6.29 Flank Margin Caves in Carbonate Islands and the Effects of Sea Level

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6.29.1 Introduction

The coastal environment, as the interface between the terrestrial and the oceanic realm, creates a variety of cave-forming situations. The most obvious of these are the pseudokarst features expected to develop in a locale of rock and high energy: sea caves, tafoni, talus caves, and fissure caves (Figure 1).

When soluble rocks such as carbonates are placed in the coastal environment, dissolution can occur through a variety of mechanisms to create caves that are quite different from those occurring in the traditional karst environments of continental interiors (Palmer, 1991). The carbonate island karst model (CIKM) has been developed to explain the special and unique circumstances of dissolution cave development in coastal carbonates (Jenson et al., 2006). The main features of that model are as follows:

1. Freshwater, as a buoyantly supported body called the freshwater lens (Figure 2), exists within carbonate coasts and, by mixing with seawater, is capable of renewed...

Glossary

Carbonate island karst model (CIKM) A conceptual model that explains cave and karst development on carbonate islands and coasts as being controlled by freshwater and saltwater mixing, sea-level position, diagenetic state of the carbonate rock, and the relationship of carbonate and noncarbonate rocks regarding meteoric catchment and freshwater lens condition.

Eogenetic A term proposed by Chouguette and Pray (1970) to describe carbonate rocks in the unburied or early burial stage, when diagenetic activity is limited and influenced by meteoric processes.

Flank margin cave A dissolutional void or cave produced in the distal margin of the freshwater lens, under the flank of the enclosing landmass, by freshwater mixing, organic decay, and enhanced lens flow velocities.

Mixing dissolution The additional dissolution potential achieved when freshwater and saltwater are mixed at the base of the freshwater lens. Similar additional dissolution can occur when vadose freshwater mixes with phreatic freshwater at the top of the lens.

Syndepositional cave A dissolutional void or cave developed in eogenetic carbonate rocks still within their environment of deposition, a subcategory of syngenetic cave.

Syngenetic cave A dissolutional void or cave developed in eogenetic carbonate rocks still undergoing consolidation and diagenetic maturation.
dissolution even though both the seawater and freshwater are themselves initially saturated with respect to CaCO₃ (Plummer, 1975).

2. The position of the freshwater lens is tied to sea level, so the lens and its associated dissolitional environments are subject to migration as a result of eustatic events (such as glacioeustasy) or local events (such as tectonics), both of which can operate rapidly in terms of geologic time.

3. Globally, coastal limestones are predominantly eogenetic, or diagenetically immature, such that primary features, such as depositional porosity and initial allochem geochemistry, are commonly unaltered (Vacher and Mylroie, 2002).

4. The configuration of the carbonate rocks relative to adjacent noncarbonate lithologies helps control the freshwater lens shape and distribution, and the chemistry of the

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**Figure 1** Pseudokarst caves found along carbonate coasts. (a) Sea cave developed in late Pleistocene aeolian calcarenites, San Salvador Island, Bahamas. (b) Tafoni developed in Holocene aeolian calcarenites, San Salvador Island, Bahamas. (c) Talus cave, in Oligocene marine limestone blocks, Pohara, South Island, New Zealand. Person in lower right for scale. (d) Fissure cave formed in Pleistocene marine limestones by sea cliff failure, Tinian, Mariana Islands. Person in extreme upper left for scale.

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**Figure 2** Cartoon of the freshwater lens environment, showing the placement of flank margin caves. Dashed arrows indicate freshwater flow to the ocean.
freshwater recharge. The results are four basic conditions, featured here as islands to present a simple end member of the carbonate coastal condition:

(a) **Simple carbonate island.** Only carbonate rocks are present within the recharge and discharge field of the freshwater lens. Recharge is entirely autogenic, and the freshwater flow regime is controlled solely by the properties of the carbonate rock.

(b) **Carbonate-cover island.** Only carbonate rocks are exposed at the surface, and recharge is entirely autogenic. Noncarbonate rocks are present in the subsurface and may partition or distort the freshwater lens. Turbulent conduit flow may develop that is perched in the vadose zone on the carbonate/noncarbonate contact.

