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KARST DEVELOPMENT AND SPELEOGENESIS, ISLA DE MONA, PUERTO RICO

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Isla de Mona consists of a raised table-top Miocene-Pliocene reef platform bounded on three sides by vertical cliffs, up to 80 m high. Hundreds of caves ring the periphery of the island and are preferentially developed in, but not limited to, the Lirio Limestone/Isla de Mona Dolomite contact. These flank margin caves originally formed at sea level and are now exposed at various levels by tectonic uplift of the island (Frank 1983; Mylroie et al. *1995b).*

Wall cusps, a characteristic feature of flank margin caves, are ubiquitous features. Comparisons among similar caves formed in the Bahamas and Isla de Mona reveal the same overall morphology throughout the entire range of sizes and complexities.

The coincidence of the primary cave development zone with the Lirio Limestone/Isla de Mona Dolomite contact may result from syngenetic speleogenesis and dolomitization rather than preferential dissolution along a lithologic boundary. Tectonic uplift and glacioeustatic sea level fluctuations produced caves at a variety of elevations. Speleothem dissolution took place in many caves under phreatic conditions, evidence these caves were flooded after an initial period of subaerial exposure and speleothem growth. Several features around the perimeter of the island are interpreted to be caves whose roofs were removed by surficial denudation processes. Several large closed depressions and dense pit cave fields are further evidence of surficial karst features. The cliff retreat around the island perimeter since the speleogenesis of the major cave systems is small based upon the distribution of the remnant cave sections.

Isla de Mona is remarkable for the large number of caves that open onto its carbonate cliffs (Fig. 1). James Quinlan (1974) used the term "phantasmagorical" to describe the immensity and grandeur of these caves. Based on the then current understanding of cave formation, he called the voids "sea caves", but it is clear from his writing that he was not fully satisfied with that explanation. The majority of the caves on Isla de Mona are located at or near the Mona Dolomite/Lirio Limestone contact. However, there are some caves that do not seem to be related to this formation boundary. The numerous caves seen in the cliffs of Isla de Mona are now known to be flank margin caves (Frank 1993; Mylroie *et al.* 1995b). Other karst features on Isla de Mona include: several extensive closed depressions, a dissolutional valley formed along a fracture, and an area containing a dense concentration of vertical shafts or pit caves (Fig. 2). An overview of the geology of Isla de Mona is provided by Frank *et al.* (1998).

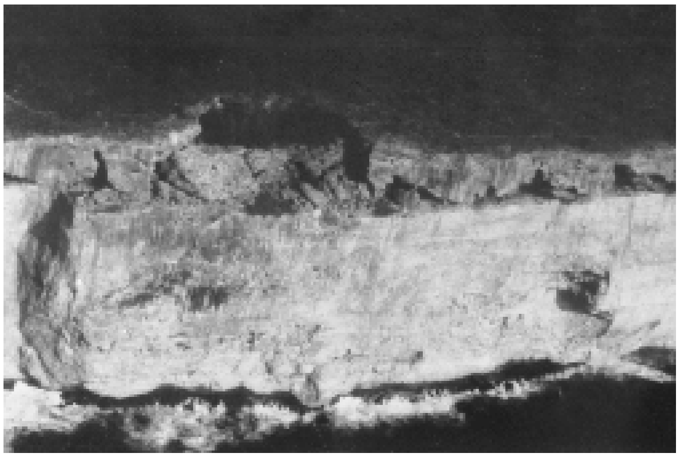

Figure 1. Vertical cliffs 40 m high on the east side of Isla de Mona, Puerto Rico. Cave openings are present near the top of the cliff at the Lirio Limestone/Isla de Mona Dolomite contact.

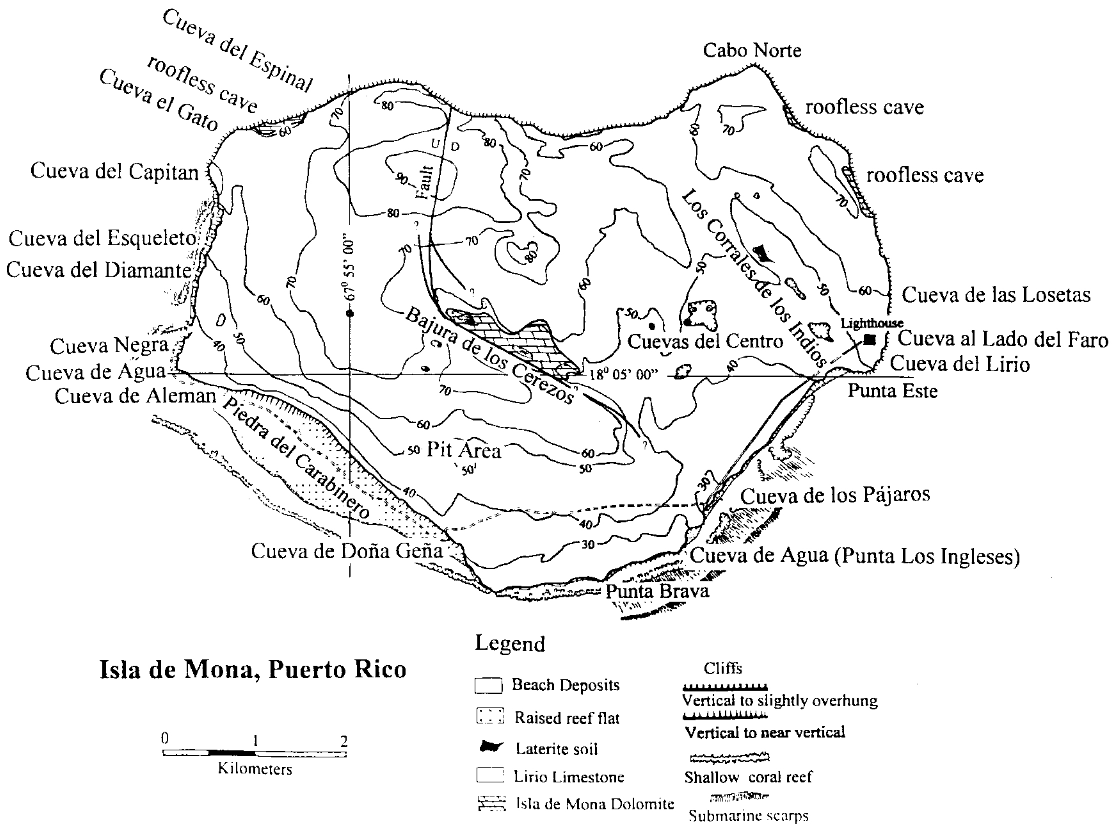

Figure 2. Major cave and karst features of Isla de Mona, Puerto Rico.

