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FLANK MARGIN CAVE DEVELOPMENT AT CALA PI AND CALA FIGUERA, MALLORCA ISLAND, SPAIN

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ABSTRACT. The development of flank margin caves on carbonate islands and coasts provides a record of sea-level position at the time of cave genesis. A study of cave abundance and position was conducted in southeastern Mallorca along Miocene limestone coastal cliffs at Cala Pi and Cala Figuera to determine if differential amounts of coastal retreat produced a similarly differential numbers of flank margin caves, i.e. did more cliff retreat result in fewer preserved caves? Caves were mapped along cliffs exposed to the open Mediterranean Sea, and within protected inlets (called *calas* on Mallorca).

At Cala Pi, 63 caves were surveyed. On the exposed coast 12 caves had 360 m^2 total areal footprint for 30 m^2 per cave, and 716 m^3 total volume for 60 m^3 per cave. Within the protected cala 51 caves had 1125 m^2 total areal footprint for 22 m^2 per cave, and 3146 m^3 total volume for 62 m^3 per cave. At Cala Figuera, 45 caves were surveyed. On the exposed coast 20 caves had 1915 m^2 areal footprint for 96 m^2 per cave, and 3625 m^3 total volume for 181 m^3 per cave. Within the protected cala, 25 caves had 3652 m^2 total areal footprint for 146 m^2 per cave, and 7845 m^3 total volume for 314 m^3 per cave.

The data show more caves present within the protected calas than on the exposed cliffs. The larger number of caves inside the more protected environment of Cala Pi, with lower average volume than those in the exposed cliffs, suggest that the small-sized caves have been preferentially removed from the exposed setting. Numbers are more balanced at Cala Figuera (20 exposed vs 25 within), but the larger area and volume numbers for the protected cala caves indicate a higher degree of chamber loss by each cave in the exposed open coast position. A question raised by the cave distribution is: are the caves within the calas there because they pre-existed, and were intersected by cala incision into the coastline, or did the caves in the calas form after cala incision, such that mixing dissolution along the cala walls produced the caves? Sedimentary slump structures at Cala Figuera indicate flank margin caves were present during Messinian time.

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INTRODUCTION

The island of Mallorca is one of the Balearic Islands of Spain, located in the western Mediterranean at 39° 30' north latitude and 3° east longitude (Figure 1). Menorca lies ~50 km to the northeast, with Ibiza and Formentera ~100 km to the southwest. The Balearic Islands represent the subaerial expression of Alpine orogenic compressional events that occurred from the Paleogene to the Middle Miocene as complex plate interactions between Europe and Africa occurred (Tuccimei et al., 2007). The deformed rocks comprise Mesozoic, Paleogene, and Early to Middle Miocene rocks overlain by relatively flat carbonate rocks from the Late Miocene up to the Pleistocene (Pomar, 2001). The carbonate rocks that formed the study areas examined in this paper are Late Tortonian to Early Messinian in age, with the Tortonian-Messinian boundary exhibiting a paleokarst surface. The units immediately above this unconformity are called the *Terminal Complex* (Fornós et al., 2005) which consists of well-bedded calcarenite and calcisiltite changing upward into massive oolitic limestones. Mallorca has an area of 3,667 km^2, a tidal range of ~0.25 m (microtidal), and along the southeast coast of the study area (Figure 1), a continuous coastal cliff more than 30 km in length, with vertical faces 5 to 56 m high (Fornós et al., 2005). The cliffs are cut by reentrants called *calas* that are commonly perpendicular to the coast and extend inland hundreds of meters, initially as cliffed bays and then continuing inland in many cases as terrestrial canyons with ephemeral surface drainage and vertical walls (Figure 2). Two specific calas were selected for examination, Cala Pi and Cala Figuera (Figures 1 and 2).

