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CAVES WITHIN DOLOMITIZED SECTIONS OF THE SEROE DOMI FORMATION ON CURAÇAO, NETHERLAND ANTILLES

JAME V DOLOMITIZIRANEM PROFILU FORMACIJE SEROE DOMIN NA OTOKU CURAÇAO, NIZOZEMSKI ANTILI

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Abstract UDC 551.44:552.543(729.882.1)
Jonathan B. Sumrall, Erik B. Larson & John E. Mylroie: Caves within dolomitized sections of the Seroe Domi Formation on Curaçao, Netherland Antilles
Remnant caves formed within the dolomitized Seroe Domi Formation on Curaçao were documented in order to determine their origin. Petrographic thin sections and geochemical analyses of samples from outcrops and cave wall rock agree with previous interpretations of a mixing zone origin for the replacement dolomite. Further, stable isotope analysis suggests migration of fluids from the underlying basalts along fracture networks in the Seroe Domi Formation. Most of the caves represent remnant phreatic caves based on morphology; however, a number of pseudokarst features were identified. Minimum cliff retreat rates were estimated (5 mm/1000 yrs to 52 mm/1000 yrs) using cave morphologies and elevations. These remnant caves, many of which were previously overlooked, have been used as indicators of diagenetic events within the Seroe Domi Formation and contain significant information when placed in the proper geologic framework.
Key words: Flank Margin Cave, Dolomitization, Seroe Domi Formation, Curaçao.

Izvleček UDK 551.44:552.543(729.882.1)
Jonathan B. Sumrall, Erik B. Larson & John E. Mylroie: Jame v dolomitiziranem profilu formacije Seroe Domin na otoku Curaçao, Nizozemski Antili
Dokumentirali smo ostanke jam v dolomitizirani formaciji Seroe Domi na otoku Curaçao in raziskovali njihov nastanek. Petrografske analize zbruskov ter geokemiče analize površinskih izdankov in vzorcev jamskih sten, potrjujejo predhodno domnevo o izvoru *(replacement)* dolomita v območju mešanja slane in sladke vode. Analiza stabilnih izotopov kaže na prenos tekočin iz bazaltne podlage vzdolž mreže razpok v formaciji Seroe Domi. Oblika večine jam kaže, da gre za dele freatičnih sistemov, odkrili pa smo tudi več psevdokraških pojavov. Morfološke značilnosti jam in njihova nadmorska višina sta nam omogočili oceno minimalne hitrosti umikanja otoških klifov, ki je med 5 m in 52 mm na tisoč let. Ostanki jam, ki so bili prej največkrat spregledani, so kazalci diagenetskih dogodkov v formaciji Seroe Domi in vsebujejo druge pomembne informacije, če jih le postavimo v ustrezen geološki okvir.
Ključne besede: Jame tipa "flank margin", dolomitizacija, formacija Seroe Domi, Curaçao.

INTRODUCTION

Curaçao (located at 12° 07' N, 68° 56' W) is a small (472 km^2) carbonate island located in the southern Caribbean approximately 80 km north of Venezuela (Fig. 1). The island is oblong in shape approximately 61 km long by 14 km wide (at its widest). The carbonate landscape is made up of relatively flat elevated benches, while the

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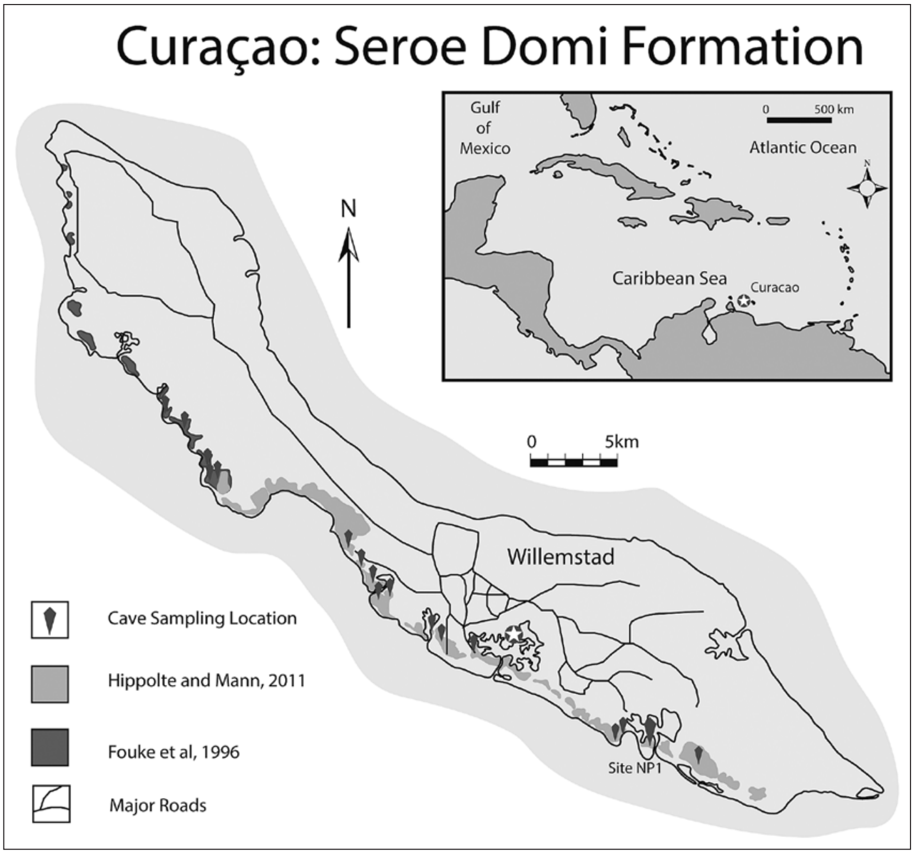


Fig. 1: Location map showing sampling sites from outcrop and caves located within the Seroe Domi Formation. The shaded regions on the southern coast correspond to dolomitized outcrops of the Seroe Domi Formation, as mapped by Hippolyte & Mann (2011) and Fouke et al. (1996).

volcanic outcrops are higher with rugged topography (Beets 1972).

Previous studies (Martin 1888; De Buisonje & Zonneveld 1960; Focke 1977; Focke 1978) have examined the morphology of cliffs of the limestones on Curaçao. Certain features in the cliffs located on the southwestern coast have been interpreted as wave-cut notches; however, this study presents evidence that reclassifies a large number of these features as dissolution caves. In addition, the value of these features are expanded by using their size and position as a proxy for cliff retreat and uplift rates.

GEOLOGIC SETTING

The geology of Curaçao can be broken into three main units, from oldest to youngest (Fig. 2): 1) Cretaceous volcanics and Danian clastics, 2) Eocene limestones, marls, sandstones, and clays, and 3) Carbonates of Neogene and Quaternary age (Beets 1972; De Buisonje 1974). The carbonates of Neogene and Quaternary age unconformibly lie on top of the Cretaceous and Danian Sequences, as well as the Eocene sedimentary units depending on outcrop location. The Quaternary carbonates are elevated marine terraces broken into 4 main units: the Lower Terrace (youngest), Middle Terrace (sometimes subdivided into Middle I and Middle II), Higher Terrace, Highest Terrace (oldest) located primarily along the island's north shore. The Neogene Seroe Domi Formation (Fig. 1) is located primarily along the south shore (Beets 1972; De Buisonje 1974). The Cretaceous and Danian Sequence is composed of basalts of the Curaçao Lava Formation, volcaniclastic sediments of the Knip Group, and turbidites of the Midden-Curaçao Formation (Beets 1972).

