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Author's contribution

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

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ABSTRACT

This article deals with speleology applied to the exploration of a siphon named "Combe du Creux". It is located in France, in the department of the Doubs. We present surveys and the specific forms that are encountered in this flooded cave; eventually we propose a possible evolution of this sump.
Cave diving, regarded as cave science, closely associated to underwater photography, is a good mean to investigate such a cave.
We have been diving in this sump since 2003 and we present the results of 13 years of explorations, up to July 2016.
After having explored this cave up to the farthest known point, we made a survey (elevation and plane view). Further dives, using a rebreather when necessary, enabled a work of observation and underwater photography.
We observed concretions – limestone as well as clay – and potholes below the current water level. We also observed ribs and scallops. The underground development of the cave seems well correlated with geologic elements that can be observed outside.
The set of all the observations leads to the conclusion that, at long time scale, the water level has fluctuated. It has been, at least once, 46 m (151 ft) below its current position. In one place inside the cave, it has been observed interactions between flutes and scallops: this new information should be taken in account in any new theoretical or computational modeling of scallops.

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Keywords: Cave diving; flooded concretions; flooded potholes; scallops.

1. INTRODUCTION

This article deals with cave diving, regarded as a mean of investigating flooded caves. The investigation of sumps (example in [1]) is of first importance because this kind of cave is less easily explored than other caves. There is a relative lack of data that can even lead to some biases, as explained for instance in [2]. Numerous explorations of sumps have already been reported. However, despite the fact a lot of them have been dived, very few sumps of the French region named “Franche Comté” have been fully described [3,4,5]. This is why describing one of the siphons of this area, the “Combe du Creux”, is particularly interesting. Fig. 1, which is an excerpt of the Geological Map [6], presents the location of the cave and sketches the geologic context. It shows that the cave develops in the Jurassic level J5 (Argovian limestones), between the Jurassic level J4 (marl of the lower Oxfordian) and the Jurassic level J6 (Rauracian limestones).

The cave entrance is pinpointed by a red arrow. The underground development of the main gallery roughly corresponds to the North-South direction. The large scale fractures that can be seen on the map have the same direction. This flooded cave, or siphon, is located in the department of the “Doubs” and belongs to the geographic massif of the French Jura. The latitude of the phenomena is 47°28'32" N and its longitude is 06°33'25" E. Thanks to some previous results from other cavers (pages 151-160 in [7]) the cave has been explored up to its current terminus and surveyed. The plane view corresponds to the Fig. 2, which includes some cross-sections of the gallery. The red points correspond to the shallow zone near the entrance and the dark blue points to the relatively deep zone farther. The two green points correspond to a secondary gallery that develops at a depth of about 6 meters, near the oxygen stops, and that has been investigated too. The blue rectangles pinpoint areas of special interest that are presented and discussed below.

The elevation corresponds to the Fig. 3. The colored points have the same meaning than in the plane view. The orange lines with Greek letters correspond to presumed former levels of the water table, which are presented and discussed below. Underwater photography is more faithful than simply memorizing things: associated with the survey of the cave, it enables the report of several genuine observations. Some of them are linked with open questions regarding

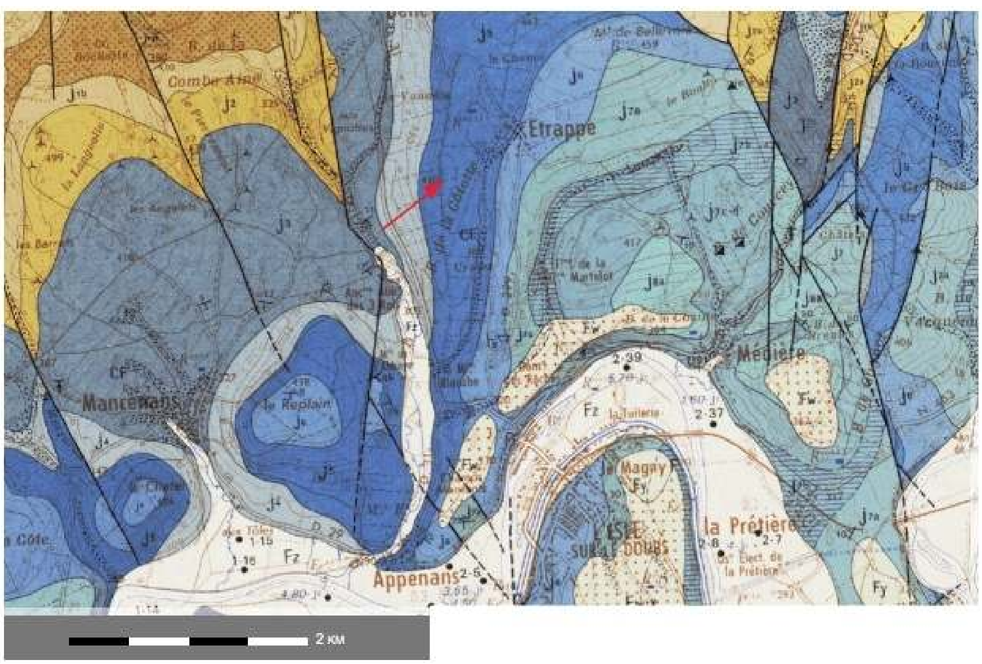

Fig. 1. Location of the Combe du Creux and geological setting. © BRGM – Excerpt of the geological map N°474 (Montbéliard) at scale 1/5000 0. Author. R16/19

