Types of granite cavities and associated speleothems: genesis and evolution

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Abstract

Fabric and foliation that affect granite bodies develop in the later stages of emplacement/cooling, so generating three main types of discontinuities: the first is formed when magma changes from viscous to plastic-rigid; the second, when magma is almost consolidated and is strained in a fragile regime; and the third, in an elastic regime when magma is wholly consolidated. With the rock close to the Earth's surface, the groundwater uses the discontinuities previously formed to weather the rock massif in depth, resulting in a network of planes infilled with regolith. Later, the water circulation through the said network washes out the regolith and produces physical erosion, dissolution and precipitation (speleothems). Biogenic opal-A is the most frequent composition of speleothems, whose morphology is defined by the type of water dynamics: dripping, evaporation or capillarity. Three types of cavities may be distinguished: (1) fissure cavities, when the in-situ rock structure prevails in the definition of the cavity, (2) tafone of tectonic origin and (3) caves among moved blocks (earthquakes, gravity, creep, etc).

Key words

Pseudokarst, granitic cavities, speleothems, tafone, opal-A.

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Background

Granite magmas on their way to the surface are exposed to stresses: lithostatic or confining, and tectonic or directed. The first one is present everywhere in the lithosphere. The tectonic stress is generated during the magma emplacement and is able to produce structures in the rock that are affected under different stress regimes: plastic, ductile, brittle, elastic (Arzi 1978; Twidale and Vidal Romaní 1994), according to the magma consolidation/cooling grade. The stresses impose structures and other mechanical discontinuities, such as shear bands, fractures, faults and diaclases on the affected material (Roman Berdiel M.T. 1995; Petford 2003; Auréjac et al. 2004). These structures mainly affect the outer zones of the magmatic body and are due to the interactions between the magma and the walls of the injection conduits (host rock) (Vidal Romaní and Twidale 1999). So, during emplacement (see Waters and Krauskoph 1941 in Turner and Verhoogen 1951), rock protoclastic fractures (brittle strain) are developed in these peripheral zones. Another effect to be considered is the Stress Concentration Effect (SCE), normally triggered by tectonic forces (acting throughout the rigid massif divided by the discontinuities system). The SCE produces a change from an homogeneous weight distribution at the contact points among blocks, to a concentration at just a few points (Vidal Romaní 1985, 1989; Twidale and Vidal Romaní 2005) until the intact rock collapses, forming plasticity volumes (lacunar spaces) on the neighbouring contact points, such as those generated under the head of the rock bolts (Vidal Romaní 1985; Twidale and Vidal Romaní 2005). If these conditions are maintained over very long periods of time (geologically speaking), they will cause a permanent textural deterioration of the rock (see Vidal Romaní 1985).

When erosion of the sedimentary or metamorphic cover leads to contact between the magmatic intrusive rocks and groundwater, the rock is weathered preferentially through the system of discontinuities. Given the low porosity of fresh granitic rocks, fractures have a controlling influence on the course of weathering because permeability/porosity increases exponentially, according to discontinuities (Gustafson and Krasny 1993; Zhang et al. 2002) producing a morphology closely guided by the structure.

Normally, when granite landscapes are described, their superficial aspect is highlighted to the detriment of the subterranean landscape, which is either ignored or unknowingly taking for granted that it does not exist (Twidale 1982; Twidale and Vidal Romaní 2005; Migoń 2006). Nevertheless, though scarce and dispersed in the scientific literature, many references on cavities developed in granite rock exist (Chabert and Courbon 1997). Perhaps the reason, which explains its apparent neglect is the size of these cavities, which are always smaller than the ones developed in soluble rocks. For example, the granite cave with the greatest dimensions in the World (Chabert and Courbon 1997), such as the T.S.O.D. cave (3.977 m long) (New York, USA), which is a medium cave when compared with the size of cavities developed in calcareous rocks.

In granites, the attack by water takes place in three phases. The first is carried out by the groundwater weathering of the rock massif. The second takes place when the weathered rock is evacuated by water circulation through the system of discontinuities. The third stage occurs when water flows freely through the pseudokarst cavity system thereby generating mechanical or physical erosion. This process is triggered by changes in the phreatic level due to base level variations, because there is no possibility of development or evolution below the stable phreatic level.

Once the system of cavities is defined, dissolution and precipitation processes conducted by water flows, act in granitoids (Vidal Romaní et al. 1979, 2003) producing speleothem formations. These processes, described in many different environments (Spain, Portugal, Brazil, Australia, Argentina, Madagascar, U.S.A., Africa, etc.), appear to be independent of the climate though they always need water for their formation. Speleothems in granitic cavities are formed, as in calcareous rocks, when the water flow is slow, and through very narrow conduits. In granite rocks, the pH changes control not only the solution/deposition but also the performance of the organic or biological activity (despite there being biological activity in calcareous cavities on a similar scale). The biological weathering of granite rocks is essentially due to the bacterial action. It produces the transformation of the crystalline quartz (the most stable out of the three main minerals of granite) into another silica polymorph of low temperature: the biogenic opal (Opal-A). This mineral is less stable and more soluble than the crystalline quartz (Twidale and Vidal Romaní 2005).