(c) **Composite island.** Both carbonate and noncarbonate rocks are exposed at the surface, producing autogenic and allogenic recharge to the freshwater lens. The lens is partitioned and distorted, and turbulent conduit flow develops in the vadose zone at the carbonate/noncarbonate contact.

(d) **Complex island.** Carbonate and noncarbonate rocks are complexly interrelated by syndeposition and/or tectonic structures. Partitioning, perching, and confining of the freshwater lens are possible.

The four cases discussed above are idealized categories. In actual conditions, islands may exhibit many of the presented characteristics, with transitional forms, in which case it is useful to classify portions of islands or carbonate coasts by the category that best describes the local conditions.

### 6.29.2 The Bahamas and Flank Margin Caves

The CIKM was developed as a result of work begun in the Bahamas, which fits the simple carbonate island construct. The carbonates of the Bahamas are mid- to late Pleistocene in age (Carew and Mylroie, 1995a, 1997) and are, therefore, diagenetically immature or eogenetic. Their young age, along with commonly small island size, provides stringent constraints on time and space for any dissolutional activity. In addition to being an entirely carbonate environment, the Bahamas are tectonically stable (other than slow isostatic subsidence), and sea level is controlled by glacioeustasy. The Bahamas therefore are an end member in terms of complexity compared to older, larger islands with tectonic overprints such as the Mariana Islands of the Pacific, or carbonate coasts with extensive inland recharge, such as the Yucatan of Mexico.

In the Bahamas, the largest dissolutional voids established today in the subaerial environment are flank margin caves that formed during the last interglacial sea-level highstand (MIS 5e), which occurred ~131–119 ka, when the freshwater lens and its speleogenetic environment were up to 6 m above today’s sea level (Chen et al., 1991). The term ‘flank margin’ arose from the observation that these dissolutional voids were always found in what would have been the distal margin of the freshwater lens, under the flank of the enclosing landmass (Figure 2), at a past, higher sea level (Mylroie and Carew, 1990). The caves have a consistent morphology (Figure 3) of irregular, globular rooms with small interconnections, laterally extensive parallel to the lens margin but vertically restricted (to past lens margin thickness). In the landward direction, the caves commonly break up into a maze of smaller passages and dead-end linear segments and rooms (Figure 3(a)), thought to be the site of the active dissolutional front when sea level fell and the caves became senescent.

The position of the flank margin caves in what was the distal margin of the freshwater lens (Figure 2) allows three mutually supporting mechanisms for the cave development to be considered (Mylroie and Mylroie, 2007). First, at the lens margin, two mixing environments are superimposed as the lens thins: (1) the vadose and phreatic freshwater mixing area at the top of the lens and (2) the marine and freshwater mixing area at the base of the lens. Second, both the top and bottom of the lens are density interfaces, such that organic material collects at these boundaries and, by oxidation, can release CO₂ to drive additional dissolution. If organic loading is significant, anoxic conditions and H₂S-mediated dissolution can also occur. Third, the margin of the lens is an ever-decreasing cross-sectional area delivering the integrated recharge of the lens to the sea; as a result, flow velocities are the fastest in the lens, and reactants are transported in and products are transported out quickly. Regardless of which mechanism is dominant, field evidence from across the Bahamas indicates that large dissolution-void development is restricted to the lens margin and such voids do not occur inland or ‘upstream’ in the freshwater lens.

Because of the globular nature of the caves, cave size is calculated as the areal footprint of the cave; because the caves tend to be much wider than high (Figure 3(c)), cave area is a good proxy for cave volume (Labourdette et al., 2007). Both an extensive map database of flank margin caves and computer modeling suggest that flank margin caves initiate as spot locations of dissolution within the lens margin. As the cave initiation locations within the lens margin enlarge, they create simple cave chambers. The enlargement of these chambers over time results in the intersection of adjacent chambers and an abrupt jump in cave size. Small collections of chambers, as they enlarge through time, intersect other collections of integrated chambers, and cave size jumps again. These collections of chambers result in the flattened globular pattern of cave development observed in the field. As these intersections continue, the caves expand parallel to the lens margin, as there is a finite geochemical limit to cave development into the lens, toward the island center (Figure 3(a)). The Bahamian cave database (Mylroie and Mylroie, 2007) shows that the caves, in a rank-order plot, self-select into four populations: caves under 20 m², caves 20–100 m², caves 100–1000 m², and caves over 1000 m² (Figure 4). Computer modeling (Labourdette et al., 2007), working on the assumption of spot initiation of dissolutional voids, creates a similar size ranking (Figure 5). The smaller caves developed within the active dissolutional zone of the lens margin, and so are irregular globular networks, but the larger caves are forced by the geochemical inner boundary of the lens margin to extend parallel to the lens margin, and can as a result develop a significant linear trend (Figure 3(a)).

