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Back Cover: Dr. H. Leonard Vacher, University of South Florida, Keynote Speaker for the 12th Symposium and author of "Keynote Address – Plato, Archimedes, Ghyben Herzberg, and Mylroie", this volume , p. ix. Photograph by Don Seale.

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NOTCHES IN CARBONATE CLIFFS AND HILLSLOPES: ORIGIN AND IMPLICATIONS

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ABSTRACT

This study reports the examination of the "notch" and related similar-shaped landform features with respect to potential genetic mechanisms on carbonate islands. For analysis, notches were grouped into three categories of hypothesized genetic mechanism: bioerosion, flank margin cave, and indeterminate. Morphologic characteristics of the three notch types were measured on San Salvador, Bahamas and Isla de Mona, Puerto Rico and qualitative observations were made from Guam, Marianas. Data analysis indicates that measured dimensions of all sampled notches are not significantly different; hence no conclusive link can be made between morphology and hypothesized genetic mechanism based upon cross-section observations. In addition, observations indicate that the presence of calcite precipitates such as stalactites and stalagmites, once thought to be indicators of cave genesis, cannot be used solely to determine notch origin.

Despite the negative results of the study, four conclusions can be drawn from observations and analysis. 1) Notches are produced as an interface feature by lateral corrosion/lateral erosion that occurs at a local base level. The net effect of these processes is that notches possess similar small-scale morphology regardless of physical location, hypothesized genetic mechanism, or lithology. 2) The genetic mechanism for notches can not be determined by measuring cross-sectional morphology alone. Rather, the lateral elevation variation of notch segments within a fixed elevation range of a few meters appears to be more important in terms of identifying a mechanism of notch genesis. 3) Notches formed by breaching of flank margin caves display great variability in elevation position within a fixed range, which implies a similar variability in groundwater lens discharge and geochemistry. 4) It may be possible to more accurately estimate denudation/hill slope retreat rates if the genetic mechanism of the notch can be determined to be flank margin cave development.

Overall, the notch morphology data provide an important insight to paleohydrologic and paleoclimatic information. Notches on carbonate islands represent sea level controlled base-level positions, regardless of genetic history. This has important implications for paleohydrologic conditions. If speleothem-rich, variable elevation notches are indeed breached flank margin caves, they represent areas of enhanced dissolution in the bedrock. This provides important insight into understanding the properties of the complex karst aquifers on carbonate islands and coasts.

INTRODUCTION

"C" shaped erosional features in a slope or cliff exist in a number of disparate locations and environments throughout the world. The two

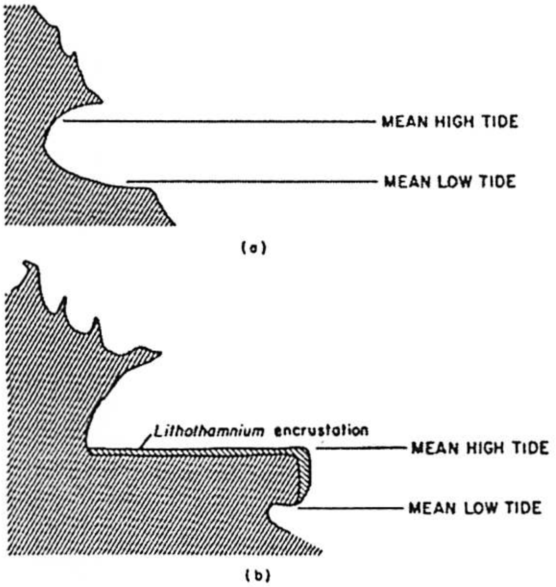

Figure 1: Typical notch profiles as seen on the north coast of Puerto Rico (from Kaye, 1959)

used to describe site specific phenomena. In order to avoid confusion, this study will use the term notch to represent any horizontal "notch-shaped" feature, regardless of location or process, as nips and notches may perhaps be end-members in a gradational system (Higgins, 1980).