the evolution of ribs, flutes and scallops (for instance pages 30-36 of [8] for clear definitions), or the depth of the conduits below the water table. Morphologies that cannot form underwater (stalactites, stalagmites, potholes, etc.) have been observed underwater: this demonstrates that the "Combe du Creux" has had a complex history, as developed below.

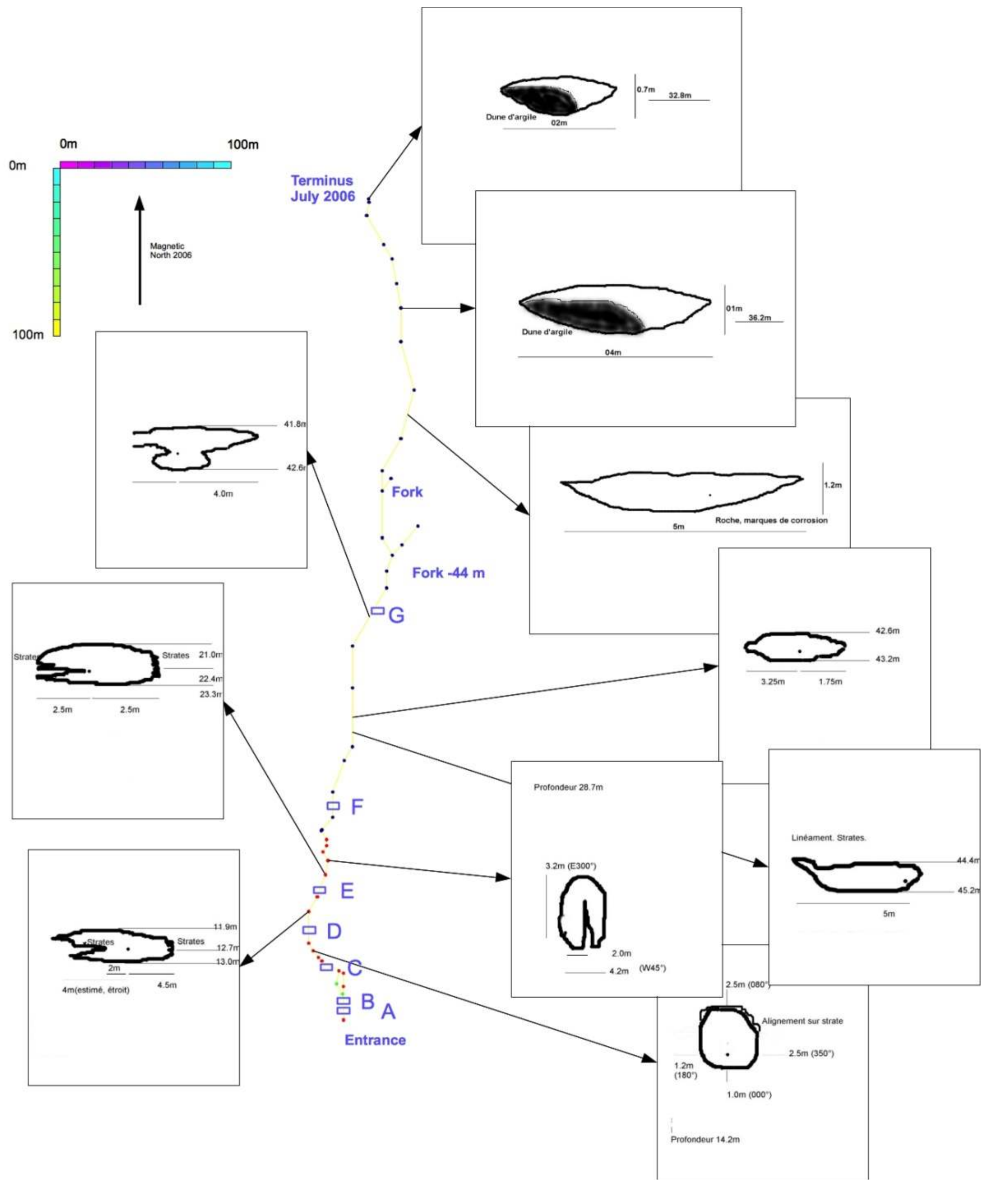

Fig. 2. Plane survey of the Combe du Creux

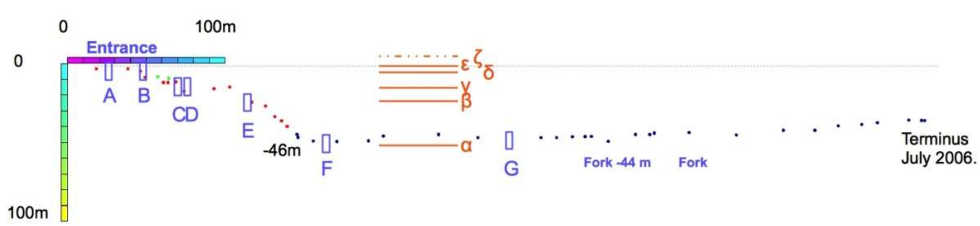

Fig. 3. Elevation of the Combe du Creux

2. MATERIALS AND METHODS

Complete explanations about the techniques and aims of speleology and cave diving are beyond the scope of this article. This section insists only on some specific details.