The Seroe Domi Formation is composed of limestone and dolomitized limestone and is located mainly on the leeward side of the island as carbonate capped slopes. Steep scarps, usually ranging from 10 to 15 m, form on the landward side of these slopes. The dipping slopes, usually between 5° and 25° were interpreted as not being a result of tectonic tilting, but rather a result of depositional slumping (De Buisonje 1974) later uplifted. The formation is detrital in nature, mainly composed of detritus of reef deposits (calcareous algae and corals), with minor constituents of eroded non-carbonate clasts.

DOLOMITIZATION OF THE SEROE DOMI FORMATION

The dolomitization of the Seroe Domi Formation occurred under mixing zone conditions (Fouke *et al.*

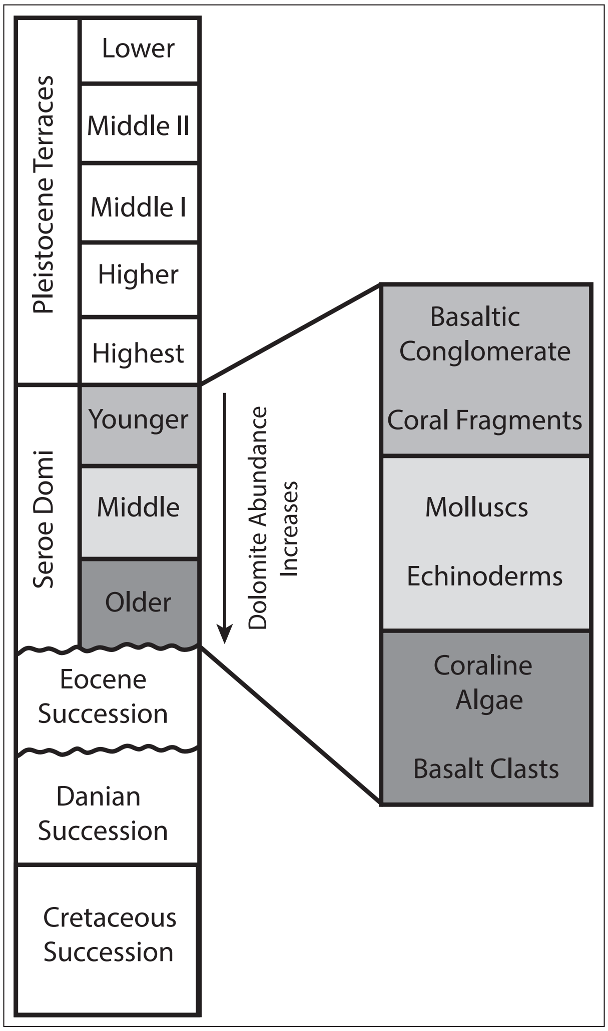


Fig. 2: Generalized stratigraphic column of Curaçao.

1996). While the geochemical data indicated that the dolomitzation mechanism was mixing of freshwater and seawater, the updip stratiform distribution of some of the dolomite units (instead of a patchy, lenticular, or pervasive bed cross-cutting distribution) implies that brine reflux dolomitization also may have occurred (Fouke *et al.* 1996). The dolomite was divided into three units based on the extent of dolomitization (Fouke *et al.* 1996). Dating by $^{87}Sr/^{86}Sr$ indicates the oldest dolomite to be Middle Miocene (~12 mya), and the youngest dolomite to be Pliocene (~4 mya; Fouke *et al.* 1996).

Caves are reported in the Seroe Domi Formation as having dome-shaped rooms with floors consisting of older, underlying, non-carbonate formations, with some accessed by openings in the ceiling (De Buisonje 1974). Dolomitization resulted in decreased permeability and an apparent relative lack of cave development within the Seroe Domi Formation (De Buisonje 1974). This paper offers further insight in to cave development in the Seroe Domi Formation.

METHODS

A total of 33 caves were mapped using a tape or Disto® laser rangefinder and Sunto® compass. Selected caves were sampled for thin section and geochemical analyses based on cave type (Fig. 1). Samples were collected from completely and partially dolomitized outcrops containing caves and from the walls/ceiling of representative caves.

A total of 22 rock samples were made into standard (27 mm x 46 mm) thin sections with blue-dyed epoxy and no cover slips attached by Spectrum Petrographics, Inc. (Vancouver, WA). Thin section porosity was calculated using a macro (jPOR) for the NIH software package ImageJ (Grove & Jerram 2011). Statistical point counts (300 points) determined the accuracy of jPOR to be ±3 %.

Thin sections were stained with alizarin red-S to distinguish calcite and dolomite. Cathodoluminescence microscopy (CL-4 Cold-cathode Luminoscope attached to a Leica DMLP microscope) with an accelerating voltage of 7000 eV was used to acquire micrographs of mineral luminescence of the petrographic thin sections.

To identify the mineral composition, X-ray diffraction (XRD) patterns of powder obtained using a low speed dental drill assembly were produced using a Rigaku Ultima III diffractometer with Cu Kα radiation. Samples containing mixtures of dolomite and calcite were leached with a weak acid (4 % acetic acid) and analyzed until 100 % dolomite remained.

Powdered samples of dolomite were dried at 50 °C for at least 24 hours and reacted with 100 %

orthophosphoric acid (H_3PO_4) to release dry CO_2 that was analyzed using a gas-source mass spectrometer. Reproducibility for the $\delta^{13}C$ and $\delta^{18}O$ measurements respectively is estimated to be +/− 0.1 % (1σ) based on multiple NBS-19 standards and sample replicates. Stable isotopic analyses were performed at Alabama Stable Isotope Laboratory (ASIL) Tuscaloosa, University of Alabama (Lambert & Aaron 2011).

RESULTS

A total of 19 remnant caves were mapped, and an additional 15 caves were photo-documented. Remnant caves occurred in a number of settings, called *cave types*, including:

1) horizontal caves along the contact between the carbonate and basaltic diabase,

2) horizontal caves regardless of bedding orientation of the carbonate unit,

3) caves oriented along dipping bedding surfaces of the carbonate unit,

4) caves associated with fractures within the carbonate unit, and

5) caves developed at the contact between basaltic diabase and brecciated carbonate/igneous detritus at modern sea level.

Speleothems were found in both types of horizontal caves (Fig. 3), while they were not found within caves associated with fractures, along tilted bedding, or along the carbonate/igneous contacts. Caves were clustered at elevations of 80 meters, 60 meters, 45 meters, 20 meters, 15 meters, and 1 meter above sea level (Fig. 4).

Caves that formed at the basalt-carbonate contact (Type 1) generally had undulating ceilings and developed along fracture networks (Fig. 5). These caves also had abundant phreatic dissolution features in the ceiling and wall morphology (Fig. 6). Caves that formed horizontally, regardless of bedding, also had undulating floors and ceilings and phreatic dissolution morphologies; however, these caves did not appear to be associated with fracture networks. These caves (Types 1 and 2) contained abundant speleothems (Fig. 3). A number of caves followed the dipping orientation of the strata that contained them (Type 3), and these caves did not contain speleothems or dissolution surfaces. Vertical caves associated with large fractures (Type 4) within the carbonate unit differ from the horizontal caves that developed along fracture

