PROCEEDINGS
OF THE
FIFTH SYMPOSIUM
ON THE
GEOLOGY OF THE BAHAMAS

Edited by

Roger J. Bain

Production Editor

Donald T. Gerace

Bahamian Field Station
San Salvador, Bahamas
1991

Printed in USA by Don Heuer

ISBN 0-935909-37-0

EROSIONAL NOTCHES IN BAHAMIAN CARBONATES: BIOEROSION OR GROUNDWATER DISSOLUTION?

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ABSTRACT

At elevations from near modern sea level up to +6 m, cliffs and rocky slopes in the Bahama Islands commonly contain notches or horizontal reentrants that have been widely interpreted to represent past coastal features produced during higher stands of sea level in the Late Pleistocene. Examination of similar notches at current sea level has revealed that such notches can be produced by a combination of bioerosion processes and mechanical abrasion in the intertidal zone. Linear notches in carbonate islands may also be produced by dissolutional processes associated with the discharge of freshwater lenses. During high sea level events of the Late Pleistocene the freshwater lenses were elevated within the remaining emergent portions of the Bahama Islands. At the lens margin, discharge of a freshwater lens results in mixing with both underlying marine water and vadose freshwater over a narrow vertical range. As a result of the complex geochemical mixing that occurs near the lens margin, dissolutional voids, or caves, develop within the bedrock a few meters inland of the shoreline. The lens geometry results in the dissolution of low, wide chambers oriented parallel to the coast. When sea level falls the caves are drained. When such caves are exposed by surface erosion processes, their morphology may make them appear similar to bioerosion notches.

The differentiation of subaerial bioerosion notches from dissolutional voids requires close observation of notch morphology and setting. Notches with flat roofs and floors, marine clasts, and borings are most likely bioerosion notches. Notches with undulating floor and ceiling patterns, speleothems, and a lack of marine sediments and borings most likely are breached dissolution pockets and caves. In either case, the notches are a good indication of sea level position at the time of their development.

INTRODUCTION

Geologists have long recognized that coastal notches form at sea level along rocky carbonate shorelines. The origin of these notches has been attributed to mechanical erosion, chemical activity, and bioerosion. The importance of bioerosion in the production of coastal notches has been demonstrated from localities around the world. The mechanics, morphology, and ecology of bioerosion notches has been investigated by a variety of workers, and the literature is voluminous. Excellent reviews of the current state of knowledge about bioerosion notches can be found in Trudgill (1985) and Spencer (1988). The typical morphology of a modern bioerosion notch can vary from a slight nick to a major recess. The shape of the bioerosion notch is controlled by tidal range, organic activity, and degree of exposure to wave energy (Trudgill, 1985). Figures 1 and 2 show

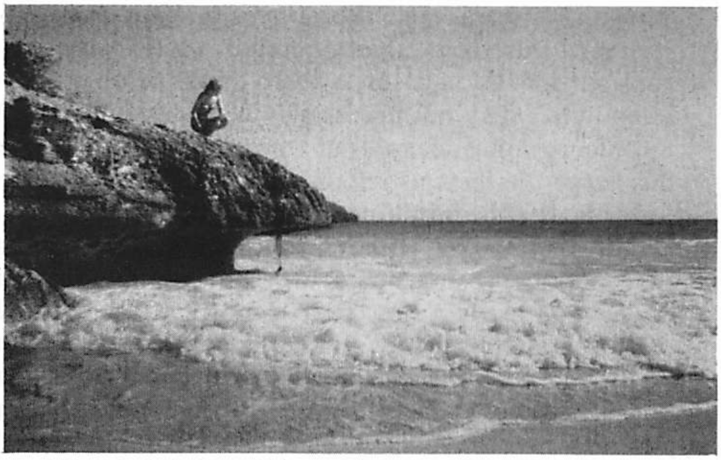

Fig. 1. Modern bioerosion notch, west coast of San Salvador Island, Bahamas.

Fig. 2. Modern bioerosion notch, southwest coast of New Providence Island, Bahamas.

representative examples of a bioerosion notch, but one should be aware that departures from this generalized form are not uncommon.