2.1 Exploration of the Cave and Survey

Cave diving can be regarded as a scientific practice in order to investigate flooded caves. According to different national or international clubs and federations, it can also be regarded as a sport or even a leisure [9]. Because of these opposite points of view, it doesn't exist only one way of practicing such an activity. However, there is a general agreement that using a guideline ([10] for instance) is necessary. The guideline that has been installed in the cave has tags every ten meters (33 ft) indicating the distance from the entrance and the sense. Associated with direction measurements using a magnetic compass and depth measurements using a diving computer, this enables to produce a survey (topography) of the cave. The procedure is explained, for instance, in [11] and [12].

The raw data can be processed with a software such as VisualTopo [13] or Survex [14] in order to produce a plan view, an elevation, or other documents. Survex has the deep advantage of being easily available also for operating system based on UNIX (such as Linux or MacOS). Only some sections of the gallery have been measured, but they have been precisely measured. They are produced along the plane view (Fig. 2). This has been preferred to systematic but less thorough measurements at each topographic point. This latter technique often leads to a much more subjective drawing, less accurate although more beautiful. The elevation of Fig. 3 shows that only a part of the siphon is shallow, the rest is below the 40 meters (131 ft). This has the practical consequence that the diver must undergo decompression stops after each important dive. Following a minor incident, it appeared that the official French decompression tables of the “Ministère du Travail” - MT92 tables [15] were not very well adapted to the very specific surroundings of flooded caves. Since, deeper and more conservative decompression stops, computed using the specific software available in [16] are preferred.

Each time it has been possible, a rebreather has been used for these stops, because it is more comfortable from the point of view of heat losses, autonomy (the amount of gas that can be breathed, then the time that can be spent underwater) and underwater balance (the fashion the diver finds her/his equilibrium underwater).

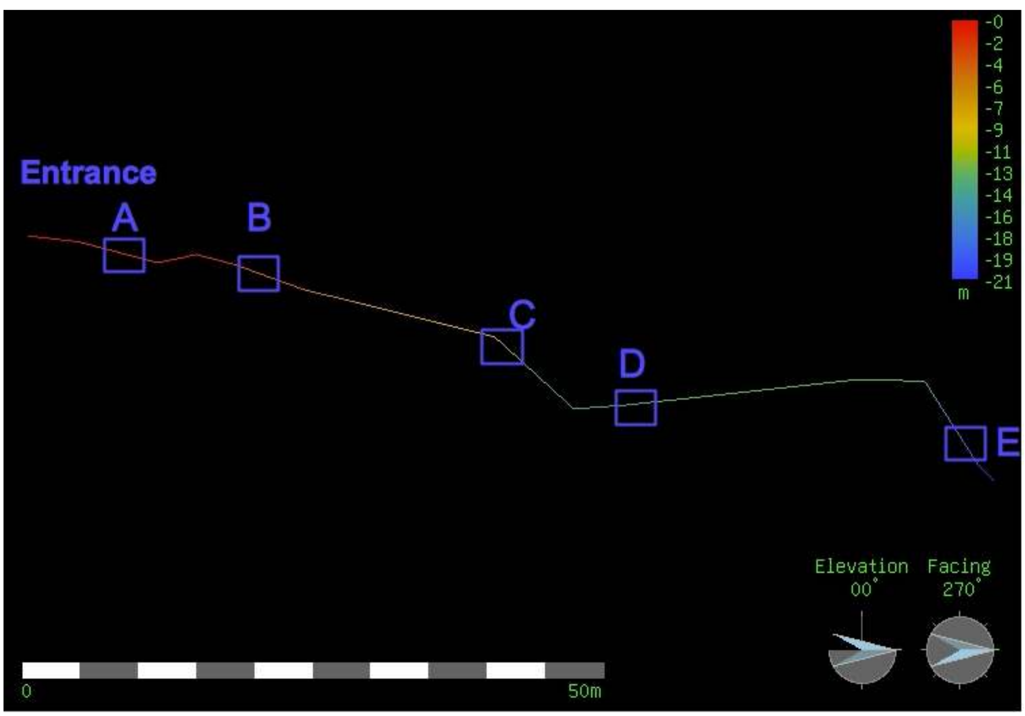

Fig. 4. Detail of the elevation of the Combe du Creux, near the entrance

2.2 Exploiting the Survey

The Fig. 4, that has been made with a screencast of the software “Survex”, shows a more detailed survey of the entrance. Since 2011, extensive underwater photography has been done, in order to document and complete the survey. In addition to the huge yield of autonomy described above and also in [17], a rebreather is also useful regarding underwater work, especially photography, for at least two reasons. First, emitting few or no bubbles, it doesn't disturb the surroundings and it enables clearer pictures, with less mud in suspension. Second, because the buoyancy of the diver doesn't vary when she/he breathes, it is easier to perform certain precise tasks.

