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INFLUENCE OF KARST DENUDATION ON THE NORTHWEST COAST OF CURAÇAO

Patricia Kambesis[a], Joan Mylroie[a], John Mylroie[a*], Erik Larson[a], Athena Owen-Nagel[a], Jon Sumrall[a] , and Michael J. Lace[b]

[a] Department of Geosciences, Mississippi State University, Starkville, Mississippi 39762
[b] Coastal Cave Survey, 313 ½ West Main St., West Branch, Iowa 52358

ABSTRACT. The northwest coast of Curaçao is characterized by a series of Pleistocene-age reef terraces at four discrete elevations with dissolutional caves formed in the terraces at specific elevations (highest to lowest terraces, in meters above sea level: 90-175 m, 50-85 m, 10-45 m, and 5-10 m). Large scale rectilinear coastal reentrants called bokas occur in the lowest terrace, and are hundreds of meters long perpendicular to the coast, tens of meters wide, and have steep, vertical walls of up to more than ten meters height. Prominent coastline erosional features formed by a combination of cave collapse and wave erosion are also present in the lowest terrace. Reconnaissance field mapping in March of 2011 and 2012 documented 17 bokas and identified and surveyed numerous flank margin caves related to the reef terraces and the bokas. Quaternary uplift is evident by the position of the four elevated reef terraces adjacent to the coast. Eustatic sea-level changes, interacting with tectonic uplift, played an important role in the development of flank margin caves associated with the reef terraces. The flank margin caves in the inland cliffs fronting the terraces have been exposed by cliff retreat. As the caves form at sea level, and the coral terrace was at wave base when alive, the difference in elevation between the caves today and the terrace today (commonly 2 to 6 m) is an indication of the degree of dissolutional denudation of the terraces since terrace deposition and exposure. A widespread system of fluvial valleys, formed on interior Cretaceous volcanic rocks, has eroded through the limestone terraces into the underlying basaltic bedrock. Large bokas are developed where these inland streams have incised through the lowest limestone terrace. Waves penetrate into the lower portions of the bokas. Their inland termini open to broad valleys on the volcanics. The bokas contain flank margin caves exposed along their vertical walls, including within the broad inland termini, which have facilitated boka wall collapse. Caves located in the lowest reef terrace that are not associated with ephemeral fluvial drainage are exposed by ceiling collapse and are eventually breached by sea-cliff retreat. As wave-influenced coastal erosion proceeds, these flank margin caves are degraded to natural bridges that parallel the coastline and eventually evolve to short coastal reentrants. The assortment of karst, marine, and fluvial features signify polygenetic processes contributing to boka formation and the erosional degradation of the coastline.

[*]Corresponding author. E-mail: mylroie@geosci.msstate.edu

INTRODUCTION

Curaçao is located in the southern Caribbean 60 km north of the coast of Venezuela and centered at 60^o west longitude (Figure 1). Curaçao is 61 km long and 14 km wide, oriented southeast to northwest, in the easterly trade winds with 565 mm of rain per year and an average temperature of 27^{o}C (Pandolfi and Jackson, 2001). The littoral environment is microtidal with an average tidal range of 30 cm (Focke, 1978). The geology found on Curaçao is similar to the geology of nearby Bonaire and Aruba, all part of the Netherlands Antilles. A brief overview to the geology of Curaçao follows, more detailed information can be found in Beets (1972), De Buisonje (1974), Pandolfi et al. (1999), Schellmann et al. (2004), and Hippolyte and Mann

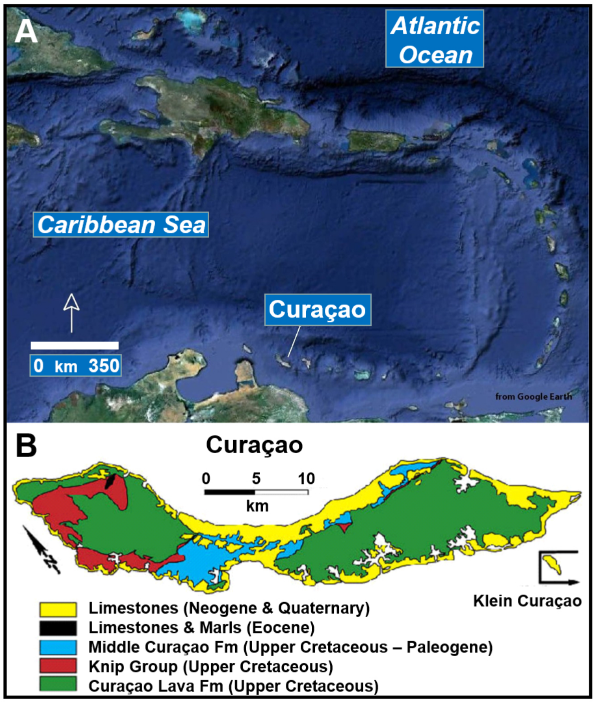

Figure 1. Study area. A) Google Earth image of the eastern Caribbean Sea, showing the location of Curaçao. B) Map of Curaçao, showing the general geology of the island (modified from http//www.dcbiodata.net/ explorer/info.islands).

(2009).

The core of the island is basaltic crust formed by volcanic eruptions on the deep sea floor in the Cretaceous 100 to 65 million years ago. On this igneous core lie conglomerates, sandstones and shales, which were deposited during the Paleogene. During the Neogene, dolomites (the Seroe Domi Formation) were deposited on top of the Paleogene units. Finally during the Pleistocene, tectonic uplift raised the platform into the upper photic zone resulting in prolific coral productivity that created the coral terraces seen today on the island perimeter (Figure 1B). This uplift in conjunction with glacioeustatic sea-level fluctuations raised the Pleistocene reef limestones out of the ocean and created the cliffed terrace system that dominates the north coast of Curaçao.

