MORPHOLOGICAL EFFECTS OF CONDENSATION-CORROSION SPELEOGENESIS AT DEVILS HOLE RIDGE, NEVADA

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The Devils Hole Ridge, a small block of Paleozoic carbonate rocks surrounded by the Amargosa Desert in southern Nevada, is located at the discharge end of the Ash Meadows regional groundwater flow system.

Continuous, long-term presence of slightly thermal (33.6°C) groundwater and the extensional tectonic setting, creating underground thermal lakes in open fractures, lead to intense dissolution above the water table. The morphology of the subaerial parts of the tectonic caves was slightly modified by condensation corrosion, and the Devils Hole Prospect Cave was almost entirely created by condensation corrosion. Caves and cavities in the Devils Hole Ridge are an interesting example of a hypogene speleogenesis by mechanism by condensation corrosion, operating above an aquifer which was demonstrably supersaturated with respect to calcite for hundreds of thousands of years.

STUDY AREA

Devils Hole Ridge is a small elongate limestone mountain jutting out about 250 m above the floor of the southern Amargosa Desert — a ca. 200 km^2 intermontane basin extending about 85 km along the California-Nevada border. At the south-west foothill of the Devils Hole Ridge lies the Ash Meadows Oasis, the discharge area of the regional-scale Ash Meadows Groundwater Flow System (Fig. 1).

Limestone of the Cambrian Bonanza King Formation exposed in the Devils Hole Ridge represents the lower carbonate aquifer underlying the Ash Meadows groundwater basin. The aquifer is primarily recharged by infiltration of snowmelt and rainfall at the upper elevations of the Spring Mountains (~3600 m a.s.l.; Winograd et al., 1998). The aquifer is alternately confined by young and partly indurated sediments beneath valleys and unconfined beneath ridges. Flow in the aquifer is little affected by

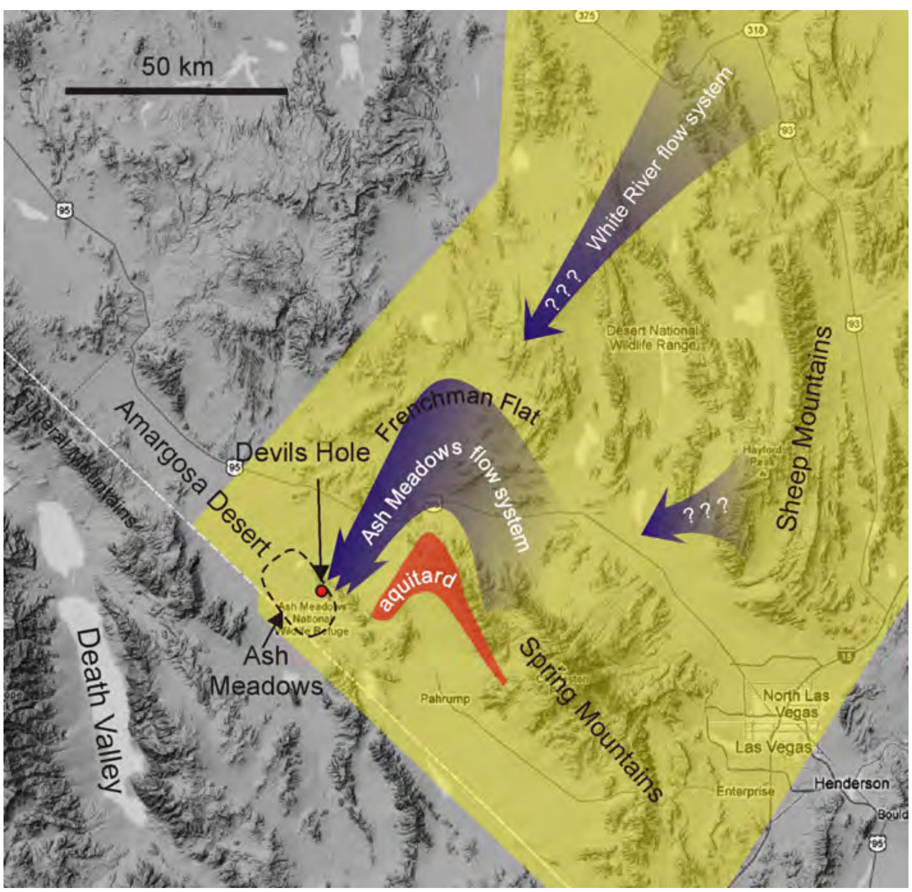

Figure 1. The Ash Meadows Groundwater Flow System. The location of the carbonate corridor (yellow) and the main flowpath of the Ash Meadows Flow System are redrawn from Riggs and Deacon (2002).