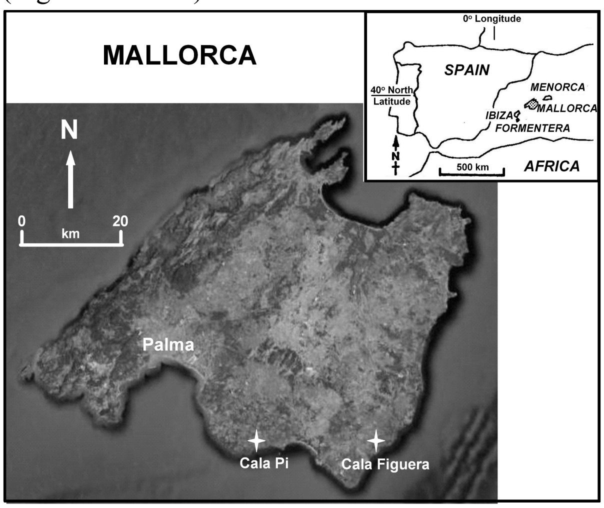

Figure 1. Location of Mallorca and the Balearic Islands, showing the two field sites presented in this study (modified Google Earth image).

Flank margin caves are produced in the discharging margin of the fresh-water lens by a combination of three factors: 1) mixing dissolution at the halocline, 2) oxidation of organic material collecting at the halocline, and 3) increased flow velocities occurring at the thinning lens margin. The voids produced tend to be the largest found in subaerially exposed carbonate platforms where diffuse flow occurs in a fresh-water lens. See Mylroie and Mylroie (2007) for a complete review of the flank margin cave model. Because flank margin caves occur in the site of carbonate deposition, they are considered syngenetic (Mylroie and Mylroie, 2009), and are preferentially disposed to preservation as paleokarst (Mylroie and Carew, 1995). Uplift in Mallorca has brought preserved flank margin caves to the surface, allowing them to be categorized for modeling purposes.

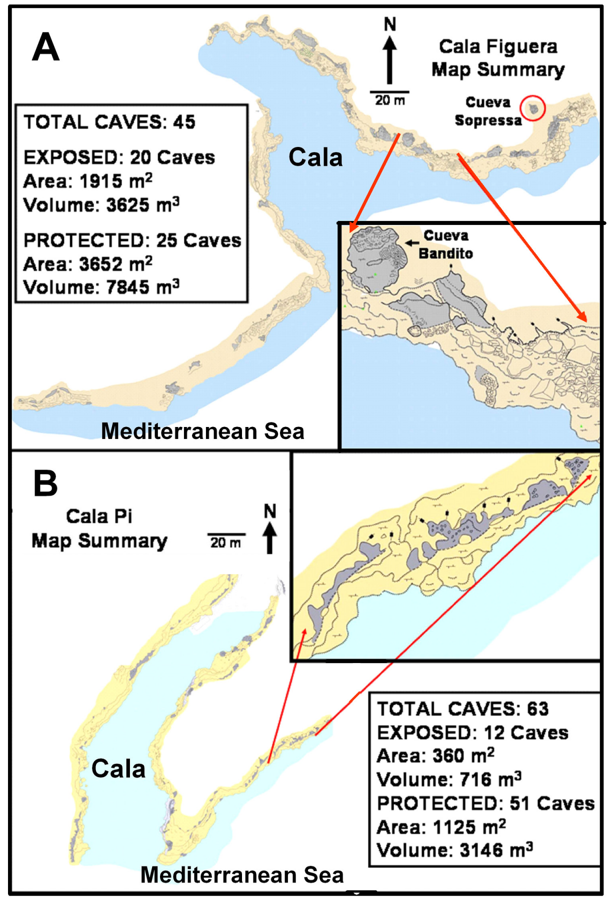

Figure 2. The field sites Cala Figuera (A) and at Cala Pi (B), with the data on cave distribution and characteristics. In (A), the locations of Cueva Sopressa and Cueva Bandito are given (see text and Figure 4).

