

HYPOGENIC CAVES IN WESTERN UMBRIA (CENTRAL ITALY)

HIPOGENE JAME V ZAHODNI UMBRIJI (OSREDNJA ITALIJA)

Marco MENICHETTI¹

Abstracts

UDC 551.44(450.55)

Marco Menichetti: Hypogenic caves in western Umbria (central Italy)

Three karst areas located in the western sector of the Umbria Region (Central Italy) are here described: one north of Perugia, and the others to the south, close to Todi. All the end members of karst processes, from solution caves to Quaternary travertine deposits, are present in this region, associated with CO₂ and H₂S emissions. The geological and hydrogeological aspects of the main karst systems are analyzed and their underground morphologies and patterns taken into account. Caves have different sizes and vary from a single conduit to complex systems, where the passages show features related to a possible hypogenic speleogenesis. In the area north of Perugia there are small horizontal and vertical solution caves developed in poorly karstified marly limestone, along fracture systems, where phreatic morphologies are prevalent. The endogenic CO₂ emissions seem to drive the underground karst evolution. Pozzi della Piana, located west of the town of Todi, is a fossil branchform network cave system developed in a Quaternary travertine and extending for more than 2500 m. The cave passages are arranged on at least two levels, with phreatic morphologies, cupola ceilings, and blind pits. Microcrystalline spalled gypsum blocks are associated with cusp features and wall pockets. The cave-forming process is believed to be linked to travertine deposition by supersaturated carbonate hydrothermal water rich in H₂S. In the Parrano area, the underground karst system consists of solution caves extending for many hundreds of meters at different elevations in both sides of a small gorge. The cave patterns vary from single conduits to ramiform passages with anastomotic galleries and pits that intercept the water table with a temperature of 26°C, *p*CO₂ of 10⁻¹ atm, and H₂S concentrations of 10 mg/l. Spongework, corrosion pockets, and cupola ceilings are common morphologies, with gypsum replacing limestone wall deposits. Cave formation by hypogenic speleo-

Izvleček

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Marco Menichetti: Hipogene jame v zahodni Umbriji (osrednja Italija)

V članku opisujemo tri kraška območja v Umbriji (osrednja Italija) v bližini Perugia. Kraške oblike v jamah in debeli sloji kvartarnega lehnjaka pričajo o procesih povezanih z izhajanjem CO₂ in H₂S. Obravnavamo geološke in hidrogeološke značilnosti območja v povezavi z morfologijo in porazdelitvijo podzemnih rogov. Velikost in geometrija jamskih sistemov na območju je zelo spremenljiva, od enostavnih kanalov do kompleksnih sistemov, ki so verjetno rezultat hipogene speleogeneze. Na območju severno od Perugia je več jam v slabo zakraselih lapornatih apnencih. Razvoj rogov je potekal pretežno v freatičnih pogojih vzdolž razpok. Na razvoj teh jam je verjetno vplival dotok CO₂ iz globin. Sistem Pozzi della Piana je razvit v kvartarnih lehnjakih zahodno od mesta Todi. Gre za 2500 m dolg sistem, katerega rovi so razviti vsaj v dveh etažah. V jami najdemo veliko stropnih kupol, slepih brezen in drugih freatičnih oblik. Razvoj jam je tu verjetno povezan z odlaganjem lehnjaka iz prenasočene vode bogate s H₂S. Na območju Parrana je več sto metrov dolg jamski splet, ki se razteza na različnih višinah na obeh straneh manjše soteske. Geometrija jamskih rogov je pestra, od enostavnih kanalov do razvejanih rogov, anastomoznih galerij in brezen, ki sekajo gladino podtalnice s temperaturo 26°C, veliko koncentracijo CO₂ (0, 1 atm) H₂S (10 mg/l). O hipogenem razvoju pričajo številne oblike (gobasti spleti, korozijske kotlice, stropne kupole) in plasti sadre, ki nadomeščajo raztopljen apnenec. Jamske oblike, ki kaejo na hipogeno speleogenezo najdemo v številnih jamah v Apeninih. V sistemu Monte Cucco in Frasi so prisotne fosilne in aktivne hipogene oblike, ki so v drugačnem kontekstu nastale s podobnimi procesi.

Ključne besede: speleogeneza, hipogene jame, H₂S, CO₂, Italija.

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genesis is also well known in the Apennine karst system of M. Cucco and Frasassi, where both fossil and active processes are observable. The same processes are responsible for the genesis of these karst systems in different geological and hydrogeological contexts.

Keywords: speleogenesis, hypogenic caves, H₂S, CO₂, Italy.

INTRODUCTION

In Central Italy all the end-members of karst processes can be found, from solution caves to carbonate travertine deposits (Fig. 1). Moreover, the main cave-forming processes are related to deep-seated hydrogeological recharge where limestone corrosion is driven by endogenic agents (Menichetti 2009). The region contains abundant Quaternary travertine deposits and is rich in volcanic, crustal and mantle-derived CO₂ and H₂S emissions (Fig. 1).

Through more than one century of speleological research, many limestone caves have been identified. These caves are characterized by a variety of patterns and morphology sizes including three-dimensional maze systems and deep shafts, with both endogenic CO₂ vents and active sulfuric streams. Although sulfuric acid-related speleogenesis typically produces gypsum deposits, in caves where the karstification processes are driven by subter-

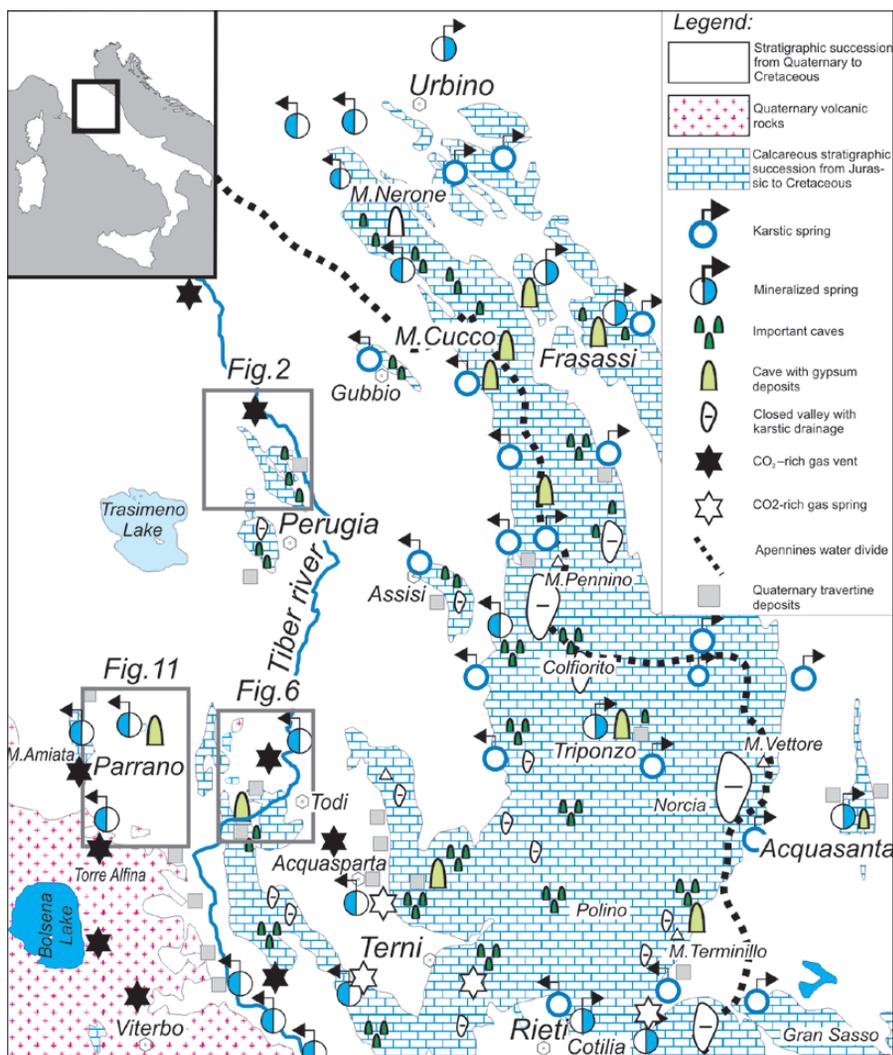


Fig. 1: Map of the main karst features of Central Italy. The insert frames indicate the figures with geological maps.

ranean CO₂ sources voids and speleothems are the only final products.