The cave contains stalagmites of clay and other peculiar clay deposits. These are very fragile forms which could be irreversibly destroyed with a single stroke of fin or finger. This adds to other reasons to dive alone. The necessity of a perfect underwater balance and positioning when swimming near these forms must explicitly be pointed out.

From a technical point of view, most of the pictures produced below have been made with a camera of type Micro HD Sealife. The lightning was made with a lamp of I-TorchFish Lite V10 of 1000 Lumens in addition to the ordinary lights of type Underwater Kinetics SL4 eLED and Mini Q40 eLED fixed on the diver's helmet.

3. RESULTS AND DISCUSSION

Before discussing them, different observations made inside the cave are presented by increasing distances from the entrance. All the observations are pinpointed on the Figs. 2, 3 and 4. Although some complementary investigations such as precise flow rate measurements outside and at different locations inside the cave may be useful, the underwater photography remains the best tool of investigation. This is the reason why it has been extensively used. There are concretions only in one area inside the cave: sampling and U/Th dating is possible but would very likely bring back no additional information. The deep and flooded parts of the cave rather contain corrosion marks corresponding to a removal of material. They are devoid of deposits that could be easily dated. Paleomagnetism in such conditions seems not very realistic: dating some clay deposits that are in the cave would imply they are in good condition and old enough for that measurement. This would also imply they have not been moved again since their initial deposit and have not been chemically re-magnetized.

The entrance of the “Combe du Creux” is a pond whose water level fluctuates according to the seasons. The Fig. 5 depicts the entrance in the wet season. The water level can even be higher than in this photograph; then the neighboring meadows are flooded. During a rise (February 2016) a total flow rate roughly estimated to about 400 liters/second has been observed. During the dry seasons the pond is almost empty as shown in Fig. 6. The black round shadow in the upper part of the photograph, below the bedding plane, corresponds to a secondary and higher entrance. The dip of the bedding planes, as well as some sub-vertical fractures that guide the cave underground, are very apparent. The static reference used for the surveys corresponds to the level during the dry seasons and is marked by a bolt (metallic anchor) at the beginning of the guideline.

Fig. 5. The entrance of the Combe du Creux during a wet episode

Fig. 6. The entrance of the Combe du Creux during a dry episode

3.1 The Entrance

During the dry seasons, when the entrance pond (Fig. 6) is empty, bedding planes are apparent: they have a direction N 075° and a dip S 12° (they plunge sub-horizontally towards the South). Some fractures are also apparent with a direction N350° and a dip E 80° (They plunge subvertically towards the East). The bottom of the pond is filled with sand and pebbles of variable size, the largest of them having a width of the order of one meter. Some voids through the filling suggest there is a gallery below, even if non-penetrable. During a dive made after huge rainfalls (spring of 2016), the pond was flooded and, at the level of these voids, a stream important enough to move sand and small pebbles has been observed. This is depicted on Fig. 7: the blue arrow shows material in suspension and the orange arrow indicates a detailed view. The entrance by itself is above the big pebbles surrounding the void, which isn't penetrable. The main entrance (used to enter the cave) is linked by a vertical part to an upper and smaller entrance (Fig. 6), some four meters (13 ft) above. This vertical path is aligned on the fractures and its inner shape suggests it has been formed "per ascensum".

Fig. 7. Underwater view of the entrance of the Combe du Creux during wet seasons

3.2 Flooded Concretions

At a depth of less than 1.5 m (5 ft) and close to the entrance, one finds (point A on the surveys) limestone deposits on the floor and stalactites. The Fig. 8 shows small gours and the Fig. 9 shows stalactites. Gours grow by accretion of calcite crystals formed at the free surface of quiet water and stalactites grow by release of calcium carbonate when water becomes in contact with air. Such objects cannot form underwater: either they formed during exceptional seasonal fluctuations or they formed with a water table lower than the current one.

Fig. 8. Flooded calcite deposits corresponding to the point A of the surveys

3.3 Shallow Pothole

At a depth of about 3 m (10 ft), one finds (point B on the surveys) the pothole depicted in Fig. 10. Its diameter is about 0.6 meter (2 ft). Potholes ordinarily form by erosion more than by corrosion and can exist even in non-soluble rocks: according to [8], a non-flooded stream with enough speed was necessary.