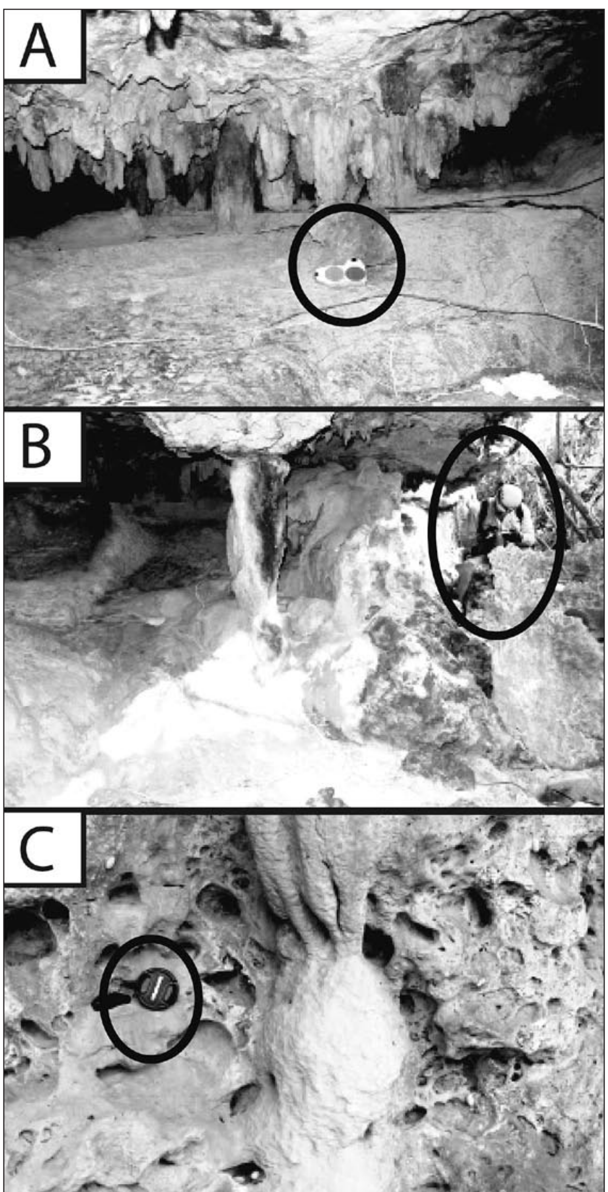


Fig. 3: Speleothems from remnant caves of the Seroe Domi Formaiton on Curaçao. A) A series of flowstone stalactites forming above a flowstone dam found in A Little Too Late Cave. Circle is around a Sunnto® tandem compass and inclinometer approximately 10 centimeters in length. B) Flowstone column found in Manchineel Cave. Circle is around person for scale. C) Flowstone stalactite found in Flat Top Cave. Circle is around lens cap approximately 4 centimeters in diameter.

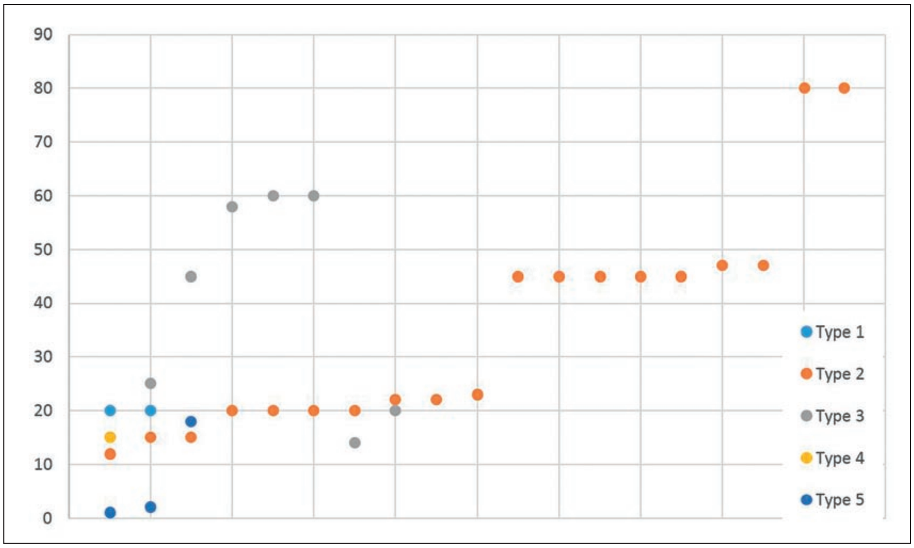


Fig. 4: Plot of cave elevation by type showing general clusters at 1, 15, 20, 45, 60, and 80 meters above sea level.

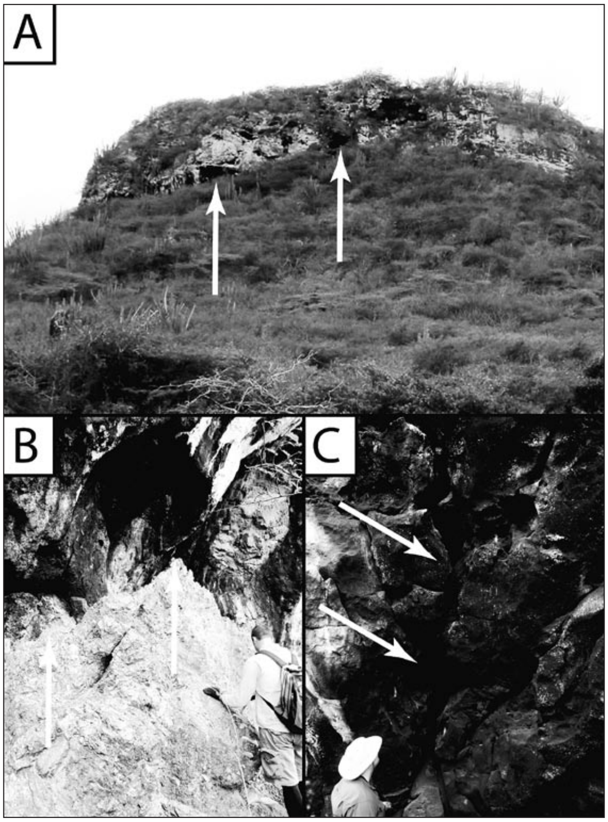


Fig. 5: An outcrop showing caves (Type 1) that formed near and slightly above the basaltic diabase and carbonate contact on Curaçao. A) Remnant caves had undulating ceilings, and caves do not follow lithologic contacts. Vertical extent of photograph is 35 meters. Arrows point to typical caves. B) The basaltic diabase contact has an irregular weathering surfaces indicated by the arrow. This contact is the unconformity between the Cretaceous succession and the Seroe Domi Formation. C) Extensive fracture networks penetrating into the overlying carbonate unit were associated with caves (arrows).

Tab. 1: Thin section porosities from outcrop and cave samples.

Sample	Porosity (%)	Location	Cave Type
1025	22	Cave Ceiling	Type 2
1030	41	Cave Wall	Type 2
1032	12	Cave Wall	Type 3
1038	2	Cave Ceiling	Type 2
1039	46	Cave Wall	Type 2
1040	10	Cave Ceiling	Type 2
1041	16	Cave Floor	Type 2
1042	13	Cave Ceiling	Type 2
1044	13	Cave Ceiling	Type 2
1047	40	Cave Wall	Type 2
1048	42	Cave Wall	Type 2
1052	37	Cave Wall	Type 2
1055	44	Cave Wall	Type 2
1004	5	Outcrop	-
1006	18	Outcrop	-
1007	35	Outcrop	-
1008	24	Outcrop	-
1009	47	Outcrop	-
1012	2	Outcrop	-
1035	9	Outcrop	-
1036	8	Outcrop	-