The limestone cliffs consist of five different terraces: the Highest Terrace, the Higher Terrace, the Middle Terrace I, and II, and the Lower Terrace (Table 1). The Middle Terrace I and II are commonly seen in the field as a combined unit forming a single terrace. All of these terraces are of Pleistocene age.

Terrace	Elevation	Age	Relative Age
Highest	90-175masl		Oldest
Higher	50-85masl		
Middle I	10-45masl		
Middle II	10-45masl	≥400kyr	
Lower	5-10masl	125ky + 210 ky	Youngest

Table 1 The terraces listed in chronological order, with their respective elevations and ages (masl = current meters above sea level). Data from Pandolfi et al., 1999 and Schellmann et al., 2004.

The Lower Terrace is the youngest and the result of a transgressive regime, and consists primarily of reef crest facies from MIS 7 (Cortalein Unit) and MIS 5e (Hato Unit) as dated by Schellmann et al. (2004). There are also a few eolian deposits within the Lower Terrace. The Lower Terrace gently dips toward the ocean at about 2°.

Pandolfi et al. (1999) and Schellmann et al. (2004) provide a detailed geological description of the terraces, which is summarized here, with ages (as known) in Table 1. Both Middle Terrace I and II were the result of a transgressing sea. Middle Terrace I was formed first (earliest). This unit was formed during a slow transgression. After a short still stand, the sea began transgressing again, but this time rapidly and the Middle Terrace II is the result of this younger transgression. Both of these terraces are made of lagoonal deposits; the Middle Terrace II also has many eolian dunes.

The Higher Terrace consists of lagoonal limestones, and is the result of a sea-level highstand followed by a regressive phase. The regressive cycles are evident from the many erosional features, including paleosols, contained within the Higher Terrace. There are also a few eolian deposits, though they are small in extent. The Hato Caves, a show cave sequence near the Cuaraco airport, are contained within this unit.

The Highest Terrace is the result of a regressing sea, similar to the Higher Terrace, and in the Netherlands Antilles is found only in a few places on Curaçao. The Highest Terrace consists mostly of transported erosional facies, though its base contains some marine fossils that are *in situ*. The Highest Terrace also contains some eolian dunes.

All of these terraces consist of eogenetic rocks, meaning that they are young geologically speaking and are relatively diagenetically immature (Vacher and Mylroie, 2002). Although they may have undergone some meteoric and sea-water diagenesis and secondary cementation, as a whole they are relatively unchanged from their original depositional state. These diagenetically immature rocks typically have a high porosity of about 20% to 30% at the pore scale, which formed as the rocks were deposited. Dissolutional flank margin caves have been found in all the terraces and represent a form of mega-porosity that was developed after the rocks were deposited.

Flank margin caves are a characteristic karst feature of carbonate islands and coasts where diffuse flow occurs in the fresh-water lens. The caves develop in the distal margin of the lens, under the flank of the enclosing landmass (hence their name, *flank margin cave*). They form in this location as a result of the superposition of three phenomena: mixing dissolution at the halocline, oxidation of organics trapped at the density interface of the halocline, and the increased flow velocities at the lens margin. For a full treatment of flank margin caves, see Mylroie and Mylroie (2007). Flank margin caves are excellent indicators of past sea-level positions, and are considered here to be important in the development of bokas.

Bokas have been described as enigmatic features (Stefanic and Cornell, 2011). They are remarkably consistent in form and structure (Figure 2), being hundreds of meters long perpendicular to the coast, tens of meters wide, and have steep, vertical walls of up to more than ten meters in height. They are relatively young in age, given that they are formed in MIS 5e Late Pleistocene limestones approximately 125 ka old, and extend downward into MIS 7 rocks at ~210 ka age. A number of origins have been speculated for bokas (Scheffers, 2004), including a tsunami origin. Stefanic and Cornell (2011) proposed that they were relict and degraded karst features, formed during the post-MIS 5e sea-level lowstands of the Late Pleistocene, by capture of stream water running off of the interior volcanic rocks. This capture created stream caves at the limestone-volcanic contact. Later collapse of these caves produced the rectilinear valleys, which subsequently were partially inundated by the Holocene sea-level rise to produce the features observed today. This model is similar to one developed by Machel (1999) for the origin of comparable features in Barbados called *gullies*. If this approach is correct, one has to assume that a similar event would have occurred during the sea-level lowstand following emplacement of the lower reef limestone unit during MIS 7 (210 ka).

METHODS

The focus of this study was to examine these rectilinear coastal reentrants (Figure 2), locally called bokas, to determine the role karst processes had played in their development, and as part of an overall reconnaissance and inventory of karst features on Curaçao. Reconnaissance field mapping was done in March of 2011 and 2012. Fieldwork mapped 17 bokas from Nordpunt at the extreme northwest of the island to Boka Grande in Cristoffel National Park to the east (Figure 3). Boka heights and widths were measured with compass, tape and inclinometer. The width measurements were used to calibrate the dimensions observed in close-up Google Earth images of the bokas (e.g., Figure 2A). Flank margin caves, sea (littoral) caves, and hybrid caves were mapped, using methodology described in Dasher (1994); compass, inclinometer, tape, and

