THE CARBONATE ISLAND KARST MODEL

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Tropical carbonate islands (and analogues along tropical carbonate coasts on continents) are a unique karst environment that differs significantly from that found in temperate continental interiors, where most cave and karst research has historically been done (e.g. White, 1988; Ford and Williams, 1989). The differences center on three factors (Mylroie and Vacher, 1999): 1) fresh water - salt water mixing occurs within the fresh-water lens; 2) glacioeustasy has moved the freshwater lens up and down through a vertical range of over 100 m; and 3) the karst is *eogenetic, i.e.*, it has developed in carbonate rocks that are young and have never been buried beyond the range of meteoric diagenesis.

The outcome of the first factor is that enhanced dissolution results from the mixing of fresh and saline waters at the base and margin of the lens (Plummer, 1975). This dissolution in the lens base is augmented by the enhanced dissolution at the top of the lens produced by mixing of fresh vadose and phreatic waters (Bogli, 1980). These dissolution effects modify the shape of the lens over time. The consequent increase in hydraulic conductivity in the rock permeated by the lens eventually results in a thinner lens.

The second factor, glacio-eustatic variation of the lens position—and variation in the time during which the lens occupies any given position in the section—results in a complex variation of porosity and hydraulic conductivity over the section of carbonate bedrock. If later carbonates are added above or adjacent to the original units, the lens will be thicker in the younger carbonates than in the older ones, creating a significant departure from an idealized lens shape (Vacher, 1988). This phenomenon is somewhat counter-intuitive, as the younger rocks often have a higher primary porosity than the older rocks. However, dissolution has re-arranged the original porosity into preferred flow paths, and the hydraulic conductivity is thus greater in the less porous older rocks. Along the margin of the lens, flow velocity increases and the mixing zones at the top and bottom of the lens converge to form *flank margin caves*, typically the largest voids observed on small carbonate islands (Mylroie and Carew, 1995). Flank margin caves are not true conduits, but mixing chambers. Their position with respect to the margin indicates former sea-level stillstands, and their size and spacing along the island margin are indicators of past flow conditions within the associated paleo-lens.

The main consequence of the third factor is that progressive diagenesis everywhere throughout young, highly porous carbonates results in a re-ordering of the host rock porosity. Development can also be influenced by the nature of the depositional environment of the carbonate rock, which can vary from eolian, lagoonal, shoal or reef. Variations in island size create differences in catchment and lens volume/island perimeter ratios that might inhibit conduit development in small carbonate islands but favor it in larger ones (Mylroie and Vacher, 1999). Young carbonates have not undergone the deep-burial diagenesis associated with older rocks. Such older rocks commonly lack significant primary porosity, and water flow is primarily via bedding planes, joints, faults or fractures. They are best modeled as dual porosity aquifers combining fracture and conduit flow. Eogenetic carbonates, as found in tropical islands, retain significant primary porosity, and their eogenetic processes superimpose a vuggy porosity and permeability on that primary system, which in turn feeds conduit flow to create a triple porosity aquifer.

As a result of the effects of fresh water - salt water mixing, sea level change, and eogenetic evolution of the carbonates, carbonate islands contain karst features and caves remarkably different from the typical fluvial karst formed in dense Paleozoic and Mesozoic carbonates of continental interiors.

Sea Level-Basement Relationships

The three factors described above are common to all carbonate islands, and produce karst features exhibited by all of them. Carbonate islands can be subdivided into three physical categories (Figure 1) based on the relationship between the sea level and the carbonate-basement contact (Mylroie and Carew, 1997; 2000; Mylroie and Vacher, 1999). In tropical carbonate islands, this basement is commonly volcanic, and therefore has dramatically different hydrological properties than the overlying carbonates. The sea level-basement relationship has profound implications for the evolution of karst features. *Simple carbonate islands* have no non-carbonate rocks exposed at the surface or stratigraphically positioned within the range of glacioeustasy. *Carbonate cover islands* have non-carbonate rocks beneath a carbonate veneer, and the contact between them is within the position of the fresh-water lens for all or part of a glacioeustatic cycle. *Composite islands* (Vacher, 1997) contain carbonate and non-carbonate rocks exposed on the surface.

