Are reshaped speleothems reliable indicators of former rises of the karstic base level? Some criteria for distinguishing between flooding, hydrodynamic reuse and biocorrosion

Laurent BRUXELLES[1,2], Jean-Yves BIGOT[3], Didier CAILHOL[1,4], Grégory DANDURAND[1,4], Jean-Louis GALERA[3], Frédéric SWIERCZYNSKI[5], Nathalie VANARA[4,6] & Franck VASSEUR[7]

(1) TRACES, UMR 5608 du CNRS, 5 Allées Antonio Machado 31058 Toulouse, France Laurent.bruxelles@inrap.fr (corresponding author)
(2) GAES, University of the Witwatersrand, Johannesburg, South Africa.
(3) Association Française de Karstologie (AFK)
(4) Inrap, 13 Rue du Négoce, 31650 Saint-Orens-de-Gameville, France
(5) *Underwater Experience* (*UWX*), 13740 Le Rove, France - https://uwx.fr/
(6) Université Paris 1 – Panthéon-Sorbonne, France
(7) Celadon, France - http://celadons.free.fr/

Abstract
Classical speleothems (stalactites, stalagmites, pillars and flowstones) form in the vadose parts of karst cavities. Their presence therefore represents the total or partial, sometimes temporary, dewatering of associated parts of the karstic network. Conversely, the hydrogeological reuse of an old gallery, for example in connection with the rise of the base level, limits or even stops the development of these concretions. When cavities are flooded, corrosion of the speleothem surface or mechanical erosion (abrasion by sand, pebbles impacts) can alter their morphology. Many highly altered concretions, recognized in fossil networks across the world, have been interpreted as indicators of previous base level rises. The resultant hydrodynamic interpretations sometimes require the development of complex supporting geodynamic hypotheses. But it appears that in many cases speleothems are instead affected by biocorrosion linked to the ancient presence of bat colonies. Guano fermentation and convection of acidic gases combined to deeply reshape nearby calcite deposits – meaning that these altered speleothems were never submerged after their formation. We will present some examples of this process and some criteria that allow us to distinguish submerged concretions from those that were affected by biocorrosion.

1. Introduction

Apart from a few special cases, percolation concretions such as stalactites, stalagmites, pillars or stalagmitic flows have formed in the vadose zone of the karst. Indeed, it is the combination of the outgassing of CO_2 in the cave atmosphere and the dripping or flow of a film of water guided by gravity that are at the origin of these common speleothems. However, they are characteristic of a very specific area of the karst located between the epikarst and the submerged zone. These concretions, some of which can date back several million years, therefore characterize the ancient and present condition of this environment. In fact, when cave divers observe this type of concretion underwater, it undoubtedly indicates that the hydrogeological context has changed.

But can we necessarily assume that the presence of altered or eroded speleothems is only indicative of reflooding of the cavity? Are there other phenomena capable of significantly reshaping these concretions? If so, what are the criteria that make it possible to distinguish them to avoid the interpretative implications of a rise in the base level and complication of the local geodynamic or geomorphological evolution each time an eroded concretion is observed? Here, we will demonstrate that biocorrosion may represent an important contributor to the erosion of concretions and that there are distinctive criteria that allow it to be identified.

2. Materials and methods

As part of our work on biocorrosion since 2020 (BRUXELLES *et al*., 2021), we have studied more than 200 cavities in the south of France, allowing us to compile a substantial corpus of biocorrosion evidence. Each exploration was documented by a photo session and observations were all recorded in dedicated reports. To document the processes, samples were taken, both for geochemical analyses, petrographic observations, or for dating. In some cavities, we carried out

3D scans to quantify these shapes as well as photogrammetry, for example for the pillar of the Isturitz cave (Fig. 1).

