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LITHOLOGICAL AND STRUCTURAL GUIDANCE ON SPELEOGENESIS IN SPLUGA DELLA PRETA CAVE, LESSINI MOUNTAINS (VENETO, ITALY)

ABSTRACT: SAURO F., PICCINI L., MENICHETTI M., ARTONI A. & MIGLIORINI E., *Lithological and structural guidance on speleogenesis in Spluga della Preta cave, Lessini Mountains (Veneto, Italy)*. (IT ISSN 0391-9838, 2012).

Spluga della Preta is one of the first caves in Italy to be well studied and described from a geological and morphological point of view. Eighty years after its first exploration a large amount of lithological and structural data has been collected in the whole karst system and detailed surface geological surveys were carried out. The step-like profile of the cave was initially considered as a consequence of base-level lowering stages related to the entrenchment of the nearby Adige River. In this work lithological guidance of the horizontal levels is demonstrated, considering only the deepest passages to be palaeo-phreatic. The main tectonic structures guide the oldest and inactive parts of the cave, developed mostly within weakly cohesive fault breccias, whereas the active streams are now deepened along secondary joints. Morphological analysis allows inference of a hypothesis concerning the speleogenetic evolution of the cave and its relationship with an upper perched aquifer hosted in the Cretaceous Maiolica Formation.

KEY WORDS: Cave morphology, Lithological and structural control, Cave level, Speleogenesis, Monti Lessini, Italy.

RIASSUNTO: SAURO F., PICCINI L., MENICHETTI M., ARTONI A. & MIGLIORINI E., *Controlli struttuali e litologici nella speleogenesi nell'abisso della Spluga della Preta, Monti Lessino (Veneto)*. (IT ISSN 0391-9838, 2012).

La Spluga della Preta è una delle prime grotte italiane ad essere stata descritta e studiata dal punto di vista geologico e morfologico. In oltre ottant'anni di esplorazioni speleologiche sono state raccolte numerose informazioni riguardo i controlli litologici e strutturali, anche tramite un rilievo geologico di dettaglio in superficie e in profondità. Il profilo a gradini della cavità era stato interpretato inizialmente come l'effetto dell'evoluzione idrogeologica dell'area, controllata dall'abbassamento progressivo del livello di base, legato all'approfondimento della Valle dell'Adige. Diversamente, in quest'articolo viene dimostrata l'influenza predominante dei controlli stratigrafici, mentre solo il livello orizzontale più profondo può considerarsi di tipo paleo-freatico. Le principali strutture tettoniche hanno guidato la speleogenesi dei settori più antichi ed ora inattivi della grotta, sviluppandosi prevalentemente all'interno di brecce tettoniche non coesive. I settori attualmente attivi tendono ad approfonditi lungo fratturazioni secondarie alle faglie principali. Grazie all'analisi morfologica, viene proposta una più esaustiva ipotesi sull'evoluzione speleogenetica e sulla relazione tra la cavità e un acquifero sospeso al di sopra di essa, trattenuto nella formazione Maiolica del Cretaceo.

TERMINI CHIAVE: Morfologia carsica, Controllo strutturale, Controllo litologico, Livelli paleo-freatici, Speleogenesi, Monti Lessini, Italia.

INTRODUCTION

Exploration of Spluga della Preta cave began in 1925 and went ahead by way of dozens of expeditions by Italian and international cavers. For several decades the cave was considered one of the deepest of the world. Some of the first explorers were geologists who gave detailed descriptions on the geology and the morphology of the karst system (Stegagno, 1927; Maucci, 1954; Bertolani, 1962; Badini & *alii*, 1963). The bottom of this abyss was reached for the first time in 1963 but successively many new branches were explored, bringing the current extent to 6.7 km, with a depth of 877 m. During the same period, general knowl-

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This work has been possible thanks to the effort of hundreds of cavers during the multidisciplinary «Operazione Corno d'Aquilio» *research project between 1989 and 1993. Additional field work was carried out by G. Troncon, C. Cavallo and A. Sganzerla. Discussions with G. Cascone and J. De Waele have been very helpful. Many thanks to E. Anzanello for having shared his picture of Pozzo del Chiodo and to G. Annichini for the elaboration of the cave survey. This paper has benefited substantially from the careful reviews of D.J. Lowe and M. Filipponi.*

edge on karst phenomena and speleogenesis made remarkable advances though many of the earlier ideas and theories on the origin of the cave still remain valid, like the condensation-corrosion process described by Maucci as «erosione inversa» in 1954 (Maucci, 1954; Badini & *alii*, 1963; Sauro, 1974). After the discovery of new branches (Sauro, 2007) during the past twenty years, Spluga della Preta now appears to have a more complex structure than previously believed, and its genesis appears to have involved several distinct phases.

This work focuses on the lithological and structural guidance of the general pattern of the karst system and proposes a more complete speleogenetic model.

GEOLOGICAL SETTING

The Spluga della Preta karst system is developed within the classical stratigraphical sequence of the Trento Platform, cropping out over a wide area of the Central Southern Alps with a sedimentary sequence composed of Mesozoic limestones deposited on a shallow water carbonate platform during the Triassic and Jurassic and on pelagic structural highs during the Cretaceous (Bosellini & Broglio Loriga, 1971; Bosellini & *alii*, 1978).

The cave entrance opens on the summit plateau of Monti Lessini (Venetian Pre-Alps) in the Cretaceous Maiolica Formation and develops downwards through the Rosso Ammonitico, Loppio Formation and the San Vigilio-Calcari Grigi limestone groups (fig. 1, fig. 2). Only the deepest part of the cave crosses the gradual transition between the Monte Zugna Limestone Formation and the Dolomia Principale, a coarse-grained dolomite characterized by metric beds, each one repeating a single subtidal cycle. A detailed description of the stratigraphy crossed by the karst system is provided by Artoni & *alii* (2011).