METHODOLOGY

The study was initiated to determine the spacing and configuration of relict flank margin caves located in the cliffed exposures of Cala Pi and Cala Figuera, to provide a database to be used for modeling void distribution in the subsurface. The fieldwork was conducted November 20-27, 2010 by the seven co-authors. At each study site, all known caves were tied to a surface survey using Suunto® compasses and fiberglass tape backed up by GPS readings. All caves were surveyed with Suunto® compasses, with distance measurements by Disto® laser range finder, or fiberglass tape, as lighting conditions determined, following standard cave-surveying protocols (e.g. Dasher, 1994). Flank margin caves form in a continuum of sizes as demonstrated by Mylroie and Mylroie (2007); for the purposes of this study all humanly enterable voids with a phreatic dissolutional signature, and containing vadose cave speleothems, were considered flank margin caves.

At Cala Pi and Cala Figuera, the cliffs run continuously from inside the cala to the open coastline (Figure 2). This configuration allowed comparison of the flank margin cave abundance and configuration within the calas, a protected environment, versus the exposed coastal cliffs open to the full wave energy of the Mediterranean. If no difference in cave number and configuration between exposed and protected cliffs within the embayment existed, then it could be hypothesized flank margin cave development was not really restricted to the immediate edge of the fresh-water lens, but extended inland a significant distance as a uniformly distributed field of dissolutional voids of similar size and morphology. A uniform cave-distribution hypothesis would call for the calas to be younger than the exposed caves, and so that the calas would have been incised into a field of pre-existing dissolutional voids. Such a hypothesis would require more uniform dissolution within the body of the fresh-water lens than that proposed by the flank margin cave model. On the other hand, if the numbers and configurations of the caves differed between the protected cala embayment and the exposed ocean cliffs did exist, then the flank margin caves in the cala would most likely have been produced after primary cala incision, such that the lens margin followed the cliff line, wrapping around the cala (Figure 3). In this case

