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Mario Parise
Carla Galeazzi, Roberto Bixio, Carlo Germani

SUBAQUEOUS ANTI-STALACTITES: A NEW TYPE OF SPELEOTHEM FROM THE OLD AQUEDUCT OF SASSARI (SARDINIA, ITALY)

Laura Sanna [1-2], Paolo Forti [3]
[1] *CNR-IBIMET – Istituto di Biometeorologia, Sassari*
[2] *GSAS - Gruppo Speleo Ambientale Sassari*
[3] *Istituto Italiano di Speleologia, Bologna*

Reference Author: Laura Sanna, Traversa La Crucca 3, 07100 Sassari; tel. 360.969948; speleokikers@tiscali.it

Abstract
It is well known that artificial cavities sometimes host speleothems very different from those growing in caves. This is the case of the old aqueduct of Sassari (Sardinia, Italy), an about 4 km-long tunnel dug in 1880 within Miocene carbonate in order to supply drinking water from the Bunnari dam to the town. At 2 km from the entrance, it intercepted the groundwater coming from a fracture. Close to this outlet, small subaqueous cylindrical hollow calcite speleothems have been found growing on the floor, in 10 cm-deep water, on a half-cm thick calcite crust precipitated on coarse clastic sediments transported by floods. These fragile vertical tubes range from 2 to 5 cm in height and from 0.8 to 1.5 cm in diameter, with wall typically 3-5 mm thick. The development of these underwater speleothems is controlled by the presence of steady gas bubble on top of each of them that seem to be related to the soft sediment present below the hard thin calcite crust lining on it. The air-filled bubbles induce diffusion and/or evaporation from the solution into it, allowing for high supersaturation ratio close to the speleothem top. Calcite precipitation occurs by degassing-induced crystallization at the inner margin of the bubble as dictated by surface tension. The ascent gas bubble tends to have a relatively slow degassing rate, maintaining an open canaliculus within the speleothems which acts as the feeding tube of a normal stalactite: for this reason this new type of speleothem has been named "subaqueous anti-stalactite".
Keywords: artificial cavities, old hydraulic works, speleothems.

Riassunto
È oramai assodato che le cavità artificiali possono ospitare speleotemi a volte completamente differenti da quelli che si sviluppano nelle grotte naturali. Questo è il caso anche dell'antico acquedotto di Sassari (Sardegna, Italia), una galleria di circa 4 km scavata nel 1880 all'interno di calcari miocenici, per portare acqua dalla diga di Bunnari fino alla città. La galleria sotterranea ha intercettato, a circa 2 km dall'ingresso, una frattura da cui fuoriesce acqua. Poco a valle di questa venuta d'acqua si stanno sviluppando delle piccole concrezioni subacquee di forma cilindrica allungata. Gli speleotemi sono composti di calcite e crescono in una pozza d'acqua, profonda circa 10 cm, su una crosta di calcite di mezzo centimetro di spessore che riveste un sedimento incoerente, probabilmente depositatosi sul fondo della galleria a seguito di piene. La dimensione degli speleotemi varia da 2 a 5 cm in altezza e da 0,8 a 1,5 cm in diametro mentre la loro parete esterna ha uno spessore di 3-5 mm. La genesi e lo sviluppo di questi strani speleotemi subacquei è controllata dalla presenza di bolle stazionarie di gas sulla loro sommità, bolle che provengono dal substrato incoerente al di sotto del sottile crostone stalagmitico su cui si sviluppano gli speleotemi stessi. Le bolle stazionarie inducono fenomeni di diffusione e/o di evaporazione dalla soluzione alle bolle stesse, causando così un aumento di sovrasaturazione circoscritto alla cima dello speleotema. La precipitazione della calcite avviene per cristallizzazione indotta dal degassamento al margine inferiore della bolla stazionaria come richiesto dalla tensione superficiale. Il gas all'interno degli speleotemi tende ad avere una velocità ascendente molto bassa, ma sufficiente a mantenere un canalicolo aperto, che funziona esattamente come quello delle stalattiti, alimentando lo sviluppo apicale della concrezione. Per questo motivo si è deciso di chiamare questo nuovo tipo di speleotema "anti-stalattiti subacquee".
Parole chiave: *cavità artificiali, vecchie opere idrauliche, speleotemi.*

Introduction

It is common to see large quantity of speleothems developed inside any kind of artificial cavities (Forti, 2006): most of them are practically the same of those precipitated in natural caves, even if they are typically smaller due to the scarce interval of time available in which they had the possibility to grow (Hill & Forti, 1997). Normally the nucleation of calcite speleothems within artificial cavities is controlled by just the same process ruling its formations in natural caves, but sometimes peculiar mechanisms may induce variations in the processes occurring on the walls of the artificial voids (Hill & Forti, 1997). In few occurrences, the boundary conditions existing in a given artificial cave allow for the development of completely new types of speleothems, which are thus restricted to the artificial environment: this is the case of the zig-zag helictites at the Urbino Palace (Fabbri et al., 1987), the calcite blisters of the Val di Setta roman aqueduct (Forti, 1988), and the "anti-stalactites" of the same aqueduct (Forti & Demaria, 2007).

