An Hypothesis On The Evolution Of Complex Flowstones

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Abstract

During a speleological expedition to the Puerto Princesa Underground River (Palawan, Philippines) a drapery characterized by several close-to-horizontal ribs has been noticed. Its study allowed to present an hypothesis on the evolutionary mechanism leading to its development which may fit also for other complex speleothems, like the stepped flowstones, which are very common all around the world. These flowstones present several close-to-horizontal steps, widening's and narrowing's along their growth axis, often giving rise to "organ-pipe" structures and pseudo-stalactites, the genesis of which cannot be justified by means of the general theory explaining the growth of normal speleothems, which is based on a steady flow of the feeding water.

Keywords: **C**omplex flowstones; speleothems; genetic model.

1. Introduction

The morphological characteristics of speleothems are mainly controlled by the type of water flow feeding them (Hill & Forti, 1997). This characteristic has allowed to create theoretical models defining the shape of some of the most common speleothems such as stalagmites (Franke, 1975; Curl, 1973; Dreybrodt, 1999; Kaufmann, 2003; Romanov *et al.*, 2008), stalactites (Curl, 1972, Kaufmann, 2003; Short *et al.*, 2005), and rimstone dams (Wooding, 1991). These models are mainly based on the in time evolution of supersaturation during the flow of the feeding water over the speleothem.

Detailed geochemical (stable isotope) studies and petrography on speleothems often can allow to reveal the processes that caused the feeding water to precipitate carbonate (mainly calcite and aragonite), and thus the evolution of waters in underground environments due to a variety of processes active in these environments (i.e. differential CO_2 and/or H_2O loss from a water film, differential aerosol deposition, deposition in subaqueous environments) (Caddeo *et al.*, 2015). Recent studies also focused on the effect of the steady flow hydrodynamics in developing "crenulations" (ripple-like structures characterized by a wavelength close to 1 cm) over stalactites, stalagmites and flowstones (Camporeale & Ridolfi, 2012; Vesipa *et al.*, 2015).

In this case the variation of the supersaturation was induced by variation in the thickness of the water film and/or the development of micro-bubbles of gas within the water, inducing enhanced diffusion of CO_2 to the cave atmosphere.

All these models are based on the assumption of stationary homogeneous flow conditions, but most of the real speleothems evidence complex morphological patterns, which cannot be explained in such boundary conditions.

The most common of these forms are typical in large flowstones, stalagmites and columns, which exhibit a series of "steps" along their surface with the close-to-vertical area in between steps characterized by indented surfaces resembling "organ pipes" or by upside-down conical flat surfaces (Fig. 1).

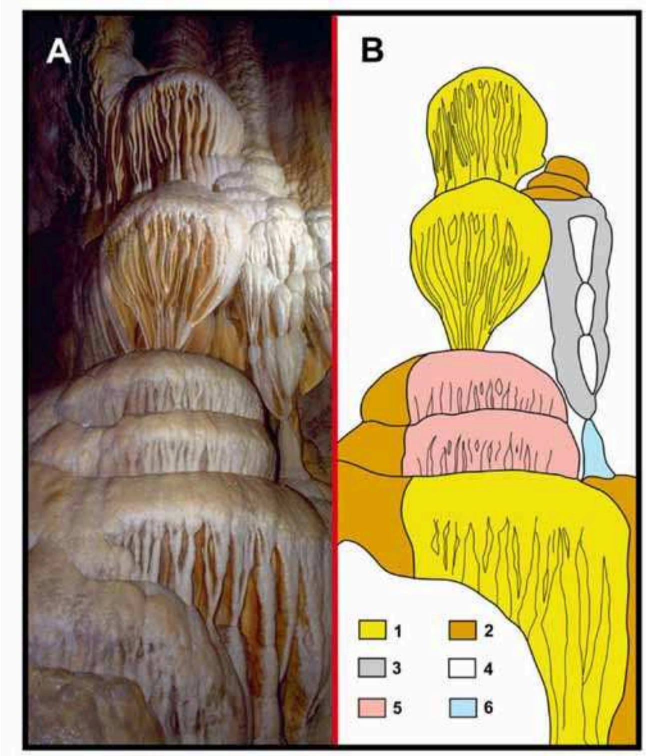

Figure 1. A: Re Tiberio cave (Emilia Romagna, Italy): a big complex flowstone, evolution of which was totally independent from the underlying shape of the rock surface. B: graphic restitution of its principal characteristics: 1: "octopus"; 2: big steps; 3: upside-down conical drapery; 4: sequence of upside-down cones; 5: "organ pipes"; 6: stalagmite. (Photo by Carlo Azzali).

