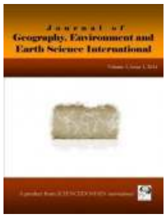

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Study of Rare Corrosion Forms Found in a Karst Syphon

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The aim of this article is to describe two-dimensional scallops (scallops guided inside ribs) found in a syphon, to compare them to the ordinary three-dimensional corrosion forms frequently found in karst systems (scallops and flutes). We also raise a certain number of questions regarding analogical and numerical modeling.

The syphon is named “Combe du Creux” (department of the Doubs, France, EU). We have been exploring this flooded cave since 2003. Since 2015, we are studying its morphology and especially its scallops.

When diving underwater underground (cave diving), observation work is more difficult. Therefore, photographs of the forms, of the tools used to measure them, have been made in order to be processed afterwards.

The ordinary scallops found at four locations inside the cave have been documented, as well as two-dimensional scallops found at a fifth location. Very likely, these particular scallops have formed inside pre-existing ribs. They seem, from a qualitative point of view, to behave like ordinary scallops: they have qualitatively the same profile and obey the Curl relationship. However, regarding details, differences appear and lead to new questions about the formation and evolution of scallops: what is the influence of the material (kinetic and diffusion coefficients)? Of the flow

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rate? Of the boundary conditions?
Ultimately, we insist on the fact that studying scallops in caves or modeling them is still an open field.

Keywords: Cave science; cave diving; Karst; scallops; corrosion; modeling.

1. INTRODUCTION

Scallops and flutes have been extensively studied since the 1960's. Curl [1,2,3] established the link between the wavelength and the velocity that is still in use. He also investigated the phenomenon at seizable scale using Paris plaster models. After this landmark, the study has continued in two different ways. On one hand, the Curl relationship and its refined versions [4] have been extensively used during field studies, in order to investigate the velocity of past flows knowing the averaged wavelength of the scallops or flutes [5,6,7]. On the other hand, theoretical studies based on hydrodynamical numerical [8,9] or analogical models [10,11] have been developed in the field of cave science or in other fields [12].

Therefore, it exists a certain gap: a majority of karst field studies assumes the validity of the Curl relationship in any circumstances and do not question it; whereas a majority of models are based on simplified situations. Paris plaster has not the same kinetic rates as limestone [13]. It has neither the same texture nor the same degree of homogeneity than limestone. Most of numerical models are bi-dimensional on the contrary of actual scallops, that are three-dimensional. Eventually, a lot of models assume a steady flow.

We have found some bi-dimensional scallops during the exploration of the syphon extensively described in [14]. These peculiar scallops are not flutes but forms that have been guided inside pre-existing ribs. By describing them, comparing them to more common three-dimensional scallops found in the same flooded cave and also recalling certain ideas developed in [15], we hope to contribute to a reduction of the aforementioned gap.

2. MATERIALS AND METHODS

2.1 Global Description of the Flooded Cave and Methods of Investigation

2.1.1 Description of the syphon

We have been diving the Combe du Creux since 2003. More recently the systematical documentation of this sump has been undertaken. This flooded cave is located in the department of the Doubs (France, EU). It has the following coordinates: latitude 47°28'32" N and longitude 06°33'25" E. Precisions can be found in the article recently published [14], which insists on the complex history of this syphon. Scallops have been observed inside the cave at the five different stations that are pinpointed on Figs. 1 & 2.

2.1.2 Working underground underwater

Throughout the rest of this article, it must be kept in mind that cave diving is the only way to investigate such a flooded cave and that underground underwater work is more difficult than ordinary work. In addition it has to be done faster. For instance, 25 minutes spent in the deep zone oblige to perform 25 minute decompression stops if using pure oxygen at -6 m, more time if using only air. The temperature of the water is 10 °C only. This is why the main method of investigation has been underwater photography of the forms and tools used to measure them (mainly rule and tiler depth gauge). The photographs can be exploited afterwards, once the dive finished. Using the software GIMP, lengths in pixels have been measured and converted into lengths in millimeters or centimeters. Due to different sources of possible errors (lens of the camera leading to aberrations, non-planeness, parallax errors), the global precision of the measurements is of order of 10%: this enable quantitative comparisons, but to a low degree of precision. Although the study isn't finished and more data are expected, the data presented and discussed here are also less numerous than in most of the studies made in non-flooded caves.