The existing literature on notches focuses almost exclusively on notches produced by bioerosion on tropical carbonate coasts, and provides multiple potential mechanisms of formation (bioerosion, wave cutting, dissolution, and remnant cave). This study is an attempt to provide an understanding of the mulitple processes involved in notch formation in carbonate rocks through a comparison of notch morphology for three categories of hypothesized notch formation. Correct interpretation of the origin of island notches will help in characterizing the nature of groundwater flow and discharge, and the development of island karst aquifer properties. If the notches observed are of a subsurface dissolutional origin, they will assist in the understanding of the concentration of groundwater flow in the karst aquifers present on these islands. As human population and activity increase on these carbonate islands, the demand on the water resources of the islands also terms commonly used in the literature to describe these erosional features are "nip" and "notch" (Higgins, 1980) while other less common terms, such as "corrosion bevel" (Graf, 1999), have been increases, underscoring the importance and need for a better understanding of notch formation.

In order to properly understand the information that notches give, we must first be able to properly interpret the process by which the notch was formed. In some instances, the process is relatively straightforward and well understood: coastal bioerosion notches in the current intertidal zone and inland notches formed by lateral corrosion (i.e.: inselbergs, bornharts). Fossil, or uplifted inland or coastal notches on carbonate islands however, can be quite problematic. It is understood that these notches can be, and most likely are polygenetic, and fit in a continuum of morphologies with two distinctive end members. Linear notches with nearly horizontal roofs have been observed in all of the modern intertidal settings and some inland settings. Notches that have undulating floors and ceilings have been commonly observed outside of the intertidal and at rare locations within the modern intertidal setting. This latter morphology has been termed "beads-on-a-string" (Vogel et al., 1990), and is believed to be indicative of flank margin caves exposed by cliff retreat (Mylroie and Carew, 1991). An example of a polygenetic notch that might fit in the middle of this continuum is a flank margin cave, exposed at modern sea level due to cliff retreat, and then overprinted by modern bioerosion.

Literature Review

Notching on rocky coastlines is just one aspect of carbonate coastal geomorphology, coexisting with a number of other features such as sea stacks, arches, and sea caves. Notching on rocky, cliffed coastlines is an important factor in cliff retreat and wave-cut platform genesis. On rocky carbonate coasts, notches are typically the undercut portion of a cliff between mean low tide and mean high tide. However, coastal notches exist both above and below the tidal range

(Neumann, 1966). These notches have generally been interpreted as "bioerosion" or "wave-cut" notches, implying that they are features of a coastal origin, resulting from a number of overprinted processes concentrated in the intertidal zone. On carbonate islands, the true bioerosion notches are a part of the coastal karst suite, e. g. Folk (1973) and Viles (1984). However, notches on the coastal cliffs of Guam and Isla de Mona contain significant speleothems, which may suggest a different origin (Figure 2).

The specific mechanisms commonly associated with notch formation is bioerosion. A large body of work has been completed on bioerosion with the majority of this work focusing on the bioerosion of coral reefs. The term bioerosion was proposed by Neumann as "the destruction and removal of consolidated mineral or lithic substrate by the direct action of organisms" (1966, p. 92). The definition of bioerosion, represents an overprinting of biological, mechanical, and chemical erosive processes intitiated by organisms. However many early studies discounted the importance of the chemical and physical processes in the overall effectiveness of bioerosion (Neumann, 1966; Focke, 1978).

The biological processes involved in bioerosion include biological abrasion of the limestone surface, as well as biogeochemical corrosion. Abrasion by invertebrates is typically broken into two distinct groups, boring and grazing (Spencer, 1988). Biogeochemical corrosion is carried out by a number of microorganisms. Microbial corrosion is typically zonated, and has been correlated with the distribution of the invertebrates that graze upon them (Radtke et al., 1996).

The physical or mechanical mechanisms associated with notch formation are driven by wave action in the intertidal zone. Wave action, which is heightened in sediment-laden conditions, provides hydraulic pressure against the cliff face to break down rock. Incoming wave action also forces air into cracks present in the cliff, acting similar to a pneumatic hammer. As the wave retreats, there is an instantaneous pressure release, which can serve to further accelerate the erosive process. It should be noted that these physical processes work in conjunction with biological processes in that some of the rock removed by the wave action that which has been loosened or partially eroded by biological abrasion or corrosion furthers overall erosion of a rock face.

Figure 2: Photograph of the cliffs at Amantes Point, Guam showing notches with significant speleothem development, suggesting the notches are of a subsurface dissolutional origin.

