An Overview of the Hypogene Caves of Sicily

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Marco Vattano, Giuliana Madonia, Philippe Audra,
Ilenia M. D'Angeli, Ermanno Galli, Jean-Yves Bigot,
Jean-Claude Nobécourt, and Jo De Waele

Abstract

Karst in Sicily develops in both Messinian gypsum and Mesozoic or Tertiary limestone rocks. Caves are also found in the basalts of Mount Etna. Except for some rare cases, until recently most caves developed in limestone were considered to be of epigenetic origin. The discovery of gypsum in some of these caves, and especially detailed morphological studies, have allowed defining a hypogenic origin for a dozen of caves up to now. In some of these, the hypogenic evidences are very clear, while others remain in doubt because of the widespread presence of well-developed condensation-corrosion morphologies not necessarily related to hydrothermal fluids. This paper reports the present knowledge of hypogenic caves in the Island of Sicily.

Keywords

Hypogenic caves • Sicily • Sulfuric acid speleogenesis • Condensation-corrosion • Wall sculpturing

1 Introduction

In recent years, knowledge on hypogene karst increased significantly in many aspects. Studies on hypogenic caves in Sicily are quite recent. Except for some investigations carried out at Monte Inici and Monte Kronio (Messana 1994; Perotti 1994 and references therein), systematic research only began in 2010. These investigations have allowed identifying several hypogenic karst systems, previously thought to be epigenetic caves fed by meteoric water. The analysis of pattern, large- and mid-scale morphologies,

M. Vattano · G. Madonia
Dipartimento di Scienze della Terra e del Mare, University of Palermo, Via Archirafi 22, 90123 Palermo, Italy
e-mail: marco.vattano@unipa.it

G. Madonia
e-mail: giuliana.madonia@unipa.it

P. Audra
University of Nice Sophia Antipolis, Sophia Antipolis Cedex, France
e-mail: audra@unice.fr

I.M. D'Angeli · J. De Waele (✉)
Italian Institute of Speleology, Department of Biological, Geological and Environmental Sciences, University of Bologna, Via Zamboni, 67, 40126 Bologna, Italy
e-mail: jo.dewaele@unibo.it

I.M. D'Angeli
e-mail: dangeli.ilenia89@gmail.com

E. Galli
Dipartimento di Scienze della Terra, University of Modena and Reggio Emilia, Largo S. Eufemia 19, 41121 Modena, Italy
e-mail: ermanno.galli@unimore.it

J.-Y. Bigot
Association Française de Karstologie (AFK), 21 rue des Hospices, 34090 Montpellier, France
e-mail: jeanbigot536@gmail.com

J.-C. Nobécourt
CRESPE, Avenue des Poilus, 06140 Vence, France
e-mail: jcnobecourt@free.fr

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Table 1 List of the Sicilian hypogene cave systems

Cave system	Studied	Under investigation	Length (m)	Depth (m)
1 Abisso dei Cocci—Grotta dell'Eremita	X		2000 2900	+61/−300; −306
2 Grotta dei Personaggi	X		1700	+15/−32
3 Grotta dei Personaggini		X	110	−16
4 Grotta Barone		X	85	−14
5 Monte Kronio	X		not available	not available
6 Grotta dell'Acqua Fitusa	X		700	+10/−16
7 Abisso del Vento		X	2,000	−210
8 Grotta dell'Acqua Mintina		X	not available	not available
9 Grotta Palombara		X	800	−80
10 Grotta Scrivilleri		X	2,000	not available
11 Grotta Monello		X	200	−32
12 Grotta Chiusazza		X	190	0

mineral deposits and the presence of warm springs in areas close to the cavities in fact suggest that the genesis of these caves is linked to hypogenic processes (Vattano et al. 2012, 2013, 2015; De Waele et al. 2016).

New explorations allowed inferring the hypogenic origin of other caves based on the presence of peculiar morphologies and deposits. In most cases, speleogenetic, geomorphological, mineralogical and biological studies are still in progress (Table 1).

In this paper, we illustrate the main morphological, mineralogical and speleogenetic features of the hypogenic caves investigated up to now.