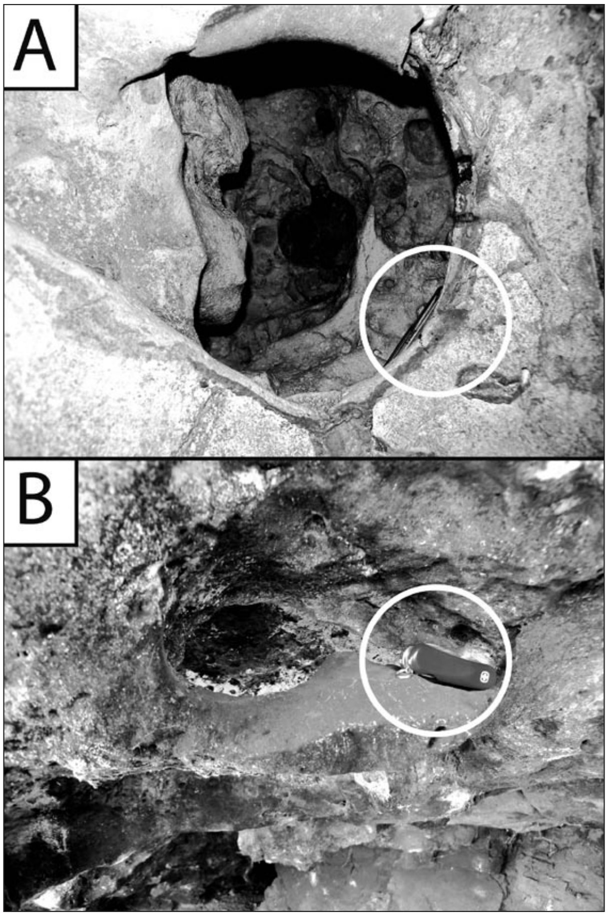


Fig. 6: Dissolution pockets that penetrate into the ceiling (A) and wall (B) of the carbonate unit at the basalt-carbonate contact. Circles are around a pocketknife approximately 6 centimeters in length.

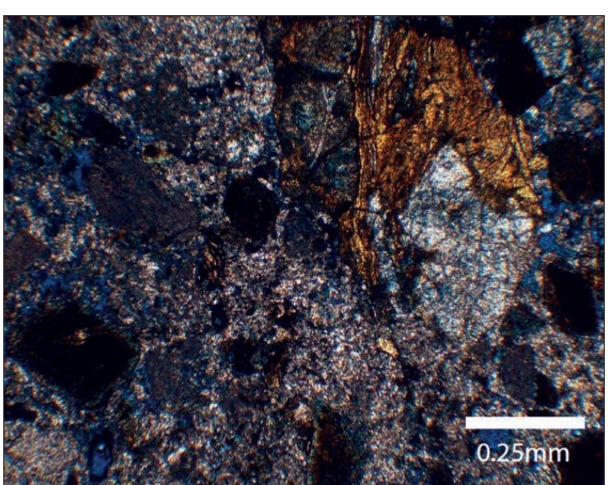


Fig. 7: Thin section micrograph showing dolomitized allochems (dark gray), dolomite cement (clear to white), and clay clasts (light brown). Blue represents porosity filled with blue-dyed epoxy.

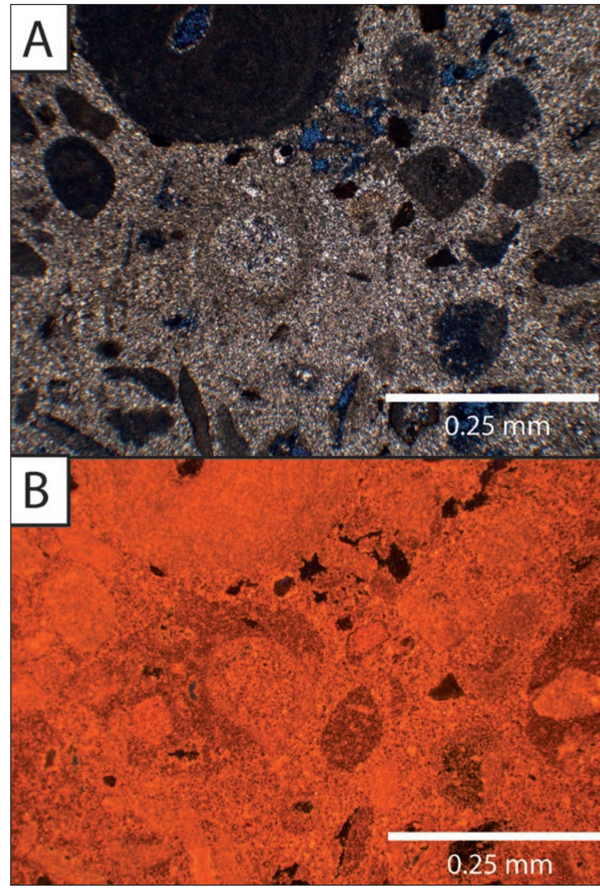


Fig. 8: A) Thin section micrograph showing a dolomitized grainstone. Blue represents porosity filled by blue-dyed epoxy. B) Cathodoluminescence micrograph of the same field as (A) showing two types of luminescence. Dolomite pore-filling cements appear zoned. The red algae allochem in the top left corner of micrograph (A) cannot be distinguished from the matrix by cathodoluminescence in (B).

networks at the basalt-carbonate contact. These fracture caves did not contain dissolution morphologies, were vertically extensive, and lacked speleothems. Caves that formed at modern sea level (Type 5) did not contain dissolution features or speleothems.

Thin section porosity is presented in Tab. 1 and ranged between 2 % and 47 % with an average of 23.4 % (n=22). Outcrop samples generally had lower porosities than cave samples; however, cave wall samples had higher porosities than cave ceiling and floor samples. Cave wall samples ranged in porosity from 12 % to 46 % with an average of 36.8 % (n=6), while cave ceiling and floor samples ranged in porosity from 2 % to 22 % with an average of 12.7 % (n=6).

The mineralogy of cave samples was dominantly dolomite, with minor constituents of secondary calcite cave-filling cements. Carbonate thin sections were dom-

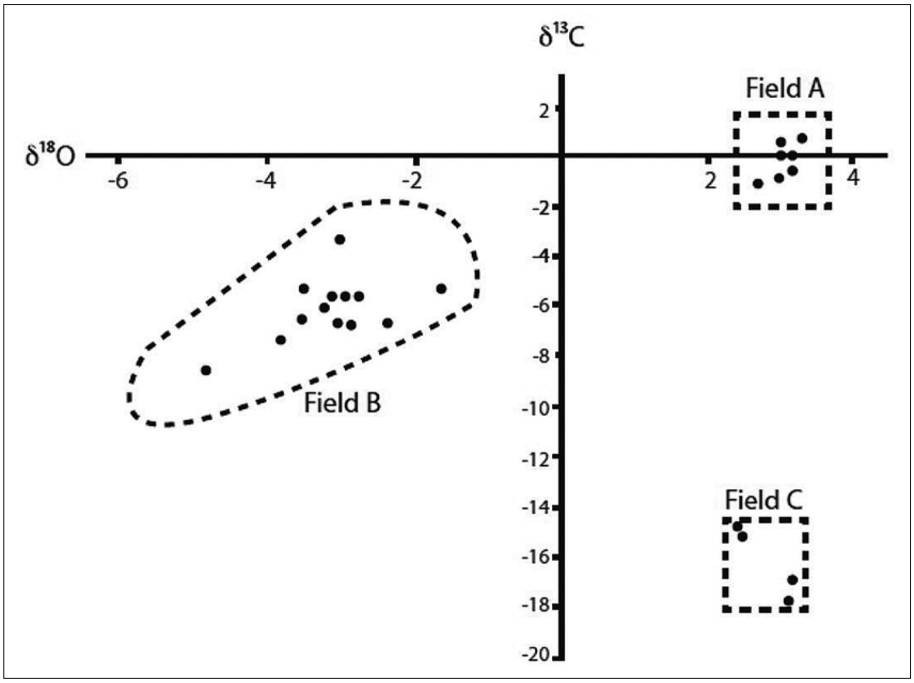


Fig. 9: Plot of $\delta^{13}C$ (VPDB) vs. $\delta^{18}O$ (VPDB) of dolomite from the Seroe Domi Formation on Curaçao. Fields A, B and C described in the text.

inantly dolomitized packstones and grainstones, with some samples containing abundant clay clasts (Fig. 7). Dolomitized packstones and grainstones appear to be consistent with forereef slope deposition (Fig. 8A).