These intervals can even be indented by draperies (commonly called "organ pipes" or "octopus") and can also allow the evolution of pseudo-stalactites and corresponding stalagmites below.

Even though the "octopus" and/or "frozen waterfall" flowstones (as they are normally referred to in the English speaking world) are very common, the commonly accepted genetic mechanism of flowstones (Hill & Forti, 1997) explains only

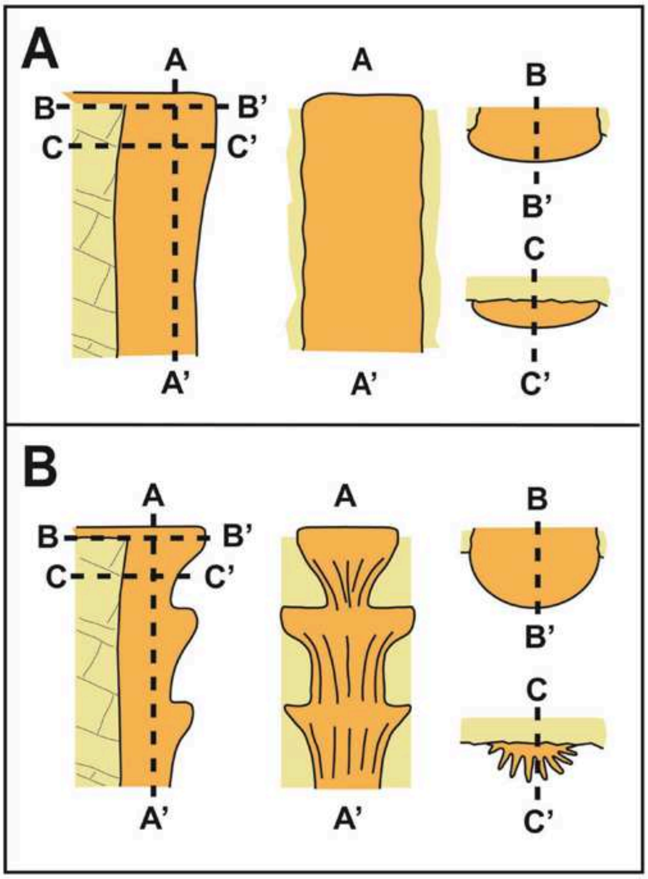

Figure 2. A: structure of a "normal" flowstone developing on a subvertical cave wall; B: superimposed "octopus" structure.

the development of rather flat close-to-vertical surfaces as a consequence of the deposition from a water film flowing simultaneously over the entire speleothem surface (Fig. 2A).

Moreover such mechanism is unable to justify the presence of steps, beside those directly inherited from discontinuities of the rock substratum, and has even more problems justifying the indented surfaces (Fig. 2B).

In fact, until now the evolution of the flowstones has been regarded as the simple consequence of the steady flow of a more or less supersaturated water layer, which consequently causes a rather homogeneous deposition over the whole speleothem. If the feeding on top of the speleothem is constant, the flow along its close-to-vertical surface will result homogeneous, thus the speleothem growth is expected to consist (and practically it is in many occurrences) of superimposed calcite layers, the thickness of which must, at least theoretically, progressively decrease from the top to the bottom of the speleothem, following the progressive lowering of the initial supersaturation induced by the $CaCO_3$ deposition.