Studying these caves permits us to expand our understanding of the different aspects of underground karst, and Central Italy is one of the world's best locations to observe both active and fossil hypogenic speleogenesis processes in different geological contexts. In the Umbria-Marche Apennine region, the presence of important hypogenic caves has been well documented since several decades of research and exploration of the vertical system of M.Cucco and Faggeto Tondo and the maze systems of the still active Frasassi and Acquasanta caves. A general description of the different morphological aspects of these karst systems permits the identification of the primary speleogenetic processes (Galdenzi & Menichetti 1989, 1995; Galdenzi 2009) of these systems within a geological and hydrogeochemical framework (Menichetti 2009).

The geological characterization of hypogenic cave development needs to consider the great variety and unusual characteristics of Central Italy's underground landscape. Even though the general speleogenetic reactions are known, the precise geological, hydrogeological and geochemical conditions of their occurrence need to be documented, in particular the role of gases (H₂S, CO₂) and their association with other mineral species. Hydrogeology and, especially, hydrochemistry are key in understanding the space/time evolution of these hypogenic karst systems.

After a decade there has been renewed interest in hypogenic cave speleogenesis studies using different approaches that explore the roles of both deep-seated hydrogeological recharge (*sensu* Klimchouk 2007) and the presence of endogenically driven limestone corrosion (*sensu* Palmer 2007) have been conducted. Hypogenic caves are well known in Europe and different parts of the world, from Central Asia to North and South America, and especially the underground fossil systems in the Guadalupe Mountains in New Mexico and Texas (Hill 1987; DuChene *et al.* 2000).

In this paper we will present a description of the underground morphologies and patterns of the main karst systems of western Umbria and place it within a geological and the hydrogeological context. These caves vary in size, ranging from single conduit to complex systems, and their passages display features that can be related to hypogenic speleogenesis. The geochemistry of the groundwater and gas emission present in these karstic areas is taken into account for understanding their role in speleogenesis and better to characterize the factors that control hypogenic dissolution during cave development. The approach to understanding the role of hypogenic processes in the cave formation is here related to the geochemistry of rising aggressive fluids with respect to the hydrogeological conditions that drive the flow of water recharge to the cave-forming zone.

GEOLOGICAL OUTLINES OF WESTERN UMBRIA

The geology of Central Italy has been shaped predominantly by the continental Cenozoic collision of the Corsica/Sardinia and the now subducted Adriatic plates. Geological and geophysical data highlight two main sectors within this region: a western, Tyrrhenian sector dominated by Neogene-Quaternary, active, back-arc extensional tectonics and an eastern Adriatic sector dominated by an active compressional stress field (Cavazza & Wezel 2003). The karstic carbonate Apennine fold-thrust belt is within a transitional area between these two domains (Fig. 1).

The Tuscan-Umbro-Marchean sedimentary cover hosting the caves is part of the Meso-Cenozoic basin and consists of three main lithological units. The lower unit is about 1 km thick and is dominated by Upper Triassic dolomites and anhydrites unconformably overlying Paleozoic phyllitic basement rocks. The intermediate sequence of limestone and pelagic cherty-marly-carbon-

ates is about 2500 m thick and spans from the Jurassic to the Paleocene. The upper unit comprises Neogene turbidite foredeep sediments about 3000 m thick. In western Tuscany and, especially, in the Apuan Alps, the carbonate succession underwent metamorphosed greenschist facies and represents the deep roots of the collisional orogen (Cavazza & Wezel 2003). The area surrounding Rome has been active since the mid-Pleistocene (~700 ka) and has remained intermittently active up to recent times resulting in the extrusion of K-undersaturated volcanics in association with some carbonatite magmas in several localities within the Apennine chain (Peccerillo 2005).

On the Tyrrhenian side of the Apennine belt, the results of the Neogene-Quaternary back-arc extension include a reduced thickness of the lithosphere, a system of NW-SE striking normal faults and associated basins, and high heat flow, producing in the areas many H₂S and

CO₂-rich hydrothermal vents (Minissale 2004). On the Adriatic side of the Apennine mud volcanoes, salt springs and CH₄ emissions are well documented in hydrocarbon exploration data (Conti et al. 2000). In western Umbria, the high heat flow is estimated at 80 mW/m², increasing westward to more than 200 mW/m² in the M. Amiata area (Della Vedova et al. 2001).

The largest caves in the area are located in a 1000 m thick Jurassic carbonate bank, where syngenetic porosity in sedimentary facies of packstone and grainstone is well developed. Occasionally, small caves are hosted in Cenozoic marly-limestone successions confined by sandstone and marl formations (Menichetti 1987). Quaternary travertine deposits are scattered throughout the region, particularly in Tuscany and Latium. However, caves as-

sociated with both thermal and cold springs are only in a few localities in the Apennine chain (Minissale 2004) (Fig. 1).

The main phase of the Apennine chain uplift, relevant to cave development, took place within the Pleistocene (Mayer et al. 2003). The primary tectonic features controlling the underground Apennine karst morphology and the carbonate reservoir groundwater drainages are a system of N-S transpressive faults and networks of conjugated joint sets distributed in primary NE-SW and secondary NW-SE directions. Specifically, the N-S faults are associated with the main passages and rooms, and control the development of the larger underground voids, while solutional morphologies are associated with joint systems (Menichetti 1987; Mayer et al. 2003).

NORTH OF PERUGIA AREA

GEOLOGY

The landscape north of Perugia is characterized by uneven morphologies with limestone and marl outcrops in the mountain range at 1000 to 200 m asl. The whole area has been intensely impacted by human activity from the time of the Etruscan civilization (VIII^o Century B.P.) by intensive agricultural activity, while the mountain slopes are covered by mesophile forests.

The geology north of the Perugia region is characterized by the presence of thick Neogene marls and sandstones from which emerge small karst limestone outcrops in two sets of NE verging rootless anticlines: the M. Acuto – M. Tezio to the west and M. Mussarello-M. Murlo to the east (Fig. 2). The Neogene tectonic compression structures are dissected by a set of en echelon normal fault systems with an offset of hundreds to thousands of meters. The fault planes are generally SW dipping but there are a few low angle NE dipping faults that place the Neogene terrigenous formations in direct contact and over Triassic anhydrites (Minelli & Menichetti 1990; Brozzetti 1995; Menichetti 2003).

The primary karst lithologies consist of Cretaceous-Paleogene pelagic limestone and marly-limestone in layers tens of meters thick, with a few small caves occurring in the Jurassic and Upper Triassic limestone (Menichetti 2003). The surface karst morphologies are represented by a few localized dolines and depressions particularly in the M. Tezio area (Dessau 1956).

On the western bank of the Tiber river, the dendritic hydrographic network drains toward the NE with an average base flow of 15 l/sec/km² (Boni et al. 1988). The main aquifers are located in the Ceno-Mesozoic

limestone, with a relatively low specific discharge of 10 l/sec/km² due mainly to the small extent of the infiltration area. The large extent of the flysch sediments represents the main aquiclude which controls the drainage network and the location of the main sink points at the boundary with the limestone outcrops. In the Pian del Nese area, several sinkholes drain the small closed plain (Viviani & Passeri 1965). The springs in the area have a discharge of a few l/sec with groundwater compositions ranging from Ca-SO₄ to Ca(Mg)-HCO₃, pCO₂ varying between 10⁻² and 10^{-0.05} atm and H₂S content reaching up to 5 mg/l (Chiodini et al. 1999).

Located along the Tiber valley, at the junction with the T. Nese, there is a travertine outcrop topped by the medieval castle of Ascagnano. At an altitude of 280 m asl and a few tens of meters above the thalweg, this outcrop is a few hundred square meters in size, with a thickness of about 10 m. The original extent may have been larger and was subsequently reduced by weathering and fluvial erosion. The travertine overlies Pleistocene fluvial sediments deposited by the Tiber and having lithologies that display high porosity, significant organic matter content, and a very low cohesion. The sediments have a δ¹³C of - 3.5 (‰ PDB) and a δ¹⁸O of 25.63 (‰ SMOW) with a Sr content of 584 mg/kg (Minissale et al. 2002).