The chemical meachanisms associated with notch formation involve dissolution of carbonates by seawater or discharging fresh groundwater. Revelle and Emery (1957) show how seawater, which is normally saturated with respect to calcite, will dissolve calcite at night due to a drop in temperature and pH, and an increase in CO_2. Higgins (1980) proposed that fresh groundwater discharging from the freshwater lens may 1) dissolve the rock from the inside out; and 2) float atop the seawater and dissolve from the seaward side in.

Beyond coastal notch formation, notches can form in inland settings. Inland notching can be divided into two broad categories: subaerial notches and notches in caves. Most subaerial inland notching in carbonates is believed to be the result of base-level lateral corrosion (Ford and Williams, 1989). This process involves water being trapped against a limestone surface by an insoluble cover of sediment which allows dissolutional removal of bedrock irregularities and a notching of adjacent hillslopes. In areas of tower karst these notches are often called foot caves or cliff-foot caves (Jennings, 1985; Sweeting, 1973; Ford and Williams, 1989). Similar corrosion occurs in other rock types, most notably in the case of bornharts and inselbergs in granites (Ollier, 1960, 1965; Thomas, 1965). In-cave notches are observed in many locations throughout the world. Notable examples have been reported from Malaysia (McDonald and Ley, 1985), and Arizona (Graf, 1999). These notches have also been interpreted as lateral corrosion features (Ford and Williams, 1989; Graf 1999) formed during flood events in a manner similar to the subaerial notches described above.

However, is should be noted that some debate and revision of proposed mechanisms of inland notch formation has occurred. Inland notches in the Bahamas and other carbonate islands were initially interpreted as wave-cut notches (Titus, 1980) and re-interpreted as remnant caves (Mylroie and Carew, 1991). This reinterpretation of inland notches as remnant caves is based upon the theory of flank margin cave development. Mylroie and Carew (1990) proposed the flank margin model of cave development for the distal margin of a discharging freshwater lens. This model was developed for Pleistocene eolian limestones of the Bahamas, and has been extended to the dense crystalline limestones of Isla de Mona, Puerto Rico (Frank, et al., 1998), Guam and Saipan (Mylroie et al., 2001). The flank margin model predicts an overprinting of three dissolutionally aggressive environments: 1) mixing of vadose and phreatic freshwater; 2) mixing of fresh groundwater and seawater; and 3) in addition, each of these mixing environments acts as a density interface that traps organic material. Organic decay creates more CO_2 and hence more dissolution, then if organic loading is significant, anoxic conditions and the production of H_2S can occur, creating even more dissolution.

The overprinting of these environments at the lens margin allows for rapid dissolution of the carbonate bedrock. Flank margin caves thus have a hypogenic origin, having formed as mixing chambers, and without regard to surface topography, and typically display a ramiform or spongework passage distribution (Palmer, 1991). As these caves are mixing chambers, and not conduits, they form without macroscopic connections to the surface; i.e. they initiate as "entranceless" caves.

As the location of the freshwater lens, and hence the location of developing flank margin caves is dependent upon sea level, it can be expected that in carbonate islands (as well as continental coastal carbonates) the fresh water lens has migrated throughout the Quaternary with glacio-eustatic sea level change. This allows for flank margin caves at different elevations. In the case of a tectonically active island (or continental coastline), an additionally complex arrangement of cave development is possible (Mylroie, et al., 2001). Uplift and cliff retreat can expose these entranceless caves, and ultimately reduce the cave to a simple notch, often containing speleothems formed when the cave was whole (Figure 3). Ultimately a cave-initiated notch may be used as an indication of a past sea level, as the conditions under which such a notch forms are tied to sea level. Because these caves form under the flank of the enclosing landmass, in the distal portion of the fresh-water lens, they are predisposed to breaching by relatively little surface denudation.

METHODS

Morphologic characteristics of the three hypothesized notch types (bioerosion, cave remnant, and indeterminant) were measured on San Salvador, Bahamas in the winter of 2000, and Isla de Mona, Puerto Rico during summer 1999, and winter 2000. In addition observations of notches on Guam, Marianas were used for a qualitative comparison during the summer of 1999.

