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Caves in caves: evolution of post-depositional macroholes in stalagmites

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Abstract: In a previous paper (Shtober-Zisu et al., 2012) we described millimeter to centimeter-sized fluid-free holes within the interiors of stalagmites of widely varying origin. We present here further observations of this phenomenon, using X-ray tomography, macroscopic and microscopic observation of sections of twenty-six stalagmites from various sites in North America and the Caribbean region. We can distinguish three types of cavities in speleothems: primary μm -sized fluid inclusions; mm to cm sized holes, aligned along the stalagmite growth axis which are clearly syngenetic; and μm to cm-sized holes away from the growth axis ("off-axis holes or OAHs") deeply buried inside their host stalagmites, and cutting primary growth layers. Neither axial nor off axis holes contain fluid today. Off-axis holes appear to have been formed by internal corrosion of the calcite host, possibly enhanced by the action of bacteria which were sustained by permeation of through the body of the stalagmite of water containing dissolved organic species. A modern stalagmite from Israel is shown to contain bacteria associated with active hole formation.

Keywords: macroholes; axial holes; off-axis holes (OAHs); diagenetic porosity; corrosion

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INTRODUCTION

Calcite fabrics in stalagmites including morphological and microstructural characteristics can often be related to environmental conditions and growth mechanisms. Physical and chemical factors within and around cave environments such as atmospheric conditions, soil and vegetation types, karstic aquifer characteristics and the feed rate of the calcareous solution can all play a role in shaping stalagmites, including the initial growth of crystals as well as their morphology and geochemistry (Dreybrodt, 1980; Frisia et al., 2000; Ford and Williams, 2007; Fairchild and Baker, 2012).

Speleothem fabrics include columnar, fibrous, microcrystalline, dendritic and calcareous tufa (Gonzalez et al., 1992; Frisia et al., 2000), which vary as a result of variations in growth kinetics, that depends on a combination of factors such as temperature, drip discharge rate, water saturation, CO_2 degassing rate, and the mechanism of transport of ions from the solution to the crystal surface (Kendall and Broughton, 1978; Boch et al., 2011). Laminar

structures with varying porosities and colors are also common in stalagmites, and have been recognized in previous studies (Railsback et al., 1994; Genty and Quinif, 1996; Baker et al., 2008).

Most stalagmites entrap microscopic fluid inclusions, considered to be "primary porosity" (Schwarcz and Yonge, 1983). These are usually found within crystals and along crystal boundaries, elongated parallel to the c-axes and the growth axis of the stalagmite (Zhang, 2007). They are also found concentrated within growth layers, and along hiatuses or weathered surfaces. These micro-inclusions range in size from ~20 nm to >1 mm in diameter (Kendall and Broughton, 1978), and can constitute up to ~0.1 wt% of the speleothem (Schwarcz et al., 1976). Over the last few decades, palaeoclimatic research has utilized water trapped in microinclusions: since drip water is derived from meteoric precipitation, the isotopic composition of the trapped water combined with the isotopic composition of the calcite can serve as a paleothermometer (Wigley, 1969; Hendy, 1971; Schwarcz and Ford, 1974; Yonge et al., 1985; Gascoyne, 1992; Bar-Matthews et al., 1997; Frumkin

et al., 1999; Fleitmann et al., 2004; Drysdale et al., 2005; McDermott et al. 2006; Matthey et al., 2008, and many others).

In addition to microporosity associated with fluid inclusions, stalagmites may also contain large voids, holes or cavities up to 3-4 cm long (Lauritzen and Lundberg, 1999; Frisia et al., 2000; Genty et al., 2002; Mickler et al., 2004; Fairchild et al., 2007). These are the subject of the present paper. While size is their principal distinguishing characteristic, note that the dimensions of the smallest of these features (a few tens of μm) overlaps the size range of primary fluid inclusions trapped during the growth of the speleothems. Large holes have long been observed, but were mostly considered a source of interference for paleoclimatic research; since this normally requires a continuous record of deposited layers, porous or hollowed stalagmites were usually avoided, and thus, their presence, characteristics and evolution have been neglected but for a few studies (e.g., Genty and Quinif, 1996; Genty et al., 2002). Frisia (1996) related post-depositional dissolution to the microstructures of specific fabrics where the pores developed, and also hinted at the possibility of organic matter oxidation as source of undersaturated waters.