The size of flank margin caves is fundamentally controlled by the duration of time that the lens is at a stable elevation.
Because of passive subsidence of the Bahamas (1–2 m per 100 000 years), and the few times in the Pleistocene when sea level was above modern elevations, the time window to create caves with areal sizes up to 2000 m² (or volumes up to $10^6$ m³) is restricted to the duration of the last interglacial (MIS 5e), which lasted in the Bahamas for 12 000 years, or 131–1 19 ka (Chen et al., 1991; Carew and Mylroie, 1995b). The Bahamian flank margin caves occur in mid- to late Pleistocene aeolian calcarenite ridges that can be as little as a few hundred meters long and $\leq$50 m wide. These ridges would have been tiny islands during the last interglacial, yet supported a freshwater lens with the geochemical power to create macroscopic dissolutional voids (Figures 3 and 6), in about $10^4$ years. These voids later became accessible to human explorers. The Bahamas indicate that the dissolutional processes that create flank margin caves operate under extraordinary constraints of limited time and space. Despite the rapidity with which flank margin caves form, the rapid rising and falling stages of Quaternary glacioeustasy were apparently too fast to make observable flank margin caves except at sea-level highstands and lowstands (Mylroie and Mylroie, 2007). The use of a submersible determined that caves only occurred on the bank wall of San Salvador Island at depths $\leq 105$ and $\leq 125$ m, and not upward to $\leq 60$ m depth (at which point Holocene coral overgrowth obscured the bank wall and reconnaissance ceased). These depths correspond with many of the sea-level lowstand positions of the mid- to late Pleistocene. Only when sea-level change turns around at the end of a glacial cycle is the freshwater lens resident at a specific location long enough to leave an observable cave. The same could be said for sea-level highstands, which have yielded the dry flank margin caves observed today.

Scuba diving of blue holes and other submerged cave features in the Bahamas indicates a variety of cave types and shapes. A few observations regarding blue holes are important here. The dry flank margin caves of the Bahamas today are the result of a single sea-level highstand event. As such, they are minimally overprinted by subsequent phreatic conditions. Blue holes, on the other hand, are polygenetic (Mylroie et al., 1995) and have been subaerially exposed and flooded many times as glacioeustasy fluctuated during the Pleistocene, so the caves occurring at depth are most likely highly overprinted. Cave divers report a number of long, linear caves at depths of approximately 20 m in the large Bahama Banks. Today, the Bahamas land area is $11 400$ km²; a sea-level stillstand at $\leq 20$ m would expose almost all of the Bahama Banks, an area

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**Figure 3** Characteristics of flank margin caves. (a) Map of Sistema del Faro (aka Lirio Cave), Isla de Mona, Puerto Rico, showing large chambers near the coast becoming maze like with dead-end passages inland. Note that the cave wraps around the island perimeter, following the freshwater lens margin. (b) Typical dissolutional morphology occurring in flank margin caves, Cueva del Agua Sardinera, Isla de Mona, Puerto Rico; wall cusps such as these are especially common. (c) Inner chamber of Salt Pond Cave, Long Island, Bahamas, demonstrating the wide, low chamber shape associated with the thinning margin of the freshwater lens. Note the cuspate nature of the floor and ceiling; the floor is visible as a result of guano mining. Persons left and right for scale.
of 136,000 km² (Meyerhoff and Hatten, 1974). It has been suggested that when the banks are exposed, the northwestern Bahamas become a series of very large islands, and that under these conditions, diffuse flow to the lens margin becomes inefficient, as island perimeter has increased linearly, but area (catchment) by the square, and conduit flow initiates (Vacher and Mylroie, 2002). The data also indicate that sea level was stable at those elevations for a sufficient time to allow conduits to develop. Note that San Salvador Island, where the previously described submersible work was done, increases in size only about 30% when sea level falls, because it is on a small isolated platform and, therefore, apparently does not show such conduit systems as it never became a big island during lower glacioeustatic sea-level stillstands.