The peculiar abundance of speleothems in the old

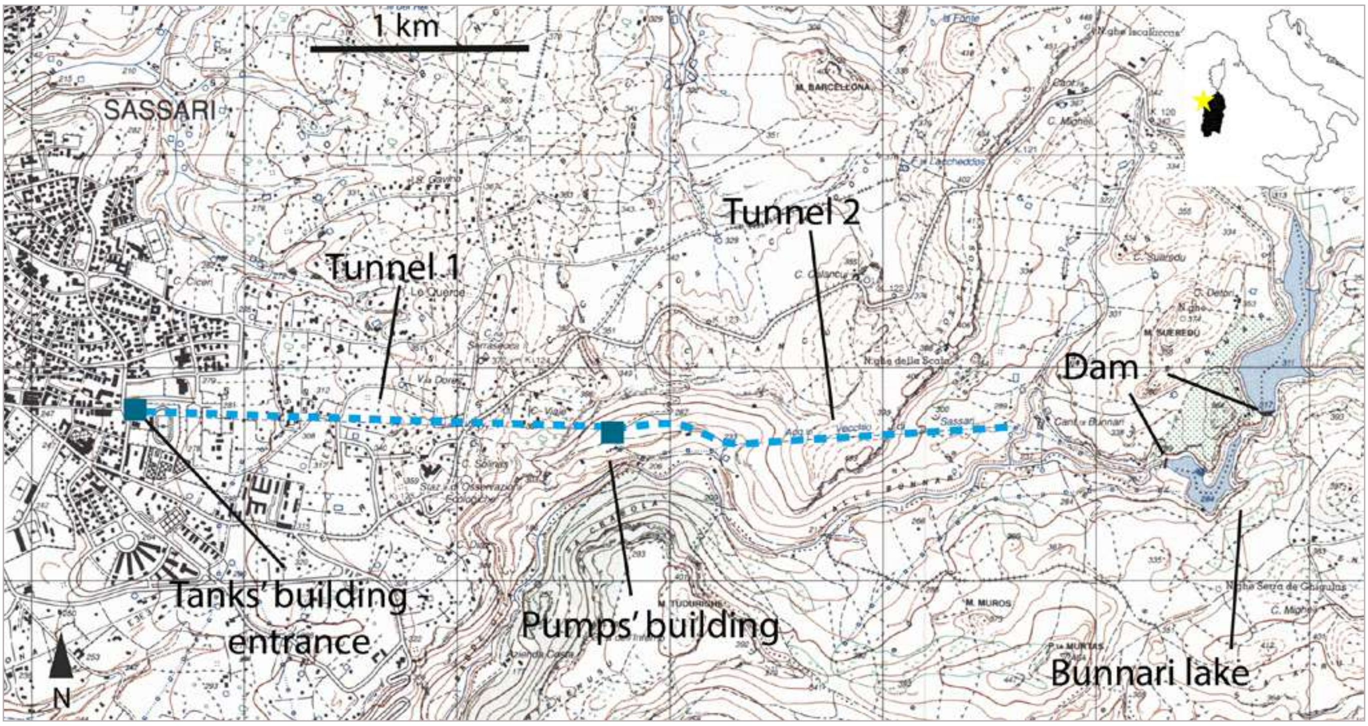

Fig. 1: location of the old aqueduct of Sassari on the topographic map (IGM, scale 1:25,000). The blue dot-line represents the projection of the underground tunnel on the surface.
Fig. 1: posizione del vecchio acquedotto di Sassari sulla carta topografica (IGM, scala 1:25.000). La linea tratteggiata azzurra rappresenta la proiezione sulla superficie della galleria sotterranea.

aqueduct of Sassari (Sardinia, Italy) was highlighted at the beginning of 1990s by some cavers that first described part of its tunnels (Mucedda & Castaldi, 1992). During a further exploration of its conduit, in 2014 a completely new type of speleothem has been observed. After a brief historical view of the old hydraulic work, this paper presents a description of this cave formation and proposes a genetic mechanism for its development.

Study area

Sassari is one of the main towns of Sardinia region (western Mediterranean, Italy) and is located in the NW part of the island. It lies at 225 m a.s.l. on the Nurra plain, a karst plateau characterised by Miocene marine carbonate formation deposited over an Oligo-Aquitanian volcanic substrate (Carmignani et al., 2001), now gently north-dipping and degrading towards the sea (Gulf of Asinara). It is delimited by the Rio Mannu stream to the W, the Logulentu dry valley to the E and the steep cliff of the Bunnari fluviokarst canyon to the S, characterised by a number of springs with low flow rate (<1 L/s) and high pCO_2 values (Biddau & Cidu, 2005). The climate of the area is typically Mediterranean, with warm and dry summers (maximum temperature in August) and mild and wet winters (minimum temperature in January). The average annual temperature (1965-2012) is 15.9 °C (mean T_{min} 11.8 °C; mean T_{max} 19.8 °C) and the mean cumulated precipitation is around 600 mm per year, mostly concentrated in October-November (Chessa & Delitala, 1997).