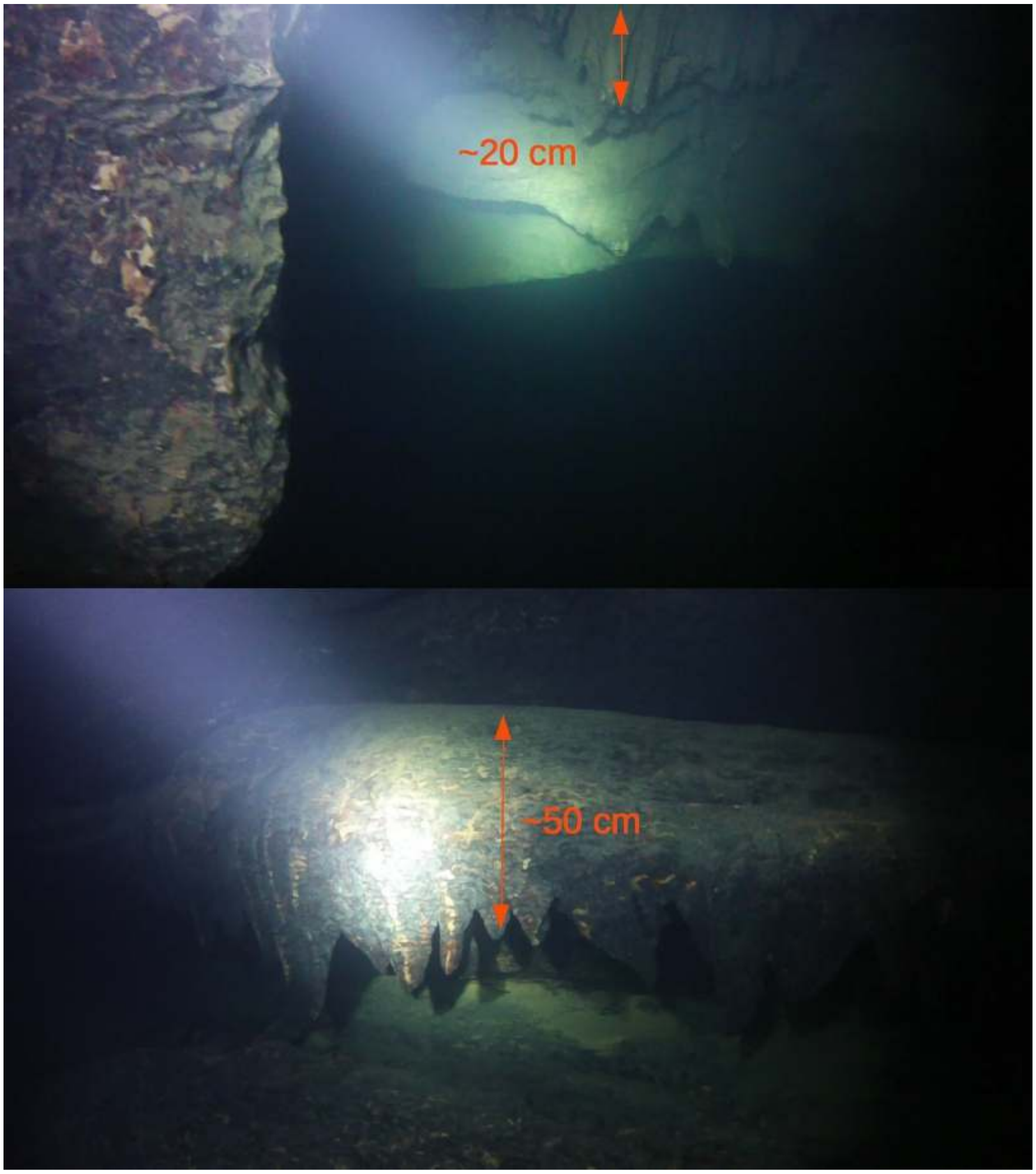

Fig. 9. Flooded concretions corresponding to the point A of the surveys

3.4 Ribs Associated with Scallops

At a depth of about 8 meters (26 ft), one finds (C on the surveys) a very rich and interesting part of the cave. This area is vertical and presents ribs as shown in the Fig. 11. These ribs are vertical, perpendicular to the bedding planes. Inside the ribs, there are forms that look like scallops. They have a size about ten times lower than the thickness of the bedding planes. The mean distance between two successive ribs depends on the precise location but is of order 3 inch (7.5 cm). On the one hand, ribs form ordinarily in non-flooded conditions, when a thin film of water flows at the surface of a soluble wall. A positive feedback takes place; the more the hollow part of a rib is dissolved the more it canalizes water for an enhanced dissolution. On the other hand, scallops form and evolve only underwater. Another positive feedback takes place, a vortex (eddy) forms in an initial void and this vortex is responsible for the enhanced corrosion responsible of the further evolution of the phenomenon. This explains the name of these forms, eponymous to the shellfish. The Fig. 12 depicts the scallops that are found elsewhere in the cave. Regarding the scale, each square of the transparent board has a size 2 cm X 2 cm

Fig. 10. Flooded pothole corresponding to the point B of the surveys

(about 0.8 inch X 0.8 inch). They have a three-dimensional shape. On the contrary, the possible scallops in the vicinity of C and that are constrained inside the ribs can be regarded as two-dimensional. Fig. 13, which is an assemblage of three photographs, shows the detail of these forms. The upper photograph gives the size of the phenomenon, the middle photograph presents a clear face view, and the lower photograph presents a top view.

