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Sistema Faro, Isla de Mona, Puerto Rico: speleogenesis of the world's largest flank margin cave

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ABSTRACT

Isla de Mona, a small, uplifted carbonate plateau jutting out of the waters of the Mona Passage, is an incredibly fragile and densely karstic environment. Expedition work was conducted by the Isla de Mona Project in cooperation with the Departamento Recursos Naturales y Ambientales de Puerto Rico (DRNA), including contributions from many researchers and cavers volunteering from across the U.S and Puerto Rico in the course of 12 separate expeditions, spanning a 14 year period (1998 to 2013). Over 200 caves have been documented on the island to date, the majority of this inventory is composed of flank margin caves but also includes sea caves, pit caves and talus caves. The most extensive example of cave development on the island is *Sistema Faro* – a sprawling maze-like series of chambers formed within the eastern point of the island with over 40 cliffside entrances overlooking the Caribbean Sea. Detailed cartography and analysis of the geomorphology and development of the *Sistema Faro* has helped form a complex model of carbonate island cave development as a function of tectonic uplift, lithology, sea level changes, karst hydrogeology and cliff retreat. This communication examines the roles these controls have played in the genesis of the world's largest flank margin cave.

Key words: cueva, flank margin cave, Isla de Mona, Puerto Rico, *Sistema Faro*

Sistema Faro, Isla de Mona, Puerto Rico: espeleogénesis de la cueva del tipo "flank margin" más grande del mundo

RESUMEN

La Isla de Mona, una pequeña meseta carbonatada levantada tectónicamente que sobresale de las aguas del Canal de la Mona, es un ambiente muy frágil y densamente karstificado. El trabajo de exploración se llevó a cabo por el Proyecto Isla de Mona, en cooperación con el Departamento de Recursos Naturales y Ambientales de Puerto Rico (DRNA), incluyendo las contribuciones de muchos investigadores y espeleólogos voluntarios de EE.UU. y Puerto Rico en el curso de 12 expediciones, que han abarcado un período de 14 años (desde 1998 hasta 2013). Más de 200 cuevas se han documentado en la isla hasta la fecha, la mayor parte de este inventario se compone de cuevas del tipo "flank margin" aunque también se incluyen cuevas marinas, simas y cuevas de talud. El ejemplo con un desarrollo más grande de cuevas en la isla es el Sistema Faro: un entramado laberíntico de cámaras en el extremo oriental de la isla, con más de 40 entradas sobre el acantilado con vistas al Mar Caribe. La cartografía detallada y el análisis de la geomorfología y el desarrollo del Sistema Faro ha ayudado a crear un modelo complejo de desarrollo de cuevas en islas carbonatadas como una función de levantamiento tectónico, litología, los cambios del nivel del mar, hidrogeología kárstica y retrocesos rápidos del acantilado. Este trabajo examina el papel que estos controles han desempeñado en la génesis de la cueva del tipo "flank margin" más grande del mundo.

Palabras clave: cueva, "flank margin", Isla de Mona, Puerto Rico, Sistema Faro

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

Las cuevas kársticas más extensas del mundo se dividen en dos categorías generales: cuevas epigénicas y cuevas hipogénicas. Las cuevas epigénicas son cuevas desarrolladas como parte del ciclo hidrológico superficial, generalmente por el paso de agua superficial al subsuelo a través de infiltración difusa y por el hundimiento de corrientes en sumideros; el agua viaja cierta distancia a través del subsuelo como una corriente y luego vuelve a la superficie por los manantiales kársticos. Las cuevas hipogénicas se forman en el subsuelo por aguas generadas en profundidad que desarrollan una gran agresividad de disolución (por procesos de mezclas o por procesos térmicos) y disuelven la roca soluble sin influencia superficial. Un tercer tipo de cueva ha sido reconocido en las últimas décadas, la cueva del tipo "flank margin".

Las cuevas del tipo "flank margin" son conocidas en costas carbonatadas de todo el mundo. Muchas son de tamaño pequeño o intermedio, porque su crecimiento depende de la permanencia constante del nivel del mar para mantener la lente de agua dulce en una posición estable. La formación de cuevas del tipo "flank margin" está impulsada por la disolución por mezcla, ya que la cinética de disolución del $CaCO_3$ es tal que la mezcla de dos aguas, incluso si ambas están saturadas con respecto al $CaCO_3$, crea una subsaturación en la mezcla resultante. El único requisito es que los dos cuerpos de agua se hayan saturado con diferentes condiciones iniciales. El encuentro de agua marina con una lente de agua dulce en un entorno costero, es capaz de crear el ambiente de mezcla adecuado. Debido a que la disolución se produce en el margen distal de la lente de agua dulce, bajo el flanco de la masa continental que las incluye, es por lo que a estas cuevas se les llama de "flank margin".

Exploración del Sistema Faro

La Isla de Mona forma parte de una isla carbonatada levantada tectónicamente, a medio camino entre la Española y Puerto Rico, dentro del Canal de la Mona (Fig. 2). Tres grandes cuevas – Cueva del Lirio, Cueva el Lado del Faro y Cueva de las Losetas ya eran conocidas previamente en el punto oriental de la isla (Punta del Este) (Briggs, 1974) donde un horizonte bien definido de entradas de cuevas se extiende casi 2 km a lo largo del acantilado (Fig. 1). Aunque antiguamente se pensó que estas cuevas estaban separadas, el estudio sistemático que comenzó en 1998 descubrió la conexión física de las estructuras en lo que ahora se conoce como Sistema Faro - el mayor sistema de cuevas en la Isla de Mona y la mayor cueva conocida de "flank margin" en el mundo (Figs. 1 y 4). La estructura general de la cueva es esencialmente una extensa interconexión desordenada de cámaras, salpicada por una miríada de coladas y columnas de roca (figs. 6 y 7).

Controles hidrogeológicos y de geomorfología costera que influyen en la génesis del Sistema Faro, Isla de Mona

El Sistema Faro debe su gran tamaño a su desarrollo anterior al Cuaternario, cuando los cambios glacio-eustáticos del nivel del mar no eran tan rápidos o de gran magnitud como los ocurridos desde hace 2.6 millones de años hasta el presente. A pesar de los 19 kilómetros explorados y su orientación paralela a la costa, la cueva se extiende hacia el interior menos de 300 metros y está asociado con la caliza de Lirio. La amplitud vertical del sistema (o distancia máxima vertical entre su entrada superior por colapso y el punto más bajo explorado en la cueva) es de sólo 36 metros. La cueva tiene numerosas entradas en la meseta, pero sólo una es usada en la actualidad como punto de entrada principal. La cueva consiste en numerosas salas grandes y pasajes con unos pocos pasajes más pequeños en el flanco continental de la cueva, asemejándose a un laberinto tridimensional de pasajes, descrito en otras áreas kársticas aunque coherente con el modelo de desarrollo de cuevas de tipo "flank margin".