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surface topography or drainage. The most conductive flow paths are associated with the NE-SW-oriented fractures, which were opening due to regional extension which started 10 to 5 myr ago (Carr, 1984; Riggs et al., 1994).

At Ash Meadows Oasis, water discharges along a linear array of springs that emerge from flat-lying Quaternary lake beds and local travertine deposits. Water discharging at Ash Meadow is slightly supersaturated with respect to calcite (SI = 0.2; Plummer et al., 2000). The discharging water is moderately thermal, with temperatures up to 32°C in Ash Meadows springs and showing a constant value of 33.6°C in the aquifer intersected by Devils Hole and Devils Hole #2 caves (Coplen, 2007; this study). These temperatures are 13.0 to 14.6°C higher than the local mean annual air temperature (Winograd and Thordarson, 1975).

The Amargosa Desert at Ash Meadows contains abundant and thick calcareous and siliceous spring and marsh deposits of the Pliocene age (2.1 to 3.2 Ma; Hay et al., 1986); groundwater-deposited calcite veins of Pleistocene age are present in alluvium and colluvium in the area (500 to 900 ka; Winograd and Szabo, 1988). The Devils Hole, located at the foothills of the Devils Hole Ridge contains a thick crust of mammillary calcite, which was depositing subaqueously over the last 500 kyr (Ludwig et al., 1992; Winograd et al., 1992). Taken together, available data indicate that groundwater at the discharge end of the Ash Meadows Groundwater Flow System has always been slightly supersaturated with respect to calcite for at least the last 3 myr.

The Devils Hole Ridge has a surface area of ca. 2 km^2 and its vadose zone is up to 250 m thick. Because of the very small potential recharge area and arid climate, active epigenic (supergene) speleogenesis is not expected in the vadose zone of this ridge, even under climate conditions of higher humidity in the past. Yet, we identified ample evidence of specific solution forms in the carbonate rocks of the Devils Hole Ridge.

CAVES AND CARBONATE DISSOLUTION IN DEVILS HOLE RIDGE

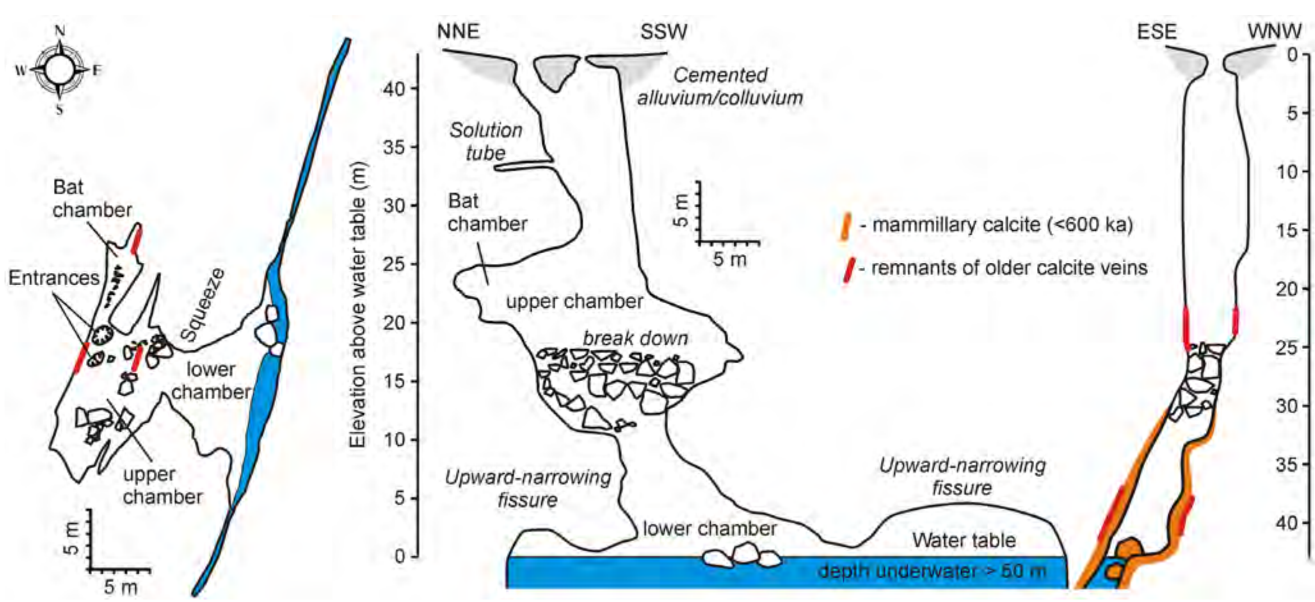
The two major caves in the Devils Hole Ridge are Devils Hole and Devils Hole #2. Although initially the origin of Devils Hole was attributed to solution enlargement of a tectonic fracture (Winograd and Thordarson, 1975), subsequently, Riggs et al. (1994) presented a compelling set of arguments supporting a purely tectonic, extensional origin of the cave. Dissolution due to condensation corrosion was first reported by Riggs and Deacon (2002) for Browns Room – an aphotic chamber located ca. 50 m to the north of the main entrance (collapse) of Devils Hole. Condensation corrosion appeared to be a minor speleogenetic mechanism, only capable of destroying secondary carbonate formations and modifying the cave wall surface.

