**Speleogenesis and Evolution of Karst Aquifers**
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# Karst development on carbonate islands

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**Abstract**

Karst development on carbonate platforms occurs continuously on emergent portions of the platform. Surficial karst processes produce an irregular pitted and etched surface, or epikarst. The karst surface becomes mantled with soil, which may eventually result in the production of a resistant micritic paleosol. The epikarst transmits surface water into vadose pit caves, which in turn deliver their water to a diffuse-flow aquifer. These pit caves form within a 100,000 yr time frame. On islands with a relatively thin carbonate cover over insoluble rock, vadose flow perched at the contact of carbonate rock with insoluble rock results in the lateral growth of vadose voids along the contact, creating large collapse chambers that may later stope to the surface.

Carbonate islands record successive sequences of paleosols (platform emergence) and carbonate sedimentation (platform submergence). The appropriate interpretation of paleosols as past exposure surfaces is difficult, because carbonate deposition is not distributed uniformly, paleosol material is commonly transported into vadose and phreatic voids at depth, and micritized horizons similar in appearance to paleosols can develop within existing carbonates.

On carbonate islands, large dissolution voids called flank margin caves form preferentially in the discharging margin of the fresh-water lens from the effects that result from fresh-water/salt-water mixing. Similarly, smaller dissolution voids also develop at the top of the lens where vadose and phreatic fresh-waters mix. Independent of fluid mixing, oxidation of organic carbon and oxidation/reduction reactions involving sulfur can produce acids that play an important role in phreatic dissolution. This enhanced dissolution can produce caves in fresh-water lenses of very small size in less than 15,000 yr. Because dissolution voids develop at discrete horizons, they provide evidence of past sea-level positions. The glacio-eustatic sea-level changes of the Quaternary have overprinted the dissolutional record of many carbonate islands with multiple episodes of vadose, fresh-water phreatic, mixing zone, and marine phreatic conditions. This record is further complicated by collapse of caves, which produces upwardly prograding voids whose current position does not correlate with past sea level positions.

The location and type of porosity development on emergent carbonate platforms depends on the degree of platform exposure, climate, carbonate lithology, and rate of sea-level change. Slow, steady, partial transgression or regression will result in migration of the site of phreatic void production as the fresh-water lens changes elevation and moves laterally in response to sea-level change. The result can be a continuum of voids that may later lead to development solution-collapse breccias over an extended area.

Keywords: karst on carbonate islands, speleogenesis in coastal and oceanic settings.

## Introduction

Carbonate platforms have become emergent throughout earth history. Karst development on such emergent platforms is a very rapid geological process. Emergent carbonate platforms are likely to develop karst over a broad area and through a significant thickness. Why is paleokarst, as described in this paper, not more common in the geologic record? Do we fail to recognize the evidence, or are these karst features vulnerable to subsequent erosion and alteration that eliminates them? The major purpose of this paper is to motivate others to re-examine ancient carbonates in light of our understanding of karst processes.

For the purposes of this paper, carbonate platforms in the oceanic realm, as defined by Smart and Whitaker (1991, 1993), will be the model used to describe carbonate island karst development. Smart and Whitaker (1991, 1993) define the oceanic realm as that in which carbonates are diagenetically immature, sea-level fluctuations are of low order, and continental influences are absent. The focus of this paper is on the effects of recharge, climate, degree of platform exposure, lithology, and rate of sea-level change upon carbonate platforms and karst development, using Quaternary carbonate settings as examples. The various hydrological environments found in oceanic carbonate islands are illustrated in Fig.1.

Whenever carbonate platforms are subaerially exposed, karst development occurs. The exposure can be the result of eustatic or local (tectonic) sea-level change. In some cases, shoaling may occur and eventually tidal flat, beach, and eolian carbonates may be deposited, producing an exposed land surface without the need of a sea-level change. Karst features may develop very rapidly, even as deposition continues, a phenomenon called syngenetic karst (Jennings, 1968).

On emergent carbonate platforms meteoric precipitation falls directly onto the carbonate land surface, and enters the subsurface vadose zone (Fig. 1). Such input is known as autogenic recharge (Mylroie, 1984a). The meteoric water, slightly acidic from incorporation of atmospheric $CO_2$, gains more dissolutional potential by addition of soil $CO_2$. Much of this dissolutional potential is expended rapidly by interaction with the exposed carbonate rocks, and, as a result, water enters the subsurface with significantly diminished dissolutional capability. On the scale of hundreds of meters, water infiltration is relatively uniform over the exposed outcrop as diffuse input (Mylroie, 1984a). Exceptions occur where carbonate platforms are on a continental margin, or on an island with significant outcrops of insoluble rocks. There, meteoric water collects in streams that flow onto the carbonates. In these cases the input is allogenic, because the water enters the limestone in appreciable volumes at point locations, its dissolutional potential persists to significant depths in the limestone. Such allogenic inputs are restricted to the contact of the carbonates and insoluble rocks; within the bulk of the carbonate outcrop, autogenic recharge, and the effects of that recharge, dominate.

## Karst processes and products on carbonate platforms

### *Surface Karst*

Autogenic recharge to a carbonate platform results in a surficial, irregularly pitted and etched karst surface, with dissolution channels and networks of great complexity that extend through only the upper few meters of rock (Fig. 2). The rock contains numerous tubes, holes, and enlarged joints in the size range of centimeters to tens of centimeters. The karst surface is all or partially covered by soil and weathered rock material which may subside into the underlying dissolutional network (Fig. 3). This surficial karst and its soil mantle is referred to as epikarst or subcutaneous karst (Williams, 1983). Epikarst follows surface topography and occurs only in the upper few meters of rock. It is, therefore, laterally extensive with potentially great variation in elevation (Fig. 4). The epikarst is intimately linked with soil development processes and biological activity. Despite the fact that the epikarst is very permeable, and that the carbonate rocks beneath the epikarst have large porosity, the epikarst is capable of significant water storage. Soil infill and the large surface area provided by the dissolutional network hold water by capillary action. The epikarst should not be

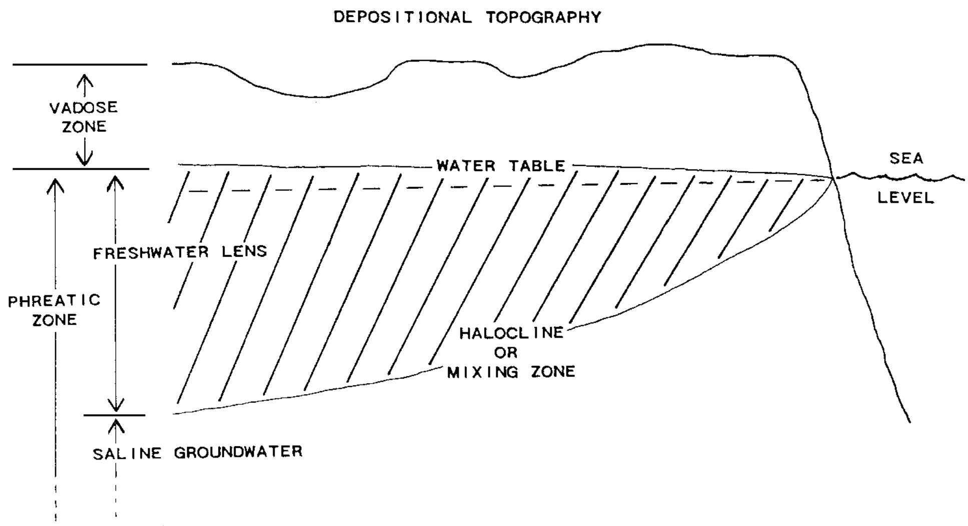


Fig. 1. Diagrammatic representation of a freshwater lens in a carbonate island showing the various hydrologic environments found between the land surface and the saline groundwater. The boundary between the freshwater lens and the saline groundwater may be a sharp halocline as pictured here, or a broad region of changing salinity called a mixing zone.

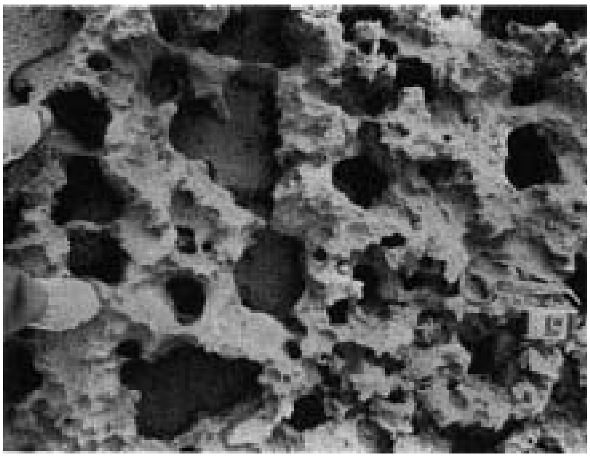

Fig. 2. Photograph of a dissolved and etched carbonate rock surface, San Salvador Island, Bahamas. Camera on right for scale.