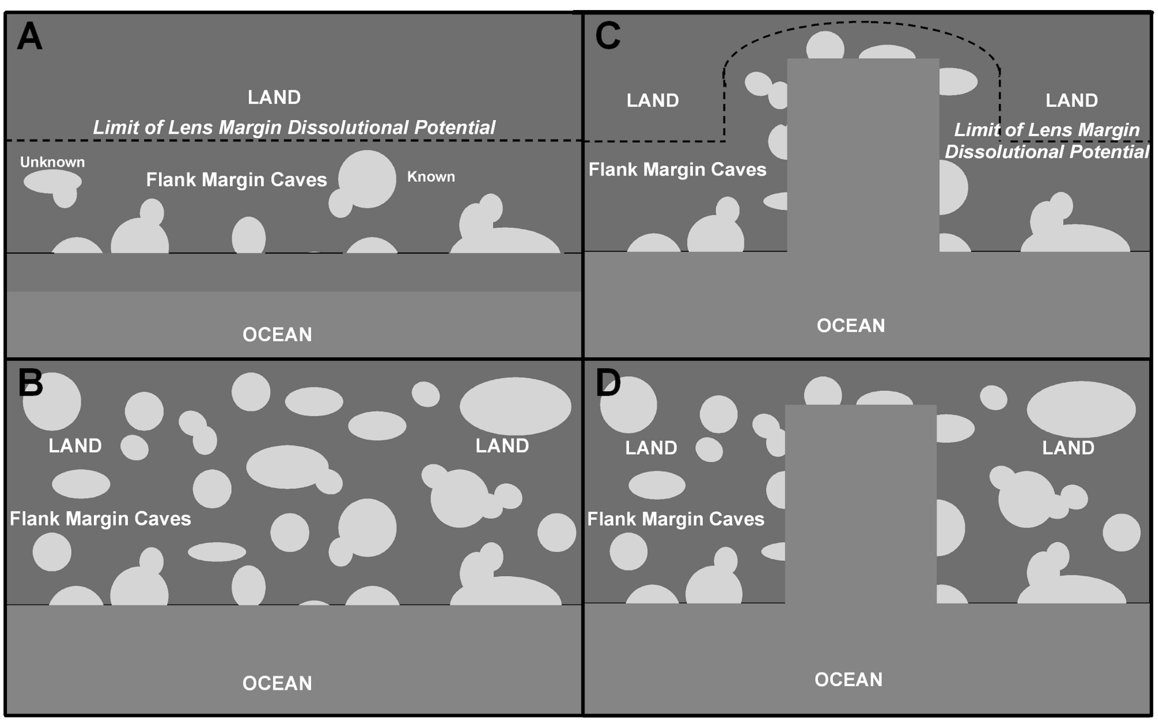

Figure 3. Simple schematic demonstrating the difference between a pervasive field of dissolutional void development versus the limited range of lens-margin void development. A) Flank margin cave development restricted to the lens margin. B) Flank margin caves as a pervasive feature extending far inland. C) If (A) is true, then the cala must be older than the caves it contains. D) If (B) is true, then the cala is younger than the caves it intersects.

the data reflect a preservational bias, whereas exposed coastal cliffs had experienced more cliff retreat which resulted in more cave loss than the protected cala sites.

This approach assumes that flank margin caves can be discriminated in the field from other pseudokarst cave types, sea or littoral caves in particular. The differentiation of sea caves from flank margin caves has been a topic of much discussion (see Waterstrat et al., 2010 for a full treatment of the situation). The problem is compounded by the effects of coastal retreat, which uncover flank margin caves and expose them to marine processes, resulting in over-printing and production of what are known as *hybrid caves* (Machel et al., 2012). As dissolutional voids developed within a laminar flow system, flank margin caves develop without entrances. Entrances form later by surface erosional process that lead to intersection by vadose dissolution pits, ceiling collapse, or by lateral breaching by slope and scarp retreat. A large void entered by a small opening in a sea cliff, or by a pit entrance from above, cannot be the result of mechanical littoral processes. Cueva Sopresa and Cueva Bandito (Figure 4) are good examples of dissolutional voids formed as flank margin caves. In addition to their restricted entrances (vertical for Sopresa, lateral for Bandito) which preclude a littoral genesis, they also contain phreatic dissolutional surfaces and numerous vadose calcite speleothems, indicative of a flank margin cave origin. From these examples, and their similarity to other breached caves found in the cala and exposed cliffs, we interpret the vast majority of the caves examined to be flank margin in origin.