Working in the area since 2010, we have commonly observed solutional forms in Paleozoic carbonate rocks of the Devils Hole Ridge.

Solutional forms in Devils Hole #2

Devils Hole #2 is a NE-striking, extensional fissure, which intersects the water table at a depth of 43 m (Fig. 2). It is an almost complete analog of the Devils Hole in terms of its (tectonic) origin. The fissure was concealed at the surface by a ca. 1.5 m-thick layer of carbonate-cemented alluvium/colluvium of Pliocene-Pleistocene age. The cave was opened when this indurated layer was breached by condensation corrosion. The cave consists of two chambers separated by a "plug" of collapsed blocks. The upper chamber is near-vertical, 5 x 15 m-wide and 25 m-high. Two calcite veins up to 40 cm-wide are present on the eastern and western walls of the cave; the veins filled two small-aperture extensional fractures, which served as precursors of Devils Hole #2 proper. The latter formed when the bedrock

Figure 2. Plan view (left) and projections (right) of Devils Hole #2 cave.



blocks located between these precursor fractures collapsed. A crawlway between boulders leads to a ledge at the top of the inclined (ca. 60°) lower chamber. Both the hanging- and footwall in this chamber are coated with carbonate deposits, which reach up to 125 cm in thickness.

Solution-smoothed walls — In the upper chamber, the walls are coated with mammillary calcite, up to a height of ca. 2 m above the chamber's floor (ca. 23 m above the water table). The coating is visibly thinned-out by corrosion, so that its initial thickness cannot be determined. The limestone walls above the calcite coating are also smoothed by dissolution (Fig. 3).

Flat channels along fractures and calcite veins — Small channels with characteristic solution morphology, precluding any involvement of gravity-driven water flow, cut through both the bedrock limestone and the old calcite veins on the eastern and western walls of the upper chamber.

Cupolas in indurated alluvium-colluvium — In the ceiling of the upper chamber, composed of carbonate-cemented alluvium-colluvium, dissolutional cupola are present. The solution surfaces cut uniformly across massive limestone bedrock as well as alluvium-colluvium consisting of cobbles, finer-grained material, and carbonate cement. The cupolas are locally separated by millimeter-thin partitions.

"Punk rock" — The southern wall of the upper chamber shows a layer of soft, powdery material, extending into the wall up to 2 cm and eventually grading into hard, unaltered limestone. Despite its softness, the layer preserves the original structure and coloration of the bedrock. This alteration zone is similar to the "punk rock" described by Hill (1987) from New Mexico caves.

Solutional Forms in Devils Hole Prospect Cave

The cave is located 50 m north of and ca. 12 m higher than Devils Hole (Fig. 4). The entrance to the cave was opened during mineral prospecting work, in the course of which indurated alluvium-colluvium material filling a ca. 1.5 m-wide fracture in the limestone was removed. Unlike other caves in the Devils Hole Ridge, whose internal volume was created primarily by extensional tectonics, the Devils Hole Prospect Cave owes its existence almost exclusively to dissolution. The cave is carved in both Paleozoic limestone and in indurated fault filling. Parts of the cave hosted by carbonate rocks show a characteristic solution-related morphology with abundant cusps, pendants, partitions, spherical niches, and cupolas (Fig. 5). Similar morphologies can be seen in the fault-fill material, but because of the poorer mechanical stability of this material, they are less well preserved.

