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Front Cover: *Porites* colony encrusted by red algae in waters of San Salvador, Bahamas; see paper by Fowler and Griffing., p. 41. Photograph by Pascal Kindler, 2011.

Back Cover:. Dr. Jörn Geister, Naturhistorisches Museum Bern, Keynote Speaker for the 15th Symposium and author of "Keynote Address – Time-Traveling in a Caribbean Coral Reef (San Andres Island, Western Caribbean, Colombia)", this volume , p. vii. Photograph by Joan Mylroie.

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OVERVIEW OF CAVE DEVELOPMENT ON BARBADOS

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ABSTRACT

The karst and caves of Barbados have not been extensively studied although the island has many caves, solution valleys, and sinkholes. Genetically, Barbados has four types of caves developed in Pleistocene marine limestones: (1) stream caves formed by fresh-water dissolution; (2) flank-margin caves formed by mixed-water dissolution; (3) sea caves formed by wave abrasion and (4) hybrid caves that formed by a combination of two or more of the above processes. Human excavations are also present and can be confused with natural caves. In addition, Miocene chalks host small flank-margin caves in localized dolomitic outcrops. Dry valleys, or gullies, formed flank-margin caves in their walls when invaded by glacioeustatic sea-level highstands. Because tectonic uplift and glacioeustasy have constantly moved sea level and the fresh-water lens, the extensive and pervasive record of flank-margin cave development on Barbados indicates rapid speleogenesis.

Many caves on Barbados appear to be hybrid caves, a result of glacioeustasy and tectonics causing different cave-forming environments to overprint each other. Flank-margin caves are the most common cave converted to the hybrid state as they are readily breached and modified by coastal wave processes and progressive cliff retreat. This conversion can be observed on modern coasts, e.g. Animal Flower Cave at the north end of Barbados, and along nearby interior paleocoastal cliffs, such as Mt. Brevitor Cave.

Stream caves are found in the upland island interior. Harrison's Cave has over 2 km of passage, open as a tourist site since 1981. Nearby Cole's Cave has over 1 km of passages perched on the older foundation of the island. Despite these known stream caves, stream sinks are rare and most springs occur along the coast. Calcite speleothems have developed almost exclusively in stream and flank-margin caves.

INTRODUCTION

Barbados is an uplifted carbonate island located on a forearc bulge, 125 km east of the Lesser Antilles volcanic island arc, formed on the crest of an accretionary prism (Speed 1983) (Figure 1, inset). The island is approximately 23 x 32 km, with 432 km^2 of area. Glacioeustasy, combined with episodic tectonic uplift, have created a series of limestone terraces fronted by cliffs (Humphrey, 1997; Schellmann and Radtke 2004). The oldest limestones are mid-Pleistocene, with ages up to 800 ka (Machel, 1999). The reef and lagoonal limestones cover about 85% of Barbados (Figure 1) and usually rest on Miocene chalks and marls of the Oceanics Group, which are underlain by coarse to fine grained Eocene clastics of an accretionary prism (Speed, 1983; Jones and Banner, 2003). In some locations the chalks, which form a regional aquitard, are missing. The clastics host hydrocarbons that extrude oil and gas seeps in some locations and sustain a small local oil industry. Dolomitic outcrops of Pleistocene limestone and Miocene chalks are found locally (Machel and Burton, 1994; Machel, 1999). Tectonics has created faults and joint patterns that influence the hydrology. The Eocene clastics are highly distorted by soft-rock deformation and tectonic folding, while the original horizontality of the Pleistocene reef terraces has been locally tilted into broad folds (Taylor and Mann, 1991; Speed 2002).

The island represents the Carbonate Island Karst Model (CIKM) classification of a *composite island* (Mylroie and Mylroie, 2007), as the clastics are surficially exposed in the northeast quadrant, and stream caves have developed in this area (Figure 2). This portion of Barbados can be termed *karst on islands*, as the cave and karst development is similar to that found on continental interiors at similar latitudes (Vacher and Mylroie, 2002). The most abundant caves are flank-margin caves found in all terraces and cliffs, both along the modern coast and inland (paleocoastal), and represent *island karst*, as the caves and karst are dominated by