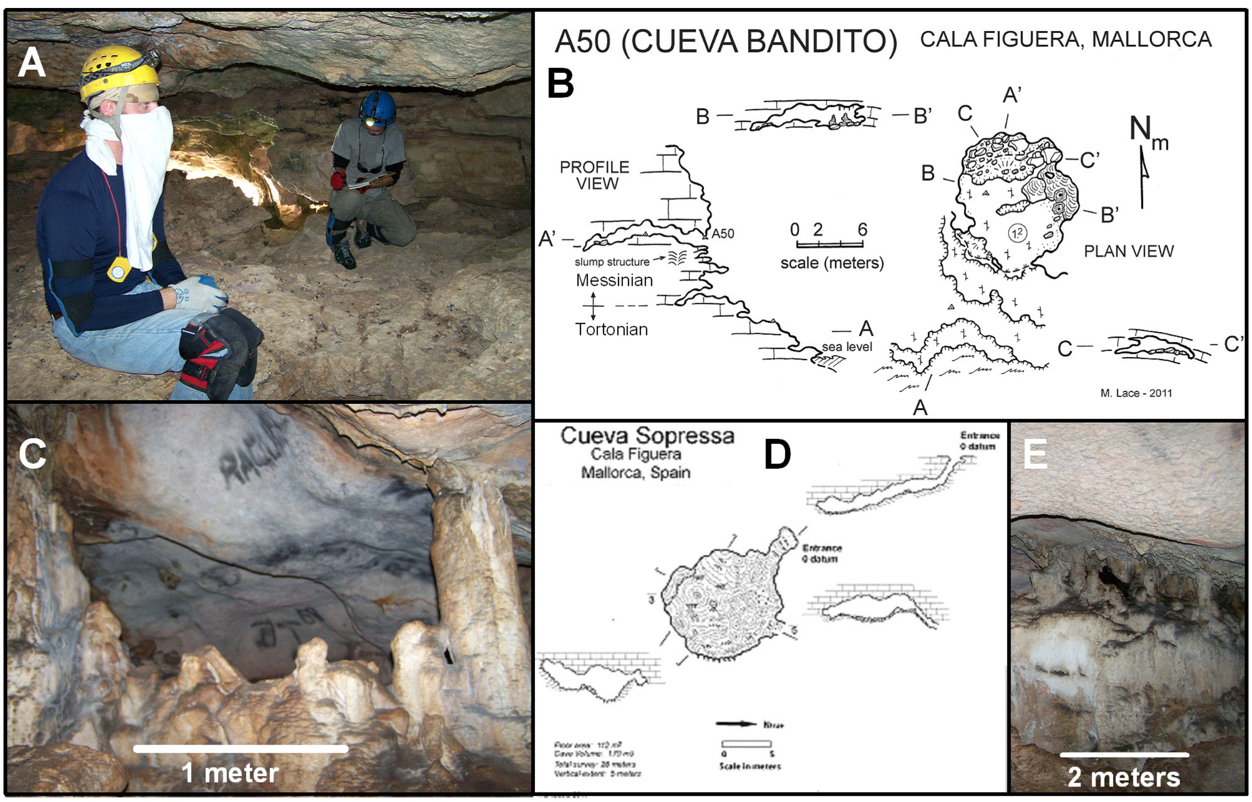

Figure 4. Image (A) and map (B) from Cueva Bandito; and images (C and E) and map (D) from Cueva Sopressa. The small entrances show in maps B and D are not consistent with a littoral marine origin for these caves. Images C and E show both phreatic dissolutional surfaces, and massive subaerial calcite vadose speleothems. These observations indicate a flank margin genesis for the caves.

RESULTS

At and around Cala Pi, 63 caves were surveyed (Figure 2B). On the exposed coast 12 caves were mapped with a total aerial footprint of 360 m^2 producing an average area of 30 m^2 per cave, and the caves had a total volume of 716 m^3 producing an average volume of 60 m^3 per cave. Within the protected cala, 51 caves were mapped for a total area of 1125 m^2, producing an average area of 22 m^2 per cave, and the caves had a total volume of 3146 m^3 producing an average of 62 m^3 per cave. Cala Pi initiates perpendicular to the coastal cliff trend, but then turns to the northeast, such that it becomes parallel to the exposed coast (Figure 2B). This setting allowed direct comparison of cave development along similar compass trends.

At Cala Figuera, 45 caves were surveyed (Figure 2A). On the exposed coast 20 caves produced a total aerial footprint of 1915 m^2, resulting in an average of 96 m^2 per cave, and the caves had a total volume of 3625 m^3 resulting in an average volume of 181 m^3 per cave. Within the protected cala, 25 caves had a total aerial footprint of 3652 m^2 resulting in an average of 146 m^2 per cave, and the caves had a total volume of 7845 m^3 resulting in an average of 314 m^3 per cave. Cala Figuera trends perpendicular to the coast for its entire surveyed length (Figure 2A).

In addition, during the survey work a large number of paleo-slump structures were observed in the cliffs both within the calas and on the exposed coast (Figure 5). In many cases, the slump structures were observed to cross the Tortonian-Messinian unconformity. The slump structures are not breccia pipes, but soft sediment flow features which would indicate they formed while the carbonates sediments hosting them were still unlithified. Going upward, the slumping gradually diminishes until upper beds cross the slump without any deformation (Figure 5).