Bioerosion notches are inherently tied to sea level, as their preferred site of formation is in the lower intertidal (Spencer, 1988). Fossil bioerosion notches found above present sea level must therefore provide evidence of a past sea level above its modern elevation, or tectonic uplift of the coast. In the Bahama Islands, which are considered to be tectonically stable and slowly isostatically subsiding (Mullins and Lynts, 1977), fossil bioerosion notches most likely record the last interglacial high sea level associated with Oxygen Isotope Stage 5 (Shackleton and Opdyke, 1973). In the Bahamas, features that have been interpreted as bioerosion notches are found along the coast and along interior hill slopes and scarps at elevations of up to six meters above current sea level. Such elevations are consistent with sea level positions during Oxygen Isotope Stage 5; however, a long notch or series of adjacent short notches found at a constant elevation along a rocky coast or on an inland cliff may not necessarily have developed by bioerosion. Because of the geometry and discharge characteristics of a fresh or brackish water lens, dissolution near the lens margin may produce a feature with morphology similar to that of a bioerosion notch. The purpose of this paper is to explain how such a morphology can develop from discharge of a freshwater lens, and how such features can be differentiated from ones produced by bioerosion.

PRODUCTION OF DISSOLUTION VOIDS IN CARBONATE ISLANDS

The existence of subaerially exposed land on a carbonate platform generally results in the development of a freshwater lens by input of meteoric water. If the lens is small, or meteoric recharge is limited, the lens may be brackish, but the resulting geochemical conditions are similar to that for a freshwater lens. Lens geometry depends upon the rate of freshwater recharge, size of the aquifer, rock transmissivity, and lateral inhomogeneities in the aquifer. The lens shape rarely has an ideal configuration (Wheatcraft and Buddemeier, 1981; Ayers and Vacher, 1986), but can be modeled by the Ghyben-Herzberg relationship in which the freshwater lens floats on the underlying denser marine water. The freshwater and marine water are separated by a halocline which can vary from a sharp boundary to a diffuse mixing-zone. The difference in geochemistry between the freshwater and the marine water results in mixed water which is undersaturated with respect to $CaCO_3$ (Palmer,and others 1977; Back and others, 1986). In carbonate islands, this renewed dissolutional aggressivity produced by mixing of marine and freshwater is capable of rapid and massive dissolution of limestone (Smart and others, 1988). The initial examinations of this phenomenon were confined to coastal carbonate aquifers of continents (Back and others, 1986; Sanford and Konikow, 1989), or to large islands with thick well-developed freshwater lenses (Smart and others, 1988). Recent work in the Bahamas (Mylroie, 1988; Mylroie and Carew, 1988; Mylroie and Carew, 1990; Vogel and others, 1990) has demonstrated that large dissolutional voids can be produced rapidly in very small islands by this mechanism.

The mechanics of discharge of a freshwater lens results in thinning of the lens along the margin of an island. The thinning of the lens brings two geochemical boundaries into close proximity: the halocline beneath the lens; and the vadose/phreatic contact at the top of the lens. Along both boundaries waters of different geochemical characteristics are mixed. At the lens margin the proximity of the upper and lower water boundaries, coupled with the narrowing of the discharge cross sectional area, results in a concentrated zone of powerful dissolutional potential. This dissolution produces low, wide phreatic chambers with inwardly radiating smaller tubes. These voids have been termed flank margin caves (Mylroie, 1988; Mylroie and Carew, 1990; Vogel and others, 1990). The size and configuration of the caves produced by this mechanism depend on the length of time during which the discharge conditions prevailed, and the degree to which the discharge was focused into a series of concentrated outputs from the lens. Greater time and greater concentration of output produces larger, more widely spaced individual caves at each output site (Fig. 3).

Fig. 3. Interior of Caves Point Cave, New Providence Island, looking north to the entrances.

If the discharge is nearly uniform along the margin of the island, then the dissolutional aggressivity is spread more evenly along the island margin, and a series of smaller and more closely spaced caves develop (Fig. 4).