Biodiversidad y geoarqueología histórica como una función de un paisaje kárstico eogenético

El Sistema de Faro también se puede considerar como una red de mini-ecosistemas que albergan una gran variedad de flora y fauna. Las entradas en los acantilados continúan siendo utilizados como hábitat para colonias de aves, mientras el colapso del techo (o "tragaluces") en algunas zonas internas permite el exuberante crecimiento de las plantas en los suelos de la cueva ricos en nitrato y la luz del sol que ilumina numerosas cámaras dentro del sistema (Fig. 5). Las evaluaciones iniciales de la biodiversidad dentro de las

cuevas de Isla Mona indican ecosistemas contemporáneos complejos y paleoambientes capaces de sostener, en algún tiempo, una gran variedad de especies (Peck y Kukalova-Peck, 1981). La ocupación humana de Isla de Mona se remonta a la época arcaica (hace 4300 años), basada en los materiales excavados en la costa oeste (Davila, 2003). Un número significativo de cuevas también ha sido identificado como sitios arqueológicos precolombinos. El arte rupestre se ha documentado, hasta la fecha, en más de 22 lugares de las cuevas. Aunque no hay evidencias de actividad cultural en cuevas del Sistema Faro, si contiene evidencia residual de la minería comercial de guano del siglo XIX que estaba extendida en la isla y en la región (Wadsworth, 1973).

Conclusiones

Forjado por las fluctuaciones del nivel del mar y la estructura hidrodinámica asociada y por la permanencia de las lentes de agua dulce, el Sistema Faro sigue siendo único en su posición como la cueva costera más grande en las islas de Puerto Rico y el más grande ejemplo de cueva del tipo "flank margin" en el mundo. La Isla de Mona continúa ofreciendo un marco de isla carbonatada única en la que desarrollar de modo excepcional investigación de campo en espeleogénesis costera, modelado climático de cueva tropical, biodiversidad de isla kárstica y geoarqueología de cuevas en la región caribeña.

Introduction

The largest karst caves in the world fall into two general categories: epigene caves and hypogene caves (see Palmer, 2007 for a review of cave types). Epigene caves are caves developed as part of the surface hydrological cycle, commonly conducting surface water underground by diffuse flow percolation and by stream sinks; the water travels for some distance underground as a flowing stream, and then returns to the surface at karst springs. Mammoth Cave, Kentucky, or the Hoelloch Cave, Switzerland are examples of large epigene caves. Hypogene caves form in the subsurface, from waters generated at depth that develop dissolutional aggressivity (by mixing or thermal processes) and dissolve soluble rock without surface influence. Lechuguilla Cave, New Mexico (mixing), or Jewel Cave, South Dakota (influenced by thermal processes) are examples of large hypogene caves.

A third type of cave has been recognized in the last few decades, the flank margin cave, commonly placed into a category called "island caves" (Klimchouk, 2007) even though they are not restricted to islands. These caves develop by the mixing of sea water and fresh water at the edge of carbonate coasts, be it islands, as in the Bahamas, or along a continental coast, as illustrated by limited examples formed within the eastern shoreline of the Yucatan Peninsula, Mexico (see Mylroie, 2013 and references therein for a full review). These caves develop in a diffuse flow environment, commonly in young carbonate rocks that retain most of their original depositional porosity (commonly ~30%). Young carbonate rocks, called eogenetic because they are diagenetically immature, are common in the tropics. Flank margin caves can form in older telogenetic (i.e., diagenetically mature) rocks when faulting or brecciation has created numerous flow pathways in an otherwise low-porosity carbonate rock (Mylroie and Mylroie, 2013). The high porosity condition (however achieved) allows the mixing of fresh and marine waters across a volume of rock. The resulting volumetric dissolution forms large chambers and passages, but there is no humanly passable pathway to the surface; entrances develop later by collapse or surface erosion breaching the cave.

Flank margin cave formation is driven by mixing dissolution, as the dissolutional kinetics of $CaCO_3$ are such that the mixing of two waters, even if both are saturated with respect to $CaCO_3$, creates undersaturation in the resulting mixture. The only requirement is that the two water bodies became saturated at different initial conditions. Marine waters meeting a fresh-water lens in a coastal setting creates the proper mixing environment. Because the dissolution takes place in the distal margin of the fresh-water lens, under the flank of the enclosing landmass, the caves are called *flank margin caves*. The flank margin position is critical, as three activities occur there to maximize dissolutional potential. Firstly, the vadose fresh water/phreatic fresh-water mixing zone at the top of the fresh-water lens is superimposed on the fresh-water phreatic/marine water mixing zone at the bottom of the lens, to create greater dissolution than that achievable by either mixing zone alone. Secondly, the top and bottom of the fresh-water lens are each a density interface that can collect organic material; oxidation of those organics creates CO_2 to drive additional dissolution. In extreme situations, the oxygen is completely consumed and anoxia results, allowing exotic geochemical pathways, such as those involving H_2S, to act. Thirdly, as the fresh-water lens thins at the lens margin, the full integrated flow of the lens is forced through an ever-decreasing cross-sectional area, and flow velocities within the lens increase. This flow brings reactants into the area, and takes products out, again enhancing dissolution (Fratesi, 2013).

Coastal cave and karst development in a small carbonate island setting

Flank margin caves are known from carbonate coasts all over the world. Many are small or intermediate in size, because their growth depends on sea level remaining constant to hold the fresh-water lens in a stable position. The glacioeustatic sea-level fluctuations of the Quaternary have prevented such lens stability, and flank margin caves from those times are not excessively large. *Sistema Faro* on the Isla de Mona, Puerto Rico (Figs. 1 and 4) is the largest known flank margin cave in the world. It owes its large size to its development prior to the Quaternary, when glacioeustatic sea-level change was not as rapid or as high magnitude as during the 2.6 million years until the present. Subsequent uplift has carried the cave upward and insured its protection from wave erosion. The pattern of the cave (Fig. 4) is the result of its mixing zone origin. Computer simulations of flank margin cave development (Labourdette *et al.,* 2007) demonstrate that these caves initiate as small, isolated chambers that intersect and connect as they grow larger (Fig. 3). This connection continues in all directions until the active lens margin area is full of voids. The cave enlarges further by the lateral connection of voids parallel to the coast, as Figure 4 demonstrates (the cave actually follows the curving coast south and then west). The failure of the cave to develop inland to a major extent is a measure of how important the distal margin of the fresh-water lens is to flank margin cave genesis; the lens interior does not support significant speleogenesis. The only caveat to this explanation is that when a lens is stable for a long period of time, the development of cave porosity at the lens margin causes the lens margin to step backwards into the island, essentially creating a new margin that is not technically under the flank of the enclosing land mass, but interior to it. Modeling of flank margin cave development (Labourdette *et al.,* 2007) has shown that this step-back occurs when cavernous porosity reaches about 20%. Figure 4 illustrates this step-back quite clearly, as rows of chambers, each parallel to the coast, the inner most chambers showing less lateral connection than those more coastward, as sea level must have fallen and stopped speleogenesis before chamber integration at that row was complete.