2 Geology

Sicily is a segment of the Alpine collisional belt that develops along the Africa–Europe plate boundary and links the southern Apennine and the Calabrian Arc to the Tellian and Atlas systems of northeastern Africa. The Sicilian collisional complex consists of several stratigraphic and tectonic elements (Catalano et al. 2013b and references therein; Avellone et al. 2010; Gasparo Morticelli et al. 2015, Fig. 1): (a) the Hyblean foreland (Hyblean Plateau) outcropping in southeastern Sicily, made up of Triassic–Liassic platform and scarp-basin carbonates overlain by Jurassic–Eocene pelagic carbonates and Oligocene–Quaternary open shelf carbonates; (b) a NW-dipping foredeep located north of the foreland, consisting of Plio-Pleistocene pelagic marly limestones, silty mudstones and sandy clays overlying Messinian evaporites; (c) a complex composed of an E- to SE-vergent fold and thrust belt consisting of: a "European" element (Peloritani–Calabrian Units), exposed in NE Sicily, composed of allochthonous Paleozoic igneous and metamorphic rocks overlain by remnants of a mostly carbonate Mesozoic–Cenozoic sedimentary cover; a "Tethian" element, characterized by repeated imbricated units deriving from the deformation of Sicilidi Units, made of uppermost Jurassic–Oligocene deepwater carbonates and sandy mudstones and covered by Upper Oligocene–Lower Miocene flysch deposit nappes; an "African" element (Sicilian Units) composed of several thrust systems involving the deformation of Permian–Miocene deepwater carbonates and bedded cherts (Imerese and Sicanian basins), and Mesozoic–Cenozoic shelf-to-pelagic carbonates (Panormide, Trapanese, Saccense and Iblean–Pelagian carbonate platform or seamount facies domain); a thrust wedge (Gela Thrust System) consisting of Miocene–Pleistocene coeval foreland, wedge-top and foredeep basin sediments (terrigenous, evaporitic and clastic carbonate rocks).

The fold and thrust belt of Sicily resulted from a progressive accretion of thrust sheets and duplex formation combined with the clockwise rotation of allochthonous blocks started in the Middle Miocene and continued up to Middle–Late Pleistocene (Gasparo Morticelli et al. 2015). Plio-Pleistocene high-angle extensional faults affect the northern coastal sectors of Sicily and the foreland area (Catalano et al. 2013a).

3 Hypogene Caves

In Sicily hypogene caves developed in carbonate rocks and are located in different sectors of the Sicilian collisional complex; hypogenic caves also occur in the foreland area in southeastern corner (Hyblean Plateau) (Fig. 1).