2. A new genetic hypothesis

The way to explain the genesis and the development of the complex speleothems was given by the study of a recently found peculiar drapery. In fact, inside the Puerto Princesa Underground River (Palawan, Philippines) a "ribbed drapery" has been discovered, the evolution of which has been controlled by the peculiar regimen of its feeding water flow (Badino *et al.* 2016). In fact it has been evidenced that the sub-horizontal ribs along the drapery sides developed due the sudden local increase in supersaturation induced by the transition from laminar steady flow to subcritical, or critical, flow during the short and rare rainstorms. Moreover the peculiar Palawan climate allowed also to state that evaporation has a very scarce, if any, influence on the development of the ribs.

The morphology of the "ribbed drapery" is obviously more simple than those sometimes present in the complex speleothems: in fact the ribbed drapery may be regarded as a bi-dimensional structure while the other speleothems are fully tridimensional.

As for the ribbed drapery of Palawan, a sudden supersaturation increase always occurring in the same place is necessary to justify the presence of the sudden variation in the flowstone steepness, and its evolution into the stepped form. The supersaturation must occur just at the beginning of the close-to-horizontal section of each step.

As in the case of Palawan, evaporation cannot play a relevant role, being unlikely that it will constantly affect only a few selected places, being inactive on all the other parts of the speleothem. Therefore the only mechanism allowing the evolution of the steps of the complex speleothems can only be the variation of the feeding water flow.

Flow velocity will, in fact induce, in some given areas, the transition from sub-critical to critical velocity (or even from laminar to turbulent flow) with consequent local variation of the thickness of the water film, up to its splitting-up, and the evolution of micro-bubbles inside the water. As explained above, all these processes induce a stationary supersaturation which causes the development of a flat surface. For this reason all stepped flowstones, if they are independent from the geometry of the substratum, must be characterized by high flow periods followed by periods of low or even null flow.

The distance between subsequent steps may be very different. This happens because in the flowstones the enhanced supersaturation may be induced not only by the increase of flow rate but also by the presence discontinuities in the substrate (Fig. 3).

In any case the development of the horizontal part is induced by turbulence, the increase of which is controlled by the flow regimen, which is directly proportional to turbulence. Therefore the development of the steps mainly occurs during the water pulses, being scarce or even null in the dry periods.

Once the genesis of the steps is defined, the fact that the dimension of their close-to-horizontal upper part may greatly vary must be explained. The step dimension not only varies among different flowstones but also from step to step within the same speleothem.

The close-to-horizontal development of a single step is controlled by the time lapse in which the turbulence-induced supersaturation is maintained in spite of the progressive deposition of $CaCO_3$.

This time, in turn, depends on two different factors: 1) the initial supersaturation degree, which is controlled by the amount of turbulence, and 2) the velocity of the feeding water, which allows a longer effect along the close-to-horizontal path.

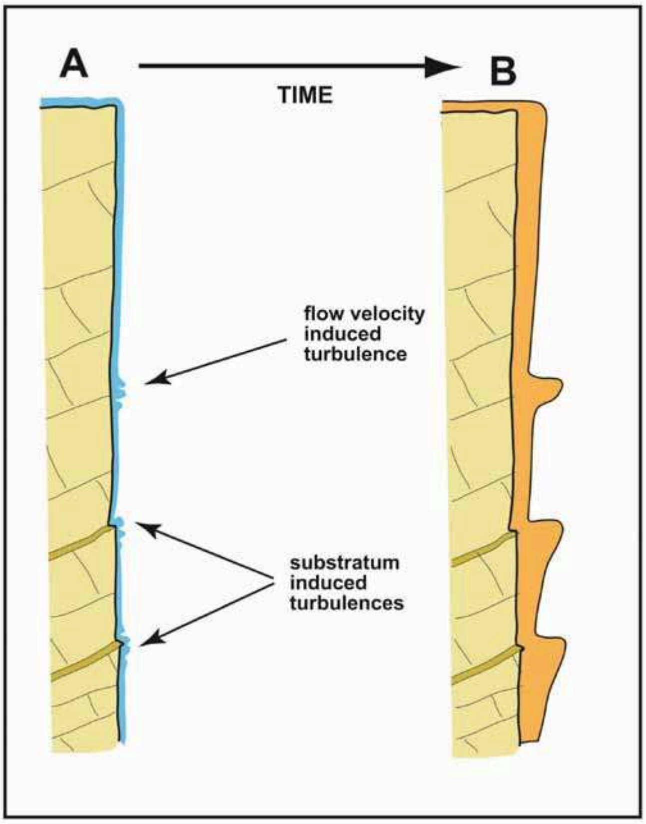

Figure 3. A: turbulence may be induced both by increase in the flow velocity or the presence of discontinuities in the substratum; B: it is impossible to distinguish steps developed by one or the other of these mechanisms on a simple morphological basis.