In a recent study searching for water trapped in stalagmites (Shtober-Zisu et al., 2012), two types of 'macroholes' were defined: (1) axial holes that form during stalagmite growth due to slower calcite precipitation at the axial drip site; and (2) off-axis holes

(OAHs), that formed penecontemporaneously, with growth in discrete layers. Building upon this work, the aims of the present study are to characterize the structure, texture and distribution of these large voids, and to propose a generic model for their development based on the inner structure of the stalagmites and the characteristics of these macroholes.

SAMPLES AND METHODS

A total of 26 stalagmites were examined in this study from different climate regions: 11 stalagmites from tropical Central America (4 from Belize, 6 from Bermuda, 1 from Jamaica), 10 stalagmites from the temperate climatic zone of the U.S.A., 2 stalagmites from the temperate marine west coast climate of Canada, one stalagmite from the Mediterranean climate region of Israel, and two stalagmites from unknown locations (Table 1). Twenty-one of these samples were previously imaged using X-ray computed tomography, with another 5 examined in this study by looking at thin sections using polarized microscopy, 15 through the study of sawed and polished surfaces (both sagittal and outer surfaces) using a binocular microscope, and 1 by scanning electron microscopy (Shtober-Zisu et al., 2012).

X-ray computed tomography (CT) offers a nondestructive technique for visualizing the internal structure of opaque solid objects, thereby obtaining information about their 3-D geometry.

The most common CT scanners are medical devices, which are optimized to image biological tissues. As a result, the sensors are designed with a limited dynamic range, being able to image objects up to a density of $\sim 3.4 \text{ g/cm}^3$. Also, the absolute system resolution is typically limited to $\sim 1 \text{ mm}$, even though the CT pixel size can be smaller. The CT scanner used for this study, at the Juravinsky Cancer Center, Hamilton, CA, was a GE Litespeed-RT, with pixel sizes varying from 0.2 to 0.5 mm. The slice spacing chosen for this study was 1.25 mm (Shtober-Zisu et al., 2012).

One sample collected from an actively growing stalagmite from the Te'omim Cave in the Judean Hills, Israel (Table 1, #26) was examined using scanning electron microscopy (SEM) at the Univ. of Western Ontario, London, CA. Humans inhabited the cave since Neolithic times (Zissu et al., 2011), however current 'residents' include microbial biofilms covering cave walls and ceilings as well as large numbers of bats. The sample was collected using aseptic techniques, with four regions targeted for detailed examination: (1) the wall within an axial hole; (2) the wall within an off-axis hole (OAH); (3) the stalagmite outer surface; and (4) interior calcite containing microholes. Subsamples were prepared within 7 days of collection by chemical

Table 1. Characteristics of the sampled stalagmites. * Number at McMaster University collection; ** Type: see Fig 11; *** Holes shape and distribution within the stalagmite: El=elongated; An=angular; Rd=rounded; Ax=Axial; OAH= Off-axis; for discussion of these terms see text].

	Number*	Location	Length [mm]	Hole size [mm]	Type**	Hole shape***
1	81008 a	Mountain Cow cave, Belize	220	25	F	El; Rd; Ax; OAH
2	81008 b	Mountain Cow cave, Belize	255	20	F	El; An; Ax; OAH
3	78031 a	Waterfall cave, Belize	100	-	A	No holes
4	78031 b	Waterfall cave, Belize	115	8	E	El; OAH
5	790512 b	Bermuda	140	10	B	An; Rd; OAH
6	76163	Bermuda	220	8	E	An; Rd; OAH
7	77703	Crystal cave, Bermuda	160	10	B	Rd; Ax; OAH
8	77704	Crystal cave, Bermuda	240	6	E	Rd; OAH
9	88808	Deep Blue cave, Bermuda	175	5	E, B	Rd; Ax; OAH
10	73027 B13	Leamington cave, Bermuda	130	14	B	El; Ax
11	75351	Coffee River cave, Jamaica	225	30	E, F	El; Rd; Ax; OAH
12	2004007	Marengo cave, US-IN	290	30	E, F	El; Rd; OAH
13	200407(BMFTL)	Marengo cave, US-IN	220	10	E	El; OAH
14	200407(MBFCL)	Marengo cave, US-IN	130	8	E	El; OAH
15	NB1	Norman-Bone cave, US-WV	100	30	D	El; Rd; An; Ax; OAH
16	NB2	Norman-Bone cave, US-WV	110	15	D	El; Rd; An; Ax; OAH
17	72009	Inner space cavern US-TX	180	6	D, E	Rd; Ax
18	2004002 P1	Vancouver Island, Canada (left)	160	3	E	Rd; El; OAH
19	2004002 P2	Vancouver Island, Canada (right)	155	4	E	Rd; El; OAH
20	770319-1	Unknown location	175	30	D	El; Rd; An; Ax; OAH
21	PMC	Unknown location	165	3	B	Rd; Ax; OAH
22	2004006	Marengo cave, US-IN	200	20	C	El; An; Ax; OAH
23	67016	Norman-Bone cave, US-WV	100	30	D	El; Rd; An; Ax; OAH
24	GV1	Grapevine cave, US-WV	300	30	E	El; Rd; Ax; OAH
25	67020	Handline cave, US-WV	120	20	C	El; Rd; An; Ax; OAH
26	-	Te'omim cave, Israel	80	15	-	El; Rd; Ax; OAH