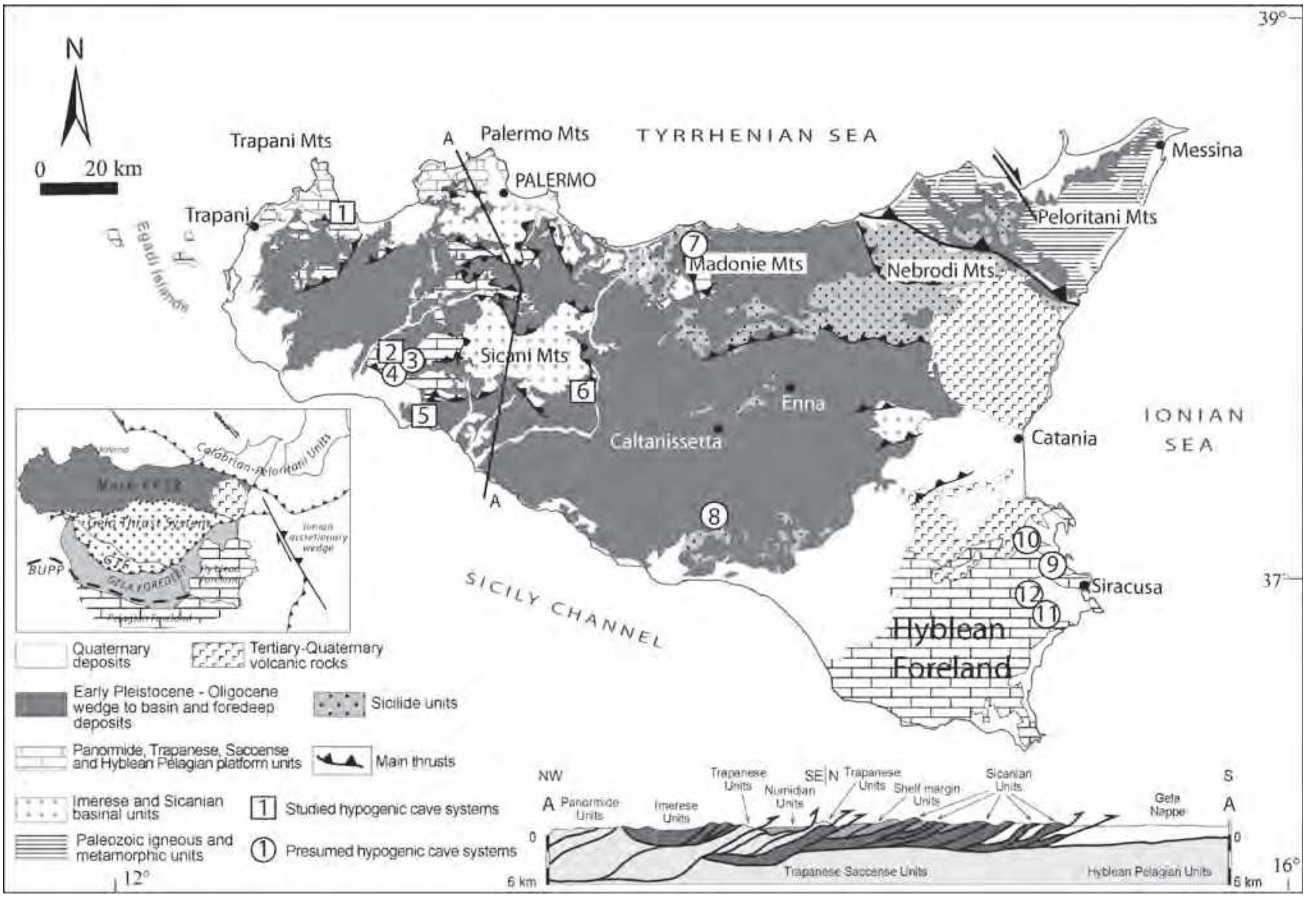

Fig. 1 Geological map of Sicily (from Catalano et al. 2000, 2013b) and location of hypogenic cave systems. *1* Monte Inici caves; *2* Grotta dei Personaggi; *3* Grotta dei Personaggini; *4* Grotta Barone; *5* Monte Kronio caves; *6* Grotta dell'Acqua Fitusa; *7* Abisso del Vento; *8* Grotta dell'Acqua Mintina; *9* Grotta Palombara; *10* Grotta Scrivilleri; *11* Grotta Monello; *12* Grotta Chiusazza. *Inset* map shows the main elements of the collisional complex of Sicily (FFTB, fold and thrust belt; BUPP, boundary of undeformed hyblean-pelagian carbonate platform)

Most of these are inactive sulfuric acid speleogenesis (SAS) caves mainly formed by corrosion processes of carbonate rock by H_2S-rich thermal water rising along important faults. Thermal waters, some of which used for therapeutic and recreational purposes, often spring out close to the caves (Grassa et al. 2006 and references therein).

These active and inactive SAS caves are among the most developed systems of the Island, reaching lengths of almost 3 km and depth of 300 m. A clear example of inactive SAS water-table cave is represented by the "Grotta dell'Acqua Fitusa," which despite its small dimensions shows many diagnostic features of this type of caves (Vattano et al. 2012; Plan et al. 2012; De Waele et al. 2016).

Hypogenic caves with dendritic pattern of stacked spheres seem to be linked mainly to condensation-corrosion processes by airflow rich in CO_2 (i.e., Grotta dei Personaggi).

All the caves have developed along structures such as bedding, fracture or fault planes; an important role in enlarging voids is played by processes of condensation-corrosion caused by thermal convective airflow in the cave atmosphere.

3.1 The Monte Inici Cave System

The Monte Inici cave system is located in NW Sicily (Fig. 1), along the SE side of Mt. Inici, a gently westward—dipping monoclinal relief affected by NW–SE, NE–SW and NNW–SSE high-angle faults. It is composed of two caves, Grotta dell'Eremita and Abisso dei Cocci, formed in Lower Jurassic platform limestones and dolomitic limestones (Inici Fm.), and Upper-Middle Jurassic pelagic reddish-gray limestones with ammonites (Buccheri Fm.) of the Trapanese Domain. Thermal springs with temperature between 44.2 and 49.6 °C and chloride-sulfate alkaline-earth waters (Grassa et al. 2006) are located eastward and at lower altitude with respect to the cave system (Fig. 2a).

Grotta dell'Eremita and Abisso dei Cocci are 3D inactive phreatic maze caves characterized by large subhorizontal