Flank margin caves are considered hypogene by some authors (e.g., Palmer, 2007); others (e.g., Klimchouk, 2007) place them in the separate category of island caves because the mixing of waters is accomplished in a shallow environment without deep waters rising from below. The argument may be simple semantics, because both cave types have very similar patterns, quite different patterns compared to typical epigenic stream caves. Stream caves are underground streams, and whether fully phreatic or with an air-contact surface, the streams flow in long linear pathways, from inputs to outputs. As such, their size, defined by overall length, is easily categorized by the summation of the cave survey segments used to measure them. Many hypogene caves, such as Carlsbad Caverns or Lechuguilla Cave, and almost all flank margin caves, have a different pattern. They develop without entrances or humanly passable connections to the surface, all entrances are accidents of later intersection by erosion of the land surface and exposure of the cave within the rock mass. Their cave passages trend in a variety of directions, and large globular chambers, dead-end passages, and mazes are common. Metrics used to define and compare cave systems vary and are often inconsistently applied. Total cave length is widely used but survey lines run through the cave can vastly underestimate cave size if the passages are simply sketched, or vastly overestimate cave size if numerous survey stations are set to map out the room peripheries. For this reason, the sizes of flank margin caves are not determined from the sum of the survey shots made to map the cave (i.e., traditional cave length), but by the cave's total areal footprint (see Mylroie, 2007 for a full treatment of this issue). Sistema Faro is defined by 19 km of total survey, larger than any other surveyed flank margin cave to date. Its areal footprint is also greater than any known flank margin cave, 234,923 m^2. This is in contrast to the longest cave in Puerto Rico, Sistema Rio Encontado, which is an active fluvial system defined by >20 km of survey and one of the longest traversable underground rivers in the world.

Geology of the Isla de Mona

Isla de Mona is an uplifted carbonate island midway between Hispaniola and Puerto Rico, within the Mona Passage (Fig. 2). The island is 12 km long (east to west) and 5 km wide (north to south) and has an area of 55 km^2 while a smaller carbonate island (Isla

Monito) is located 5 km off its northwest coast (Frank *et al.,* 1998a). Isla de Mona has a gently sloping, flat top (locally called a "meseta") up to 80 meter high bounded on all sides by steep cliffs. The cliffs plunge directly into the sea on the north and east sides of the island, and a small coastal plain of Late Pleistocene carbonates forms a narrow, irregular bench along the southern and southwestern coasts (Fig. 2). The meseta itself is made up of the Mona dolomite overlain by the Lirio limestone, both of late Miocene to early Pliocene age. Flank margin caves are abundant on all coasts of the island, with the largest and greatest number of these caves found at the contact between the Lirio Limestone and the Mona dolomite (Fig. 1B), although flank margin caves are found both above and below this contact (Frank *et al.,* 1998b). The origin of the caves at the contact has been the subject of debate, primarily centered on whether the caves are located at their position because of the contact, or alternatively, do the caves represent a fresh-water lens flow regime and mixing that created the dolomitization of the rock below them? See Sumrall (2013) for a recent analysis of this situation. Isla de Mona has been uplifted as an outcome of its position near the North American-Caribbean plate boundary and the active Puerto Rico Trench to the north. The emergent island platform exhibits limited faulting and mild folding but tectonics has not had a major influence on cave configuration or development patterns.

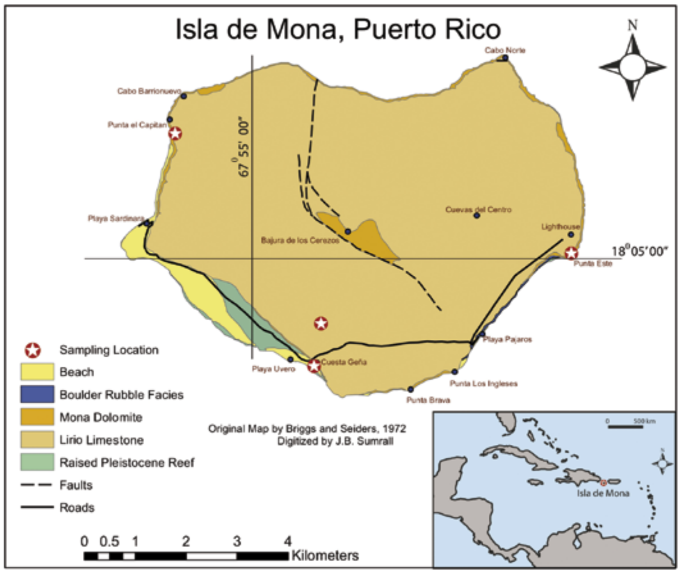

Figure 2: Map of the Isla de Mona (Sumrall, 2013).
Figura 2. *Mapa de la Isla de Mona (Sumrall, 2013*).

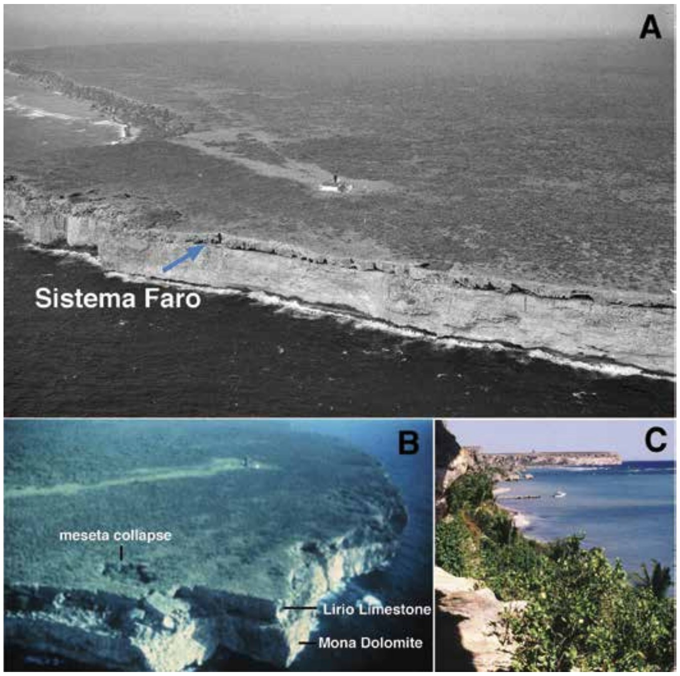

Figure 1: A) Coastal escarpment (Punta del Este) of Isla de Mona (courtesy of the U.S. Coast Guard archives) B) aerial and C) coastal views of the eastern cliff line of Isla Mona.
Figura 1. *A) Escarpe costero en la Isla de Mona (cortesía del S. Coast Guard archives) B) aérea y C) vista de la costa del acantilado oriental de la Isla de Mona.*

