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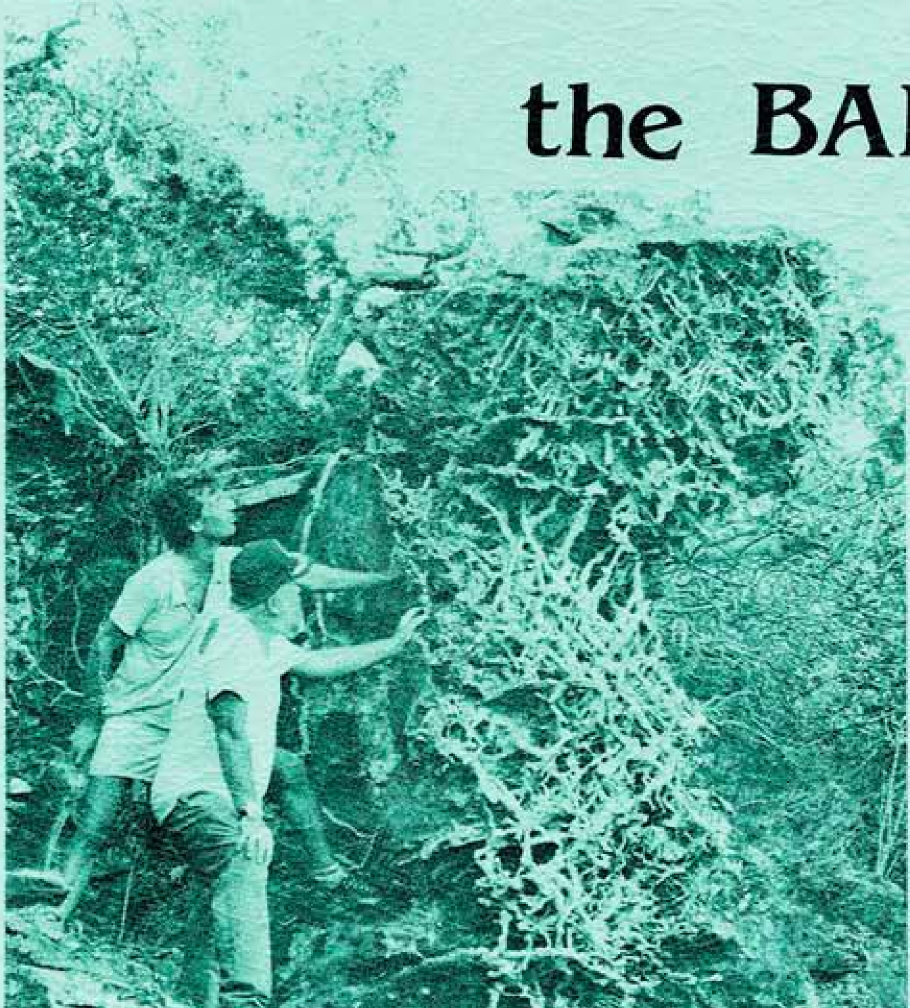

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SPELEOGENETIC CONTRAST BETWEEN THE BERMUDA AND BAHAMA ISLANDS

John E. Mylroie
Department of Geosciences
Murray State University
Murray, KY 42071

Abstract

The Bermuda and Bahama Islands have a superficially similar geology consisting of interfingering marine and eolian limestones, which has been weathered into a classic karst landscape. Aif-filled solution conduits and caves are abundant in both island groups, but differ markedly in their present configuration. Bermudian caves are large chambers or series of chambers formed almost entirely by collapse processes. Solutional surfaces are rare and the caves are floored entirely by collapse material extending to sea level. Bahamian caves are solution conduits of a tubular nature with bedrock floors and well developed solutional surfaces.

The differences in cave development are due to the presence in the Bermuda Islands of volcanic material immediately beneath a thin limestone cover. During Pleistocene low sea level stands, the limestone/basalt contact, which has considerable relief, acted to channel subsurface flow into a few major pathways, producing extremely large conduits. During and after formation, these conduits, because of their large size, underwent progradational collapse to the surface, forming typical Bermudian caves. During past high sea level stands, the limited catchment area of the exposed island produced minor small solution tubes.