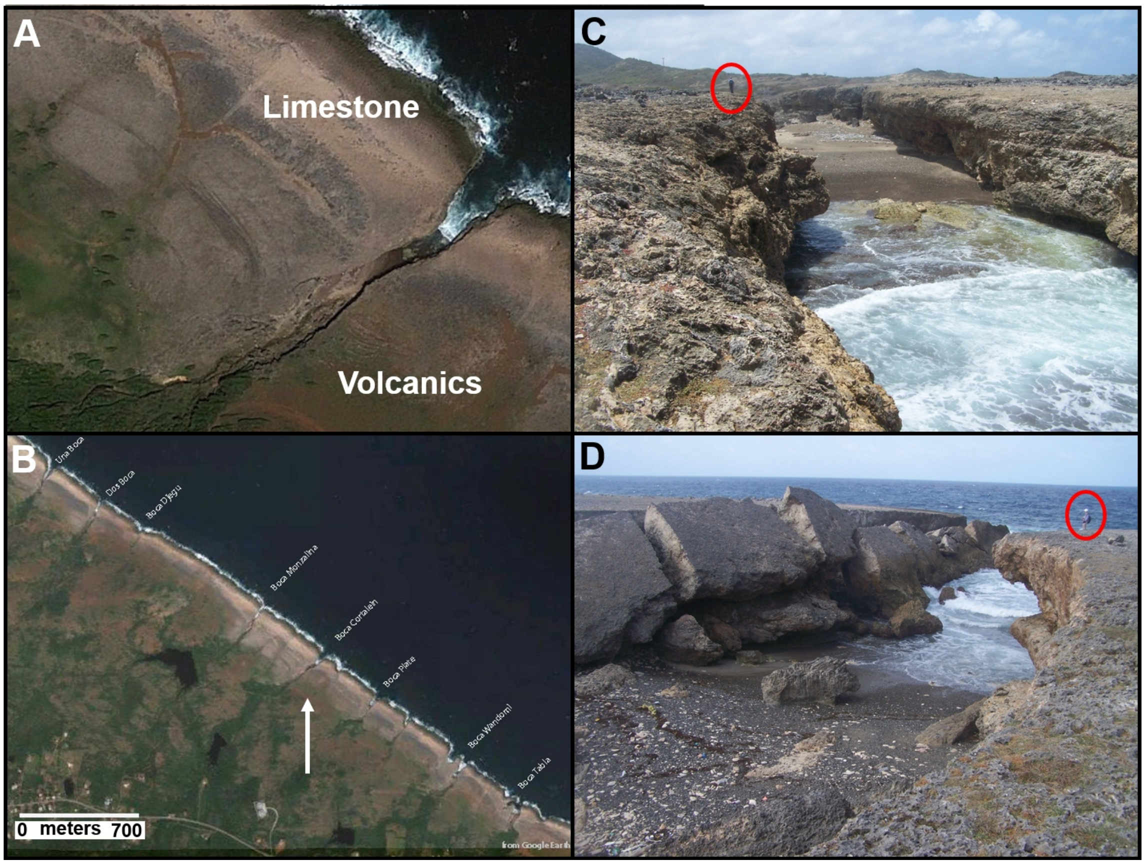

Figure 2. Bokas on Curaçao. A) Google Earth image of a typical boka. B) Google Earth image of a series of bokas at the northwest end of the Curaçao (see Figure 4); arrow points to the boka of 2A. From upper left to lower right, the labeled bokas are: Boka Uno, Boka Dos, Boka Djegu, Boka Monzalina, Boka Cortalein, Boka Plata, Boka Wanderni, and Boka Tabla. C) Image of a boka looking landward (south), person in circle for scale. D) Image of a different boka looking seaward (north), note the massive collapse along the west wall; person in circle for scale.

when lighting conditions allowed, Disto® laser range finder. Hybrid caves are flank margin caves opened by coastal processes and overprinted by marine erosion (Machel et al., 2012).

RESULTS

The main geologic features of the bokas are summarized in Figure 4: the rectilinear walls, flank margin caves, stream channels, wall collapse blocks, and curving inland walls. The coral reef origin of the limestones is evident in the boka walls (Figure 5A), and the underlying basaltic basement is commonly exposed (Figure 5B). Flank margin caves are common in the boka walls (Figure 5C). The inland terminus of the bokas is commonly a broadening of the boka as the limestone walls curve away from the boka axis (Figure 5D). Many bokas have large collapse blocks that represent structural failure of the boka walls (Figures 2D and 4). The bokas are typically 10 m deep, and 30 to 40 m wide, extending inland several hundred meters.

Numerous flank margin caves were discovered and mapped in the walls of the cliff separating the Lower Terrace from the Middle Terrace on Curaçao (Figure 3B). These cave entrances are found on distinct horizons at significant elevations above the elevation of the flat Lower Terrace, e.g. as seen in Figure 3B. Small entrances are found at about 2 m above the Lower Terrace, and large entrances at 6 m above