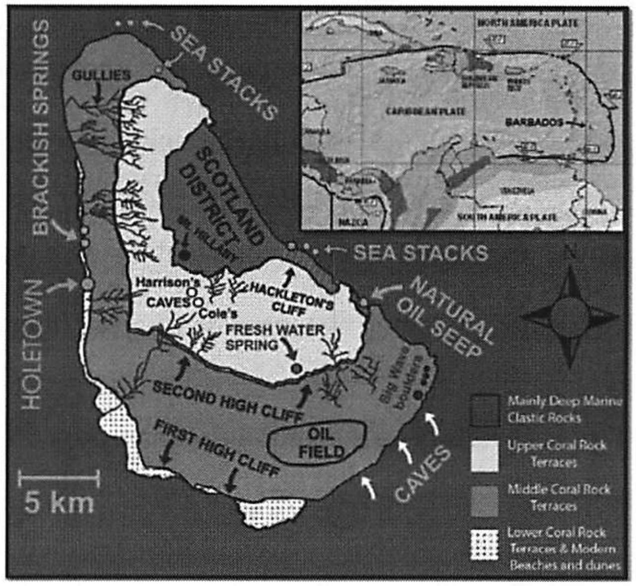

Figure 1. Map of Barbados, showing the major geologic units and other significant features. Modified from Machel, 1999. Inset: Map of the Caribbean region, showing the location of Barbados in the subduction zone of the North American plate, 125 km east of the Lesser Antilles island arc. Modified from *http://earthquake.usgs.gov/earthquakes/eqarchives/poster/regions/caribbean.php*

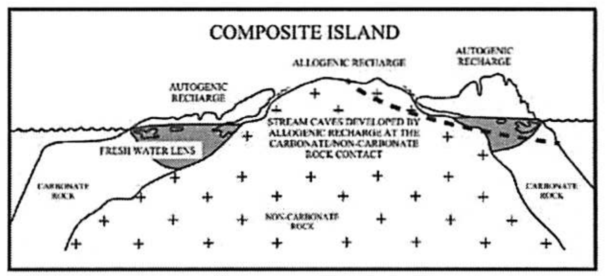

Figure 2. Diagram of the features of the Composite Island classification within the Carbonate Island Karst Model (CIKM). Both carbonate and non-carbonate rocks are exposed at the surface, producing autogenic and allogenic recharge to the fresh-water lens. The lens is partitioned and distorted, and turbulent conduit flow develops in the vadose zone at the carbonate/non-carbonate contact. Removing the figure material right of the dashed line shows how Barbados would appear in a Figure 1 cross section from Holetown on the west through the Scotland District northeast to the coast. Modified from Mylroie and Mylroie (2007).

coastal processes such as fresh/salt water mixing, sea-level change, and tidal pumping (Vacher and Mylroie, 2002). Surficial karst features are primarily sinkholes or dolines; sinking streams and springs are relatively rare, but dry valleys are common. Wandelt (2000) counted 2,830 dolines across the island from a combination of aerial photography and ground surveys. Day (1983), covering a smaller geographical area, found sinkhole abundance to be 9.47 /km^2.

Our field work was conducted in December 2009 as an initial reconnaissance of the island to assess the abundance and types of caves present, with a focus on flank-margin cave development. Activities over 12 days resulted in 49 caves being catalogued and surveyed from around the island. Minor sampling was conducted to determine the nature of the dolomitization at one chalk outcrop, and of differential coral dissolution in one flank-margin cave.

CAVE TYPES

Barbados hosts several different cave types with genesis controlled by dissolutional and mechanical processes. Dissolutional types include flank-margin caves, formed within a paleo-freshwater lens margin as indicated by various cliffs containing these caves, and stream caves which form from allogenic catchment perched on the limestone/chalk contact. Mechanical processes make littoral caves that result from the erosive action of ocean waves aided by bioerosion (mainly by mollusks) on cliffs. Hybrid caves form from a combination of any of the above processes.

Stream Caves

Stream caves are epigenic caves (Palmer, 1991), meaning they are directly coupled to the surface hydrology and commonly involve sinking streams and springs. Stream caves form when there is recharge of meteoric water into soluble rock. If that recharge is onto the limestone surface directly it is autogenic, and concentration of the water into a discrete stream occurs in the subsurface. At the other extreme, a limestone outcrop can receive a stream from non-carbonate catchment as allogenic water and channel this stream through the subsurface. Either way, the dissolutional conduits typically display dendritic drainage patterns and carry the water to points of discharge, i.e. springs or seeps. Harrison's Cave (2 km in length) and Cole's Cave (1 km in length) located in the upland interior of the island carry underground streams that are perched on the Pleistocene limestone/clastic contact. The caves contain active stream passages and host a variety of speleothems. Harrison's and Cole's Cave are recharged from sinkholes on the surface and from direct input of water at the upstream end of Harris Gully near Sturgis (Groves 1994).