Historical setting

The development of Sassari has been related to the depopulation of the Roman harbour, Turris Libisonis (ancient Porto Torres) during the 12th century. Since that time, the town started its expansion, and assumed an urban spatial structure which still is partially preserved in its ancient centre within the medieval walls (Carta et al., 2005). Since 1562 one of the oldest universities was settled in Sassari thanks to its lively culture. With its current 125,000 inhabitants, the demographic evolution has had a continuous growth during the last 150 years. Due to the periodical droughts that affect the area, the local authority has always paid attention to solve the water supply problems. In 1853 as a means to remedying the unhygienic conditions besetting the city the administration was led to carry out water prospecting around the urban area in order to achieve a precise plan to provide people with clean water. After the cholera epidemic of 1855 that cost the lives of 5,000 people out of a population of 20,000, citizenship felt the need to adopt a modern aqueduct that ensured the home delivery of water (Manconi, 1989). Before then, the water supply was assured by fountains and "*dragonaie*" (local name for underground water pipes excavated into the rock) located in and out of the medieval walls. The water collected from fountains was transported in homes by "*carrajoli*" (persons engaged in the transport of water) with terracotta containers and "*mezzine*" (bottles of wood) loaded on the back of the donkeys, with over 300 of that roamed the streets of Sassari. Some houses had wells, but the groundwater was not potable, because brackish or polluted by discharges of sewage system dug into the limestone. In 1863 the local government funded the project of the French Roux that involved the construction of 5,000 m of underground pipes to channel the water of the spring in the Bunnari valley and lead them to the northern part of the city where an industrial area would built. Two years later trenches, wells and 636 m of tunnel were already dug, but the company went bankrupt in 1868. The municipality asked the presentation of new projects and in 1873 the Fumagalli Company was awarded the contract, planning to replace the 15 L/s discharge of the Bunnari spring with those of an artificial reservoir that collected rainwater tumbling in the heights of Osilo village. With tunnel and siphons, water would reach the building of the filters and then through an underground tunnel would flow to a depth of half a meter below the tunnel floor (to keep it fresh) towards those of the tanks. The work was completed in 6 years, and on August 15, 1880, Sassari inaugurated its aqueduct in front of 10,000 people; the result, however, was not the one advocated by the population. In fact the water had a disgusting smell of hydrogen sulphide, a revolting taste and oiliness to the touch due to the presence of organic substances leached from the cultivated field and grazing as well as by flax manufactory in the recharge area and it could only be used for agricultural purpose. To attempt to solve these problems, the Osilo drains were excluded in another catchment area and the not-submerged sand filtration system was built 130 m downstream of the backwater. Not achieving the expected results, at the beginning of 900s a mechanical water pumping station at the Bunnari spring and a second dam in the upstream catchment were built. For drinking purpose inside the aqueduct a lateral channel was created in which the water of Bunnari spring and those of a groundwater artery intercepted during the excavation of the tunnel converged. Only in 1932, after realizing new works and spending 16 million of the old Italian currency, the city was able to ensure quality and quantity in the water supply (Manconi, 1989).