Hydrogeological and coastal geomorphological controls influencing the genesis of the *Sistema Faro*

Sistema Faro is located at the Mona Dolomite/Lirio Limestone contact. The cave has numerous entrances that open directly onto the sheer sea cliff that plunges down to the Caribbean. The cave has been exposed by cliff retreat that has opened the most coastal proximal of the chambers and passages on the coast margin to the outside. Despite the 19 km of survey, and the coast-parallel orientation of the cave, it extends inland less than 300 m. The system's vertical range (or the maximum vertical distance between its uppermost collapse entrance to the lowest recorded point in the cave survey, is only 36 meters. However, the maximum vertical extent of the dissolutional margin comprising the system's configuration is significantly less. As noted previously, the cave wraps from the eastern side of the island around to the southern side. The cave must be younger than the rock that contains it, but how much younger? At a cave farther to the west, *Cueva del Aleman,* Panuska *et al.* (1998) demonstrated by paleomagnetic analysis of cave sediments and flowstone, that the cave had a minimum age of 2 million years. It is likely that

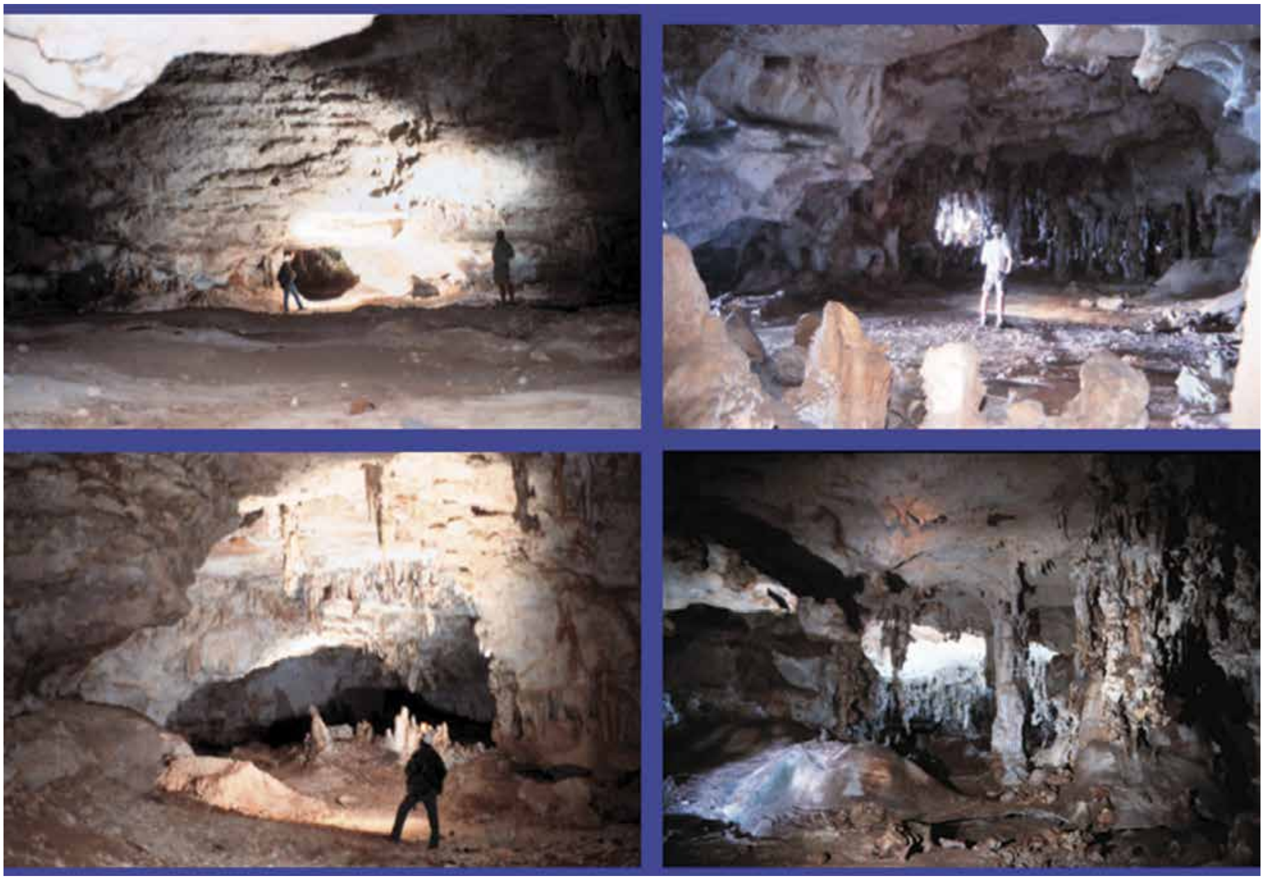

Figure 3 : Example of passage cross sections in the caves of the Isla de Mona.
Figura 3. *Ejemplo de la sección de un pasaje en las cuevas de la Isla de Mona.*

Sistema Faro is similar in age, which places its development somewhere between early Pliocene and early Pleistocene. The great size of *Sistema Faro* requires a stable fresh-water lens, which would indicate the cave formed prior to the high amplitude, short wavelength glacioeustatic sea-level oscillations of the Quaternary period. A mid to late Pliocene age would fit these observations.

The existence of *Sistema Faro* appears to be the result of its genesis during a time of relative sea-level stability, which allowed the flank margin dissolutional environment to penetrate into and around the island margin. The placement of the cave within carbonates of an uplifted island helped create a preservational environment that allowed the cave to persist into the present.

Exploration and Survey of Sistema Faro

Three large caves – *Cueva del Lirio*, *Cueva el Lado del Faro* and *Cueva de los Losetas* were previously known to occupy the eastern point of the island (Punta del Este) (Briggs, 1974) where a well-defined horizon of cave entrances stretches nearly 2 km along the cliffline (Fig. 1). Once thought to be separate caves, systematic survey started in 1998 resulted in the physical connection of the component structures into what is now known as *Sistema Faro* (Fig. 4). The overall cave structure is essentially a sprawling array of interconnected chambers, punctuated by a myriad of flowstone and bedrock columns (Fig. 4). The maze-like system is both sufficiently large and complex enough for even experienced explorers to become disoriented. The cave is predominantly dry with few dripping formations and ephemeral catchment pools formed within numerous rimstone dams (gours) during the rainy season.

Similar to other caves on Mona, advanced redissolution of speleothems is commonly noted in Sistema Faro. The term "redissolved speleothem" is often used to described speleothems such as flowstone, stalagmites and stalactites that show dissolutional incision of their original depositional surface.