The Monti Lessini plateau is incised by deep valleys that are closely guided by two fault systems (the NNE-SSW system known as *giudicariense* and the NNW-SSE system or *scledense*), which create a «horst and graben» setting. These two fault systems record a Palaeogene extensional phase that is associated with the emplacement of basaltic dykes and sills. A subsequent compression phase, of Neogene age, generated transverse, only locally extensional, movements of the same inherited fault systems, as well as the formation of the south-vergent Corno d'Aquilio-Monte Belfiore monocline (fig. 3; Artoni & Rebesco, 1990). As in the Southern Alps, the Lessini Mountains have been affected by a compression phase, certainly since the Miocene, when uplift brought the limestone plateau to its final emergence and initiated karst processes. From Pliocene to Quaternary the region is affect by strike-slip and extensional fault systems (Zampieri, 2000).

THE CAVE

Spluga della Preta opens at 1484 m a.s.l. on the northern slope of Corno d'Aquilio mountain in the north-western sector of the Monti Lessini plateau. With a depth of 877 m and almost 6.7 km of length it represents one of the biggest caves in the Venetian Pre-Alps (Mietto & Sauro, 1989). During more than eighty years of exploration many topographical surveys have been carried out, some of which were inaccurate, especially concerning the depth of the first shafts (Busolini, 1960). Only from 1989 to 1993, during the «*Operazione Corno d'Aquilio*», a detailed and precise map of the whole cave was completed.

It is evident from the vertical section (fig. 2) that the cave shows a step-like profile, with vertical shafts (some more than one hundred metres deep) alternating with almost horizontal passages made of meanders and galleries. Whereas in the upper part of the system vertical sections dominate, sub-horizontal cave passages prevail from –600 m to the bottom. This pattern is also observable in the plan view (fig. 7), where the first 400 metres of depth are restricted to an area of about 6 hectares (200 x 300 metres), whereas from –600 m the cave develops toward the north-west, dividing into two main branches, the Canyon Verde and Vecchio Trippa galleries.

From an hydrological point of view the present cave stream results from the joining of minor flows at a depth of –360 (1125 m a.s.l.) and it descends up to a sump at a depth of –734 (733 m a.s.l.). This sump is clearly perched and not related to the water table position. Two main tributaries join the main stream at depths of –380 and –570 metres. The discharge is generally low and usually ranges from 40 to 80 l/minute before the sump (Menichetti & *alii*, 2011). Most of the lateral branches are inactive and only slight drippings are present. Also the deepest part of the cave and the Vecchio Trippa branches are not active now, even if they are located one hundred metres deeper than the sump. During the Operazione Corno d'Aquilio the main resurgences of the karst system were identified by dye tracer tests on the eastern slope of the Adige Valley (Menichetti & *alii*, 2011). The present base level of the area is supposed to be at the same height of these springs (located between 250 and 120 m a.s.l.), that is much lower than the known bottom of the cave (607 m a.s.l.).

A BRIEF HISTORY OF RESEARCHES

The first study of the geological and speleogenetic aspects of the cave was made by Stegagno (1927) during the second and third exploration of the cave in 1926 and 1927. He understood the predominant role of the joint network in guiding the genesis of the cave. Later, Maucci (1954) provided a detailed topography of the cave and a morphological description of the main passages. He was the first to recognize the different roles of lithologies and fractures in the morphological guidance of the karst system. In his original genetic model (fig. 4) Maucci suggested the occurrence of a different surficial morphology with a much wider catchment area in the main phases of speleogenesis. The horizontal passages were interpreted as guided by less permeable layers, while shafts and canyons connecting different horizontal levels were guided by tectonic surfaces like faults and