fixation in a 2%(aq) glutaraldehyde solution followed by dehydration through a graded ethanol series (25%, 50%, 75%, and 100%). All samples were then critical-point dried using a Tousimis, Samdri-PVT-3B critical point dryer and platinum coated using a Denton Vacuum Desk II sputter coater to reduce sample charging. This sample was subsequently imaged on a LEO (Zeiss) 1540XB field emission gun SEM equipped with a secondary electron detector.

A single experiment to demonstrate the potential permeability of a stalagmite was conducted. We attached a calibrated tube containing 1 cm³ of water over the course of an hour, to the outer unpolished surface of stalagmite NB1 and observed the time needed for a calibrated volume of water to permeate into the stalagmite.

RESULTS

Distribution and characteristics of macroholes

We herein define macroholes as holes, cavities or voids, larger than 1 mm. These have been observed in all but one of the 26 stalagmites we examined, forming axial or off-axis holes (OAHs). Macroholes shapes (both axial and off-axis), vary from equi-dimensional to, more commonly, elongated, with the long axis approximately parallel to the stalagmite's local direction of growth. Of the stalagmites examined here, some display dense calcite laminations with few holes, whilst others exhibit abundant cavities forming up to 10% of the total volume (Shtober-Zisu et al., 2012).

Axial holes form along the stalagmite axis and are usually elongated parallel to the growth axis of the stalagmite. The uppermost hole, may connect with the central depression observed on the stalagmite's apex (Fig. 1). They range in length from 0.5 to 4 cm and their width may reach 1 cm. A significant feature of the axial holes that can be seen in sections is the downward bending of growth layers towards the

holes; this can persist over many cm of the growth history (Figs. 2, 3A, 4). Successional CT slices show the axial hole persisting along the stalagmite axis, being trapped by encircling calcite layers (Fig. 4). Sixteen stalagmites displayed prominent axial holes; all but one also displayed OAHs.

Off-axis holes (OAHs) are mainly developed away from the stalagmite axis. They cut discordantly through growth layers, and rarely extend to the surface of the stalagmite (Figs. 2, 3B, 5, 8). OAHs are usually more rounded and smaller than the axial holes, ranging from 1 mm up to 2 cm. Most are slightly elongated parallel to the growth axis even though they are distant from it, or oriented approximately perpendicular to the local growth layers. Several OAHs were also visualized using CT, dominated by elongated shapes (Fig. 5). These holes are parallel to the orientation of the stalagmite axis and are interconnected by either direct conduits or micro fractures (Fig. 6). For example, in the stalagmite presented in Fig 5, water dripping on the top, reached the bottom in a few seconds, emphasizing the large, interconnected holes present within. OAHs were observed in 23 out of 26 stalagmites.

Corrosional and depositional features in macroholes

Although corrosion and deposition are two chemically opposite processes, in a few samples their traces are observed together within the same stalagmite. Direct examination as well as thin sections of macrohole interiors shows evidence for these processes along their walls, both in axial and OAHs.

a) Corrosional features - Features include spike-like shapes, dissolution thorns or irregular masses of calcite (Figs. 7A-C and 8). Locally, areas surrounding the holes have a darker color. Thin sections of OAHs show various aspects of their detailed shape and evolution (Fig. 8): their shape is mostly irregular and they are interconnected in places by thin fissures (Fig. 8C). The walls surrounding the holes exhibit evidence of corrosion, along with later deposition of new crystals (Fig. 8D).

b) Depositional features - Calcite films or layers coat the walls of some macroholes, whereas in many others small new crystals up to 1 mm are developed along the walls or the coating layers, growing non epitaxial on the substrate (Fig. 9). These features were observed within both axial as well as OAHs. In a few holes, micro-granular debris is observed (Fig. 7D).