Solution Cavities at the Topographic Surface

We found numerous small-scale solution cavities on the slopes of

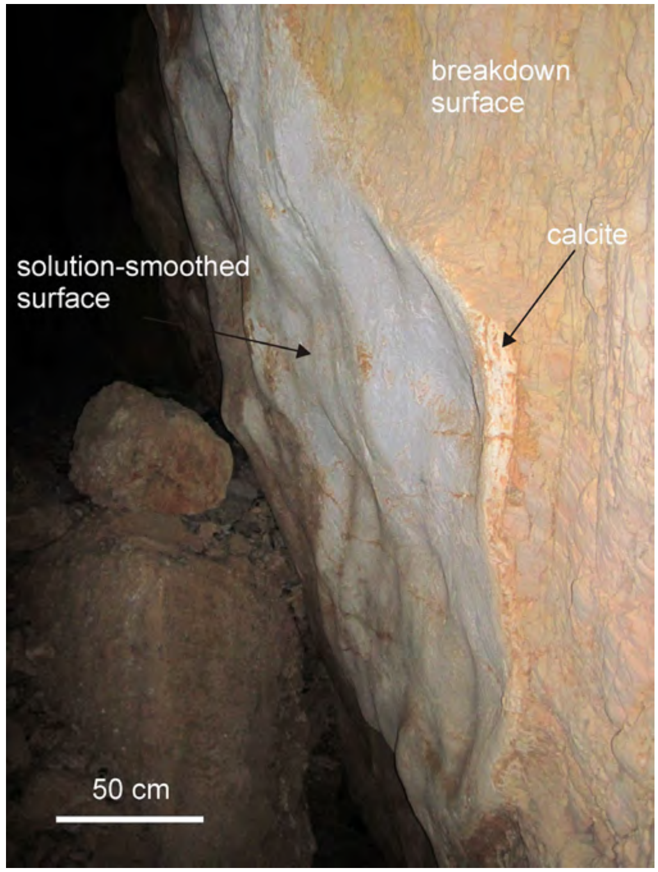


Figure 3. Solution-smoothed wall in the upper chamber of Devils Hole #2. Note that a solution surface cuts uniformly both mammillary calcite and hostrock.

the Devils Hole Ridge, within 18 to 41 m-elevation range above the present-day water table. Cavities are exposed on bedrock slopes, and are truncated by solutional slope retreat to different degrees: some of them open as small-diameter (7-10 cm) holes which widen inward, whereas others are severely truncated or even almost completely destroyed (Fig. 6). The common morphological feature of these cavities is their circular cross-section in plan view; in vertical projection they show spherical, spheroidal, and tubular shapes. The maximum diameter of the cavities ranges between 10 and 130 cm. Most of the cavities have barren walls, but some host speleothems forming in subaerial conditions (corallites, popcorn).

MICROCLIMATE AND EVIDENCE OF ACTIVE CONDENSATION CORROSION IN DEVILS HOLE #2

Devils Hole #2 is the only cave in the study area hosting a thermal lake and only partly open to the surface. A 24 hour-monitoring on November 8-9, 2011, demonstrated that cool, dense, low-humidity outside air descends and displaces the less dense, humid cave air, penetrating all the way down to the bottom of the lower chamber. The RH in 1 m above the thermal water table

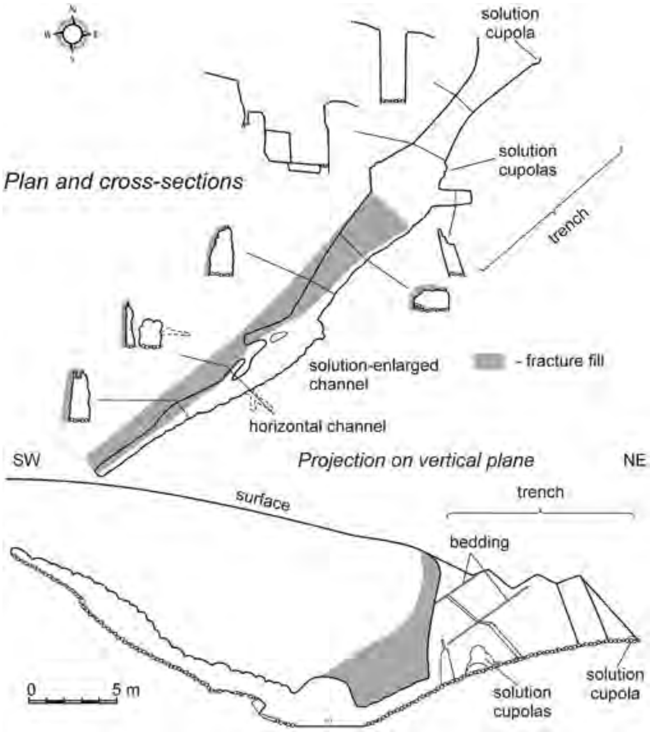


Figure 4. Plan view and projection of the Devils Hole Prospect Cave.

ranges between 60 and 70 % (Fig. 7).