The underground aqueduct

The access to the tunnel of the old aqueduct of Sassari is possible through the newly renovated building located in Viale Adua at 260 m a.s.l. It also contains the water tanks, constituted of underground structures carved into the rock, 33 m x 25 m in size and 7 m in height, equipped with spillways for the disposal of excess water and still preserving two float gauges. The aqueduct consists of three sections: one in the open air near the dam of the Bunnari and two underground tunnels dug into the rock and connected each other by the building that hosts the pumps. The two conduits are 2,250 m and 1,940 m long, respectively, for a total length of almost 4,200 m, with a E-W orientation (Fig. 1). For convenience we refer to these two branches as "Tunnel 1" for the straight section from Viale Adua to the pumps' building, and "Tunnel 2" for the part that goes with some curves, from this building towards the dam. The underground environment is characterized by a strong air current which varies seasonally, while temperature and humidity are pretty stable at 16.1 °C and 100%, respectively. The concentration of CO_2 in the air is equal to 520 ppm. The waters of the artificial lake of Bunnari (now dry) flowed into a water line located in a trench under the decking of the aqueduct, with a constant slope of 6 cm per 100 m, in the way to preserve the channel and to maintain good quality of the water (Paris, 1990). On the right side of the entire aqueduct an adductor canal, 50 cm wide and about 1 m high, is present (Fig. 2A), collecting the waters flowing from the vein intercepted during excavations, at 2,000 m from the entrance, and those coming from the Bunnari spring. Currently the discharge of this water vein has been estimated in approximately 3 L/s with a temperature of 16.1 °C, an almost neutral pH of 7.3 and a relatively high conductivity of 0.73 mS/cm. The alkalinity is quite high too (290 mg/L of HCO_3). On the concrete floor the metal grates of drainage convey the dripping water into the underlying pipe. The vertical drains are sometimes completely occluded, due to precipitation of calcium carbonate. The floor is also covered by debris deposits rich in organic matter that in the Tunnel 2 reach a thickness up to 30 cm. Close to the entrance, the walls and the ceiling of Tunnel 1 are protected with red bricks, as well as all the other areas within the aqueduct that showed signs of structural failure or rock friability. The entrance area was ventilated from above through aerators with a diameter of 50 cm, of which currently exists only that located 40 m away from the tanks' building. Most of the Tunnel 1 is entirely carved in Miocene biocalcarenites and it crosses the marls only at 1,700 m from the opening, and for a length of 200 m. The Tunnel 2 is hosted within Tertiary ignimbrite visible only for a hundred metres, while the rest of this conduit is completely covered by limestone blocks and red bricks. In the part of the aqueduct cut into the carbonate, the intense dripping produces thick calcite coatings on the walls and on the ceiling as tiny stalactites, soda straw and flowstones. Part of the floor is flooded by water that slowly flows with a few centimetres to half a meter of depth (Fig. 2B). A 1 mm-thick layer of calcite raft typically floats on top on surface water whereas in some zone large white pisolites lie on the bottom (Fig. 2C). Also the structures, objects and artefacts (pipes, electrical cables, etc.) are covered with calcite. At 450 m, 660 m and 1,000 m from the entrance three rectangular ascending chimneys, about 3 x 2 m in size, depart toward the surface, reaching a height of 15 m, 35 m and 7 m, respectively. The taller one is equipped with iron rungs plugged to the rock now fully enclosed in calcium carbonate (Fig. 2D). This shaft was used to raise the water to a large underground tank dug into the rock at the surface (295 m a.s.l.). From an architectonic point of view, the two tunnels have 1.8 m-wide square section, shaped with a ceiling slightly curved with 2.10 m of height at the top of it. Only in the last sector of the Tunnel 2 the cross section sometimes is reduced for ten meters and the conduit has oval shape completely covered with red bricks, whose vertical and horizontal axes are 1.65 m and 1.30 m, respectively. Furthermore, in the middle of the Tunnel 1 a longitudinal ceiling

Fig. 2: main features of the Bunnari aqueduct. A: the adductor canal on the right side of the tunnel where water reaches a deep of 50 cm. B: the calcite coating covers walls, ceiling and any artefacts where the tunnel pass through calcarenites. C: white pisolites occur on the floor below few cm of water. D. the rectangular ascending chimney equipped with iron rungs. E: the niche where the anti-stalactites form (photo A. Romeo).

Fig. 2: principali caratteristiche dell'acquedotto di Bunnari. A: il canale adduttore sul lato destro della galleria dove l'acqua raggiunge una profondità di 50 cm. B: le incrostazioni di calcite coprono le pareti, il soffitto e qualsiasi oggetto presente nelle parti del tunnel scavate nelle calcareniti. C: sul pavimento sotto pochi centimetri d'acqua si osservano bianche pisoliti. D: il camino rettangolare ascendente fornito di scalini di ferro. E: la nicchia in cui si formano le anti-stalattiti (foto A. Romeo).

channel has been subsequently excavated to facilitate the progression. Along the same branch at the bottom of the left wall some lateral niches, 2 m large and 1 m deep, have been carved. In one of these niches, close to the water vein, this new type of underwater speleothem has been formed (Fig. 2E).

The subaqueous anti-stalactites

As mentioned before, the water emerging from the fracture intercepted by the works during the construction of the underground aqueduct has been collected into the adductor canal through a pipe crossing the tunnel. Over the years, the pipe system has suffered some failures and part of the water is poured on the floor creating a small stream that slowly flows toward the entrance. A 1 mm-thick continuous layer of calcite raft is often present at the air-stream interface, with smooth crystals in contact with the tunnel atmosphere and small well-shaped calcite crystals growing at the water side.

Close to the water vein, in one of the lateral niches, small subaqueous cylindrical hollow calcite speleothems have been found growing on the floor (Fig. 3A), in 10 cm-deep water, on a half-cm thick calcite crust precipitated on coarse clastic sediments transported by floods. These fragile vertical tubes range from 2 to 5 cm in height and from 0.8 to 1.5 cm in diameter, with wall typically 3-5 mm thick. Their outer surface is covered by spherical agglomerates of sub-millimetres dendritic calcite crystals constituted of botryoidal overgrowth while the inner canaliculus has smooth face with growth bands. The tip of these cylinders has feathery morphology (Fig. 3B) or more solid rhombohedra shape. These underwater speleothems are characterized by the presence of a steady gas bubble on top of each of them ascending from below through the canaliculus, with a relatively slow degassing rate (Fig. 3C). At the interface between the air-filled bubble and the stream water, very small calcite crystals have been precipitated as a kind of cave raft. In fact they are characterized by smooth faces oriented toward the core of the gas bubble, while the botryoidal surfaces look up to the stream water. The ascent gas bubble maintains an open canaliculus which acts as the feeding tube of a normal stalactite but with a reversal direction of growth: for this reason this new type of speleothem has been named “subaqueous anti-stalactite”.