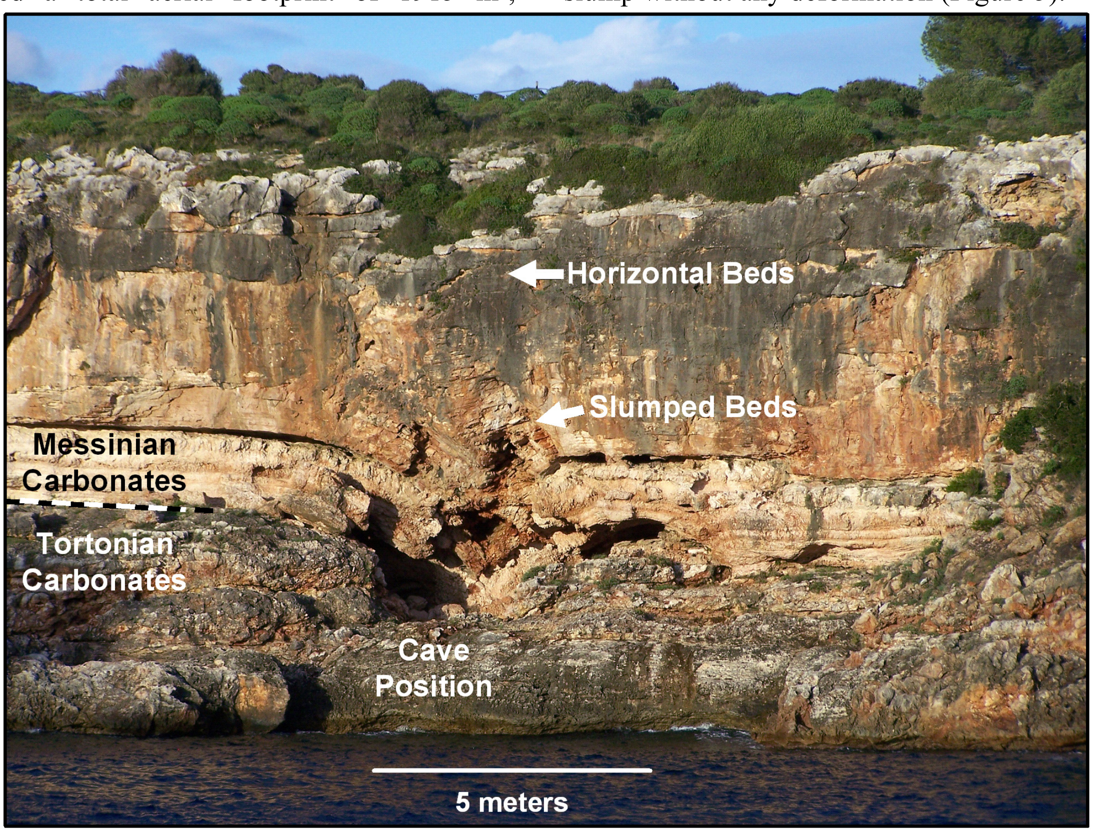

Figure 5. Image of a slump structure in Cala Figuera, Mallorca. Note the soft-sediment nature of the slump morphology, the Tortonian-Messinian boundary, and the continuous horizontal carbonate layers at the top of the structure.

DISCUSSION

The data show more caves present within the protected calas than on the exposed coastal cliffs at both field sites. The larger number of protected caves inside Cala Pi, with their lower average volume compared to the exposed cliffs, suggests that the small-sized caves have been preferentially removed from the exposed setting, biasing the volume data to larger values on those open cliffs. In other words, if cliff retreat on the exposed coast had been, for example, 10 meters, then all caves that began and ended within that 10 meter band would have disappeared; i.e. the small caves. Caves that were large enough to extend beyond the inland 10 meter erosion line would still be counted, and being larger caves, would be wider than the smaller caves that had been totally eroded away. This outcome would bias the volume calculation as large caves would leave a preferential record. In the protected cliffs within the calas, for comparison purposes we will say 5 m of cliff retreat had occurred. Many more small caves would survive, and with their smaller widths, create a situation of more cave numbers but less average volume compared to the exterior, exposed setting. Cave numbers are more balanced at Cala Figuera (20 exposed vs 25 within), but the larger area and volume numbers for the protected cala caves, compared to the exposed caves, indicate a higher degree of chamber loss by each cave in the exposed position; i.e. even large caves have small widths when they are reduced to a remnant portion of the cave's back wall

