HYPOGENIC CAVES OF SICILY (SOUTHERN ITALY)

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First results of a study on hypogenic caves in Sicily are presented. Inactive water-table sulphuric acid caves and 3D maze caves linked to rising of thermal waters rich in H_2S were recognized. Cave patterns are guided by structural planes, medium and small scale morphological features are due mainly to condensation-corrosion processes. Calcite and gypsum represent the most common cave minerals. Different types of phosphates linked to the presence of large bat guano deposits were analyzed.

1. Introduction

Hypogenic caves are recognised as generated by water recharging from below independently of seepage from the overlying or immediately adjacent surface. Waters are often thermal and/or enriched in dissolved gases, the most common are CO_2 and H_2S. Hypogenic caves can be thermal caves, sulphuric acid caves, and basal injection caves. They differ from epigenic caves in many ways, such as: speleogenetic mechanisms, morphological features, chemical deposits, and lack of alluvial sediments (Klimchouk 2007; Klimchouk and Ford 2009; Palmer 2011). Several studies were conducted to evaluate the hypogenic origin of a large number of caves (Klimchouk and Ford 2009; Stafford et al. 2009; Audra et al. 2010; Plan et al. 2012; Tisato et al. 2012). A significant contribution was given by the work of Klimchouk (2007) that systematically provided instruments and models to better understand and well define the hypogenic karst processes and landforms.

Studies on hypogenic caves in Italy were carried out since the 90s in different karst systems, especially in the central and southern Appenines. These studies mainly concerned chemical deposits related to sulphuric ascending water and micro-biological action (Galdenzi and Menichetti 1995; Galdenzi 1997; Piccini 2000; Galdenzi and Maruoka 2003; Forti and Mocchiutti 2004; Galdenzi 2012; Tisato et al. 2012).

This paper aims to describe preliminary the first results of a study conducted in some hypogenic caves in Sicily, highlighting their main features such as pattern, morphology, mineralogy and speleogenesis. These are Monte Inici karst system and Acqua Fitusa Cave. For this purpose topographic and geomorphological surveys were carried out, and about 40 samples of cave minerals were taken in different parts of the caves. In addition, a brief description of Monte Kronio karst system is given. It represents one of the most important hypogenic karst systems of Sicily, characterized by flows of hot air and vapor rising from below.

2. Karst in Sicily

Karst in Sicily is widespread and exhibits a great variety of surface and underground landforms related to the wide distribution of soluble rocks (Di Maggio et al. 2012). About 20% (more than 6,000 km^2) of the land area consists of carbonates and evaporites, primarily gypsum (Fig. 1). Carbonate karst lies mainly in the northwestern and central sectors of the Apennine chain and the foreland area in southeastern Sicily; gypsum karst occurs chiefly in the central and southern areas of the island, though evaporite landscapes are also present in the northern and western parts of Sicily.

Carbonate and gypsum karst systems develop under unconfined conditions and in most cases constitute epigenetic systems fed by meteoric waters. Hypogene caves are located only in carbonate rocks and are linked to the presence of deep thermal waters.

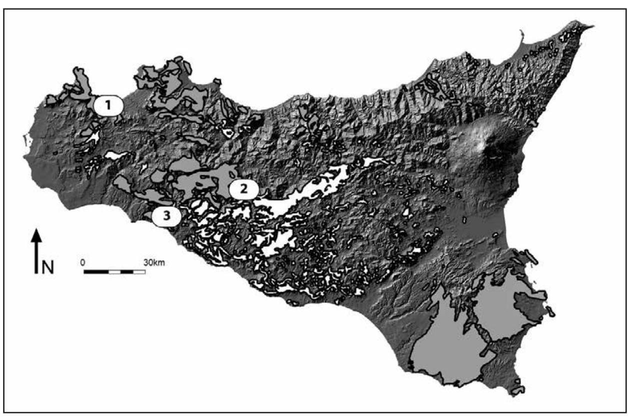

Figure 1. Gypsum (white) and carbonate karst areas (grey) and localization of investigated hypogenic karst systems. 1. Monte Inici; 2. Acqua Fitusa. 3. Monte Kronio.