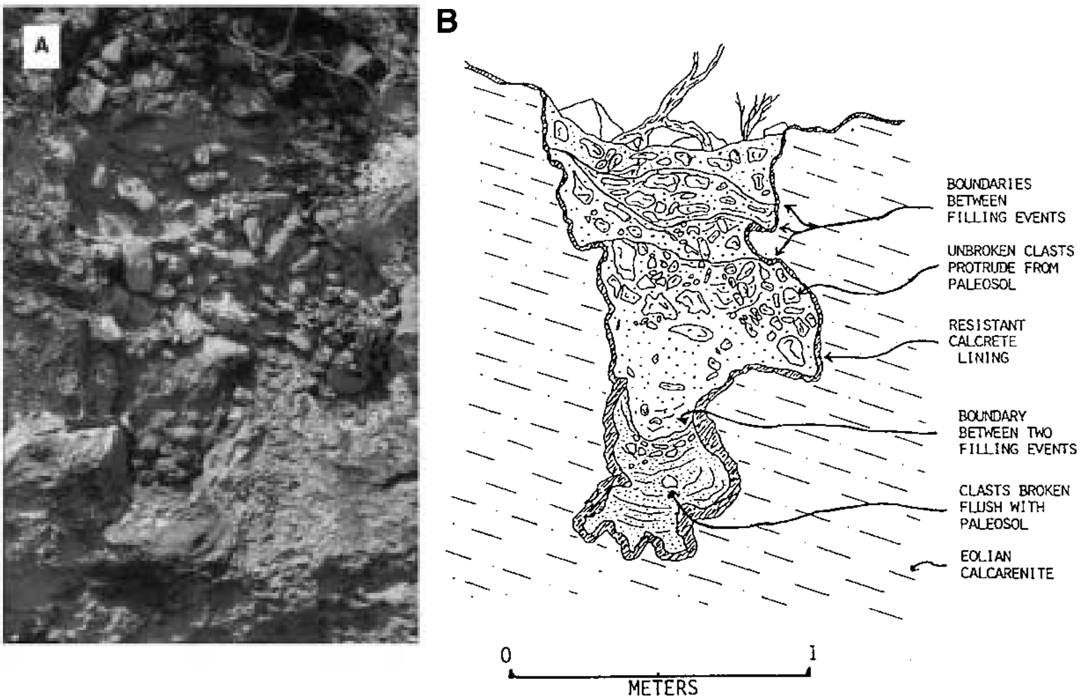


Fig. 3. (A) Photograph of a small dissolution pit, filled with weathered rock and paleosol material; (B) diagram of the feature indicates that this infilling may have been episodic.

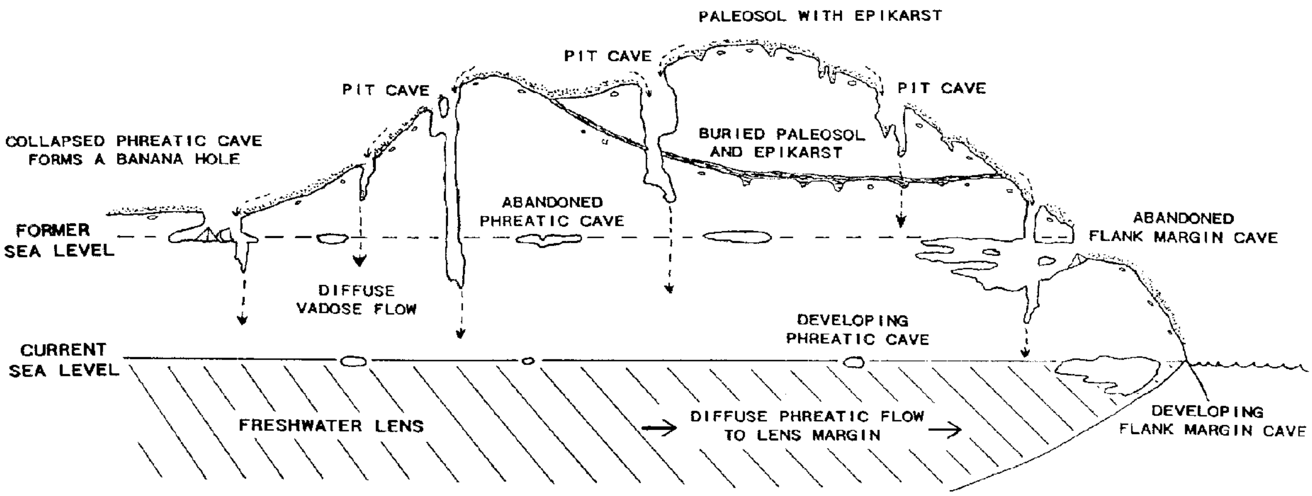


Fig. 4. Diagrammatic representation of the main dissolutional features found on carbonate islands: epikarst (with paleosol), pit caves, banana holes and phreatic caves, and flank margin caves. Also shown are their positions relative to a freshwater lens and halocline. Changes in sea level move the position of the karst features. In the Quaternary, these sea level changes led to overprinting of dissolutional environments.

Fig. 5. Typical example of a terra-rossa paleosol from San Salvador Island, Bahamas. Note the resistant micritic crusts above figure, and the complex rhizomorphs beneath thosecrusts.

Fig. 6. Outcrop at The Bluff, San Salvador Island, Bahamas. Vertical exposure is 20 m. Overhanging layer at the top of the outcrop is a resistant terra-rossa paleosol similar to that in Fig. 5. In the middle of the outcrop, trending horizontally, is a white, unstructured calcarenite protosol.

confused with coastal karst (commonly referred to as phytokarst), which is the result of modification of carbonate rocks in shoreline settings, where endolithic algae, sea spray, grazing invertebrates, dissolution and precipitation, and wave action combine to produce complex, but spatially restricted, etched carbonate surfaces (Viles, 1988).

*Paleosols*

Coincident with karst development, the land surface becomes mantled with soil formed by collection of residual insolubles and atmospheric dust. Where the soil development has been pronounced, the underlying epikarst can be completely covered. On Quaternary carbonate islands, resistant and relatively impermeable micritic paleosols (terra-rossa paleosols) have developed (Fig. 5). Locally, these micritized layers can be relatively impervious to infiltration, and are capable of diverting meteoric recharge to a limited number of point inputs to the subsurface. While this development of small streams may occur over a lateral scale of meters to tens of meters, nevertheless the water input to the subsurface on the larger scale (hundreds of meters) remains roughly equal per given area.

The proper interpretation of paleosols and the past exposure surfaces they represent can be difficult in carbonate islands (Carew and Mylroie, 1991). Topography, whether depositional or erosional, can result in poorly-developed, thin paleosols on ridge crests, and well-developed, thick paleosols in topographic lows. In the rock record, the difference in elevation and degree of development of the resulting paleosol in cores or widely-spaced outcrops may lead an observer to incorrectly interpret multiple exposure events.

Calcarenite protosols must be differentiated from terra-rossa paleosols (Fig. 6). Calcarenite protosols are fossiliferous, unstructured paleosols formed during brief emergence events or temporary pauses in carbonate deposition that occur within a single sea-level highstand. They represent a minimal exposure time for the carbonate platform. Terra-rossa paleosols are the result of the cumulative weathering effects of long-term exposure associated with sealevel lowstands, and are underlain by a porous epikarst. Terra-rossa paleosols commonly separate carbonate deposits formed during different sealevel highstands, and, therefore, represent a substantial exposure time for the carbonate platform.

Carbonate deposition, especially that on platforms that are incompletely flooded, is spatially patchy, so paleosols may be merged into composite paleosols at the localities that remained emergent. Yet the same paleosols may be separated by significant sediment packages at other locations that were flooded and underwent carbonate deposition. On Quaternary carbonate islands such as Bermuda or the Bahamas, the patchy deposition of eolianites commonly produces this result, as seen in Fig. 4, where buried and exposed paleosols at the right of the figure merge into a single composite paleosol on the left. Conversely, apparent terra-rossa paleosol horizons can develop within existing carbonates as a result of shallow vadose flow and weathering, and be misinterpreted as exposure surfaces (Carew and Mylroie, 1991; Rossinsky, et al., 1992). In addition, paleosol material may be transported into vadose and phreatic caves at depth (Fig. 7). Because phreatic caves may form at common elevations, such as the water table, the collection of soil infill at the specific horizons represented by these caves can be later misinterpreted as a surface paleosol formed at a true exposure surface (Carew and Mylroie, 1991).


Fig. 7. Outcrop on New Providence Island, Bahamas, showing modern soil at A, collecting in shallow depression at B, and being piped into a number of dissolutional voids at C, D, E, F and G. The vertical dashed line illustrates what would appear in a core drilled along that line. Soils at B, C, D, and G are all the same age, but might be misinterpreted in core as separate exposure horizons.

*Large scale karst landforms*

Quaternary carbonate islands today are found in tropical and subtropical settings. One would expect these islands to have karst landforms of the same type as that found in similar climatic settings on continents; however, this is not the case. Widely recognized tropical karst landforms such as sinking streams, springs, blind valleys, and tower karst are not found in these carbonate-island environments. Their absence is caused by the lack of allogenic recharge, specifically, major streams crossing onto the carbonates from non-carbonate terrain.

*Depressions*

On exposed carbonate platforms that have only autogenic recharge, the dominant karst landforms are closed depressions and caves. Closed-contour depressions of a variety of sizes are found on Quaternary carbonate islands, but many of these, including the largest, are of depositional origin. Their continued expression as topographic depressions is the result of internal drainage by karst processes. While it is clear that these depressions may undergo significant modification by karst and related weathering processes, the majority of their volume is a result of initial depositional topography. Purdy and Bertram (1993) have argued that the major karst process on oceanic carbonate islands is the dissolutional excavation of large central karst depressions, with an elevated residual island rim. However, they fail to explain why the island center should dissolve more rapidly than the island perimeter. Additionally, in the Quaternary, the rate of carbonate deposition during sea-level highstands is equivalent to the lessor amount of carbonate dissolution that takes place during the longer duration sealevel lowstands, so no net carbonate is lost (Mylroie, 1993a,b). Depressions should experience the longest time for carbonate deposition, elevated rims the least. Mass-balance considerations indicate that these large depressions on carbonate islands must have been created by means other than surface dissolution.