The data appear to support an interpretation of cave development after incision of the calas. A pre-existing uniform field of cave development, intersected at a later time by cala incision, should have produced no numerical difference between exposed and protected environments. If the cave field was uniform and extensive, as depicted in Figure 3B, the retreating cliff faces would have simply opened more caves to replace those lost by cliff retreat, while maintaining a uniform distribution of morphologies. If cave development was limited to the chemically active lens margin, then the cave numbers would decrease inland, as the coastal cliff retreat would have removed caves from a finite, coast-parallel population. In the protected calas, that finite cave population would be less eroded and therefore preferentially preserved. The data, however, show a numerical difference in cave numbers between exposed and protected sites, indicating that cave development is limited to the paleo-lens margin, and that primary cala incision thus occurred prior to the most recent flank margin cave development. The interaction of tectonics and glacioeustasy has created a complex sea-level history for Mallorca. That complexity is demonstrated by the calas and their flank margin caves, which require the calas to be incised, and subsequently invaded by marine waters to create a fresh-water lens margin inside the cala cliffs. Given that the flank margin caves in the calas are at many different elevations, the sea-level position must have been highly variable, stable at any position long enough to create flank margin caves, but not long enough to allow large, complex and integrated cave systems to form.

This interpretation is supported by flank margin cave data from around the world (Mylroie and Mylroie, 2007). The largest flank margin cave in the world, the Sistema Faro cave system on Isla de Mona, penetrates only a maximum of 257 m inland, despite having almost 20 km of passages. The cave's large size is the result of long-term fresh-water lens stability at a constant horizon. Sistema Faro is pre-Pleistocene in age, and therefore developed before the high-amplitude, short-wavelength glacioeustasy that characterized the Pleistocene (Mylroie and Mylroie, 2007). On tectonically active islands, such as in the Mariana Islands, lens stability was much shorter, and while a large number of flank margin caves have developed, they do not show the high degree of passage interconnection that results in the long cave passage length seen on Isla de Mona (Jenson et al., 2006). Mallorca flank margin caves are very similar to those found in the Mariana Islands, with abundant chambers of modest size that show few interconnections with each other. These observations indicate that the sea-level stability around Mallorca was transient, and fresh-water lens stability was short term, to produce the small but numerous unconnected flank margin caves observed.

These results all indicate that the flank margin cave production on Mallorca was limited to a thin coastal area coincident with a transient (i.e. a few thousand years) fresh-water lens position. These observations preclude an extensive field of voids going inland to any significant degree, which supports an interpretation that the cala caves formed after the calas were incised. These results are critical to successful modeling of flank margin caves as paleokarst in the deep subsurface, as the caves may not be resolvable at depth, but the coastal reentrants might be.

Flank margin caves can also be used on Mallorca to explain the numerous slump structures in the Upper Miocene units (Figure 5). The Tortonian-Messinian boundary is an unconformity with a paleokarst surface, which indicates subaerial exposure of the Tortonian carbonates. These slump structures can be explained as the result of failure of the flank margin caves produced when the Tortonian rocks were subaerial. These observations indicate a syngenetic origin for the slump structures, producing soft-sediment deformation pre-dating lithification. As shown in Figure 6, proposing flank margin caves as the cause of the slumps provides numerous advantages. First, a sea-level position near the top of the Tortonian would allow flank margin caves to form with relatively thin roofs that would later be vulnerable to collapse when loaded by the Messinian carbonates after sea-level rise. Second, the isolated, single chamber nature of flank margin caves would limit accommodation space, such that the slumping