3. Hypogenic caves

3.1. Acqua Fitusa Cave

Acqua Fitusa Cave opens in the eastern section of the Sicani Mounts (west-central Sicily), along the north-eastern fault scarp of a N-S anticline, westward vergent, forming the Mt. La Montagnola (Fig. 1). The cave formed in the Upper Cretaceous Rudist breccias member of the Crisanti Fm., composed of conglomerates and reworked calcarenites with rudist fragments and benthic foraminifera (Catalano et al. 2011).

At present it is inactive with a thermal spring occurring 300 m north and 30 m below the cave. The waters have a temperature of about 25 °C, and are indicated as chlorine-sulphate alkaline (Grassa et al. 2006 and references therein). During the spring-summer-early autumn the cavity hosts a large colony of bats, including *Myotis myotis* and *Miniopterus schreibersii* species (Mucedda pers. comm.), that produce significant amounts of guano.

The first explorations of Acqua Fitusa were carried out in the early XXth century by some inhabitants of the neighboring villages, but the first human frequentations of the cavity have to go back to the Paleolithic and Chalcolithic periods, as evidenced by the discovery of numerous lithic fragments, remains of food and burials (Bianchini and Gambassini 1973). Lombardo et al. in 2007 gave a description of the cave and some studies concerned the hydrogeochemistry and isotopic composition of the nearby spring waters (Grassa et al. 2006 and references therein).

According to the survey made in 2011, the cave consists in at least three stories of subhorizontal conduits, displaying a total length of 700 m, and a vertical range of 25 m (Fig. 2). The main passages are generally low and narrow and follow sets of joints oriented in ENE-WSW, E-W and N-S directions. Very small passages develop from these galleries making incipient mazes.

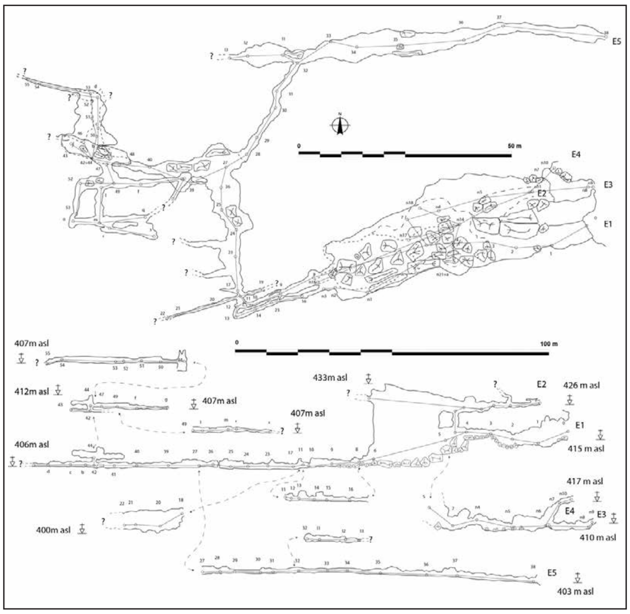

Figure 2. Acqua Fitusa Cave: plan view and extended profile (Survey: Ceresia, Inzerillo, Provenzano, Sausa, Scrima and Vattano, 2011).

The conduits breach the fault scarp in more points at different heights. The main entrance leads to a large chamber enlarged both by corrosion and breakdown processes, connected to an upper subhorizontal passage that likely formed during a past higher karst base level.

Acqua Fitusa Cave represents a clear example of inactive water table sulphuric acid cave (Audra et al. 2009). Despite the small size, the cave is very interesting for the abundance and variety of morphologies and deposits formed at and above the water table where H_2S degassing and thermal convection produced strong condensation-corrosion processes.