Microbial colonization

The stalagmite sampled from Te'omim Cave is actively growing. It exhibits an axial hole, filled with water due to contemporary inputs, as well as off axis macroholes. Both coccoid and filamentous microorganisms are observed on the stalagmite surfaces,

Fig. 1. Central depression is visible on the stalagmite apex, surrounded by small holes, gours and other irregular shaped cavities (in situ stalagmite at Te'omim Cave).

Fig. 2. Axial and off-axis macroholes; note the growing layers bending towards the axial holes, and the clear cutting of the growing layers by the off-axis holes, in polished surfaces (middle) or in petrographic thin sections (right).

within the axial hole (Figs. 10A and B) and within OAHs (Fig. 10C). While in direct contact with mineral surfaces, there is no conclusive evidence for chemical weathering due to the presence of microorganisms, such as pitting. In contrast, microorganisms are not observed in micro holes (presumably syngenetic) within the stalagmite (Fig. 10D).

Classification of macroholes

Based on our analyses, we recognize six types of macrohole distributions and architecture in stalagmites (Fig. 11).

A) Intact - Having no visible macroholes. This type of stalagmite was observed in only 1 out of 26 of the stalagmites examined.

B) Random sparse distribution - Having few macroholes which are spherical and randomly distributed. Holes are not interconnected. While calcite layers of variable CT density are observed, the holes do not appear to have preferentially formed in layers of a particular density. This type of stalagmite was observed in 5 out of 26 of the stalagmites examined.

C) Axial holes dominant - Dominated by axial holes, however OAHs are also present but in lesser abundance. Growth layers bend towards the axial holes. Multiple axial holes, 1-4 cm long, are usually formed one above the other, separated by undisturbed layers of calcite. This type was observed in only 3 out of 26 of the stalagmites examined.

D) Abundant random holes ("Spongy structure") - These samples display a deceptively dense surface ("skin") covering a spongy core consisting of laminated calcite perforated by numerous cavities ranging up to

3 cm in maximum dimension and dominantly elongated parallel to the stalagmite axis. The holes are connected; by submerging stalagmite #770319-1 (of Fig. 6) in a water-filled tank, we observed that water passed freely from hole to hole throughout the stalagmite core, along the axis as well as throughout OAHs (Shtober-Zisu et al., 2012). The compact outer skin of these stalagmites indicates that the dissolution activity was restricted to the stalagmite core. This pattern was observed in 6 out of 26 of the stalagmites examined.

E) Layer-confined holes - Macroholes are concentrated in discrete layers, interposed with dense, hole-free calcite layers. OAHs are usually elongated roughly parallel to the local direction of growth (normal to the local growth surface). Their laminated distribution indicates periods of deposition followed by

phases of dissolution activity. The OAHs invariably cut growth layers in their host calcite, while the layers themselves do not alter their orientation as they approach the holes, indicating that the holes were formed subsequent to calcite growth. This is the most common type observed, comprising 9 out of 26 of the studied stalagmites.

F) Mixed type - Both randomly distributed and layer-confined holes are present (as well as axial holes) implying on a succession of phases of corrosion activity. This type of stalagmite was observed in 2 out of 26 of the stalagmites examined.

DISCUSSION

Morphology and distribution of holes

Form of the holes - OAHs tend to be prolate ellipsoids, with the major axis of the ellipsoid oriented approximately perpendicular to the local growth layers and commonly parallel to the stalagmite growth axis. This suggests that the rate of corrosion is greatest in a direction following the 'c' axis of the calcite crystals, which are also usually oriented perpendicular to

Fig. 3. Sample 81008 from Belize. A) Axial hole formed along the stalagmite axis; note the growth layers, bending towards the hole. B) Typical corrosion-associated off-axis hole. Entire surface of the stalagmite was eroded by corrosive drip water as shown by truncation of growth lines at paleo-surface, after which growth was renewed again, totally covering the eroded surface.