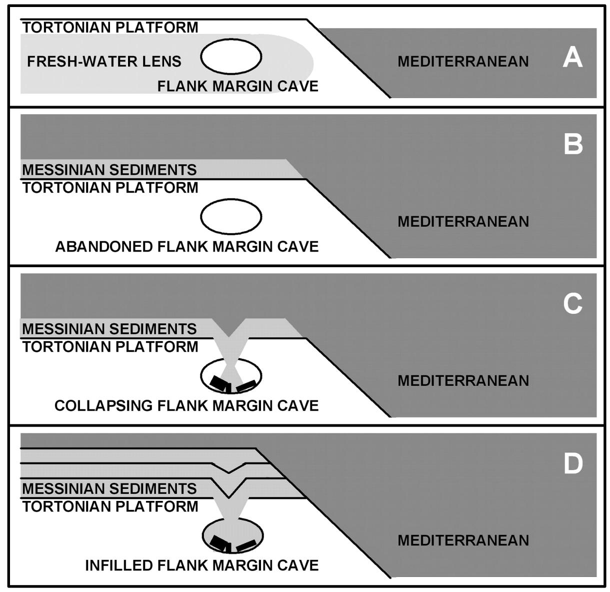

Figure 6. Schematic showing the stages of slump structure formation at Cala Figuera. A) The subaerial exposure of the Tortonian carbonates allows flank margin cave development at a shallow depth. B) Sea-level rise in Messinian time removes the fresh-water lens and begins carbonate loading of the Tortonian surface. C) Carbonate sediment loading collapses the cave roof, allowing soft sediment slumping into the cave void. D) The limited accommodation space of the flank margin cave results in a cessation of slumping, and carbonate sediments eventually become planar across the slump structure.

would initially occur, but then cease as the cave chamber became infilled, progressively attenuating the slumping, and allowing continued carbonate sediment deposition to form smoothly over the slump structure. Finally, only the flank margin model would account for isolated dissolutional void production in the numbers necessary to generate the large number of observed slump structures. While many slumps can be observed to originate below the Tortonian-Messinian boundary (Figure 5), not all do. This observation can be explained by noting that not all slumps have been sectioned by cliff retreat to their central axis. If a slump has only been partially sectioned (or has been sectioned beyond the axis), then it will show the slump *apparently* ending above the Tortonian-Messinian boundary (Figure 7).

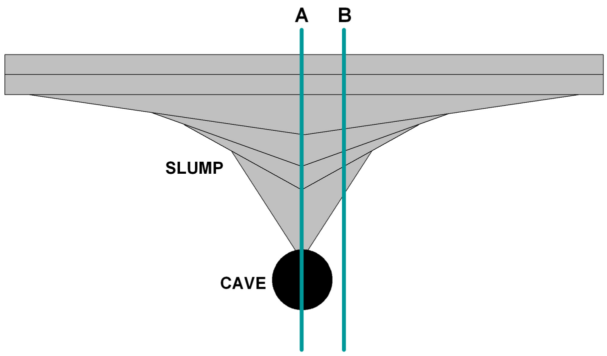

Figure 7. Schematic of a carbonate sediment slump structure ending in a flank margin cave. In section A, the section is along the vertical slump axis, such that the flank margin cave that originated the slump can be observed. However, in section B, the section is not along the vertical slump axis, so the observer does not see the flank margin cave as the causative body; the position of section B can be seaward or landward of the section A slump axis.

SUMMARY

Analysis of flank margin cave abundance and configuration at Cala Pi and Cala Figuera, Mallorca, demonstrated that the exposed cliffs fronting the Mediterranean Sea had experienced more cliff retreat, with attendant loss of flank margin caves, than the cliffs within the comparatively protected calas. The data also indicate that the current suite of flank margin caves formed subsequent to cala incision, and that sea level was highly variable during the time of cave formation, resulting in numerous small caves at varying elevations. Modeling of flank margin caves in the deep subsurface must take into account the sea-level positions and their duration at the time of cave genesis.

Slump structures in the Upper Miocene limestones of Cala Pi and Cala Figuera represent the collapse and infill of relict Tortonian flank margin caves during Messinian time. The investigator must be aware of the location of the vertical slump axis relative to the observed plane of section to properly interpret the flank margin origin of the slump structures.

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