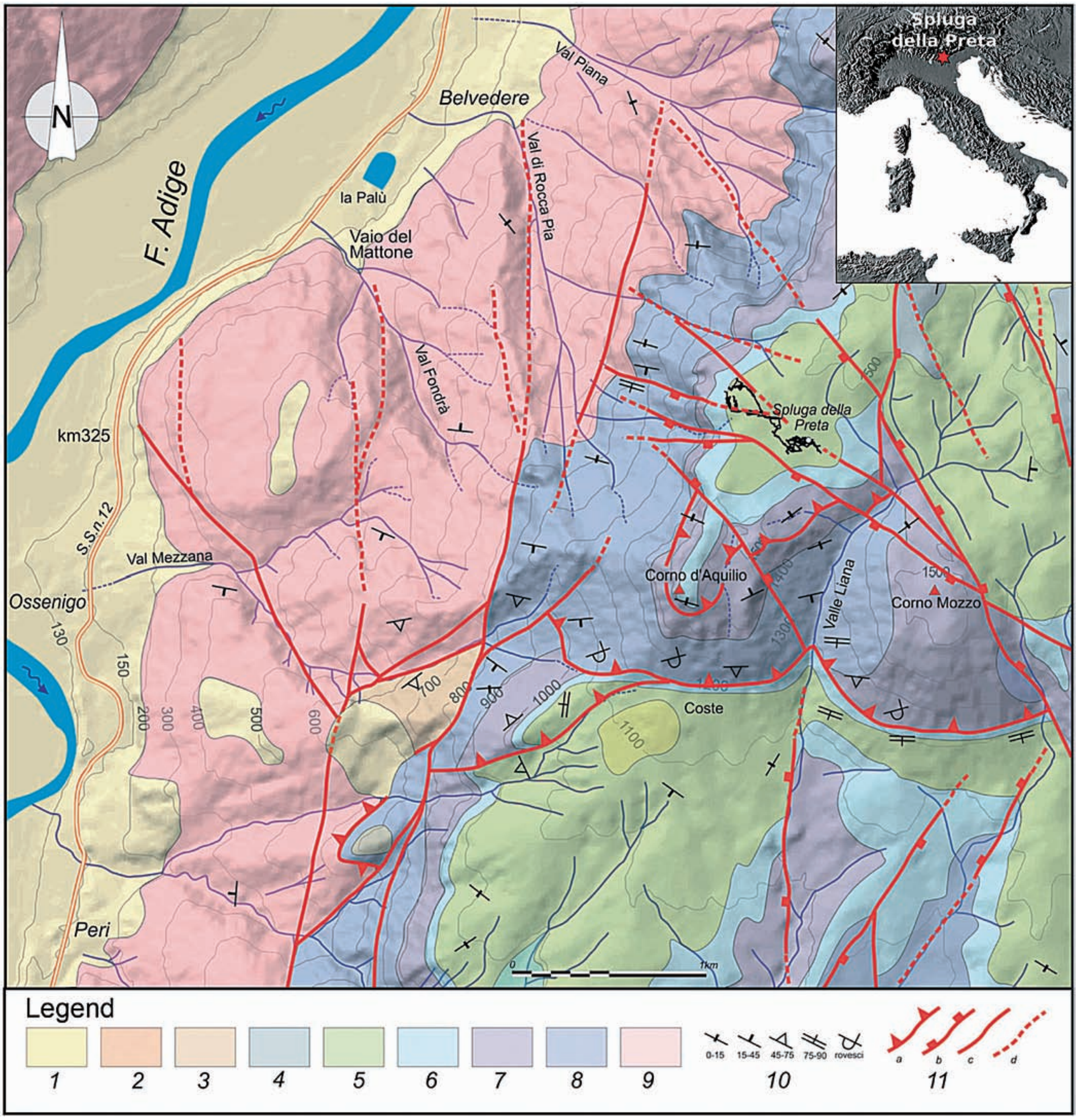

FIG. 1 - Geological map of the Corno d'Aquilio area. Legend: 1) Quaternary detrital, alluvial and glacial deposits; 2) Eocene limestones; 3) Volcanic rocks (Palaeogene); 4) Scaglia Rossa Fm (Upper Cretaceous); 5) Maiolica Fm (Lower Cretaceous); 6) Rosso Ammonitico Fm (Upper Jurassic); 7) San Vigilio Group (Middle Jurassic); 8) Calcari Grigi Group (Lower Jurassic); 9) Dolomia Principale (Triassic); 10) dipping orientation of the strata with different inclination; 11a) thrust; 11b) normal fault; 11c) strike-slip fault; 11d) uncertain fault (from Menichetti & *alii*, 2011).

joints. The study of Maucci was of great importance also because he proposed the «erosione inversa theory», which is now widely accepted in literature as condensation-corrosion process (Sauro & Rossi, 1974; Palmer, 2007) to explain the morphology of the first great shafts of the cave. Anyway he didn't consider properly the influence on the cave of the morphological evolution of the near Adige Valley and the subsequent lowering of the base level.

Sauro (1974) underlined the importance of the perched aquifer in the Maiolica Formation, which acts as

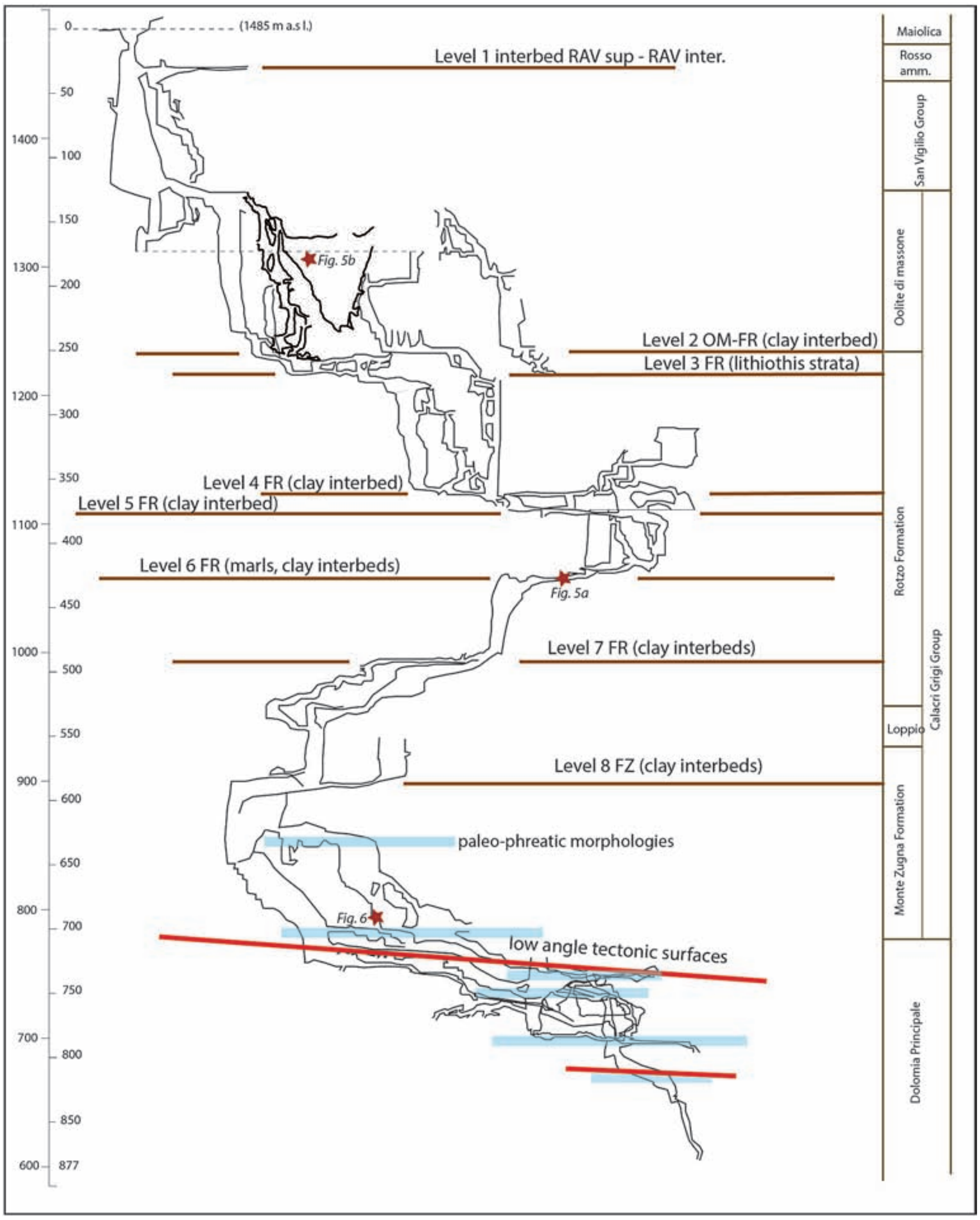

FIG. 2 - Schematic unfolded (not projected) profile of Spluga della Preta with the most important horizontal levels guided by lithology (brown line) or controlled by a palaeo-water table (blue line). Areas where low-angle tectonic surfaces were observed are highlighted in red.

a permanent reservoir feeding a concentrated flux of water into the joint systems of the underlying Rosso Ammonitico.