In carbonate cover islands, vadose waters infiltrating downward are shunted along the carbonate-basement contact, producing stream caves that carry water to the lens and/or sea level. In composite islands, this process is augmented by the development of sinks and insurgences at the surface expression of the carbonate-basement contact, which capture allogenic water. The carbonate outcrop surface captures autogenic surface waters as well. In the phreatic zone of carbonate cover and composite islands, the lens can be subdivided into the *basal zone*, where the base of the freshwater forms the transition zone to the underlying marine water, and the *parabasal zone*, where the base of the fresh water rests on basement rock (Mink and Vacher, 1997). The parabasal zone is the zone of choice for groundwater development on carbonate islands because wells placed in the parabasal zone are relatively immune to lateral intrusion or upconing of marine waters.

Surface features

The surface of carbonate islands contains a characteristic epikarst, which marks the intense dissolution zone associated with the weathering front, and consists of etched rock surfaces, small dissolution tubes, dissolutionally-enlarged cracks and joints, and disarticulated blocks of carbonate rock. Tropical island epikarst differs from that in typical continental settings mostly as a result of the youthful age of the carbonates and the pervasive presence of salt spray, which collects on the rock surfaces and mixes with meteoric water to create a distinctive etching pattern. Recharge to the lens through the epikarst appears to work at a variety of scales and rates (Contractor and Jenson, in press). In the absence of allogenic catchments on adjacent non-carbonate terrain, sinking streams, blind valleys, and springs are rarely found. Closed depressions are common, but many represent constructional features produced by initial depositional variation, or subsequent tectonics in an eogenetic environment. In such cases, the depressions, while internally drained by dissolution pathways, have not had the majority of their volume created by dissolutional excavation. Vadose flow along the contact between the carbonate and non-carbonate basement on carbonate cover and composite islands, however, can undercut the overlying carbonate, producing large collapse voids that may prograde to the surface, as observed on Bermuda (Mylroie et al., 1995).

Guam and Saipan

Guam was selected to apply insights gained in the Atlantic-Caribbean province to a Pacific location, while also incorporating the additional complexity of the island to extend and refine the development of a model of island carbonate aquifers. Guam is one of the larger open ocean islands, with an area of 554 km^2. Guam is a dual island–the southern half is volcanic with a few carbonate outliers, the northern half is carbonate with a few volcanic inliers. The carbonates are young, ranging in age from Miocene to Holocene. Tectonic uplift has been continuous in the Quaternary, overprinting the glacioeustatic sea level record and imposing a complex structural grain (joint and fault orientations) on the limestone units.

Guam displays features from each of the three subdivisions of carbonate islands described in the previous section. The northern half is mostly carbonate, with attributes of a simple carbonate island over about 80% of its surface area, *i.e.*, the limestone bedrock extends down to well below sea level. Beneath the other 20% of the surface, however, the volcanic basement lies well above sea level, as in the carbonate cover model. At two locations the basement extends to the surface, rising above the northern Plateau to give it attributes of a composite island. The southern half of Guam is uplifted volcanic terrain upon which lies remnants of once extensive reef-lagoonal limestones and occasional fragments of older shallow-water carbonate deposits that were incorporated into the younger volcanic units (Tracey et al., 1964). In all cases except a few on the eastern coast, the base of the southern carbonate rocks is elevated above modern sea level. Such a position removes them from the direct influence of glacio-eustacy, and from the dissolution effects of fresh and salt water mixing. The karst of southern Guam is thus more analogous to larger islands such as Puerto Rico and Jamaica, where the interior carbonates produce caves and karst landforms similar to those in tropical continental settings. The diversity of karst environments on Guam has thus produced an especially wide variety of karst landforms and cave development, ranging from features characteristic of the simplest islands to features resembling continental landforms.