The area is characterized by the presence of several CO₂ vents, the largest of which is located a few kilometers west of Umbertide, along a slope a few tens of meters above the western bank of the Tiber valley (Fig. 2). The gas vent is located in the Neogene sandstone and marls in proximity of a regional thrust fault. The cold vent (about 13°C) consists of a vigorous roiling pool of

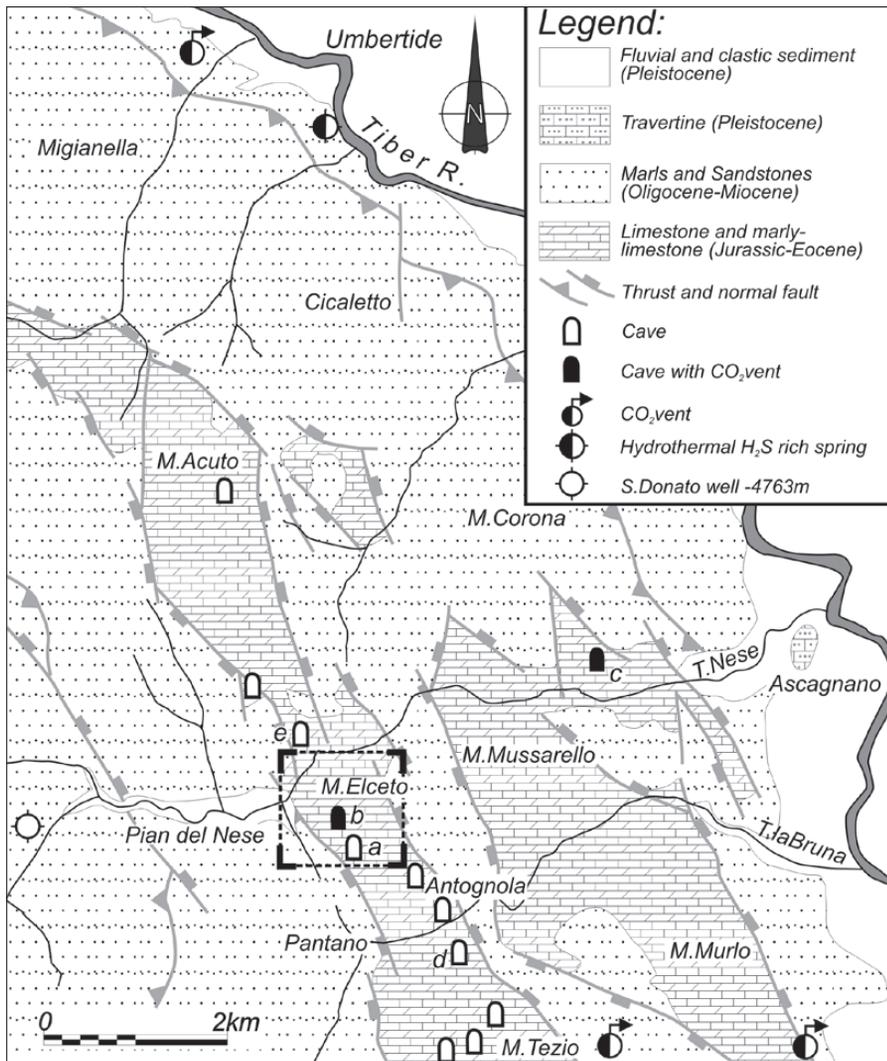


Fig. 2: Geological map of the M. Acuto and M. Tezio areas showing the locations of the main karstic features (geology after Compagnoni et al. 1981). Caves described in the text: a) Abisso I di Montecelli; b) Abisso II di Monticelli; c) Buca del Serpente; d) Pozzo dei Piantoni; e) Buca della Scanata. Location of the map in Fig. 1. The insert frame shows the location of Fig. 3.

muddy water at the bottom of an elongated depression of about 5 m in depth and 20 m in diameter (Fig. 5a). The estimated discharge of gas is about 3 m³/sec with a composition of 93% CO₂, 6% N₂ and 0.25% CH₄ (Rogie et al. 2000; Italiano et al. 2004). An oil exploration well (4763 m deep) drilled a few km west of Pian del Nese (Fig. 2) through a few hundred meters of Neogene marls and sandstones reached the Triassic anhydrites. The bottom hole fluid pressure was found to be 96 MPa, corresponding to about 85 % of lithostatic load with a gas composition of 99% CO₂ (Chiodini et al. 1999). This scenario is completed by the existence of many other dry vents and degassing areas, closer to the karst limestone outcrops north of Perugia, in the M. Tezio area (Fig. 2).

CAVES

A few of the scattered caves distributed in this area are in Cretaceous limestone of the M. Tezio – M. Elceto hill. The caves are generally small, with single passages of a few

tens of meters in length, located in correspondence with the main tectonic lineaments (Fig. 2). North of the Pian del Nese area, small decametric caves present morphologies with single circular conduits, cupolas, and other phreatic features (Viviani & Passeri 1965).

The most important of these caves are the Abisso Monticelli II° and Buca del Serpente (Fig. 2a & c, respectively), which have high CO₂ concentrations in the underground air. Both caves have been known and explored since the middle of last century (Lippi Boncambi 1941; Dessau 1956).

The Abisso Monticelli cave is a vertical shaft that opened in the SW slope of M. Elceto during a strong storm in 1961 (Passeri 1963). The entrance is a depression a few meters wide, located in proximity to a small stream and an outcrop of slope debris a few meters thick. The cave is located in sub-horizontal strata of Paleocene-Eocene marls and limestone, in a block delimited by a system of NW-SE normal faults and N-S strike-slip

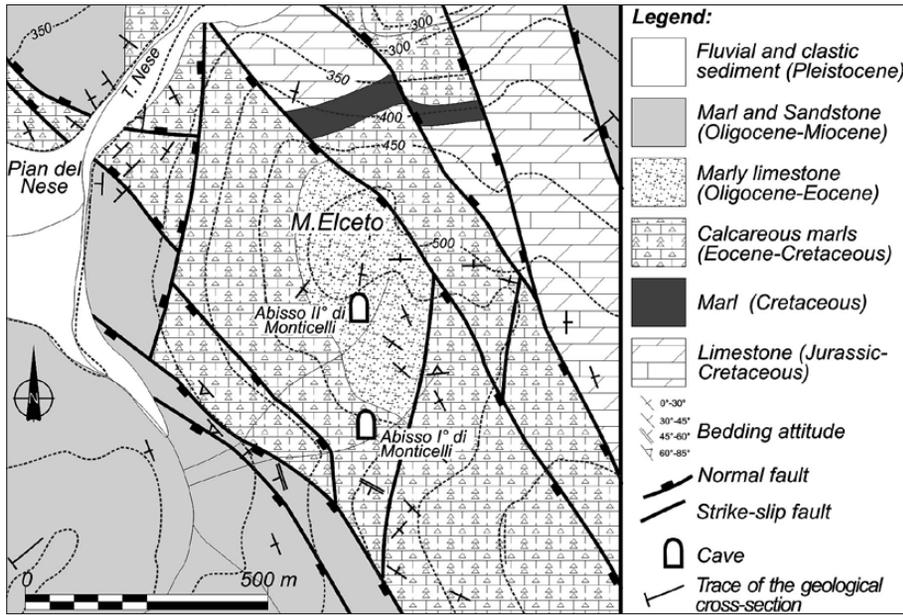


Fig. 3: Geological Map of Pian del Nese – Monticelli area. Location in Fig. 2.

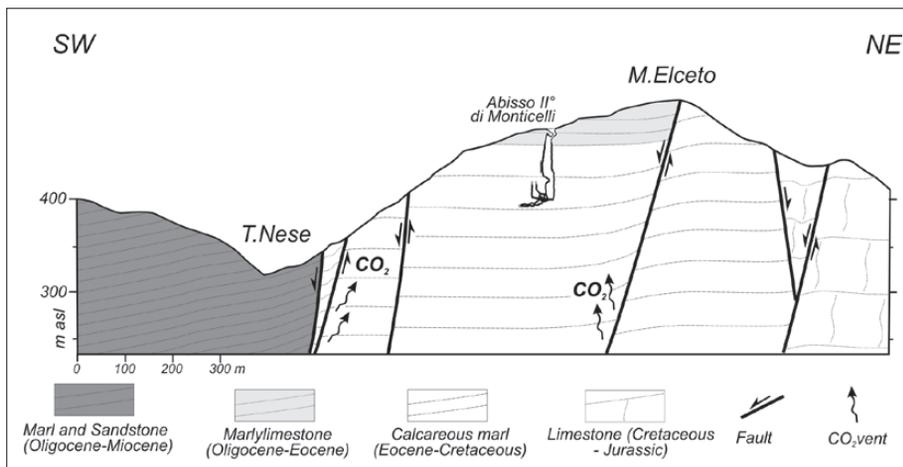


Fig. 4: Geological cross-section of M. Elceto with the location of Abisso II di Monticelli and the possible origin of CO₂ indicated. Trace of the section is in Fig. 3. Note that the horizontal and vertical scales are different.