Flank-margin caves

Flank-margin caves were first described in the Bahamas as forming on the flanks of eolianite dunes at the distal margin of a freshwater lens (Mylroie and Carew 1990). Frank et al. (1998) first expanded the flank margin model to islands outside of the Bahamas; subsequently, the model has been demonstrated in as disparate environments as the Marianas (Jenson et al. 2006), Australia (Mylroie and Mylroie, 2009), and Croatia (Otonicar et al., 2010). As flank-margin caves form from conditions that are decoupled from surficial hydrological processes, they are considered hypogene (Palmer, 1991). Our reconnaissance trip to Barbados was a continuation of an on-going global effort to compare flank-margin cave development in a variety of coastal and paleo-coastal settings.

On Barbados, flank-margin caves were identified within the reef, back-reef, and fore-reef limestones; eolianites are non-existent. Caves such as Flat Top Cave and Mt. Brevitor Cave (also called Indian Castle) have typical flank margin morphologies within reef limestones (Figure 3), such as globular chambers and irregular, cuspate walls. Flat Top Cave

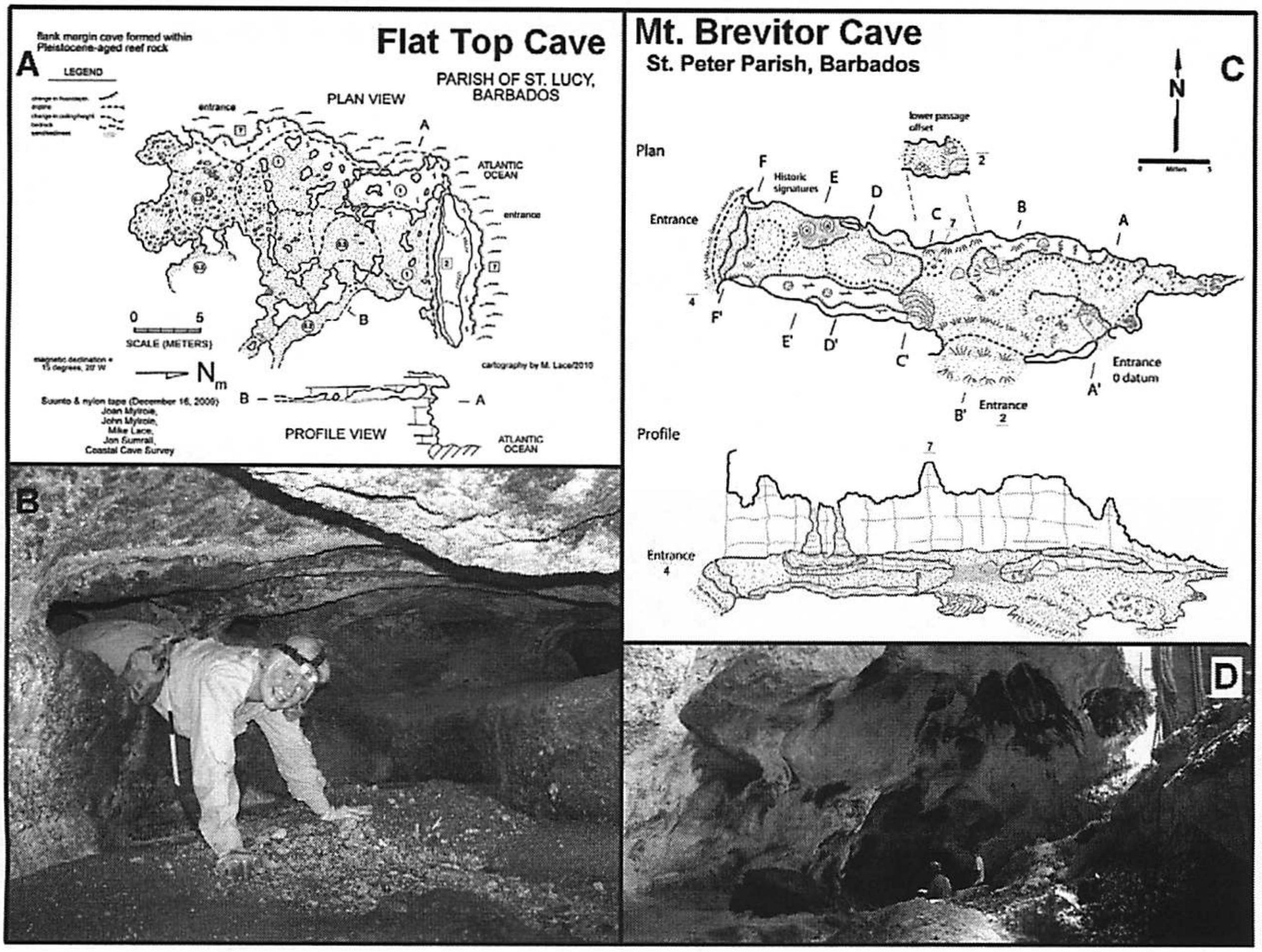

Figure 3. Typical flank-margin caves on Barbados. A) Map of Flat Top Cave, showing the globular nature of the chambers, and their limited vertical range. B) Low, wide chamber in Flat Top Cave; note phreatic surfaces and cusps. C) Map of Mt. Brevitor Cave, which has been breached to the outside in three places. The cave has a high (7 m) vertical extent, compared to Flat Top Cave. D) Image looking east in Mt. Brevitor Cave, showing large chamber size and phreatic dissolutional surfaces.