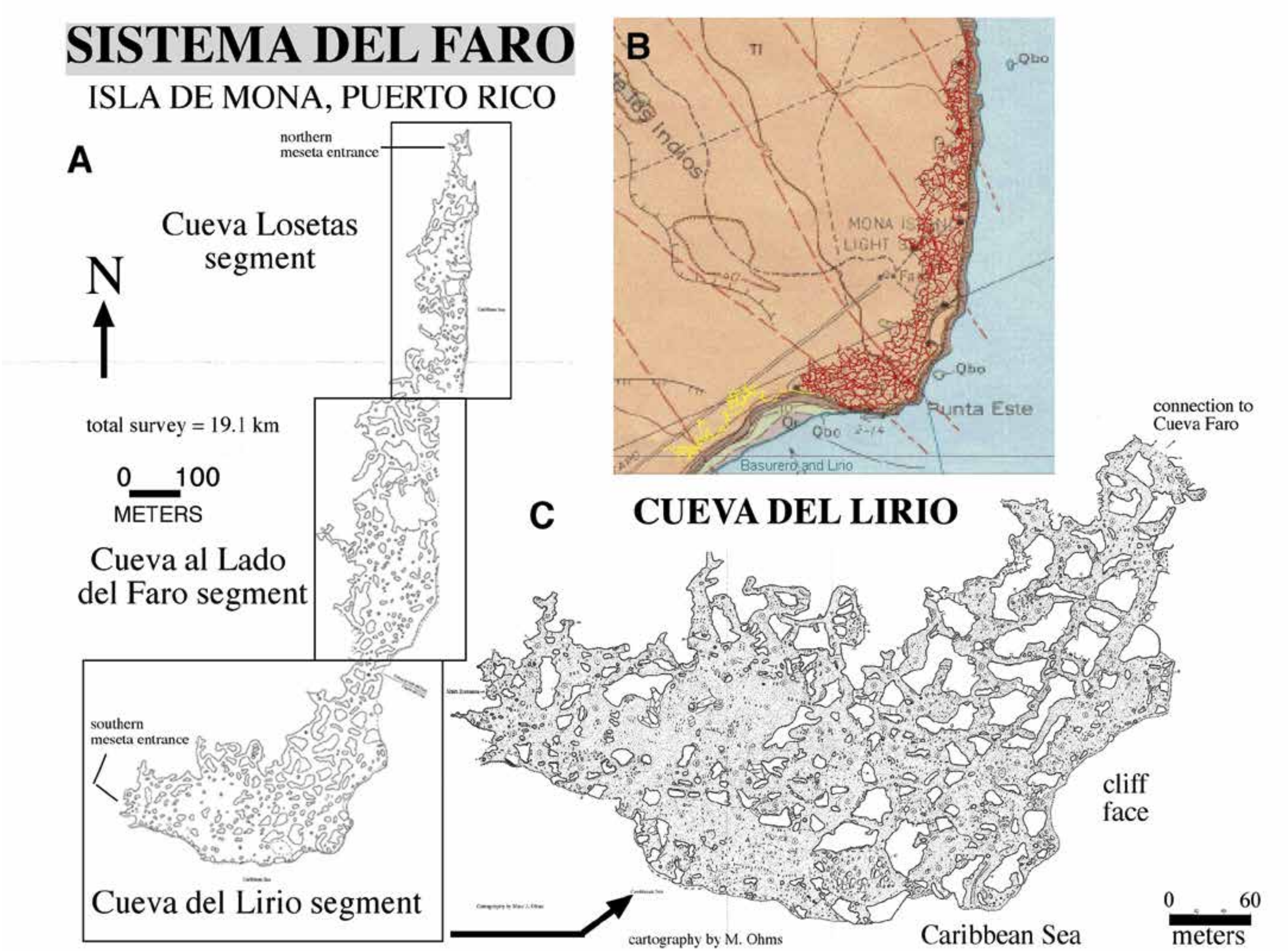

Figure 4: Map of the *Sistema Faro.*
Figura 4. *Mapa del Sistema de Faro.*

The term "redissolution" is meant to indicate that the original bedrock $CaCO_3$ was dissolved and then precipitated as the speleothem, and subsequently dissolved again by a later process. In other words, the speleothem itself has not been redissolved, it is being dissolved for the first time, but the $CaCO_3$ within the speleothem is being dissolved a second time. There has been much debate about how this redissolution takes place. Some authors argue that the process is phreatic, and indicates a re-flooding of the cave by dissolutionally aggressive water after a vadose interval that allowed vadose speleothem deposition (e.g. Frank et al., 1998b). Other authors feel it is formed by condensation corrosion in the vadose zone and a second phreatic event is unnecessary; the condensation being a function of the cyclical interaction between the surface climate and unique cave microclimates (Tarhule-Lips and Ford, 1998) (Fig. 6B). These dissolved speleothem surfaces are quite common in flank margin caves in the Bahamas where glacioeustasy can easily explain a series of alternating phreatic and vadose events as sea-level change moves the fresh-water lens vertically (Carew and Mylroie, 1999). It is also obvious in the cliff-side chambers of *Sistema Faro* that there is a clear directionality of speleothem dissolution, indicating an air-movement dependence. Most likely these "redissolved speleothems" are polygenetic, forming by both vadose and phreatic processes. It could be considered analogous to the development of voids in epigenic stream caves, where the major conduits formed by phreatic dissolution at or below the water table, but shafts and dome pits formed later by downward vadose flow.

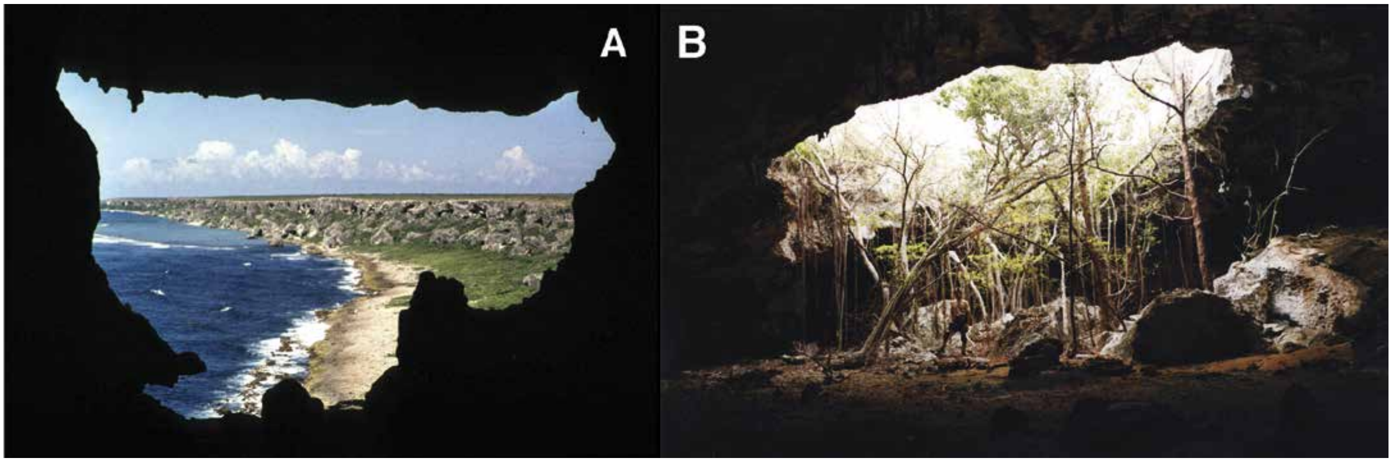

Figure 5: A) One of many cliff-side entrances to the *Sistema Faro*. B) Skylight area in the *Sistema Faro*.
Figura 5. *A) Una de las entradas en el acantilado del Sistema Faro. B) Vista de paisaje en el Sistema Faro.*