The floor of some passages is breached for several meters by an inactive thermo-sulphuric discharge slot that can reach a depth of 7 m (Fig. 3). In some sections of the caves, notches with flat roof, linked to lateral corrosion of a water table with concentrated sulphuric acid, carve the walls at different heights, recording past stages of base-level change.

Several forms of small and large sizes, generated by condensation-corrosion processes above the water table, can be observed along the ceiling and walls. Ceiling cupolas and large wall convection niches occur in the largest rooms of the cave. Here and in the upper gallery, pendants at junctions of more cupolas or between braided channels are widespread. Cave walls of many passages are carved at different heights by deep wall convection niches that in places form notches (Fig. 3). Condensation-corrosion channels similar to ceiling-half tubes carve the roof of some passages; replacements pockets due to corrosion-substitution processes are widespread; boxwork created by differential condensation-corrosion were observed in the upper parts of the conduits.

Figure 3. Acqua Fitusa. Passage with discharge slot at the floor and different levels of wall convection niches.

The most abundant cave mineral is gypsum which displays different shapes and colours. Replacement gypsum crusts are common in many passages; the gypsum is located in large vertical fissures along the walls, it can partially cover wall convection notches, or replacement pockets. A gypsum body of about 50 cm of thickness was found on the floor of the biggest room in correspondence of which small ceiling cupolas and pendants are associated on the roof. Centimeter-sized euhedral gypsum crystals grew inside mud sediments. Finally, the walls of a feeding fissure are covered with a network of gypsum “roots” in which the biological control is obvious. Further investigation on these apparently subaqueous gypsum speleothems is still ongoing.

Phosphate minerals, such as apatite [$Ca_5(PO_4)_3(OH)$], were found in the form of thin crusts near large deposits of bat guano.

3.2. Monte Inici Complex

Monte Inici karst system is situated in northwestern Sicily (Fig. 1), in the eastern sector of the Trapani Mountains, and opens along the southeastern slope of Mt. Inici, a gently westward – dipping monoclinal relief affected by NW-SE, NE-SW and NNW-SSE high angle faults. The karst system is composed of two caves, Grotta dell'Eremita (or Grotta del Cavallo) and Abisso dei Cocci, formed in Jurassic limestones and dolomitic limestones. Thermal waters emerge from three hot springs east and at lower altitude respect to the caves (Fig. 4). These are of chloride-sulphate alkaline-earth type and have a temperature respectively of 48.3 °C (Gorga 1), 49.6 °C (Gorga 2), and 44.2 °C (Terme Segestane) (Grassa et al. 2006 and references therein).

The caves preserve clear signs of prehistoric and medieval human presence, such as several lithic and bone fragments, food remains, ceramic finds typical of the Middle Neolithic-Middle Chalcolithic (Grotta dell'Eremita), and large amounts of medieval pottery (XI^{th}–XV^{th} century), identified mainly within Abisso dei Cocci (Tusa 2004). These caves were explored and described in the early 90s. On the basis of morphological features a genesis linked to thermal waters was supposed (Biancone 1993; Messana 1994).

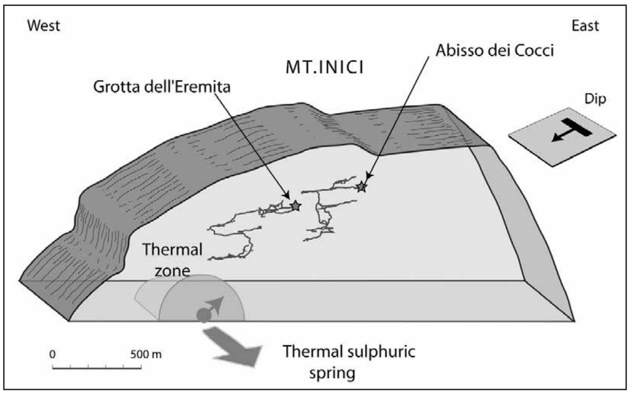

Figure 4. Sketch of Monte Inici karst system and localization of the thermal zone.