Fig. 4. CT image of an axial hole consecutively sliced every 1.25 mm. The hole persists for over 13.75 mm. A) upper slice; L) lowest slice, M) the axial hole as viewed in sagittal view. Dashed lines mark the stalagmite axis. Stalagmite 73027/B13 Leamington Cave, Bermuda.

that surface. In other cases, OAHs tend to develop parallel to the stalagmite growth axis. In no case do we see an oblate ellipsoidal form (with the major axis much less than the minor axis). From their form, we might conclude that the growth process is one in which the hole begins as a smaller feature of similar ellipsoidal plan and then extends in all directions at a rate which depends on the orientation of the calcite crystals, finally ending when a critical maximum size is reached.

Termination of the holes - As expected from their ellipsoidal form, the upper end of most OAHs is a narrow dome-shape feature, which continues to cut through growth layers to its very top. From this we conclude that at no time in their history did these OAHs penetrate to the growing surface of the stalagmite for, if they had, there would be some evidence of a disturbance or deformation of the growth layers at their upper (or distal) ends. Therefore we conclude

that these holes are formed entirely enclosed within the pre-existing stalagmite and must be entirely post-depositional. Occasionally, OAHs do terminate at a present or former growth surface as described above, and we refer to them as “corrosion-associated”.

Distribution of holes inside stalagmites - Fig. 11 shows that the distribution of OAHs can vary. However OAHs are not frequently found in the outer 1 to 2 cm thick outer portion of the stalagmite. In a large proportion of stalagmites, OAHs are concentrated in a specific series of growth layers (e.g., Fig. 11E, 11F) but do not extend above or below. While these clusters might suggest that the holes were formed penecontemporaneously with those layers, there is no evidence of this in their detailed form. Even in these cases, there is no evidence that the OAHs penetrated the growth surface. Therefore, we propose that these laminar concentrations of OAHs are due to some preferential tendency for hole formation in

Fig. 5. CT images of consecutively cut CT slices at distances of 1.25 mm. Note the shape and size of an off-axis hole (marked by arrow or encircled). A) hole's top is reaching the stalagmite surface; B - G) the hole is enlarged underneath the stalagmite surface; H) off-axis hole cutting through several growth layers. The dashed line marks the stalagmite axis (Stalagmite 81008b).

specific layers and that the period of hole formation is not connected in time with the period of growth of those particular layers, but postdates it.

Mutual distribution. In both CT scans and visual examination in cross section, we observed that two adjacent holes rarely if ever intersect. They tend to be spaced at distances of a few millimeters to centimeters. This even spacing suggests that there is some tendency to avoid coalescence. This would be difficult to account for if the process of OAH formation were purely physical in nature. However, if a biological mechanism is responsible, it is possible that there is some molecular signaling or nutrient dynamic occurring between adjacent OAHs as they form, causing them to limit their size so as not to intersect an OAH being formed nearby (Miller and Bassler, 2001).

Internal surface features

a) Overgrowth - The internal surfaces of most OAHs have been covered wholly or in part with calcite overgrowths in the form of μm -sized crystals, which are typically not epitaxial on the host calcite. The lack of an epitaxial orientation may suggest that at the time of the formation of these overgrowths, the eroded crystal surface was covered with a biofilm, which prevented nucleation of new crystals with their crystal lattice epitaxially oriented with respect to the host.

Fig. 6. CT image of stalagmite 770319-1. Several large off-axis holes were chosen as examples, to emphasize the shape and nature of these holes. A) the holes are marked within the calcite in 3D imaging; B) details of panel A.

Another possibility is of nucleation of a new phase onto structural defects at the surface of the former crystals, which have been enhanced by dissolution processes. However, some crystals do seem to be epitaxially (or at least homogeneously) oriented and to have grown out from the eroded wall as “microstalagmites” (Fig. 8D).

Internal overgrowth of crystals has also been reported in previous studies (Railsback et al., 1997; Sletten et al., 2013).

b) Corrosional features - Some internal surfaces appear to have been eroded into spikes or thorn-like protuberances. These are reminiscent of

Fig. 7. Dissolution in off-axis holes. A) dissolution of calcite layers adjacent to a hole; B and C) spikes and thorns as irregular dissolved shapes within a hole; D) microgranular debris is present along with new crystals [Panels A-C: stal. # 81008:2; panel D: stal. # NB1].