In the case of the Palawan drapery the amount of the feeding water was necessarily constant over each rib and therefore the only conditioning factor was the initial supersaturation. For this reason most of the ribs have a similar size, with significant variations only induced by the coalescence of two or more subsequent ribs (Badino *et al*. 2016).

In the case of flowstones, the amount of feeding water, and consequently the flow velocity, may be very different from step to step: this because the complex shape of the speleothem allows for an easy local diversion and/or merging of the original feeding water. If the starting supersaturation for each step is kept roughly constant, which is reasonable (the feeding water is generally homogeneous), their close-to-horizontal length will be controlled only by the flow rate, because the deposition will always last roughly the same time, but the distance covered by the water will increase with velocity (Fig. 4).

Anyway this is not completely true because the larger steps will increase their elevation more than the smaller ones.

This occurs because the longer close-to-horizontal path will cause a slightly higher reduction in the water flow velocity with consequent increase of the thickness of the deposited calcite layers.

The high variability of the water flow over the different sections of a complex flowstone makes it extremely difficult to exactly define the mechanisms by which other forms beside the just discussed ones develop. Anyway, on the basis of the diversion and merging of the feeding water it is possible to justify the existence of inclined surfaces linking an upper step to a lower one: in fact the inclined surfaces develop as a

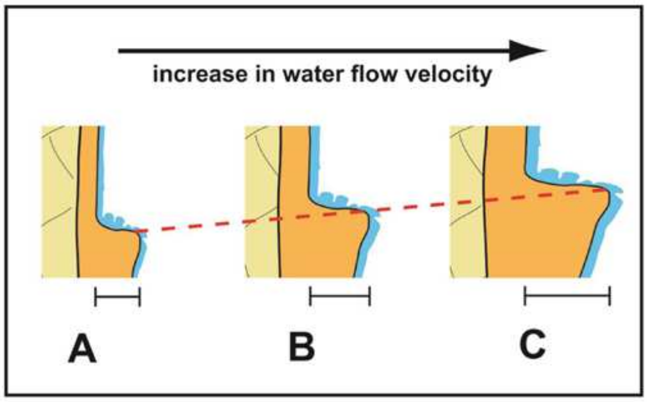

Figure 4. The dimension of the close-to-horizontal upper part of the step is directly proportional to the flow rate and the larger steps increase their elevation more rapidly than the smaller ones.

consequence of the very different flow rate characterizing the two steps, which consequently have a different vertical growth velocity.

The evolution of the flowstone just below a close-to-horizontal step may result even more different: it may be close-to-vertical or progressively more indented, and may exhibit rather flat surfaces or more or less indented ones and finally may progressively reduce its size assuming a shape of a reverse cone, eventually becoming a true drapery (pseudo-stalactite) which, finally, sometimes allows the evolution on the lower step of a small stalagmite.

The evolution of all these different forms is ruled by the flow regimen in that specific flowstone area and of its variation in time. In reality the controlling factor is just the water flowing after the water pulse, because the supersaturation created during these pulses is almost completely consumed for the close-to-horizontal expansion of the steps.

At the end of a feeding period, if the still flowing water is enough to maintain a homogeneous layer over the whole close-to-vertical area, the resulting speleothem surface will be more or less smooth and flat, and its projection will be inversely proportional to the flow velocity (Fig. 5A).

This happens because the residual supersaturation will be exhausted over a short distance and consequently the growing layers will become thinner downwards.

But if the water flow after the pulse is scarce, the water layer becomes unable to cover the whole surface below the step and the surficial tension downstream will progressively reduce the area interested by active flow, giving, once again, rise to flat and smooth surfaces but more or less resembling an upside-down triangle or cone. This kind of evolution may also be induced if the available water downstream is progressively reduced by evaporation.