FLANK MARGIN CAVE MODEL

Carbonic acid, formed by the dissolution and ionization of carbon dioxide in water, is capable of dissolving limestone and forming caves. Infiltrating water in limestone areas quickly approaches calcite saturation. Bogli (1980) described a process for enhancing calcite dissolution termed *mischungskorrosion*, or mixing corrosion. Because the saturation curve for calcite is not linear, mixing of two solutions saturated at different partial pressures of CO_2 yield a third solution that is undersaturated with respect to calcite. This phenomenon allows additional dissolution at the mixing zone between infiltrating vadose water and phreatic water at the water table.

Plummer (1975) showed that fresh water saturated, or even slightly supersaturated, with respect to calcite, became undersaturated when mixed with up to 70% sea water that is also saturated. These calculations indicated dissolution can take place at the halocline, or mixing zone, at the base of the fresh-water lens within carbonate coasts and islands. This principle, explaining the origin of many caves in Bermuda (Palmer *et al.* 1977; Mylroie *et al.* 1995a), along the Yucatan coast (Back *et al.* 1979), and in the Bahamas (Mylroie & Carew 1990), is now a well accepted phenomenon.

The flank margin model for the genesis of caves was first proposed for the caves of the Bahamas (Mylroie & Carew 1990). It suggests that the margin of the fresh-water lens is an area of intense dissolution driven both by the mixing of vadose and phreatic water at the top of the fresh-water lens, and by mixing of fresh water and sea water at the halocline. Those two mixing zones merge at the lens margin. Flank margin caves have a distinctive morphology. "They consist of oval or linear chambers that are oriented parallel to the trend of, and just under the flank of, the ridge in which they have formed. Small radiating tubes extend from these large chambers into the ridge interior where they end abruptly or pinch out. Many cave passages loop back into one another or the main chamber, and isolated bedrock pillars and thin wall-partitions are common." (Mylroie & Carew 1991: 140).

A variety of other chemical processes may also play a role in the rapid development of flank margin caves. The top and bottom of the freshwater lens are density interfaces where organic material may collect. After the initial dissolution cavities form, bacterial decomposition of the organic matter depletes the available oxygen and increases the partial pressure of dissolved CO_2. Anaerobic bacteria then use more organic matter to reduce the sulfate to form H_2S. If oxidizing conditions return, oxidation of the H_2S can produce H_2SO_4 which reacts to dissolve the limestone and produces gypsum (Bottrell *et al.* 1993). These processes may be taking place simultaneously in different parts of the system.

Flank margin caves receive and discharge their water by diffuse flow through the carbonate aquifer. The caves form as mixing chambers and, over time, they tend to develop headward into the fresh-water lens. Salt Pond Cave on Long Island,

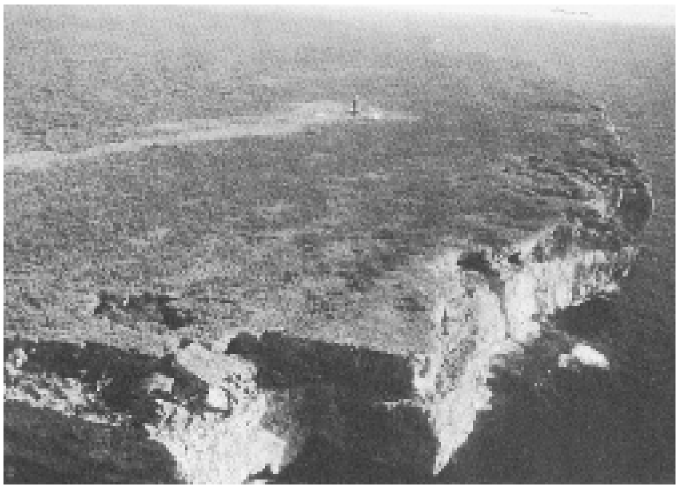

Figure 3. Punta Esta, Isla de Mona, Puerto Rico, showing many entrances leading into Cueva del Lirio and Cueva el Lado del Farro at the Lirio Limestone/Isla de Mona Dolomite contact near the top of these 40 m high cliffs.

Bahamas (Mylroie *et al.* 1991), includes a chamber with a volume in excess of 14,000 m^3 that formed in a maximum time period of 12 Ka, representing a dissolution rate of over 1 cm^3/year. As the fresh-water lens thins at the lens margin, the water discharges through an ever decreasing cross-sectional area. As a result, flow velocities are high, allowing the rapid removal of dissolutional products (Reisi & Mylroie 1995). Flank margin caves fit the hypogenic model of Palmer (1991), in that these caves develop through mixing of waters in the subsurface, and are not directly coupled to the surface hydrology.

CAVES OF ISLA DE MONA

Caves literally ring the perimeter of Isla de Mona, preferentially developed at the Lirio Limestone/Isla de Mona Dolomite contact. A geologic map of the island (Briggs & Seiders 1972) depicts the entrances of 25 large caves, and outlines the extent of the largest caves. On the southeast corner of the island Cueva de los Losetsa, Cueva el Lado del Faro, and Cueva del Lirio extend continuously for over 2 km along the coast (Fig. 3). Other significant caves include Cueva de los Pájaros on the southeast coast, Cueva de Aleman (Fig. 4) and

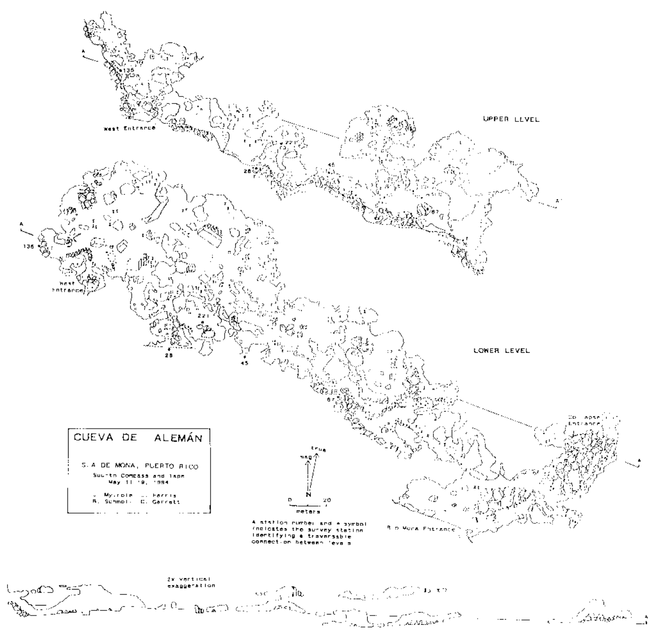

Figure 4. Map of Cueva de Aleman, Isla de Mona, Puerto Rico, an example of a typical plan for a large flank margin cave.