Lens discharge on Guam is mainly by diffuse flow, modified by porosity re-arrangement as diagenesis creates high-conductivity pathways in the rock occupied by the lens. Joints and faults appear important in developing these high-conductivity pathways (Jenson et al., 1997). Given that glacio-eustatic lowstands have occurred several times during the Pleistocene and that the entire Pleistocene section has been raised above sea level on northern Guam, it is likely that a considerable span of the carbonate section now below sea level was in the vadose zone long enough for stream caves to have developed along the carbonate-basement contact. The hydrological implications of the vadose flow paths that formed during sea-level lowstands, and which now are partially embedded in the lens of the parabasal zone, are uncertain at this point. Several levels of terraces and horizontal grooves in the cliff faces indicate episodes of relative sea-level stillstands in the exposed subaereal section. In recent field work, we have observed that these horizons also exhibit widespread development of moderate-sized flank margin caves. The caves show clear evidence of re-invasion by chemically aggressive waters, another result of lens migration and overprinting following the interplay of tectonics and glacio-eustasy. As a result of basement interaction with the fresh water lens on Guam, a major portion of the lens discharge is focussed to certain coastal areas. At these locations, fractures discharge large amounts of water, indicating that the diffuse flow is selecting favored pathways for ultimate outflow (Jocson, et al., 1999).

Saipan provides further complications. Unlike Guam, where the bulk of the limestone deposition followed deposition of the volcanic and volcaniclastic rocks (Tracey et al, 1964), on Saipan many limestone units are syndepositional with volcaniclastics (Cloud et al, 1956). The interbedding of these units has produced confined conditions in some of the carbonate units on the island today (Hoffman et al, 1998). Field work has demonstrated fossil phreatic lift passages (i.e. passages rising towards their outlet) in the limestones, that would indicate paleo-confined conditions as well during aquifer evolution. Other caves are progradational collapse features that have migrated through the carbonate section from a zone of active dissolution at the volcanic-carbonate contact, as noted previously on Bermuda.

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The variability of the initial carbonate depositional environment (*e.g.*, reef, shoal, lagoon), the differential dissolution and diagenesis these rocks have undergone, and the relationship between carbonate and non-carbonate rocks thus combine to profoundly modify the classic Ghyben-Herzberg-Dupuit model of the freshwater lens of ideal islands. To provide an appropriate systematic geologic model, we seek to synthesize these characteristic features into a coherent framework, which we have labeled the Carbonate Island Karst Model (CIKM) (Mylroie et al., 1999). The model is summarized schematically in Figure 2. It provides the basis for accurate aquifer conceptual models for hydrologists working on water resource development, or for other engineering applications on carbonate islands. The initial research for the CIKM began in the Bahamas and Bermuda, simplistic carbonate and carbonate cover islands, respectively, in tectonically stable settings. Work progressed to Isla de Mona, Puerto Rico, a simple carbonate island that has been tectonically uplifted. The research has been extended to the islands of Guam and Saipan, composite islands in the western Pacific with a complex tectonic history. It is important to recognize that carbonate islands do not always fall into distinct categories, but may contain a range of characteristics that blend many island conditions, as shown below.

Guam and Saipan contain a bewildering variety of caves, karst features, and water flow pathways that defy existing simple island or continental models. The CIKM, however, provides a common framework for uniting the geology and hydrology of these and other carbonate islands into a single picture. In figure 2A, the CIKM is presented as a three-dimensional arrangement that address island size on the x-axis, sea-level on the y-axis, and bedrock relationships on the z-axis. The greatest degree of change in carbonate island aquifer characteristics occurs in the transition from a small carbonate island to a large composite island.

For a given island, sea level change may control the transition of island type. When sea level falls, an island will become larger as lagoons and forereef slopes become exposed. A drop in sea level may also drop the fresh-water lens into the area of influence of basement rocks, forcing a simple carbonate island transition to a carbonate cover island. If a carbonate island has a minor basement rock inlier at a high elevation, a rise in sea level can decrease overall island size and carbonate outcrop area, making the basement outcrop a more substantial aspect of the island's hydrology.