3.2.1. Abisso dei Cocci

Abisso dei Cocci is an inactive 3D maze cave formed in Lower Jurassic limestones and dolomitic limestones (Inici Fm.), arranged in decimetric westward dipping beds. The cave is one of the largest of Sicily, reaching a total length of over 2,053 m and a vertical range of -300/+61m. It consists of several stories of large subhorizontal galleries and chambers connected by deep shafts. In plan view the galleries are mainly oriented in NW-SE and NE-SW direction, parallel with the main tectonic discontinuity lines. Some conduits are gently inclined and follow the dip of bedding planes, whereas the shafts develop along vertical fissures or fault planes. Passages display sub-circular cross-sections, sometimes with vadose entrenchments (Fig. 5).

Several features linked to rising thermal water and air flow were recognized in many sections of the cave. Many passages are characterized by large convection wall niches, mega-scallops, ceiling cupolas, and ceiling spheres. In some cases adjacent passages are separated by partitions (Fig. 5).

The cave lacks alluvial sediments; on the other hand chemical deposits are abundant mainly in the middle level of the cave, where dripping is still active. Here, a large variety of calcite speleothems, such as stalactites, stalagmites, flowstones, shelfstones, etc., occur. Calcite is present also in the shape of powder, thin crusts, and frostwork. Gypsum was recognized in the middle and deepest sections of the cave in the form of tabular or acicular colourless small crystals (Fig. 5).

Figure 5. Abisso dei Cocci. Passages displaying sub-circular cross-section with vadose entrenchment characterised by uncovered ceiling and walls with cupolas and gypsum in the lower parts.

Different types of phosphate minerals were found in several parts of the caves. Hydroxylapatite occurs as thin crusts or powder above the bedrock, and even forms true stalactites. Crandallite [$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$] is present as soft white grains at the contact between weathered rock and bat guano, in association with green small spherical masses of montgomeryite [$Ca_4MgAl_4(PO_4)_6(OH)_4 \cdot 12H_2O$]. Phosphates are linked to the presence of large fossil bat guano deposits occurring in many parts of the cave.

3.2.2. Grotta dell'Eremita

Grotta dell'Eremita formed in Middle-Upper Jurassic reddish-gray limestones with ammonites (Buccheri Fm.), and in Lower Jurassic limestones and dolomitic limestones (Inici Fm.) in its deepest parts. The cave is a relict 3D maze cave, which reaches a total length of 2880 m, and a vertical range of -306 m. The air temperature, measured in

December 2011, was 17.6 °C in the passages near the entrance area, gradually increasing up to 21.0 °C in deepest chamber of the cave.

Grotta dell'Eremita shows many morphological and depositional features similar to Abisso dei Cocci, although some differences were recognized. The cave is made up of large subhorizontal passages and big chambers connected by deep shafts, which are guided by the main tectonic discontinuity planes. Some galleries are gently inclined following the dip of bedding planes and display sub-circular cross-sections. Along the walls of these passages, in correspondence of the bedding planes, several small conduits filled by well-cemented fine reddish sediment of continental nature, are visible. Large convection niches, mega-scallops, ceiling cupolas, ceiling spheres, and drip holes are widespread in the chambers and in the largest passages of the cavity (Fig. 6).