The long-term monitoring (Nov 2008 to Oct 2010) in two chambers of Devils Hole #2 showed that the RH remained low (40 to 70 %) from October through April. From May on, as the outside air became warmer than the air in the cave, invasions of outside air became less frequent and the RH in the lower chamber gradually increased, stabilizing for a short period at 90-94 % (July). It is possible that during this period (two to three weeks during the year) the RH in the lowermost (closest to the thermal lake) part of the lower chamber exceeds 100%, enabling condensation. The data suggest that condensation corrosion is presently not an active speleogenetic process in Devils Hole #2. It was observed only in a small semi-isolated, chamber just above the water (Fig. 8). The walls of the chamber host patches of white powdery material, as well as droplets of water. This material is the calcite precipitate, which forms when the film of condensed water dries out. In contrast to the hanging walls of the lower chamber, coated by dense folia, the walls of this small chamber (at the same elevation above water) are smooth due to solution.

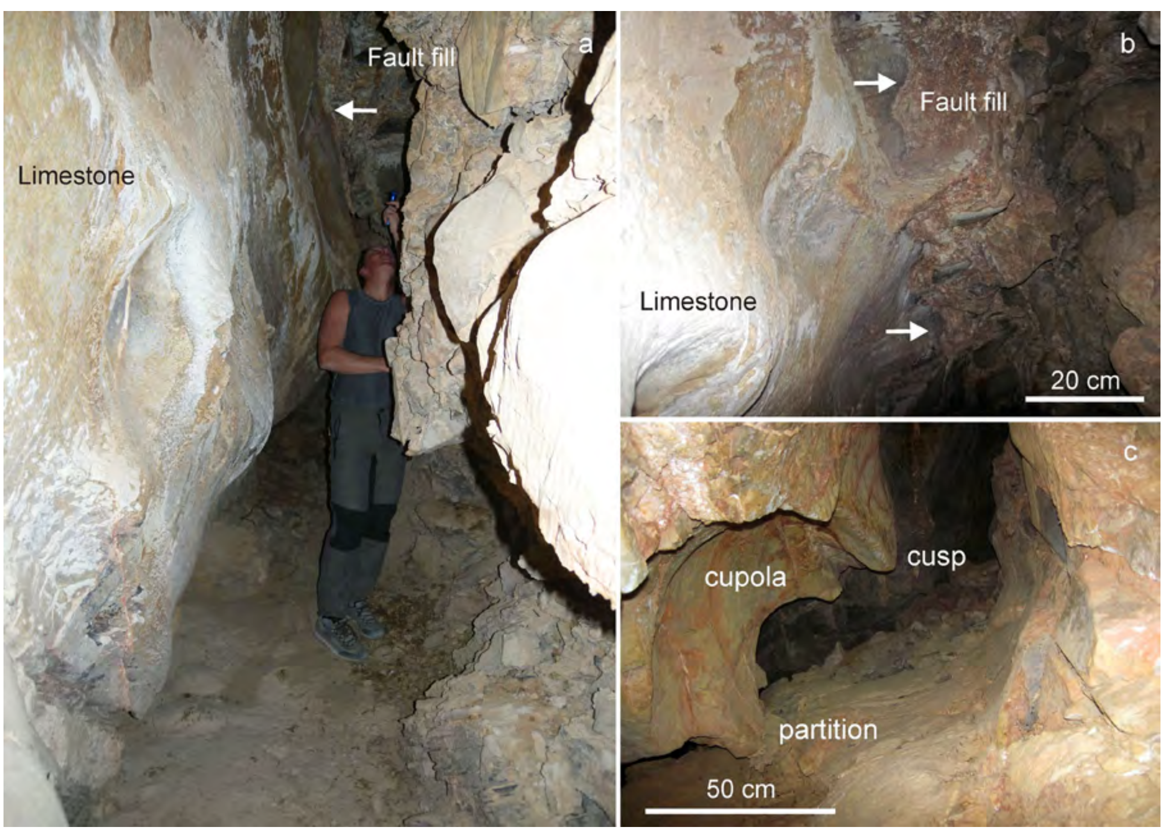


Figure 5. Solutional morphology of the Devils Hole Prospect Cave: a and b – rift-shaped passage with left wall in limestone and right wall in fault fill (arrows show contact between limestone and fault fill); c – cupola-, partition-, and cusp morphologies in massive limestone.