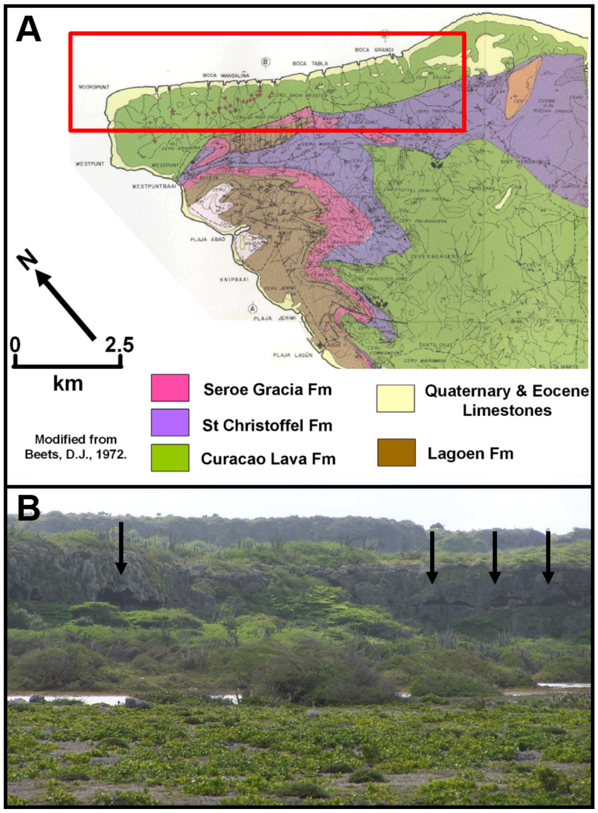

Figure 3. Geology of northwestern Curaçao. A) Details of the geology of the northwest coast of Curaçao, modified from Beets, 1972. Study area in box. Note the consistent geology of Quaternary limestones onlapping Cretaceous basalts where the bokas are found. B) Image, looking south, of the Quaternary limestone terraces. The photographer is on the Lower Terrace, with the Middle Terrace in the foreground and the Higher Terrace in the background. Note flank margin cave entrances visible in the wall of the Middle Terrace (arrows); left entrance is approximately 15 m across for scale.

the Lower Terrace.

Several flank margin caves, not directly associated with the bokas, were located within 50 m of the coast (Figure 6). These caves are significant as they are entered through small vertical collapses and are otherwise completely intact, which indicates that they are not relict sea caves, as there is no opening into them on the sea cliff. Numerous caves open on the exposed coastal cliffs, displaying varying degrees of

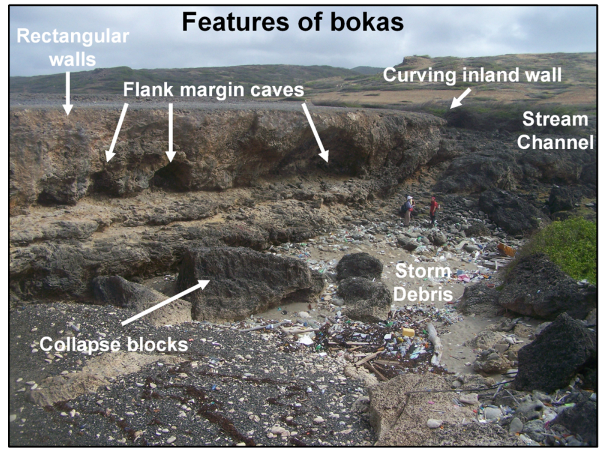

Figure 4. An image of a typical boka, showing the main features associated with bokas. See text for a complete explanation.

degradation. Some caves are nearly intact, others have lost a portion of the roof, creating natural bridges, and others are nearly fully eroded, leaving only indentations in the coastal cliffs. These are the hybrid caves of Machel et al. (2012)

Flank margin caves in the boka walls are found in both the MIS 7 limestone, and in the overlying MIS 5e limestone, as those units comprise the lowest terrace (see Table 1 and associated references). Some minor lateral dissolution has occurred at the unconformity separating the two units that may be related more to vadose water perching on the micritized unconformity than to flank margin cave processes.

Flank margin caves were found in the Middle and Higher Terraces (Figure 3). Their position above the flat terraces that lie in front of the cave entrances is an indicator of the amount of dissolutional denudation that has occurred since subaerial exposure of the terrace, given that the caves are a measure of sea level, and the coral terraces are thought to have grown to nearly wave base (Pandolfi and Jackson, 2001).

DISCUSSION

We propose an alternate interpretation to boka formation than the interpretations presented earlier. The main problem with the Stefanic and