In the Bahamas, the limestone is of a relative uniform lithology for many kilmeters of depth. Regardless of Pleistocene sea levels, the production of conduits is not influenced by subsurface topography or lithology, but by competition for available surface freshwater recharge. The conduits produced, while of appreciable size, are smaller and more stable than in Bermuda, and collapse features similar to those in Bermuda are rare. More surface area of the Bahama Islands was exposed during past high sea level stands resulting in large meteoric catchments, and major dry fossil systems can be entered today. Solution conduits formed at low sea level stands in both island systems are currently flooded, but can be observed with appropriate technology.

Introduction

The Bermuda Islands, located 1300 km due east of the Carolinas, and the Bahama Islands, extending southeast for 1000 km from the Florida Straits, have a superficially similar geology. Both island groups are made up of a variety of

Pleistocene and Holocene carbonate rocks of marine and terrestrial origin. These rocks interfinger in a complex manner that reflects the sea level and climatic variations of the Pleistocene. The major difference in these two tectonically stable platforms is in the thickness of the carbonate rocks. In the Bahamas, the carbonates extend at least several kilometers downward, resting on pervasively intruded crustal fragments (Mullins and Lynts, 1977), while in Bermuda, the carbonates are a thin veneer a few hundred meters thick or less, overlying the basalt of the original volcanic cone (Mylroie, 1978). Detailed discussions of Bermuda stratigraphy and geology can be found in Land, et al (1967) and Harmon, et al (1983), and Bahamian stratigraphy and geology is discussed in Garrett and Gould (1984) and Carew and Mylroie (this volume). In both island groups, the bulk of the land surface is made up of eolian calcarenites, which interfinger with marine limestones below elevations of +6 m.

The porous limestone surface of the island groups has made karst processes the dominant agent in landform production. Closed depressions, sinkholes and caves are abundant, and surface streams non-existent. The freshwater lens is minimal in Bermuda, and in the Bahamas ranges from very large, as on Andros Island, to isolated patches on San Salvador Island.

One of the major geomorphic differences of the island groups is in the nature of their cave formation. The presently air-filled caves of Bermuda are distinctly different from their Bahamian counterparts, and reflect the impact of Pleistocene sea level changes on the major geologic difference between the island groups.

Caves of Bermuda

The caves of Bermuda have been known and studied for a fairly long time, including early works by Swinnerton (1929) and Bretz (1960) and continuing to later studies by Palmer, et al (1977). The significance of the caves is in their morphology. With few exceptions the enterable caves consist of collapse dolines or fissures leading into a chamber or series of chambers formed by collapse of rock into an underlying void, which often leads downward to sea level and below. The bedrock ceiling and walls exhibit fracture faces, and rarely show solutional forms (speleogens). The size and continuity of a given cave is dependent on the amount of collapse that has occurred, the degree to which the collapse has left a stable overhung ceiling, and the ability of the underlying void to accept the collapsed material. Figure 1 shows the plan and profile of two adjacent, typical Bermuda caves. Major secondary modification of the chambers occurs due to speleothem deposition and piping of surface residual soil into the cave. The water level in the caves fluctuates with the tides, and piles of collapse material are known to continue at least 30 m below water level (Harmon, et al, 1983). At locations where these caves intersect open bays and lagoons, tidal bores can be observed flowing into (high tide) and out of (low tide) the island. The tidal bores, combined with the tidal fluctuatons of the water found in the caves, suggests a great deal of interconnection between the caves below sea level.