2.2 Description of the Studied Scallops

2.2.1 Ordinary 3D-Scallops

The scallops found at the locations 1, 2, 4, 5 are the normal, three-dimensional, objects commonly found (see for instance [2]) in caves. The location 5 consists of two parallel vertical pits, a main one having a width of about 3 m separated by a wall from a narrower pit (top view in Fig. 3, elevation in Fig. 4). This part of the cave has not always been flooded: when it was not, ribs formed on the separation wall and on the wall of the secondary pit.

2.2.2 Peculiar 2D-Scallops

Two-dimensional 'abnormal' scallops can be observed inside the aforementioned ribs (Fig. 5). Fig. 6 shows that these forms are not forced by the bedding planes, which are thicker. Fig. 7 shows the symmetrical cross section of a rib. It has not the profile of a flute (described for instance in [1]). This excludes the possibility these ribs formed in flooded conditions. Fig. 8 shows the asymmetrical cross-section of a 2D-scallop. It has qualitatively the same asymmetry than ordinary scallops, which suggests the same morphogenesis. This profile doesn't support the hypothesis that ribs formed over pre-existing ordinary scallops. In addition, the repartition of these 2D-scallops suggests they formed only in areas exposed to the main stream (Fig. 9).

2.3 Longitudinal Size of the Scallops

Table 1 presents measured lengths of scallops at the five locations pinpointed in Fig. 1 and 2. Table 2 presents the corresponding velocities deduced from averaged lengths. It includes the location 3, treated regarding velocity calculations like 'ordinary' 3D-scallops. For each location, Table 2 presents three different mean velocities. The first (a) has been produced calculating

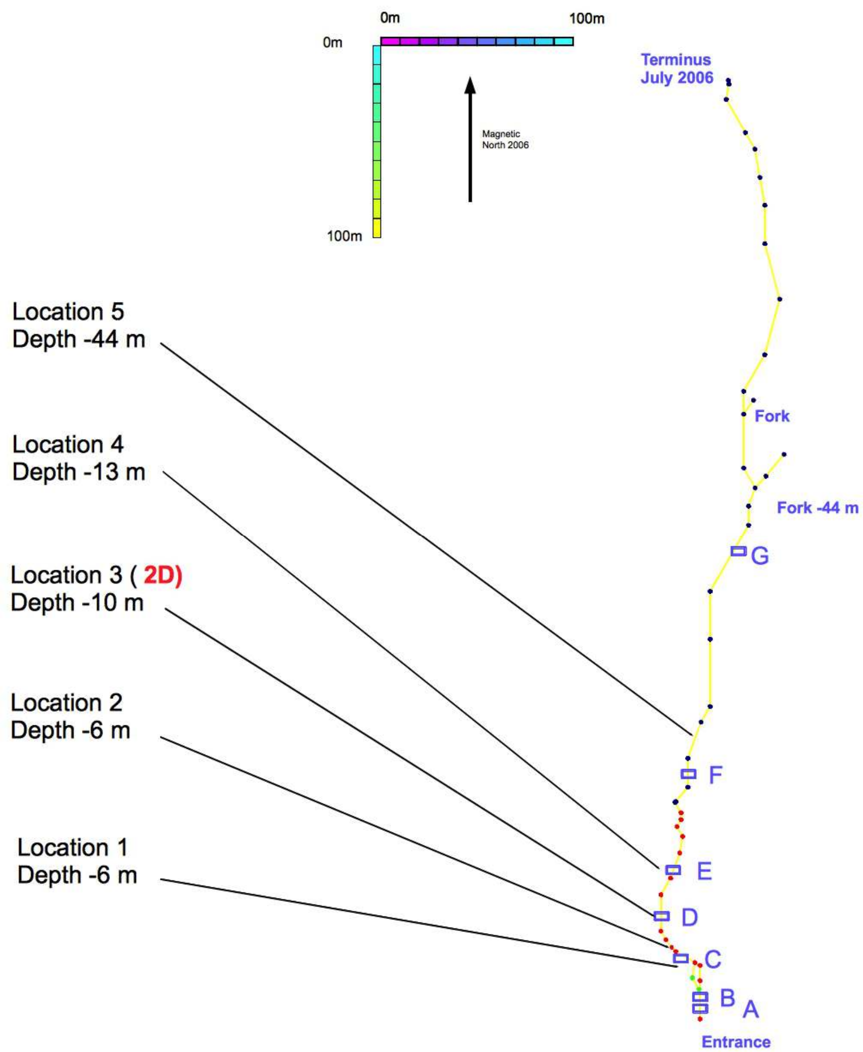

Fig. 1. Plane survey of the Combe du Creux indicating the locations where the scallops have been studied. Redrawn after Fig. 2 of [14]