exhibits a low, wide profile, consistent with development in the distal margin of the fresh-water lens, but Mt. Brevitor Cave has high ceilings which may indicate tectonic uplift of Barbados while the dissolutional fresh-water lens margin remained stable and active. Flank-margin caves were also found in back-reef rubble facies. In Berwick Cave (Figure 4), morphologies such as wall cusps, ceiling cusps, and fine-scale dissolutional features are altered due to the large grain size of the limestone. The back-reef limestone facies at this locality consists mainly of *A. cervicornis* and *Porites* fragments, both of cm-dimensions. This facies comprises a large-scale vuggy porosity that effectively masks small cm-scale dissolution features (Figure 4B); however, larger-scale features on ceilings and walls such as bedrock pillars and cusps remain (Figure 4C).

Very small flank-margin caves were also identified within the chalks of the Miocene Oceanics Group (Figure 5). In localized areas, the chalks of the Oceanics Group crop out as the lower part of large cliffs. The chalks are mechanically weak and survive in the cliff face only because the top of the cliff is resistant Pleistocene reef limestone. However, some outcrops of chalk are hard and resistant, and one site also contains a series of small caves. The caves are oriented along fractures in the chalk

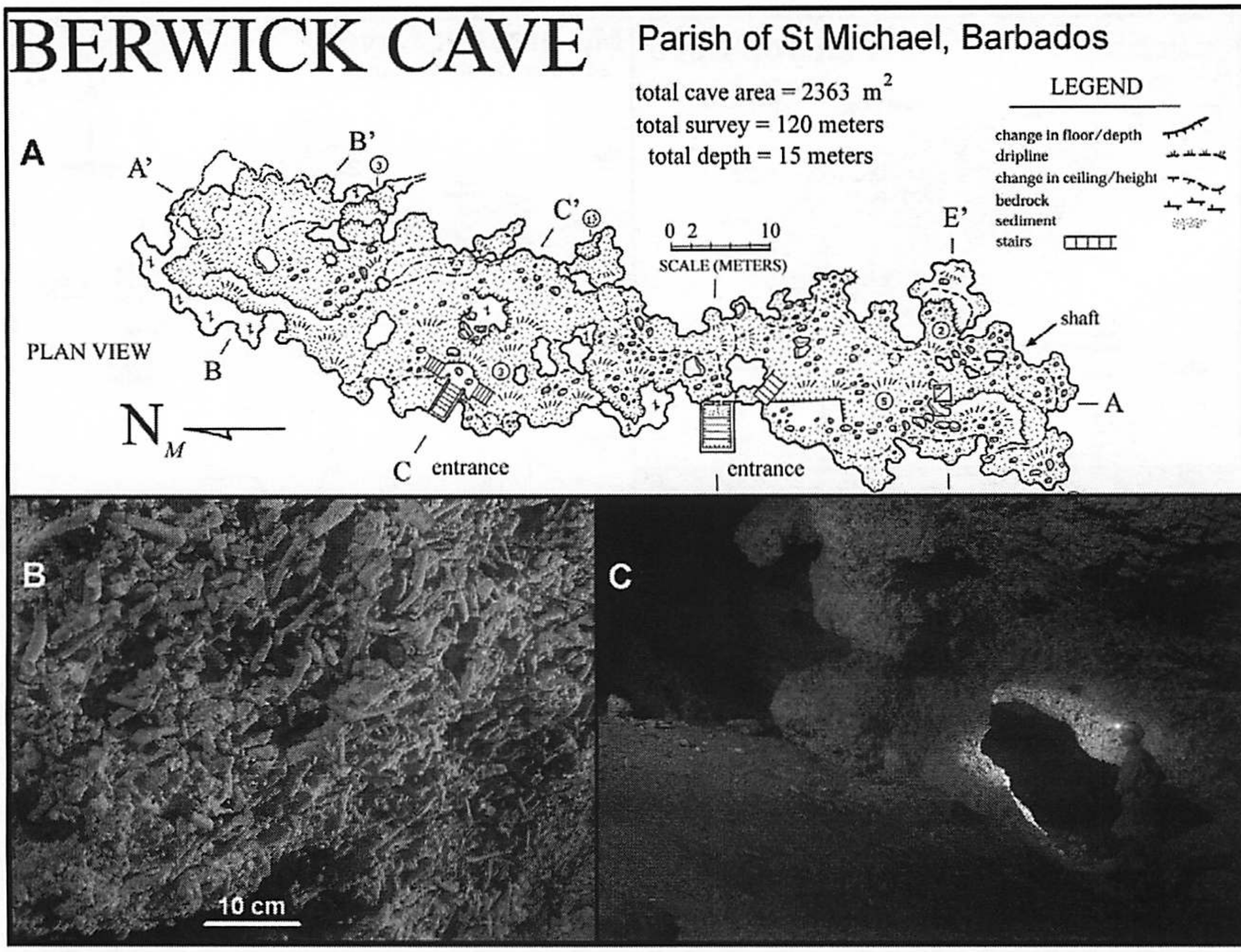

Figure 4. Berwick Cave, Barbados. A) Map of Berwick Cave, showing globular chambers and cuspate wall morphology typical of flank-margin caves. B) Close up of the Porites facies. This coarse-grained nature of the walls disrupts expression of small dissolutional features. C) Chamber in Berwick Cave, showing a large remnant dissolutional pillar. The large-scale dissolutional morphology is unaffected by the Porites facies.