The genetic mechanisms for the development of the subaqueous anti-stalactites

The development of the subaqueous anti-stalactites is strongly controlled by several environmental settings, which probably explain why they have never been observed before. The needed boundary conditions may be summarized as follow:

1. Presence of shallow unstirred water

The depth of the water must be scarce to make easy the development of gas bubbles at the sediment-water interface (a high column of water would hinder this process). Quiet environment is needed to allow submerged gas bubbles to survive for enough time and to enable the gas diffusion from the bubbles to the solution and the reverse.

2. Undersaturated condition of the atmosphere with respect to water

The strong air circulation increases evaporation from the water surface, thus maintaining a slight supersaturation with respect to calcium carbonate. High concentration of this salt, as that normally induced by CO_2 diffusion, must be avoided because it would lead to the evolution of normal flowstones (like those present close to the subterranean spring).

3. Constant oversaturation within the water

The progressive diagenesis of the cave rafts needs oversaturation to form botryoidal surface of the anti-stalactites.

4. Absence of dripping over the area

Dripping over the water surface would cause selective sinking of cave rafts, thus giving rise to tower cones and avoiding the possibility of enhanced sedimentation on top of the anti-stalactites.

5. Presence of an organic rich substratum

The decomposition processes supply enough gas to allow a slow but constant flux of bubbles to the water while the grain-size of the sediment makes possible the development of small vertical tubes (chimneys) along which the gas escapes to reach the water.

Only if all the above conditions are satisfied, the evolution of a subaqueous anti-stalactite may start. The development of these peculiar speleothems is sketched in figure 4 in four steps.

The first step of anti-stalactites formation involves the production of carbon dioxide (CO_2). The water seeping inside the soft clastic layer covering the floor of the tunnel slowly oxidizes the dispersed organic matter which is partially transformed into carbon dioxide.

$$C_nH_{2n}O_n + O_2 \rightarrow H_2O + CO_2\uparrow$$
$$\text{Organic matter + oxygen} \rightarrow \text{water + carbon dioxide}\uparrow$$

When the concentration of the dissolved CO_2 is high enough, part of it gives rise to gas micro-bubbles that migrate from the sediment towards the water along the inter-granular voids of the sediment (Fig. 4A, left). At the interface sediment-water, the bubbles develop until they reach a size which allows them to exceed the cohesion strength and to escape from the floor reaching to upper surface of the water, where they join the atmosphere. Where the migration of the gas bubbles within the clastic material is more frequent, it causes the development of few vertical micro-tubes which progressively capture an increasingly higher quantity of gas and eventually become the single way for their uplift (Fig. 4A, right). In the meantime the diffusion of CO_2 and the evaporation at the water-air interface maintain a slight supersaturation with respect to $CaCO_3$ on the water surface where calcite rafts develop and sinks within the water. The progressive accumulation of rafts on the floor produces the evolution of a rather continuous layer of calcite crystals, which is rapidly transformed by diagenesis into a continuous carbonate layer. At the outlets of the chimney calcite precipitation is inhibited for both mechanical and chemical reasons. The development of the gas bubble mechanically avoid cave rafts deposition just over the chimney mouth and later the slight turbulence induced by the detachment of the bubble obliges the cave rafts too close to the speleothem rim to move away radially, or to sink inside the chimney. Moreover, in the chimney the uplifting gas bubble has a relatively high CO_2 content and therefore its diffusion into the boundary layer along the chimney and at its mouth, produces a fairly aggressive solution that chemically dissolves at least part of the cave rafts in contact with it. The combined actions of the chemical and mechanical processes are responsible for the dimension of the area uncovered by the calcite layer: practically the diameter of chimney mouth is defined by the dimension of the gas bubble at the moment of its detachment.

The second step comprises the vertical growth of the subaqueous anti-stalactites that begins when the equilibrium diameter of chimney mouth is reached and the rim of the chimneys becomes a preferential site for calcite crystals accumulation. Most of the carbon dioxide present in the uplifting gas bubble has been already neutralized by the dissolution of calcite rafts fallen into the chimneys. Thus, when CO_2 diffusion from the bubble toward the water occurs, the water boundary layer becomes oversaturated with respect to calcite. In the meantime H_2O evaporation from the water into the bubble (Fig. 4B) increases the calcite oversaturation in an area close to the interface. If the dwell time of the gas bubble before its detachment from the tube rim is long enough, calcite rafts precipitates just along the outer surface of the bubble (Figs. 4B1 and 4G). At the time that the bubble rises the surficial tension is destroyed and a strong turbulence is created close to the chimney mouth (Fig. 4C). Most of the calcite rafts