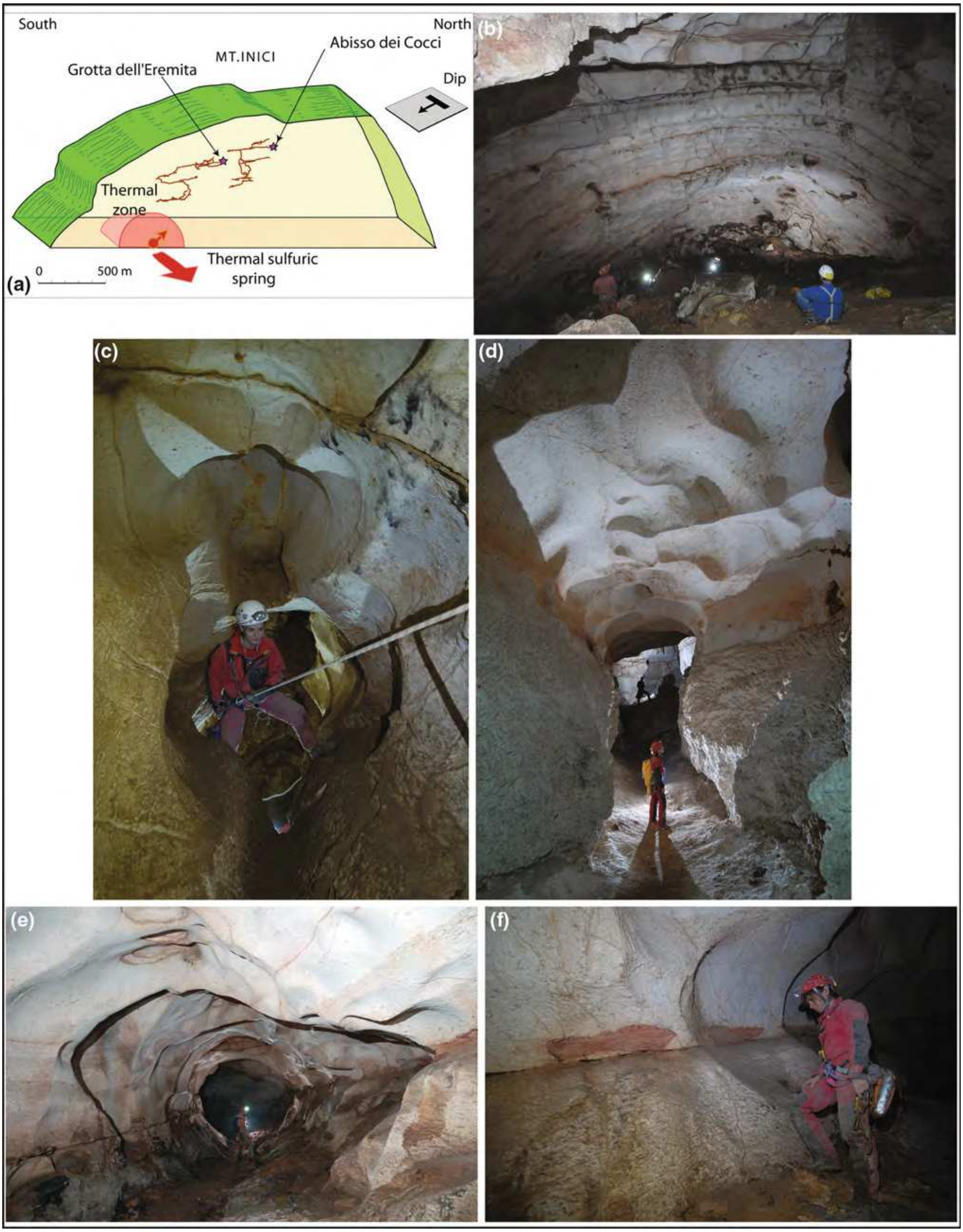

Fig. 2 Monte Inici cave system. **a** Sketch of Monte Inici and its caves and location of the thermal zone (from Vattano et al. 2013); **b** big chamber enlarged by condensation-corrosion processes caused by huge guano deposits (Grotta dell'Eremita); **c** vertical passage with rounded walls and cupolas on the roof (Abisso dei Cocci); **d** entrenched phreatic passage characterized by cupolas, and calcite/aragonite and gypsum deposits in the lower parts (Abisso dei Cocci); **e** inclined passage along a bedding plane with large convection wall niches and ceiling cupolas (Grotta dell'Eremita); **f** close view of protoconduits filled by continental silt along the gallery shown in Fig. 2e

galleries and chambers connected by deep shafts, which reach, respectively, a total length of more than 2 km and a depth of about 300 m (Fig. 2b, c). Some galleries are inclined and follow the dip of bedding planes, whereas the shafts correspond to vertical fissures or fault planes. Passages display subcircular cross sections, or vadose entrenchments (Fig. 2d, e). In some galleries of the Grotta dell'Eremita several small conduits filled by well-cemented fine reddish sediment of continental nature occur at the bedding plane along which the passage develops (Fig. 2f).

Morphologies due to condensation-corrosion processes are widespread in both caves. The walls and ceiling of several passages are tapered by convection wall niches, megascallops, ceiling cupolas (Fig. 2d) and spheres, spongework-like forms, while in some cases passages are divided by partitions.

Both caves lack alluvial sediments. Chemical deposits consist mainly of calcite occurring in powder, thin crusts, frostwork, popcorn or reddish laminae (Grotta dell'Eremita) and gypsum in the form of crusts, and small acicular, fibrous or tabular crystals along the lower parts of the walls of several passages. The caves are rich in phosphate minerals (i.e., hydroxylapatite, taranakite, crandallite, carbonate-apatite, montgomeryite) derived from the transformation of large fossil bat guano deposits. Beside powders or crusts, apatite often occurs as small stalactites and stalagmites (Messana 1994; Vattano et al. 2013).