The continued development of depositional closed depressions as major karst landforms is controlled in part by climate. For example, whereas Bermuda and San Salvador Island, Bahamas, are carbonate islands of similar size and geology, they have markedly different depression morphologies that result from the effects of their different climate (Vacher and Mylroie, 1991).

Bermuda has a positive water budget (annual precipitation exceeds evapotranspiration), which results in the depressions being sites of recharge to the fresh-water lens. In the depressions, vegetation is lush, soil $CO_2$ is abundant, and soil acidity is high, so, with time, the depressions deepen and expand by dissolution. Eventually the depression-forming processes may breach topographic barriers and the depressions are invaded by the sea. Subsequent marine bioerosion further enlarges the depressions.

In contrast, on San Salvador Island, Bahamas, the water budget is negative (annual evapotranspiration exceeds precipitation). Where constructional depressions extend below the water table, lakes occur. Extensive evaporation produces hypersaline lakes by upconing of marine water through the freshwater lens. Significant dissolution of the depression margins is inhibited by the hypersalinity, and the original depression morphology (in this case, swales between eolian calcarenites) persists through time.

### *Caves*

Caves found on carbonate platforms fall into three main categories: vadose, phreatic, and fracture caves. Vadose caves consists of pits, which are dissolutional pathways formed by water descending from the surface toward the water table. Phreatic caves (flank margin caves and "banana holes") developed below the water table in the fresh-water lens by the mixing of chemically-distinct waters. Fracture caves developed along the margin of carbonate platforms as a result of mechanical failure of the platform margin.

#### Pit Caves

On a large scale, carbonate platforms have autogenic diffuse input, whereas on the scale of meters and tens of meters, even without the presence of an impermeable paleosol layer, vadose waters do not infiltrate uniformly. Spatial variation in vadose input can leave a recognizable diagenetic record in the underlying vadose zone (Pelle and Boardman, 1989). The small-scale variation in vadose input is a result of the epikarst gathering meteoric water into discrete point inputs, which produce vadose shafts. These vadose shafts are called pit caves (Fig. 4), and they penetrate deep into the limestone (Pace et al., 1993). Pit caves are characterized by their near vertical, often stairstep pattern; by vertical grooves on the walls; and by the absence of the curvilinear dissolutional surfaces associated with phreatic conditions (Fig. 8). Pit caves rarely deliver water directly to the water table, but end above the water table. The water completes its journey to the water table as diffuse flow (Fig. 4). The fact that pit caves rarely reach the water table reflects the relatively low dissolutional potential of autogenic water derived from an epikarst. While surface dissolution is active and widespread, continued contact with carbonate rock as the water moves downward through the vadose zone consumes dissolutional capability. The active lifetimes of individual pit caves is relatively brief, as their downward development is arrested when a newly formed pit cave develops upstream in the epikarst and pirates their recharge. This process forms pit complexes, where the landscape is studded with numerous pit caves, far more than seem justified based on the available catchment and climate (Pace et al., 1993). Pit complexes represent accumulated pit cave development and abandonment over time. In the Bahamas, pit-cave complexes have developed in eolianites that are only 125,000 yr old (Fig. 9); the pit caves themselves must have formed at a faster rate to have produced a complex containing both active and abandoned pit caves (Pace et al., 1993).

Fig. 8 (above). Typical pit cave, Isla de Mona, Puerto Rico. Pronounced vertical grooving common to vadose dissolution can be seen adjacent to theperson.

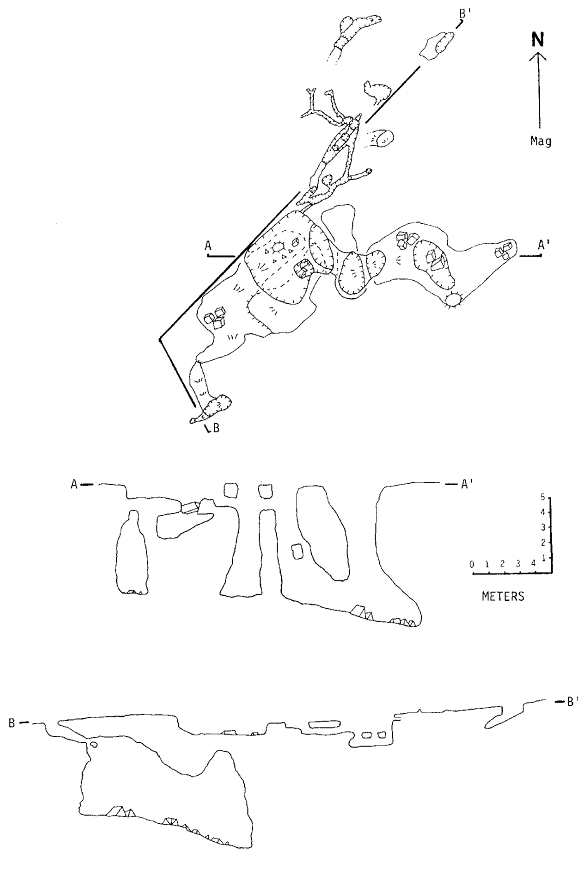


Fig. 9 (left). Map and cross section of a typical pit complex at Sandy Point, San Salvador Island, Bahamas. Note the dendritic pattern of shallow channels in the epikarst, and the series of pits associated with the shallow flow system.

On islands such as Bermuda, where the carbonates consist of a thin veneer over noncarbonate rocks, vadose flow is channeled along the base of the limestone contact, which results in the lateral growth of vadose voids. Subsequent collapse of these voids, with continued dissolution of the collapse debris, creates large chambers that may stope many tens of meters toward the surface (Fig. 10A) (Palmer et al., 1977; Mylroie, 1984b). Though technically not pit caves, these collapse caves owe their origin to dissolutional activity in the vadose zone (Fig. 11). A similar phenomenon is reported from Kangaroo Island, Australia (Jennings, 1968).

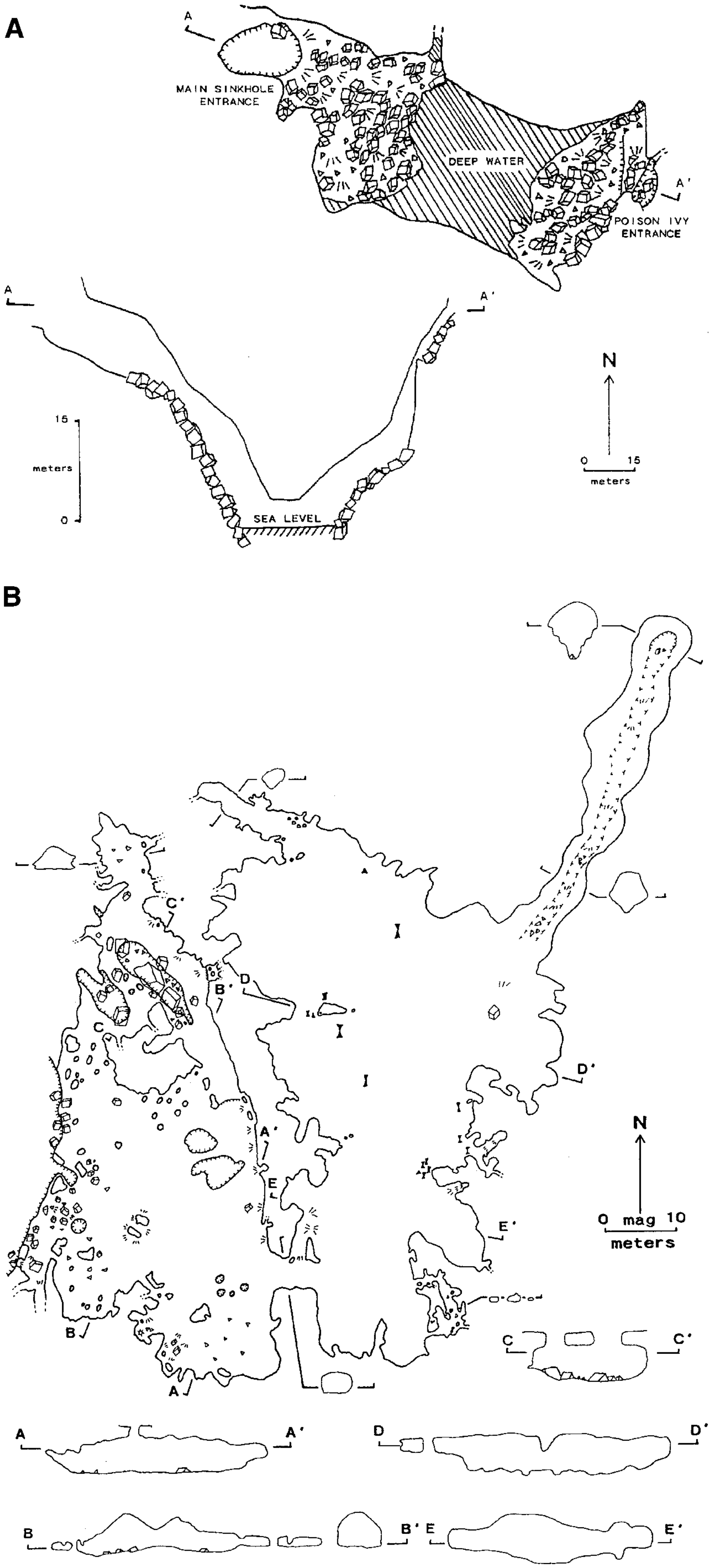


Fig. 10. Maps with cross sections of typical caves formed by vadose-induced collapse (A) and flank margin conditions (B). Cave walls shown in bold line, collapse debris shown as blocks, slopes shown as short diverging lines, stalactites and stalagmites as solid triangles, hachures indicate a vertical drop (hachures point to lower elevation), diagonal lines indicate water. (A) Church Cave, Bermuda, formed by stoping upwards from a deeper void developed by vadose dissolution at the carbonate/igneous rock contact. Note that the floor of the cave is entirely collapse debris, sediment, or sea water. Vertical scale is 2x horizontal scale (re-drawn from Mylroie, 1984b). (B) Salt Pond Cave, Long Island, Bahamas, a flank margin cave. The cave has an irregular phreatic morphology as discussed in the text, and is horizontally extensive but vertically restricted.