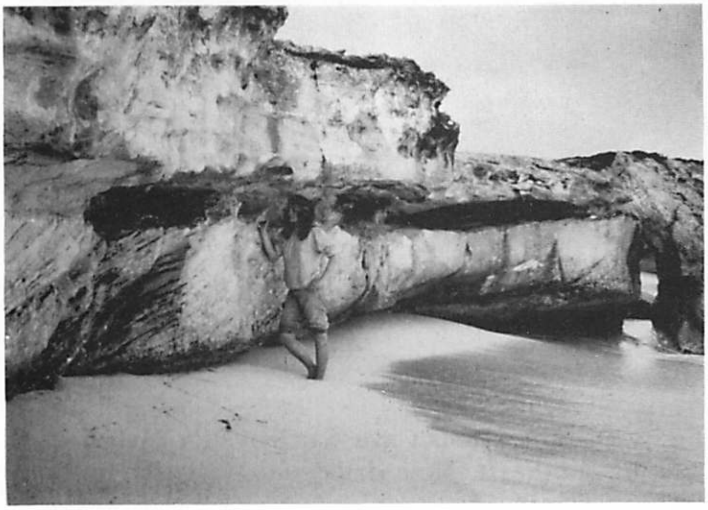

Fig. 4. Small phreatic pockets exposed by coastal erosion, Sandy Point, San Salvador Island.

These caves will be spread out along the strike of the coast, just inland of the actual shoreline.

If sea level falls, the ground-water lens will also drop in elevation. The flank margin caves, whether large or small, will be drained and subaerial processes will begin to dominate cave evolution. Subaerial speleothems, such as stalagmites and stalactites, may form in the closed atmospheric conditions of the caves. Surficial weathering processes acting on rocks of the now-terrestrial former shoreline will result in hill slope and scarp retreat. Vadose karst process may produce vertical shafts that deliver surface water to the ground-water lens lying some distance below the elevation of the abandoned caves. Both vadose shaft development and hill slope and scarp retreat may breach into the abandoned flank margin caves. Continued hill slope or scarp retreat will begin to destroy the cave chambers. The progressive destruction of flank margin caves can be seen in Figures 3, 5 and 6.

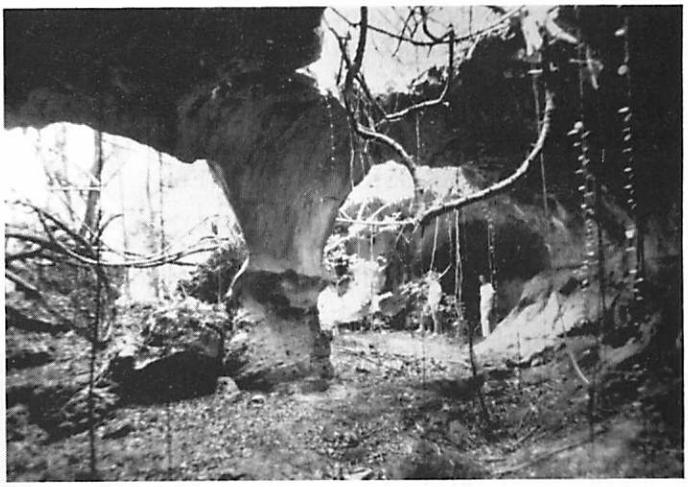

Fig. 5. Harry Oakes Cave, New Providence Island, looking west.

Fig. 6. Breached flank margin cave near Altar Cave, San Salvador Island, looking north.

Figure 3 illustrates a large phreatic chamber that has been barely intersected by slope retreat; Figure 5 illustrates a cave in which slope retreat has left only remnants of the enclosing flank margin of the dune; Figure 6 illustrates the reentrant left after almost complete destruction of a flank margin cave.

Once the chambers are open enough to allow normal terrestrial atmospheric circulation, any actively growing speleothems will switch from a CO_2-diffusion precipitative geochemistry to a H_2O-evaporation precipitative geochemistry, and speleothem deposition will effectively cease. Evaporative crusts may form on the cave walls (Vogel and others, 1990). If hill slope and scarp retreat continue, the cave may be almost entirely destroyed. If the caves comprise a series of small phreatic chambers spaced along the strike of the former coast, uniform hill slope retreat will intersect them all at approximately the same time. This series of low, wide reentrants found at a uniform elevation and extending laterally for a considerable distance has a morphology that is very similar to that of a bioerosion notch (compare Figures 1 and 2 with Figures 4 and 6).