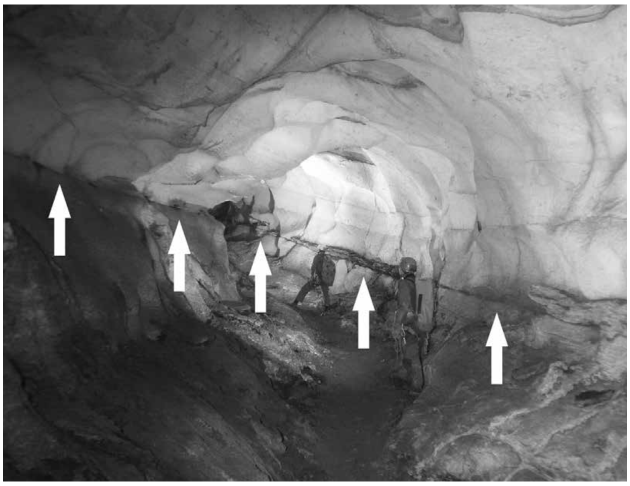

Figure 6. Grotta dell'Eremita. Passage along a bedding plane where filled protoconduits are visible. Walls and ceiling are characterised by large convection niches and cupolas.

A breccia consisting of decimetric carbonatic clasts in a reddish silt matrix characterized by thin laminas and decantation structures is exposed at walls and ceiling of some deep passages.

Different chemical deposits were identified: besides calcite, occurring in the form of white cigar-shaped crystals grown under old bat guano, reddish laminae, or coralloids, gypsum was found as tabular or fibrous crystals. Phosphate minerals, such as hydroxylapatite and taranakite, occur mainly in form of powders or crusts near or above deposits of bat guano. Carbonate-apatite was recognised as crusts or small stalagmites (Messana 1994). As in Abisso dei Cocci clastic sediments are absent.

3.3. Monte Kronio karst system

Monte Kronio karst system opens in the southern scarp of Mt. Kronio or Mt. San Calogero, north-east of Sciacca town (southern Sicily) (Fig. 1). Mt. Kronio consists of an imbricate fan system linked to ENE-striking, closely spaced imbricate thrust sheets, involving Triassic to Miocene platform and pelagic platform carbonate deposits (Monaco et al. 1996). The karst system is made up of a series of cavities characterized by rising of hot air and vapour flow at temperature of about 38 °C, connected to the presence of thermal waters. These waters, emerging along the southern slope of Mt. Kronio at lower altitude respect to the cave entrances, are of chloride-sulphate alkaline type and have a temperature ranging between 32 and 55 °C (Grassa et al. 2006 and references therein; Capaccioni et al. 2011). Actually they are used for aesthetic and therapeutic purposes.

The caves were visited by man since the end of the Mesolithic for residential use, place of worship, necropolis, and from the Ist century BC for thermal purposes. The first attempts to explore the caves date back to the end of the XVIIth century; since the 40s several exploration campaigns conducted by the Commission Grotte "E. Boegan" of Trieste identified and surveyed the cave system nowadays known. The explorations, carried out with great difficulty, due to the critical environmental conditions with temperatures of about 38 °C and humidity of 100 %, have allowed the discovery of an extended maze cave system about 200 m deep (Perotti 1994).

The system is composed of more cavities, located at different altitude, characterized by subhorizontal passages connected by deep shafts or steep passages, but there is not always a passable connection between the several branches of the caves. Some galleries breach the southern scarp of Mt. Kronio through small openings some of which emit hot air, other ones aspire cold air from outside (Perotti 1994).

The upper section of the system, known also as Stufe di San Calogero, consists of a series of chambers separated by man-made walls, connected to a maze of narrow passages. Some chambers are characterized by hot vapour flow rising from a deep shaft which connects these passages with two large hot galleries, oriented in NW-SE direction, where abundant archeological finds were discovered. A small cave (Grotta del Lebbroso), interested by rising of hot vapour flow, develops eastward at the same altitude, but to date no passable connection to the rest of the system was recognized. The deepest part of the cave is represented by a large and deep shaft (Pozzo Trieste), from which more levels of narrow passages, both hot and cold, develop breaching the southern cliff of Mt. Kronio (Fig. 7). A large breakdown deposit occurs at the bottom of the shaft.

Walls and ceiling of the caves are weathered and important gypsum deposits, in form of powders or crusts, were observed (Perotti 1994).