One of the main questions not answered in the previous studies concerns the relationship between the lowering of the base level (due to the downcutting of the near Adige Valley), and the step-like pattern of the cave, i.e. if the main horizontal passages are former palaeophreatic levels representing subsequent base level stillstands, or if they are controlled more by lithological characteristics of some layers rather than by the hydrological evolution of the area (see «cave levels» in Palmer, 2007). Also the guidance of the tectonic features and the role of the main faults zones in the speleogenesis was not well investigated.

LITHOLOGICAL AND TECTONIC FEATURES

Along the stratigraphic sequence crossed by the cave, about 8 different marl beds or clay interlayers were identified (fig. 2). They guided small horizontal conduits and the flat ceiling of deep incised meanders and canyons. The highest one (within the middle member of Rosso Ammonitico Formation) is characterized by cherty centimetre-scale beds. Anyhow most of them are within the Calcari Grigi Group and Dolomia Principale Formation. During the Operazione Corno d'Aquilio research project, the mineralogical composition of some of these layers (level 4 and 6 in fig. 2) was obtained by X-ray difractometry (Bertolani, 2011) showing the presence of quartz, illite and smectite together with calcite. A different bed, characterized by a

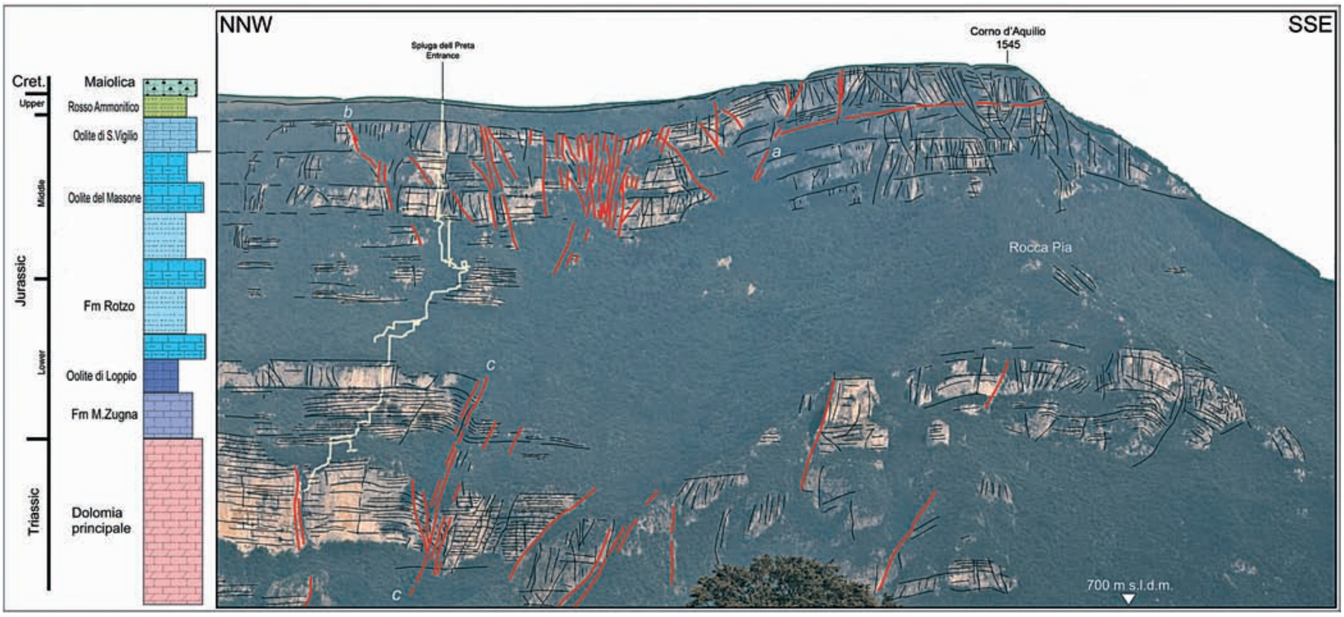

FIG. 3 - Photo of Corno d'Aquilio's western side, aligned with the stratigraphical sequence along the Valley of the Adige river. Faults and joints are highlighted in red. Signed with letters: a) Val Liana Fault, b) Preta di Sotto Fault, c) Torre Azzurra Fault. The cave profile was projected parallel to the strike of the valley side (in white).

concentration of *lithiothis* shells fragments and silicified corals (Benini, 2003) at the passage between the Oolite di Massone and Rotzo formations, guided the development of some other horizontal passages (level 2 and 3 in fig. 2).

At about –550 metres the limestone of Monte Zugna Formation gradually changes to the dolostone of Dolomia Principale in a range of about 50 metres. Here many green and red clay interlayers typical of the Monte Zugna Formation are present. Tectonic low angle movements are easily recognizable and the clays are squeezed along the major high angle vertical fault surfaces.

Many tectonic features, such as different sets of joints and fault surfaces with kinematic indicators related to brittle tectonics are observable inside the cave. Tectonic surfaces belong to two main groups:

i) nearly vertical fault surfaces with slickensides, calcite fibres and other kinematic indicators, which show a dominantly dextral movement (related to the Casara Preta, Valle Liana and Torre Azzurra faults: fig. 3, 5a, 7);
ii) surfaces with dip angles of 10-20°, where kinematic indicators suggest movement consistent with compressive low-angle faults (thrusts) moving toward the south-east. The near-vertical strike-slip surfaces have three main directions (NNW-SSE, SSW-NNE, E-W) and are common throughout the cave.