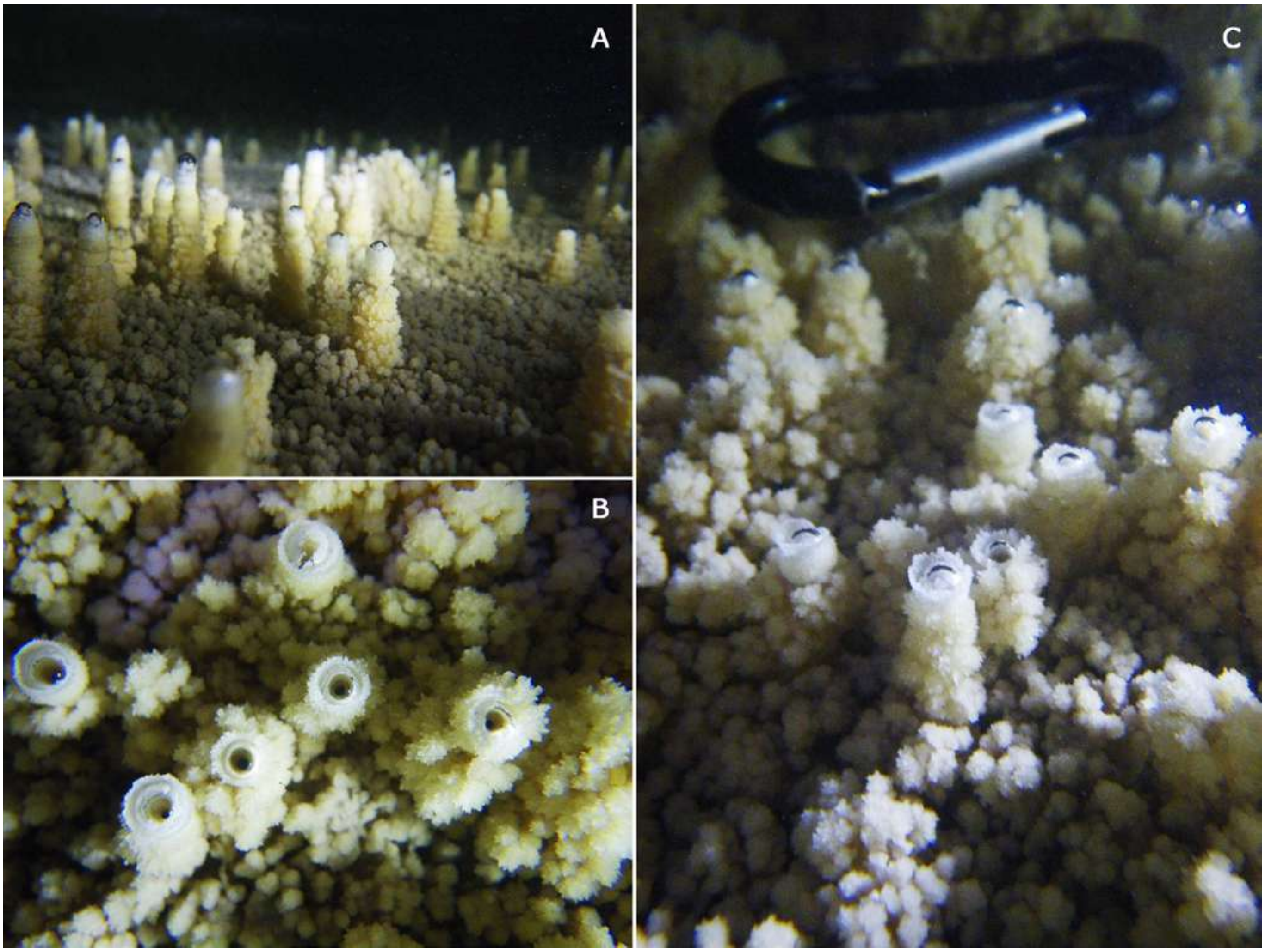

Fig. 3: underwater pictures of the anti-stalactites. A: the 5 cm-high tubes show the small gas bubble on top. B: the gas uplifts through a small canaliculus while at the water-bubble interface, calcite raft precipitates. C: calcite rafts are stuck around the rim of the speleothem when the gas bubble leaves the top of the canaliculus; carabineers for scale (photo L. Sanna).

Fig. 3: immagini subacquee delle anti-stalattiti. A: i tubi alti 5 cm hanno sulla cima delle piccole bolle di gas. B: il gas risale attraverso un piccolo canalicolo mentre all'interfaccia acqua-bolla precipita la calcite flottante. C: quando la bolla di gas lascia l'estremità del canalicolo, i cristalli di calcite flottante sono appiccicati sul bordo dello speleotema; moschettone come scala (foto L. Sanna).

accumulates there, thus forming a small cone around the mouth, while a minor portion of it sinks inside the chimney (Fig. 4C1) and supplies the needed calcium carbonate to neutralize the excess of CO_2 in the rising bubble within the chimney. Once the gas bubble leaves from the top of the anti-stalactite, the water cannot penetrate inside the chimney because the gas pressure from the depth balances the water pressure: in this manner the processes occurring in the boundary layer (CO_2 diffusion, evaporation and calcite deposition) are active also immediately after the detachment of the previous bubble.