Fig. 5: a) CO₂ vent close to Umbertoide; the pool is about 3 m wide; b) Abisso II° Monticelli shaft.

faults (Fig. 3). The main fractures are represented by a system of NW-SE and N-S joints. The cave entrance is a narrow passage, in weathered marls, the top of a single sub-vertical and circular shaped shaft 10 m in diameter and 78 m in depth, known as Pozzo Dessau (Fig. 4). The

cave developed in 30 m of Paleocene–Upper Cretaceous limestone beds. At the base, the pit is connected with a blind chimney of similar shape and with a N-S oriented gallery composed of a narrow subvertical passage with several steps of a few meters containing a seasonal

stream with discharge of several l/sec (Fig. 4). The cave ends in an impassable narrow passage where CO₂ concentrations close to 10% have been detected, representing a serious hazard for further speleological exploration. The underground morphologies are characterized by a contrast of the large shaft and the small fissure passage at the cave end. In the lower section of the shaft, phreatic morphologies as well as vadose corrosion forms are well developed (Fig. 5b). The cave's origin in this poorly karstified lithology seems to be connected to the high concentration of endogenic CO₂.

The Buca del serpente is a small, single passage cave, a few meters wide and many meters long, in Cretaceous cherty limestone of the northern slope of the T. Nese valley (Fig. 2c) (Lippi Boncambi 1941). The cave is characterized by the presence of seasonal air flow with CO₂ concentrations of 1 to 5%. The cave is located in proximity to a N-S fault with a large shear zone, which most likely represents the primary conduit for the endogenic gas flow.

TODI AREA

GEOLOGY

Southwestern Umbria, around Todi, is a hilly terrain with a mean altitude of 400 m, dotted with small villages and a prevalent cover of deciduous mixed mesophile forests. The geological landscape is characterized by Oligo-Miocene marls and turbidite sandstone outcrops. Plio-Pleistocene continental sediments with fluvial and marsh facies are present along the Tiber valley at different altitudes above the thalweg (Fig. 6).

Outcrops of Cretaceous limestone and calcareous-marls occur in association with a rootless NE verging anticline of M. Piatto – Civitella del Lago (Fig. 6) dissected by several N-S right-lateral strike-slip faults related to thrust emplacement. These Neogene compression structures are cross-cut by a set of NW-SE striking Plio-Pleistocene normal faults with an offset that can reach many hundreds of meters (Fig. 7).

In the vicinity of the town of San Venanzo (Fig. 6), there is a small volcanic center characterized by olivine melilitite lavas and dykes associated with carbonate-rich (about 10 wt %) pyroclastic rocks with an ⁴⁰Ar/³⁹Ar age of 265 ka (Laurenzi *et al.* 1994). In the M. Piatto area (Fig. 6) and close to Acquasparta (Fig. 1) there are small outcrops of phreatomagmatic deposits of ashes and lapilli with a kamafugitic affinity and an ⁴⁰Ar/³⁹Ar age of 390 ka. They are believed to have been erupted from monogenetic centers aligned along a N-S fault (Peccerillo 2005).

The hydrographic network is well developed with a dendritic pattern in marls and sandstones, with a regional drainage toward the Tiber River. In the carbonate outcrops close to Titignano, several sinkholes drain the superficial streams with resurgences located along the Tiber valley. The main aquifers are located in the Ceno-Mesozoic limestone, with a specific discharge of 15 l/sec/km².

There are gas vents and sulfuric springs in the western bank of the Tiber valley in the Monte Castello di Vibio area (Fig. 6). The main emission is located in the Miocene marls in a few meter wide depression on the hill slope, where a bubbling pool of muddy water releases a cold (14°C) gas flux of about 1 m³/sec, where CO₂ represents 92% of the gas (Italiano *et al.* 2004). The southernmost natural sparkling water springs that are partially utilized for industrial purposes are located close to Acquasparta (Fig. 1). These carbonate/sulfuric water springs have a pCO₂ in the range from 0.08 to 0.006 atm and a H₂S content of 3 mg/l (Chiodini *et al.* 1999).

Quaternary travertine outcrops of different size and thickness have been noted on both sides of the Tiber Valley at two altimetric levels. The northernmost outcrop, near Titignano Castel, is at an altitude of 490 m and has an area of about 1 km² with a thickness of about 50 meters (Fig. 6). Further south at the same altitude, around Civitella del Lago, there are two smaller travertine outcrops of about 0.5 km² with a thickness of a few tens of meters. Both outcrops overlie Upper Pliocene (1.6 Ma) continental yellow sands and blue clay.

The lowermost travertine bank, hosting the Pozzi della Piana cave, is east of Roccaccia at an altitude of 190 m, with an area of about 0.5 km², and an average thickness of 100 m. It discordantly overlies Upper Cretaceous limestone with a contact characterized by a hydrothermally altered cataclastic shear zone related to a subvertical N-S fault.

The origin of these fossil travertines is also believed to be thermogenic (Passeri 1973) when spatially unassociated with thermal water. In the Lazio and Tuscany regions, thermal springs and CO₂ vents associated with travertine deposits are very common (Fig. 1). In the Rome area, travertine deposition started just after or

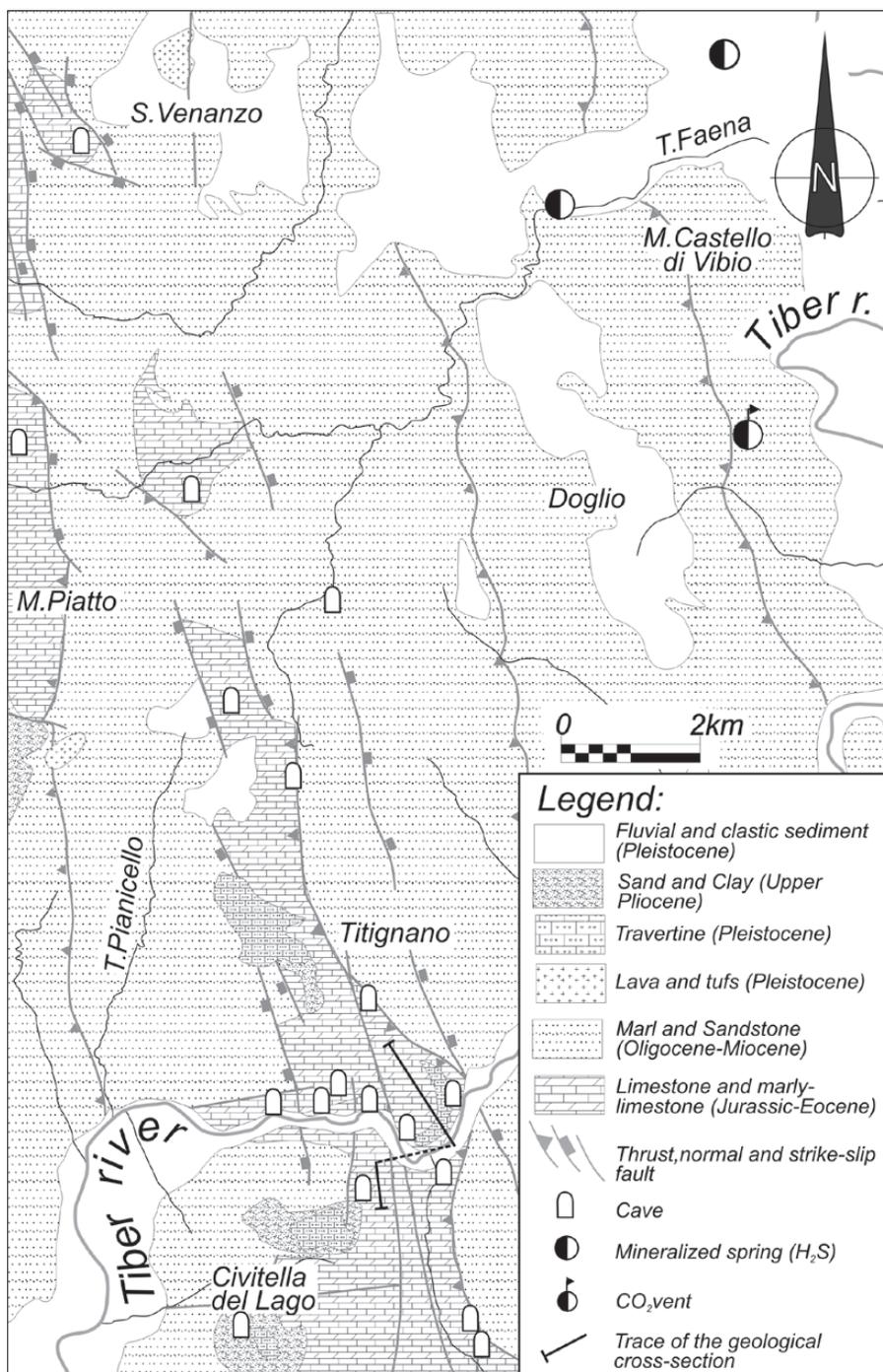


Fig. 6: Geological map of Titignano - Pozzi della Piana area (after Compagnoni et al. 1981). Location in Fig. 1.

concurrent with the last phase of volcanic activity in the late Pleistocene (Minissale 2004).