One example of the vertical fault surfaces is exposed in the meander above Pozzo del Chiodo at around 400 m depth (fig. 5a) where the fault plane has an E-W direction related to faults of similar orientation recognizable on the plateau (fig. 7). Another impressive vertical fault was found in the Via Antika branch, with a fault plane exposed on about 7000 m^2 (110 metres height and 70 metres length, fig. 5b). Fault breccias more than ten metres thick are found within this tectonic feature.

However the sector of the cave with the greatest number of both vertical and sub-horizontal tectonic surfaces is situated at –700/–800 metres depth, corresponding to the main concentration of horizontal passages (fig. 6). In the Vecchio Trippa branches, breakdowns have profoundly modified the original morphologies, showing the different systems of fractures and faults. Here it has been possible to observe clearly the different tectonic surfaces and their kinematic indicators while the original and erosional morphologies are in most places unrecognisable.

Most of the vertical surfaces have characteristics of strike-slip faults with dextral movement and directions between 160° and 175°N. The entire first part of the Vecchio Trippa branches is guided by one of these surfaces oriented 160°N, related to the Preta di sotto Fault recognizable on the slope of the Adige Valley (fig. 3, 7). These passages at about –720 m of depth (760 m a.s.l.) are also guided by low angle tectonic surfaces imposed on sedimentary clay interlayers dipping at 25° toward 350°N.

The existence of these surfaces in a well defined altitude range together with tectonic breccias suggests the presence of an important thrust, related to the Corno d'Aquilio flexure. In the Canyon Verde the situation appears different: vertical tectonic surfaces have not been observed and the whole passage is guided by low-angle surfaces imposed on the green clay interlayers typical of the top of the Dolomia Principale beds (sub-tidal unit cycles; Bosellini & Hardie, 1985).

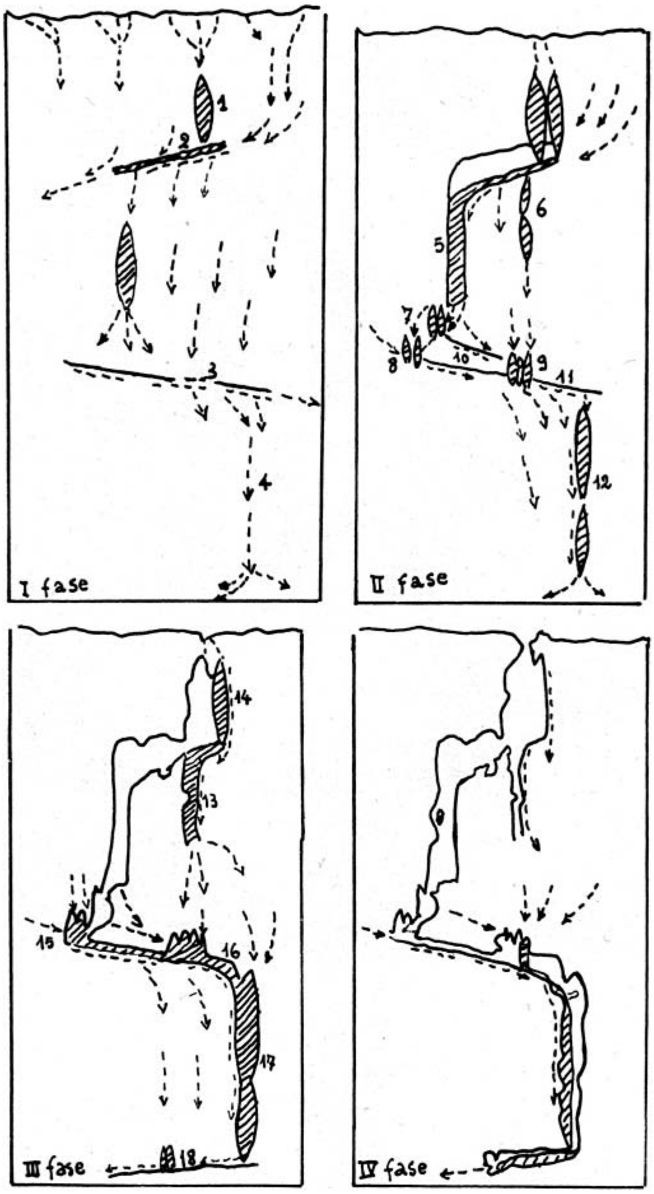

FIG. 4 - The speleogenetic model proposed by Maucci (reproduced from Maucci, 1954). I) in the first phase, the surface drainage was collected in the Maiolica Formation and then conveyed into specific stream sink points (like Ciabattino Cave at the bottom of a blind valley). At the same time, less permeable layers in the Rotzo Formation supported local perched aquifers. II) The widening of fractures allowed the water flow to cross the impermeable layers and to convey the drainage along structurally guided routes towards the base level. III) Independent open conduits were connected and a continuous karst network was formed. IV) In the final phase the karst system was intersected by the surface landscape, when the main drainage is only encountered in the deepest part of the cave.

STRUCTURAL AND LITHOLOGICAL GUIDANCE

The general tectonic setting, with joints, faults and folds, of a carbonate massif is the main factor that determines the secondary permeability of the rocks and the development at depth of the karst process (Klimchouk & Ford, 2000). The lithological characteristics of the stratigraphical succession, on which the degree of rock dissolution capacity ultimately depends, eventually have an influence on the development of well-defined cave levels (Lowe, 2000; Filipponi & *alii*, 2009). In literature the stratigraphical surfaces on which the karst process is enhanced and which often guide the horizontal levels are known as «inception horizons», that in the definition of Lowe (1992) are zones «*especially favourable to karstification by virtue of physical, lithological or chemical deviation from the predominant carbonate facies*».