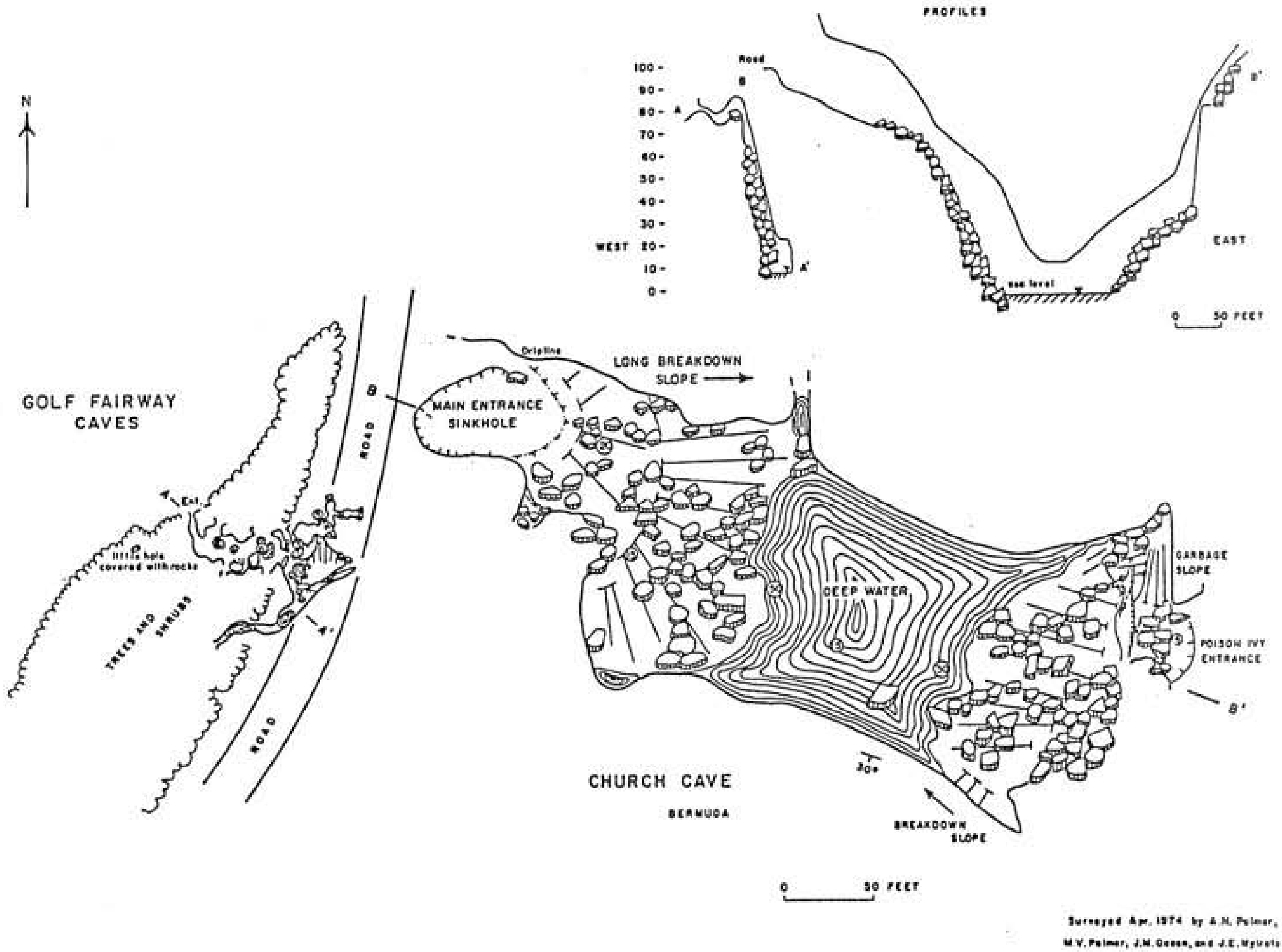

Figure 1: Plan and profile of two typical Bermuda caves. Both caves are enterable portions of collapse piles extending beneath an overhanging ledge down to sea level. In the case of Church Cave, two adjacent collapses have united to produce a large lake chamber. No bedrock floor or solution surface (speleogen) is seen in either cave. Note dimensions are in feet and the plan and profile are not at the same scale.

The abundance of collapse features, coupled with the relative paucity of speleogens, has led most investigators of Bermuda caves to propose the creation of solutional voids at depth, with a subsequent progradational collapse of the ceiling to an elevation above present sea level.

The genesis of the Bermuda caves is strongly interrelated to eustatic sea level changes associated with the Pleistocene glacial episodes. Stalactites can be observed located well below present sea level, indicating deposition during a low sea level stand. Large breakdown blocks, some showing stalactites with two or three different growth orientations, are located below water level. Such features indicate a complex history of solution at depth, collapse, calcite deposition, block rotation, more calcite deposition, ending in submergence by rising sea level. Calcite speleothem samples have been dated from Bermuda caves in excess of 100,000 years old (Harmon, et al, 1983), indicating a significant age to the cave chambers in which the calcite was deposited.