Patterns and cross sections of the main passages of the Abisso dei Cocci and Grotta dell'Eremita suggest that the early speleogenetic phases took place under phreatic conditions by rising thermal water. In the Grotta dell'Eremita, phreatic conditions are recorded also by the several sediment-filled anastomosed protoconduits visible at the bedding plane, along which the passages develop. After switching from phreatic to vadose conditions, as a consequence of the uplift phases of this sector of the Sicilian chain, entrenchment of passages and development of 3D maze caves occurred. In addition, widening of subterranean voids was connected to significant condensation-corrosion processes by airflow rich in H_2S that also favored the deposition of gypsum deposits in the lower parts of the passages.

In the Abisso dei Cocci, a more recent epigenetic phase is recorded by important calcite speleothems (i.e., flowstones, stalactites, stalagmites) fed by dripping meteoric water.

3.2 The Monte Kronio Cave System

The active hypogenic Monte Kronio cave system is unique in Sicily and probably in the world. It is characterized by the rising of hot moist air linked to a deep thermal aquifer, lying below the explored caves. Although this system was visited by man since the end of the Mesolithic for shelter, place of worship, necropolis and from the I century BC for thermal purposes, yet little is known about its real development and speleogenetic mechanisms due to the harsh environmental conditions with temperatures of about 38 °C and humidity of 100%, which make exploration extremely difficult. The first attempts to explore the caves date back to the end of the seventeenth century; since the 1940s several exploration campaigns organized by the Commission Grotte "E. Boegan" of Trieste identified and surveyed the cave system discovering an extended maze of passages up to 200 m deep (Perotti 1994).

The cave system opens NE of Sciacca town (South Sicily), in the southern scarp of Mt. Kronio or Mt. San Calogero. Mt. Kronio consists of a complex structure linked to ENE-striking, closely spaced imbricate thrust sheets, involving Triassic to Miocene platform and pelagic platform carbonate deposits (Monaco et al. 1996). It is made up of a series of caves, whose origin is probably linked to Na–Cl waters some of which rich in H_2S (Dongarrà and Hauser 1982), with temperature ranging between 32 and 55 °C (Grassa et al. 2006 and references therein) emerging along the southern slope of Mt. Kronio at lower altitude with respect to the cave entrances.

The caves are located at different altitudes and consist of subhorizontal passages (Fig. 3a) connected by deep shafts or steep passages. The passages linking the different branches of this cave system are not always big enough to allow a person to pass (Fig. 3b). Some galleries breach the southern scarp of Mt. Kronio through small openings, some of which emit hot air, while other ones let cold air in from outside. Walls and ceiling of the caves are weathered, characterized by condensation-corrosion forms and powdery and/or crusty gypsum deposits are present (Fig. 3c, d; Vattano et al. 2013). Multidisciplinary studies are currently in progress to improve our knowledge on the extent, speleogenesis and the evolution of this important cave system.

3.3 Grotta dell'Acqua Fitusa

The Grotta dell'Acqua Fitusa represents a good example of inactive water-table sulfuric acid cave (De Waele et al. 2016). The cave is located in central Sicily (Fig. 1), along northeastern fault scarp of a N–S-oriented westward-vergent anticline forming the Mt. La Montagnola. This relief consists of rocks belonging to the basinal Imerese Domain, overthrusting the succession of the Sicanian Domain and the clastic Oligo-Miocene covers (Catalano et al. 2013a). Triassic interbedded calcilutites and marls with abundant pyrite and bitumen may occur at the base of the basinal Imerese and Sicanian Domain. The cave formed in the Upper Cretaceous rudist breccias member of the Crisanti Fm. (Imerese