Hydrological conditions that depend on the climatic history of the area and on its hydro-morphological evolution, control the development of the general pattern of the cave system (position of vadose or saturated zones). Recharge parameters control the dissolution rate inside the conduits and direct conduit development toward the local base level.

Researchers who have described the cave agree on the fact that the pattern of the karst system is conditioned primarily by the characteristics of the lithologies (fig. 2), by the systems of faults and fractures, and by the presence of zones characterized by tectonic breccias, rather than by hydrological factors. From a morphological point of view three main groups of features related to tectonic or stratigraphical guidance can be described:

- vadose joint-guided vertical shafts widened by erosion and/or corrosion by active streams or by condensation-corrosion processes.
- meanders and small conduits with a dominantly horizontal trend developed along thin marl or clay layers characterized by a low permeability. These began to develop under local phreatic conditions (testified by the upper small circular to elliptic conduits) and evolved to vadose conditions due to subsequent entrenchment of the less permeable layer (lower narrow meanders);
- large voids (rooms, galleries and wide shafts) related to faults or other fractures characterized by a high proportion of tectonic breccias, in some cases many metres thick. In these environments the original morphologies are commonly unrecognizable, probably destroyed shortly after their initial formation, due to breakdown processes and the build-up of massive boulder chokes. Anyhow in some place both vadose and palaeophreatic (in the deepest part of the cave) features were observed.

The main tectonic structures such as faults and poorly-cohesive breccias seem to have guided the oldest, now inactive, parts of the cave (like Via Antika, Via Nuova and Vecchio Trippa branches,), whereas the active streams are now entrenched along sets of secondary joints related to the main faults. We observed that the fault-breccia guided voids are discontinuous and often filled by breakdowns and residual clays, while the secondary joint guided passages (both parallel or at low angle from the main fault surface) are more continuous and free from sediment fillings.

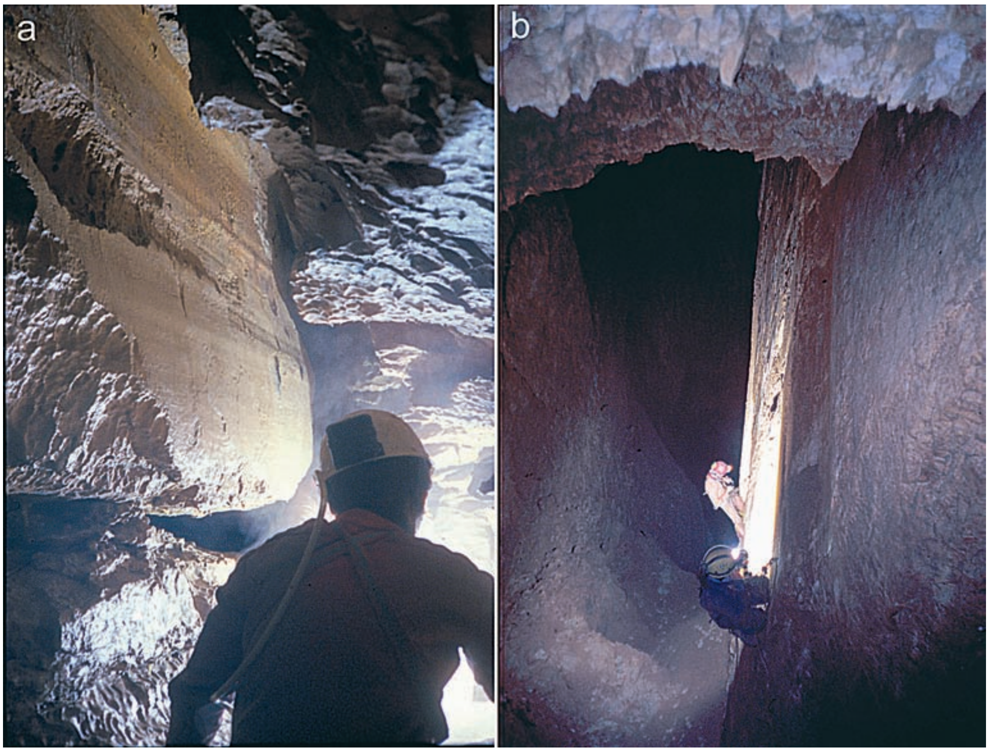

FIG. 5 a) - Tectonic high-angle surface, «mirror fault» type at 550 metres depth. The kinematic indicators show a strike-slip dextral movement (photo E. Anzanello). b) The high-angle fault surface of Via Antika. Note the several metres-thick tectonic breccias on the roof (photo F. Sauro).

DISCUSSION

The Lowe's «Inception Horizon Hypothesis» (1992) supposes that the cave levels develop within the most favourable inception features within the epiphreatic zone (related to the water table position). An horizontal network of stratigraphically guided phreatic conduits is expected to develop in these conditions and so palaeo-phreatic levels at different altitude represent subsequent base-level still-stands.

The step-like pattern of Spluga della Preta cave profile was considered to be a consequence of the entrenchment of the nearby Adige River by many authors (e.g. Maucci, 1954; Badini & *alii*, 1963; Corrà, 1975) with subsequent former palaeo-phreatic tiers. Actually the lithological guidance of the horizontal passages related to thin marl and clay layers is evident.

In the case of Spluga della Preta, above 900 m a.s.l. palaeo-phreatic morphologies are not common and related to small conduits on the top of canyons and meanders.

FIG. 6 - Tectonic low angle surface on a clay interlayer between metre-scale beds of Dolomia Principale, Vecchio Trippa Branch. (Photo F. Florio).