The Pozzi della Piana develops in a massive travertine with low organic content and a well developed moldic and shelter porosity. The Titignano travertine is composed of a sequence of benches separated by erosional surfaces gently dipping south, with a thickness of many meters. The geometry and the attitude of the deposit

show that the travertine grew in a southward aggradational fashion in lenticular mound/ridge type deposits (*sensu* Pentecost 2005). Calcite is the most common carbonate phase within travertine with a significant content of Sr (about 1500 mg/kg) related to the thermal water rising through the Triassic anhydrites. The superficial karst in the travertine is well developed and contains several large depressions and dolines of a few hundred meters in

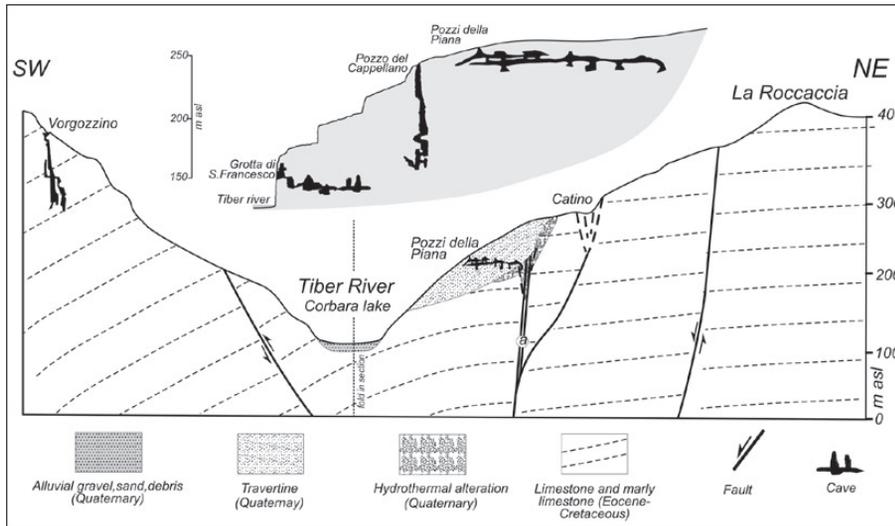


Fig. 7: Geological cross-section of the Pozzi della Piana area. The possible hydrothermal conduits for travertine deposition are indicated (a). In the upper part, schematic altimetric relationships between the karst systems are shown. The cross-section trace is shown in Fig. 6. Note that horizontal and vertical scales are different and the cross-section fold corresponds to the Tiber River.

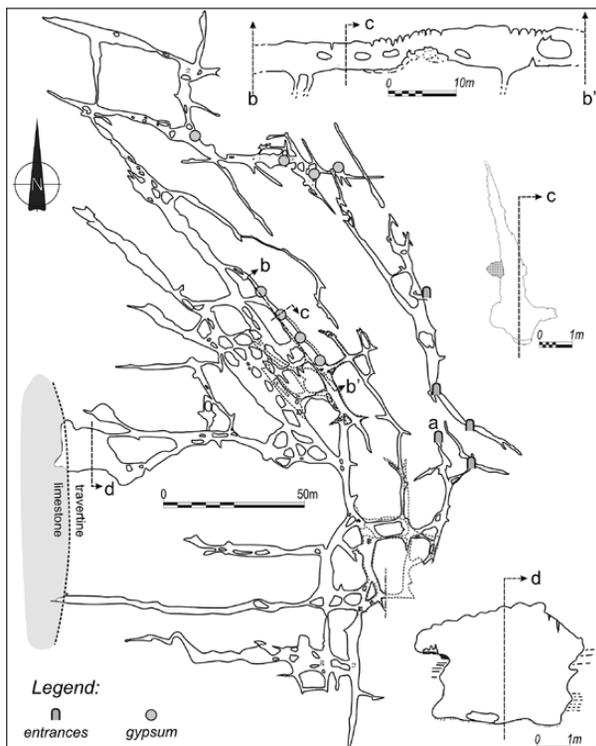


Fig. 8: Map of the Pozzi della Piana cave with transversal and longitudinal sections. The boundary between travertine and Upper Cretaceous limestone is indicated. Entrance pit (a), Galleria Gotica (b) and Sala dei Vortici (d). From: www.cens.it – used with permission.

diameter (Passeri 1973). In the bare rock outcrops small karren are observable.

Underground karst can be found in both the Rocca della Roccaccia travertine bank, where Pozzi della Piana has developed over about 2500 m of hypogenic branchform, solutional galleries, and in Upper Cretaceous limestone

with deep shafts and small solution passages located in correspondence with different Tiber river terraces (Fig. 7).

CAVES

The Pozzi della Piana cave and the surrounding area, which is also known for an archeological site of Neogene age (Passeri 1967), developed as a system of fossil solution maze, fissure, and network passages, arranged in at least two levels. The prevalent morphology is a network of single passages, with primary horizontal galleries at -15 m, connected to a smaller, shallower level a few meters below the surface where the entrances are located (Fig. 8). Several ascending ellipsoidal shape conduits connect the main level to the deepest passages at -25 m (Passeri 1973). The cave developed in the travertine bank, but only in its western branch, in the wall of the Sala dei Vortici (Fig. 8, point d), is the altered contact with the Upper Cretaceous limestone observable (Fig. 9b). Here, in the floor, a few blind pits a few meters deep and partially filled with clay sediments could represent the original ascending hydrothermal conduits. In the same branch partially eroded and weathered stalagmites are present (Fig. 9b).

With respect to the entrance (Fig. 8, point a), the northern part of the cave is arranged in a system of longitudinal NW-SE oriented galleries. In the central part, a maze system of anastomotic passages interconnects the main corridors. This preferential direction is related to a system of joints associated with the main extensional faults. In the southern branch, the main passages are developed along an E-W direction and linked with a N-S oriented maze system. Here, several collapsed blocks associated with an E-W left-lateral strike-slip fault control the morphology of this part of the cave.

The single passages are a few meters in size and have triangular shape morphology with planar pave-