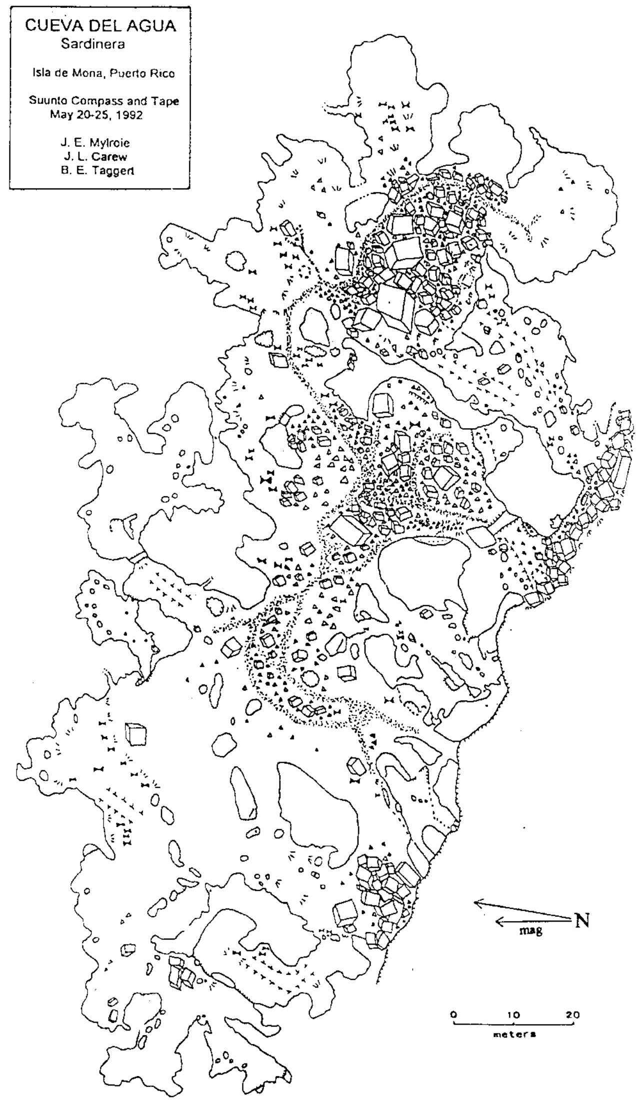

Figure 5. Map of Cueva de Agua, Isla de Mona, Puerto Rico, an example of a typical plan for a large flank margin cave.

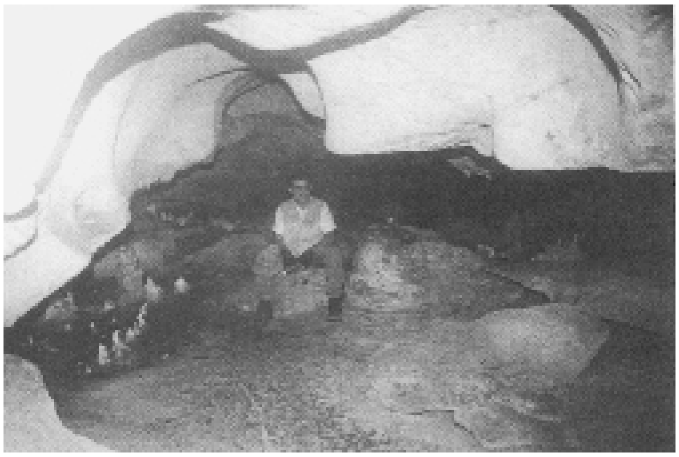

Figure 6. Wall cusps found in Cueva de Agua, Isla de Mona, Puerto Rico.

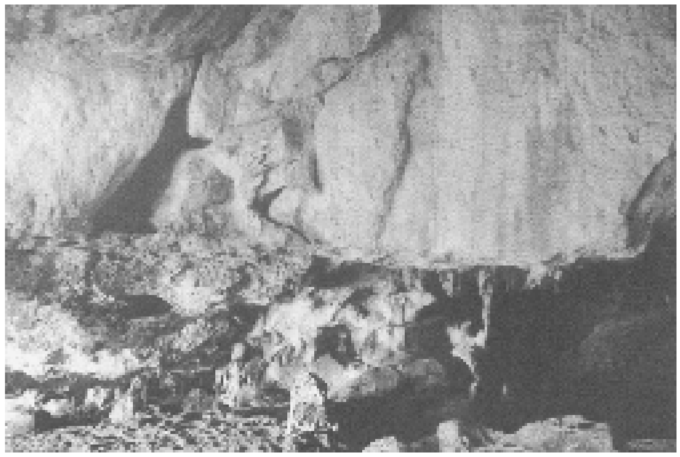

Figure 7. Cave wall section in the lower entrance to Cueva de Aleman, Isla de Mona, Puerto Rico. The upper portion is a relatively smooth breakdown face. The lower portion, containing wall cusps, is from the part of the cave formed by bedrock dissolution.

Cueva de Agua (Fig. 5) on the southwest, Cueva del Diamante/Cueva de Esqueleto and Cueva Capitan along the west, and Cueva de Esperanza, Cueva del Gato, and Cueva de Espinal along the northwest coast of the island (Fig. 2). The combined floor areas of the twelve major caves, as explored by Briggs and Seiders in the 1960s, totaled 444,000 m² (Briggs 1974). Frank (1993) and Mylroie *et al.* (1995b) contain descriptions and maps of many of these caves.