Types of granite caves

From the three types of structures that are distinguished in granite massifs, only two of them, the ones corresponding to the protoclastic stage and the ones associated with the elastic stage, may generate the formation of cavities in the exogenous stage of the massif. From the authors' experience and revision of the main specialized texts on the subject (Twidale 1982; Vidal Romaní and Twidale 1998; Twidale and Vidal Romaní 2005; Migoń 2006), the types of granite caves are classified as follows:

1. Caves developed along major fracture planes. Weathering is essentially due to mineral washing, leading to further widening of the fracture (Fig. 1).

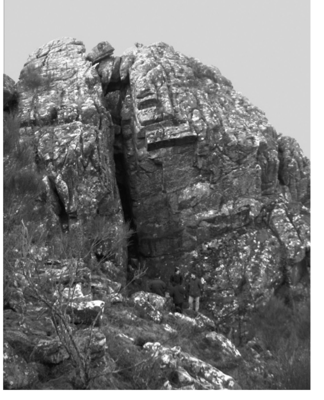

Fig. 1. Cave type 1 developed along a major fracture plane, (Serra de Galiñeiro, Pontevedra, Spain). Photo J.R. Vidal Romani, M. Vaqueiro.

2. Caves associated with residual blockfields. Here the finer fractions of the granite regolith, if exist, have been washed away, leaving the coarse fractions - blocks and boulders- in situ, (Fig. 2). Voids between these residuals

Fig. 2. Cave type 2 associated with a residual blockfield (Serra de Galiñeiro, Pontevedra, Spain). Photo J.R. Vidal Romani, M. Vaqueiro.

have become linked in some places, giving rise to caves of irregular shape (Twidale and Vidal Romaní 2005; Migoń 2006).

3. Tafone is the third type of cavity. It is linked to the elastic deformation stage of the massif, though similar types of cavities have been attributed to epigenic environments (Twidale 1982, 2002; Migoń 2006). The term refers to a cavern or hollow developed inside a fracture-defined block (Fig. 3). The inside wall or vault may develop

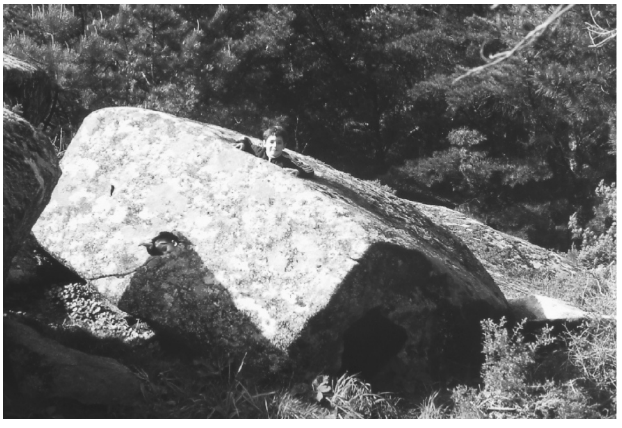

Fig. 3. Cave type 3. Boulder tafone. (Monte Louro, Coruña, Spain). Photo J.R. Vidal Romani, M. Vaqueiro.

alveoles (honeycomb structure), mamillated (convex relief) or scalloped (concave relief) forms (Twidale and Vidal Romaní 2005) and also negative exfoliation forms (Vidal Romaní 1985).

The speleothems associated with granite caves

All these types of cavities are associated, in many cases, with the presence of speleothems, whose morphology is directly related to the way in which the water flows through the fissure. Up to now, two main types have been described (Vidal Romaní et al. 1998): cylindrical speleothems and blanket speleothems in crusts or layers.

Cylindrical speleothems are associated with either water dripping points (stalactites) or growing centres where water supplies are produced by capillary movements through previous porous accumulations of opal-A (blanket speleothems), located on the bottom, wall or roof of the cavities thereby giving rise to antistalactites. Their formation is therefore independent from gravity, which permits the growth of the speleothem in any direction. Stalactites may be individual forms or appear branched (coralloid speleothems) (Fig. 4). Antistalactites may also

Fig. 4. Opal-A stalactite (Castelo da Furna, Boivão, Portugal). Photo J.R. Vidal Romani, M. Vaqueiro.

appear in individual or branched forms, though with thicker cross sections than the stalactites.