Cathodoluminescence shows two types of dolomite based on luminescence. The matrix of most samples is moderately to high luminescent, while small portions show poor to moderate luminescence (Fig. 8B). Dolomite cements show slight zoning with darker cores and high luminescent rims.

The isotope values of this study are presented in Fig. 9. The $\delta^{13}C$ values of dolomite from the Seroe Domi Dolomite range from −17.6 to +0.9 ‰ and the $\delta^{18}O$ values of dolomite range from −4.9 to +3.3 ‰.

DISCUSSION

Proper identification and interpretation of cave type is important to understand the process and timing of cave formation, while also determining unknowns such as sea level position at the time of formation. Differentiation of remnant caves is often difficult, and most geologists commonly dismiss these features as surface erosional in nature with little or no scientific value. The remnant caves within the Seroe Domi Formation on Curaçao formed through a variety karst and pseudokarst processes. Cave classification falls into 5 types:

1) Dissolution caves near the contact between the Seroe Domi Formation and the underlying layers,

2) Dissolution caves located within the Seroe Domi Formation that do not follow bedding orientation,

3) Erosional caves developed along dipping bedding surfaces,

4) Fracture caves,

5) Sea caves,

Groups 3-5 are pseudokarst caves. Remnant flank margin caves (specifically Type 2) were the most abundant type of cave documented within the Seroe Domi Formation (Figs. 10 and 11). Many of these features were likely dismissed as surface erosional features by previous authors (e.g. De Buisonje 1974; Focke 1978); however, due to the presence of speleothems, undulating floors and ceilings, and phreatic dissolution morphologies, these caves are interpreted as remnant flank margins caves that later experienced vadose conditions and breaching by surface erosion (Figs. 3, 5, 6). Since the largest width of most of these caves is the entrance width, large portions of passages are interpreted to have been lost to cliff retreat. A similar interpretation has been made for notches with undulating floor and ceiling patterns, speleothems, and lack of marine sediments as breached dissolutional pockets and caves in the Bahamas (Mylroie & Carew 1991).

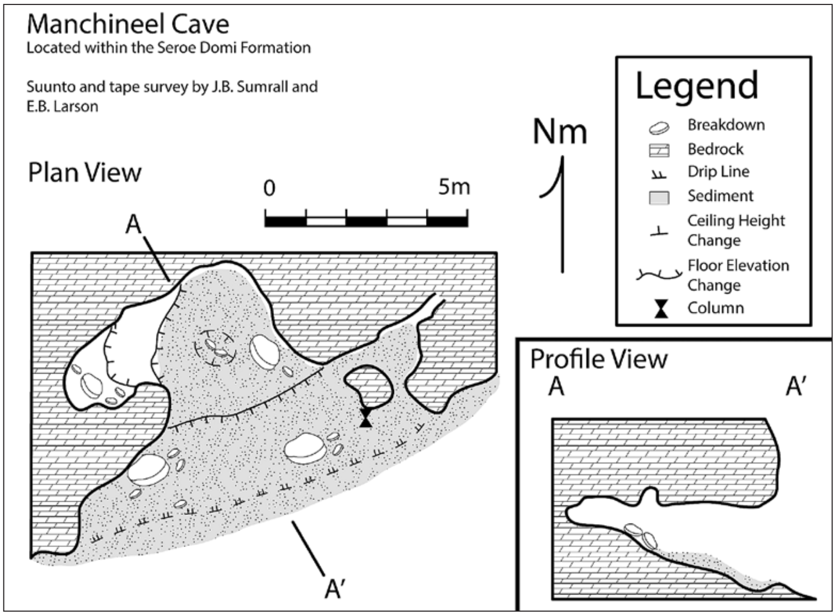
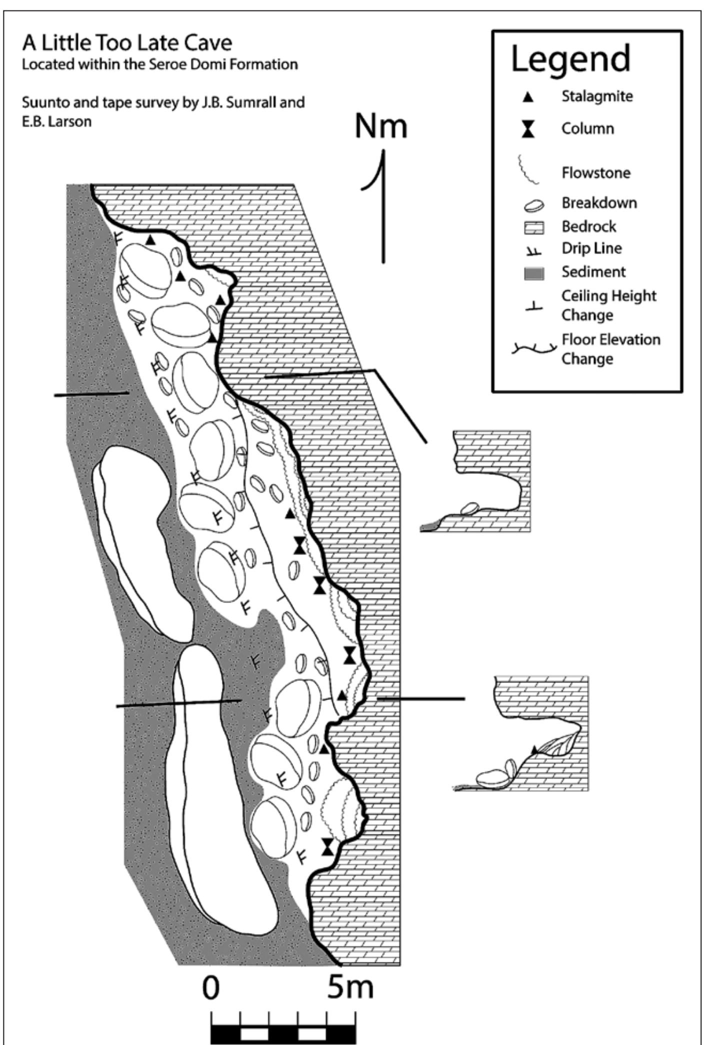


Fig. 10: Map of Manchineel Cave (Type 2) located within the Seroe Domi Formation on Curaçao. This cave is interpreted as flank margin in origin based on morphology. This map corresponds to the photograph in Fig. 3A.



The next type of cave was pseudokarst produced by non-uniform erosion of dipping strata (Type 3; Fig. 12). These caves followed the dipping beds, did not have morphologies that indicated a dissolution origin, and lacked speleothems (Fig. 12B). Sea caves (Type 5) were found at the contact between the Curaçao Lava Formation and the Seroe Domi Formation (Fig. 13A and C). Breccia Sea Cave lacked dissolution features, and the entrance was the widest point of the cave (Fig. 13A). A vertically extensive fracture cave (Type 4) was documented within the Seroe Domi Formation (Fig. 13B, D, and E). Lonely Bat Fracture cave was developed along a fracture extending ~20m in vertical extent, lacked dissolution features, and had extensive breakdown at the base of the fracture (Fig. 13D and E). It is possible that this fracture was originally enlarged by dissolution; however, breakdown at the base of the cave confirms the cave wall lacked dissolution features.