ORIGIN OF WALL CUSPS

An important unresolved question in the flank margin model is the origin of the ubiquitous meter-scale curvilinear dissolution features that cover the walls, floors, and ceilings of the cave chambers (Fig. 6). These features are called "cusps" to differentiate them from scallops found in stream passage caves. In places, these cusps cut through a joint-filling breccia made of light-colored carbonate clasts in a reddish matrix. This breccia is interpreted to have originated as a soil that slumped into fractures, lithified, and was subsequently cut by dissolution. Cusps cut through both the wall rock and the breccia material as smooth dissolutional surfaces.

Several lines of evidence indicate these cusps are primary dissolution features. Hundreds of large cave chambers on Isla de Mona have been enlarged by upward stoping of their ceilings. Cusps are present on all original dissolutional cave walls, but are absent on broken rock surfaces produced by stoping between cave levels (Fig. 7). No exceptions were found to this observation.. Panuska *et al.* (1998) conclude from paleomagnetic data that portions of these caves are at least 1.8 to 2.0 Ma old. Collapse features formed by stoping are also very old as shown by the large masses of stalagmites and flowstone that have overgrown portions of the breakdown debris. Cusps are also known to exist on comparatively young cave walls. Cueva de Agua (Punta los Ingleses) is developed in a 125 Ka coral rubble facies (Mylroie *et al.* 1997) at a level corresponding to the oxygen isotope 5e sea-level highstand occurring during the same period. These 125 Ka old cave wall surfaces are marked by cusps, yet cusps are absent on stoping wall surfaces in many upper-level caves which may be sixteen times older. The ubiquitous distribution of the cusps on cave dissolutional surfaces and their absence on stoping surfaces are evidence that the cusps are primary features formed during the primary speleogenesis process. Another argument is that the basic shapes of the large cave chambers themselves appear to be part of the same progression of curved features that include the cusps (Rice-Snow *et al.* 1997). This suggests that the same primary dissolution process that produced the cave chambers also produced the cusps.

Lips (1993) and Tarhule-Lips and Ford (1995, 1996, 1998) propose that condensation corrosion associated with air currents could have formed the wall cusps after the caves were subaerially exposed. If cusps are formed by condensation corrosion, then they should be equally likely to form, given sufficient time, on breakdown surfaces as on dissolutional surfaces within the caves. Some of the breakdown surfaces are many times older than the ages of the dissolutional surfaces in Cueva de Agua (Punta los Ingleses) marked by cusps. The absence of cusps on old breakdown surfaces is evidence that condensation corrosion is not responsible for cusp formation.

Other arguments against condensation corrosion and air current eddies as the mechanism of cusp formation include the following: (1) cusps are universally present on dissolution surfaces in the caves. Secondary overprinting of the cave surfaces is unlikely to produce as pervasive a cusp distribution as is observed; (2) if air circulation is the driving mechanism of the condensation corrosion process there should be a progressive change in the cusp pattern moving away from a cave entrance as air circulation characteristics change. No such pattern is observed on Isla de Mona; however, such a pattern has been suggested for caves on Cayman Brac (Tarhule-Lips & Ford

1998); (3) no mechanism has been suggested to remove the material stripped from the walls by the condensation corrosion process, and there is no evidence of accumulated residue; (4) even if condensation corrosion were affecting the morphology of the cave walls, it is not clear that the dissolution pattern would reflect the circular pattern of the hypothesized wind eddy currents, so there is no reason to believe that curvilinear cusps would result. We recognize that condensation corrosion does occur, but it plays a minor role in the alteration of specific features within caves. For example, some speleothems that have been eroded by condensation corrosion can be seen at a few localities, such as near the lower entrance to Cueva de Aleman.

Water enters and leaves the developing cave chamber by diffuse flow rather than turbulent flow through open conduits. Therefore another mechanism must generate the currents necessary to produce the cusps. At the large scale, these circulation phenomena could serve to maintain the overall circular to oval shape of the chambers and on a smaller scale to form the cusps that cut across the lithologic variations. Several mechanisms might be responsible. Tidal fluctuations could provide a pumping mechanism that affects circulation, particularly if there is some hysteresis between different portions of the system. Thermally driven convective flow, solute-density driven convective flow, or flow from vadose input could also generate such circulation.

CAVE MORPHOLOGY

Isla de Mona caves have the same overall morphology as flank margin caves previously described from the Bahamas; however, on Isla de Mona many caves are larger and better integrated. This difference can be attributed to differences in fresh-water lens size, stability of lens position, and time available for speleogenesis between the two localities. The flank margin caves exposed in the Bahamas formed in small freshwater lenses within partially flooded dune ridges over a period of 12 Ka (Carew & Mylroie 1987; Mylroie *et al.* 1991). On Isla de Mona, a larger freshwater lens, possibly a single freshwater lens occupying the entire 55 km² mass of the island, drove the dissolution process. The 1.8 to 2.0 Ma age (Panuska *et al.* 1998) for some cave segments place the genesis of these segments prior to the onset of Quaternary glacioeustacy and its rapid, large sea level fluctuations. Several periods of relative lens position stability, allowing extended periods of speleogenesis, have also likely occurred during the last 2.0 Ma.

Isla de Mona caves are found in a variety of scales and degrees of complexity. The simplest caves consists of single disk-shaped chambers. These chambers enlarge laterally and deeper into the hillside. Eventually adjacent caves may link to form a cave complex consisting of a series of linked chambers than run parallel to the margin of the lens. Several such bands may develop at the same horizon at progressively farther inland positions within the cave. The central portion of Cueva del Diamante (Fig. 8) consists of an outer band of large chambers linked laterally by small passages and archways. Off the back of this first band of chambers is a second band of laterally linked chambers. This second band is similarly interconnected laterally and to the chambers in the outer band by smaller passages and archways. Further back in the cave is a third band of chambers which, while linked to the second band, are laterally discontinuous. A similar scaling of size and complexity eventually can produce the complex mazes found in Cueva de los Pájaros and Cueva del Lirio.