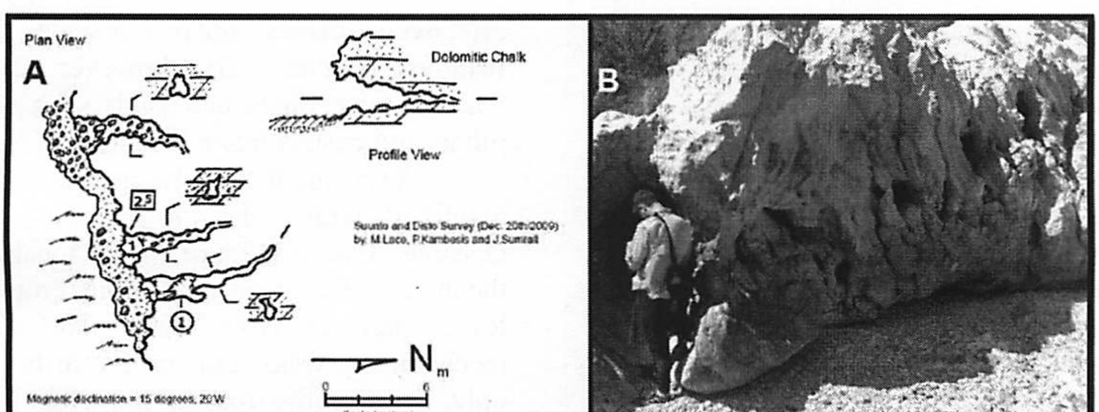

Figure 5. Small flank-margin caves developed in dolomitic Miocene chalks. A) Map of the caves. B) Cave entrances in the outcrop; the largest entrance (over 1 m in diameter) is obscured by the person. Note the well-expressed jointing in the outcrop.

and consist of small tubes and chambers with clear evidence of phreatic dissolution. XRD analyses indicate that the prominent carbonate mineralogy is dolomite. Stable isotope analysis reveals that these dolomites were formed from cold seep methanogenesis ($\delta^{13}C$ ranging from -2.6 to -25.4 per mil PDB and $\delta^{18}O$ ranging from +0.8 to +8.4 per mil PDB). While the regular chalk outcrop is relatively impermeable (Jones and Banner, 2003), these dolomitic sections of chalk support fractures that permit seepage, allowing the development of a fresh-water lens. The caves of the dolomitic areas of the chalk are all at the same elevation, indicating possible control by the margin of a paleo fresh-water lens. The proposed mechanism for the formation of these caves involves the chalk being partially dolomitized during methanogenesis. As a consequence, the dolomitic sections of the chalk are more resistant, supporting fractures to host the fresh-water lens and being able to resist subsequent wave erosion after uplift and exposure. These caves are later breached by cliff retreat due to wave erosion, and exposed to the outside environment. While dolomite is less soluble than aragonite and calcite, it is still soluble in mixing zone conditions. Without dolomitization the chalk outcrop has neither the pathways for fluid flow to allow dissolution, nor the mechanical strength to host macroscopic dissolutional voids. Based on the setting and conditions, these caves are interpreted as flank-margin caves.