The indentation of the sub-vertical lower part of the step is inversely proportional to the flow rate.

If after the pulse, the water flow becomes heterogeneous, some places below the step will be characterized by a higher flow (rills), and therefore they will develop faster with respect to the others with scarce or no flow at all. In other words, the

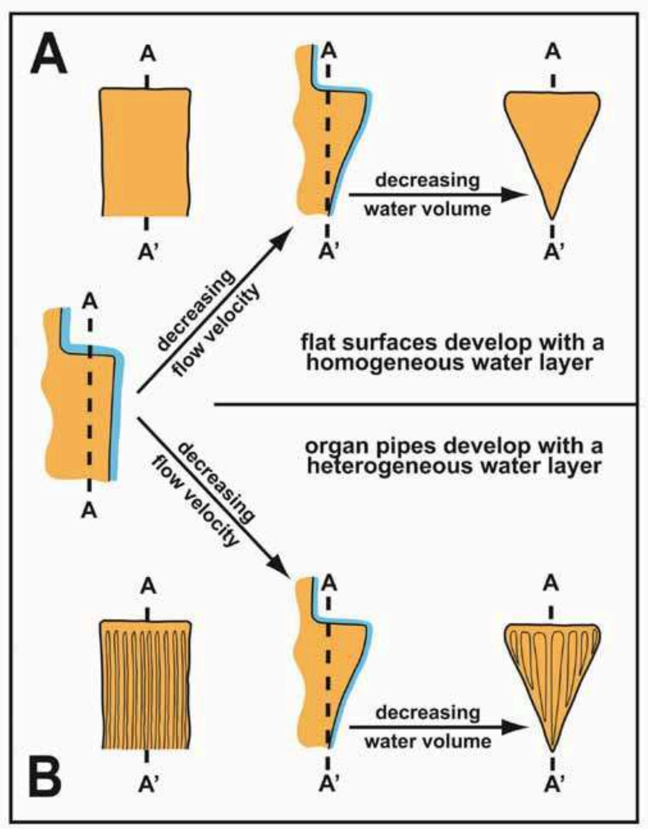

Figure 5. Evolution of the lower part of a step. At the end of the water pulse flat surfaces develop if the speleothem remains completely covered by water, otherwise indented structures (organ pipes) develop.