DIFFERENTIATING BREACHED FLANK MARGIN CAVES FROM BIOEROSION NOTCHES

Features Indicative of a Bioerosion Origin

The presence in a reentrant of molluscan grazing marks and attachment scars, and sponge and other borings, could indicate a bioerosion origin for the notch. Because of the potential for rapid erosion of carbonates (White, 1988), such marks would be likely to disappear rapidly. Further, it should be pointed out that the presence of such features in a reentrant is not necessarily conclusive evidence as to origin, as it is possible that the reentrant was a breached flank margin cave that was modified by bioerosion during a subsequent high stand of sea level. Such a scenario is possible, but highly contrived. Other indicators of a bioerosion origin for notches are the presence of a flat roof, a consistent vertical profile, and a very uniform morphology over a long lateral distance (see Figures 1 and 2).

Features Indicative of a Flank Margin Dissolution Origin

The origin of a reentrant as a flank margin cave may be indicated by the presence of fossil speleothems in the back of the reentrant (see Figures 7 and 8).

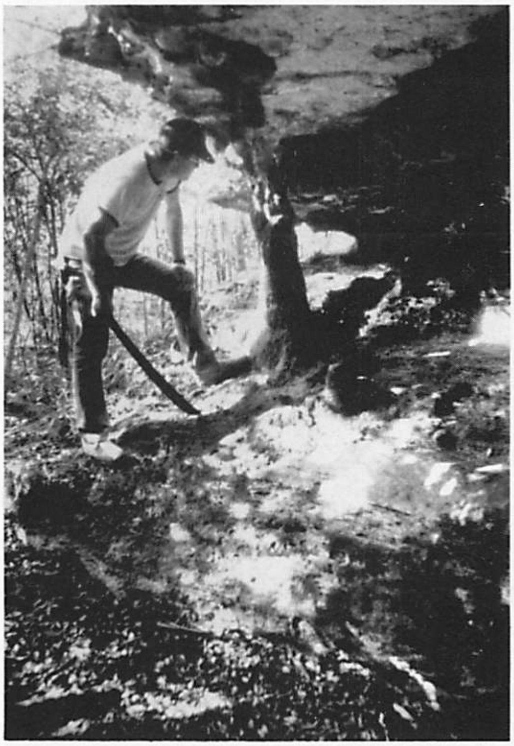

Fig. 7. Breached flank margin cave near Altar Cave, San Salvador Island, looking north. Note stalactic column in front of figure.

Fig. 8. Dripping Rock Cave, San Salvador Island, looking southeast. Note dried-out stalactites in front of figure.

The development of dense layered calcite speleothems such as stalactites and stalagmites requires a subaerial enclosed humid atmosphere. Under those conditions vadose drip water that enters the cave loses CO_2 by diffusion to the humid cave atmosphere. The loss of the CO_2 results in an elevated pH that forces the $CaCO_3$ out of solution, with the resultant precipitation of speleothems. Under normal surface atmospheric conditions, as would be found on limestone cliffs or extensively breached cave chambers, evaporation effects dominate the geochemistry of dripping vadose water, and $CaCO_3$ and other dissolved species are precipitated as crumbly crusts. Occasionally, lumpy porous stalactitic features can develop, but their exterior and interior morphology is readily separable from that of true cave stalactites. The evaporative process limits speleothem development, which is why speleothems are rarely found developing on natural surface exposures. Therefore, the presence of well-developed, but dried-out speleothems in a reentrant indicates that the reentrant was once sealed from direct communication with the atmosphere (Figures 7 and 8). The most likely scenario to explain the presence of a speleothem in such a reentrant is one in which the reentrant is the remaining part of a signifcantly eroded flank margin cave. It is possible to construct an elaborate scenario in which a bioerosion notch was sealed by sediments to produce a closed atmosphere in which speleothems could form by CO_2 diffusion, followed by erosion to expose the bioerosion notch as a reentrant containing a speleothem. The reentrant might then be incorrectly identified as a breached flank margin cave; however, such a sequence of events seems highly fortuitous. Although Carew and Mylroie (1985, p. 38-40) have described a similar history for one site on San Salvador Island, widespread application of such a complex sequence of events to explain all reentrants containing speleothems would be unreasonable and violate Occam's Razor.