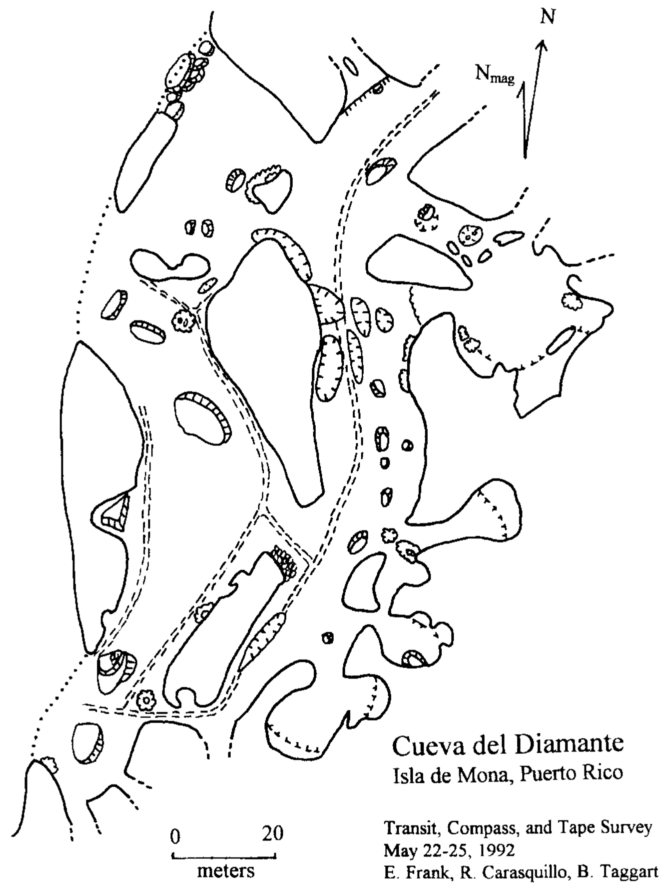

Figure 8. Map of Cueva del Diamante, Isla de Mona, Puerto Rico. Cave map symbols used generally conform to standard symbols by Sprouse and Russell (1980). Parallel lines have been used on selected maps to represent rail beds for mine carts during guano mining operations within the caves.

A few isolated caves on Isla de Mona exhibit a limited degree of structural control on passage morphology. Cueva Negra, for example, contains several passages oriented along steeply dipping foreset beds. Upward stoping cave ceilings are in many cave chambers with large roof spans. Since Isla de Mona is tectonically active, caves have developed at a variety of levels and on occasion these levels are interconnected by ceiling stoping. In other cases, an extensive horizontal cave may be separated by a meter or less thickness of rock from another extensive, overlying cave.

A fractal analysis of wall cusps and chamber shape in Cueva de Agua (Sardinero) on Isla de Mona by Rice-Snow *et al.* (1997) indicated that these features seem to be morphologically the same and that the process of cusp formation and cave chamber formation scales across at least two orders of magnitude. Based upon maps and observations of these caves, we suggest the gross morphology similarly scales across alcove, single-chamber cave, and multi-chamber cave complexes.

CAVE DEVELOPMENT AND THE LIRIO LIMESTONE/ISLA DE MONA DOLOMITE CONTACT

Given that the primary zone of cave development is at the base of the Lirio Limestone, at the contact with the underlying Isla de Mona Dolomite, the question arises as to whether the caves formed at that location because of preferential dissolution associated with the difference in composition between the two rock units, or whether the caves are one manifestation of the processes that created the compositional differences between the two units. Kaye (1959) reported that there were two lesser zones of cavern development at stratigraphic positions 15 and 50 m below the Lirio Limestone/Isla de Mona Dolomite (Isla Mona Limestone of Kaye) contact. Briggs (1974) also reported the lesser zones of cave development, and he speculated that because those zones were less dolomitic, the caves formed there because those horizons were more soluble than the surrounding dolomite. Structurally a low amplitude, southwest plunging syncline-anticline-syncline fold sequence is in the island. Overall, the island itself is slightly tilted to the south with the Lirio Limestone/Isla de Mona Dolomite contact at an elevation of 80 m msl along portions of the north coast and absent or below sea level along much of the south and southwestern coast.

Gonzales *et al.* (1990) suggest that dolomitization of the Isla de Mona Dolomite took place in a fresh-water/salt-water mixing zone. Ruiz *et al.* (1991) further suggest that dolomitization of the unit was simultaneous with cave development. Schmoll *et al.* (1997) found, in thin sections of wall rock from Cueva de Aleman, that a significant proportion of the dissolutional porosity in the samples was from diagenesis of high-Mg-calcite red algae, whereas Ruiz (1993) reported that the red algae were not significantly altered in his surface samples. This disparity may represent a difference in dissolutional processes between the carbonic acid systems in the epikarst vadose zone and the mixing-zone chemistry associated with flank margin cave development. These results raise the possibility that Mg-calcite was selectively dissolved in the mixing zone during cave formation and redeposited as part of a concurrent dolomitization of the underlying units. The presence of less dolomitic zones and minor cave development at 15 m and 50 m below the Lirio/Mona contact is interpreted here to be a different stage of this magnesium redistribution process related to a different sea level position, at a different time.

Flank margin caves are in the island at a variety of elevations. Because these caves form at or near sea level, these cave positions represent the position of relative sea level at the time of their formation. Changes in relative sea level on the island have occurred because of both tectonic activity and glacioeustatic sea level fluctuations. The effects of tectonic uplift are obvious, because there are caves along the northern coast that are now 80 m msl, which is much higher than any glacioeustatic sea level maximum since the deposition of the carbonate units. The effects of glacioeustatic fluctuation can also clearly be seen in some caves. For example Cueva de Agua (Punta los Ingleses) has a passage containing subaerial speleothems that is now below sea level.

SPELEOTHEM MODIFICATION

The caves of Isla de Mona contain abundant subaerial calcite speleothems such as stalactites, stalagmites, columns, flowstone, and rimstone pools. The majority of these speleothems usually appear dry and dead, but a small number are wet and active. However, after 23 cm of rain in 3 days (May 1992), the caves all had large amounts of drip water. Rimstone pools, which had been dry, were then full and flowing. Almost all stalactites and stalagmites were actively dripping water. These chance observations following the biggest storm over a 3-year period indicate that speleothem growth and subsequent modification may be tied to the infrequent precipitation events or to periods of wetter climatic conditions.