In the subsequent step the further sequences of gas bubble formation and their detachment from the chimney rim allow for the evolution of an anti-stalactite (Fig. 4D), which is characterized by an external cylindrical surface with the presence of botryoidal overgrowth and an internal tube with constant diameter. The botryoides develops thanks to the enhanced oversaturation area present around the anti-stalactite that led the nucleation of small coralloids (Fig. 4D1). In turn they act as preferential places where sinking rafts accumulate. Final diagenesis induces a relatively fast transformation into a layered speleothem. The constant diameter of the inner hole is the direct consequence of the antagonistic processes occurring in between the rising gas bubble, the boundary layer and the calcite of the chimney wall (Fig. 4D2). Corrosion prevails when boundary layer partially migrates upward driven by gases during the movement of the gas bubble to the top of the anti-stalactite. Deposition and diagenesis are active just after the detachment of the bubble, when boundary layer descends fed by the oversaturated water coming from outside. As a consequence the diameter of the feeding hole along the entire subaqueous anti-stalactite is maintained perfectly constant and equal to the diameter of the equilibrium bubble that leaves from the top of the speleothem. The internal structure of the anti-stalactite is practically the same of a well-known tubular (Hill & Forti, 1997) even if the mechanism responsible for the genesis and the development of the internal tube is totally different. In fact in the tubular no process at all occurs inside it (CO_2 diffusion and $CaCO_3$ deposition are active only outside the tip of this