Therefore the CIKM can characterize the aquifer "trajectories" through time, taking into account tectonic uplift, glacio-eustasy, or continued volcanic activity. Figure 2B shows sample trajectories for some islands. Bermuda, for example, becomes larger, but also moves more into the carbonate cover field as the influence of its volcanic basement increases with sea level decline. Barbados, on the other hand, currently has a minority of its area as basement rock, and a drop in sea level increases the amount of exposed carbonates relative to basement rock. Guam becomes more complex, and various parts of the island follow separate trajectories. The Bahamas, on the other hand, change only in size as there is no basement rock within the range of glacio-eustasy.

The CIKM is a new development in how to view carbonate island aquifers. The ramifications of this model are still being actively investigated. The model clearly demonstrates that besides the unique karst behavior expected in eogenetic rocks placed in a mixing zone environment, the behavior of a carbonate island aquifer also depends on sea level history, tectonics, and basement configuration.

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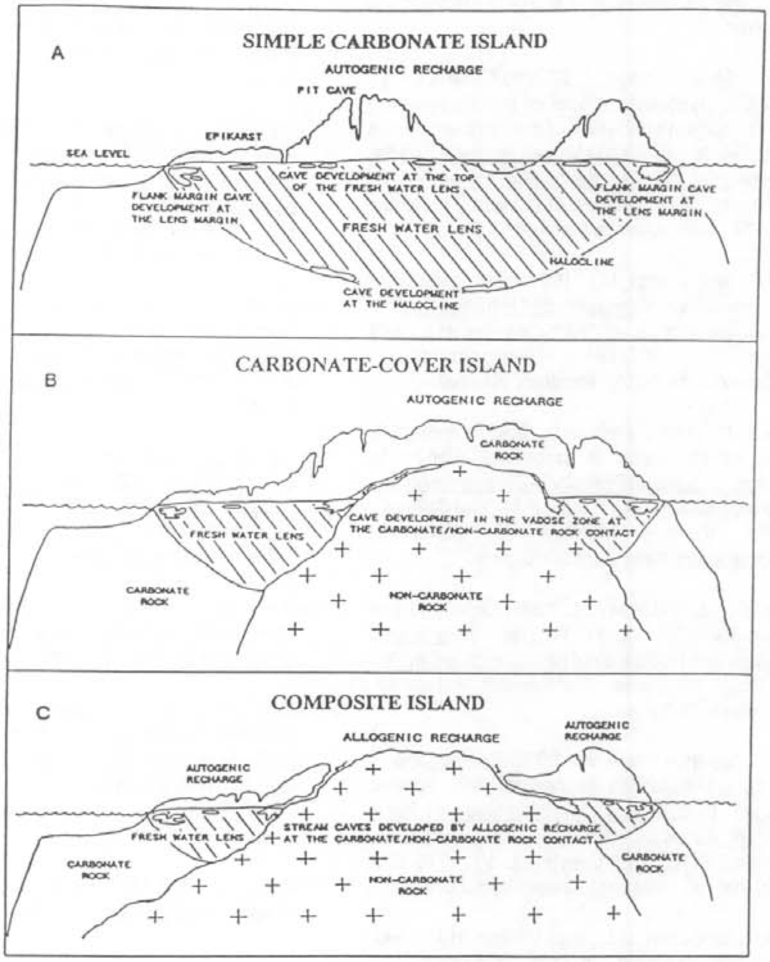

Figure 1. Sea level and basement relationships for carbonate islands. (A) The simple carbonate islands, with no non-carbonate rock within the region of the fresh water lens. (B) The carbonate-cover island, where non-carbonate rock at depth can deflect vadose flow and distort the freshwater lens. (C) Composite island, where non-carbonate rock influences both surface and subsurface flow.