Fig. 11: Map of A Little Too Late Cave (Type 2) located within the Seroe Domi Formation on Curaçao. This cave is interpreted as flank margin in origin based on the morphology and abundance of speleothems. Since the maximum width is the entrance, a majority of the cave has been lost to cliff retreat. This map corresponds to the photograph in Fig. 3B.

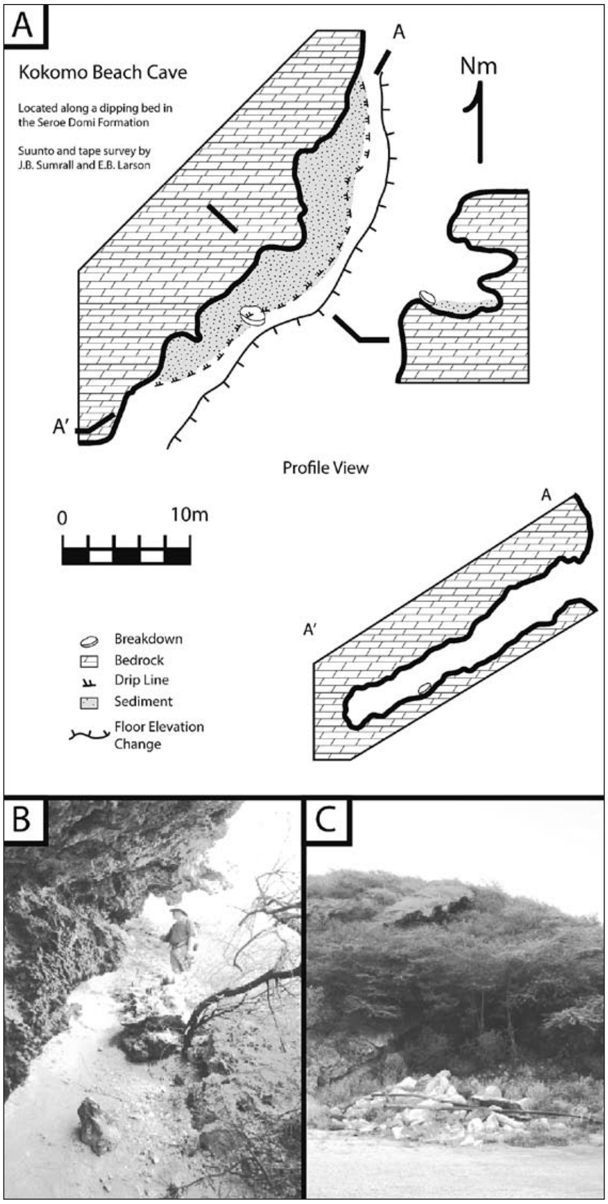


Fig. 12: A) Map of Kokomo Beach Cave (Type 3 cave) located along a dipping bed within the Seroe Domi Formation on Curaçao. B) Photograph along profile of A' to A from the cave map showing a general lack of dissolution morphologies. C) Outcrop view showing that cave formation occurred along the dipping beds of the Seroe Domi Formation.

Elevation data reveals the presence of several horizons of cave development (Fig. 4). Cave horizons exist at 1, 12–15, 20–25, 45, 60, and 80 meters. These data represent 33 cave features identified on the slopes of the Seroe Domi Formation. When examining the horizons closer, interesting trends are present. Type 2 caves (flank margin caves) are found at multiple horizons. These caves form tied to sea level, and their presence suggests that the cave horizons represent paleo-sea levels. Type 3 caves are located at several horizons also; however, the abundance of type 3 caves increases in elevation with exception above 60 meters. Type 3 caves are interpreted as being the result of differential erosion due to varying lithologic characteristics of the host rock. Due to this lithologic control, these types of cave are often found following bedding. The cave exists because the host rock is more susceptible to surface erosion. The increase in frequency is interpreted as being a relic of exposure time. The interesting trend is the lack of Type 3 caves found above 60 meters. This can be explained by one of two explanations. First, it is possible that there were features present and they became so large due to erosion that identification was impossible. As shown in Fig. 12, these caves did not extend far into the host rock. Larger versions of these features may simply have been ignored due to not appearing as a cave. The second possibility involves exploration bias. It is possible that these voids exist at elevations higher than 60 meters, but they were not found due to access difficulty. Many of the slopes of the Seroe Domi Formation cliff out at the top 10 meters, and it is possible that there were type 3 caves present where access was impossible. Cave types 4 and 5 were found at lower cave horizons. The lack of these caves at higher elevations is caused by cliff retreat destroying these caves. It is important to note that many researchers have interpreted most of the caves on the cliffs of the Seroe Domi Formation as sea notches (this study would classify a sea notch in a similar manner of formation as sea caves, Type 5). Sea notches would also not likely survive cliff retreat once uplift occurs.

PETROGRAPHIC AND GEOCHEMICAL ANALYSES

Thin section analysis of cave wall, ceiling, and floor samples showed that the highest porosities were found in remnant phreatic cave wall samples, which is similar to results from San Salvador Island, The Bahamas (Vogel *et al.* 1990). The lowest wall rock porosities were samples from erosional caves along dipping beds. Cave wall rock thin section porosity may be related to the genetic mechanism of the cave; however, more research is needed to characterize this relationship. The dominant type of porosity found in remnant phreatic caves thin-section samples was touching-vug and moldic porosities.

Stable isotope results differ slightly from values of previous studies (Fouke *et al.* 1996). A field of dolomite isotope values cluster around a marine signature (Fig. 9, field A), which corresponds to two types of dolomite identified by Fouke *et al.* (1996). Other isotope values follow a mixing trend between meteoric and marine end-members (Fig. 9, field B). The covariance of the iso-

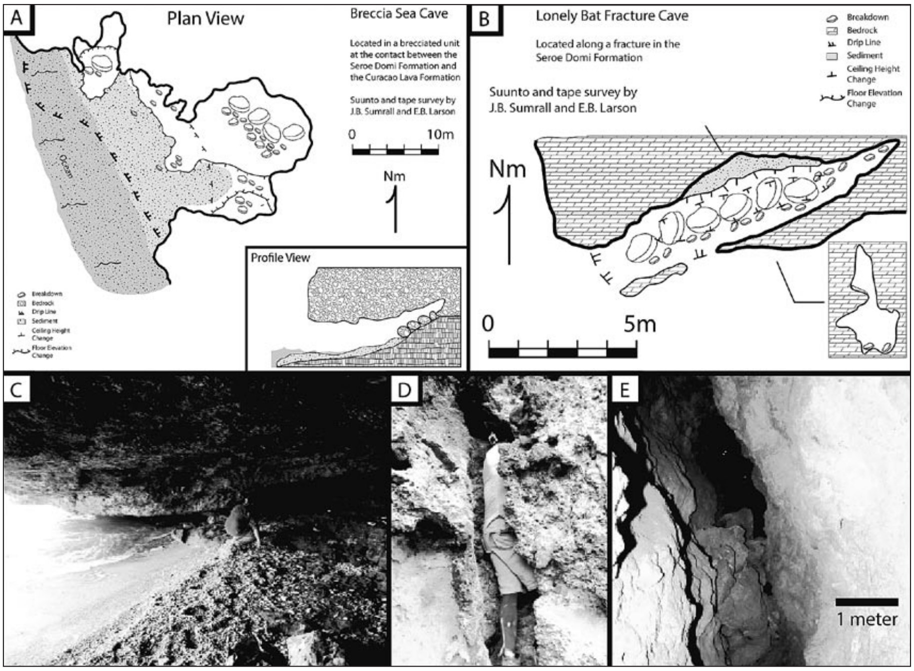


Fig. 13: A) Map of Breccia Sea Cave (Type 5) located at sea level along the contact between the Curaçao Lava Formation and the Seroe Domi Formation on Curaçao. B) Map of Lonely Bat Fracture Cave (Type 4) located along a fracture within the Seroe Domi Formation on Curaçao. C) Photograph within Breccia Sea Cave. D) Entrance to Lonely Bat Fracture Cave. E) Photograph from within Lonely Bat Fracture Cave showing the vertical development and breakdown.