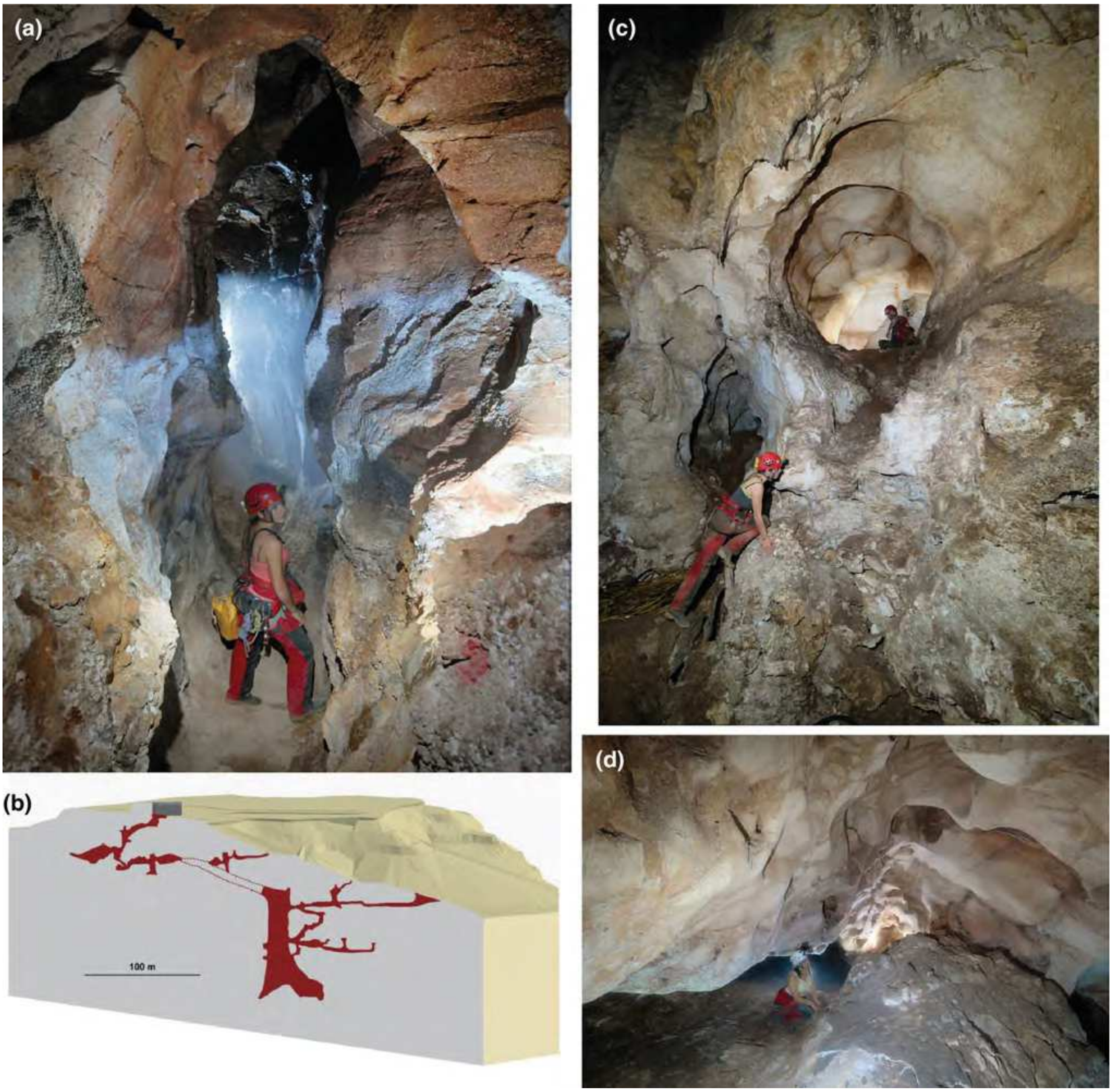

Fig. 3 Monte Kronio cave system. **a** Gallery where the condensation level of the airflow is visible on the walls. Above the caver it is possible to see fog linked to different air temperature: hot in the *upper* part, cold at the *bottom*; **b** 3D sketch of the karst system (after www.boegan.it); **c** passages with forms due to condensation-corrosion processes, separated by partitions; **d** gypsum deposits in the form of crusts, below cupolas in the hot part of the cave system

Domain), composed of conglomerates and reworked calcarenites with rudist fragments and benthic foraminifera. Chloride-sulfate alkaline-earth waters with temperature of 25.2 °C (Grassa et al. 2006) still emerge 300 m north and at a lower altitude than the cave.

The cave consists of at least three stories of subhorizontal conduits (Fig. 4a), arranged in a maze pattern following sets of joints oriented in ENE–WSW, E–W and N–S directions, forming large rooms on their intersections. The cave reaches a total length of 700 m and a vertical range of 25 m.

The passages are developed at the former level of the piezometric surface and are characterized by a very low gradient from the upstream discharging points to the spring. They all show a flat floor breached by discharging feeders up to 10 m deep along their path and notches with flat roof along the walls indicate lateral corrosion processes by the