Fig. 11. Photograph of a portion of Admiral's Cave, Bermuda. Note the angular, broken nature of the ceiling, the result of upward progradational collapse of a deep-seated void. Photograph by A. N. Palmer.

## Flank margin caves

In carbonate platforms, large phreatic dissolution voids, called flank margin caves, form preferentially along the margin of the discharging freshwater lens as a result of freshwater/saltwater mixing (Fig. 4) (Mylroie and Carew, 1990). The mixing of fresh and marine water, even if both are saturated with respect to $CaCO_3$, results in a mixture undersaturated with respect to $CaCO_3$ (Plummer, 1975). This phenomenon has been recognized as a major means of cave production in the Yucatan of Mexico (Back et al., 1986), where fresh water discharges are high because the Yucatan carbonate platform is fed by allogenic recharge from the North American continent to the west. Based on models from the Yucatan, Sanford and Konikow (1989) determined that large-scale dissolution and cave production resulting from simple physical mixing of fresh and marine water could not operate effectively on small carbonate islands due to limitations of time, catchment and discharge. Despite this evidence from aquifer modelling, numerous caves are found on small carbonate islands. The dissolution that produces these phreatic voids is only partly the result of physical mixing of fresh and marine waters (Smart et al., 1988a; Mylroie and Carew, 1990). In addition, the presence of organics in the water allows oxidation that produces further $CO_2$ that drives carbonate dissolution. This process also results in anoxic conditions in the mixing zone of the freshwater lens. Complex oxidation/reduction reactions involving sulfur can occur there, producing acids that lead to further dissolution. Such reactions have been implicated in the development of large phreatic caves in the Bahamas (Bottrell et al., 1991, 1993; Mylroie and Balcerzak, 1992).

Flank margin caves have a morphology that is common to caves formed by mixed-water dissolution in other geologic environments (Fig. 10B). That morphology includes large, globular chambers, bedrock spans, thin bedrock partitions between chambers, tubular passages that end abruptly, and curvilinear phreatic dissolutional surfaces (Figs 12 and 13) (Mylroie, 1991; Mylroie et al., 1991). These caves lack ablation scallops, stream channels, and other indications of turbulent conduit flow. Flank margin caves are not conduits, but rather mixing chambers. They receive water from the lens in the island interior as diffuse flow, and discharge that water, after mixing, as diffuse flow to the sea. The caves develop without an external opening to the sea or the land. Entry today is gained as a result of surface erosion breaching into the cave (Fig. 10B).

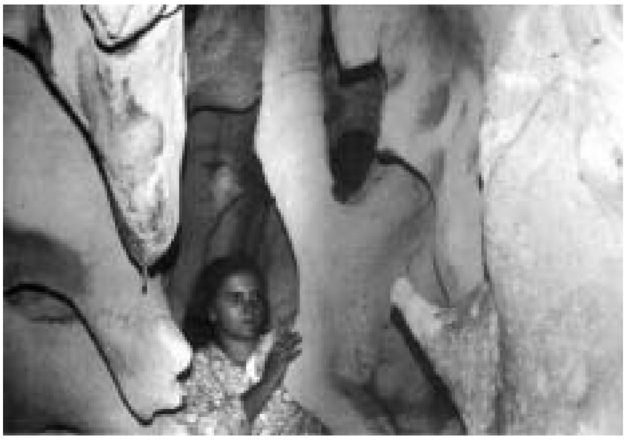

Fig. 12. Photograph of a portion of Lighthouse Cave, San Salvador Island Bahamas. The depositional dip of the eolianites can be seen from upper right to lower left. The configuration of rock pillars and pendants is typical of rock dissolution in the phreatic zone.

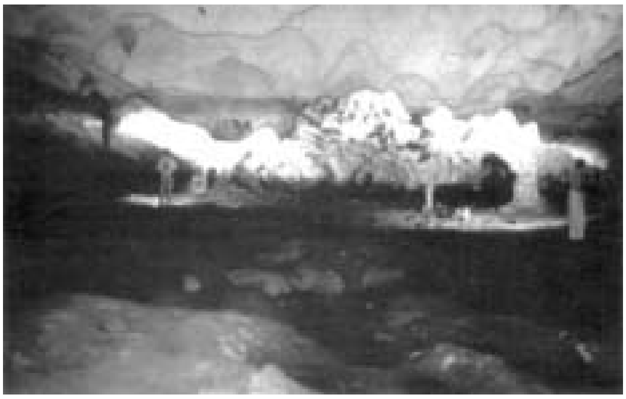

Fig. 13. Photograph of a portion of the main inner chamber of Salt Pond Cave, Long Island, Bahamas (see map, Fig. 10B). Floor and ceiling show typical phreatic morphology; dark floor stain is caused by guano, since mined out. The cave is horizontally extensive, but vertically restricted.

Inland from the lens margin, at the top of the lens where vadose and phreatic fresh waters mix, smaller phreatic dissolution voids may also develop (Pace et al., 1993). Collapse of the thin bedrock roofs of these voids form broad, vertical-walled depressions up to 10 meters across, called "banana holes" in the Bahamas (Fig. 4). In both banana holes and flank margin caves, the phreatic voids have limited vertical development but are horizontally extensive, the opposite of the pattern seen in pit caves. In the Bahamas, flank margin caves and banana holes are found at elevations of 1 to 6 m above sea level. The Bahamas are tectonically stable, undergoing only isostatic subsidence. Therefore, these caves could only have formed during a glacio-eustatic sea level highstand that reached elevations above modern sea level. Given the subsidence rate of the Bahamas, and the age of these Late Quaternary carbonates, only the last interglacial sea level highstand centered approximately 125,000 years ago (oxygen isotope substage 5e) could have produced the caves (Mylroie et al., 1991). This highstand was above modern sea level for only about 15,000 years (Chen et al., 1991); at that time, the Bahamas consisted of islands even smaller than today, as all land below 6 m elevation was inundated by the sea. These phreatic caves formed in fresh water lenses of very small size in as little as 15,000 years (Mylroie et al., 1991; Carew and Mylroie, 1992, in press). Rapid cave development by the complex geochemistry of the mixing zone leads to a definitive diagenetic record in the cave wall rock that includes trace amounts of dolomite and survival of significant amounts of aragonite in these young rocks (Vogel et al., 1990; Schwabe et al., 1993). Flank margin caves have been described from a number of sites in the Bahamas (Mylroie, 1988; Carew and Mylroie, 1989; Mylroie et al., 1991) and from Isla de Mona, Puerto Rico (Frank, 1993; Mylroie et al., 1993).

### Fracture caves

Many Quaternary carbonate platforms are steep sided. Such steep slopes are prone to mechanical failure, and that may be a major part of how carbonate platform margins are modified through time (Mullins and Hine, 1989). Fractures parallel to bank margins are common in the Bahamas (Daugherty et al., 1987; Carew and Mylroie, 1989; Carew et al., 1992). These fractures are commonlyh the site of cave systems with extensive vertical and linear development (Palmer, 1986). Such fracture caves may also represent a means by which Neptunian dikes and fissure fills are developed (Smart et al., 1988b). Fracture caves are not dissolutional in origin; however, once they are formed, they act as pathways for water flow into and/or out of the carbonate platform. While they may form without the platform becoming emergent, platform emergence, with subsequent dissolution at the discharging margin of the fresh water lens, may help promote overall rock weakness that leads to bank-margin collapse and fracture development. During glacio-eustatic sea level lowstands, loss of buoyant support that was provided by the water during the highstand is probably a contributing factor in the fracture development.

## Effect of sea level change on karst processes

Sea level change has an important impact on island karst. Sea level position controls the location of the freshwater lens, and therefore the placement of vadose and phreatic dissolutional environments (Mylroie and Carew, 1988). Whereas the development of vadose voids can occur at a variety of elevations between the surface and the water table, the development of phreatic dissolution voids occurs at discrete horizons that represent past sea level stillstand positions. Flank margin caves are especially indicative of sea level position, because they form in the margin of the lens, where it thins near sea level.

Because flank margin caves develop at the margin of the lens at the edge of islands, they are vulnerable to destruction by scarp and hillslope erosion during subsequent platform emergence. Such erosion appears to be the origin of many long, linear notches found in the sides of hills in the interior of Bahamian islands that were formerly interpreted as fossil bio-erosion notches (Fig. 14). Most of these notches are now thought to be the eroded remnants of flank margin caves (Mylroie and Carew, 1991). Such features may be preserved in the rock record, but whether these features originated as bio-erosion notches or flank margin caves makes little difference in their usefulness in determining past sea level position.