Fig. 8. Off-axis holes as viewed in thin sections: A and B) oval shaped, rounded off-axis holes cut irregularly through growth bands. Micro inclusions are visible in growth bands (black); C) angular off-axis hole cut through thin calcite layers. Micro fissure connections to adjacent holes are also visible; D) "micro-stalagmitic" infillings. Note that each spike has internal growth lines, which mimic the external form of the tip of the spike.

"hoodoos", where selective corrosion has left pillars of rock. However, some of these features are ambiguous and may in fact be overgrowths as just described in Fig. 8D.

Lack of water: as reported in our previous paper essentially none of the OAHs that we have investigated contained significant amounts of trapped water, although, if present, water would be readily detectable in macroholes by Magnetic Resonance Imaging (MRI) scanning of uncut stalagmites (Shtober-Zisu et al., 2012). A previous study by Genty et al. (2002) had observed macroholes filled with water in stalagmites from two French caves. However, we have not found water present in any of the 26 stalagmites, which we studied. We here infer that water was probably present at the time when the holes were forming although whether they were partly or wholly filled is unclear (Shtober-Zisu et al., 2012).

Origin of holes

It is generally assumed that the interiors of stalagmites remain intact after deposition, although diagenetic features can be recognized in some stalagmites (Frisia, 1996; Railsback et al., 1997; Muñoz-García et al., 2012). However, the form and spatial arrangement of the macroholes described here suggests that post-depositional events – both corrosional and depositional – must occur in most cases of stalagmite formation.

Axial holes

Axial holes can be interpreted as syngenetic features resulting from local variation in the rate of calcite precipitation. These are aligned along the stalagmite axis and maintain open contact with the cave atmosphere during the formation of the stalagmite. While the exact cause of their formation is unclear, it presumably relates to the action of the falling drop locally reducing the rate of deposition of calcite and thus causing a small depression to form on the stalagmite apex. The rim of the hole continues to grow at a normal rate determined by the degree of supersaturation of the water and the rate of outgassing (Dreybrodt, 1980). When the process terminates (possibly due to a decrease in drip rate, or change in the position of the falling droplet), the cavity is then sealed by further calcite precipitation.

Off-axis holes (OAHs)

Corrosion-associated OAHs (which make up <5% of the total OAHs) date to a period in which the drip-water falling on the stalagmite was dissolving rather than depositing calcite. A large number of irregular notches, micro gours or small cavities are visible on many stalagmites surface (e.g. Fig. 1) which may indicate syngenetic development of OAHs with the stalagmite growth. We hypothesize that dissolutional features (e.g., Fig. 3B) were produced when drip water undersaturated with respect to calcite penetrates along micro-fissures within a stalagmite. Like normal OAHs, the resultant cavities tend to be oriented normal to

Fig. 9. Calcite coatings and new crystals growing epitaxially within off-axis holes. A) SEM imaging; B) new crystals grow to form new coatings along the hole's walls; C and D) no coatings are visible, new crystals grow directly on the holes' substrate. Note the stalagmite growth layers cut by the holes.

the growth surface but are clearly enlarged upwards, showing that they formed during corrosion of the surface. Such erosive events were also reported by Railsback et al. (2013), who interpreted: (1) irregular termination of layers present on the stalagmite's flank; (2) dissolution cavities; and (3) coatings of non-carbonate detrital materials as wet periods during which drip water dissolved pre-existing stalagmite layers.

However, most OAHs do not terminate at a growth surface but cut discordantly through internal growth layers. This requires dissolution processes occurring within the sealed stalagmite and their formation necessitates the presence of undersaturated, corrosive water. Certain other characteristics of these OAHs may be relevant to explain the mechanisms by which they form. While these characteristics are not universally exhibited by all OAHs, they are sufficiently common as to characterize them as a discrete natural phenomena.

The mechanism of formation of OAHs

Based on these observations, we propose a hypothesis as to the mechanism of formation of OAHs.

The corrosion-associated OAHs (<5% of the total OAHs) were clearly associated with a former growth surface during a corrosional stage earlier in the history of the stalagmite (Fig 3B). Within these stalagmites, the holes appear beneath the stalagmite surface suggesting that calcite precipitation during stalagmite growth has subsequently sealed cavities off from the outside environment under new calcite layers. When environmental conditions change, the corrosion

associated holes are closed and dense calcite is deposited for the next period.