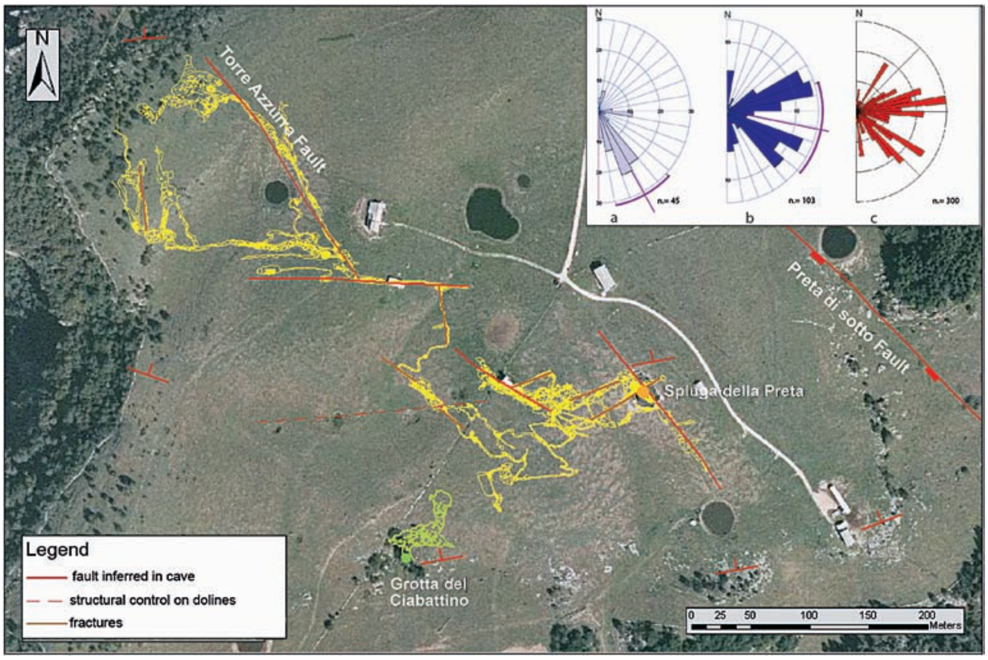

Fig. 7 - Aerial view of Corno d'Aquilio with a projected topographic plan of the karst system superimposed. The main tectonic features recognizable inside the cave are shown in red. The rose diagrams indicate the directions of faults (a), joints (b) and the direction of the galleries taken from the survey data (c).

The higher horizontal steps of the cave probably reproduce «fake» cave levels (i.e, not related to the water table) because they represent original conditions of water flow along confining layers. Where these layers were cut by tectonic features like faults or joints the water flow could bypass the confining zone and continue downward. The canyons and deep meanders were formed by the floor entrenchment of these perched small conduits. So the hydrological evolution of the area and the lowering of the base level does not seem to have affected the cave development above 900 m a.s.l (–600 m).

Only the deepest galleries of Vecchio Trippa and Canyon Verde zone could be considered as a phreatic level related to a past water table position. Here the palaeophreatic morphologies are evident with more than five metres in diameter, circular and elliptic conduits (phreatic tubes), local spongework patterns and solution pockets.

Beyond the local role of structure and tectonic surfaces on the cave passages geometry, the morphological evolution of the Adige Valley must have had also some effects on the cave development.

The western slope of Corno d'Aquilio follows an important tectonic lineament that has influenced the regional water drainage since Miocene time (Curzi & *alii*, 1992). During the Messinian Crisis and the consequent lowering of the sea level in the Mediterranean area, the northern part of the Adige Valley was deeply downcutted extending along the present Sarca and Garda valleys (Bassetti & Borsato, 2007), whereas the southern sector between Baldo and Lessini Mountains was entrenched by glaciers only later during Quaternary (Habbe, 1969).

Some considerations of the local base level evolution can be inferred by the analysis of three topographical cross-sections perpendicular to the Adige Valley (fig. 8). The slopes of the valley display a morphological low-gradient surface between 600-700 m a.s.l., which could be related to the only clearly recognizable palaeo-phreatic level of the cave, where most of the horizontal conduits are concentrated. A major concentration of caves in the western sector of Monti Lessini corresponds to the same altitudes (Rossi & *alii*, 1996).

Furthermore the cave is developed only a few hundred metres away from the valley slope (more than one thousand metres high). This is clearly visible in the 3D model (fig. 9). It is thus logical to expect the cave to be influenced by structures related to gravitational tectonics.

Although a direct relationship between the entrenchment of the Adige Valley and the cave is not clear, its closeness has almost certainly influenced the speleogenesis, with gravitational deformations and major opening of pre-existent tectonic structures, as well as the only recognizable water table stillstands in the deepest part of the karst system.

Sauro (1974) and Zorzin (1996) suggest that in the early speleogenetic stages a morphological situation where the plateau was characterized by a uniform cover of Maiolica Limestone is necessary. This Formation is in fact characterized by a very closely-spaced fracture-cleavage which produces a centimetre-scale porous aquifer perched by less permeable clayey layers.

This hydrological behaviour of the Maiolica Limestone is emphasized by the occurrence of small springs all along the contact with Rosso Ammonitico, which testify a diffuse water flow and no karst conduit development. Such fractured low-confined lithology, that retard but not prevent the flow of water to the lower units, can be defined as an «aquitard» (Sauro, 1973, 1974, 2011) similar to those of the Paris Basin «Chalk» described by Megnien (1964). In addition, the closely spaced cleavage, the decimetre-scale thickness of the layers and the presence of clay interlayers in the Maiolica and Rosso Ammonitico (particularly its middle member) favour the formation of middle/small-