Gullies

Caves in Barbados are commonly associated with dry valleys (locally called gullies). Hundreds of gullies of variable lengths and depths are distributed on the carbonate terraces. The gullies trend toward the northern, western, and southern coastlines, resembling a network of narrow creek beds in the interior highlands, merging progressively to fewer and wider channels downslope and seaward (Figure 1). The average gradient of the gullies is steep, about 2° (3.8%), and some are up to are 30 m deep (Fermor, 1972). Most gullies are dry much of the year, although some have narrow creeks running for several months. On the other hand, literally all gullies carry major floodwaters after heavy rains, especially during the rainy season. The Scotland District (Figure 1), where the Pleistocene carbonates are eroded or were never deposited, is a varied topography of deformed Eocene siliciclastics without gullies.

The origin of the gullies is not well understood. Fermor (1972) reviewed the various ideas as follows: Schombergk (1848) noted there was too little catchment per valley and he invoked cracks and fissures due to uplift. Harrison and Jukes-Brown (1890) suggested each valley segment was tied to a sea-level stillstand; as sea level fell, a new downstream segment was added. Trechmann (1955) thought gullies were inherited submarine features (e.g. spurs and grooves). Tricart (1968) believed the gullies were fossil tidal creeks and inlets, enhanced by infrequent storm events. Fermor (1972) argued the gullies were simple stream valleys, formed in competition with karst under a wetter climate. Modern observations follow Fermor's interpretation of gully origin as flood event pathways; however, the climatic change aspect remains open.

Massive and abundant speleothems along some gully walls suggest an origin from stream cave dissolution and subsequent collapse (Machel, 1999). While stream caves over 1 km long exist in the interior, none are as wide as the open channels in the distal parts of the gully system. If the gullies are collapsed caves, the speleothems on these wide gully walls indicate that the gullies have not enlarged significantly by surface erosion from their pre-collapse state, otherwise the speleothems would have been eroded away. Massive speleothems with well-ordered calcite structure, as found in the gullies, are usually indicative of an enclosed cave environment (Taboroši et al., 2006).

Our new alternative explanation is that the gullies are seasonal surface channels, typical of the limestone gorge landform category well known from karst areas globally (Ford and

Williams, 2007). During glacioeustatic sea-level highstands seawater invaded the gullies, and fresh-water lens discharge from the gully walls developed flank-margin caves by mixing dissolution. Subsequent sea-level fall, either by glacioeustasy or by uplift, allowed surface streams to re-establish erosion to breach and erode the caves, revealing the speleothems. Caves and cave remnants found in the many gully walls, such as Sailors Gully, support the flank-margin cave interpretation (Figure 6), and the lack of dendritic tributary caves in those same gully walls argues against the collapsed cave conduit model. It is likely, however, that both or some combination of these two genetic processes were involved in gully formation. One example is Jack-in-the-Box gully that bears characteristics of a collapsed stream cave in the highlands (narrow width, relatively shallow, decorated walls, boulders from the collapsed cave roof), yet the gully appears significantly widened and deepened by mixing zone dissolution farther downstream.

Sea Caves

Sea caves, also called littoral caves, form as a result of wave and biological action on lithologic or structural heterogeneities in coastline bedrock, or from the focusing of wave energy on specific coastal locations (Waterstrat et al., 2010). The combination of the hydraulic power of waves, erosive action of suspended sediment, and the compressive force of air being forced into a confined space, mechanically widen and deepen rocky sea cliffs, and develop caves. These processes are aided by bioerosion. Wave energy is especially very high on the Barbados north coast (Figure 7) where sea cave formation is common. However, the problem on Barbados, and on carbonate coasts world-wide, is differentiating sea caves, formed by mechanical and bioerosion from outside of the cliff inward, from flank-margin caves that form from inside of the cliff outward. Attempts have been made to establish criteria that allow segregation of coastal caves into sea caves and breached flank-margin caves (e.g. Waterstrat, et al., 2010; Lace, 2008); while the qualitative criteria seem to be successful (e.g. phreatic surfaces and speleothems in flank-margin caves), the quantitative criteria (e.g. area to perimeter ratios, entrance width to maximum width ratios) still need work.

Hybrid Caves

Changes in hydrologic setting due to tectonics and/or glacioeustasy result in changing geological and hydrological conditions which can overprint caves of any type. For islands like Barbados, where more or less continuous tectonic uplift is accompanied by glacioeustatic sea-level variations, the most common overprint is that flank-margin caves are exposed by erosion from the sea and then wave forces enter the originally hypogene caves. Animal Flower, a popular tourist site at the north point of Barbados, is an example of a flank-margin cave that has been breached by cliff retreat and modified by wave action on the coast (Figure 8). Mt. Brevitor Cave (Figure 3), located within an interior cliff, is an example of an abandoned flank-margin cave likely cut open by cliff erosion and overprinted by wave action during a sea-level rise. In addition, if a flank-margin cave undergoes cliff-side collapse, the cave could appear to be a talus cave, a type of cave made of large jumbled blocks as found on talus slopes (Ford and Williams, 2007).