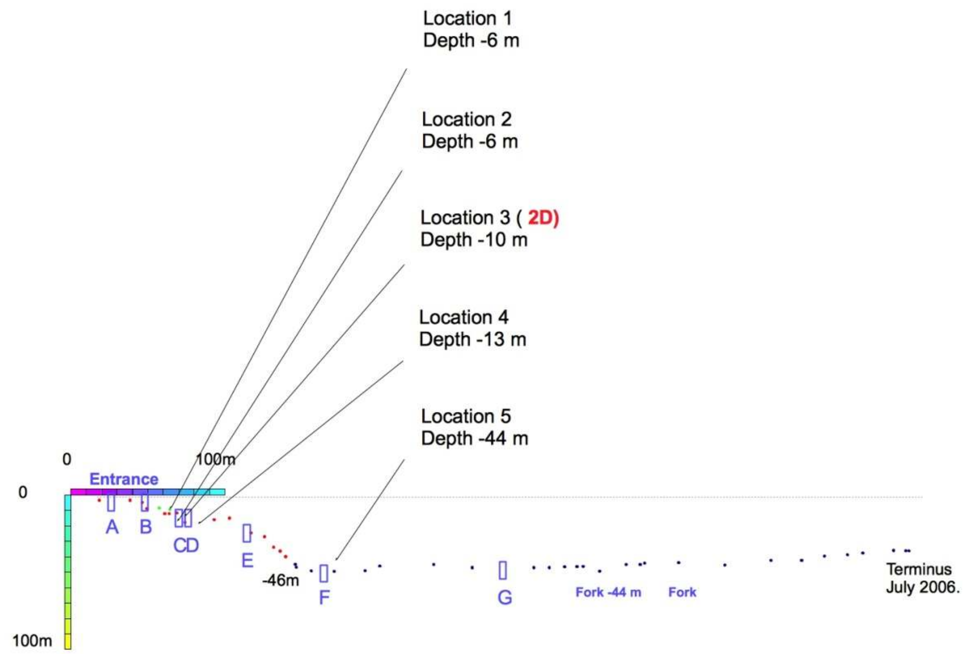

Fig. 2. Elevation of the Combe du Creux indicating the locations where the scallops have been studied. Redrawn after Fig. 3 of [14]

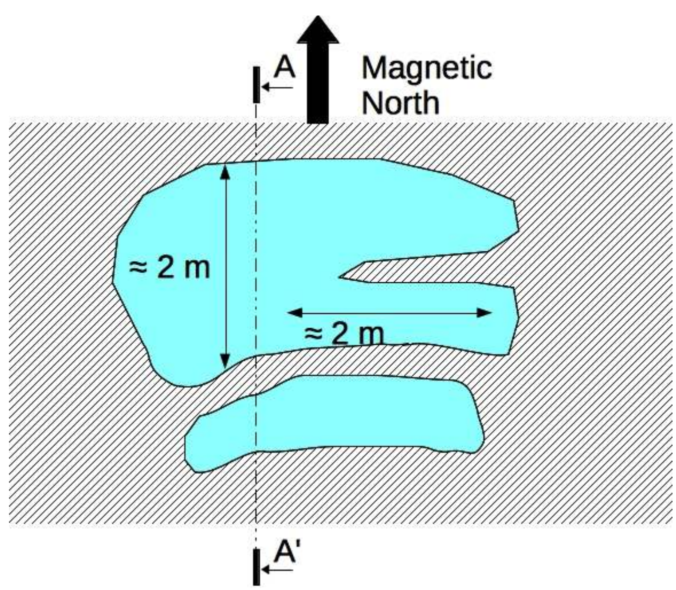

Fig. 3. Top view of the passage exhibiting two-dimensional scallops

an ordinary mean length, then producing the corresponding velocity using the Curl relationship. The second (b) has been produced calculating a non-linear Sauter mean value (presented, for example, in [4]), then producing the corresponding velocity using the Curl relationship. The third (c) has been produced calculating the velocity corresponding to each length using the Curl relationship, then averaging the velocities. For 10 ℃ water, the Curl relationship is tantamount to velocity (cm/s) = 320/lenght (cm). It must be pointed out that doing the Sauter average (b) gives more importance to the long wavelengths, whereas doing the average (c) gives more importance to the short wavelengths. The ordinary average (a) lays in-between.