### 6.29.3 Syngenetic and Syndepositional Caves

The development of caves in very young eogenetic rocks has been described as syngenetic (Ford and Williams, 2007); meaning development while the rock is still undergoing consolidation and diagenetic maturation. The development of dissolutional caves in carbonates while the rock is still within its environment of deposition is called syndepositional (Mylroie and Mylroie, 2009a). In the Bahamas, flank margin caves developed in supratidal, intertidal, and subtidal deposits as those deposits were formed by carbonate sediment progradation into lagoons. As the supratidal deposits were laid down, subaerial meteoric catchment became available and the freshwater lens advanced into the deposits, forming flank margin caves (Figure 7). Early cementation was sufficient to support dissolutional voids produced in this advancing lens. Because of the sea-level history of the late Pleistocene, both the units and the caves within them had to be deposited on the same glacioeustatic sea-level highstand, MIS 5e (Mylroie and Mylroie, 2009a).

### 6.29.4 Tectonics and Increasing Carbonate Island Complexity

Tectonics introduces complexity in flank margin cave development, but that complexity can be illuminating as regards the processes that create the caves. Isla de Mona is a tectonically uplifted carbonate island midway between Hispaniola and Puerto Rico. It consists of Mio-Pliocene carbonates with some late Pleistocene coastal units. In its 40–80-m-high coastal cliffs are numerous bands of cave openings (Figure 3(a)), including Sistema del Faro (Lirio Cave), the largest known flank margin cave in the world with 20 km of survey line covering 180,000 m² (Frank et al., 1998). Paleomagnetic analysis of cave-fill material indicates that the large Mona caves are pre-Pleistocene in age (Panuska et al., 1998). The large size of the caves is attributed to a longer duration of freshwater lens stability at a given elevation prior to the onset of high-amplitude, high-frequency glacioeustasy.
in the Pleistocene. Subsequent tectonic uplift elevated the caves beyond further sea-level change and hence overprinting. Very large caves similar to those on Isla de Mona, and also uplifted by tectonics, exist in coastal Cuba and are thought to be flank margin caves (Kambesis et al., 2009). The Bahamas indicate that flank margin caves can form extremely rapidly, in the time range of $10^4$ years or less; Isla de Mona indicates that flank margin caves can persist through time, in the range of $10^6$ years or longer.

The southern Mariana Islands of the western Pacific are tectonically uplifted carbonate islands with significant structural deformation, primarily high-angle faults. A former volcanic island arc (the active arc has shifted slightly westward), the southern Mariana Islands, are now made up of extinct volcanoes mantled to varying degrees by Neogene carbonates. The interaction of the carbonate rocks with the volcanic rocks creates conditions ranging from simple carbonate islands to complex carbonate islands (Jenson et al., 2006). The tectonic overprint of joints and faults tends to result locally in the diffuse flow of the freshwater lens being concentrated into specific linear flow paths, and the flank margin caves that result tend to exhibit a linear trend, perpendicular to the shoreline, beginning with their initiation. Perching of both autogenic and allogenic recharges on the subsurface carbonate/volcanic contact creates stream caves, similar to what would be seen in continental interiors. Some of these stream caves may discharge at the coast, but others descend to the freshwater lens where the flow changes from turbulent to diffuse, and large mixing chambers develop. As episodic tectonic uplift continues, these chambers are abandoned and undercut by the vadose flow as it meets the lens at a new,

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**Figure 5** Rank-order plot combining a computer simulation of void enlargement (circles) with the empirical database produced from actual cave surveys (triangles). (a) The two data sets are coincident, confirming the intersecting chamber hypothesis. (b) The computer model demonstrated that a fourth size set, less than 20 m$^2$, exists but because cave mappers prefer larger caves, were not surveyed, creating an explorational bias in the empirical data set.