Figure 6. Solutional cavities on the southwestern slope of Devils Hole Ridge showing different degrees of truncation by slope processes: a–c – barely opened cavities (widen inward); d – combination of a vertical tube and a small cupola cut by slope erosion; e - three cavities (arrows) truncated to different degrees (cavity on the left hosts subaerial calcite speleothem; the other two are barren); f - cavity hosting popcorn-like speleothems. No leading fractures are observable; dissolution cuts across various lithologies (b).

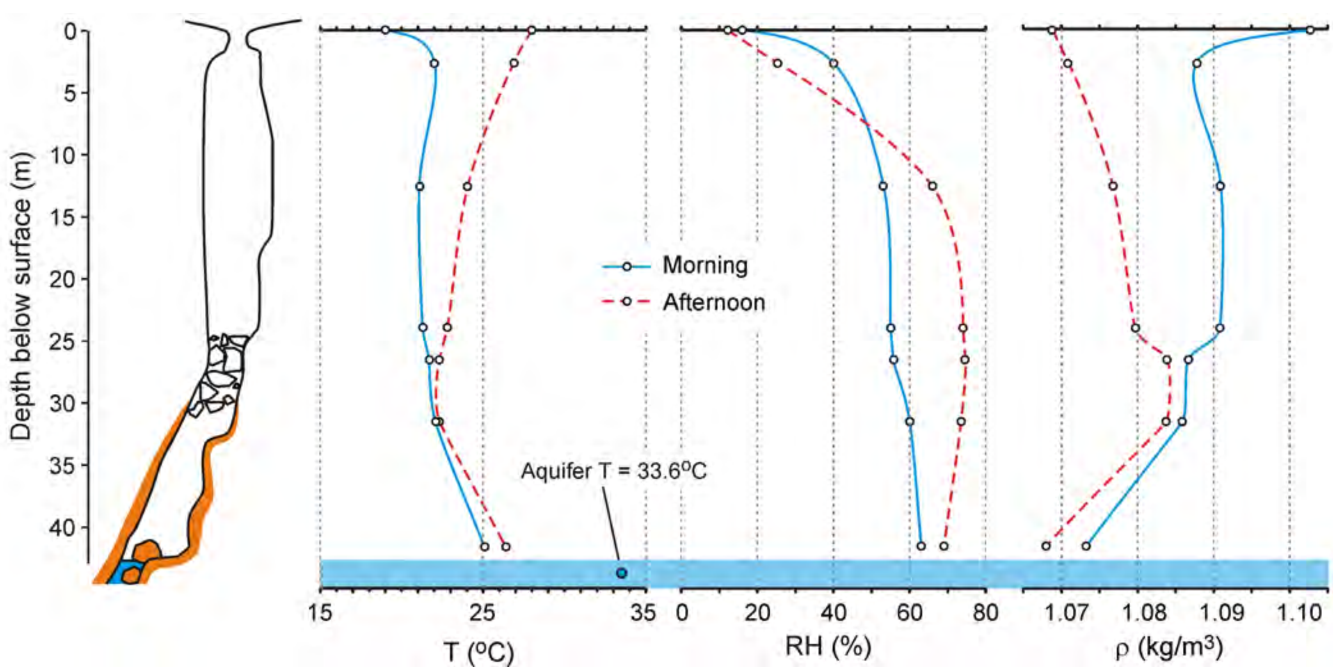


Figure 7. Temperature, relative humidity, and calculated air density in Devils Hole #2 in the morning and in the afternoon.