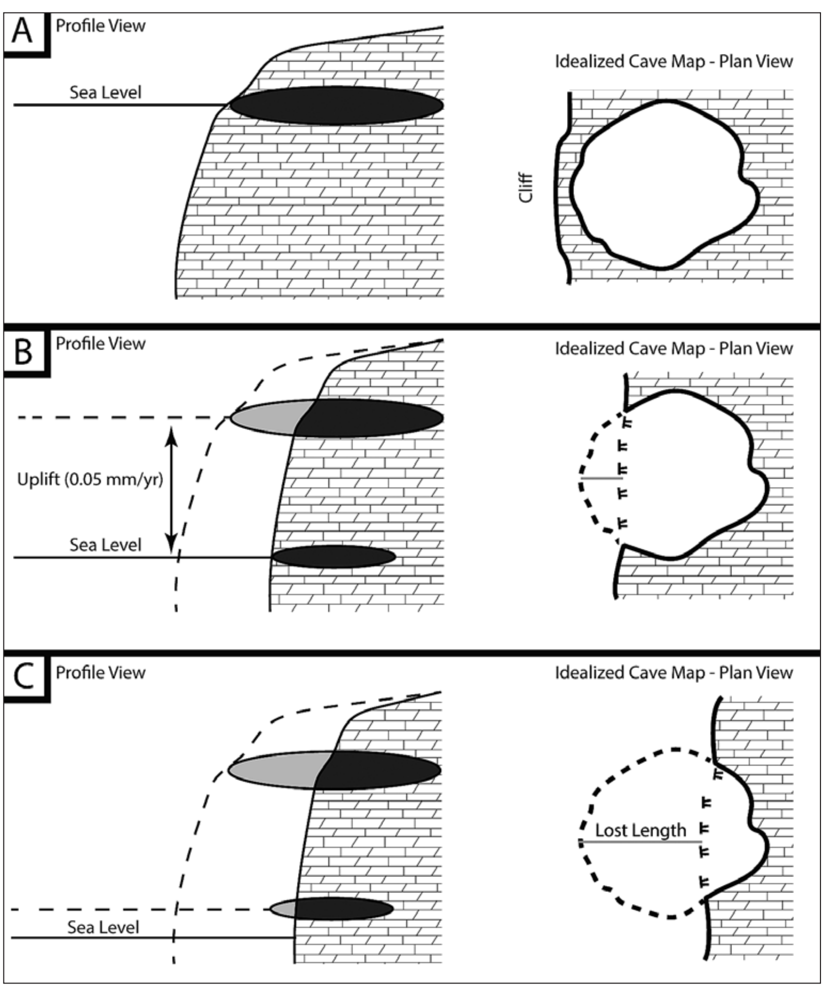


Fig. 14: Idealized cave showing cliff retreat. Uplift from a sea level position of +6m asl is calculated using the rate 0.05mm/yr. The idealized cave map in plain view of the upper cave is shown on the right of each panel. Originally flank margin caves form as entrance-less caves. Cave entrances are the result of breaching by cliff retreat and denudation. When the entrance width is the maximum width, the cave is considered to be at least half lost to cliff retreat. By first establishing cliff retreat rates, lost length can be estimated and original void area can be calculated.

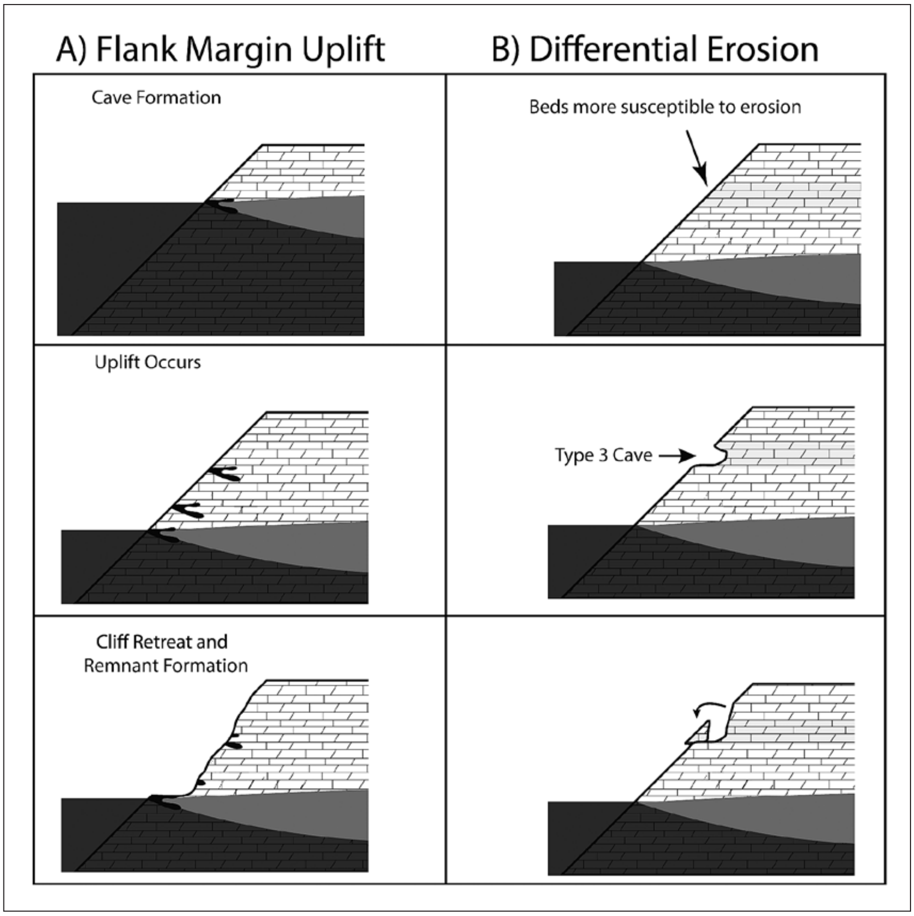


Fig. 15: A) Genetic model for the formation of remnant flank margin caves (Type 2). Other cave types that form at sea level (such as sea caves) would follow a similar process; however, only flank margin caves appear to survive the duration of cliff retreat experienced by higher elevation caves. B) Differential erosion model showing the development of Type 3 caves and how these caves are "lost" due to erosion undercutting the resistant overlying beds.

topes agrees with interpretations of mixing zone origin (Budd 1997). Using $\delta^{18}O$ of seawater, calculated mixing ratios near 25 % seawater would produce dolomites with the observed isotopic signatures. A third field of dolomite is present with a highly ^{13}C-depleted (−14 to −18 ‰) signature (Fig. 9, field C). This dolomite possibly represents equilibration with fluids derived from weathering of basalts or fluids rich in dissolved hydrocarbons such as methane. Since the Seroe Domi Formation lies stratigraphically on top of igneous rocks, it is likely that the signature is related to weathering of this basement material. Similar ^{13}C values (−2.0 to −26.0 ‰) have been reported in secondary carbonates associated with basaltic lavas cored from the Norwegian Sea (Love *et al.* 1989).