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**Figure 6** Development of flank margin caves in a variety of settings. (a) Flank margin caves developed in Pleistocene marine limestones, exposed by cliff retreat, Tinian, Mariana Islands. Note the horizontal beads-on-a-string pattern. The height of largest cave opening is 4 m. (b) Flank margin caves in telogenetic Oligocene marine limestones, South Island, New Zealand. Joints (dipping upper right to lower left) control lateral placement of the caves. Person in lower left for scale. (c) Flank margin cave developed in late Pleistocene aeolian calcarenites, intercepted by sea-cliff retreat, Cat Island, Bahamas. Compare to Figure 1. Person at far right for scale. Photo by M. Lace. (d) Map of Salt Pond Cave, Long Island, Bahamas, developed in aeolian calcarenites (see Figure 3(c)). This map shows the wall detail and chamber separation sometimes necessary to differentiate sea caves from flank margin caves.
relatively lower elevation. A series of such stepped chambers can be found at Awesome Cave on Mt. Santa Rosa, Guam.

Saipan, north of Guam, is one of the most complex carbonate islands described so far (Jenson et al., 2006). Faulting has partitioned and isolated the freshwater lens, and syndeposition of carbonates and volcaniclastics has resulted in the lens being confined in some localities (such partitioning and confinement violate the true definition of the lens as a buoyant body). At Kalabera Cave, normal faults perpendicular to depositional strike, and overlying volcaniclastics, have created a confined hydrologic compartment that in the past discharged up-section over 30 m to create a vertical phreatic lift tube as an outlet for the aquifer. Along strike, tubular passages collected the water in the confined unit and conducted it laterally toward the vertical escape route.

Despite all the volcanic/carbonate rock interactions, and the tectonic overprint, the current coasts and the interior cliffs of the Mariana Islands show numerous flank margin caves of traditional configuration. Although local areas may depart from the idealized flank margin model as a result of jointing, faulting, or volcanic rocks, areas not disturbed react to the freshwater lens and its favorable distal-margin dissolutional environment in a predictable manner.

6.29.5 Eogenetic Lithological Controls of Flank Margin Caves

The Bahamian flank margin caves, the largest group of such caves studied so far, are almost all developed in aeolian calcarenites, a very well sorted and uniform deposit. As these rocks have almost no secondary structures, primary structures such as foreset and related depositional layering are the only potential heterogeneities within the individual lithified dunes. Whereas primary lithologic features are locally important in some chambers or portions of chambers, overall the cave development ignores the bedding (Mylroie and Carew, 1995; Figures 3(c) and 8(a)). However, as has been demonstrated in Bermuda and the Bahamas, as these aeolianites age and spend more time in the freshwater lens, their permeability alters from the random primary porosity of initial deposition to an organized touching-vug system, with high hydraulic conductivities. The conductivity difference is sufficient that the freshwater lens distorts where passing from a younger unit to an older one, such that it is thinner in the more conductive older unit (Vacher and Wallis, 1992).

Terra rossa paleosols, fossil soils representing subaerial exposure of the dune surface, can contain micritic horizons that can later distort the freshwater lens, generally in cases in which a younger dune has been deposited over or adjacent to an older dune, such that the freshwater lens must transit both units and the terra rossa paleosol between them. Hatchet Bay Cave on Eleuthera Island, Bahamas, has an unusual linear passage extending several hundred meters that resulted from the freshwater lens in a younger dune ramping up on the paleosol covering an older dune. The cave passage follows the strike of this contact (Mylroie and Mylroie, 2007).

One of the best examples of facies control of flank margin caves is on Mallorca Island, Spain (Gine`s et al., 2009). In that setting, freshwater lens flow originates in the island interior and transits eogenetic limestones consisting initially of fine-grained but jointed lagoonal facies before entering the reef facies near the coast. The change in cave morphology is striking. Within the porous and permeable reef facies, the cave morphology is similar to that occurring in the Bahamas or Isla de Mona: large globular chambers with numerous intersections and dead-end passages. As the cave transitions inland to the lagoonal facies, the reduction in primary porosity restricts cave development to joints (much as in a telogenetic carbonate rock, see below) and the cave pattern becomes a linear maze.