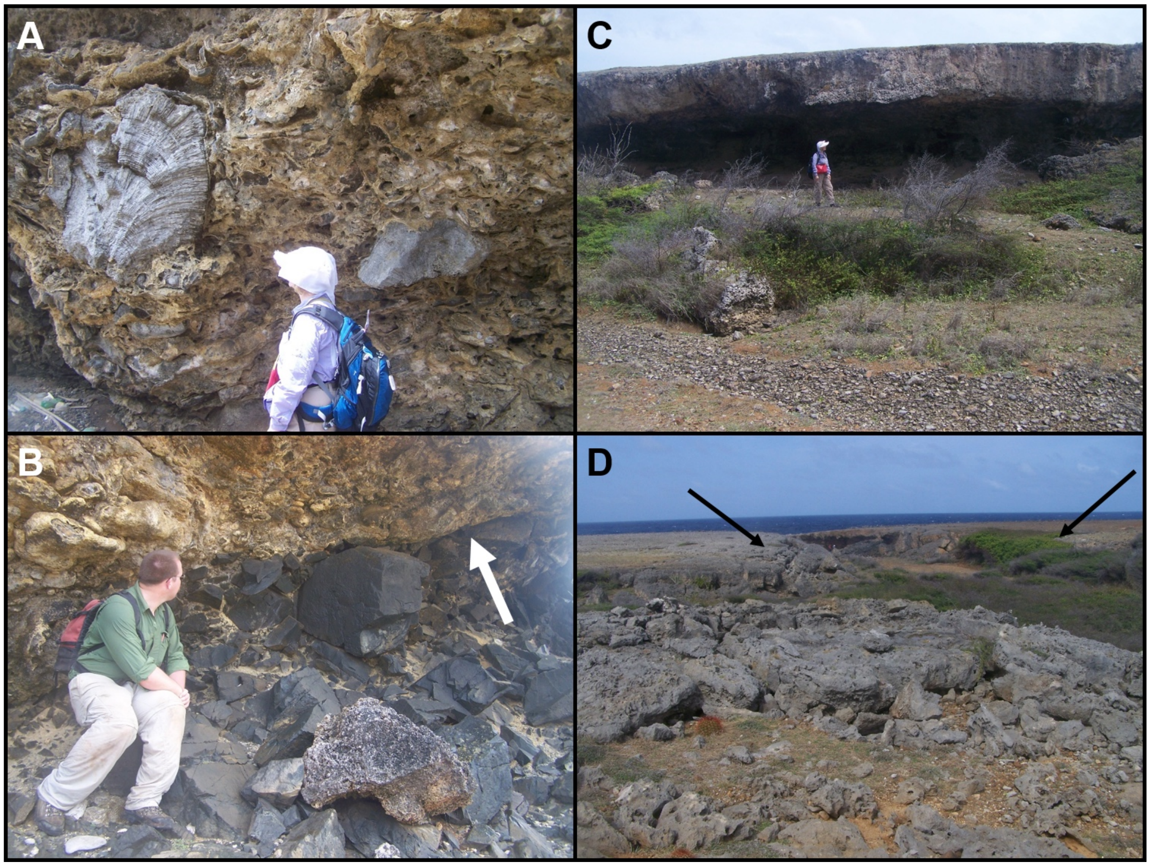

Figure 5. Bedrock components of bokas. A) Massive Late Pleistocene coral heads in a boka wall. B) Basalt-limestone contact near the inland end of a boka (white arrow). C) Typical flank margin cave along a boka wall. D) Inland terminus of a boka, with the boka walls curving away from the boka axis (black arrows).

Cornell (2011) model is the lack of evidence for stream cave development at the bokas; these authors apparently misidentified the flank margin caves as stream cave remnants. It appears highly unlikely that every single stream cave in all 17 bokas would have entirely collapsed in the last 100 ka (including any collapse between 210 and 125 ka from an earlier generation of stream caves). While invasion of the distal ends of the bokas by Holocene sea-level rise would apply high wave energies to those portions of the bokas, perhaps facilitating cave collapse there, it can be speculated that the inland portions of the original stream caves should be intact in at least some cases. There are no tributary stream cave passages entering from the side walls of the bokas, which would be expected in a conduit cave system displaying a typical dendritic, tributary form. No relict stream cave deposits are present, as should be found in a turbulent-flow conduit cave draining volcanic uplands. There is also the problem of the abundant flank margin caves found in the boka walls, including the inland curving walls of the boka (Figure 5D). These remnant flank margin caves are currently above modern sea level, but require sea level at their position in order to form. The two intact flank margin caves above modern sea level on the Lower Terrace, located by this study (Figure 6), indicate that true flank margin caves exist in the MIS 5e and MIS 7 limestones. For these two caves and the numerous flank margin caves of the bokas to be present requires that the MIS 5e and MIS 7 limestones were subaerially exposed to capture meteoric water and create a fresh-water lens; however, these caves also require that sea-level was at the position of