Figure 7. Monte Kronio. Forms linked to condensation-corrosion (on the right); weathered flat roof affected by condensation (on the left).

4. Discussion and Conclusions

The study of the geological setting, cave pattern, medium and small scale morphological features, and the analysis of cave minerals allowed defining a hypogenic genesis for the investigated karst systems. All the caves developed along structural planes, such as bedding, fracture or fault planes, whose enlargement is due to corrosion by H_2S-rich thermal waters, and to condensation-corrosion processes by air flow in the cave atmosphere.

Acqua Fitusa cave is an inactive water-table sulphuric acid cave linked to corrosion processes of carbonate rock with replacement of gypsum by H_2S-rich thermal water (Fig. 8). Occurrence of notches with flat roof indicates lateral corrosion processes by sulphuric thermal water fed through discharge slots still open on the floor of some passages. Ceiling cupolas, large wall convection niches, condensation-corrosion channels, boxwork testify that enlargement of voids occurred mainly above the water table where H_2S degassing in the cave atmosphere, oxidation of sulphides and thermal convection produced strong condensation-corrosion processes. In addition, large amounts of gypsum, replacement pockets, in places containing gypsum, suggest the corrosion of the carbonate rock occurred with replacement of gypsum according to the sulphuric acid speleogenesis (Galdenzi and Maruoka 2003; Audra et al. 2010 and references therein). Like other sulphuric acid systems (Galdenzi and Menichetti 1995) the different levels of passages record past stages of the water table, in relation to changes of the base-level.

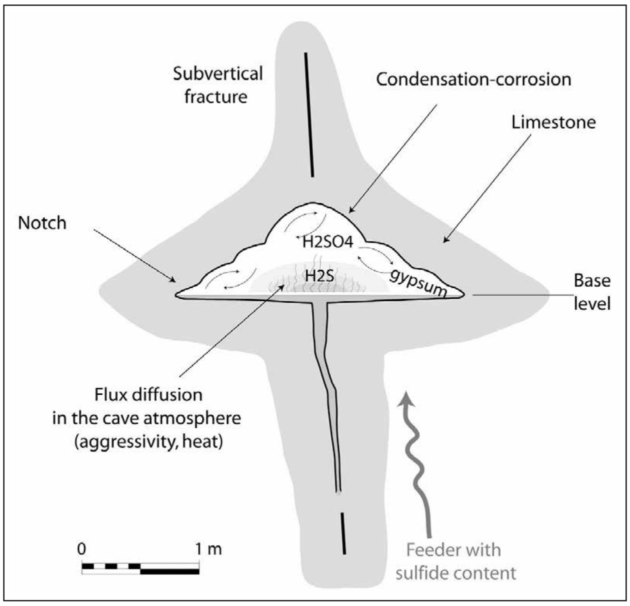

Figure 8. Acqua Fitusa. Genetic mechanism of cave passages due to H_2S degassing in the cave atmosphere.

Grotta dell'Eremita and Abisso dei Cocci caves were identified as inactive 3D maze caves. Pattern and cross sections of the main passages of Abisso dei Cocci suggest the early speleogenetic phases to have occurred in phreatic conditions by rising thermal water which formed a well developed 3D maze system. An important role in the evolution and widening of the subterranean voids was played by air flow when the cave passages switched from phreatic to vadose conditions, as a consequence of the uplift phases of this sector of the Sicilian chain. In this case, the processes of corrosion by condensation from air flow rich in H_2S, favoured on one hand the enlargement of the early voids with the formation of large megascallops and ceiling cupolas, on the other hand the deposition of gypsum in the lower parts of the passages (Fig. 9).