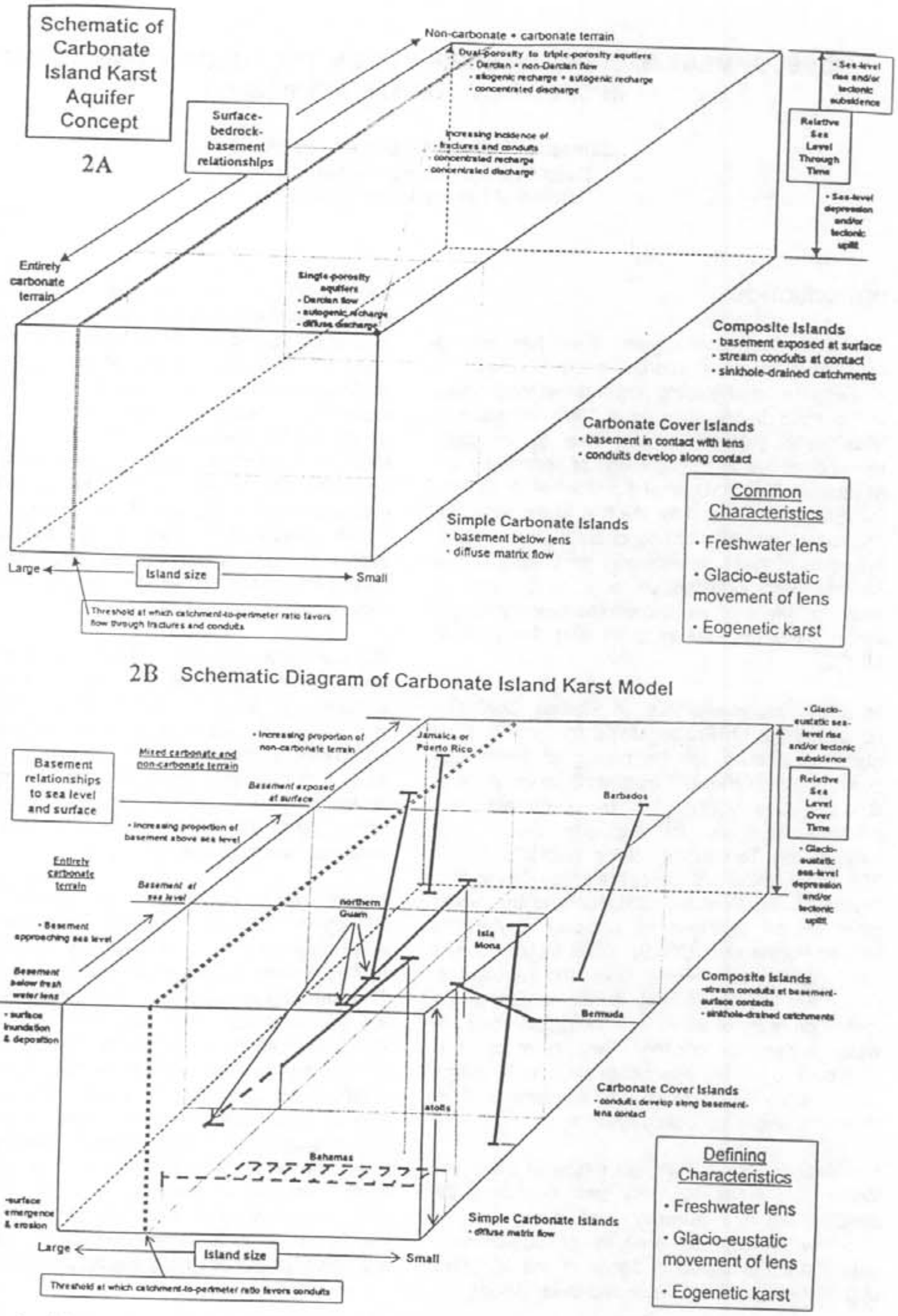

Figure 2. A) Schematic diagram of the Carbonate Island Karst Model (CIKM). Any island karst should fall somewhere in the three-dimensional field presented here. B) Placement of sample islands within the field of the CIKM creates trajectories that demonstrate how changes in island size, lens discharge, and island category occur when sea level varies.