True solution conduits are rare on the islands. Even finding a cave passage with an in-place bedrock floor is difficult, regardless of the lack or abundance of speleogens. Many small solution tubes can be found on the surface, although most are much too small to enter. Some caves, such as Crystal Cave and Leamington Cave, have areas where speleogens can be observed. The best examples of solutional conduits are found in the Government Quarry area. Here low (0.25 - 1 m), wide (1 - 3 m) solution tubes can be found at a single horizontal datum approximately 6 m above present sea level. These tubes cut across existing primary structures in the limestone (foreset beds), and the walls have extensive speleogen development. Immediately below the solution tubes in the quarry is a large collapse cave which extends below sea level, and extends upward to intersect one of the solution tubes. The orientation of the Government Quarry solution tubes at a single horizon suggests control by a widespread feature, such as a freshwater lens supported on an older, but higher sea level. The solution conduits are older than the most recent collapse event in the underlying cave.

Speleogenesis

Mechanisms have been proposed (Palmer, et al., 1977) to explain the solution kinetics of the limestones in Bermuda, taking into account the age of the rock, relative amounts of fresh and salt water present, the various types of $CaCO_3$ involved, and the ion concentrations.

Bretz (1960) has proposed that the Bermuda caves were formed during low sea level stands produced by the Pleistocene glacial episodes. The entire carbonate platform would be exposed during these conditions, and the greater surface area would support a large freshwater lens. Movement of water seaward along the air/lens boundary would establish large solution conduits at a horizon(s) well below present sea level. Progradational collapse, as earlier described, would yield the existing morphology of the caves.

Study of the volcanic/carbonate interface or boundary on Bermuda indicates that it is undulatory and contains significant relief (Stanley and Swift, 1968). There is evidence that shows the contact to be above sea level, though masked by carbonates, at one location (R. Harmon, pers. comm.). In the Government Quarry, marine limestones exposed near sea level in the lower cave contain basalt chips up to 2.5 cm across, indicating a nearby source of basalt at the approximate elevation of the limestone when it was deposited.

The significance of the volcanic/carbonate boundary is that it represents an insoluble and relatively impermeable basement to ground water flow. This may be of little importance at present sea levels, due to a probable small area of exposure of this contact above sea level within the island mass. During past, lower sea levels, the entire carbonate platform would have been well above sea level, and a much larger portion of the volcanic/carbonate boundary also would have been exposed above sea level within the island mass. Downward percolating groundwater would be concentrated by the subsurface watershed of the volcanic/carbonate boundary. Solution conduits would form at and immediately above this contact, following the topography of the contact in the available down-gradient direction to sea level at that time. Very large solution conduits could be expected to form, and collapse debris would be removed and/or consolidated by vadose stream action. Voids would be produced with sufficient volume to accept the collapse that seems to have produced the configurations of the existing caves on the island. This model of cave devlopment for Bermuda is shown in Figure 3a.

Caves of the Bahamas

The unique nature of the Bermuda caves becomes more apparent when compared to the caves of the Bahama Islands. The major differences between the Bahamas and Bermuda are the larger size of many of the Bahama Islands, and the lack of any volcanic/carbonate contact in the vicinity of past or present sea levels. The larger island size attenuates the effect of tidal fluctuation and agitation of the groundwater, allowing a substantial freshwater lens to develop on some Bahamian islands. The top of this lens is slightly above present sea level, and migration of water from the interior of the island to its margins is capable of forming traditional cave conduits at this horizon under conditions envisioned by Bretz (1960) for Bermuda.

