island size on the X-axis, sea level on the Y-axis (vertical), and carbonate/non-carbonate relationships on the Z-axis. Also shown are island "trajectories" demonstrating how islands move within the three-dimensional space of the model, depending mostly on how sea level changes.

than base level changes would be expected in continental interiors (unless glaciated). Tectonism may act with greater rapidity. Island karst is arguably as different from continental karst as continental karst is different than classic porous media flow. The application of karst principles to carbonate islands thus requires that the unique setting and conditions of carbonate islands be taken into account.

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