An additional indicator of flank margin origin of notches results from the fact that flank margin caves form without the mechanical and biological activity that tends to produce the uniform cross section and significant lateral extent of most bioerosion notches. The caves can be laterally extensive and vertically restricted, as are bioerosion notches, but within those limits the flank margin caves may occupy a variety of positions. Flank margin caves tend to have undulating bedrock floors and ceilings, and chambers that connect laterally by small holes between thin walls. This morphology has been described as "beads on a string" by Vogel and others (1990, p. 23). Figure 9 illustrates the connection of phreatic flank margin chambers by a small window, seen in section after breaching on a modern coastline. Figure 10 illustrates the undulating floor of a breached flank margin cave in the interior of an island.

Fig. 9. Breached flank margin cave, Sandy Point, San Salvador. Note how passage constricts in front of figure.

Fig. 10. Breached flank margin cave near Alter Cave, San Salvador Island, looking south. Floor rises towards figure, then drops away behind the figure.

Summary of Reentrant Development

If a reentrant has an undulating floor and/or ceiling, rounds off laterally, or necks down and then re-opens into an adjacent reentrant, contains true speleothems, and lacks evidence of marine encrustation, boring, or mechanical wave action, then the reentrant is most likely a breached flank margin cave. Conversely, if a reentrant has a flat floor and ceiling, is of uniform morphology and is laterally extensive, lacks speleothems, contains rounded boulders and pebbles, and if there is evidence of grazing and boring in the rock, then the reentrant is most likely a fossil bioerosion notch. In cases of severe surface erosion, it may not be possible to differentiate remnant flank margin caves from weathered bioerosion notches.

To the authors' knowledge, no inland (more than 50 m from the current coast) reentrant described in the Bahamas is a fossil bioerosion notch. Based on what we have seen in the field or have read in the literature, they are all interpreted as breached flank margin voids. Such features are found not only in the Bahamas, but are also described from the Netherlands Antilles (Hummelinck, 1979, p. 134). The authors agree that fossil bioerosion notches may exist in island interiors, but generally the three or four meters of scarp retreat that has occurred to breach flank margin caves is enough to have totally removed fossil bioerosion notches. Reentrants found nearer to modern coastlines are more equivocal, and many appear to be fossil bioerosion notches. Why inland scarp retreat should be more significant than coastal scarp retreat, and therefore cause the preferential removal of fossil bioerosion notches there, is a problem that remains unresolved to the authors' satisfaction. The increased soil CO_2 from vegetation and associated biological activities in island interiors may accelerate karst denudation there relative to unvegetated rocky coastlines, and thus lead to the removal of fossil bioerosion notches and the breaching of flank margin caves.

CONCLUSIONS

Reentrants found on interior hill slopes and scarps of Bahamian islands are probably polygenetic. Some may have been produced by bioerosion, and some by dissolution under the margin of the island in the groundwater lens. Criteria exist by which the two morphologies may be distinguished. For fossil bioerosion notches these criteria are: the presence of a uniform flat-roofed and floored morphology over a significant lateral distance, evidence of bioerosion, presence of a marine pebble lag, and lack of true speleothems. On the other hand, undulating floor, wall, and ceiling morphology, the absence of evidence for marine erosion, and the presence of true speleothems are the criteria for identifying a reentrant as a breached flank margin cave.

Fossil bioerosion notches are indicators of past high sea level position in the Bahamas, and breached flank margin caves provide almost exactly the same information, as they too are precisely controlled in elevation by sea level position. Therefore, while this paper discusses an alternative origin for many of the elevated notches seen in the Bahamas, the use of scarp reentrants as indicators of past sea level positions is unaffected.

ACKNOWLEDGMENTS

The authors thank Dr. Donald T. Gerace, Executive Director of the Bahamian Field Station, for support in the conduct of this research. Conrad Neumann, Peter Smart, Fiona Whitaker and Peter Vogel provided insight and discussion that helped formulate these ideas.

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