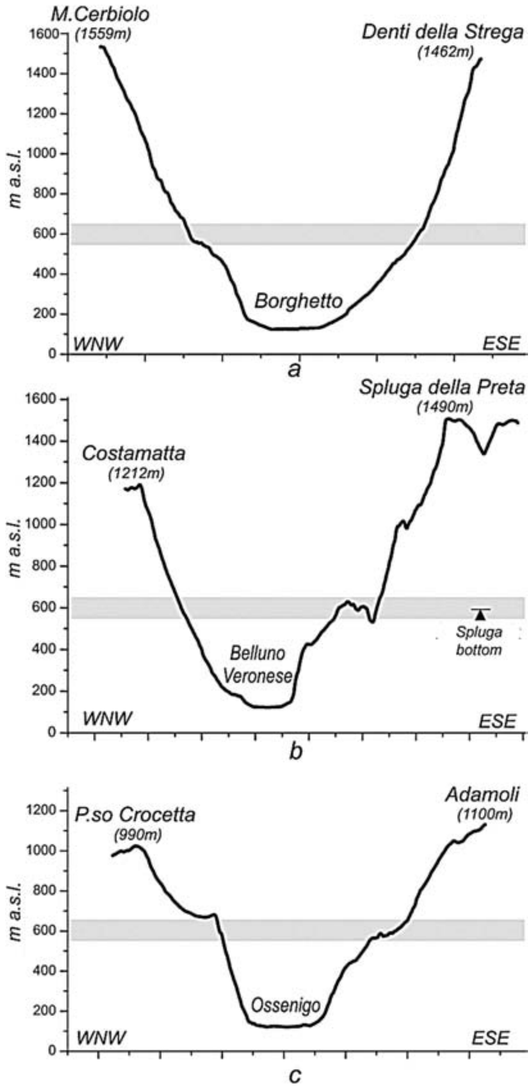

FIG. 8 - Topographical cross sections of the Adige Valley to the north (a) and south (c) of Corno d'Aquilio (b). The grey band represents the altitudinal level where most of the palaeo-phreatic morphologies were found inside the karst system.

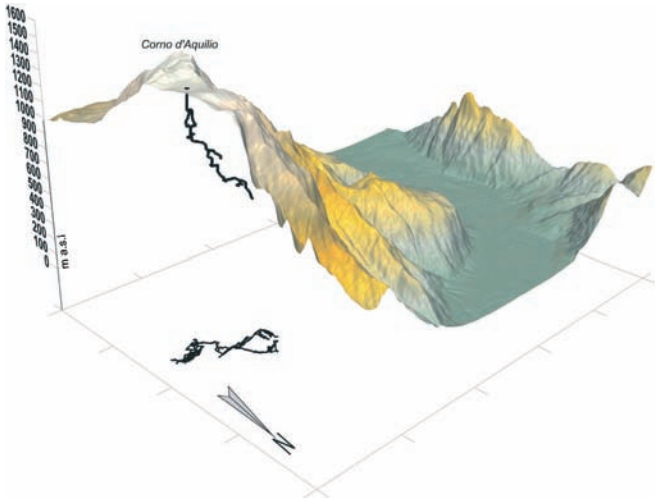

FIG. 9 - Digital terrain model of the Adige Valley and Corno d'Aquilio western slope. The 3D survey of Spluga della Preta cave is shown in black.

scale folds rather than large-scale fractures. Conversely the limestone of the San Vigilio and Calcari Grigi group are characterized by metre-scale beds intersected by large-scale systems of faults and fractures.

The perched aquifers hosted within the Maiolica slowly transferred seepage water to the large-scale fracture network in the Rosso Ammonitico. Once it reached the Loppio Formation this water passed into high-angle faults characterized by metre-thick cataclasite that was easily dissolved and removed by erosion and gravitational collapsing. Water flowed through these preferential routes at depth, encountering local perched phreatic zones characterized by minor permeability barriers up to a regional water table related to the Adige Valley base level. Within this former phreatic level, the conduits developed mostly along tectonic surfaces and breccias related to an important thrust.

Considering the recharge of the Maiolica perched aquifer, it is expected that slow flow in calcareous rocks generally results in $CaCO_3$ saturation of the water. For this reason the water collected from the Maiolica Formation in the early stages dissolved the underlying limestone very slowly. This suggests a slow speleogenesis during the proto-conduit development stage and a late connection with the local base level.

In our opinion, the main speleogenetic phases were probably linked to a surface morphology similar to that observed now, in conditions where the base level was already much lower than the Corno d'Aquilio plateau, and there is no need to envisage a recharge area greater than the current one. This may explain the lack of palaeophreatic conduits, which occur only at the level of the tectonic thrust contact between the Dolomia Principale and the overlying limestone formations.

Even if the main speleogenetic factors are well known, we still do not have enough data on the timing of the different processes. Menichetti & *alii* (2011) proposed a minimal time of 80 ky for a 1 metre enlargement for dissolution of a joint surface in the area (the situation of the first shafts of the cave), inferred from a speleogenetic model based on geochemical analysis of spring waters and chemical weathering rates of limestone in the area, assuming a climate similar to now. This hypothesis indicates the order of magnitude of speleogenesis time in this region but is probably underestimated in view of the complexity of the underground water flow however. In addition it is necessary to consider the time-consuming circulation of the water in the Maiolica aquitard, which is the main factor affecting mineral concentrations in the water (decreasing its dissolution potential), or the variability of climate in the past.

The deepest part of the cave (above all the zones of Vecchio Trippa galleries and Canyon Verde) demonstrates a highly mature morphology (sediment filling, diffuse collapses with complete obliteration of the original morphologies) that suggests an ancient origin, in the order of several hundred thousand years, as confirmed in many other karst systems of the Alps by U-Th on speleothem and cosmogenic burial dating (Audra & *alii*, 2007; Plan & *alii*, 2009 Christian & Spotl, 2010; Meyer & *alii*, 2011).

CONCLUSIONS

Thanks to the efforts of many cavers and researchers during more than eighty years of explorations we now have a sufficiently detailed vision on what were the factors leading to the formation of this famous karst system. The importance of tectonic and stratigraphical guidance on speleogenesis is evident in the general pattern of the cave. Palaeogeography and palaeoclimate play only secondary roles. The evolution of the Adige Valley seems not to be connected directly with the vertical step-like pattern of the cave, but it has certainly influenced speleogenesis through gravitational tectonics in the proximity of the valley slope. Actually, only the galleries at 700 m a.s.l. show phreatic morphologies (true cave levels) that justify a base level stillstand at this altitude. The time-consuming circulation of the water in the Maiolica aquitard probably caused a slow speleogenesis and a late karst development with respect to the palaeogeographic evolution of the area and the deepening of the base level. This explains the lack of water-table levels in the upper section of the cave. More researches are needed to understand the timing of the different processes.

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