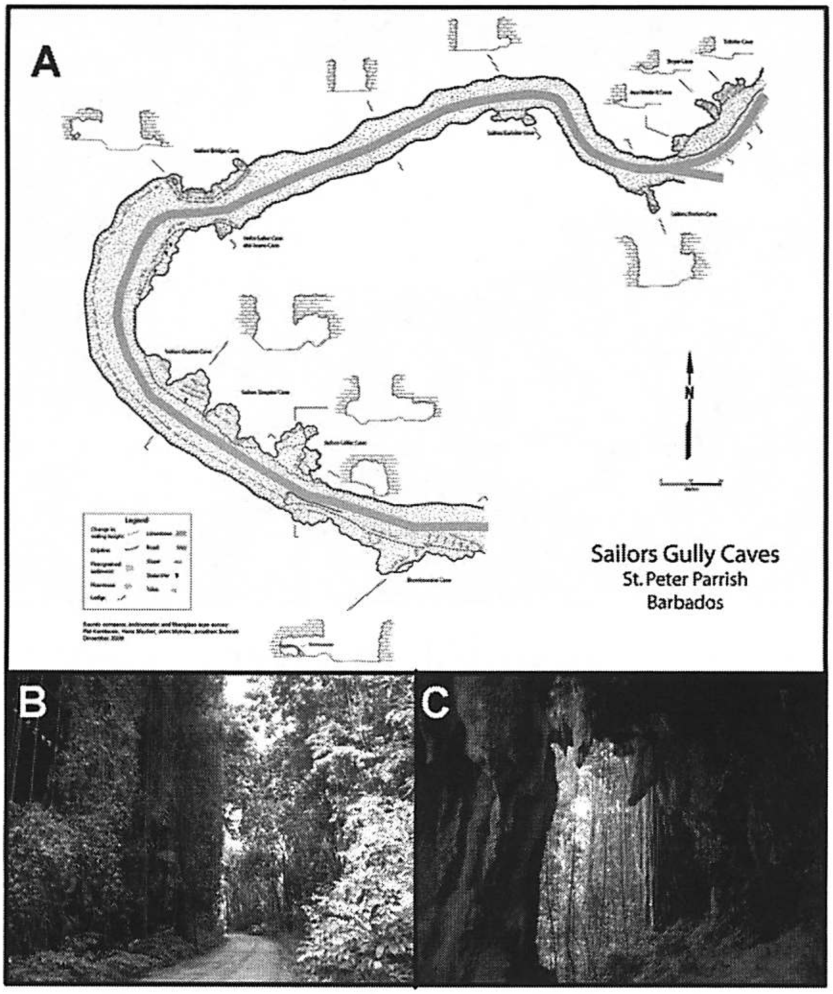

Figure 6. Sailors Gully, Barbados. A) Map of Sailors Gully, showing breached flank-margin caves at various positions along the gully walls, but no tributary cave passages. B) Looking south in the lower part of Sailors Gully; note the vertical nature of the gully wall. C) Calcite speleothems formed inside a cave, now exposed by cliff retreat in a Barbados gully.

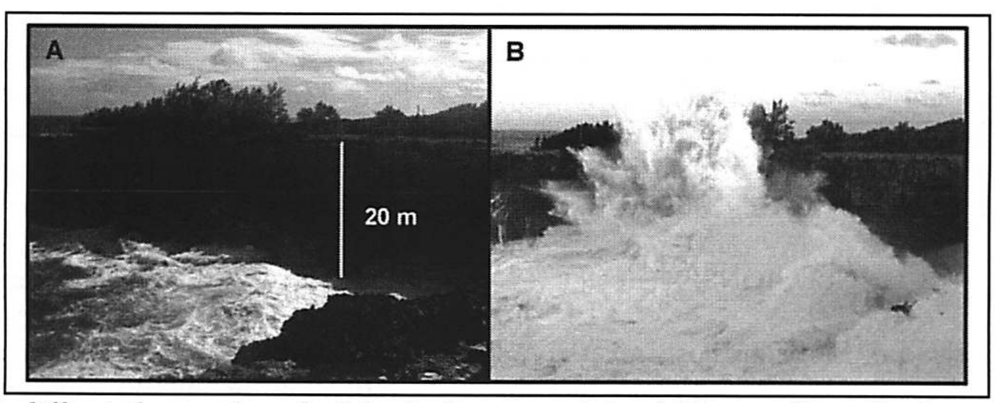

Figure 7. Coastal cliffs at the north end of Barbados, near Animal Flower Cave (background, left, in shadow). A) Wave conditions December 15, 2009. B) Wave conditions two weeks later on December 29, 2009.