6.29.6 Diagenetically Mature Carbonate Coasts

Most carbonate coasts worldwide occur in the tropics and subtropics and are made up of young, eogenetic limestones, as these areas are where carbonate deposition is ongoing, and
glacioeustasy, tectonics, or both can easily place such recently deposited rocks into the subaerial environment where meteoric dissolution can begin (Vacher and Mylroie, 2002). However, diagenetically mature or telogenetic carbonate rocks can also eventually end up in coastal environments, including coasts at high latitudes. In these rocks, primary or matrix porosity is negligible, and water flow is primarily fracture controlled by bedding planes, joints, and faults (Ford and Williams, 2007; Palmer, 2007). Not many areas of telogenetic coastal carbonate rocks have been investigated, but what has been done revealed some interesting results. As might be expected, results from telogenetic rocks in Great Britain (Proctor, 1988) and New Zealand (Mylroie et al., 2008) indicate that the fracture pattern of the rock had a major influence on cave development and morphology (Figure 6(b)). This result would be anticipated based on the eogenetic Mariana Islands and Mallorca examples. The relatively impermeable matrix of the telogenetic rocks distorts the type of cave intersection and amalgamation seen in eogenetic rocks from places such as the Bahamas.

The largest flank margin caves of New Zealand occur in a highly tectonized carbonate rock (Figure 6(b)), in which numerous fractures occur over short distances (Mylroie et al., 2008). In this environment, the telogenetic carbonate rock behaves in a similar manner to eogenetic rocks, in that a multitude of fracture flow paths allow dissolution to occur over a volume, as opposed to widely separated and isolated planar features. In an analogous situation, flank margin caves along the coast of the Adriatic mainland and islands of Croatia occur preferentially in a Pleistocene breccia facies (a paleotalus) made up of telogenetic Cretaceous limestone clasts (Otonićar et al., 2010). As with the New Zealand example, the rock now behaves similar to an eogenetic rock, as the breccia has numerous flow pathways that allow dissolution to again act over a volume instead of being restricted to planes.

6.29.7 Coastal Conundrum: Differentiating Coastal Pseudokarst Caves from Karst Caves

As noted in the Introduction, coastal areas are the dynamic meeting point of the terrestrial and marine environments. Wave energies are significant, and can produce pseudokarst caves such as sea caves, talus caves, and fissure caves from peeling coastal cliffs (Figure 1). In addition, coastal cliff
production, by exposing rock mass interiors, can create vertical faces in which tafoni can develop. In an actively eroding cliff, differentiating the pseudokarst caves from flank margin caves may not be obvious. Flank margin caves are tied to sea level as are sea caves. Because both of these cave types form as chambers irregularly spaced along a line parallel to sea level (Figure 1(a) vs. 6(a)–6(c)), their placement does not uniquely define them. Tafoni are not controlled by sea level and can develop anywhere on an exposed rock face where conditions are right for selective removal of rock material by subaerial weathering processes. Their misidentification as either sea caves or flank margin caves can lead to incorrect paleo-sea-level interpretations. Although talus caves are obvious, they may represent a collapsed sea cave or flank margin cave and coastal fractures may resemble fracture-controlled, flank margin caves.

The observer can be confronted with a marine cliff in carbonate rock in which exist three sorts of globular chambers: sea caves, tafoni, and flank margin caves. Sea caves and tafoni form by exterior weathering process working into the rock or from the outside inward; flank margin caves form from interior chemical process working from the inside outward. Flank margin caves, as chambers that develop in the distal margin of the freshwater lens, form without entrances. These caves become accessible only later when denudation breaches into them, either laterally (Figure 6) or from above. Successful recognition of breached flank margin caves in coastal areas allows rates of denudation to be established, especially if, as in the Bahamas, the age of the cave is known from its geomorphic and stratigraphic setting (Waterstrat et al., 2010). Flank margin caves also represent past freshwater lens configuration, and senescent flank margin caves have been successfully used to determine anisotropic flow in past freshwater lenses on Fais Island, Federated States of Micronesia (Mylroie and Mylroie, 2007).

There are a number of ways to determine if a cave on a coastal cliff is karst or pseudokarst (Waterstrat et al., 2010). Breached flank margin caves commonly contain a variety of speleothems (stalactites, stalagmites, flowstone, etc.) that are unique to the sealed cave environment. Sea caves and tafoni are too open to the atmosphere for true cave speleothems to occur (Taborosi et al., 2006). The well-ordered calcite found in cave speleothems requires high humidity to prevent water evaporation while CO₂ diffusion forces the CaCO₃ to precipitate. Open surface exposures dominated by evaporation commonly produce a crumbly tufa material. Flank margin caves commonly contain delicate dissolutional forms (Figure 8) that could not be produced by wave erosion (Mylroie et al., 2008). However, in coastal settings, once a flank margin cave is breached, wave action can strip out speleothems and dissolutional bedrock forms, removing key identifiers.