While the impact of biocorrosion on speleothems has been clearly demonstrated (AUDRA *et al.*, 2016; BRUXELLES *et al.* 2021), particularly using geochemistry, it was important to review, for comparison, those subjected to more classic karstic processes to be able to distinguish their forms. Thus, several cave studies were devoted to active or semi-active caves without traces of biocorrosion. We were then able to document the impact of floods and erosion on the speleothems. Similarly, it was important to take into account examples of flooded galleries in our repository. We have therefore integrated observations of cave divers carried out on concretions from different karstic areas.

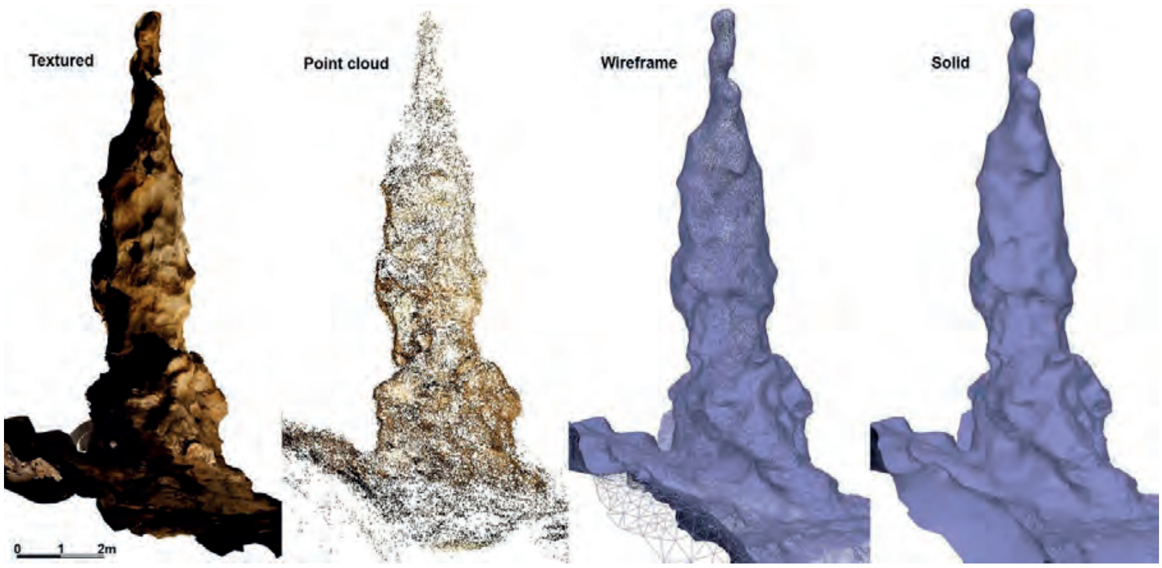

Figure 1: Photogrammetric model of the biocorroded pillar from Isturitz cave (France). We can clearly see the curious morphology of this concretion, hollowed out by numerous large scallops, generally interpreted as proof of the reflooding of the cave. But here, these forms correspond to biogenic conches which are typical signs of intense biocorrosion (photogrammetry: L. Bruxelles).

3. Results

It is not possible to present an exhaustive analysis in the context of this article, so only some results will be presented here, but it is already possible to propose distinctive criteria.

First of all, the reflooding of a fossil and concretionary gallery is not necessarily accompanied by a dissolution of the calcite. In some cases, they are not altered (Fig. 2) or even serve as foundations for new kind of concretions. However, if the water is under-saturated in calcite or even slightly aggressive, the submerged concretions are subject to dissolution. Dissolution operates in a differential manner, the finest forms or the smallest crystals being altered first, resulting in an irregular, jagged appearance. Centimeter to multi-centimeter spoon-shaped scallops affect their surface, oriented in the direction where the water is flowing. When the flow is powerful enough, the concretions decorated with scallops are also profiled. In all the cases, the eroded calcite forms and limestone walls are significantly rough. Due to the different size of the crystals between calcite and limestone, for example, a differential response between the walls and the concretions is perceptible. The micritical rock (like limestone) is much less resistant than concretions made up of larger calcite crystals: it is dependent on contact surface structure. The result is that the retreat by dissolution is therefore less for calcite than for limestone.