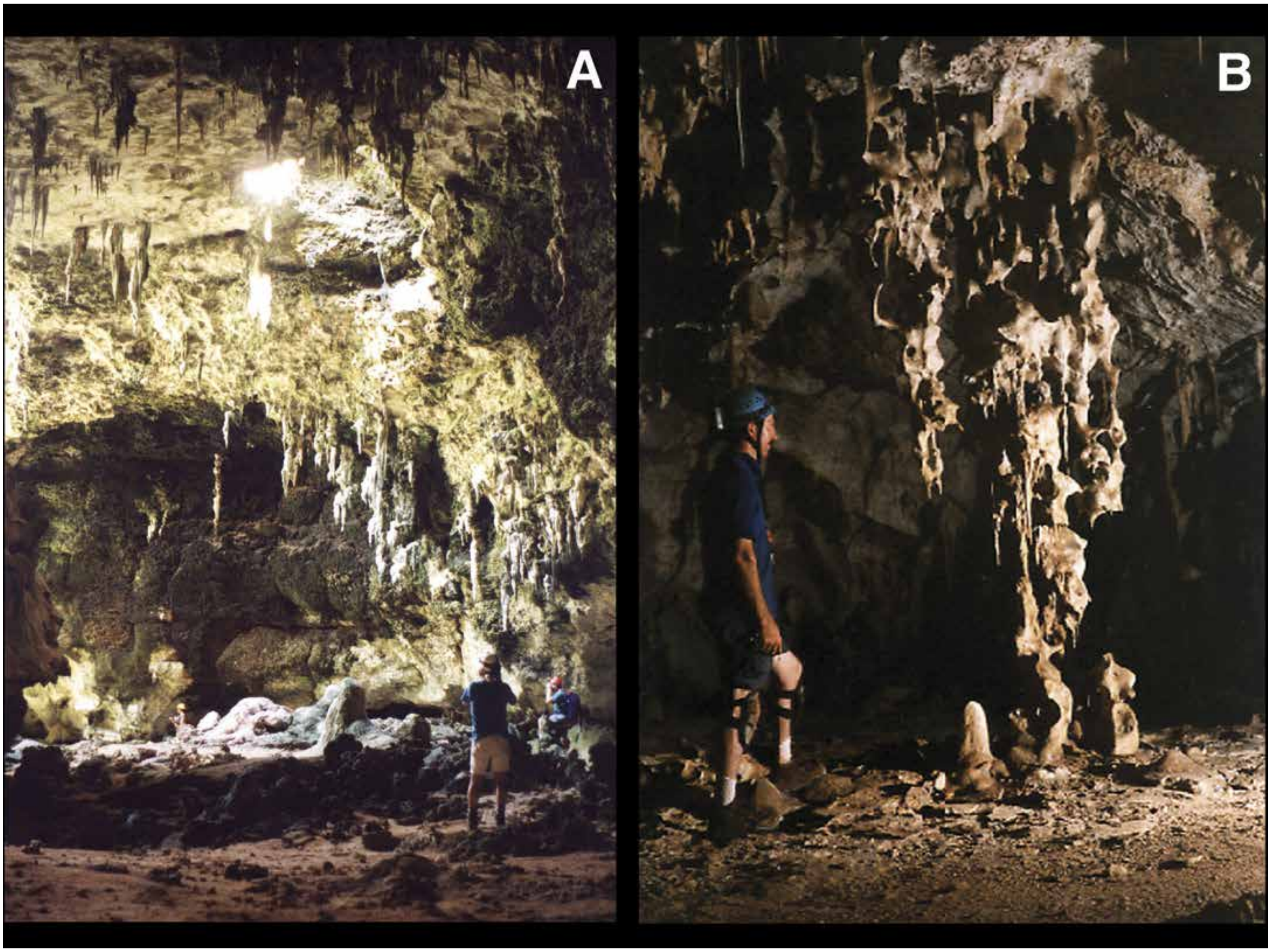

Figure 6: A) The Cathedral Room in *Cueva Lirio*. B) "Redissolved" speleothems ("grotesqueries") in *Cueva Faro.*
Figura 6. A*) Sala de la Catedral en la Cueva Lirio. B) Espeleotemas redisueltos en la Cueva Faro.*

Cueva del Liro comprises the southern segment of the system, with 9.3 km of total survey and featuring large interconnected chambers, several shallow vertical entrances ("skylights") (Fig. 6) and 23 cliff entrances that overlook the Caribbean Sea more than 40 meters below (Fig. 5A). Passages extend inland from the cliff face up to 257 meters – the greatest inland extent of the system which becomes progressively more limited as one moves north along the system's lateral extent This shift in cave penetration may reflect flow dynamics in the fresh-water lens at the time of cave formation, or greater cliff retreat to the north, such that more cave has been lost to coastal erosion.

Cueva Faro forms the central, most complex segment of the system. The cave has numerous entrances on the meseta but only one is currently used as the principal entry point. The cave consists of many large rooms and passages with a few smaller passages at the landward flank of the cave, many resembling three-dimensional (boneyard) maze passage described in other karst areas yet consistent with the flank margin model of cave development. Limited passage development within the underlying Mona Dolomite is restricted to this section of the system.

The impacts of guano mining in terms of passage modification are most prevalent here with trails constructed for transport of excavated sediments through the cave and related period artifacts. Rail line remnants from that period are still evident today– some of which extend from the cave interior to the cliffline where large horizontal openings lead to shear drops up to 40 meters to the Caribbean Sea where excavated guano was vertically offloaded to awaiting barges. This is discussed in greater detail in the following sections.

Cueva Losetas forms the northern end of the Faro system. As one enters this northernmost cave segment, the maximum inland extent from the cliffline is reduced to only 120 meters or half that of the southern segments. *Cueva Losetas* harbors some of the best-preserved passage morphologies, spelothems and speleogens as this area was less impacted from guano mining compared to the southern segments. Though chamber sizes are generally smaller, the spelothem diversity is more notable in this segment with cave shields, pearls and abundant gypsum speleothems (Fig. 7).