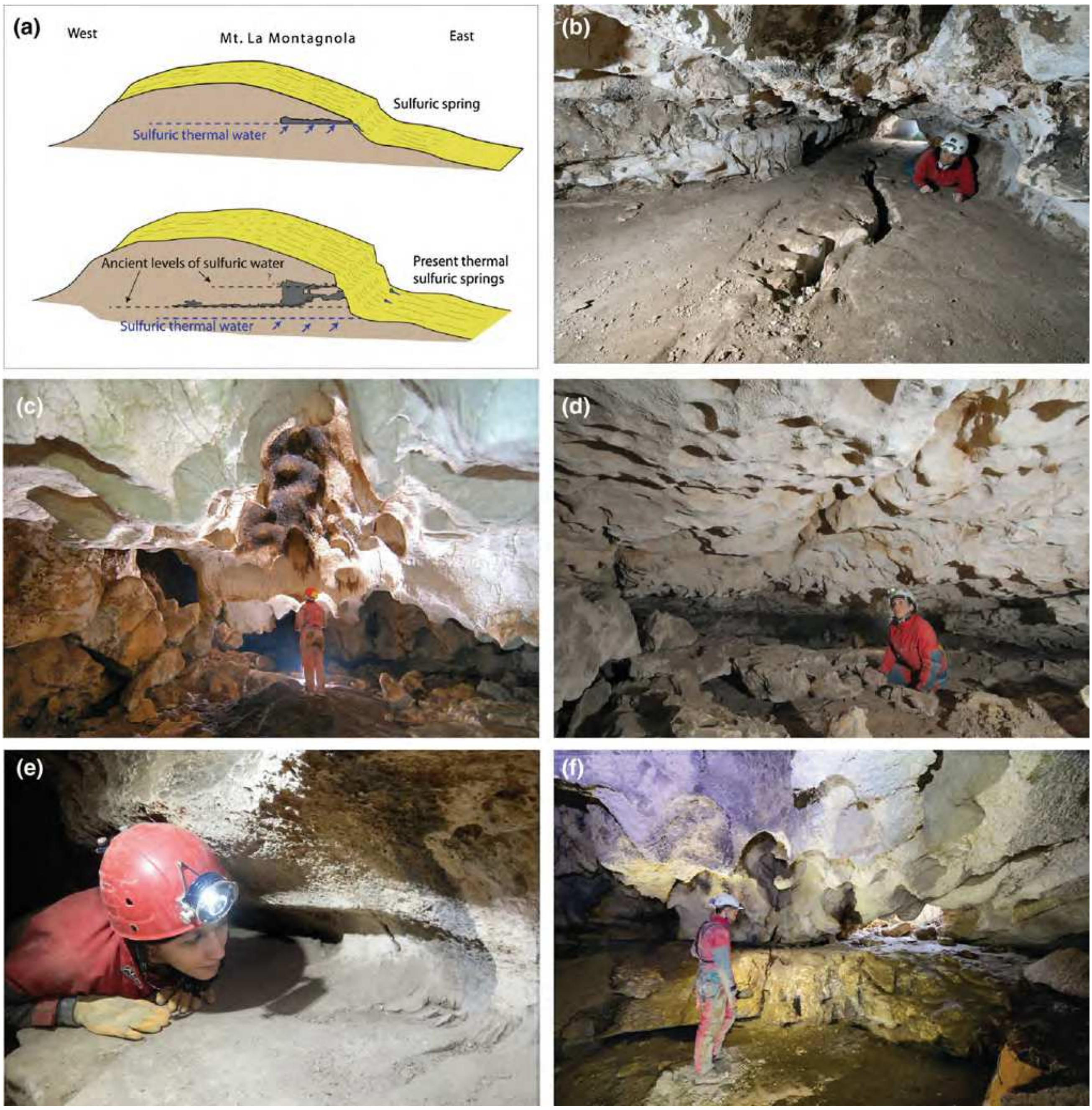

Fig. 4 Grotta dell'Acqua Fitusa. **a** Sketch of the cave and its evolution due to different stages of base-level lowering; **b** passage with discharge feeder at the floor and different levels of wall convection niches; **c** convection ceiling cupolas in the largest chamber of the cave; **d** room characterized by replacement pockets on the roof; **e** sulfuric karren formed by condensation water film; **f** massive gypsum deposit below cupolas

sulfuric thermal water (Fig. 4b). Blind-ending passages develop upstream of the discharge points.

The cave is rich in different small and large morphological features generated by condensation-corrosion processes above the water table, due to H_2S degassing in the cave atmosphere, oxidation of sulfides and thermal convection of the acid air flows (Audra et al. 2010 and references therein). Ceiling cupolas and large wall convection niches occur in the largest rooms of the cave (Fig. 4c); deep wall convection niches, in places forming notches, incise cave walls at different heights (Fig. 4b); condensation-corrosion channels similar to ceiling-half tubes carve the roof of some passages; boxworks, and replacement pockets due to condensation-corrosion processes are widespread (Fig. 4d). In some places, the condensation waters with a high degree of acidity have produced sulfuric karren, such as rills and solution pans (Fig. 4e).

Beside calcite speleothems due to recent dripping water, gypsum is the most abundant mineral in the cave. Replacement gypsum crusts fill large vertical fissures along the walls, cover wall convection notches or replacement pockets and totally coat narrow blind passages. A deposit of about 50 cm of thickness occurs on the floor of the biggest room in correspondence of which on the roof small ceiling cupolas and pendants are associated (Fig. 4f). Finally centimeter-sized euhedral gypsum crystals grew inside mud sediments.

Since the genesis of the cave is closely related to the piezometric surface position, the different stories of passages record past stages of stability of the water table, in relation to changes of the base-level (Fig. 4a; Audra et al. 2010 and references therein).

Further research on dissolution rates, according to Galdenzi (2012), is being performed.