Figure 2: Calcite flow and small stalactites minimally affected by the flooding of the gallery (Cova del Drac de Santany, Spain; photo: F. Vasseur).

If the flows carry a coarse detrital load (as often in the epiphreatic zone or in temporarily active karsts), mechanical abrasion locally affects the speleothems in addition to dissolution. The upstream face, sandblasted and impacted by pebbles, develop erosion facets and spoon-shaped scallops (Fig. 3). Here, one no longer recognizes initial details of the speleothem surface that are still preserved on the other side of the concretion protected from abrasion. The stalagmites even sometimes give the impression of curving upstream, their base being systematically eroded by the saltation of the grains. In the case of coarser sediments, calcite shows greater sensitivity to the impact of pebbles. Indeed, the large crystals are more easily exposed by the percussion of the pebbles, and we observe a greater retreat for the calcite surfaces than for the limestone (Fig. 4).

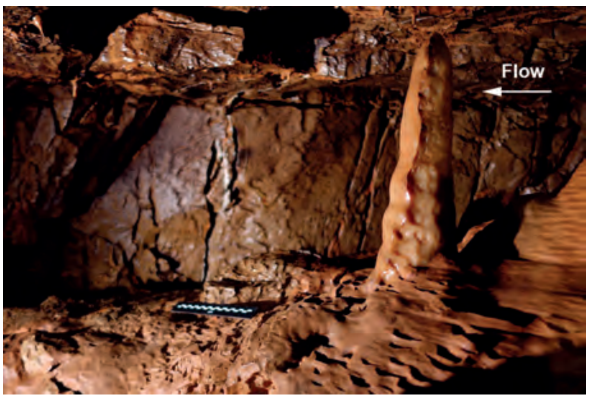

Figure 3: Stalagmite subjected to dissolution and sandblasting during floods. The part exposed facing the current (on the right) is faceted and affected by spoon-shaped scallops, while the other part is almost intact (Grotte du Sergent, France; photo J.-Y. Bigot).

Figure 4: Calcite flow eroded by the impact of gravels and pebbles. The retreat of the orange calcite is greater than that of the limestone (Grotte du Sergent, France; photo: J.-Y. Bigot).

Biogenic corrosion results from the occupation of a gallery by colonies of bats (MC FARLANE *et al*., 1995; LUNDBERG and MC FARLANE, 2012; AUDRA *et al*., 2016; BARRIQUAND *et al*., 2021). The release of CO_2 from their breathing, but above all, the acidic gases and aerosols released by the fermentation of the guano, radically change the conditions of the environment and affect both on the limestone walls and calcite concretions. One of the characteristics of biocorrosion is the smoothing of shapes. The speleothems take on a “ghostly” appearance (Fig. 1, 5, 6 and 7) revealing internal calcite laminae.

They can develop guano pot holes or biogenic lapiaz (see BRUXELLES *et al*, this volume). Sometimes, concretions may appear streamlined. This is due to the circulation of acid gases and aerosols in the cavity, either by convection above the piles of guano or due to the general aerology of the cavity. In all cases, biocorroded concretions do not show spoon-shaped scallops pattern and are smooth with very soft general shapes (Fig. 6). This is very different from the sharpness due to water dissolution.

Another distinctive criterion is that biocorrosion allows calcite and limestone to intersect on the same plane (Fig. 6). This phenomenon involves such strong acids (sulphuric, nitric) that no differential dissolution is observed: biogenic domes or conches develop between these two materials indistinctly, which is in contrast to the observations cited above concerning dissolution or abrasion. Stalagmites, pillars and stalagmitic flows are often marked at the base by a guano pile notch. It is then surmounted by cupolas of multi-decimetric order, smooth, organised vertically (Fig. 1 and 6). These are biogenic conches, formed by the condensation of acidic gases that rise by convection from the guano talus. The small draperies are the most sensitive to this phenomenon and can be the starting point of these conches.