Many abandoned solution conduits are exposed today in the Bahamas at elevations approximately 6 m above present sea level, related to an earlier, higher sea level. Examples include Nicholstown Cave (Figure 2) and Morgans Bluff Cave on Andros Island, Hunt's Cave on New Providence Island, and Lighthouse Cave on San Salvador Island. For a description of some of these caves, see Mylroie (1978 and 1983). These caves are classic phreatic tubular conduits that exhibit later vadose incision features. They contain relatively little collapse, with well developed speleogens abundant, including ceiling pockets, spongework, natural bridges and boneyard. Figure 2, showing Nicholstown Cave on Andros Island, is a typical example and

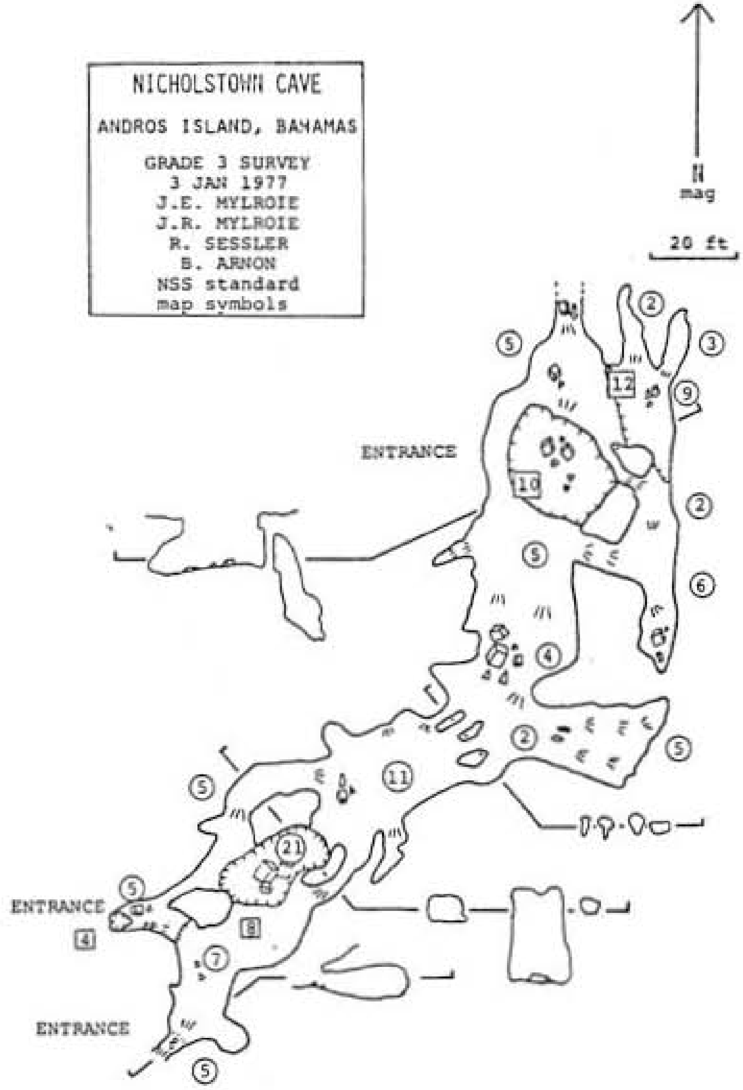

Figure 2: Plan view with cross sections of Nicholstown Cave, Andros Island, Bahamas, a typical subaerial Bahamian cave. The cave is a series of solutionally formed bedrock tubes that migrate in three dimensions. Later vadose incision has produced vertical shafts in the cave floor. The maximum elevation of solutional surfaces is approximately 6 m above sea level. Collapse is minor, although the cave no longer relates to the present surface topography. Note dimensions are in feet.

contrasts sharply with the Bermuda example in Figure 1. Some of these conduits have impressive dimensions, as in Lighthouse Cave, San Salvador, where the main passage is 15 m wide and 5 m high for a 50 m stretch. The cave has only minor collapse, indicating that perhaps even larger conduits are necessary to produce large collapse caves.

Solution conduits have also been located at -105 m depth, and -125 m depth in the Bahamas. The development of solution conduits at preferred horizons in a relatively uniform lithology suggests a freshwater lens controlled by sea level. The significance of a freshwater lens controlled by sea level, as opposed to a non-horizontal lithologic boundary, is that conduit placement and size is controlled by competition for surface recharge. This produces many competing phreatic conduits at shallow depths which may interconnect. Competition for recharge and the lack of vadose flow (no perching lithology present) prevent conduits from developing the massive proportions seen in Bermuda. Large scale collapse caves are therefore rare in the Bahamas. This model of cave development in the Bahamas is presented in Figure 3b.