The caves of Isla de Mona also contain a wide variety of modified speleothems with pockets, scars, and holes that cut through the primary layering of the speleothems. In certain environments, such as in the twilight of entrance areas, the secondary dissolution of the speleothems is clearly associated with algal and moss growth on the speleothems. However, deep in the caves, where sunlight never reaches, large stalagmites, stalactites, columns and flowstone masses are etched into complex forms. In other places, large dissolution cusps are cut through both the bedrock and adjacent flowstone masses. Like the cusps that cut through the cave wall rock and breccia material, these dissolutional cusps cut through the wall and flowstone mass as a single smooth surface (Fig. 9). Similar features have been reported from Hunts Cave on New Providence Island, Bahamas (Mylroie *et al.* 1991)

While the wall cusps that cut smoothly across rock, breccia, and flowstone clearly seem to be phreatically formed in the fresh-water lens, the complex etching of the stalagmites, stalactites and columns within cave chambers may be more problematic. In a limited number of cases, it is possible that condensation corrosion is at work on these speleothems (Lips 1993; Tarhule-Lips & Ford 1995, 1996, 1998), because many of the caves are very well ventilated through numerous openings on to the cliff face and up to the surface. Such ventilation is uncommon in most other cave settings, so it is possible that minor condensation corrosion effects may be better expressed in the Isla de Mona cave environment.

Another possible explanation for some speleothem etching is the potential for vadose drip water to enter the cave in the aggressive state, and dissolve calcite in places where drip water had previously precipitated it. The chemistry of the drip water could change as a result of seasonal variations, land use variations, or longer term climatic variations. We believe, however, these highly etched speleothems are mainly the result of phreatic dissolution (Mylroie *et al.* 1995b).

The flank margin caves of Isla de Mona show evidence of: (1) original formation within a fresh-water lens; (2) draining of the lens by a drop in sea level (tectonic or glacio eustatic); (3) abundant growth of subaerial speleothems; (4) partial infill by surface soil to form a breccia; (5) re-occupation of the caves by a fresh-water lens with further dissolution of all components to form cusps and etched speleothems; and (6) tectonic uplift of the island to drain the caves.

SURFICIAL KARST FEATURES

There is some evidence for lowering of the meseta surface by dissolutional removal of bedrock. This includes several small areas (averaging 100 m by 400 m) around the periphery of the island's meseta where the Isla de Mona dolomite is

Figure 9. A pocket of flowstone and wall rock cut smoothly by a wall cusp in Cueva del Lirio, Isla de Mona, Puerto Rico.

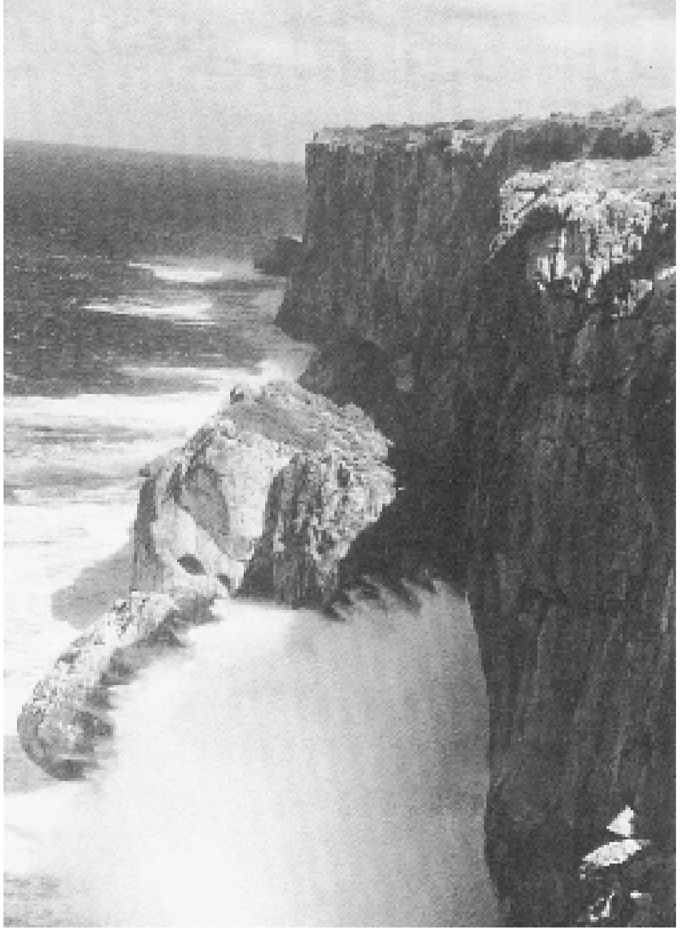

Figure 10. Cliff 70 m high along the north coast of Isla de Mona. Foreground area on cliff top is an Isla de Mona Dolomite exposure where a former cave has lost its roof through denudation. The cave entrances in the background are to Cueva de Espinal developed at the Lirio Limestone/ Isla de Mona Dolomite contact. Sections of cave are still present in the upper parts of the blocks that have fallen from the cliff.

exposed at the surface (Fig. 10). These areas are thought to represent caves whose roofs have been removed. They have the following characteristics: (1) they are observably lower in elevation than the adjacent Lirio Limestone areas; (2) the size, shape, and distribution of these dolomite exposures are comparable to adjacent large caves developed at the Lirio Limestone/Isla de Mona contact; (3) the elevations of these surface exposures are approximately the same as the floor elevations in adjacent caves; (4) flowstone is commonly present on the meseta surface within these areas; (5) remains of large stalagmites are occasionally present in these areas; and (6) in some cases, the outline of cave rooms can be distinguished. All of these characteristics support the conclusion that these are caves that have been de-roofed by denudation of the meseta surface.

LARGE SCALE DEPRESSIONS

There are three major internally drained features in the interior of the island: Bajura de los Cerezos, Cuevas del Centro, and Los Corrales de los Indios (Fig. 2). Bajura de los Cerezos consists of a large closed depression and associated valley along a southwest-trending fault in the central part of the island. The edge of the depression is developed in the Lirio Limestone, but the lower part penetrates into the Isla de Mona Dolomite. During heavy rains a small stream forms and sinks in the bottom of the depression.

Cuevas del Centro consists of a multiple sink feature. The largest closed depression consists of a 550 m diameter sinkhole that drops 20 m below the surrounding countryside. From the side of the largest of several small sinks in the basin, a cave extends downward as a wide, short, low crawlway before becoming blocked with rock debris and rubble (M. Morales, personal communications 1992).

Los Corrales de los Indios is a series of shallow sinks aligned in a southeastern trending valley in the eastern portion of the island. Briggs (1974) reported that no caves are known to have developed off any of these sinks. The linear nature of this feature suggests that it may be developed along a dissolutionally enlarged joint swarm or fault.