Specifically, three sites on San Salvador were chosen for this study: a modern bioerosion notch, a representative flank margin cave, and a series of indeterminate notches. The Thumb, a micropeninsula on San Salvador's east coast is the location of the modern bioerosion notch. Five notch profiles were measured at The Thumb. The representative flank margin cave used for this study was Garden Cave. Fourteen cave passage cross sections were measured in Garden Cave. A detailed survey and twelve cross sections of the notches along the Grotto Beach Ridge between Dripping Rock Cave and Altar Cave were the data source for the indeterminate notches used for the study.

Two sites on Isla de Mona were chosen. Twenty seven notch profiles were measured from the modern bioerosion notches at Punta Los Ingleses on the southeastern tip of the island. Eleven notch profiles were measured from the modern and fossil notches at the south end of Playa Pajaros, below Cueva Sopressa.

Qualitative comparisons of modern and fossil notches, as well as flank margin caves were made on Guam. Specific site localities on Guam include the modern and fossil notches at Tarague Beach on the northwest coast and Puntan Dos Amantes on the west coast. Coconut Crab Cave and other unnamed caves along the west coast were also used for comparisons.

In order to determine genetic history, a detailed morphological analysis has been completed. This analysis involved a detailed survey of modern bioerosion notches and known flank margin caves using a handheld compass, clinometer, and fiberglass tape. The techniques are standard cave survey techniques, where distance, azimuth, inclination, and a detailed sketch are recorded. For a detailed description of these techniques, see Dasher (1994). These surveys involved a baseline to demonstrate spatial arrangement of the notch or cave where possible, including minor changes in elevation and floor/ceiling undulations.

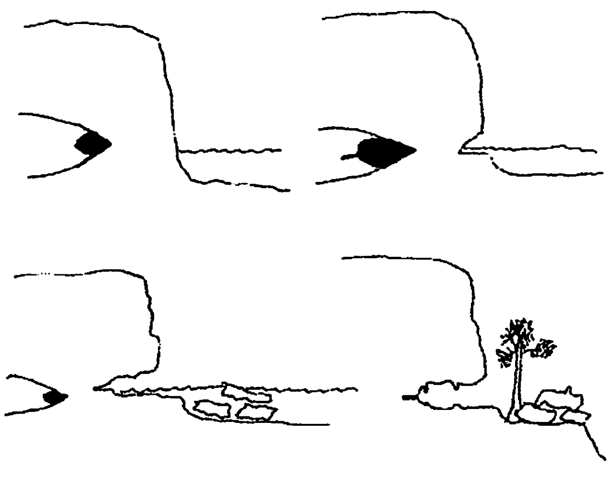

Figure 3: Model showing the evolution of a flank margin cave that receives a bioerosion overprint. a) flank margin cave forming in the freshwater lens b) flank margin cave and bioerosion notch forming simultaneously c) breaching of flank margin cave by cliff retreat, bioerosion overprint occurs, new flank margin cave begins forming as lens retreats further inland d) flank margin cave after uplift and cliff retreat.

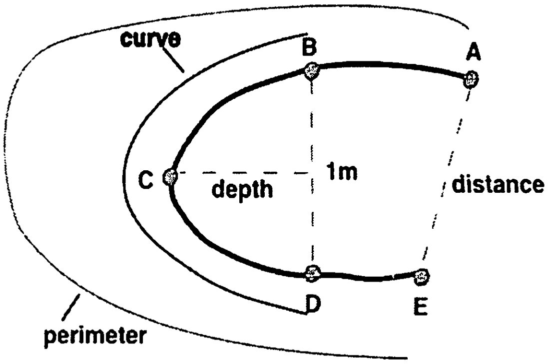

Figure 4: Schematic diagram of notch measurements used in this study. Point A is the top edge of the notch "visor", Point E is located at the sharp drop at notch floor, Point C is the maximum horizontal penetration of the notch. Perimeter is the measured segment A-B-C-D-E; Depth is the measured segment from the line B-D, to point C; curve is the measured segment B-C-D, and distance is the measured line from A-E. The distance from B-D is standardized at 1 meter for all data points.

Cross-sectional profiles are included at select locations to further illustrate notch or cave morphology. Data from these surveys was reduced using Compass, a popular, shareware Windows-based cave survey data-management software package.