Discussion

The difference in caves of the two island groups appears to depend on conditions controlling the position, orientation, and relief on the water table during low sea level stands. Data from San Salvador Island, Bahamas (Carew and Mylroie, 1983), shows that the large conduit of Lighthouse Cave must have formed

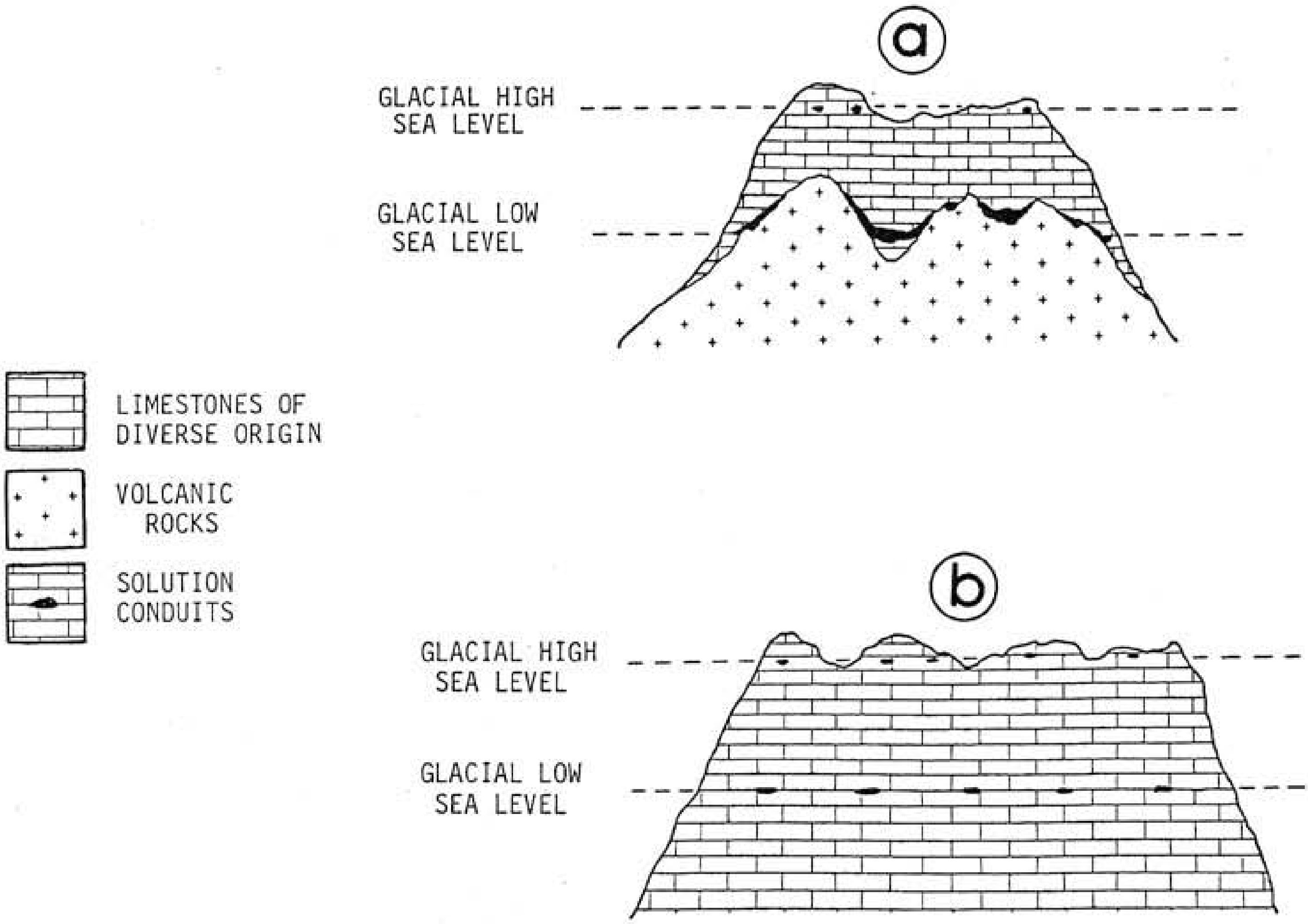

Figure 3: Idealized and diagrammatic comparison of cave formation in Bermuda (a) and in the Bahamas (b). Present sea level and intermediate glacial sea levels and the solutional features associated with them are eliminated for clarity. In both cases, a and b, glacial high sea level stands produce modest solution conduits in a freshwater lens perched on sea water. Conduit size is limited by the available meteoric catchment. During glacial low sea level stands, meteoric catchment area increases in both cases, and conduits are larger accordingly. In Bermuda (a), the presence of the irregular basalt/limestone contact channels groundwater into a few major conduits of significant size. Later progradational collapse produces the typical Bermuda cave pictured in Figure 1. In the Bahamas (b), no lithologic concentration of groundwater occurs, and recharge competition leads to many moderately sized conduits. These conduits are not large enough to produce the collapse features seen on Bermuda. Note the diagrams are not to scale.

over a maximum time of 30,000 years, at a higher sea level stand when catchment area would have been even less than that at present. Clearly a controlling lithology, as shown in Figure 3a, could form the larger conduits needed to produce the scale of collapse seen on Bermuda (Figure 1).

Jennings (1968) describes cave and karst development in eolian calcarenites of Australia. He makes a strong argument for syngenetic karst development in eolian calcarenites (i.e., karst development concurrent with consolidation of the eolian calcarenites). This may explain some of the karst features seen on Bermuda and in the Bahamas, but in itself cannot explain the large collapse caves. Jennings also describes large collapse features in the Australian eolian calcarenites that are very similar to those from Bermuda. Many of the Australian caves, especially the largest ones, are formed where an impervious basement underlies the eolian calcarenite, perching the cave stream and producing long, linear patterned caves. The ability of the perched cave stream to remove and consolidate collapse material, and to undercut cave walls is documented. From these processes, very large cave conduits can form. The impervious basement is responsible and a simple freshwater lens would not produce the same results. Sub-water table (phreatic) caves produced by a freshwater lens can form broad chambers in the subsurface, but they cannot produce, consolidate or remove collapse material the way a perched vadose stream can, and so produce the volume of void necessary for large scale progradational collapse.