The use of cave morphometrics has been successful in differentiating flank margin caves from tafoni and sea caves, and sea caves and tafoni from each other in the Bahamas (Waterstrat et al., 2010). Two criteria have been especially successful, based on data obtained from cave maps. The first is perimeter-to-area ratio. In this case, the cave area is measured from the map, removing the area of bedrock columns and islands. The perimeter is measured, including the perimeter of interior bedrock columns and islands. The expected P versus A plot on a linear scale for regular geometric shapes such as squares or circles is a curve. However, for flank margin caves it is a straight line, because perimeter complexity increases as the cave enlarges, a result of the amalgamation of initial small chambers. Sea caves and tafoni have simple perimeters, reflecting their outside to inward method of development, and are regularly distinguished on a P-versus-A plot from flank margin caves, and from each other (Figure 9). This technique has been demonstrated to be effective in differentiating sea caves from flank margin caves on Puerto Rico (Lace, 2008).

The second morphometric that is useful is the ratio of entrance width to maximum interior width (Waterstrat et al., 2010). For sea caves and tafoni, which form from the outside inward, the widest part of the cave is commonly the entrance; if not, the entrance width/maximum width ratio is close to 1. For flank margin caves, however, the entrance is commonly a small breach in the wall or top of the cave, and the entrance width is much less than the maximum width of the cave. This method suffers when flank margin cave denudation has been substantial, such that the outer wall is entirely gone. In this case, the entrance width and maximum width are commonly the same. For an idealized circular chamber, once the flank margin cave is half gone, the ratio of the entrance width to the maximum width will always be 1 until the cave is entirely removed.

6.2.9.8 Flank Margin Caves Relative to Other Cave Types

The configuration of flank margin caves initially appears unique. The pattern of globular chambers, dead-end passages, and maze-like cave peripheries are diagnostic characteristics (Figures 3, 6, and 8). Also diagnostic is the lack of any evidence of high-speed turbulent flow, such as scallops or similar flow markings on the cave walls, or stream-laid sediments or other fluvial signatures. In this regard, flank margin caves are similar to hypogenic caves produced by mixing of waters at depth, such as the H₂S caves that occur in the Guadalupe Mountains of
New Mexico (Mylroie and Carew, 1990). Because mixing of
marine water and freshwater appears to be an important
component of development of flank margin caves, and because
the caves lack direct hydrologic connection to the epigene
cave environment (no sinking streams, springs, etc.), flank margin
caves are also considered to be hypogenic (Palmer, 2007).

The important aspect of flank margin caves for studying
hypogenic caves overall is that by using Bahamian examples, it
can be shown that the unique suite of dissolutional features
occurring in hypogenic caves can be produced in short time
frames, in small aquifers, and at shallow depths. The similar-
ities of forms suggest that fundamental hydrodynamic flow
conditions are the primary control of hypogenic cave morph-
ology and can be exhibited by a variety of geochemical dis-
solutional processes (Mylroie and Mylroie, 2009b). Although
there has been some debate about the primacy of the three
mutually supportive mechanisms that create flank margin
caves (mixing vs. organics vs. flow velocities), there is no doubt
that the actual mechanism is extremely powerful. Phreatic
dissolutional surfaces in flank margin caves can be observed to
cut across terra rossa paleosols, subaerial calcite deposits, and
primary structures (Figure 8) as if they were not different than
the host rock (Mylroie and Carew, 1995). At the local scale,
rather than exploiting subtle differences in rock type or texture,
the dissolutional surface cuts across all. On the larger scale,
lithological variations can be important, as was noted for
Mallorca. The power of the dissolutional mechanism is also
displayed by the development of large voids in small amounts
of time, sometimes in very small lenses, as in the Bahamas.
Syndepositional caves in particular require a potent and
fast-acting dissolutional mechanism (Mylroie and Mylroie,
2009a).