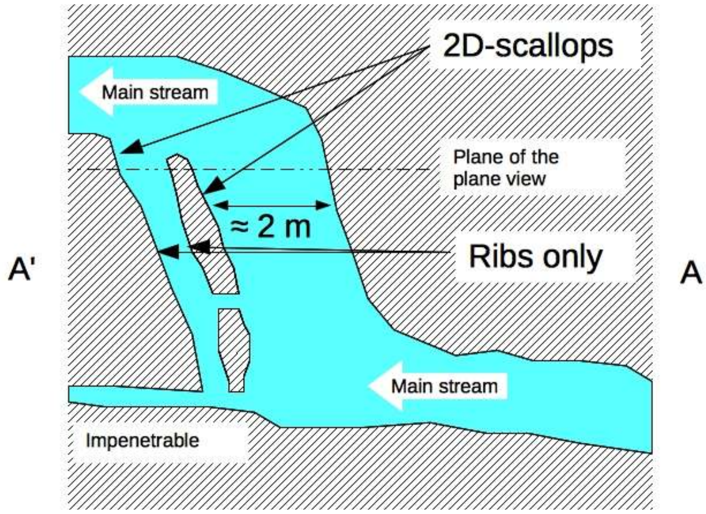

Fig. 4. Elevation (AA' of Fig. 3) of the passage exhibiting two-dimensional scallops

Fig. 5. Photograph of the passage exhibiting 2D-scallops. The video lamp and the rope (about 10 mm thickness) give the scale. The main pit is at left and the secondary one at right

Table 1. Measured lengths (cm) of scallops at different locations inside the syphon

Location 1	Location 2	Location 3	Location 4	Location 5
3.0	2.6	4.5	5.0	2.8
3.5	3.5	4.9	5.2	3.2
3.6	4.3	7.5	6.8	4.0
5.3	5.2	7.8	7.0	4.9
5.4	6.0	8.1	7.4	5.2
5.7	6.8	3.9	8.0	6.2
6.0	7.2	4.1	8.3	6.7
6.2		4.9	8.3	6.9
6.8		5.7		7.5
7.3		6.2		8.1
10.4				9.9
11.6				10.7
16.0				

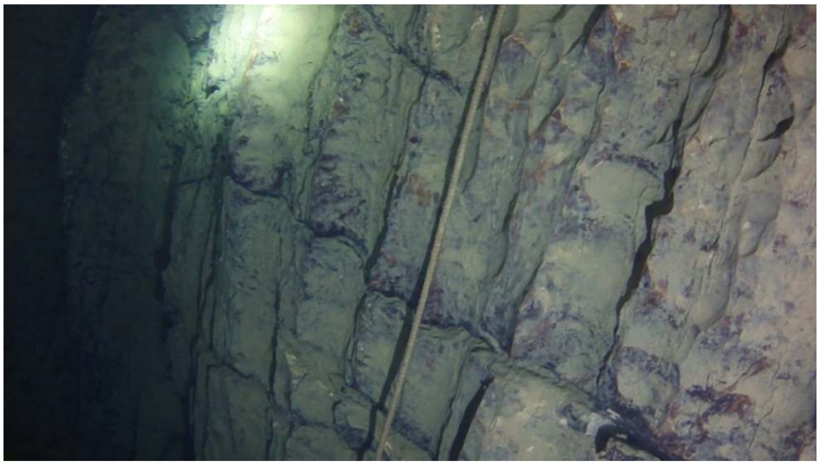

Fig. 6. Photograph of 2D-scallops and bedding planes. The rope (about 10 mm thickness) give the scale