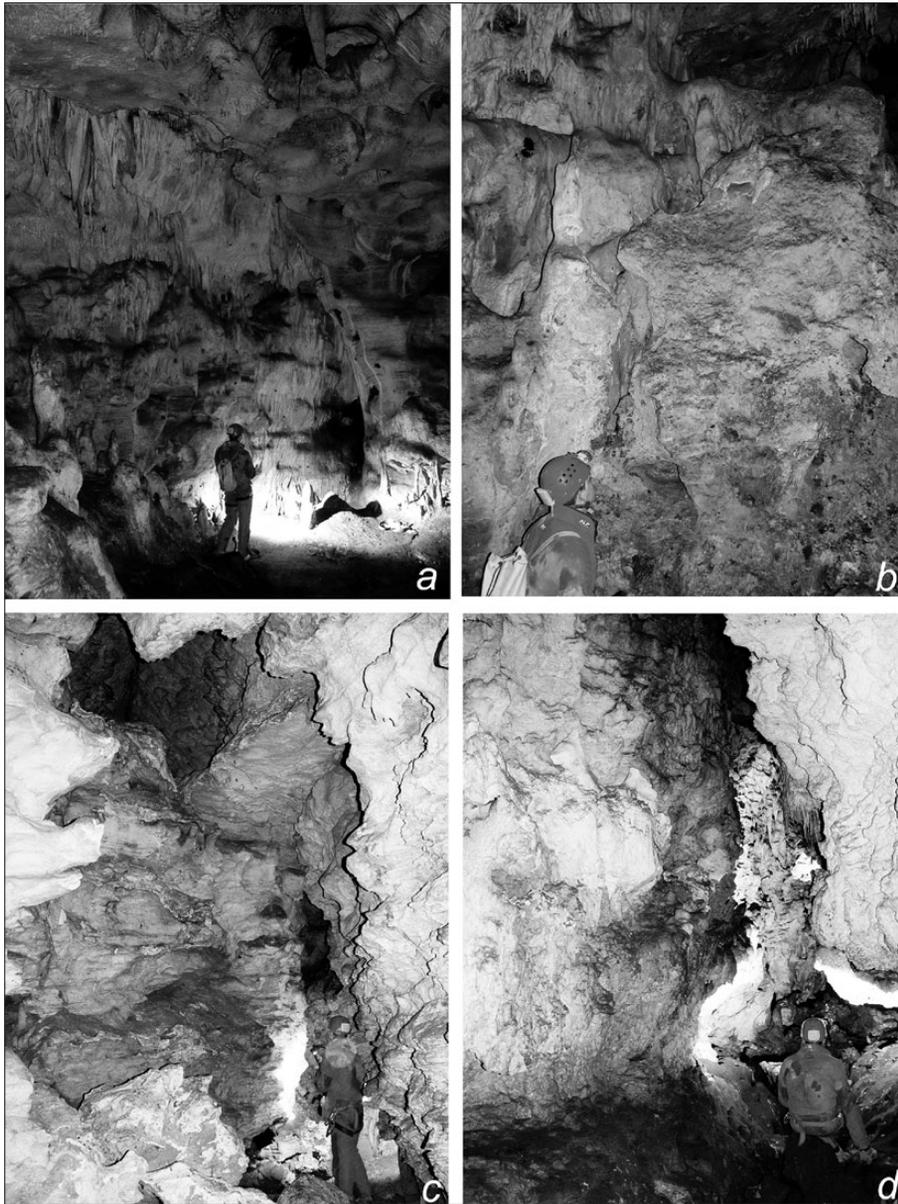


Fig. 9: Pozzi della Piana – a) Sala dei Vortici morphologies; b) Sala dei vortici – alteration crust at the boundary between Travertine and Upper Cretaceous limestone; c) Galleria Colonna travertine spongework morphologies; d) Galleria Gotica with gypsum deposits in the large pocketed wall.

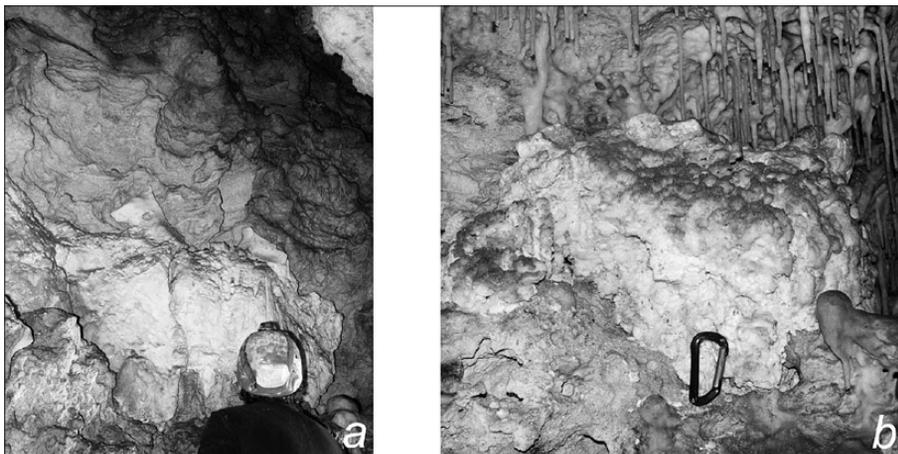


Fig. 10: Pozzi della Piana - primary gypsum microcrystalline deposits. a) morphologies in correspondence of gypsum deposits; b) gypsum associated with carbonate speleothems.

ments and irregular walls with notches, solution pockets and spongework (Fig. 9c). Blind pits as well as chimney shafts ascending toward the surface are scattered along the main passages. The anastomotic voids correspond to the main drainage points located in travertine with the highest porosity (Fig. 9c). Convection cupola morphologies from decimetric to metric size are present, especially in Galleria Gotica and in the ceiling of Sala dei Vortici (Fig. 8, point b and d – Fig. 9d).

Wall morphologies are characterized by rounded and elongated bulges resulting from differential solution of the travertine levels. These cusp features, found in a few of the passages, contain microcrystalline gypsum (Fig. 10a). The pockets are centimeter-sized and located at the gypsum/bedrock interface. The gypsum rinds and blocks hang on the walls and have volumes varying from cubic decimeters to cubic meters. The primary gypsum is white and microcrystalline, with a thin brown alteration crust at the rock interface, while the recrystallized selenite crystals are present at the base of the main deposits. Various types of wall residues are present in different parts of the cave; however, they are mainly clay-rich and possibly related to the condensation/corrosion weathering processes. Carbonate flow and dripstones as well as both stalagmites and stalactites can be found in all the passages, while the presence of large columns is evidence of an important phase of carbonate deposition.

Boulders on the floor, travertine tilted blocks and breakdown deposits are especially common in the central part of the cave in association with a tectonized E-W lineament. A comparison of the cave passage altitudes

and the terraces along the Tiber valley/Lago di Corbara (Fig. 7), aside from a few apparent correlations, paints a general picture that does not take into account differential uplift rates and needs to be investigated in more detail.

The presence of phreatic as well as vadose morphologies associated with gypsum deposits indicates a highly probable hypogenic origin of the Pozzi della Piana cave. Several unresolved questions remain, in particular the age of the travertine and speleothems. Moreover, the temporal relationship between cave deposits suggests that the corrosion sculptures pre-date gypsum deposits and carbonate speleothems (Fig. 10b). The known ages of the travertine outcrops in the area range between 60 and 300 ka and correspond to the latest volcanic activity in the San Venanzo area. However, the temporal relationship between the travertine deposits and cave formation is ambiguous. On one hand, the travertine is the host rock for the cave, but its deposition could be contemporary with the emerging calcite supersaturated hydrothermal water. In addition, the presence of gypsum deposits suggests the participation of sulfuric acid in the carbonate dissolution. Possible development of travertine-hosted caves concurrently with the emergence of sulfur-rich hydrothermal springs is common in different geological contexts (Van Everdigen *et al.* 1985; Erol 1993; Pentecost & Tortora 1989; Pentecost 2005; Menichetti 2008). In several cases, the caves represent the conduits for hydrothermal groundwater flow that fed the springs during travertine deposition.

PARRANO AREA

GEOLOGY

The hilly area of Parrano is located between the ridges of M. Peglia-M. Piatto (900 m asl) to the east and M. Cetona (1148 m asl) to the west, on the border with the Tuscany region (Fig. 1). The mean altitude is 400 m, with prevalent deciduous mixed mesophile forests. The valleys are located at an altitude of 200 m and contain agricultural lands and several towns. The geology of the area is characterized by Pliocene post-orogenic continental sediments that uncomformably overlie marine Miocene turbidite sandstones and marls. Isolated Jurassic-Eocene karst limestone anticlines emerge in the Parrano Gorge and in the M. Cetona area (Fig. 11). Sets of NW-SE striking normal faults with offsets that reach thousands of meters dissect the Neogene compression structures (Piscopo *et al.* 2009).

The southernmost outcrops, around the town of Orvieto, consist of Quaternary volcanic rocks dominated by pyroclastic flow deposits and ignimbrites with minor lava flows of trachybasalt to trachyte and leucitite-leucite tephrite to phonolite compositions related to the Roman Magmatic province of the Vulsini district (age 0.6 to 0.15 Ma) (Peccerillo 2005). The magmatic necks of M. Amiata (0.3-0.2 Ma) and Torre Alfina (0.82 Ma) are located a few kilometers to the west (Fig. 1).

The hydrographic network in the area is dendritic with drainage toward the Paglia river at an average base flow of 12 l/sec/km² (Chiodini *et al.* 1982). The main aquifers are located in the Ceno-Mesozoic limestone, with an average specific discharge of 10 l/sec/km².

The karst system is developed in Upper Cretaceous siliceous-calcareous marl that underlies very