A question about these internally drained features concerns the distribution of the water they capture. The possibilities include: (1) water is drained and stored in a diffuse aquifer within the Isla de Mona Dolomite; (2) water is discharged along the periphery of the island at current sea level, and (3) water is discharged from subsurface springs around the edge of the island. Work on Guam (Barner 1997) has shown that such internal depressions in Miocene carbonates there drain by both diffuse and fracture flow with different flow rates and destinations. Subsea-level springs have been reported by divers (R. Van Damm, written communication 1995) along the northern coast of the island near Cabo Noroeste. It is not clear what proportion of the water is being distributed by fracture flow or diffuse flow. Some water may also be discharging via sub-sea level conduits that developed during relative sea-level lowstands during the Pleistocene. However, there are no known conduits (as opposed to flank margin caves, which are not conduits) that relate to the +6 m sea-level highstand of the last interglacial that could have drained these internal depressions.

CAMINO DE LOS CEREZOS PIT COMPLEX

The Camino los Cerezos Pits are a dense concentration of vertical shafts and pits located in the south-central portion of the island approximately 1 km north of Playa del Uvero. These are marked as area "N" on the geologic map of the island (Briggs & Seiders 1972). The locations of the pits in a small part of the area were mapped to document their density (Fig. 11). There are hundreds of additional pits and many large sinkholes in the interior of the island (Frank 1993; Mylroie *et al.* 1995).

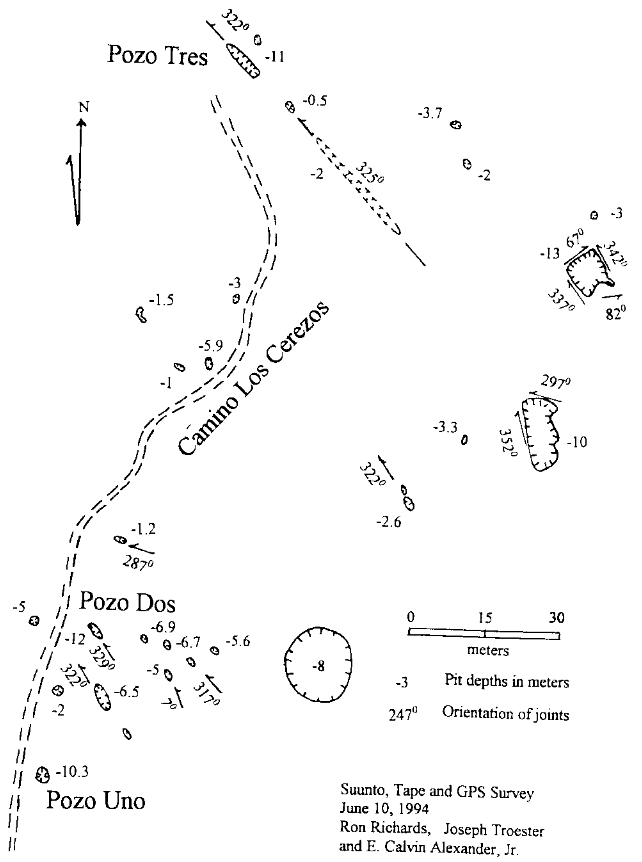

Figure 11. Map of pit locations along a survey loop in the Camino de los Cerezos Pit Complex, Isla de Mona, Puerto Rico.

Quinlan (1974) entered and examined 30 pit caves in this vicinity. In one small area he reported that four cylindrical pits, each 8 m deep, are located within 3 m of each other, yet do not connect, do not have enlarged bottoms, and do not have any passages leading away from their bottoms. Investigations by the authors confirm these observations. On Isla de Mona the pits are typically vertical shafts whose bottoms bell-out into small chambers (Fig. 12). Many pits seem to end at about the same elevation, possibly indicating stratigraphic or past fresh-water lens control.

In December 1996, a deep pit named Quinlan Pit, was discovered and explored (Fig. 13). A 4- to 5-m-wide entrance shaft drops vertically 19 m to a flat floor, with a 5-m-wide-balcony extended off the side of the pit 10 m below the surface. The top of the pit begins in limestone, the floor of the balcony is developed on dolomitic limestone, and the base of the shaft extends into dolomite. The balcony may mark the transition from the Lirio Limestone to the Isla de Mona Dolomite. A similar pit was described by Quinlan (1974) with the same interpretation.

Pace *et al.* (1993) discussed the origin of similar pit complexes found on San Salvador, Bahamas. They proposed that the pits on San Salvador were fed by subterranean flow as well

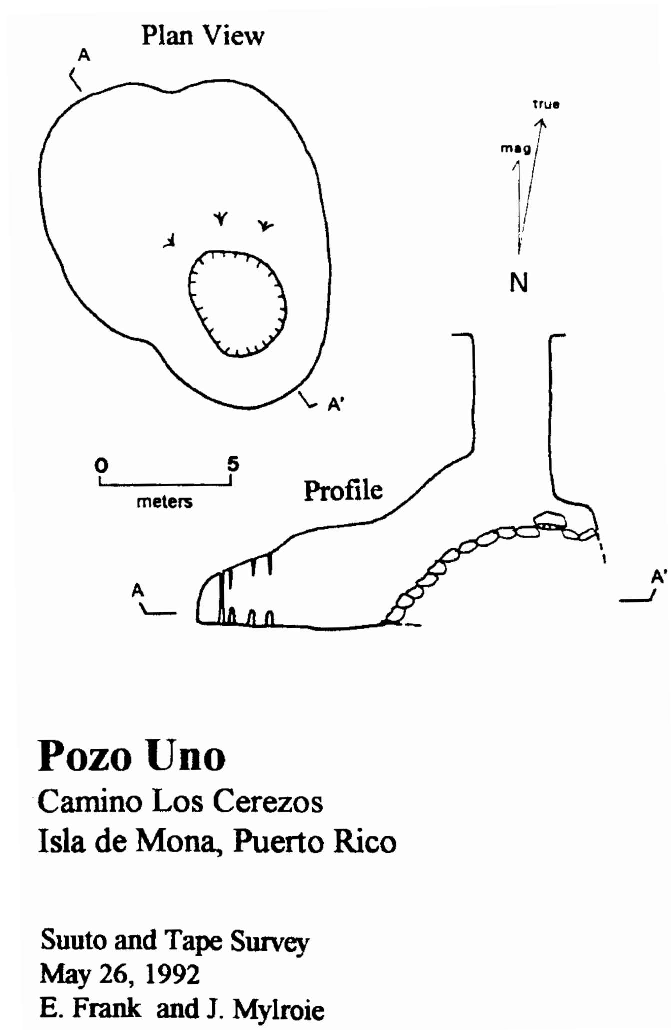

Figure 12. Map of Pozo Uno in the Camino de los Cerezos Pit Complex. The profile is typical of many of the larger pits in the area.