However, most stalagmites we studies showed no external corrosion features. Indeed, it is striking that stalagmites, which appear from the outside to be wholly intact reveal extensive internal macrohole formation. From a chemical perspective, this means that water in contact with the outside of these stalagmites was always at least slightly supersaturated with respect to calcite. That is, the ratio of the equilibrium constant to the activity product for calcite was always > 1 or, as it is usually expressed:

$$(1) \Omega_{ct} = \log [K_{sp} / a_{CO_3} * a_{Ca}] > 0$$

Therefore we conclude that the hole-forming process is a post-depositional shift in the chemical equilibrium to $\Omega_{ct} < 0$ at specific loci inside the stalagmite, causing dissolution and thus, diagenetic (secondary) porosity.

In our SEM studies of the Te'omim stalagmite, we observed abundant evidence of bacteria and bacterial activity inside OAHs and on the surface of this stalagmite. This is not surprising, given the ubiquity of bacteria in near-surface environments. Furthermore, it is known that some microorganisms can enhance the dissolution of $CaCO_3$ (Cañaveras et al., 2001; Jones, 2001). Heterotrophic bacteria that consume reduced carbon and produce CO_2 as a waste product, can react with calcite as follows:

Fig. 10. Secondary Electron Scanning Micrographs of: A) bacteria coating an axial hole surface, forming biofilms along the wall of the axial hole (B); C) organics, filaments and coccoid cells on an off-axis hole surface (note weathered calcite crystals); D) clean surfaces of calcite within and around micro-inclusions.

Two other unrelated facts are necessary to understand the origin of OAHs. First is the observation that stalagmites display varying degrees of permeability. We have demonstrated this by attaching a calibrated tube containing 1 cm³ of water to the surface of a stalagmite, which displayed no obvious fissures or cavities on its surface. Over the course of an hour the water penetrated into the stalagmite. Munoz-Garcia et al. (2012) carried out more careful experiments to show a wide range of capillary uptake of water across surfaces of cubes cut from the interior of a stalagmite. The most likely loci for the pore system along which fluids can migrate is the boundaries between crystals, especially linear triple junctions where three crystals meet, each oriented with its 'c' axis normal to the growth surface, rugged surfaces of stepped and kinked crystals, crystal defects or other features related to the calcite fabric (Railsback et al., 1994; Frisia et al., 2000).

The second relevant fact is that organic matter is present in caves which could be transported into the interior of stalagmites by permeating water. One source is cave drip water which contains dissolved or suspended organic matter, and which could serve as

a nutrient for heterotrophic organisms (Hartland et al., 2012). Also, various organic materials are present in many caves including the excreta and remains of bats and other spelean fauna, and fungi living on these deposits. Thanks to the permeability of speleothems, organic-laden water could penetrate into the deep interior of stalagmites through micro fissures or along rugged surfaces of the crystals (Shtober-Zisu et al., 2012). Humic substances and other organic molecules have been extracted from stalagmites (van Beynen et al., 2000; Blyth et al., 2007).

Although the majority of previous studies relate speleothem evolution to purely chemical process, in recent years many studies identify microbial activity as a factor which affects the rate and form of speleothems (e.g. Cox et al., 1989; Cunningham et al., 1995; Jones, 2011). Conversely, bacterial activity is also an important factor in controlling bio-erosion in caves (Viles, 1984; Northup and Lavoie, 2001; Naylor et al., 2002; Cockell and Herrera, 2008). These two competing effects can occur simultaneously. Constructive processes include calcification, trapping and binding detrital particles and microbially induced calcite precipitation. Destructive processes include

Fig. 11. Six types of stalagmite inner structures, as visualized by CT: A) Intact; B) Random sparse distribution; C) Axial hole dominant; D) The spongy type; E) The layered confined holes type; F) The mix type.

substrate breakdown by dissolution, boring and residue micrite production (Danin, 1993; Jones, 2010). For example, a strain of *Shewanella oneidensis* was allowed to colonize calcite and dolomite surfaces, resulting in a) inhibition of carbonate dissolution through interference with etch pit development; and b) excavation of carbonate material at the cell-mineral interface during bacterial attachment to the mineral surface (Davis et al., 2007). Other organisms known as active agents in biokarst are algae, fungi, lichens and other living macroforms (Vaughan et al., 2011, Fairchild and Baker, 2012).