Fig. 11. Ribs corresponding to point C of the surveys

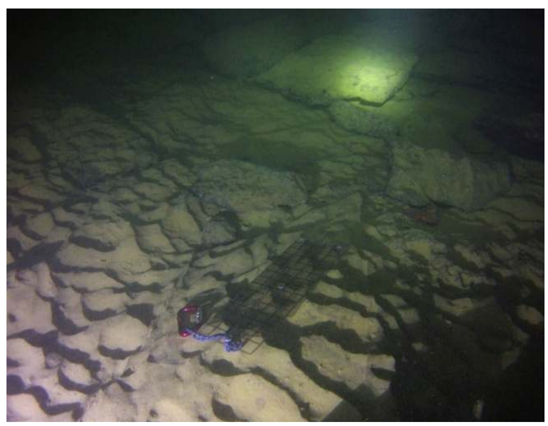

Fig. 12. Ordinary scallops inside the cave

3.5 Scallops at the Floor of the Gallery

Near point D of the surveys, when during a short length the depth decreases instead of increasing, Fig. 14 shows that the gallery exhibits scallops by far more marked on its floor than on its ceiling. If these shapes had formed when the gallery was totally flooded, they would have formed in an isotropic fashion, on the ceiling as well as on the floor. The total width of the gallery is about 4 meters.

Fig. 13. Two-dimensional scallops inside the cave, corresponding to the point C of the surveys

Fig. 14. This part of the gallery (just after the area C of the surveys) exhibits marked scallops only on its floor

Just before point D, and below the vertical zone whose top corresponds to point C, one finds two impenetrable galleries. The Fig. 15 depicts one of them. The cave contains several other secondary galleries at other locations. They all have roughly the same direction North-South than the current entrance, although at different altitudes. The impenetrable void between the pebbles of Fig. 7 suggests that a similar gallery also develops few meters below the current entrance.

Fig. 15. Impenetrable gallery

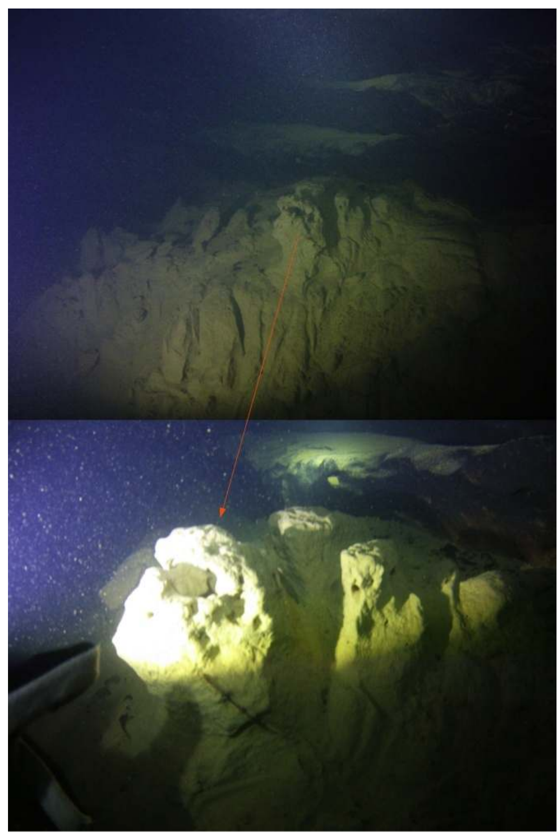

Fig. 16. Flooded clay stalagmite

3.6 Flooded Clay Stalagmites and Clay Deposits

Near point E, at a depth of about 16 m (53 ft) one finds clay deposits and a form that resembles a stalagmite but is purely made of clay. The Fig. 16) shows a large scale view (upper photograph) and the detail of the clay stalagmite (lower photograph). This shape is very fragile and very difficult to protect from destruction by clumsy divers. It seems unique. An underwater formation is impossible A closer look suggests a dig by water droplets having fallen from the ceiling when this part of the cave wasn't flooded.

3.7 Deep Pothole

Farther in the cave, at the beginning of the deep zone (46 meters, about 151 ft, point F of the surveys), another pothole is found as depicted on Fig. 17. As already mentioned, potholes can form only with a free surface and enough stream. So, this one formed with a water level lower than the current one, and with enough stream. The diving compass that gives the scale has a size 6 cm X 7.5 cm (about 2.3 inch X 3 inch).

Fig. 17. Deep flooded pothole at -46 m

3.8 Deep Scallops

In the deep zone, between points F and G, one finds a lot of scallops as shown in Fig 18 and 19. The light gives the size and shows that the size of these scallops isn't uniform. The scallops of Fig. 19 have a size comparable to the scallops existing near point C and therefore formed within the same range of velocities, whereas the scallops of Fig. 19 are larger and could correspond to lower velocities.