Along each notch, several profiles were measured. At each profile, four distinct dimensions were measured (Figure 4): notch perimeter, notch height, a standardized depth from where ceiling-to-floor distance was 1 meter, and the notch perimeter relative to this depth, labeled the notch "curve". These data, as well as their ratios (perimeter:height, perimeter:depth, height:depth, and perimeter:curve) were entered into a spreadsheet data base. This expanded data set was then analyzed for statistical relationships with Microsoft Excel using both parametric statistical, as well as bivariate correlation analysis (Pearson's product-moment correlation coefficient). For the statistical tests, the null hypothesis stated that the measured notch dimensions were not significantly different by location or hypothesized genetic mechanism. With the bioerosion notches, analysis of variance (ANOVA) and the Fisher's LSD was used to test the difference in variance between the sample localities, while comparisons of the other hypothesized genetic types was tested with a Student t-test. All tests were completed at the 95% confidence level.

RESULTS

Statistical analysis indicates that based upon variance the two Isla de Mona sites are more similar to each other than the San Salvador sites. However, the results of the ANOVA and Student's t-tests indicate no statistically significant difference between measured notch characteristics of the bioerosion and cave remnant categories (Table 1).

The survey data of the indeterminate notches show a great elevational variability over distance, in direct contrast to the modern bioerosion notches found along current coastlines. Notch floors along the cliffline between Dripping Rock and Altar Caves (Figure 5) have a 5.4 m elevational range (approximately 0.46 m to +6.06 m above sea level) (Figure 6). A detailed discussion of the data and the statistics used can be found in Reece (2004).

SUMMARY & CONCLUSIONS

This study represents the first attempt to examine the phenomenon of the "notch" and relate notch characteristics to different genetic mechanism on carbonate islands. Morphologic characteristics of notches were measured on two islands, and qualitative observations were made from a third. The notches used in this study were grouped into three categories of hypothesized genetic mechanism: bioerosion, flank margin cave, and indeterminate. Statistical analysis of collected data determined that measured dimensions of all sampled notches were not statistically different, hence no conclusive link can be made between notch morphology and hypothesized genetic mechanism based on cross-section measurements. It is the variability of the notch over distance that seems to be the factor with greatest potential in determining notch genesis.

Further, four conclusions can be drawn from the research presented. 1) Notches are produced by lateral corrosion/lateral erosion with the net effect of this processes is that notches exhibit a similar small-scale morphology regardless of physical location, hypothesized genetic mechanism, or lithology. All of the hypothesized notch types are related to some local base level, and are produced as an interface feature. 2) The lateral elevation variation of notch segments within a fixed elevation range of a few meters may be the most important factor in linking notch morphology to notch genesis. 3) Notches formed by breaching of flank margin caves display great variability in elevation position within a fixed range, which implies a similar variability in lens discharge and geochemistry. 4) It may be possible to more accurately estimate denudation/hill slope retreat

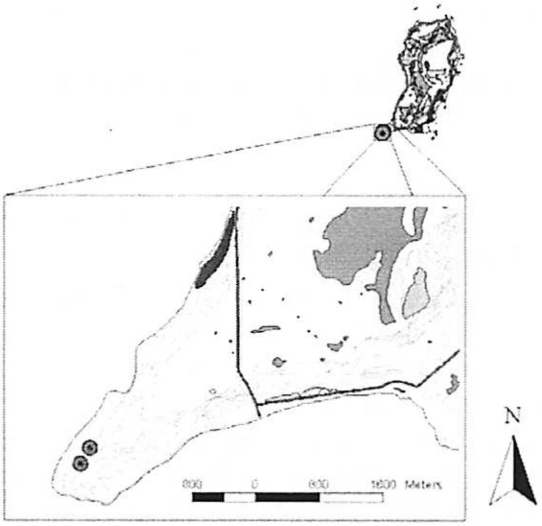

Figure 5: Map of San Salvador Island, showing location of indeterminate notches along the Grotto Beach Ridge considered in this study. Southern marker is Dripping Rock Cave, northern marker is Altar Cave. GIS data derived from The San Salvador Island GIS database- compiled by Matthew C. Robinson and R. Laurence Davis - the University of New Haven and Bahamian Field Station, 1999.