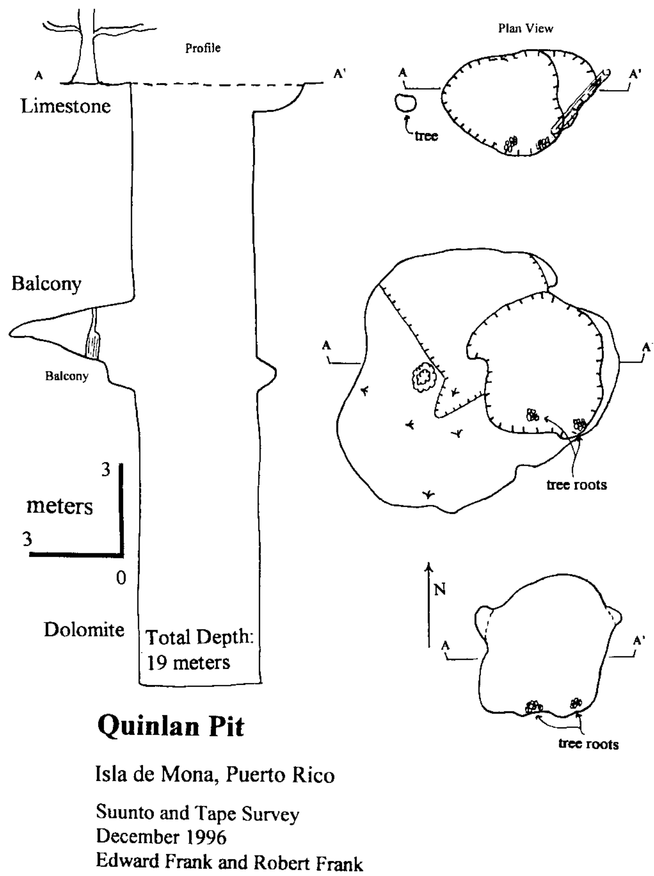

Figure 13. Map of Quinlan Pit in the Camino de los Cerezos Pit area, Isla de Mona, Puerto Rico.

as surface runoff. Pits develop when a fracture, or other path, to the subsurface was encountered by flow in the epikarst. As new paths to the subsurface develop, pre-existing pits are abandoned. New pits form in a growing ring out from the center of the complex. The presence of subterranean tubes and the similarity of the general plan of the pit field to that found on San Salvador Island support this mode origin for the pit complex at Camino los Cerezos on Isla de Mona.

CLIFF RETREAT

Flank margin caves form without natural entrances, so caves on Isla de Mona that open to the cliff face are evidence that cliff retreat has taken place. Also, many of these cliff-face entrances contain large, hard, massive speleothems, which do not form in open environments Speleothems formed in the light zone tend to be porous, soft, and contain inclusions of algae.

Jennings (1985) describes vertical cliffs in limestone coastal settings in a variety of rocks. Limestone cliffs are typically under cut by bioerosion notches, flank margin caves, and sea cave. These features promote the mechanical collapse of the cliff from the cliff base upward and help maintain the vertical profile. Isolated fallen slabs of rock from the vertical cliff face and cliff parallel fractures along the coast of Isla de Mona are consistent with this base-upward collapse model (Fig. 10). Massive rock boulders can be seen at the base of the cliffs in many places, some with segments of cave still contained within the blocks.

The amount of cliff retreat cannot be determined precisely, but there are several general indications. If the original cave population, formed almost continuously around the island, included tiny, small, medium, and large caves as in the Bahamas, then different amounts of cliff retreat would result in different patterns of cave remnant distribution. A small amount of retreat would remove the tiny caves, leaving a gap between the remaining caves. A large amount of retreat would remove the tiny, small, medium, and much of the large size caves leaving bigger gaps between the remaining segments of the large caves and the scattered original caves. The continuity of caves around much of the island perimeter is best explained by a small amount of cliff retreat. As flank margin caves do not develop deep into the fresh-water lens, the amount of cliff retreat has likely been a few tens of meters to a maximum of around 100 m since these caves formed over 1 Ma.

Bioerosion notches +6 m above the base of the vertical cliffs at many localities are associated with fossil coral reefs radiometrically dated to 125 Ka and correspond to sea level during that time. If the cliffs formed by this base upward collapse process, then the presence of the bioerosion notches near the base of these cliffs indicate that the cliff profile in these areas has not changed significantly in the last 125 Ka.

CONCLUSIONS

The caves of Isla de Mona are flank margin caves that represent development in a past fresh-water lens. These caves resulted from the exceptional dissolutional potential created by the mixing of fresh and marine waters, coupled with possible oxidation/reduction reactions from decomposing organic matter that was concentrated by density contrasts at the top of the lens and at the halocline. These flank margin caves are morphologically similar to those reported in the Bahamas, but they are older and larger.

The caves of Isla de Mona may date to before the start of the Quaternary, about 2 Ma (Panuska *et al*. 1998). They contain a complex history of development and modification by vadose and phreatic processes, coupled with glacioeustasy and tectonics. The caves near the top of the cliffs formed when the carbonate platform was emergent, and they have been modified by collapse, speleothem deposition, re-flooding by sea-level highstands, and segmentation by cliff retreat. On the island surface, pit caves and large closed depressions have developed since emergence of the platform.

As flank margin caves form at sea level, the sequence of events required to explain their distribution is as follows: (1) deposition of the Isla de Mona and the Lirio units as limestones; (2) folding resulting in the southeast-plunging synclines and anticline; (3) faulting that may have been contemporaneous with folding; (4) subaerial exposure of the carbonate platform; (5) dissolution of the major cave systems; and (6) tilting of the island to the south. The juxtaposition of the major level of cave formation with the top of the dolomitized zone marking the Lirio Limestone/Isla de Mona Dolomite contact can hardly be coincidental.

Isla de Mona is one of the most cavernous localities on Earth. The large size of the caves, the tropical warmth, and the maze-like character of their large rooms and chambers make exploration and cave science unusually enjoyable.

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