As water permeates through the calcite, it would equilibrate with the calcite and reach $\Omega_{ct} = 0$. But somehow, at a point deep inside the stalagmite, it must then become under-saturated; a conceivable mechanism for this is a biological one, namely bacterial oxidation of organic matter. We therefore propose that OAHs could be enlarged, affected, or produced by the action of bacteria living inside the stalagmites, forming secondary/diagenetic porosity. Through their metabolic activity as described above they would locally generate a lowered pH, which would result in the dissolution of the host calcite. The elongated form of the resultant cavities indicates that the area of maximum bacterial activity is focused along a linear feature than is oriented normal to growth layers. This could be the boundary between two calcite crystals, or the triple junction between three crystals (Railsback et al., 1994).

The process of hole formation in a particular stalagmite would begin sometime after the layer had finished growing and was buried by some 1 to 2 cm of further growth. Then water could permeate into the interior, carrying bacteria as well as organic molecules (nutrient). In some cases it is possible that access to the interior of the stalagmite could be through a pre-existing axial hole that had not yet been sealed, along crystal boundaries or micro fissures. This model would predict that holes tend to be concentrated in layers within the stalagmite in which the crystal fabric allows most easy access of water, bacteria and nutrients. Future studies will attempt to test whether there is a correlation between the permeability of a layer and the occurrence in it of OAHs. We would also predict that OAHs would be more commonly encountered in caves in which the drip water is richer in dissolved nutrients. This could be tested either by analysis of the drip waters (which would give only current values) or through analysis of the speleothem itself for content of organic carbon.

In most cases, the process of hole formation will have taken place long ago and approximately coeval with the time of formation of the stalagmite itself, when organic-bearing drip water was still flowing over the surface of the stalagmite. The fact that the inner walls of most holes are covered by later overgrowths of calcite shows that the hole forming period when $\Omega_{ct} < 0$ eventually ends, and water with $\Omega_{ct} > 0$ enters the hole, causing it to fill in partly with new calcite: a “cave within a cave”.

CONCLUSIONS

We have examined twenty-six stalagmites from a variety of settings and shown that almost all have a variety of microscopic to macroscopic pores. X-ray computed tomography (CT) confirms that these holes are true spelean features, rather than artifacts of sectioning or of preparation of thin sections. These individual holes can be divided according to their position into two important categories: axial holes and off-axis holes. *Axial holes* form along and parallel to the stalagmite axis; they are usually elongated, ranging in length from 0.5 to 4 cm and their width may reach 1 cm. A significant feature of the axial holes is the downward bending of the surrounding growth layers towards the holes; *Off axis holes* (OAHs) are developed away from the stalagmite axis. They cut discordantly through growth layers, and rarely terminate at a current growth surface. OAHs are usually more rounded and smaller than the axial holes, ranging from 1 mm up to 2 cm; their axis vary from parallel to the stalagmite axis to parallel to the crystal growth axis.

Stalagmites can be divided into six categories according to the spatial distribution of their macroscopic holes: intact stalagmites (having no holes at all), stalagmites with random sparse distribution of holes, stalagmites dominated by axial holes, stalagmites with abundant random holes, stalagmites with layer-confined holes, and stalagmites with a combination or mixture of holes. Holes can also be categorized by internal surface features, i.e. by eroded walls, or on the contrary, by new overgrowths of crystals along the walls.

Possible origins of OAHs in stalagmites include (1) corrosion of micro gours on the surface of the growing stalagmite, enhanced by further dissolution beneath the stalagmite surface and followed by calcite precipitation during further stalagmite growth sealing off these cavities; (2) a post-depositional shift in the chemical equilibrium to $\Omega_{ct} < 0$ at specific loci inside the stalagmite as water penetrates through micro fissures and dissolves the calcite, forming diagenetic porosity. The process could be enhanced or even triggered by the action of bacteria living inside the stalagmites. Bacteria are capable of creating the lowered pH conditions necessary for corrosion of the host calcite through their normal metabolic activity. The known permeability of stalagmites would permit entry of the bacterial spores and continued supply of nutrient in the form of dissolved organic species derived either from the soil or from excretions of resident spelean fauna (principally bats). We have shown bacteria inside off-axis macroholes, and on the surface of an active growing stalagmite from a cave in Israel.

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