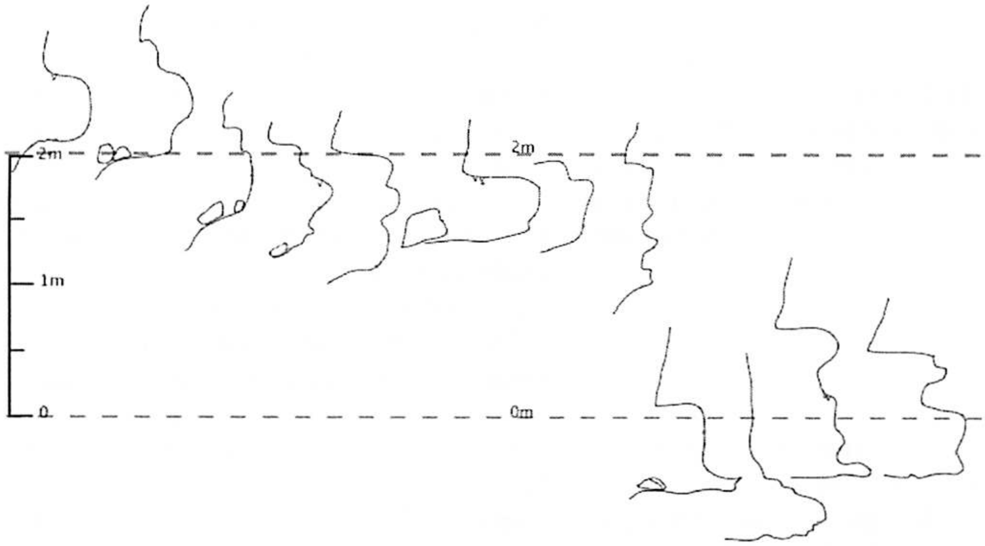

Figure 6: Cross section correlation for Grotto Beach Ridge. Black lines represent notch cross section profiles. Blue dashed lines represent zero meter datum (floor of Dripping Rock Cave, approximately 2.26m asl) and plus two meters.

1a) Garden Cave, The Thumb d.f.=4, t value =2.776								
Dimension	Perimeter	Depth	Distance	Curve	P/De	P/Di	Di/De	P/C
t score	0.966	0.002	0.009	0.060	0.003	0.0001	0.009	0.022
Result	*	*	*	*	*	*	*	*

1b) Garden Cave, Sopressa d.f.=10, t value =2.228								
Dimension	Perimeter	Depth	Distance	Curve	P/De	P/Di	Di/De	P/C
t score	0.020	0.044	6.32 e-7	0.102	0.004	0.0007	0.056	0.257
Result	*	*	*	*	*	*	*	*

1c) Garden Cave, P. Los Ingleses d.f.=13, t value =2.160								
Dimension	Perimeter	Depth	Distance	Curve	P/De	P/Di	Di/De	P/C
t score	0.039	0.011	1.34 e-13	0.033	0.0002	0.0005	8.76 e-7	0.180
Result	*	*	*	*	*	*	*	*

1d) Garden Cave, All Bioerosion Notches d.f.=13, t value =2.160								
Dimension	Perimeter	Depth	Distance	Curve	P/De	P/Di	Di/De	P/C
t score	0.059	0.012	1.76 e-11	0.039	0.0001	0.0005	3.27 e-7	0.150
Result	*	*	*	*	*	*	*	*

* = A statistical test indicates no significant difference

Table 1: Statistical comparison of Garden Cave cross sections and Bioerosion Notches

rates if the genetic mechanism of the notch can be determined to be flank margin cave development, in that the degree of cave segmentation is a measure of how much the hill slope has retreated. If the cave is tied to a known sea level position, the time of cave development is also known and hence the denduation rate can be determined.

Beyond analysis of notch morphology and notch genesis, the data in this study provide an important insight to paleohydrologic and paleoclimatic information for a given location. Notches on carbonate islands represent sea level controlled base-level positions, regardless of genetic history. This has important implications for paleohydrologic conditions. If speleothem-rich, variable elevation notches are indeed breached flank margin caves, they represent areas of enhanced dissolution in the bedrock. Previous studies have hypothesized that notches which contain significant speleothems are likely of a speleogenetic origin (Mylroie and Carew, 1991). Recent work suggests that spelothems must be analyzed to determine if they are truly cave deposits (Taboroši et al., in press) This provides important insight into understanding the properties of the complex karst aquifers on carbonate islands and coasts.

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