In the Bahamas, Quaternary glacio-eustatic sea level changes have repeatedly moved vadose, fresh-water phreatic, mixing zone, and marine phreatic environments through a significant elevation range. The top of the freshwater lens has been as high as +6 m, and as low as -125 m (Carew and Mylroie, 1987). The geochemically active mixing zone would have covered an even larger vertical range, as the mixing zone extends well below sea level (to -30 m today on Andros island). In addition to vertical changes as sea level fluctuated during the Quaternary, the freshwater lenses and their attendant mixing zones changed horizontal position, thickness and lateral dimension as the amount of exposed

Fig. 14. Altar Cave area, San Salvador Island, Bahamas. The notch was originally interpreted as a fossil bio-erosion notch, but the undulating floor and ceiling of the feature, plus the existence of remnant calcite speleothems such as the column shown here, indicate that it is the back wall of a breached flank margin cave.

platform changed. Caves found at depth in the Bahamas today represent the cumulative dissolutional effects of many sea level events. Many of these caves are accessible through blue holes, which are water-filled shafts that commonly extend downward as much as 100 m. Blue holes are polygenetic; that is, they developed variously as open portions of bank-margin fractures, as prograding collapse (stoping) from voids at depth, or as drowned pit caves formed during a sea level lowstand (Burkeen and Mylroie, 1992). Many contain subaerial speleothems, which indicates that they have been through at least one vadose/phreatic cycle as sea level has changed in response to glacio-eustasy (Palmer, 1985). The overprinting produced by numerous sea level changes, combined with bank-margin fracture development and cavern collapse, makes proper interpretation of the history and origin of blue holes extremely difficult.

## Karst processes and the development of porosity and permeability

In carbonate islands, dissolution can produce large-scale porosity in a variety of ways over a significant vertical range. This porosity development can occur in a very short time and requires only a minimal area of exposed platform. It is important to note that the term porosity has come to be casually, but inappropriately, equated to permeability, when in fact the two terms identify distinct rock properties (Lucia, 1993). Over time, the redistribution of carbonate material by diagenesis usually produces a decrease in bulk porosity, but if karst processes occur there is a consequent increase in permeability as continuous dissolutional flow paths develop.

For karst processes to function, some portion of the carbonate bank must be emergent to collect meteoric input, or there must be an adjacent landmass that delivers allogenic recharge to the carbonates. Research from the Bahamas, discussed earlier, indicates that karst processes produce significant features during a time scale of tens of thousands of years. Karst features can, therefore, be expected to be produced in response to all but the fastest of sea level changes. To determine how much and where permeability will develop within the carbonate platform requires that four basic criteria be taken into account: 1) position of the lens relative to the exposed bank surface, 2) climate, 3) lithology, and 4) rate and magnitude of sea level change.

## Freshwater lens configuration

### *Sea level change*

The starting point for discussions of island karst processes and permeability development is a shallow carbonate platform undergoing carbonate deposition. If the platform is submerged, there is no autogenic freshwater input. If the platform is isolated, there is no allogenic freshwater input from the subsurface and the carbonates are uniformly experiencing marine phreatic conditions. Depositional shoaling, wind, and wave action can produce local areas of emergence without sea level change, and these shoals can develop their own fresh-water lenses and begin to experience meteoric diagenesis (Budd and Land, 1990). Such land phenomena, however, tend to be very small (< 1 km$^2$). A local (tectonic) or eustatic sea level change would be necessary for a large portion of a platform to become emergent. Platforms that become emergent for whatever reason are subject to autogenic input of meteoric fresh water (Fig. 15A).

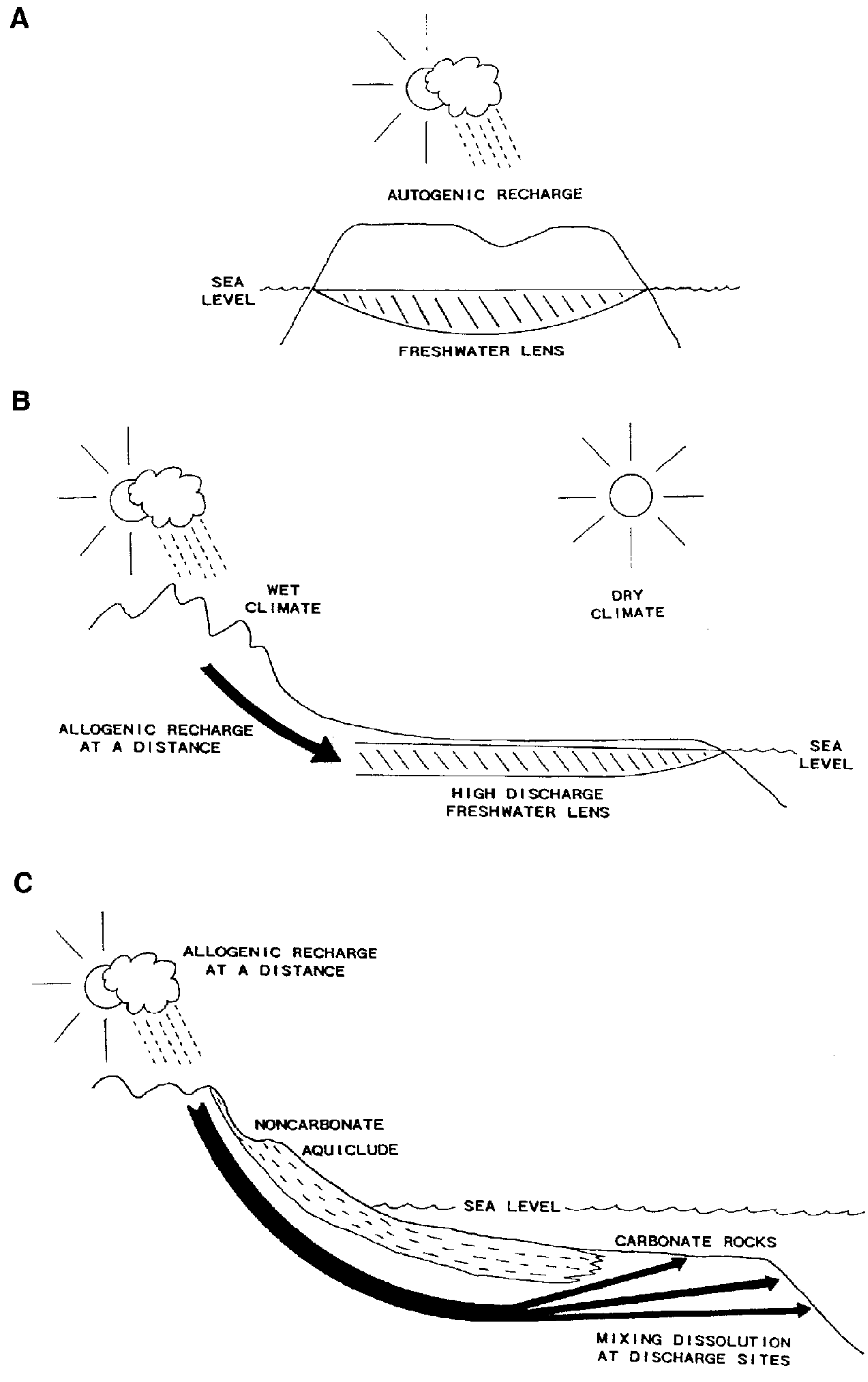


Fig. 15. Diagrammatic representation of various carbonate platform recharge situations. (A) Simple autogenic recharge. (B) Allogenic recharge at a distance, with a high discharge freshwater lens in carbonate rocks under conditions that are locally arid (similar to Yucatan, Mexico). (C) Allogenic recharge at a distance that produces submarine fresh-water discharge. Mixing-zone dissolution can occur at the platform surface and within the platform, even though the carbonates themselves were never subaerially exposed.

*Allogenic recharge*

Emergent carbonate platforms that grade landward into substantial non-carbonate land masses receive allogenic recharge in the subsurface. The resultant groundwater body may have characteristics that are not in agreement with local conditions (Fig. 15B). An excellent example is the Yucatan, an emergent carbonate platform that extends westward into the landmass of Mexico (Back et al., 1986). The carbonate aquifer receives substantial allogenic recharge from highlands to the west. Despite the local semi-arid conditions in the carbonate terrain, the fresh-water lens is well developed and has a high discharge.

If the carbonate bank shares an aquifer with a distant meteoric catchment (Fig. 15C), it is possible that this aquifer can recharge the carbonate bank from below. Mixing-zone geochemical conditions could then occur within the carbonate platform. If the aquifer discharges through the carbonates of the bank to the ocean, mixing-zone dissolution could occur at the discharge point, and produce an unique in situ submarine karst. Such a scenario has been hypothesized for the Florida-Hatteras Slope (am Ende and Paull, 1991).

*Amplitude of emergence*

The degree to which a bank is emergent will control many aspects of karst development, and, therefore, significant aspects of permeability formation. If the emergence is slight, then the water table is just below the surface, and the epikarst communicates directly with the phreatic zone. The surface ecosystem has ample water supply and significant biological productivity, which results in high soil $CO_2$ that drives karst processes in the epikarst and vadose zone. Interior water bodies are likely to occur if topographic depressions intersect the top of the lens. If the climate is humid, these lakes will recharge the aquifer, and the water-filled depressions will enlarge by dissolution (Fig. 16A). If the climate is arid, the lakes will experience excessive evaporation and the underlying marine groundwater will be upconed, thereby partitioning the freshwater lens, as reported for San Salvador Island (Davis and Johnson, 1989) and Exuma Island (Vacher and Wallis, 1992), Bahamas (Fig. 16B). In low-lying areas where upconing has occurred, or in coastal lowlands where saltwater intrusion is extensive, the mixing of meteoric water with saline water in the epikarst results in an extremely jagged and fretted rock surface (Fig. 2). In the Bahamas, such surfaces are called "moonrock" (Davis and Johnson, 1989) because of the cratered and chaotic appearance of the rock surface. If this epikarst can be buried and preserved, it has the potential to form a laterally extensive high permeability zone with limited vertical extent.