DOLOMITE KARST FEATURES

Flank margin cave (Type 2) remnants were found at elevations of 15, 20, 45, and 80 meters above modern sea level within the Seroe Domi Formation on Curaçao. Since the dolomite was produced in a mixing zone environment that requires subaerial exposure to produce a freshwater lens, it is likely that the phreatic caves formed during the same exposure event as the event that formed the dolomite. A similar interpretation has been made on the remnant flank margin caves located in dolostones on Isla de Mona, Puerto Rico; however, it is possible that later exposure events resulted in flank margin development (Sumrall *et al.* 2014). Stable isotopes suggest that rising fluids from depth flowing along fracture networks interacted with some of the carbonates producing a ^{13}C-depleted signature (Fig. 9, field C). Phreatic caves at the basalt-carbonate contact formed along fractures that penetrated into the overlying carbonates.

Uplift rates of 0.05 mm/yr (Herweijer & Focke 1978; Fouke *et al.,* 1996) can be used to estimate cliff retreat rates by using modern and remnant sea caves (Type 5). The maximum elevation that sea caves were identified on the Seroe Domi slopes of Curaçao was ~19 meters above sea level. Using Breccia Sea Cave's size as a proxy for the size of older remnant sea caves, the total cliff line distance that would be lost (distance perpendicular to cliff line to "deepest" point of cave) is 21 meters. Assuming the amount of time to completely remove a sea cave of similar size by cliff retreat is the same as other remnant sea caves, this produces a cliff retreat rate of 52 mm/1000 years.

Tab. 2: Calculated cliff retreat rates based on minimum length of cave lost (determined from cave maps) and last time caves experienced sea level at +6 meters.

Cave	Elevation (meters)	Last time caves were at +6m asl (million years)	Uplift since +6m asl (meters)	Length of Cave Lost (meters)	Cliff Retreat Rate (mm/1000 yr)
HH Cave	80	1.48	74	8.9	6
Refine View Cave	60	1.08	54	5.9	5.5
A Little Too Late Cave	45	0.78	39	3.9	5
Manchineel Cave	20	0.28	14	5.2	18.6
Dead Cow Cave	20	0.28	14	5.7	20.4

Another method for producing cliff retreat rates is using remnant flank margin caves. Since the maximum width of any flank margin remnant identified is the entrance width, more than half of the cave area has been lost to erosion. Assuming that the flank margin caves were originally somewhat elliptical in shape, the caves should have been at least 50 % larger (Fig. 14), as demonstrated on Tinian Island (Stafford *et al.* 2005). The last time a mixing zone was present, as a minimum value, can be determined by using the elevation of the cave and correlating to previous glacioeustatic sea level highstands of +6 meters (Tab. 2). Highstands of ~+6 m above modern sea level are the highest elevation that sea level has been estimated to during the last ~2.5 million years (Hansen *et al.* 2013). Using this to determine the minimum age of cave formation (last time at +6m asl), a cliff retreat rate can be calculated for each cave (Tab. 2). The flank margin caves found within the Seroe Domi Formation show minimum cliff retreat rates of approximately 5 mm/1000 yrs up to approximately 20.4 mm/1000 yrs (Tab. 2). It must be noted that these rates are extremely conservative (especially compared to values calculated from sea caves of ~52 mm/1000 yrs) because the original cave size is unknown. The cliff retreat rate is reflected in the outcrop tendency of the Seroe Domi Formation. In general, dolomite capped basalt hills control the topography of the western coast of Curaçao, and there are no significant basalt slopes in areas where the dolomite has been eroded away. This observation indicates that the basalts erode faster than the dolomites.

An estimate of the original size of the older caves can be determined by using the cliff retreat rate of the younger caves (Tab. 3). Estimated areas were calculated using areas calculated from cave maps. As mentioned above, the entrance is the widest point of these caves. The minimum amount of cliff retreat that would occur is simply doubling the area (considering flank margin caves are ovoid in shape, circular in area). Assuming these caves formed in proximity to the cliff edge, cliff retreat estimates can be used to estimate the length of cave lost (Fig. 14). A ratio between the maximum length perpendicular to cliff to the estimate length of cave lost was used to determine the approximate area of the original void. Caves, such as HH Cave that currently have an area of approximately 223 m^2, would have originally had a minimum area of approximately 979.5 to 2151.3 m^2 (Tab. 3).

Dolomite karst features on Curaçao represent alternation between uplift and cave formation (Fig. 15). The flank margin caves found at higher elevations today represent features that were large enough to survive cliff retreat and surface erosion (Fig. 15A).

Tab. 3: Calculated areas of remnant caves based on estimated cliff retreat rates of 20.4 mm/1000 yr (younger flank margin cave estimate) and 52 mm/1000 yr (sea cave estimate).

Cave	Estimated Length Lost (meters)	Remnant Area	Estimated Area using 20.4 mm/1000 yr (m^2)	Estimated Area using 52 mm/1000 yr (m^2)
HH Cave	30.2	223.0	979.5	2151.3
Refine View Cave	22.0	27.0	127.8	284.0
A Little Too Late Cave	15.9	67.0	340.4	763.8
Manchineel Cave	5.7	35.0	73.4	133.0
Dead Cow Cave	5.7	115.0	230.2	408.8

Certain caves are psudokarst features formed by differential surface erosion (Type 3 caves). These caves are not found at lower elevations due to not having enough time to form, and they are not found at higher elevations because spalling of overlying portions of cliff (Fig. 15B).

CONCLUSIONS

The remnant caves within the Seroe Domi Formation on Curaçao suggest that multiple cave forming processes are represented. By using the methods employed by previous studies and field observations, cave identification and classification is possible. Most of the caves likely represent remnant phreatic caves, probably of flank margin origin, that have almost completely been removed by erosion. The presence of dissolution features, morphologies, and presence of speleothems suggests these caves have a phreatic origin that later experienced vadose conditions. A number of strata-bound erosional features with a dip uniform to the surrounding slope were documented. These caves were determined to not have a dissolutional origin. These caves likely represent preferential surficial erosion of a mechanically weak stratum bound by mechanically resistant strata. Other pseudokarst features such as sea caves and fracture caves were identified within the Seroe Domi Formation on Curaçao. Successful interpretation of karst cave development requires that they be differentiated from other pseudokarst cave types.

Petrographic analyses indicate that cave wall thin sections had higher porosities than cave ceiling, cave floor, and outcrop thin sections. The cave wall samples from surficial erosional caves were the lowest porosity values suggesting that cave wall porosity may be able to differentiate cave types. Therefore, phreatic dissolution appears to be laterally concentrated (consistent with the lens margin dissolution model), producing higher cave wall porosity values while surficial erosion yields lower cave wall porosity, possibly due to increased cementation. Stable isotope analysis suggests that most of the dolomite formed in marine to mixing zone environments. One group of samples from caves at the basalt-carbonate contact suggests fluid migration from the underlying basalts.

Due to the amount of overprinting and erosion that has occurred, it is nearly impossible to determine the relative timing of dolomitization and karst development within the Seroe Domi Formation. In addition to documenting flank margin cave development within dolomite, these remnant caves are useful in estimating post-speleogenetic events, even when more than 50 % of the cave has been destroyed. These remnant caves, many of which were previously overlooked, have been used as indicators of diagenetic events within the Seroe Domi Formation and contain significant information when placed in the proper geologic framework.

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