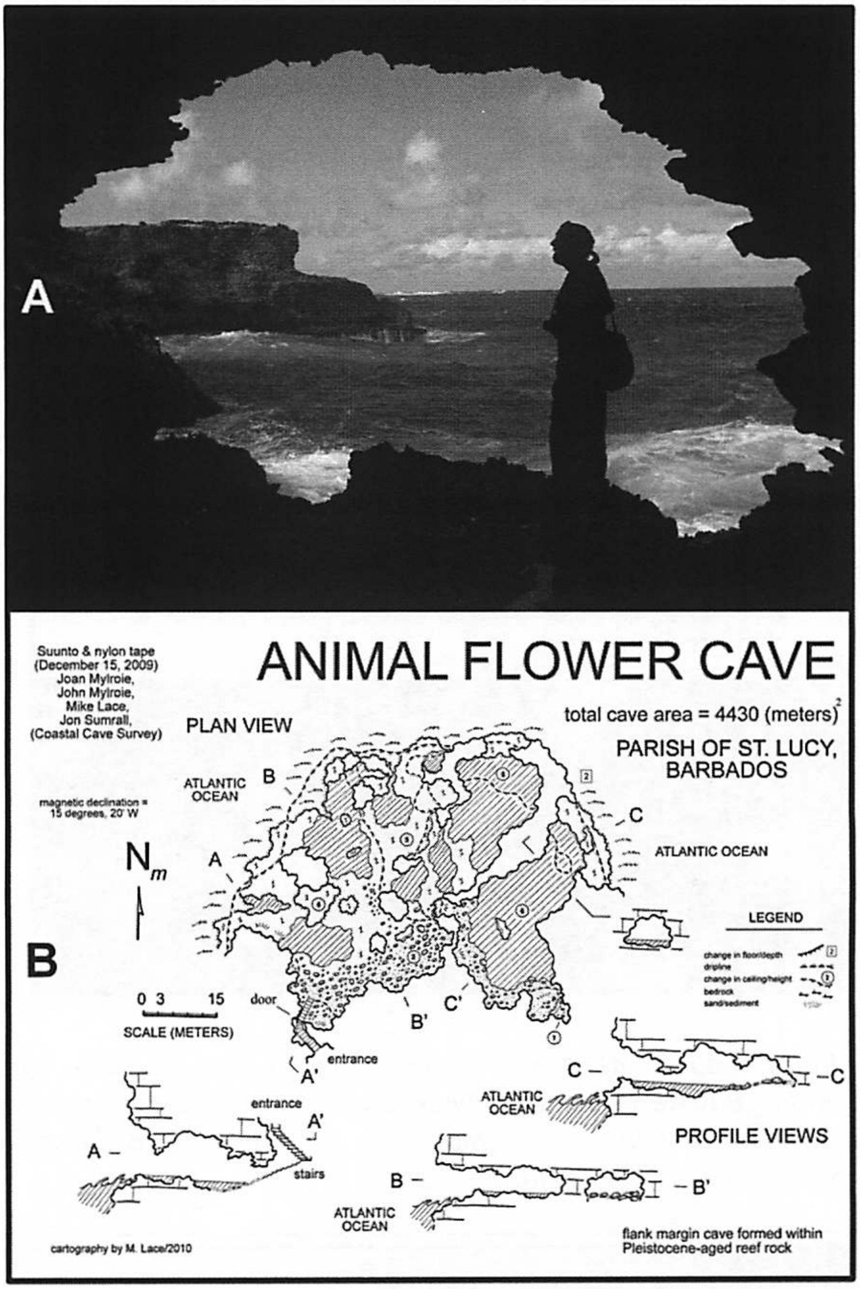

Figure 8. Animal Flower Cave, north Barbados. A) View from an entrance to a distant point on the horizon. The cliff of Figure 7 is between these two locations. B) Map of Animal Flower Cave. It has the overall passage morphology consistent with flank-margin cave development, but is routinely scoured by wave action which is modifying the cave into a hybrid condition.

CONCLUSIONS

The island of Barbados hosts a variety of caves that reflect the island hydrology and the mechanical processes that continue to modify its internal and coastal areas. Dissolutional cave development in the form of flank margin caves and stream caves record the changes in sea level and island hydrologic processes. High-energy mechanical processes modify the coastline and result in the development of littoral caves and the formation of hybrid caves from pre-existing flank margin caves. Erosional cliff retreat exposes and overprints dissolutional and mechanical caves and provides a record of denudation rate. Methanogenic dolomitization of chalks, otherwise poor cave-forming rocks, results in unique expressions of flank margin cave development. Glacioeustatic invasion of stream gullies creates flank margin caves in gully walls. All of the caves hold important clues to the geological and hydrological evolution of the island of Barbados.

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