If the platform is significantly emergent, then the epikarst is separated from the freshwater lens by a substantial vadose zone (Fig. 17). If the topographic depressions do not penetrate down to the top of the lens, evaporative upconing of underlying marine water does not occur, moonrock does not form, and the epikarst is dominated by meteoric karst forms. If the emergence is significant, then the surface ecology is diminished because only some plants will be able to reach deep enough to tap the freshwater lens. Lower organic productivity will mean less soil $CO_2$ and subsequently lessor amounts of karst development in the epikarst and the vadose zone.

Slight emergence will produce a better developed epikarst than significant emergence. Additionally, slight emergence will tend to superimpose the epikarst onto the dissolutional zone that occurs where vadose and phreatic waters mix at the top of the water table. In the rock record, the proximity of these dissolutional environments may lead to important permeability. When the platform is significantly emergent, two permeability zones develop with respect to the vadose zone: one at the surface epikarst and one at the top of the freshwater lens. Neither horizon is likely to be as permeable as the composite one developed when emergence is slight.

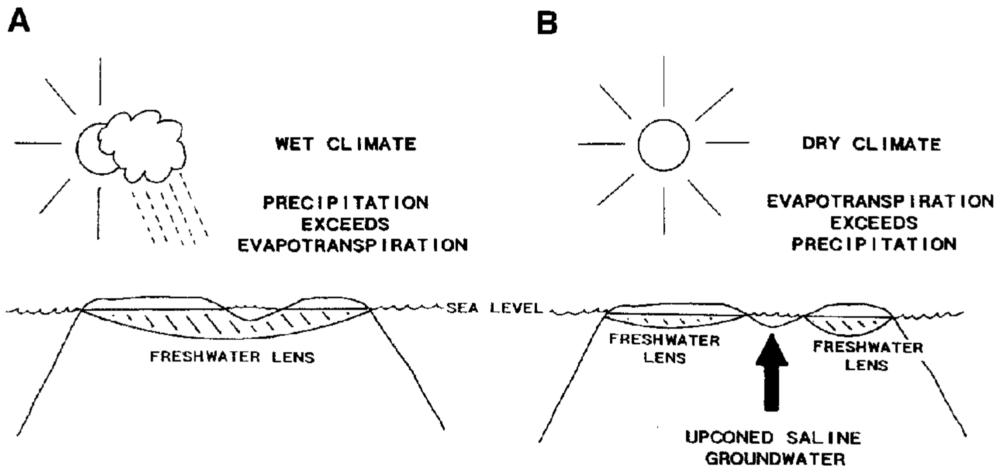


Fig. 16. Diagrammatic representation of carbonate islands where the lens is shallow and in communication with the epikarst. For simplification, the diagrams assume uniform lithology and uniform permeability, conditions unlikely in the real world. (A) In a wet climate, where precipitation exceeds evapotranspiration and where interior depressions intersect the lens, they form freshwater lakes and marshes, which recharge the lens. (B) In a dry climate, where evapotranspiration exceeds precipitation and where interior depressions intersect the lens, evaporation removes the exposed lens and saline groundwater is upconed to the surface. Interior water bodies are saline or hypersaline.

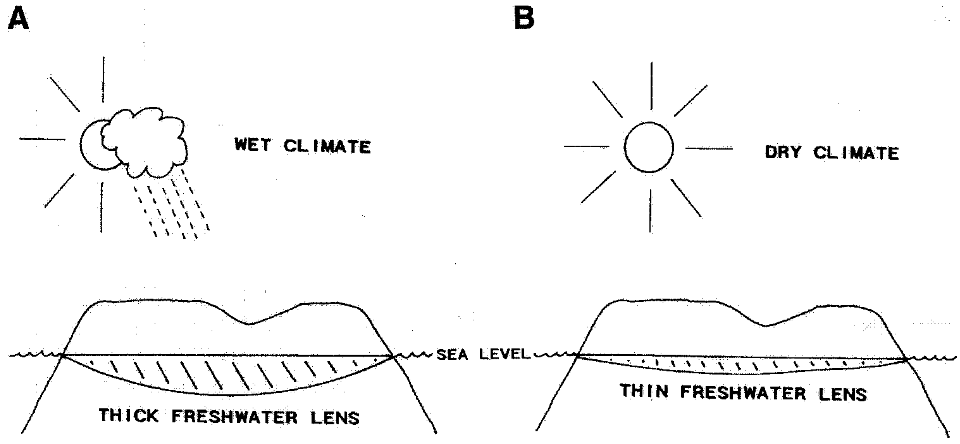


Fig. 17. Diagrammatic representation of the effect of climate on a freshwater lens separated from the epikarst by a substantial vadose zone. For simplification, the diagrams assume uniform lithology and uniform permeability, conditions unlikely in the real world. (A) The large amount of water recharge from the wet climate produces a thick freshwater lens. (B) The small amount of water recharge from the dry climate produces a thin fresh-water lens.

*Effects of climate*

Given a carbonate platform of uniform lithology with a substantial amount of emergence, climate differences will change the position and nature of karst processes at depth. If the climate is humid, the lens will have ample recharge, will be thick, and discharge will be high, relative to a lens formed under arid conditions in the same physical setting (Fig. 17A). Because the humid environment generates a thick lens, the base of the lens will be well below sea level. The greater discharge from the lens will entrain more of the underlying marine water, and the mixing zone will be thick as well. The resulting dissolutional permeability will not correlate with sea level except at the discharging lens margin.

On the other hand, in the same physical setting, if the climate is dry, the lens will have less recharge, will be thinner, and discharge will be lower (Fig. 17B). Because the lens is thin, the base of the lens will be relatively close to sea level, and the mixing-zone dissolutional permeability will develop near sea level. If a thick vadose zone exists, it will prevent the arid climate from causing evaporative upcoming of marine water into the lens.

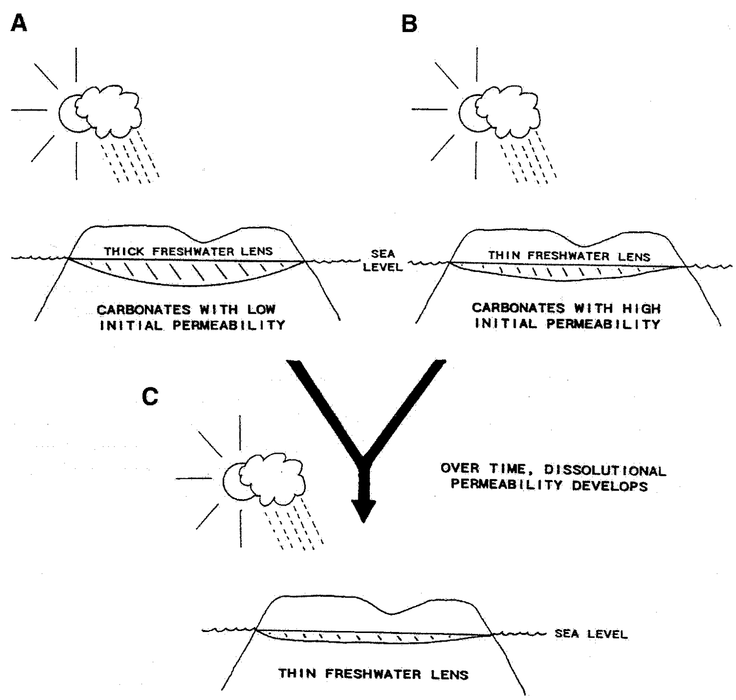


Fig. 18. Diagrammatic representation of carbonate islands with different primary permeabilities. For simplification, the initial and subsequent permeabilities are assumed to be uniform over the entire platform, an unlikely occurrence. (A) With low primary permeability, groundwater transmission is impeded and the lens is thick. (B) With high primary permeability, groundwater discharge is facilitated and the lens is thin. (C) Through time, the development of secondary dissolutional permeability makes both lenses efficient in the transmission of water, and the lenses become thinner.

*Effects of lithology*

Two carbonate platforms with identical amounts of emergence and identical climates may still exhibit different lens configurations depending on the permeability of the rock. For simplicity, the discussion here assumes single lithologies for the sample platforms; in reality significant lithologic differences, and hence lens differences, occur in short distances on carbonate platforms. A platform composed of micritic material is likely to have low primary porosity and permeability; so the lens will discharge slowly, thereby causing the water to "pile up" as a thick lens (Fig. 18A) (Vacher, 1988). A platform with the same conditions except that it is composed of coarse bioclastic material is likely to have high primary porosity and permeability, so the lens will discharge readily and will be thin (Fig. 18B). In the latter case, the mixing zone will be shallower, relative to sea level, than in the former case. In the rock record, the resulting permeability horizon (if preserved) produced by mixing zone dissolution will be closer, in vertical section, to the platform exposure surface for rocks with high primary porosity than for rocks with low primary porosity.

## Rate and magnitude of sea level change

*Carbonate platforms*

The rate at which sea level changes and the duration of stillstands at any given sea level position will control the distribution of karst porosity and permeability produced by the freshwater lens. Time alone is significant; the more time a carbonate rock body has spent in a freshwater lens, the more permeable it will become as dissolutional pathways develop. Such a relationship has been demonstrated for Bermuda (Vacher, 1988). With increased time, the differences in lens shape produced initially by primary porosity will diminish as karstic permeability becomes fully developed in the lens, and the lens thins (Fig. 18C).