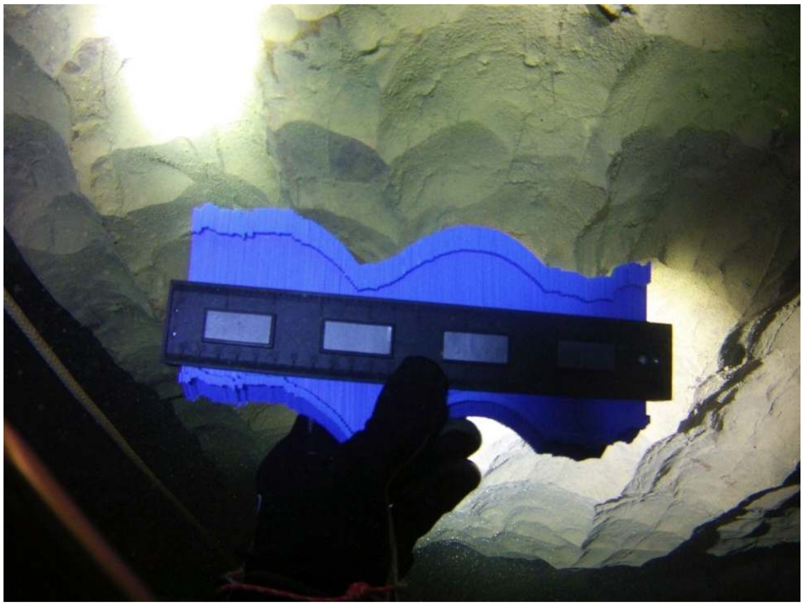

Fig. 7. Cross-section of a rib. The black part of the measuring tool is graduated in cm (below) and inch (above). Obviously, this profile is more symmetrical than a flute

Table 2. Averaged velocities (cm/s) at different locations in the syphon

Averaging	Location 1	Location 2	Location 3	Location 4	Location 5
a [1]	46	63	56	46	50
b [2]	30	54	50	43	40
c [3]	57	71	59	47	59
Interval [4]	27	17	10	4	19

[1] Deduced from an ordinary average of the lengths of Table1
[2] Deduced from a Sauter average of the lengths of Table 1
[3] Deduced from an average on individual velocities, each deduced from Table 1 applying the Curl's relationship at 10 ℃
[4] Subtraction of line c and line b

Fig. 8. Longitudinal section of 2D-scallops. The black part of the measuring tool is graduated in cm (right) and inch (left), stream from bottom to top

Fig. 9. Detailed photograph of an area exhibiting ribs. Scallops formed only in the part of the ribs that was exposed to the main stream.

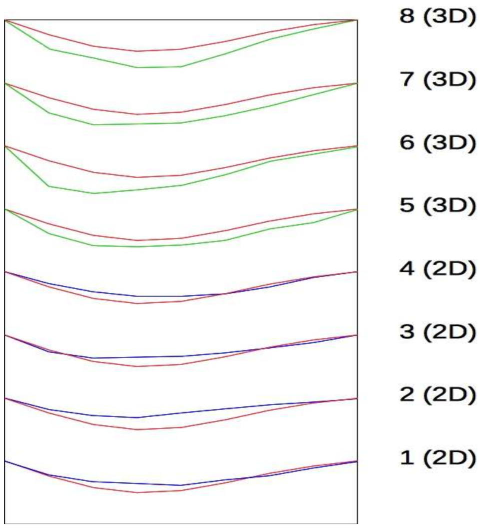

Fig. 10. Comparison of eight points of longitudinal profiles of 2D-scallops (green) and 3D-scallops (blue) found in the syphon with eight points of the standard profile (red) given by Lauritzen and colleagues in [8]. Flow from right to left

2.4 Longitudinal Profile of the Scallops

Fig. 10 enables to visualize longitudinal profiles of 3D-scallops and 2D-scallops. The profiles have been measured with the tiler tool visible on Fig. 7 & 8. Four profiles of 3D-scallops at or near the location 5 and four profiles of 2D-scallops at the location 3 are compared. All the profiles have been magnified or narrowed, rotated if necessary, in order to enable comparisons with the standard profile of Hammer, Lauritzen and Jamtveit [8]. According to the authors, their standard profile has been established with Paris plaster models. The eight points, regularly spaced, that have been treated for each profile enable a qualitative comparison. More measurements, of higher quality, would be required for a precise quantitative comparison: this is still in process.

3. RESULTS AND DISCUSSION

3.1 Sizes of the Scallops and Corresponding Velocities

3.1.1 Dispersion of the velocities corres-ponding to 3D-Scallops

The last line of Table 2 presents the dispersion of velocities according to the method a), b) or c) used. The right column of Table 3 present the dispersion of velocities according to the location 1, 2 3, 4 or 5. Both dispersions are of order 20 cm/s. This is compatible with the fact that 3D-scallops of locations 1, 2, 4, 5 formed in streams of the same order of magnitude: 51± 9cm/s according to a), 42±12 cm/s according to b), 58±12 cm/s according to c).