Fig. 18. Deep scallops between the points F and G

Fig. 19. Deep scallops between the points F and G

3.9 Deep Clay Deposits

In the same deep zone between F and G, some clay deposits are also found (Fig. 20). The upper photograph of Fig. 20 suggests that these deposits have been recently plowed by the stage tanks of some cave divers. The lower photograph of Fig. 20 shows also a tag on the guideline. As explained in 2.1, this tag indicates the distance from the entrance and the sense of the entrance. This is more comfortable and safer than a knot every five meters, and this enables to pinpoint any interesting phenomena in an easy way.

3.10 Fracture and Deep Pothole

At the level or just before the bifurcation, at point G, potholes are, again, found. The upper photograph of the Fig. 21 presents a top view whereas the middle and lower photographs present the measuring of another pothole. Each segment of the yardstick is 20 cm long. Very clear traces of fractures transverse to the gallery can also be observed. The upper photograph of Fig. 22 presents a fracture as it can be seen, intersecting the banks of the gallery (bedding planes). The lower photograph presents a bell located at the ceiling and whose formation was guided by the fracture. In both photographs, the orange line corresponds to the same direction N330° of a vertical plane. After G, the ceilings of the two galleries become lower and there is an almost continuous clay deposit. At the present time, neither detailed observations nor interesting photographs have been done.

Fig. 20. Deep clay deposits between the points F and G

3.11 Discussion

The synthesis of all the observations reported above gives insights about the past evolution of the cave at long-time scale. At the present time, no precise chronology, with absolutes dates, has been established. The present study rather provides material for correlations with other observations in other places of the same massif. This material can also feed the theoretical or computational modeling of scallops and other karst features.

3.11.1 Strong evidences of water level fluctuations

At the very outside, the observation corresponding to point A on the surveys could be linked to very extreme seasonal fluctuations: during each very dry season, with a very low water level, some stalactites could grow and some calcite could deposit on the floor. However, the observations of point B cannot correspond to seasonal fluctuations: if potholes need a free-surface stream to form, they need also enough velocity, not stagnant water. This is also the case for the potholes of points F and G. At least once, the water level has approximately coincided with the positions of B, F and G.

Fig. 21. Deep potholes near G

On the contrary of potholes and according to the Hjulström diagram (for instance [18]), clay can deposit only when the velocity almost vanishes (and it can be transported only if the velocity of the water is high enough). Finding clay deposits at point E, between F and G, and after the bifurcation, but not everywhere in the cave, indicates that the water level corresponded, at least once, to the level of these clay deposits. Regarding E, things are even more constrained: clay could only deposit below or at the water level and a clay stalagmite could only form at or above the water level. The fact this stalagmite has been entrenched by water drops indicates that, once, it has been above the water level.

Fig. 22. Fracture near G

Fig. 23. Underwater bottom view of the secondary entrance

3.11.2 About the amplitude and the number of the fluctuations

If potholes formed at F and G and if one finds clay deposits between F and G, this means that, at least once, the water level was about 46 meters (151 ft) lower than the actual. The Fig. 23 shows from below and underwater the vertical passage described in 3.1 and in Fig. 6. It has a width of about 0.8 meter and its precise shape suggests, like the bell of Fig. 22, a formation "per ascensum" (from the bottom towards the top). This strongly suggests that, once, the only fashion for the water to reach the surface was to ascend four meters higher than currently.

The clay deposits and the clay concretion of E strongly suggest that, at least once, the water level was 16 meters (53 ft) lower than the current level. At that time, the water could very well escape through impenetrable galleries analogous to those described in 3.5 and now under the clay deposits. The several other impenetrable galleries located at different levels and having the same N-S direction, including the impenetrable gallery that very likely develops few feet under the entrance pond, could have led the water during certain episodes.

The total amplitude of the fluctuations, as observed, is about 50 m (164 ft). There has been at least five former water levels in addition to the actual (Fig. 3). This can be compared with some other observations of the same geographic massif. In the "Source du Pont du Diable" [19], a flooded pit has been dived and it has been observed that it was clogged up by blocks at a depth of about 86 meters (269 ft). In the "Gouffre du Paradis" [20] another sump has been dived and it has been observed observed that it was, very likely, clogged up by blocks at a depth of about 50 meters (164 ft). Extensive and detailed studies and observations are still to be done. However, the partial observations reported above suggest that many sumps of the Doubs may have been exposed to important water level fluctuations, of order of several dozens of meters.