3.4 Grotta dei Personaggi

The Grotta dei Personaggi is located in SW Sicily, south of the Montevago village. The cave is known since the early 1900s and is famous for the archeological findings inside, but it was never surveyed and studied in detail from a geological point of view. The cave opens along a fault scarp in the NW sector of the Magaggiaro Mount and developed in well-bedded white platform limestones (Inici Fm., Lower Jurassic) and in nodular or massive reddish to brown pelagic limestones with ammonites (Buccheri Fm., Upper-Lower Jurassic) of the Saccense Domain (Di Stefano et al. 2013). Thermal springs, characterized by chloride-sulfate alkaline-earth waters with an average temperature of 39.2 °C (Grassa et al. 2006), are located about 3 km NW of the cavity.

The cave consists of subhorizontal passages that follow bedding and fault planes oriented in the NNE–SSW, NE–SW and NW–SE directions forming a maze pattern. In many sectors of the cave cupolas develop upward in a dendritic pattern of stacked spheres. The cave reaches a total length of roughly 1.7 km, a highest point at +15 m and a depth of −32 m. It is characterized by morphologies linked mainly to condensation-corrosion processes by convective airflow. Deep feeders guided by the main joints and fault planes (Fig. 5a), and vents connecting levels of galleries occur in several sectors of the cave. Megascallops and cupolas (Fig. 5b) are found in all the passages; big cupolas develop mainly on the pelagic limestone where they sometimes stack upward forming vertical passages. Condensation-corrosion channels often associated with cupolas are widespread. Pillars, blades and thin partitions preserved from condensation-corrosion separate different passages located at different levels or along the same level (Fig. 5b, c). Limestone on the walls and roof is weathered, whereas boxwork occurs in the upper portions of the walls.

In many cases, calcite rims and popcorn due to evaporation of condensation waters are located in the lower sides of the corrosion forms such as cupolas, channels and vents (Figure 5c).

The Grotta dei Personaggi hosts a large bat colony (Vattano et al. 2015) responsible for an extensive amount of guano, which influences the cave morphology in several places through condensation-corrosion processes or by chemical corrosion at the guano–rock contact.

The cavity lacks alluvial deposits; on the other hand, mineral deposits rich in phosphates, iron, manganese and silica are present (Fig. 5d). The speleogenetic evolution of the cave after a first phase under phreatic conditions seems to be linked mainly to intensive convective thermal condensation-corrosion processes by acid airflow. Calcite speleothems linked to seepage water are related to a more recent epigenic evolution of the cave.

3.5 Grotta dell'Acqua Mintina

The Grotta dell'Acqua Mintina is located in south-central Sicily and was described by Lugli et al. (2014). It opens in the Messinian Calcare di Base of the Gruppo Gessoso-Solfifero in the brecciated and laminated clastic limestone facies (Fig. 6a; cf. Manzi et al. 2011), along a valley slope cut by a small stream fed by a sulfur spring.

It is a small horizontal cave in which carbonate walls and ceilings are extensively covered by native sulfur and gypsum. Sulfur occurs as centimeter-thick laminated and microcrystalline speleothems, crystals up to 1 cm long, clouds and popcorn-like speleothems (Fig. 6b) and dusty crusts covering acicular gypsum crystals. Fibrous and prismatic crystals of gypsum have been recognized (Fig. 6c; Lugli et al. 2014); they formed both in small pools on the floor of the room close to the entrance and near clay deposits.

Some morphologies such as wall convection niches due to condensation-corrosion and the large amount of gypsum and native sulfur deposits suggest that the cave is linked to sulfuric acid dissolution of limestone in an oxidizing environment.

Fig. 5 Grotta dei Personaggi. **a** Deep feeder along a fault plane enlarged by condensation-corrosion processes; **b** passage with cupolas interpenetrating upward and partitions in the lower parts; **c** cupolas due to condensation-corrosion and calcite popcorns in their lower part linked to evaporation processes; **d** passage characterized by megascallop-like forms partially covered by phosphate crusts

Fig. 6 Grotta dell'Acqua Mintina. **a** Entrance of the cave in laminated limestone. **b** Native sulfur covering almost completely roof and walls; **b** prismatic gypsum crystals

4 Conclusions

The new surveys carried out in several karst systems highlighted that hypogenic caves are very common in Sicily and that several caves previously considered to be of epigenic origin are instead connected to the rising of deep thermal water. All the hypogenic caves are developed in carbonate rocks. Most of them are SAS caves, and their speleogenetic evolution is strongly influenced by the structural features of the rocks, changes of the water-table position and by significant thermal convective condensation-corrosion processes in aerated environment.

Recently detailed studies started to better understand their morphologies, deposits, environmental features and their evolution in relation also to the geomorphological evolution of the area in which they develop. New studies are planned to improve knowledge about the origin and characteristics of rising deep fluids and the residence time of deep water in the caves.

Multidisciplinary researches are in progress in the newly presumed hypogenic caves to establish their origin and speleogenetic evolution.

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