The tip of cylindrical speleothems usually ends in a crest of gypsum whiskers, exhibiting minor growth in the stalactites and better development in the antistalactites, giving rise to the so-called cauliflower crystals (Vidal Romaní et al. 1998). Gypsum whiskers are developed as a crest or druse where crystals appear twinned with an astonishingly perfect morphology. They are associated with concavities, channels or pores (Twidale and Vidal Romaní 2005) as (1) prismatic twins: monoclinic class 2/m, (2) acicular twins and (3) planar twins, respectively (Fig. 5). Their average size is 0.2-0.6 cm and generally not more than 1 cm long (exceptionally they may have 2 or 3 cm).

The other type of speleothems is the blanket speleothem produced by circulation of a water laminar flow. Its genesis is similar to the one of the same deposits in soluble rocks. Three types of blanket speleothems are distinguished (Vidal Romaní et al. 1998):

- Flowstone: continuous coatings of the rocky surface that have variable thicknesses and may also hide the micro-rugosity of the rock (Fig. 6).
- Gour-dams: accumulations with linear and sinuous development that retain water temporarily. They are associated with plane or low slope surfaces (Figs 7a and b).
- Rimstone: halos of opal-A surrounding the output points of water that circulates through a system of discontinuities. They are associated with the cavity roof of caves or rocky shelters or subvertical planes. The water movement is governed by surface tension and the speleothems may have some microns of thickness.

Mineralogy of speleothems

Speleothems have been analysed with the use of different techniques (Vidal Romaní et al. 1979); namely

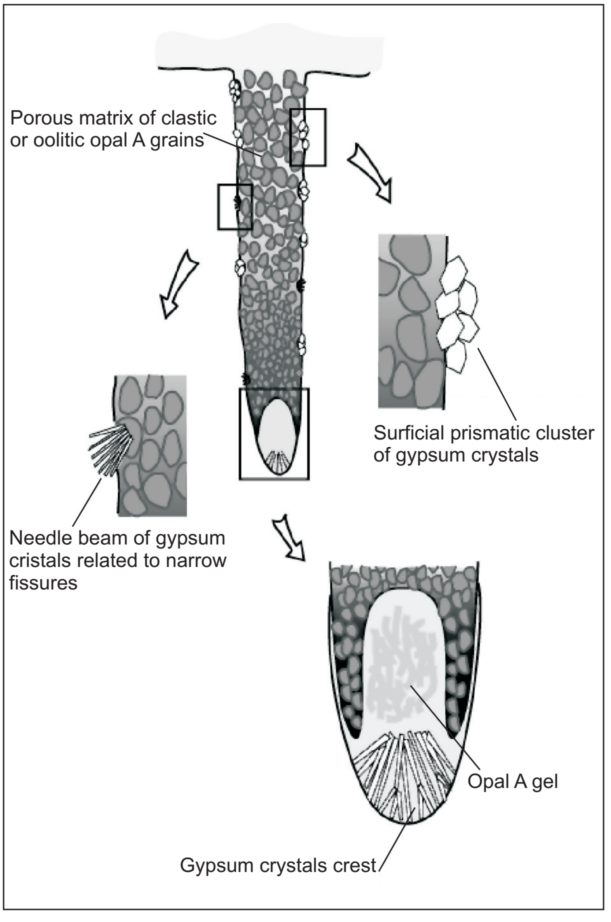

Fig. 5 Sketch of a stalactite with the location of gypsum whiskers of different shapes.

by X-rays or DTA and GT. Results of the X-ray analysis show that they are non-crystalline amorphous materials. They show a diffuse band between 8.8 Å and 10 Å, and small characteristic peaks of silica polymorphs, especially of cristobalite (4.04 Å and 3.18 Å) and quartz (3.32 Å and 3.18 Å), which is due to small crystal fragments coming from the rock and included in the amorphous matrix of the speleothem (Vidal Romaní and Vilaplana, 1983). In the DTA diagrams (Calvo et al. 1983), the presence of an endothermic peak of low temperature was observed, that corresponds to hydration water in the speleothem (145ºC), followed by an exothermic peak between 300 and 450ºC (sometimes 500ºC) assigned to organic matter oxidation (Vidal Romaní and Vilaplana 1983).

Texture of speleothems

The observation by SEM is the one that has provided more information on the genesis and development of speleothems. They show an external surface of irregular

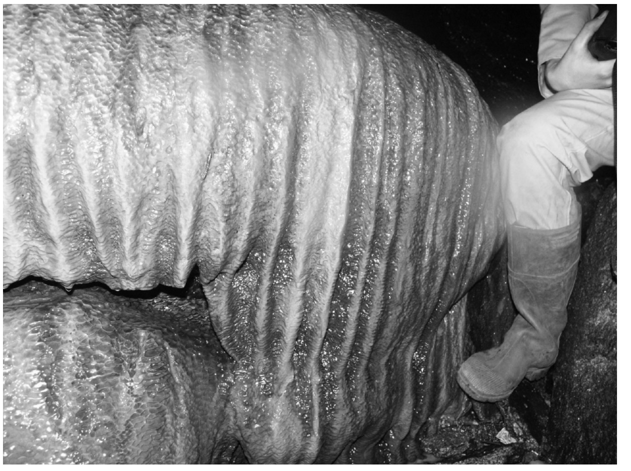

Fig. 6. Flowstone of pigotite in the O Folón Cave (Pontevedra, Spain). Photo J.R. Vidal Romani, M. Vaqueiro.