Biodiversity as a function of an eogenetic karst landscape

Sistema Faro can also be viewed as a network of mini-ecosystems, harboring a range of flora and fauna. Cliffside entrances continue to be used as habitat for roosting bird colonies while the internal collapse areas (or "skylights") feature comparatively lush plant growth supported by the nitrate-rich cave soils and sunlight that penetrates numerous chambers within the system (Fig. 6B). Initial assessments of biodiversity within the caves of Isla Mona indicate complex contemporary ecosystems and paleoenvironments capable of supporting a range of species (Peck and Kukalova-Peck, 1981). Several caves on the island have revealed fossil records of past faunal diversity. *Cueva Losetas*, for example, is the only known cave on the island where crocodilian fossils have been recorded (Frank and Benson, 1998). While no large contemporary bat colonies are found in the *Sistema Faro*, there is evidence of significant bat roosts in the past. Whether there were bat populations sufficiently large enough to generate the extensive guano deposits found in the majority of Mona caves or some other mechanism was responsible, however, remains a point of debate (e.g., Frank, 1998).

Historical geoarchaeology

Human occupation of Isla de Mona dates back to the Archaic period (~4300 ybp), based on cave materials excavated from its western coast (Davila, 2003). A significant number of caves have also been identified as pre-Columbian archaeological sites. Rock art has been documented in over 22 cave sites on the island to date, such examples of cultural cave uses have not been recorded in *Sistema Faro*. Thus, the site selection criteria for rock art placement and associated cave uses, be they ritual or practical, remain enigmatic in spite of ongoing, in-depth site documentation in Puerto Rico (Lace, 2012). This underscores the complexities incumbent on modeling ritual cave uses on Isla de Mona and similarly problematic in other island and continental settings on regional and global scales. The keystone of such efforts is the detailed documentation of the associated landscape. In this case, the thorough exploration, survey and inventory of all caves on Isla de Mona, including the smallest to most extensive cave structure on the island – the Faro System.

The majority of the caves on Isla de Mona once contained large amounts of guano. The fertile, phosphate-rich guano deposits were highly prized in the 19th century as economically significant fertilizer that were aggressively extracted and exported on a large scale by European interests (Briggs, 1974) until the development of the Haber-Bosch process

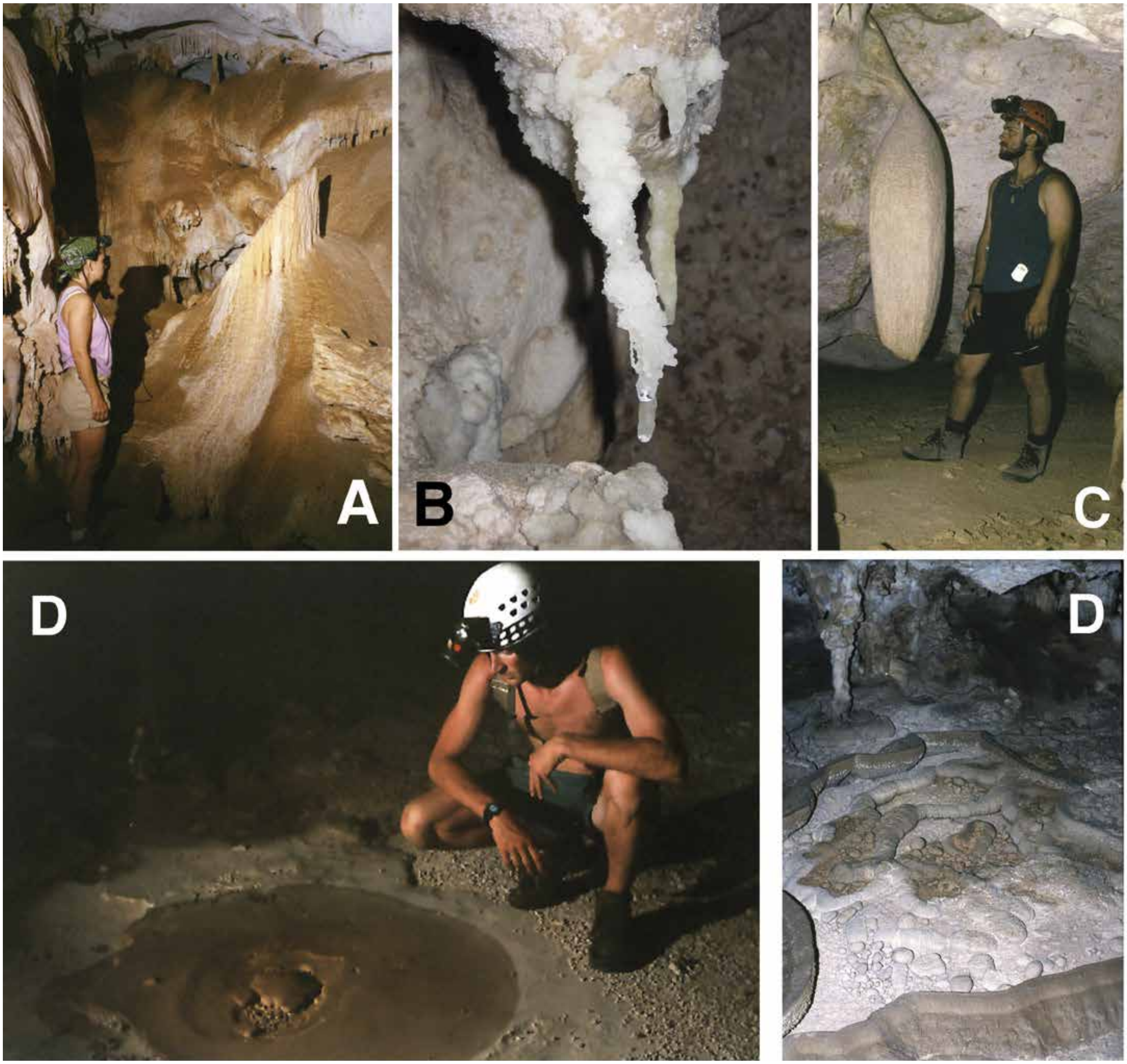

Figure 7: Speleothem and speleogenetic development in the *Sistema Faro*: A) cave shield (photo by C. Beck), B) active gypsum formations, C) pendant, D) calcite deposits and E) gours.

***Figura 7**. Espeleotemas y desarrollo espelegenético en el Sistema Faro: A) colada en la cueva (photo by C. Beck). B) formacioes de yeso activas, C) pendant, D) depósitos de calcita y E) gours.*

for producing ammonia inorganically just before WWI impacted the raw nitrate market (Frank, 1998). *Sistema Faro,* for example, shows that extensive systems of trails, railways, rock walls, paths and small bridges were constructed to allow access and removal of guano deposits, remnants of which are still evident in a number of Mona caves.