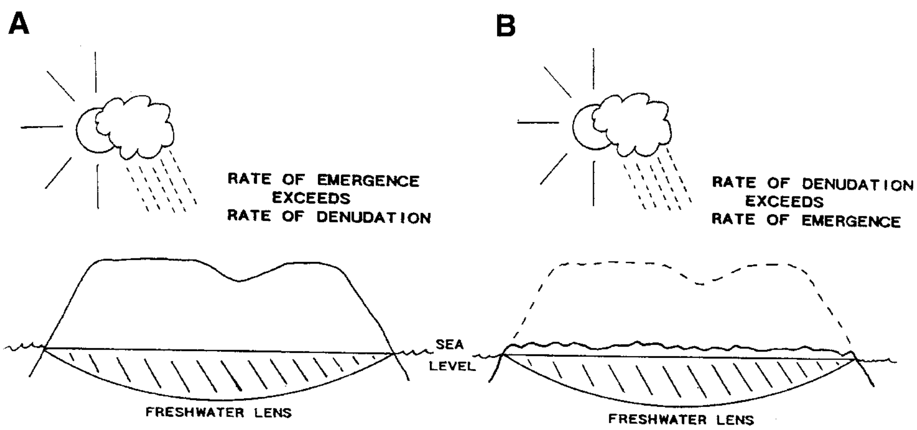


Fig. 19. Effects of rate of emergence versus denudation rate. (A) If the rate of emergence greatly exceeds the denudation rate, the epikarst loses contact with the lens, and the vadose zone enlarges with time. (B) If the denudation rate exceeds the rate of emergence, the epikarst stays in contact with the lens and the vadose zone is always minimal.

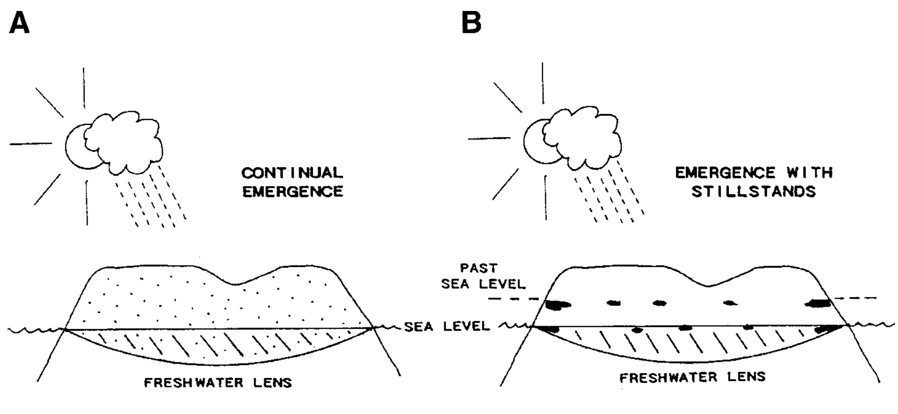


Fig. 20. Effects of steady emergence versus episodic emergence with sea level stillstands. (A) When emergence is rapid and uniform, the development of minor dissolutional porosity and permeability is also uniform throughout the emergent portion and lens of the carbonate island (shown as stippling). Large-scale dissolutional voids may not develop. (B) When emergence is punctuated with times of no emergence, the dissolutional potential of the freshwater lens is concentrated and numerous large dissolutional voids develop in the lens (shown as solid patterns).

If a carbonate platform experiences slow, steady emergence through time, initially the fresh water lens will be a shallow lens (i.e. the epikarst will be in contact with the freshwater lens), and with time the lens will migrate downward through the platform as sea level falls. If the emergence rate exceeds the denudation rate, then the epikarst will lose contact with the freshwater lens, and the vadose zone will enlarge with time (Fig. 19A). The mixing zone and its dissolutional effects will migrate downward through the carbonate platform. The degree of alteration of the rock at any given level will depend on how long the lens is at that level (all other influences being equal).

If the rate of emergence is slow and does not exceed the karst denudation rate, the landscape will be lowered as well, and the platform will maintain a shallow lens configuration with the epikarst in contact with the freshwater lens (Fig. 19B). Because the denudation rate is controlled by climate, variations in climate could fortuitously combine with a variety of platform emergence rates to produce the same end result. Rapid emergence will disperse the development of both phreatic and vadose dissolutional permeability through a large section the platform thickness, whereas slow emergence or a stillstand will concentrate such dissolutional permeability at a single horizon approximating the elevation of the sea level stillstand.

A steady, continual, and rapid emergence of a carbonate island will result in a relatively uniform but low level of porosity and permeability production (Fig. 20A). If sea level stands at specificlevels, then the mixing zone and its attendant effects (physical mixing, organic carbon oxidation, and sulfur oxidation/reduction processes) will be focused on specific zones in the rock (Fig. 20B). The development of large, phreatic dissolution voids (flank margin caves and banana holes) in carbonate platforms can depend on such sea level stillstands. Flank margin caves and banana holes from the Bahamas clearly record the high sea level stillstand of the last interglacial, and observations from submersibles has demonstrated that submerged flank margin caves can be found at specific levels that relate to past glacio-eustatic low sea level stillstands (Carew and Mylroie, 1987). The transition between these various stillstand events by glacioeustasy occurred too fast to allow mixing-zone dissolution processes the time to make large caves at intervening elevations.

As noted earlier, not only is the rate of sea level change important, but reversals in the direction of sea level change have a significant impact. The glacioeustatic sea level fluctuations of the Quaternary repeatedly subjected the carbonate rocks of the Bahamas to a variety of subaerial, vadose, freshwater phreatic, mixing zone, and marine phreatic conditions. The overprinting of the rock with multiple karst and diagenetic features from these fluctuations has introduced a bewildering variety and complexity into the Bahamian rock record. These complexities can be very difficult to resolve after millions of years, especially if geologists are looking at scattered outcrops and well records.

*Carbonate ramps*

In contrast to a bank setting, when a carbonate ramp undergoes emergence, successively larger areas of carbonate rock are exposed through time. If the rate of emergence is slow, then the degree of epikarst and soil development on the platform will vary laterally; that is, the part of the ramp that becomes emergent first will have the greatest degree of karst and soil development, and the part last exposed will have the least development (Fig. 21A). On the other hand, if the emergence is rapid, relative to the rate of karst and soil development, then the emergent ramp will have similar karst and soil development across its entire breadth. If the platform is subsequently submerged, burying the exposure surface in new sediment, the last exposed outcrops will be the first covered, and their karst and soil development will be much less than that of the outcrops farther up the ramp, which will not be buried until submergence of the ramp is almost complete. All other things being equal, the differences in degree of karst and soil (paleosol) development on the ramp will be due solely to duration of exposure.

In the subsurface, the migration of sea level across a carbonate ramp will cause the freshwater lens to migrate as well, and successively different parts of the subsurface will be in the appropriate position for flank margin cave development (Fig. 21B). In platform settings, flank margin cave development can be continuous along the lateral margin of the lens, as noted on Isla de Mona (Frank, 1993; Mylroie et al., 1993) and in the Yucatan (Back et al., 1986). In a ramp situation, this laterally continuous zone of cave development will migrate with the migration of the lens. One of the possible end results of this void production is subsequent collapse of these voids (Fig. 22). On carbonate ramps, if the migration of the flank margin conditions up (transgression) and down (regression) the carbonate ramp is slow enough to allow full dissolutional expression at each elevation, the result may be to produce successive arrays of cave chambers that subsequently collapse. Over the long term, this will produce (in the subsurface) an extensive solution-collapse and breccia facies. Conceptually, the process is similar to the long-wall coal mining process, in which the working face is advanced into the seam, and the mined void is left behind to collapse.

The characteristics of the collapse features produced by the processes described above depends on many factors. Unlike stream caves formed in continental settings, flank margin caves are not conduits, but mixing-zone chambers. Flank margin caves do not contain fluvial deposits unless the voids collapse to the surface and allow surficial waters to wash material into the caves. If the overburden above the caves were thick, collapse processes would stabilize before the surface was reached, and the cave chambers and their associated collapse debris would be free of material washed in from the surface. On the other hand, if the overburden is thin, collapse would open cave chambers to the surface (especially during a regression), allowing fluvial sediments to work their way into the collapsed voids. In any case, carbonate platforms with autogenic diffuse recharge do not have significant surface streams and fluvial transport is a minor and very local occurrence. Therefore, caves developed in flank margin settings should not have significant volumes of fluvial debris. Mass wasting of soil material into caves opened by collapse or penetrated by pit caves can be significant, however, and cave fills due to this process are recognized in the rock record (Jones and Smith, 1988) (Fig. 23). The presence or absence of surface sediments in paleokarst caves is not sufficient, by itself, to determine whether the caves developed as mixing-zone dissolution chambers or as through-flowing conduits. In oceanic settings, carbonate platforms receiving autogenic recharge should develop phreatic caves notably free of washed-in fluvial material.