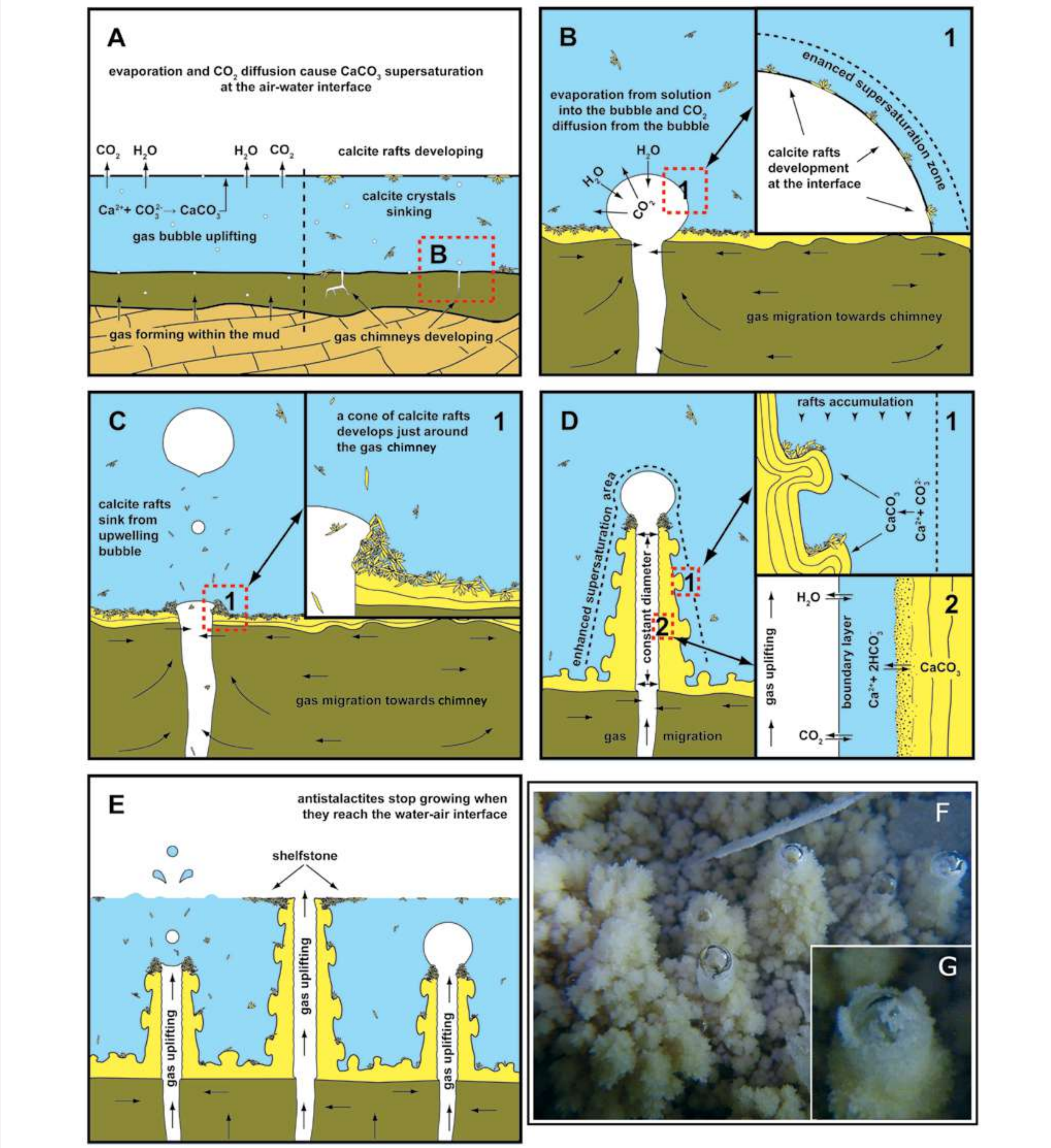

Fig. 4: genetic sketch for the evolution of subaqueous anti-stalactites (full explanation in text). A: the uplifting of the gas within the sediment creates small chimneys from which bubbles escape, while on the water surface the evaporation and CO_2 diffusion allow for the evolution of cave rafts. B: physico-chemical processes at the bubble-water interface cause the local development of cave rafts, which are forced to accumulate around the chimney mouth when the bubble leaves the top of the cylinder (C). D: a long sequence of bubble forming and detaching from the speleothem gives rise the evolution of steep cylindrical formation with an external botryoidal surface while the inner feeding tube is forced to maintain a constant diameter; E: the evolution of the anti-stalactites is designated to stop when the water surface will be reached; F: a gas bubble ready to leave the top of the anti-stalactite; G: cave raft nucleation at the water-bubble interface.

Fig. 4: schema genetico per l'evoluzione delle anti-stalattiti subacquee (spiegazione completa nel testo). A: la risalita del gas nel sedimento crea un piccolo camino da cui la bolla scappa, mentre sulla superficie dell'acqua l'evaporazione e la diffusione di CO_2 permettono la formazione della calcite flottante. B: i processi fisico-chimici all'interfaccia bolla-acqua causano lo sviluppo localizzato di calcite flottante, che quando la bolla lascia la cima del cilindro si accumula intorno alla bocca del camino (C). D: una lunga sequenza di formazione e distacco di bolle dallo speleotema da origine all'evoluzione di una ripida formazione cilindrica con una superficie esterna botrioidale mentre il tubo di alimentazione centrale mantiene un diametro costante. E: l'evoluzione delle anti-stalattiti è designata a fermarsi quando lo speleotema raggiungerà la superficie dell'acqua. F: una bolla di gas pronta a lasciare la cima dell'anti-stalattite. G: la nucleazione della calcite flottante all'interfaccia acqua-bolla.

speleothem) and the single controlling factor is the diameter of the falling drop. On the other hand, in the subaqueous anti-stalactites corrosion and deposition are alternatively active inside the canaliculus and are responsible for maintaining the tube diameter coincident with that of the leaving bubble.

The last step in the evolution of the submerged anti-stalactites is their growing stop. There are two factors that may break off the calcite deposition: (i) the gas supply interruption, and (ii) the emersion of the top of speleothem (Fig. 4E).

If no more organic matter is available in the soft sediment below the anti-stalactite, no more gas will be produced and therefore bubbles will stop to escape from the speleothem tip. The water would fill the internal hole as a consequence of the lacking of balancing pressure and the surrounding supersaturation layer would disappear. Thus also the botryoidal growth over the external surface would end. The single possible evolution would be related to the sinking of the calcite rafts from the water-air interface at the surface of the stream. As a consequence, the anti-stalactite would slowly transform into a tower cone, unless their production would were sufficiently high with respect to diagenesis. On the contrary, if the diagenesis prevails, they will be fossilized inside a normal calcite layer. Even if the gas production went ahead, the anti-stalactites would suddenly stop growing when they reach the height of the thickness of water that represents the maximum height for this kind of speleothem. In fact, if no more water is left over them, the gas inside the chimney would escape directly in the air without bubble formation. Also in this situation, the single possible evolution of the submerged speleothems would be related to cave rafts forming on the stream surface. The mouth of the anti-stalactite would act as the preferential site for calcium carbonate deposition, which in turn would cement calcite crystals to the speleothem rim causing to a shelfstone to grow just around it. The inner hole would be maintained unaltered at least until the gas escaped from the chimney.

Final Remarks

The genetic study of the subaqueous anti-stalactites observed inside the old aqueduct of Sassari allowed the definition of the complex boundary conditions that lead for the development of this completely new type of speleothem. This new discovery confirms that the artificial caves are ideal places where searching for different types of calcite formations never seen before even within natural caves. Anyhow, it is worth to be stressed that the boundary conditions ruling the development of the subaqueous anti-stalactites could easily be achieved also in a natural environment and therefore it is highly probable that in a near future such kind of speleothems will be seen also inside a natural cave.

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