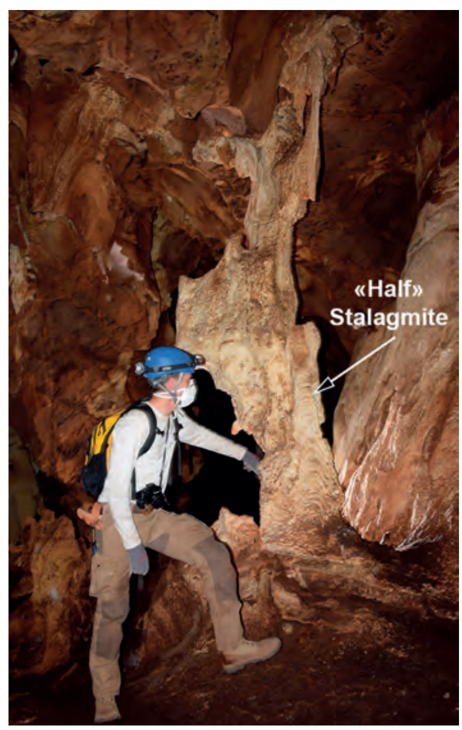

Figure 5: Biocorroded “ghostly” column. We recognize the internal laminae of the initial stalagmite which constituted the core of the column and therefore illustrate the importance of erosion (Gcwihaba cave, Botswana; photo: L. Bruxelles).

Finally, biocorrosion is accompanied by a large quantity of by-products, particularly phosphatic minerals. These are a result of the mineralization of the guano or the reaction of the guano fluids with the host rock. In the latter case, they form crusts that are found on the speleothems (Fig. 7) or residually in the crevices. If doubt still persisted solely on the basis of the forms of alteration of the concretions, the presence of these phosphates is an unmistakable sign of the action of biocorrosion and makes it possible to attribute the alteration of the concretions to corrosion of biogenic origin.

Figure 7: Grey light phosphate crust formed by the epigeny of limestone and calcite concretions, the truncated forms of which are recognized by biocorrosion (Grotte de la Roquette, France; photo: J.-Y. Bigot).

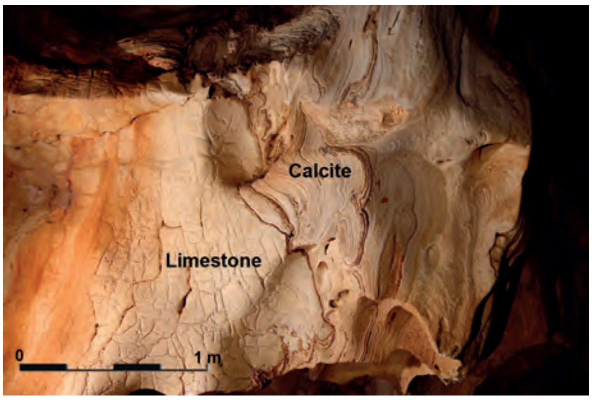

Figure 6: Biocorrosion forms are expressed in a comparable and continuous manner from the limestone wall (left) and over the entire calcite flow (Grotte des Fées, France; photo: J.-Y. Bigot).

4. Conclusion

Many caves around the world show altered or deeply eroded concretions. It is not always possible or relevant to interpret these as indicative of a reflooding of the system, a process that often carries important geomorphological implications. It is therefore important to ensure that the morphologies are not due to biocorrosion, which simplifies hydrogeological interpretations. A few distinctive criteria, resulting from extensive fieldwork, have been presented here and are sufficient in many cases to provide an initial diagnosis. The general smoothing of the detailed forms, the truncation of the bedrock and the concretions on the same plane, the presence of other forms of biocorrosion or the persistence of phosphate encrustation are all evidence that allow us to rule out the likelihood of reflooding.

Of course, the answer is not always binary. For example, in the Mescla cave (France), biocorroded concretions, covered with a layer of phosphate, were observed at a depth of more than 10m under water. They thus testify to the fact that the network was re-flooded after a phase of concretion and a period of occupation of the cave by bats. This shows the complexity of the karst, but also the wealth of information it contains if you have the right reading criteria.

Acknowledgments

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