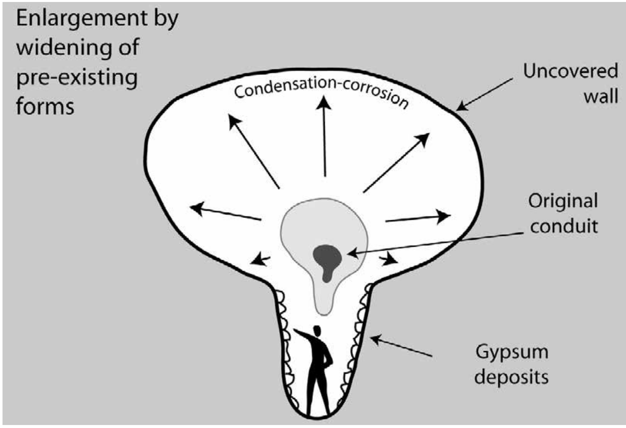

Figure 9. Abisso dei Cocci. Enlargement of passages by widening of pre-existing forms due to condensation-corrosion.

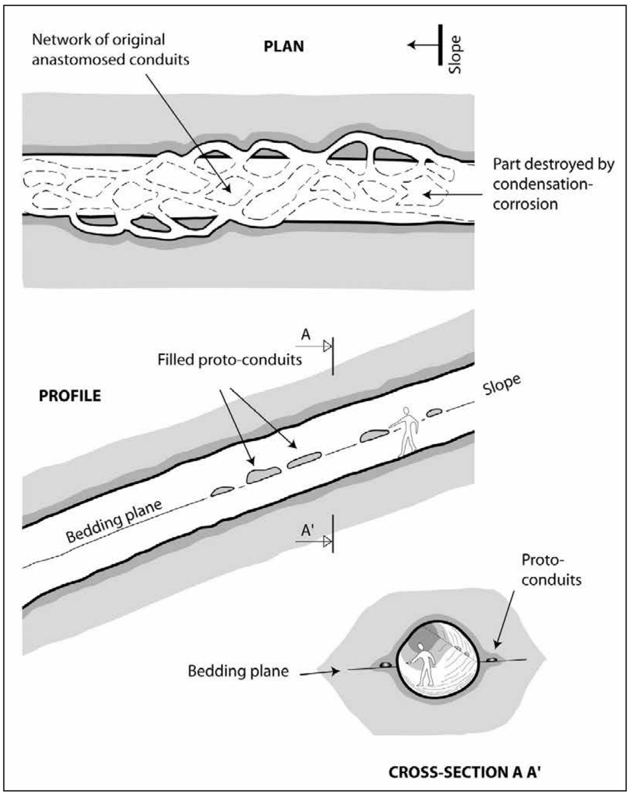

Figure 10. Grotta dell'Eremita. Genesis of passages along a bedding plane with formation of protoconduits enlarged by condensation-corrosion.

The first speleogenetic phases in phreatic conditions of Grotta dell'Eremita are recorded, beside the pattern, by the presence of several filled anastomosed protoconduits visible at the bedding plane, along which the passages develop. The next phase of evolution of the system may have followed two possible ways: a) enlargement of voids by condensation-corrosion processes which destroyed the network of protoconduits and formed the main passages as testified by the presence of megascallops, ceiling cupolas, etc. (Fig. 10); b) corrosion processes by a deep sulphuric thermal water enlarging the early voids, destroying the protoconduits and forming the main passages in phreatic conditions. Successively, condensation-corrosion processes by acid sulphuric air flow enlarged the early phreatic voids with the formation of megascallops, ceiling cupolas etc., and deposition of gypsum. The question is open, future studies will clarify the issue.

Finally, in all the investigated caves the presence of different types of phosphate minerals is linked to the large deposits of bat guano (Hill and Forti 1997).

Monte Kronio system is an active hypogenic karst system and is unique in Sicily and probably in the world. It owes its peculiarity to the rising of hot air and vapour flow, linked to a deep thermal aquifer, still not identified within the system. Although this system is known since prehistoric times, yet little is known about its real development and speleogenetic mechanisms due to the harsh environmental conditions that make exploration extremely difficult. Multidisplinary studies are currently in progress.

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