DISCUSSION: CONDENSATION CORROSION INSIDE DEVILS HOLE RIDGE

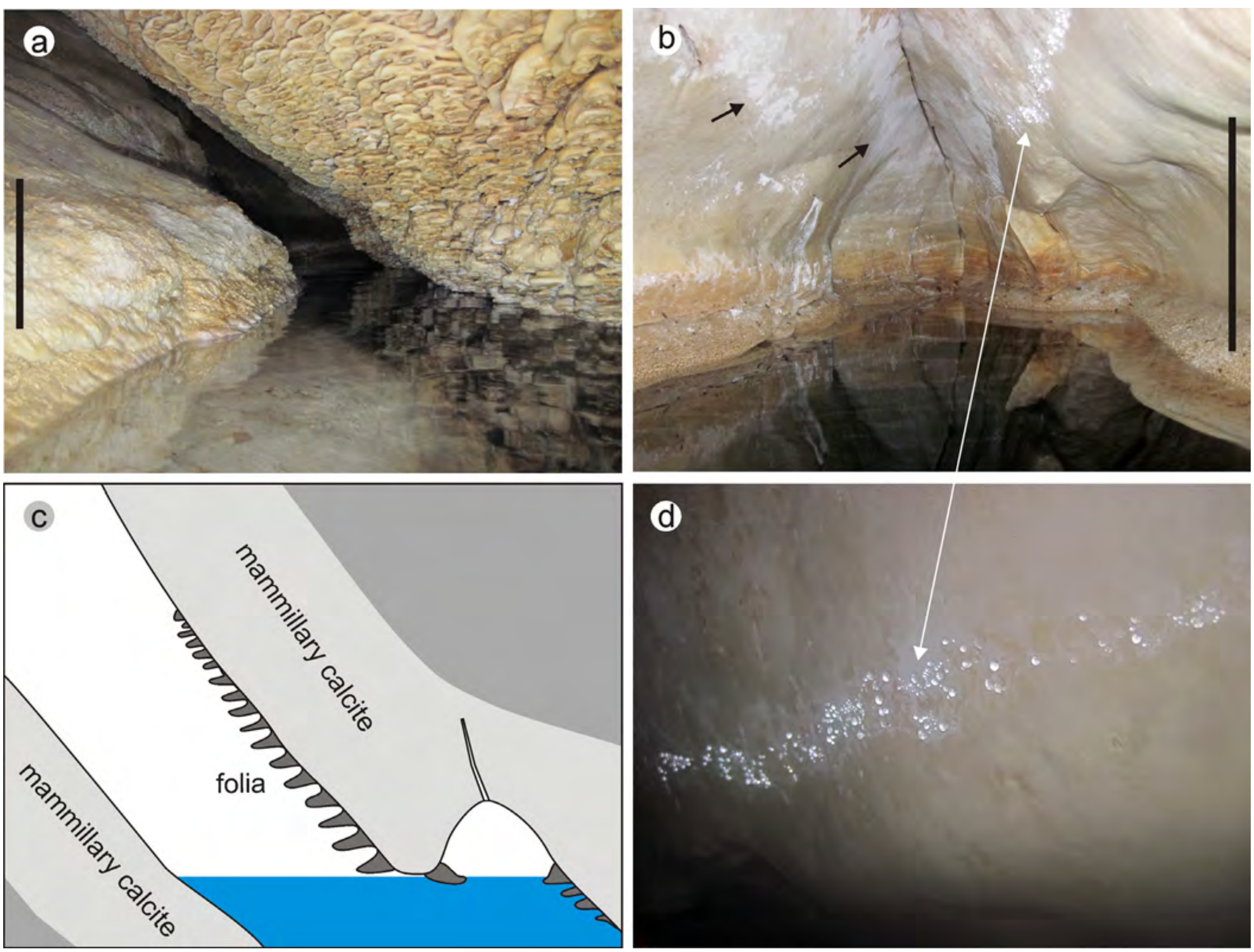
Controls of condensation corrosion

The condensation-corrosion features described above formed when the cavities inside the ridge were essentially closed to the outside atmosphere. For this type of condensation corrosion to become an efficient speleogenetic mechanism, a number of conditions must be met.

Structural conditions — One of the parameters controlling the amount of the evaporation from a thermal water table (i.e., the amount of water available for condensation corrosion), is the surface area of the subterranean thermal lake. In most hypogene caves described so far (e.g., Cigna and Forti 1986; Audra et al., 2002) the process occurred during late stages of hypogene karstification, above thermal lakes. At Devils Hole Ridge, subaqueous karstification can be ruled out, because the water has been saturated with respect to calcite for hundreds of thousands of years. The subterranean voids occupied by the thermal lakes were instead created by extensional tectonics. Because the region has remained in an extensional regime since the mid-Tertiary, such subterranean thermal water surfaces are likely to be widespread.

In addition to creating evaporation surfaces, extensional fractures provide an open space above the thermal water table in which free convection of moist air can develop. Extensional tectonics, collapse, and condensation corrosion operate in concert in creating and enlarging the open space underground. The result of this concerted action may remain unnoticed at the topographic surface.