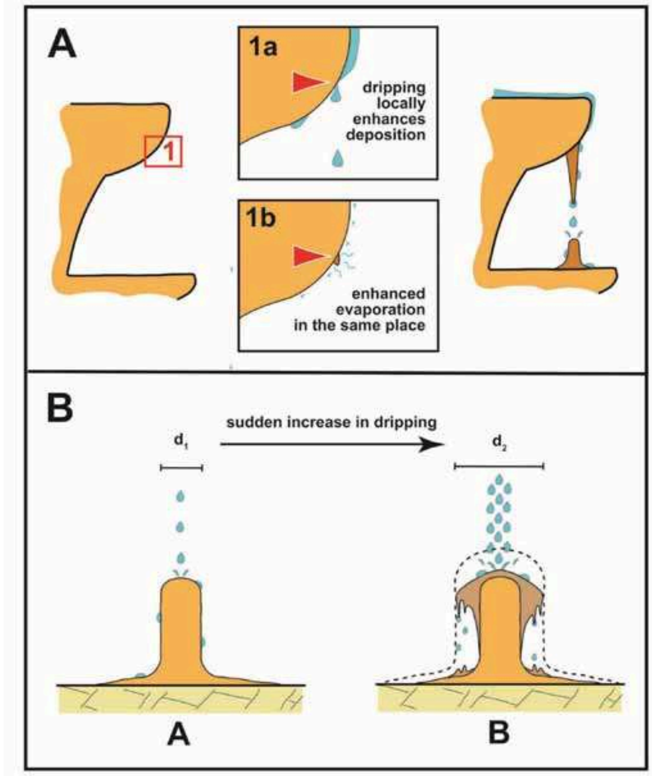

Figure 6. There are two mechanisms causing the evolution of pseudo-stalactites from an "octopus" structure and the consequent possible growth of a stalagmite. A: during high flow periods a stationary dripping forms in a place where enhanced deposition becomes active due to a localized increase in supersaturation (1a), exactly in the same places enhanced evaporation occurs during the low flow to dry periods (1b). B: a sudden increase in the water flowing during the pulses will cause an evolution similar to the well-known one of the stalagmites: A- the shape of a stalagmite in equilibrium with the feeding water; B- the stalagmite shape induced by a recent sudden increase in feeding water (the dotted line shows the new and not yet achieved equilibrium diameter)

heterogeneous flow gives rise to privileged flow paths, which will induce the evolution of an "organ pipe" structure, becoming progressively more spaced, thinner and with deeper divides if the heterogeneity of the flow is greater (Fig. 5B).

Normally the "organ pipe" flowstones are still close-to-vertical or scarcely protruding, because the feeding flow is fast enough to ensure a constant deposition from the top to the bottom of the "pipes". Finally, when the feeding water after the pulse is scarce and slow, thus allowing a fast downstream decrease of the deposited $CaCO_3$, the protruding of the structure becomes progressively higher, while the few active rills decrease and coalesce downstream, the whole structure becomes similar to an elongated reverted cone with only a few deep indentations: in this case octopus-like forms develop. During the pulses, the octopus shape enhances the possibility of dripping from the edge of some of its "tentacles". This process will induce the evolution of small pseudo-stalactites (secondary draperies) over the "tentacles", while the falling drips from their tips will possibly cause the development of a true stalagmite over the flat close-to-horizontal surface of the underlying step (Fig. 6A). Eventually, if this process remains active for enough time, the pseudo-stalactite joins the stalagmite to form a true column.

Anyway the evolution of pseudo-stalactitic draperies will be induced also by another mechanism, which activates only if the flow changes dramatically from high flow to dry periods. If this happens, in the periods of highest flow the amount of water reaching the step cannot remain totally adherent to the speleothem, mainly at the transition between the upper close-to-horizontal part and the octopus below. In this manner the same conditions are achieved which rule the development of a stalagmite that undergoes a great sudden increase of feeding water (Fig. 6B). In fact it is renown that in steady dripping conditions, the stalagmite diameter is directly proportional to the amount of the feeding water (Franke, 1965), lowering when it decreases and becoming larger if it increases.

But when the increase is very high, before reaching the equilibrium diameter, the top of the stalagmite will expand rapidly with respect to its lower part thus transforming itself into a kind of "mushroom".

The excess of feeding water, dripping from the edge of the "mushroom cap" causes the development of pseudo-stalactite draperies and possibly of stalagmites below them (Fig. 6B).

It is easy to distinguish the stalagmites developing below a flowstone step thanks to this mechanisms: in fact they will correspond to small pseudo-stalactites not necessarily related to pre-existing octopus tentacles.

In conclusion it has been demonstrated that the complex flowstones evolve only when the amount of the feeding water dramatically changes in time. Their close-to-horizontal surfaces develop mostly during high flow periods, while the forms characterizing the close-to-vertical parts below are controlled by the water regimen during the low flow periods.

3. Final remarks

The study of the Puerto Princesa Underground River ribbed drapery (a simple bi-dimensional structure) suggested that its evolution was totally controlled by the feeding flow regimen during the short but strong rainstorms which characterize this island's climate (Badino *et al.* 2016).

This study allowed also to give a first genetic explanation for other more complex (tridimensional), extremely common but poorly understood speleothems: the stepped flowstones. The transition from subcritical to critical flow velocity and/or the variation in the water layer thickness are the parameters ruling the development of the steps.

Anyway it has to be stressed that if the definition of the evolution of the ribbed drapery may be considered fully exhaustive, the same cannot be said for the stepped flowstones. In fact, at the moment it was only possible to define the main mechanisms allowing the evolution of their general forms, while an explanation for their second order characteristics is still lacking. Further detailed petrographic and geochemical studies might allow to unravel their genesis in more detail.

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