Sistema Faro contains residual evidence of the extensive 19th century commercial mining of guano that was widespread on the island and the region (Wadsworth, 1973). As a result, cave sediments were significantly disturbed as large-scale commercial excavations removed up to one meter in depth of fertile guano from numerous chambers throughout much of the system (Kaye, 1959). Though such passage modification has had devastating effects on the archaeological record of most Mona caves, several of the *Sistema Faro* cave chambers remain relatively pristine – a condition entirely dependent on continued proactive resource management and preservation.

Coastal resource management

Isla Mona and nearby Isla Monito were designated a National Natural Landmark in 1975 by the U.S. Department of the Interior based on the unique biodiversity and the significant geologic and cultural resources associated with their pristine island landscapes. Isla de Mona, Isla Monito and the associated reefs also form the largest marine protected area (MPA) in the Puerto Rican islands. Isla de Mona continues to be actively managed as a natural preserve by the Puerto Rico DRNA. Limited camping permits are issued to visitors but access to the majority of the cave sites, including the *Sistema Faro,* is currently restricted to research activities overseen by the Puerto Rico Department of Natural Resources.

Anthropogenic impacts to Mona karst have ranged from minimal alteration to the island surface to extreme modification within many of the caves as a result of commercial guano mining and associated sediment removal. A lighthouse and station were constructed in 1899 at Punta del Este, at the inland perimeter of the *Sistema Faro* and was decommissioned and abandoned in 1974 (Fig. 8). The only permanent structures currently occupied on the island are a ranger station and recently constructed interpretive center located on the western coast at the *Playa Sardinera*, which was built upon a U.S Civilian Conservation Corps (CCC) camp constructed in the 1930s which in turn was built upon a pre- and

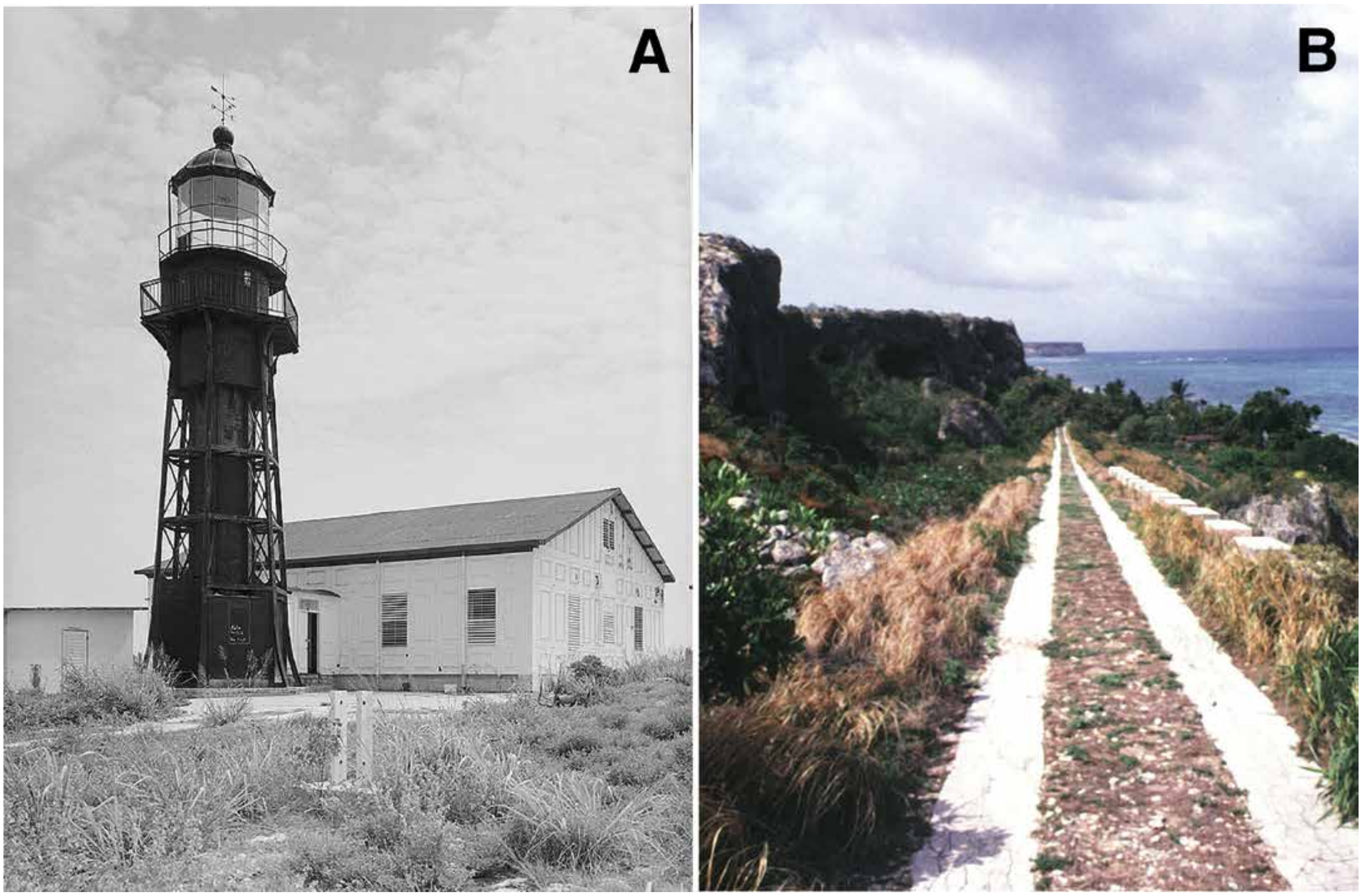

Figure 8: Historic uses of the *Sistema Faro* karst landscape. A) *Punta del Este* lighthouse (courtesy of the U.S. Coast Guard archives) B) concrete road linking the lighthouse station to the *Playa Pajaros*.
Figura 8. *Usos históricos del area kárstica del Sistema Faro. A) Faro de Punta del Este (cortesía del U.S. Coast Guard archives) B) Camino asfaltado que une el faro con la Playa Pájaros.*

post-contact Taino settlement site (Wadsworth, 1973). European arrival also coincided with the introduction of invasive species, such as feral pigs, cats, goats and rats, which have had a significant negative impact on endemic species. The lack of long-term, large-scale human habitation has played an obvious and critical role in preserving one of the last pristine island karst ecosystems in the Caribbean.

Conclusions

Isla de Mona continues to offer a unique carbonate island setting in which field research in coastal speleogenesis, tropical cave climate modelling, island karst biodiversity and geoarchaeology of caves in the Caribbean region can be conducted. While the potential for the discovery of undocumented caves on the Isla de Mona is still possible (as newly recorded caves are routinely added to the Mona cadaster with each successive expedition), the probability of finding another cave equivalent to *Sistema Faro* is very low. Forged by the interplay of sea level fluctuations and the associated hydrodynamic structure and duration of fresh-water lenses, *Sistema Faro* remains unique in its position as the largest coastal cave in the Puerto Rican Islands and the largest example of flank margin cave development in the world.

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