6.29.9 The Consequences of Coastal Cave Location

The coastal location of flank margin caves allows the for-
mation of minerals rarely found in caves from continental
interiors, primarily because of the ubiquitous presence of
halides (Onac et al., 2001). Stalagnites demonstrate hiatuses
and regrowth (in some cases with marine overgrowths) caused
by sea-level rise and fall. Sea-level changes of only a few meters
can be resolved (Figure 8c) and, therefore, provide a high-
resolution indicator of sea-level position (Carew and Mylroie,
1995b; Mylroie, 2008). Such information extends the utility of
these caves as sea-level indicators beyond their actual physical
position at the time of speleogenesis. Flank margin caves
may be the only caves on widely spaced carbonate islands in
deep ocean basins and, therefore, contain the only available
speleothem stable-isotope paleoclimatic record available in
those broad basins.

Around the world, many flank margin caves were first
identified as sea caves, primarily because of their globular
nature and the lack of traditional epigenic flow markings
and stream-laid deposits. Although flank margin caves are now
widely recognized and understood, in actively eroding coasts,
developing sea caves and senescent flank margin caves can
appear remarkably similar (Figure 1 vs. Figure 6). Some tafoni
also bear a striking resemblance to fossil sea caves or flank
margin cave chambers. Proper differentiation of these cave

types is essential to utilizing flank margin caves in making
interpretations of sea level, paleoclimate, denudation rates,
and freshwater resources. The recognition of flank margin
caves for the first time on Kangaroo Island, Australia, placed
constraints on the amount and degree of Quaternary uplift in
that location (Mylroie and Mylroie, 2009c).

Flank margin caves develop in response to very local con-
ditions of coastal carbonate aquifers. As has been previously
noted, they can form in very tiny islands. In Quintana Roo,
Mexico, flank margin caves developed in coastal aeolian cal-
ccrenites during the last interglacial, while at the same time,
the large integrated conduit systems were actively carrying
large water flows beneath them (Mylroie and Mylroie, 2007).
On carbonate coasts, other than coastal karren (see Chapter
6.28), flank margin caves are the most common karst land-
form. The eogenetic nature of coastal carbonates in settings
such as the Bahamas, and the ubiquitous presence of flank
margin caves, means that surface depressions on carbonate
coasts are of two main types: constructional depressions pro-
duced by carbonate-depositional topography (dune swales
and fossil lagoons) and collapse features into underlying
caves. The youth and purity of the limestones mean that the
rock commonly has only a thin soil veneer, such that cover-
collapse sinkholes do not form, and the youth and high pri-
mary porosity of the limestones means that traditional, con-
cial-dissolution sinkholes (dolines) are not present.

6.29.10 Summary

Flank margin caves are a type of hypogenic cave that has a
predictable form and location. These caves provide important
information about past sea levels, freshwater lens character-
istics, and how slow-flow dissolutional morphologies form. As
with any cave, they contain deposits of scientific value, such as
minerals, fossils, and infiltrated sediments; however, these
deposits may contain high-resolution sea-level and paleoclí-
mite indicators otherwise unavailable in ocean basins.

Flank margin caves are more than a special case of dis-
solution in a limited karst environment. They are a regionally
dominant karst landform that contains unique information
not accessible or available in other cave environments. Their
abundance and high accessibility make them an easily studied
resource for cave genesis in slow-flow or hypogenic regimes.
Their rapid formation, yet persistence through geologic time,
makes them a high-resolution, but long-duration, repository
of sea-level and paleoclimatic information.

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Biographical Sketch

John Mylroie is a Professor of geology in the Department of Geosciences at Mississippi State University. He received his BSc degree in biology from Syracuse University in 1971. John earned his PhD in geology at Rensselaer Polytechnic Institute in 1977. He is a past president of the Karst Waters Institute, and a continuing member of the Board of Directors. He won the National Speleological Society's Science Award in 2000 in recognition of his work in island karst, and the Society's highest award, the Honorary Member, in 2008 for lifetime achievement in karst science. Along with Joan Mylroie, he has recently done fieldwork in Australia, the Bahamas, Barbados, Croatia, Federated States of Micronesia, Mallorca, Marinas, and New Zealand in pursuit of island cave and karst research.