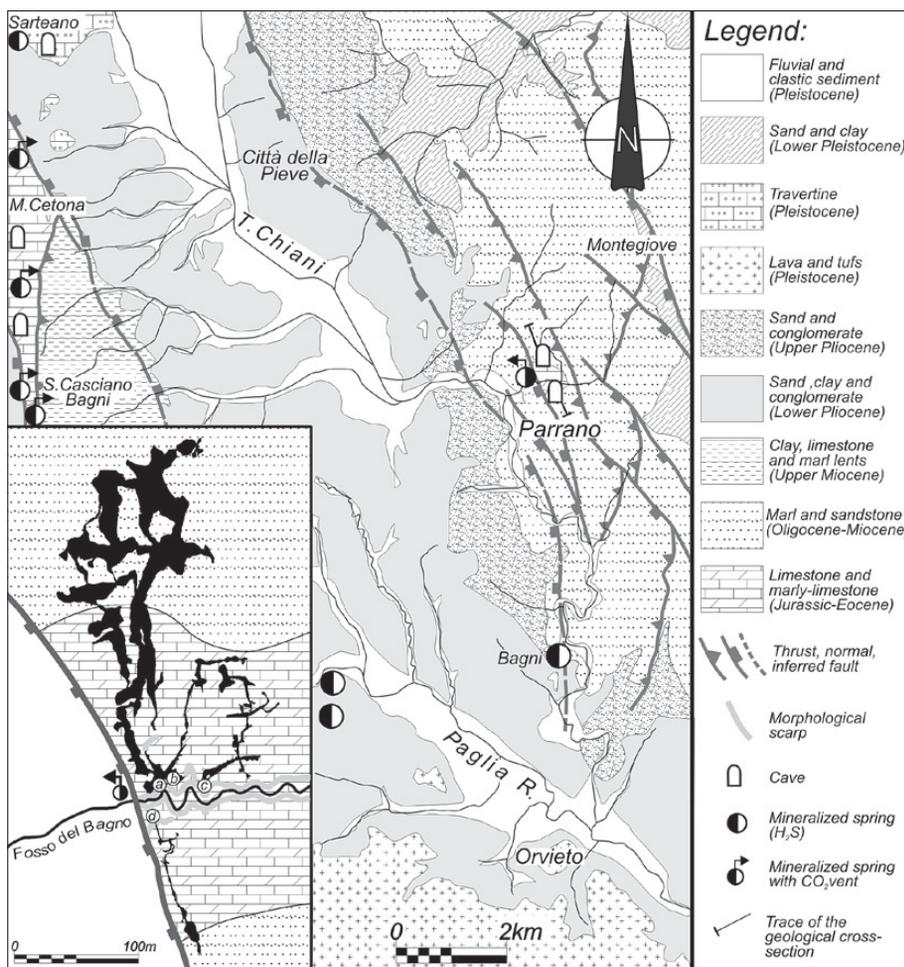


Fig. 11: Geological map of the Parrano area. The insert shows a map of the Fosso del Bagno Gorge with a plan of the main caves. Grotta Grande di Parrano (a); Tana principale inferiore (b); Tana principale superiore (c); Complesso Tane minori (d).

thick, low-permeability marls and a sandstone succession of Oligo-Miocene age (Fig. 11). The Parrano Gorge is within a small NE verging anticline, delimited by a Miocene thrust fault. The SW limb of the anticline is downthrown by a system of Plio-Pleistocene normal faults with an offset of 100 m. Several fracture systems are associated with the faults. Along the southernmost fault scarp, in the north bank of Fosso del Bagno there is a spring with an average discharge of 15 l/sec and a temperature of 26°C. The spring is characterized by TDS (Total Dissolved Solids) of up to 1700 mg/kg, pH <6.5, pCO_2 of 10^{-1} atm, H_2S content of 10 mg/l, and Ca-Na and Cl- HCO_3 composition (Fig. 9) (Minissale *et al.* 2000; Italiano *et al.* 2004).

Other important mineralized springs and gas vents are located throughout the area, especially at the boundary between limestone and terrigenous sediments (Fig. 11). In Sarteano, large travertine deposits are associated with CO_2 -rich springs with temperatures of 24 °C. In the outcrops of these travertine deposits, several small caves with prehistoric settlements are located. At S. Casciano dei Bagni, a few springs have

temperatures higher than 40 °C with a gas phase of 6% CO_2 (Minissale *et al.* 2000; Piscopo *et al.* 2009). A few kilometers to the south there is an important, medium enthalpy geothermal field of Torre Alfina with many superficial gas vents. Here, the impermeable turbidite sandstone and marl cap rocks seal a 400 m thick carbonate reservoir, with pCO_2 of 4 MPa and temperatures of 140-150°C (Barelli *et al.* 1978). The high pCO_2 in the groundwater results from the degassing of deep, pressurized reservoirs as well as the mixing of shallow, cold Ca- HCO_3 groundwater with deep, thermal saline Ca- SO_4 (HCO_3) groundwaters.

CAVES

The Parrano gorge underground karst system consists of at least eight solution caves developed at different altitudes in both sides of a small, deep gorge containing a stream carrying seasonal runoffs. The caves are locally known as Tane del Diavolo (Devil's Holes) and represent an important Neolithic archaeological site, known since the beginning of the last century (Lippi Bomcambi 1938).

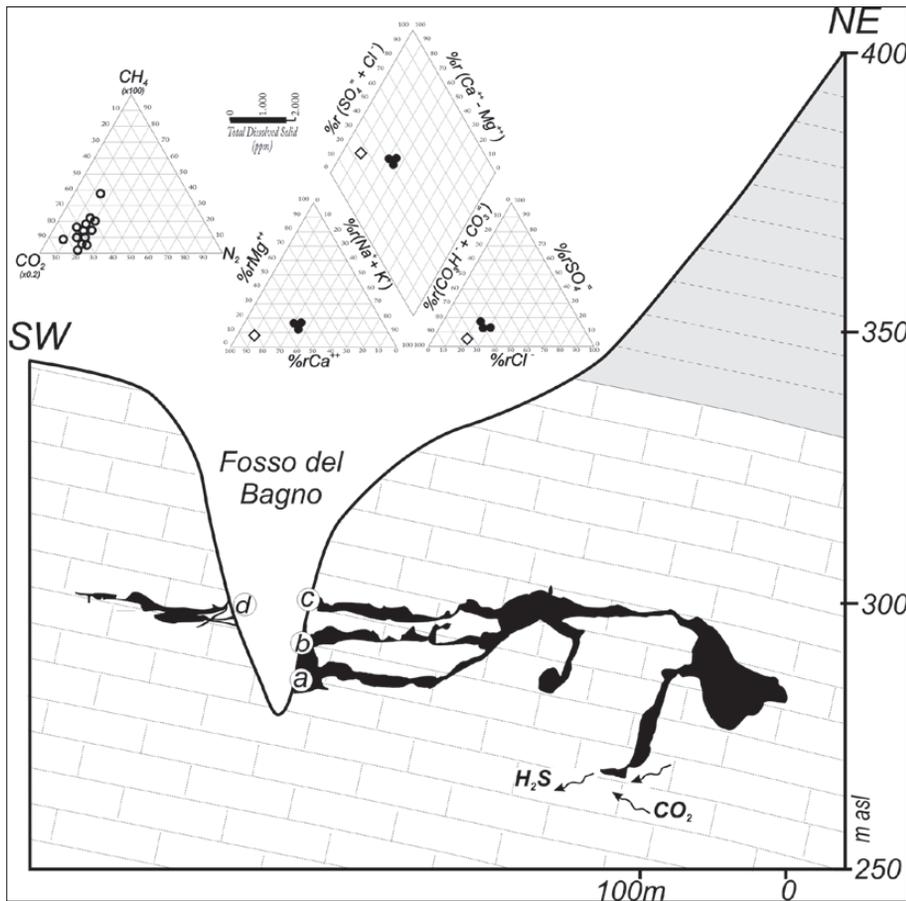


Fig. 12: Geological cross-section through the Fosso del Bagno indicating the caves. Brick pattern represents the Upper Cretaceous cherty limestone and the grey, Paleocene marls. The cross-section trace is in Fig. 11. Note that horizontal and vertical scales are different. In the upper part, the Piper diagram shows the compositions of the principal ions and gases of the Bagno spring water (from Italiano *et al.* 2004).

The Grotta Grande di Parrano, located in the northern bank of the gorge a few meters from the stream, is about 600 m long (Figs. 11 & 12). The solution ramiform passages consist of a main gallery (several meters wide) that ascends to a large room where a network of anastomotic passages and pits extend to a maximum depth of 50 meters. The cross-section of the passages is subcircular with cupola and blind shaft morphologies as well as protruding chert balls and discs formed by differential solution (Fig. 13). Carbonate speleothems are common in the upper levels. In the lower branch, a 30 m deep, subcircular shaft extends to a small room where a sulfuric stream flows. In the proximity of the sulfuric stream, the air moisture is rich in H₂S and CO₂ released from the groundwater that act as the main promoters of limestone corrosion in the cave walls (Menichetti *et al.* 2008). The thermal water heats the air in the cave to 25°C, and the CO₂ concentration is 0.02%. The process of limestone corrosion manifests as small white spots on the limestone of about one cm in diameter, where gypsum replaces the calcium carbonate. This microcrystalline gypsum is often mash and can easily fall off. Alternatively replacement gypsum crust can contain centimeter-sized recrystallized selenite crystals formed as a result of the

dissolution of preexisting gypsum. Spongework, corrosional limestone pockets and cupola ceilings are common morphologies. Alteration crusts within yellow clay deposits as well as recrystallized gypsum rosettes are present in different rooms of the cave.