Table 3. Velocity interval (cm/s) over the different locations in the syphon

Averaging	Interval
a – Ordinary average	17
b – Sauter average	24
c – Average on individual velocities	23

As already pointed out, the cave has had a complex history, it has undergone several variations of water level (designed by the levels α, β, γ, δ, ε, ζ in [14] and in Fig. 2). Fig. 11 suggests that the scallops at location 5, that are found only at the floor of the passage, formed when this passage was not totally flooded; this corresponds to a water level by far lower than the one needed to form scallops at locations 1 or 2. Therefore, the 3D-scallops of locations 1, 2, 4, 5, which formed at different altitudes, certainly also formed and evolved at different times.

3.1.2 Link between the size of the 2D-Scallops and the corresponding velocity

The fact the scallops of locations 1, 2, 4, 5 correspond to the same order of velocity doesn't prove, but strongly supports, the hypothesis that the 2D-scallops of location 3 also formed with this order of velocity.

Table 2 then shows that, if one uses the Curl relationship for 2D-scallops as if they were 3D-scallops, the velocities deduced from the mean lengths are located in the right ranges. According to a) the velocity 56 cm/s of 2D-scallops is within the range 51± 9 cm/s of 3D-scallops; according to b) the velocity 49 cm/s is within the range 42±12 cm/s; according to c) the velocity 59 cm/s is within the range 58±12 cm/s.

So we can conclude that, to the degree of precision of our measurements (semi-quantitative, no less than 10%), the Curl's relationship established for 3D-scallops is valid for these 2D-scallops as well.

Fig. 11. Photograph of the passage near location 5. Width about 5 m. Scallops are more apparent at the floor than at the ceiling; this suggests they formed when this part of the cave was not completely flooded

3.2 Comparison of Longitudinal Profiles of Different Scallops

3.2.1 Comparison between the profiles of 3D-Scallops and the standard profile

Fig. 10 shows that some 3D-scallops found in the deep zone of the Combe du Creux don't fit the standard profile of Lauritzen and colleagues [8]: they are deeper than this standard profile. The two simplest explanations for this discrepancy are the following: either modeling with Paris plaster cannot render all the aspects of limestone scallops; or the conditions of Paris plaster modeling (with a steady stream) are not realistic (scallops found in flooded caves undergo at least seasonal variations of velocity).

In [16], Thomas suggests that details regarding the transportation of matter are not essential, on the contrary of hydrodynamics: vortices inherent in turbulent flow near a wall would be responsible for the creation and evolution of scallops. This possibility is also discussed, from a theoretical point of view, in [15]. If the case, further analogical or numerical models should include non-steady streams. The results of simulations with a constant velocity may be not completely realistic.

3.2.2 Comparison between the profiles of 2D-Scallops and the standard profile

Fig. 10 also shows that some 2D-scallops found at location 3 are slightly shallower than the standard profile. It exists several explanations to such a discrepancy. 2D-scallops may have a different precise profile than 3D-scallops. These 2D-scallops might be still in evolution and have not acquired their definitive profile yet. These 2D-scallops might be vanishing due to a too low velocity. In any case, further analogical or numerical models should focus on scallops guided inside ribs, whose boundary conditions are different from the boundary conditions of flutes. It is worth to point out that, at our knowledge, any study about the stability of flutes (why do they not split into several scallops?) has never been made.

4. CONCLUSION

To our knowledge, the form of two-dimensional scallops we reported has not been described yet. Investigating 2D-scallops in other caves and sumps would be particularly interesting.

The comparison of these 2D-scallops with the more common 3D-scallops shows that modeling this kind of phenomenon is still an open field. There is no evidence of discrepancy regarding the Curl relationship. Common questions about scallops and flutes, developed for instance in [9], are: how does an initial profile evolve towards a stable form? How do dissolution flutes evolve from initial surface defects? Beyond these questions, our observations raise other questions such as: how evolve scallops undergoing velocity variations? What is the influence on the shape of the scallops of the chemical properties of the material? Of the diffusion coefficients? What is the influence of the boundary conditions on the precise shape of the scallops?

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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