The evolution of an inland cave can be as complicated as the evolution of a coastal cave ([21] for instance). It exists many fashions to explain the six probable water levels α, β, γ, δ, ε, ζ pinpointed on Fig. 3. The simplest way is the following (although there is no additional evidence proving that the cave evolved exactly according to this scenario):

> First, the cave formed with the lowest possible water level (α level on Fig. 3, about -46 m below the current one), in a unique phreatic loop. Some minor variations could explain the formation of potholes around point G whereas point E was flooded, then the formation of potholes around E and the deposit of clay between F and G with a slightly lower level. The water flowed perhaps through galleries that are no longer visible, for instance through the gravel heap that lies just before F.
>
> Second, the water level raised up to E (β level on Fig. 3). The water flowed through

impenetrable galleries and, with small level fluctuations, clay sedimented.

Third, the water level raised enough to create the galleries around D and C (γ level on Fig. 3). The water flowed through impenetrable galleries. There has certainly been small level fluctuations, leading to the formation of the scallops observed only on the floor of the gallery near D and of the ribs near C. With other minor fluctuations, water flowed on the ribs and led to the evolution of the presumed two-dimensional scallops.

Fourth, the water level raised just below the current one (δ level on Fig. 3); the water flowed through impenetrable galleries or through the gallery corresponding to the green dots on the surveys of Figs. 2 and 3. Small level fluctuations enabled the pothole near B to form.

Fifth, the water level raised to the current one (ε level on Fig. 3). The level ζ on Fig. 3 could correspond to a time when the current entrance pond was clogged up by sediments; for instance during a glacial episode.

Further investigations remain to do, but the morphological change of the cave beyond G on Figs. 2 and 3. could correspond to a passage (see Fig. 1) from J5 (limestone) to J4 (marlier). The cave develops mainly according the North-South direction that can be read on the vertical fractures of Fig. 1.

3.11.3 Links with hydrodynamics and physics applied to karst

The theoretical or computational modeling of scallops is an active field. These shapes have been investigated by Curl [22] during the 1960's; and it is currently admitted that it exists a direct relationship between their averaged length and the velocity of the stream responsible for their formation. This is very useful because it enables to reconstitute flow rates (for instance as in [23]). Despite these early investigations, open questions still remain (for instance [24,25]). The underground observation "in situ" is the bottleneck which constraints any modeling: observing forms that look like scallops guided inside ribs, or in other words two-dimensional scallops, suggests that two-dimensional models of scallops could be more realistic than expected. The comparison with nearby three-dimensional scallops, having a wavelength of the same order, suggests that there is less difference between the simplified 2D hydrodynamics of the phenomenon and its real 3D hydrodynamics than expected.

The observations inside the "Combe du Creux" correspond to a velocity parallel to the main direction of the ribs (vertical ribs and water ascending in a flooded pit). In some other caves, including caves from the Doubs, ribs perpendicular to the direction of the velocity are found. For instance, this can happen in the case of a large horizontal flooded gallery where, formerly, a film of water created ribs on the walls. In such a situation, the interaction between ribs and scallops or flutes is an open question. Regarding the reconstruction of ancient flow rates, the two following questions are very important: does the relationship between velocity and wavelength always correspond to the ordinary Curl's relationship? Is it possible that the wavelength of the pre-existing ribs forces the wavelength of the scallops or flutes?

Scallops are found only on the floor of the gallery near D (Fig. 14), as described in 3.5. If the gallery was totally flooded when they formed, they had certainly occupied all its perimeter. Since it is not the case, one can deduce that they have been formed by a stream having a free-surface, that occupied only the bottom of the gallery, as explained in the subsection 3.5. When the water level raised, these forms have not been erased, they are still sharp. With the reasonable hypothesis that the flow rate didn't vary too much, the velocity in a given gallery is lower when it is flooded and higher when it is not flooded. This means that the scallops don't have registered the lower velocity that has been superimposed on them. This lack could be explained by kinetic reasons (the speed of evolution of the scallops becoming too low) or by the fact that the scallops no longer match the Curl's relationship. A possible mechanism explaining such a mismatch is developed in [24] and also in the unpublished study [26].

4. CONCLUSION

Simple observations as those reported here enable to reconstitute a large part of the history of a cave and to show that this cave underwent several variations of water level. These observations are neither too expensive nor too difficult to do. They should be done in the most systematic fashion during any dive in any siphon. In addition to any sportive aspect, cave diving is an essential tool of karst investigation. This is the only mean to penetrate active galleries and to observe them. This practice can bring back direct observations instead of the less direct inferences of more theoretical forms of karstology. Diving a siphon is tantamount to being inside an active system. This is tantamount to having a direct look on its functioning. This is why, although cave diving is regarded as a very hazardous activity, it has huge scientific worth. The huge yield of this activity appears also in other works dealing with other caves in other areas submitted to other constraints ([27] for example).

The “Combe du Creux” isn't a very complex karst system: the fact it has undergone numerous variations of its water level suggests that such variations should be systematically taken in account in any model of karst, even the simplest ([28,29,30,31] for instance).

Some observations, especially the interaction between ribs and scallops, can also be used for a better hydrodynamical modeling of the local details (by opposition to their whole shape or spatial distribution) of karst conduits. In the future, the collection of enough data in other caves of the same area could improve the understanding of these hydrodynamical details as well as the regional understanding of the karst.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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