The rapid time of formation for Lighthouse Cave, and the lack of coordination of it and many other Bahamian caves with present day topography, suggests that denudation rates for Pleistocene carboates are extremely high. Examination of the data available imply that the combination of climatic and sea level change during the Late Pleistocene, coupled with vulnerable carbonate material, can produce landforms that evolve very rapidly, both on the surface and in the subsurface. Such compression of events magnifies the effect of geologic processes.

Conclusions

The absence of a significant number of collapse caves in the Bahamas suggests that water migration seaward in a freshwater lens at a low sea level stand is not sufficient to produce conduits large enough to generate and accept the scale of collapse seen in Bermuda. Instead, many competing conduits of moderate size develop. This implicates the volcanic/carbonate contact for large conduit formation (with subsequent large scale collapse) in Bermuda. The large solution conduits located in the Bahamas at approximately 6 m above sea level do not seem large enough to produce collapse as seen in Bermuda. They do indicate the ability of a freshwater lens to produce conduits in eolian calcarenite, and they may be related to the same sea level event that produced the small solution tubes in the Government Quarry, Bermuda. Collapse caves similar to those seen in Bermuda, or conduits large enough to produce such collapse have not been described as yet in the Bahamas.

The evidence from Australia indicates that the largest voids are produced in eolian calcarenites when an impervious basement exists that can channel water flow as a perched stream, and these voids are capable of producing the magnitude of collapse seen in Bermuda. Small scale collapse also can occur due to solution on a freshwater lens, and perhaps some of the smaller collapse structures in Bermuda and the Bahamas have this origin.

The geology of the Bermuda and Bahama Islands, coupled with the variables of the Late Pleistocene, have accentuated the basic geologic difference between the island groups, as expressed by cave development. There are considerations that other geological aspects may be similarly enhanced.

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