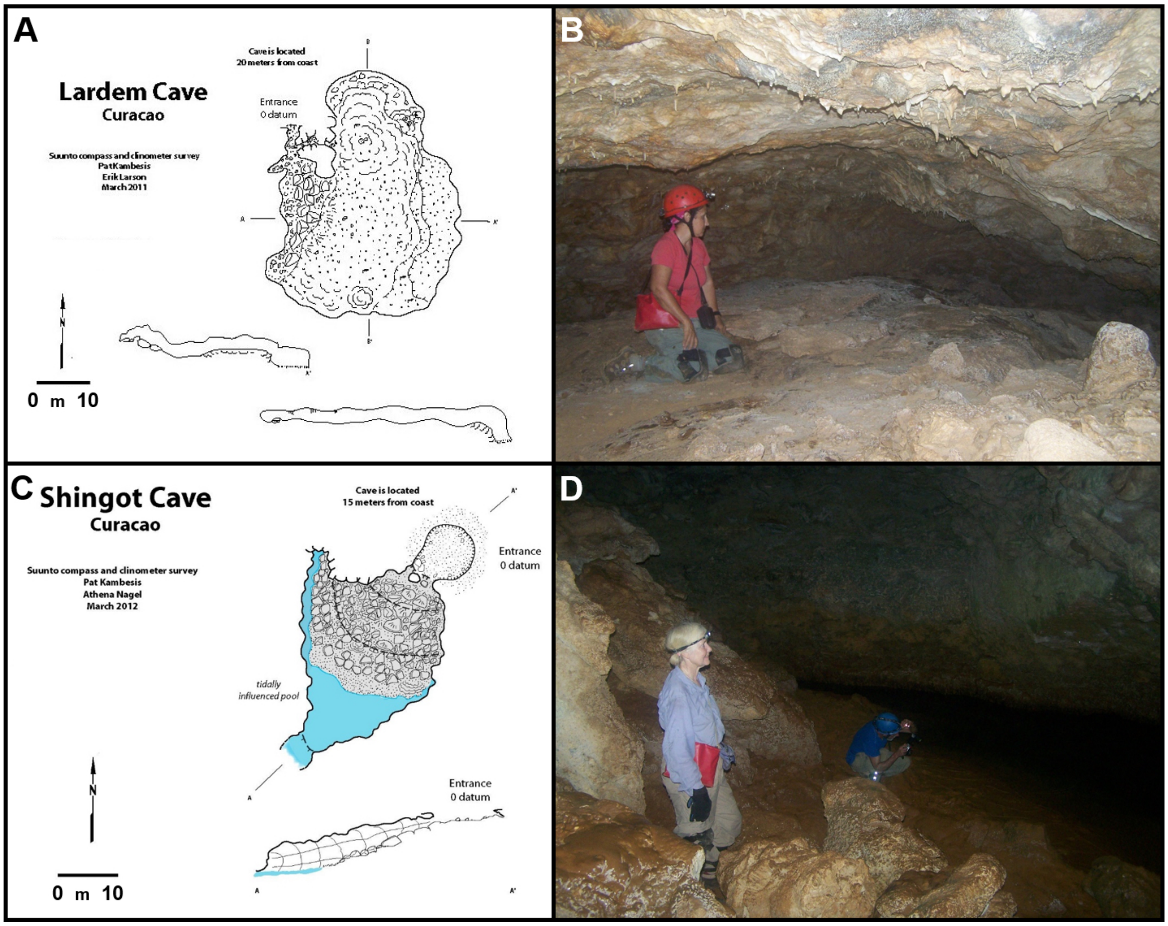

Figure 6. Intact flank margin caves of the Lower Terrace. Map of Lardem Cave, a flank margin cave located adjacent to the Boka Sheeta natural bridge, entered by a small vertical collapse. B) Image of the interior of Lardem Cave. C) Map of Shingot Cave, a flank margin cave located on the Hato Plain (MIS 7 and 5e limestones of the Lower Terrace), entered by a small vertical collapse; the cave reaches the modern freshwater lens. D) Image of the interior of Shingot Cave.

the caves to place the margin of the fresh-water lens at the necessary elevation to form the caves. In other words, there had to be a fine balance in sea-level position to have the reef terrace surface subaerially exposed, but to have sea level still within a few meters of that surface, for that position is where the flank margin cave are. The dissolutional denudation of the terraces since the end of MIS 5e is perhaps several meters (based on older terrace denudation presented earlier), so the terrace was once higher than observed today, independent of uplift activity. Still, the spatial window to make a lens and have it in the proper position is small.

For the MIS 7 limestones, the necessary subaerial exposure could have occurred during MIS 7 by tectonic uplift, to create a fresh-water lens, or at the end of MIS 7, as regression occurred and perhaps paused (only a few thousand years are needed to make a flank margin cave; e.g., Mylroie and Mylroie 2013). During the initial MIS 5e sea-level rise, a pause in that transgression could also have placed a fresh-water lens in the MIS 7 rocks. There are three options that would create the required subaerial exposure of the MIS 5e limestones, and still keep a fresh-water lens within those limestones. One option is a simple tectonic uplift episode(s) of a few meters during MIS 5e.

A second option is a pause on the MIS 5e regression. These two options replicate those that could have worked for the MIS 7 flank margin cave speleogenesis. The final option is a potential mid-MIS 5e sea-level drop of a few meters (e.g. Neumann and Hearty, 1996). All three scenarios would create subaerial exposure of the reef to create a fresh-water lens, but with sea level still high enough to place that lens within the MIS 5e limestone. A mid-MIS 5e lowstand, and its possible effect on flank margin cave development, has been discussed for a similar situation in the Bahamas (Carew and Mylroie, 1999).

The Stefanic and Cornell (2011) model assumes stream capture after the end of MIS 5e during the subsequent drop in sea level. Today, these streams originate on the interior volcanic highlands and flow seaward. They would have also done so during the both the MIS 7 and the MIS 5e sea-level highstand, building small clastic deltas out into the shallow lagoon. The clastic sediment, and the fresh-water input, would have limited reef growth in areas adjacent to the deltas, and perhaps along the discharge axis of the fresh water as it moved across the shallow reef crest towards deep water. The initiation of the bokas most likely began from this process. The curving inland walls of the bokas developed as reef growth was inhibited by the adjacent clastic delta and its fresh water.

The lack of evidence of such stream flow, and the inhibition of coral reef growth, such as faunal changes or volcaniclastic debris, has been lost to the process that has created the boka. The unconformity separating the MIS 7 and MIS 5e units, when viewed in a coast-parallel cross section, does not slope downward to the boka when viewed today, as would be expected if the MIS 5e material infilled the gap in the MIS 7 sequence produced by boka formation between MIS 7 and MIS 5e.

The overall scenario representing our interpretation of bokas is presented in Figure 7. As sea level fell a few meters during MIS 5e, either by tectonics or by the mid-MIS 5e lowstand, marine water would remain in the already existing trough in the reef flat. It is during this minor lowstand that flank margin caves would have formed along both boka walls, and in the inland curving sections of those walls, as the fresh-water lens established within the MIS 5e limestones discharged to the lens margin in all directions. After the end of MIS 5e, and sea level fall, surface fresh water flowed through the incipient boka to the sea. Over time, boka wall collapse occurred, facilitated by the numerous flank margin caves within the boka walls that also created boka wall instability.

The re-invasion by the sea into fluvial valleys cut into limestones has been used to explain cave development in the gullies of Barbados (Machel et al., 2012) and the *calas* of Mallorca (Mylroie et al., 2012). The same arguments work well for the bokas of Curaçao. While it is common to assume that streams crossing limestone surfaces will sink to form stream caves, simple surface incision also occurs. The result of this surface incision may be a steep-walled, narrow valley called a *limestone gorge*. The debate about whether limestone gorges represent collapsed caves or simple fluvial incision has been fully discussed in Ford and Williams (2007), who report that in most cases, a limestone gorge is the result of simple fluvial incision. We apply that interpretation to the bokas of Curaçao, as a simple fluvial incision model that best fits the current field data.