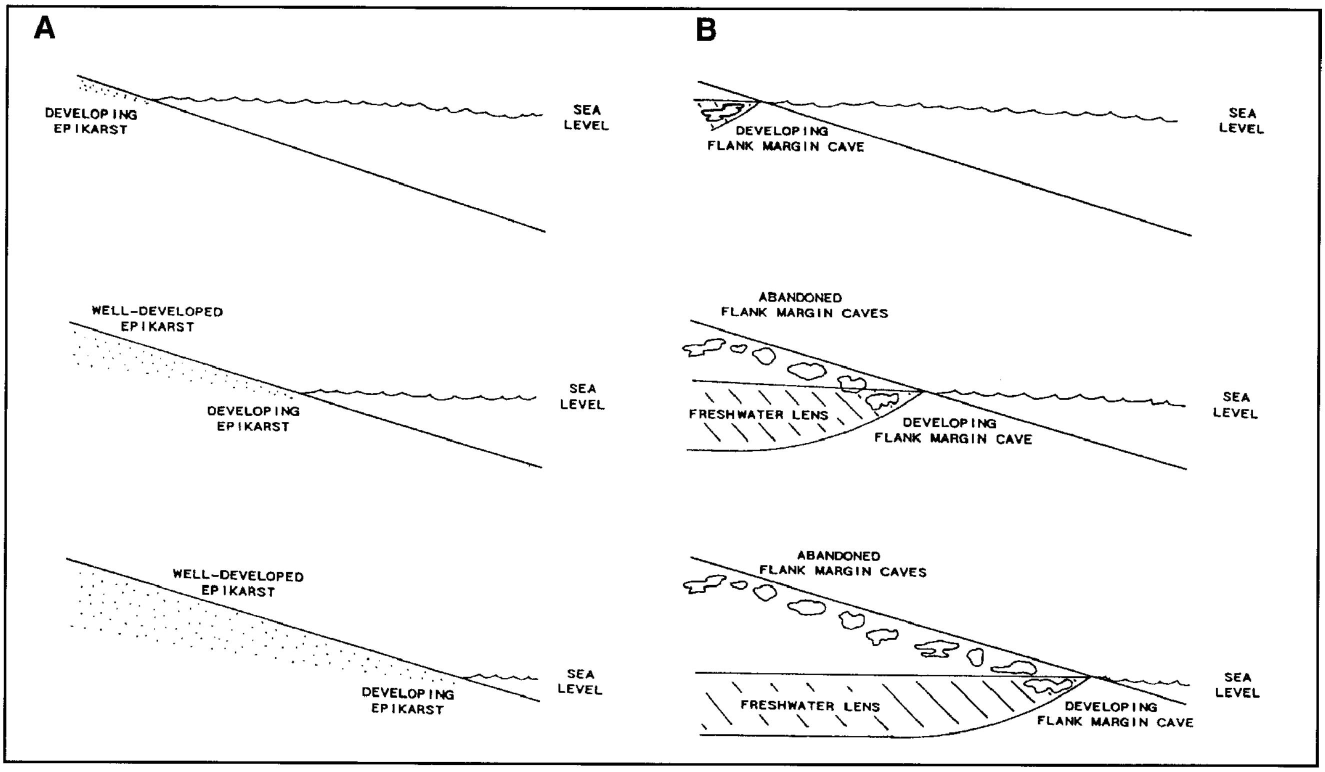


Fig. 21. (A) Epikarst development during emergence of a carbonate ramp. Because of exposure time (all other things being equal), the epikarst at the highest position is the best developed, that at the lowest is least developed. Were sea level to reverse and transgress the platform, epikarst development high on the ramp would still continue the longest. (B) Flank margin cave development during emergence of a carbonate ramp. If the rate of emergence is less than or equal to the time necessary for flank margin cave development, a continuous series of caves would be expected on the ramp. Subsequent erosional degradation and collapse of these caves would produce a continuous horizon of solution-collapse breccia. This figure has been separated into parts A and B, and pit caves omitted, for clarity.

Fig. 22. Edge of Isla de Mona, Puerto Rico, showing breached flank margin caves receding into the distance. The talus in the background represents the former outer walls of these chambers.

Fig. 23. Infilling paleosol breccia in Cueva de Pajaros, Isla de Mona, Puerto Rico; lens cap at left for scale. This material piped into the cave from the surface, lithified, and has been subsequently etched by phreatic dissolution, most clearly seen at lower left and right.

## Karst to paleokarst: the rock record

The material presented to this point has been based on examples from Quaternary carbonate islands. If "the present is the key to the past", then the rock record should contain karst preserved as paleokarst. Successful identification of paleokarst in cores and outcrop has important implications for sequence stratigraphy, paleo-environments, and hydrocarbon reservoirs. Caves, whether conduits in continental settings or mixing chambers in island settings, are regions of very high porosity and permeability. Can paleokarst caves be easily located, and if located, easily identified? In modern karst environments, a major part of the research effort is to locate and characterize caves. Caves are difficult to find, and determining their water flow paths requires sophisticated techniques such as quantitative dye tracing and humanly rigorous exploration. To locate and characterize unknown and unenterable caves millions of years old and thousands of meters beneath the surface is a daunting task.

The first question is, do cave and karst features recognizably survive time and burial? The literature has many references to paleokarst (James and Choquette, 1988; Bosak, 1989), so clearly the answer is yes; in most cases it has been recognized in surface outcrop, or after the fact in cores and mines. Less commonly has there been deliberate prospecting for paleokarst in the subsurface.

Do dissolution voids survive deep burial in carbonate island settings? In the Bahamas, cavernous porosity has been penetrated by wells at depths ranging from 21 m to 4,082 m, the deepest void being large enough to accept 2,430 m of drill pipe (Meyerhoff and Hatten, 1974). On Isla de Mona, Puerto Rico, caves with volumes in excess of 100,000 $m^3$ have survived since initial uplift over 1Ma (Briggs and Seiders, 1972; Mylroie et al., 1993). Dean's Blue Hole, on Long Island Bahamas, is a upwardly-prograding collapse feature 202 m deep, with a volume of $1.15 \times 10^6$ $m^3$ (Wilson, 1994). The initial void, which accepted collapse material as the blue hole prograded upward, formed below any past Quaternary sea-level lowstand, and thus represents a cave of significant age (pre-Quaternary). Clearly large voids can survive long periods of time and deep burial.

Can paleokarst cave locations be predicted in the subsurface? Based on the flank margin model presented in this paper, the margin of carbonate platforms would be the most likely spot for caves to have developed if the platform was ever emergent. The classic work of Craig (1988) from the Yates Field of west Texas demonstrates, that with large amounts of data from a producing field, good correlations can be made with models of an island freshwater lens, cave development, and cave location by borehole. Cave height was used by Craig (1988) to determine mine lens thickness and position. Cave height is a poor measure of these characteristics, because adjacent cave horizons formed on successive but closely spaced sea level stillstands can merge by dissolution and collapse. If a borehole intersects a pit cave, it will yield a large "cave height" but be almost impossible to differentiate from a flank margin cave. The extremely large flank margin caves of Isla de Mona, Puerto Rico, the largest currently known in a subaerial position, generally have original dissolutional ceiling heights of less than 8 m. Flank margin caves, as their name suggests, tend to form on the margin of carbonate platforms. This makes them vulnerable to destruction by bank-margin fracture and other weathering processes. Flank margin caves formed in the Bahamas during the last interglacial (circa 125,000 years ago) can be found in various stages of degradation (Mylroie and Carew, 1991), suggesting that their life span isbrief. Conversely, those on Isla de Mona have survived a million years of exposure, primarily because they were so large that despite the loss of exterior chambers to cliff retreat, major portions of these caves survive (Fig. 22).

To successfully predict the occurrence of paleokarst caves in ancient carbonate platforms requires use of additional information (Kerans, 1988). Evidence of emergence is a critical factor (Saller et al., 1994). If the platform was never emergent, then the caves as described in this paper are unlikely to have ever formed, although special cases, as noted in Fig. 15C, are possible. Subaerial unconformities or evidence of mixing-zone diagenesis would be an important clue that pit caves and flank margin caves were possible. If subaerial unconformities in the carbonate section can be identified, the degree to which the epikarst has been developed can provide clues as to the climate at the time of karstification, and the degree of separation of the surface from the water table (Webb, 1994). While a paleo-epikarst may itself be a region of high permeability, the existence of an epikarst is an indication of emergence and the potential for pit caves and flank margin caves.

## Conclusions

Carbonate platforms that receive only autogenic recharge may appear to be a special case, but many areas in the world, both today and during the Pleistocene, fit this case. The Bahamas are the most notable example. With only regionally diffuse meteoric input, macroscopic karstic porosity and cave permeability occurs in three basic areas: the epikarst of the surface; the pit caves of the vadose zone, and the phreatic caves (flank margin caves and banana holes) of the fresh-water lens.

Through time, emergent carbonate platforms may develop karst features faster than other diagenetic processes can alter the carbonate rock. The groundwater geochemistry that develops carbonate-platform karst features is affected by atmospheric and soil $CO_2$, subsurface oxidation of organic carbon to $CO_2$, inorganic mixing of fresh and saline waters, and oxidation/reduction reactions involving sulfur. A possible area of future work is to study these diverse and complex chemical reactions to see if they introduce unexpected variations in stable isotopes that may confuse results aimed at assessing the occurrence of exposure events.

Climate and lithology are obvious controls of karst processes. The amount of emergence of carbonate terrains, and the rate at which this emergence occurs, interacts with climate and lithology to place karstic porosity and permeability, especially that developed within the fresh-water lens, at a variety of locations within the carbonate section. Because macroscopic dissolutional voids that are meters to tens of meters in size can form in as few as tens of thousands of years, even minor variations in the rate of sea level change can greatly affect the size and location of the caves. The primary site of flank margin cave formation is at the margin of the freshwater lens. The freshwater lens margin occupies the exposure margins of carbonate platforms. The caves are therefore developed in a location in which minimal erosion will disrupt and collapse the caves. This collapse may produce breccia horizons in the carbonate section. If subaerial erosion is significant, it can remove all evidence of the caves, obscuring the important role of cave formation.

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