Figure 8. Active condensation corrosion in a small semi-isolated chamber close to the water table in Devils Hole #2. a – massive folia on the hanging wall in the main part of the cave; b – solution walls in the small chamber (note white powdery material on the walls (black arrows) – the result of dissolution and re-evaporation of water); c – schematic vertical transect showing the position of the small chamber shown in b; and d - condensation droplets on the powdery material in the small chamber. Temperature of the pool water is 33.6°C. Vertical black bar in a and b is 25 cm.



Thermal conditions — A temperature gradient exists between the body of thermal water and the land surface. The aquifer underneath Devils Hole Ridge maintained a nearly constant temperature of ca. 34°C for (at least) hundreds of thousands of years. For most of the late Pleistocene, thermal gradients in the vadose zone were likely greater than they are today because the thermal water table was 6 to 9 m higher (Szabo et al., 1994). Thermal conditions favorable for condensation corrosion may have persisted for an equally long period of time. Extensional-tectonic conditions could also create open fractures which are open to the surface but do not intersect the thermal water table. Inflow of cool air in such fractures provides additional cooling of the rock mass.

Microclimatic conditions — Condensation corrosion is least intensive near the thermal water table, where the difference in temperature between the thermal water pool and the surrounding rock is small. As the warm moist air buoyantly moves up along an open fracture, it cools down, and at certain distance its temperature may reach thermal equilibrium with the surrounding rock. Both buoyant movement and condensation will then no longer be possible. Additionally, the heat released due to condensation warms the rock surface, decreasing the local thermal air-rock gradient. For condensation to proceed, this heat must be removed through solid-state thermal conduction and/or by downward flow of the condensate. It can be inferred, therefore, that there is a certain combination of parameters at which condensation corrosion is most effective; this combination is specific to a given cave configuration.

When a channel or cupola, carving its way up through the rock, opens to the surface, cool dry air flowing into the cave dilutes the ascending moist air. This makes condensation corrosion less efficient, and increasing openness of the cave to the outside atmosphere eventually terminates the process entirely.

Age Constraints for Condensation Corrosion in the Devils Hole Ridge

Solutional channels intersect the mammillary calcite veins in the upper chamber of Devils Hole #2. Although the latter have not been dated radiometrically, they are likely older than 588±39 ka (the oldest age of the main-stage calcite in Devils Hole #2, which overgrows the petrographically and isotopically identical veins in the lower chamber). Thus, the age of ca. 550-600 ka can be considered as a minimum estimate for the initiation of active condensation corrosion in the vadose zone of the Devils Hole Ridge. Before that time the water table could have been significantly higher (Winograd and Szabo, 1988) so that the present-day vadose zone could have been, partly or entirely, under phreatic conditions.

A subaerial speleothem (popcorn) from a condensation corrosion cavity exposed at the surface of the Devils Hole Ridge yielded U-Th ages of 413±12 ka and 318±8 ka. These dates provide a lower limit for the age of this particular cavity. The maximum time span available for the formation of this 40 cm-diameter cavity is thus on the order of 150-200 kyr. Theoretical calculations suggest similar values, e.g. the formation of a spherical cavity with a 50 cm-diameter by condensation corrosion requires 200 to 250 kyr (Dreybrodt et al., 2005). Having started in the Late Pleistocene, the condensation corrosion process inside Devils Hole Ridge locally continues in the vadose zone today, as suggested by observations on condensation in a small semi-isolated chamber at the bottom of Devils Hole #2.

CONCLUSIONS

Condensation corrosion is the only karstic speleogenetic mechanism operating in the Paleozoic limestones of the Devils Hole Ridge since the Pleistocene. It develops above the water table of a slightly thermal aquifer, despite the fact that this groundwater has been saturated with respect to calcite at least for the last ca. 600 kyr. The effects of condensation corrosion range from the modification of the surfaces of underground extensional cavities to the creation of purely solutional cavities. One of the three caves known in the ridge, Devils Hole Prospect Cave, owes its origin almost entirely to condensation corrosion. No sizable underground cavities attributable to epigenic (supergene) karst were found. Our observations confirm the role of condensation corrosion as an important speleogenetic mechanism, capable not only of modifying the pre-existing cave morphology, but also of creating significant caves.

ACKNOWLEDGMENTS

The authors thank the Death Valley National Park Service for permission to conduct research at Devils Hole, the Park personnel (K. Wilson, R. Freeze, A. and J. Snow) for field assistance, and the Southern Nevada Grotto (S. Deveny) for logistic support.

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