Cave openings also occur on the exposed coastal cliffs of northwestern Curaçao, and are problematic, as two processes are ongoing on these cliffs. Wave energy is attacking the rock, creating sea or littoral caves by wave action alone. Coastal cliff retreat is also uncovering dissolutional flank margin caves. Once exposed, these caves are modified by wave action, which can obscure their dissolutional origin, to produce an overprinted feature known as a hybrid cave (Machel et al., 2012). When cliff retreat has

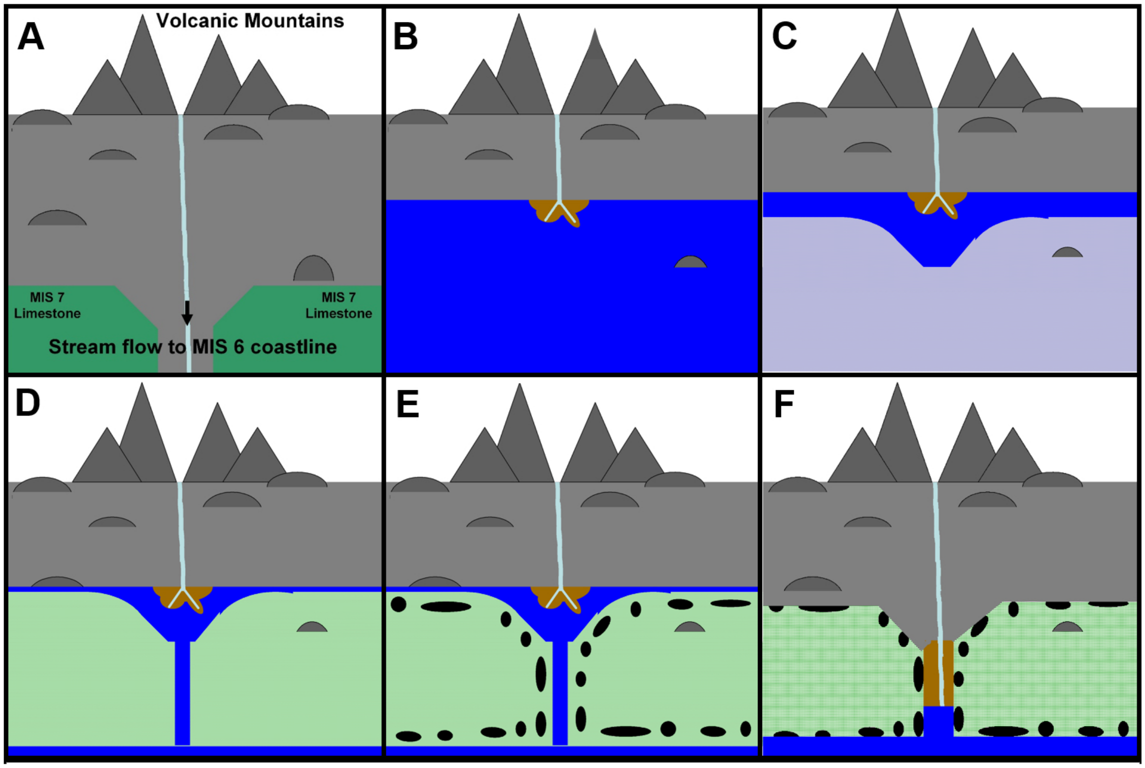

Figure 7. Schematic model of the events that produced the bokas during MIS 5e (125 ka) on Curaçao, presented in oblique view with volcanic uplands in the background as a cross section, and shallow lagoon and reef crest in the foreground as a plan view. Domal structures are low volcanic hills protruding through cover sediments. A) Initial conditions, before MIS 5e, sea level is low and no MIS 5e limestones yet exist; MIS 7 limestones are present and a boka has been incised into them by surface streams from the volcanic upland that flow to the sea. B) The MIS 5e sea-level highstand begins, and a clastic delta builds into the lagoon. C) Carbonate reef deposition catches up and approaches lagoon wave base, but suspended clastics and fresh water inhibit coral growth in the vicinity of the delta and along the stream discharge line to the shelf edge. D) A minor sea level fall subaerially exposes the reef carbonates, and meteoric precipitation creates a fresh-water lens in the carbonates; sea water invades the diminished lagoon. E) Flank margin caves develop at the margin of the fresh-water lens at its contact with the diminished lagoon. F) Current conditions. Sea level is lower than MIS 5e, a surface stream flows through the boka to the sea. Cliff retreat has exposed flank margin caves along both the active coast and the boka walls.

opened these caves, wave energy commonly invades and causes a roof collapse, creating initially what the locals call an *eye*, with a view to the waves below. Continued roof failure creates a natural bridge, such as the one at Boka Sheta National Park (located at Boca Tabla, shown inside the red box of Figure 3A). Failure of the natural bridge leaves a coastal indentation that can be difficult to differentiate between an original dissolutional feature versus a mechanical erosion feature formed solely from wave energy. Waterstrat et al. (2010) discuss the sea cave versus breached flank margin cave question in detail.

Given that the flank margin caves represent a stable sea-level position (noting that only a few thousand years is necessary to create an enterable small flank margin cave), the difference in elevation between the Middle Terrace cave horizons and the Lower Terrace (2 to 6 m) is a measure of the degree of denudation of the Lower Terrace surface since its deposition 125 ka during MIS 5e (see below).