Fig. 7a. Macro-gour or drip pool of opal-A (pigotite) in the O Folón Cave (Pontevedra, Spain). Photo J.R. Vidal Romani, M. Vaqueiro.

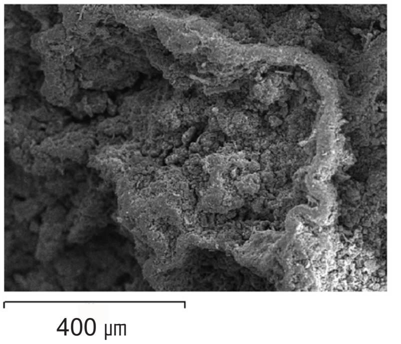

Fig. 7b. Micro gour (SEM image) of opal-A from Cerros Blancos (Pampa de Achala, Córdoba, Argentina). Photo J.R. Vidal Romani, M. Vaqueiro.

micro-relief with clasts or oolites of different sizes, partially or totally formed by concentric coats of opal-A. Their structure and internal composition have also been established from thin sections, analysed with the petrographic microscope or by SEM (Twidale and Vidal Romaní 2005). Some cylindrical speleothems show a rhythmic texture, formed by layer-by-layer accretion as it occurs in their congeners developed in limestone (Vidal Romaní and Vilaplana 1983)

The growth process of these speleothems is discontinuous because they develop according to the water contribution that they receive, normally rain. In the formation and growth of speleothems, the water flow regime through the fissure system or on the rock surface towards the point where the speleothem will form (Vidal Romaní and Vilaplana 1983), has great importance because quick water flow impedes the precipitation of elements dissolved by water. Otherwise, a slow flow is best for the development of speleothems, of whichever type (blanket or cylindrical type) (Vidal Romaní et al. 1998). The evaporation of water is the prevailing effect that establishes the precipitation of amorphous silica.

In the precipitation processes the biological activity that influences the rock degradation process, especially of quartz, is very important. The biogenic weathering is helped by the production of metabolic compounds by different types of organisms (bacteria, fungi, lichens) (Fig. 8) that accelerate rock degradation (Bennett 1991; Ehrlich 1996), transforming quartz into amorphous silica (opal-A) with a solubility approximately ten times higher than the alpha or beta quartz. As it is seen, quartz weathering processes are underlined, and the ones that affect the other two main components of granitoids: feldspars and micas, are not mentioned. It is evident that the biogenic weathering affects all the granite minerals but the existence of amorphous silica speleothems, is restricted to rocks with an abundance of free quartz being absent in the more basic facies, e.g., syenites (Twidale and Vidal Romaní 2005). This makes us think that the mobility of chemical elements that form these minerals is greater than the one of silicon, which prevails in quartz.

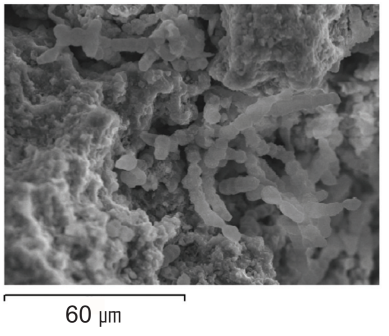

Fig. 8. Bacteria colony (SEM image) in living position located in a speleothem void from Cerros Blancos (Pampa de Achala, Córdoba, Argentina). Photo J.R. Vidal Romani, M. Vaqueiro.

Conclusions

In the first phase the formation of cavities in granite rocks is closely related to the development of discontinuities (diaclases, fractures, faults, etc.), which are the only ways that will allow the progress of chemical or physical weathering inside the rock massif, given the low rock porosity. Somehow, the same occurs with soluble rocks. In a second phase, evacuation of the regolith associated with the system of discontinuities takes place, carried out by water circulation dynamized by changes in the base level due to isostasy, tectonics or climatic changes. Once the space is formed inside the rock massifs, the evolution continues, according to the conditions of water flow through the pseudokarstic system, through mechanical erosion. In this stage a generation of speleothems may also be produced, whose composition, opal-A, is closely related to the mineralogy and chemistry of the granite rock. It is evident that there are morphological similarities between cavities developed in granite rocks and their equivalents in soluble rocks (carbonates, sulphates, etc.). The main difference is the dimensions of the cavities, the magnitude of rock solubility and the mineralogy of the speleothems in both cases.

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