The Tana Principale Inferiore opens with a large entrance on the gorge bank about 10 meters from the stream. The cave extends for about 200 m with passages that reach a gallery about ten meters high. The section is developed along a system of N-S fractures from which ramiform passages split off, ending abruptly in narrow fissures (Fig. 13a). The terminal room is characterized by carbonate speleothems dominated by stalactites. The ceilings commonly display cupola morphologies and chert protrusions (Fig. 13b). Brown and yellow clay sediments cover the pavements, and gypsum microcrystals are observable in several passages.

The Tana Principale Superiore is located about 30 m above the stream and developed as a single passage of about 150 m in length (Figs. 11 & 12). The fossil passages consist of subcircular galleries of metric size, present morphologies that are primarily controlled by stratigraphy and a system of N-S fractures that end abruptly in narrow galleries.

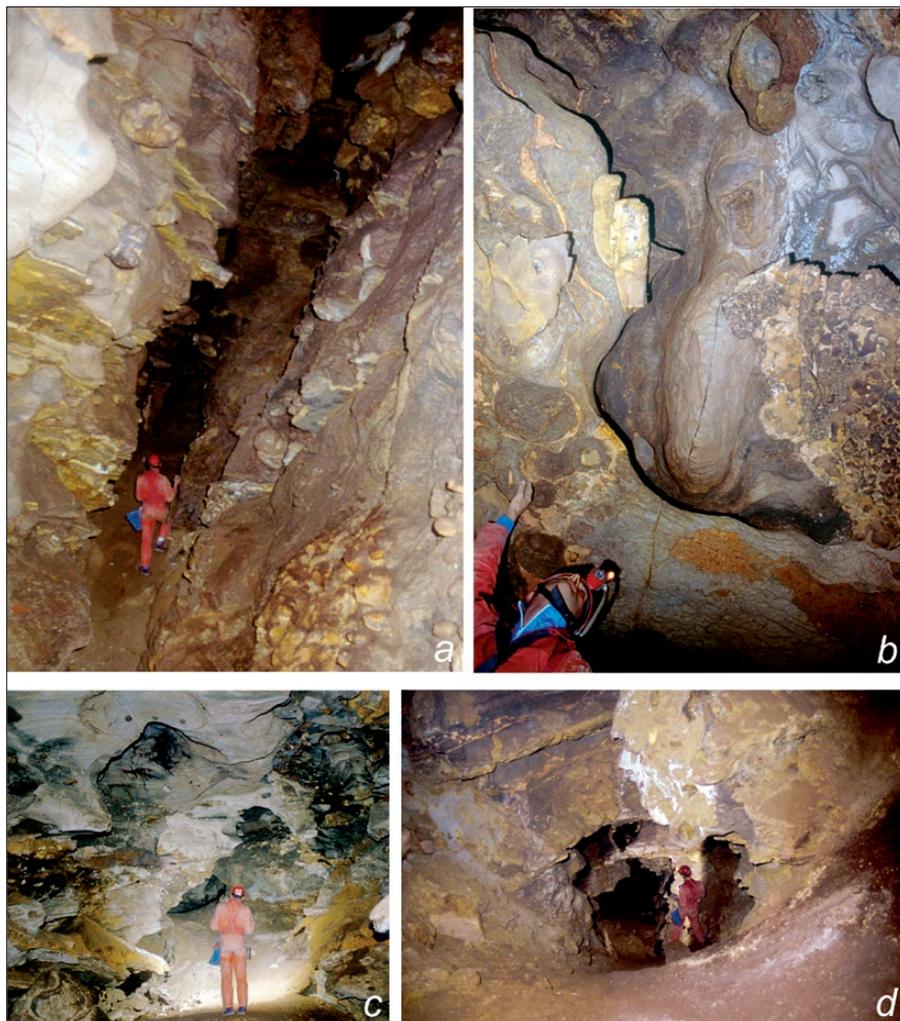


Fig. 13: Parrano caves – a) fissure gallery with chert protrusions in the walls; b) cupola ceiling morphologies; c) phreatic passages with pendants; d) vertical conduits with clay deposits.

In the southern bank of the gorge at an altitude of about 300 m is the entrance to the Complesso della Tane minori (Figs. 11 & 12). This solution cave is a single ascending elongated passage, metric in size, that extends to a large room 130 m from the cave entrance. Other small caves open on both sides of the gorge; a few are solution passages and many others are scattered blind fissures. All the karst systems of the Parrano gorge present morphologies, speleothems and cave deposits similar to those found in the active hypogenic system of the Umbria Marche Apennines of Frasassi and Acquasanta Terme (Galdenzi & Menichetti 1995).

Underground karst evolution can be linked to the ascending CO_2 and H_2S -rich waters as the regional water table falls. The gorge morphology and the cave entrance locations suggest that the stream has cut through the preexisting underground karst system. The ages of the different stages of the karst evolution are poorly constrained, but they can be placed within the framework of the Quaternary morphologic evolution of the area, during which volcanic activity played an important role.

DISCUSSION AND CONCLUSION

Despite the fact that the western Umbria caves have developed in different geological and hydrogeological con-

texts, most show patterns and morphologies that can be linked to a hypogenic origin. The karst in the region is

not homogeneously distributed, and a relationship between the cave development and the regional geomorphic events is not well established. A more dynamic view of cave pattern development and evolution in space and time will take into account the general elevation variations of the regional water table together with episodic gas emissions.

The caves are characterized by both fossil and active passages in which thermal water rich in H_2S as well as endogenic CO_2 plays a determinant role in speleogenesis. These hypogenic processes can be linked to the oxidation of the H_2S to sulfuric acid by oxygen-rich groundwaters. The cave morphologies suggest that the oxidation zone of H_2S is not restricted to the shallow groundwater levels but can be extended to deeper sections of the aquifer to which input of fresh water via a complex regional hydrogeological circuit could occur.

In western Umbria, there are several low-temperature CO_2 gas emissions with flow rates estimated at 10^{11} mol yr^{-1} (Rogie et al. 2000) in close proximity to the main outcrops of travertine deposits (Fig. 1). In the region, the origin of the gases is still debated since both CO_2 and H_2S are often associated with CH_4 and He (Minissale 2004). The origin of the non-volcanic CO_2 appears to be mantle degassing and the subsequent thermogenic reactions of carbonates. The H_2S is a product of gas reactions and re-equilibration in rock/mineral buffered geothermal systems in the buried Triassic anhydrites (Minissale et al. 2000).

The pCO_2 values of the groundwaters in Central Italy range from 0.03 to 0.1 atm, increasing the solubility of $CaCO_3$ by an order of magnitude with respect to the normal karstic waters. The breakthrough mechanism of progressive fracture widening by epigenic CO_2 corrosion is here modified to a homogeneous widening of the fracture walls along their complete length by the rising of endogenic CO_2 . An increase in pCO_2 of 0.002 atm from a continuous volcanic input is sufficient to reduce the breakthrough time for a fracture aperture by about half (Gabrovšek et al. 2000). Additionally, there is a positive feedback between H_2S oxidation and the release of CO_2 in the shallower groundwaters providing supplementary

aggressiveness towards the carbonate dissolution (Palmer & Palmer 2000).

The travertine deposits represent the other end member of these karst processes. They form as a result of degassing of surfacing carbon dioxide-rich groundwaters containing >2 mmol l^{-1} calcium (Pentecost 2005). In order for this to occur, the dissolution of previously deep-seated carbonate rocks by corrosive, CO_2 -rich groundwater is necessary. The origin and evolution of a cave, such as Pozzi della Piana within a travertine deposit where H_2S action has been linked to gypsum deposits, leaves open several questions related to the timing of the speleogenesis.

Several caves have developed in cherty and marly limestone normally considered non-karstic rocks. These lithologies have a $CaCO_3$ content of 60 to 80%, with the remaining composition represented by clay minerals, mainly illite and montmorillonite (Johnsson & Reynolds 1986). The corrosive H_2S/CO_2 gases, both in vadose and in phreatic zones, react with the carbonate rocks as well as alter the insoluble residues producing various speleogenetic products. The presence of carbonate cement in the marly rock fabrics accelerates the rock weathering process. Furthermore, the abundant microbial communities associated with active caves today need to be taken into consideration (Sarbu et al. 2001; Engel et al. 2004).

The complex chemical reactions between the different minerals in contact with carbonate rocks, the presence of significant concentrations of Cl and Na in several karstic groundwaters as well as the reactions at the gas/water interface and the role played by organic matter all require more detailed study. Moreover, the cooling of thermal water during its ascent along conduits increases the CO_2 aggressiveness, thus corrosion acting almost uniformly along the surfaces, producing a dramatic increase in the hydrologic flow and karst void development (Andre & Rajaram 2005).

The key to understanding the unusual nature of the cave patterns in Central Italy is to take into account the geology, hydrogeology and water and gas chemistry that control the hypogenic speleogenesis.

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