Cave size correlates with the duration of time the fresh-water lens occupies a single position, and therefore for flank margin caves corresponds with stable sea-level position (Mylroie and Mylroie, 2007). The larger caves 6m above the Lower Terrace in the Middle Terrace wall most likely reflect the elevation of sea level during most of MIS 5e. The smaller, lower caves at +2m relative to the Lower Terrace might reflect a slightly lower MIS 5e sea-level position, as hypothesized for the boka flank margin caves (which are similar in size). If the upper surface of the Lower Terrace is assumed to have been at or near wave base during MIS 5e (Pandolfi et al., 1999; Schellmann et al., 2004), then the vertical separation of the large flank margin caves in the Middle Terrace wall from the Lower Terrace reef flat indicate how much surficial denudation has occurred in the Lower Terrace since MIS 5e time.

Similar work (Miklavič et al., 2012a and b) has demonstrated up to 8 m of surface lowering by dissolutional denudation of MIS 5e reef limestones on Guam over 115 ka, the end of MIS 5e. The Guam work used both field evidence, and theoretical calculations to determine the denudation rate, and the two methods were self-consistent. The denudation difference of 8 m for Guam versus 6 m for Curaçao is likely a result of regional climatic differences, Guam being wetter than Curaçao, which would increase denudation on Guam. Such denudation needs to be considered when using coral reef terraces as indicators of past sea-level positions.

The lower, smaller caves at +2m relative to the Lower Terrace can be explained as forming during a pause as the sea-level rose to the MIS 5e acme, and therefore would have been later entombed during MIS 5e by the coral reef, and subsequently have been "uncovered" by denudation processes after MIS 5e. That denudation would require erosional lowering of the Lower Terrace, as well as some cliff retreat to breach and expose caves at both the 6 m and 2 m positions. However, another explanation is possible. The 2 m cave location at what would have been the lateral contact between the older, Middle Terrace limestones (~ 400 ka, Table 1) and the younger (125 ka) Lower Terrace MIS 5e limestones reflects the fresh-water lens dynamics of crossing from the older to the younger limestones. As demonstrated by Vacher and Mylroie (2002), though younger Quaternary limestones have more primary porosity than older Quaternary limestones, that porosity is unorganized. As limestones age, their porosity decreases but their permeability increases, as the remaining porosity is organized into what is called a *touching-vug* flow system (Vacher and Mylroie, 2002). When limestones of two different ages abut each other, the lens distorts, being thicker in the less permeable (and younger) limestone relative to the thinner lens in the more permeable (and older) limestone. This boundary is the *defacto* margin of the fresh-water lens in the older limestone, in this case the Middle Terrace limestone. As a result, small dissolutional caves may have developed at this location.

The Curaçao literature (e.g., Schellmann et al., 2004; Lescinsky, 2008) refers to notches found within bokas, and in the interior terrace cliffs as bioerosion notches. It is highly unlikely that these notches are bioerosion in origin, except possibly in a few locations. This issue has been discussed for the Bahamas by Mylroie and Carew (1991), and explored in detail regarding littoral versus surficial denudation in Waterstrat et al. (2010). The key issue is that the amount of lateral scarp retreat necessary to display flank margin caves in a breached condition with open entrances (Figure 3B) is very much in excess of what is needed to completely remove a bioerosion notch once formed on the original sea cliff. In places where by chance scarp retreat has been minimal, bioerosion notches may survive, however those locations should not also show open flank margin cave entrances in the same cliff. However, there is evidence of bioerosion activity in some of the notches (Lescinsky, pers. comm.), which brings denudation rate arguments into conflict with bioerosion notch evidence. As with modern coasts, past coasts may have retreated at some locations and not at others along the coastline

SUMMARY

Bokas on Curaçao represent an inherited topographic trough from the time of MIS 7 (210 ka) and MIS 5e (125 ka) limestone deposition, when inland fresh-water discharge inhibited coral reef growth along linear pathways to the sea. Bokas initially formed after the MIS 7 sea level fall into the glacial sea-level lowstands of MIS 6, by simple fluvial incision. Subsequent transgression during MIS 5e may have infilled the original boka with reef crest coral rubble and associated debris. A minor drop in sea level during MIS 5e created subaerial exposure of the reef flat, allowed the establishment of a fresh-water lens within the reef flat. That fresh-water lens produced flank margin caves along the exposed coast, on the trough or proto-boka walls, and on the landward interior curving walls of the reef flat of the Lower Terrace. Subsequent major sea-level fall at the end of MIS 5e allowed full fluvial erosion through the proto-boka, to again produce a limestone gorge. Scarp retreat widened the gorge into the boka as seen today, assisted by major collapse events as the flank margin caves were exposed, and their unsupported void space weakened the gorge walls. Holocene sea-level rise allowed the distal portions of the bokas to be invaded by high wave energies, further modifying the boka walls. Intact flank margin caves can be found in the Lower Terrace MIS 5e limestones as proof that flank margin caves were formed during MIS 5e.

Flank margin caves within coastal carbonate exposures are breached by cliff retreat and subjected to marine wave erosion. This erosion overprints the dissolutional cave into what is known as a hybrid cave. The development of hybrid caves on Curaçao encompasses a progression from sealed chambers, to breached chambers, to chambers with roof collapse to form natural bridges, to coastal indentations. Differentiating between simple sea caves and overprinted hybrid caves is a significant field problem.

The position of flank margin caves on the walls of the Middle Terrace indicate that up to 6 m of dissolutional denudation has occurred on the Lower Terrace since MIS 5e. Such denudational lowering needs to be taken into account when paleo-sea levels are estimated from reef facies. The lower caves on the Middle Terrace cliff may be indicators of dissolutional cave development controlled by fresh-water lens distortion at the boundary between limestones of differing permeability.

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