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Cave clastic sediments and implications for speleogenesis: New insights from the Mugnano Cave (Montagnola Senese, Northern Apennines, Italy)

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ABSTRACT

The study of cave clastic sediments has been considered one of the hottest topics during the last years because of their importance in paleoclimatic reconstructions and archaeological surveys.

This paper focuses on clastic deposits of the Mugnano Cave, a small cave located in the Siena district (Northern Apennines, Italy), showing unique features regarding the sedimentary fill, mostly made of grey-blue dolomitic silts. The sedimentary succession was investigated through a detailed sedimentological analysis aimed at a better understanding of sedimentary processes active during the deposition.

The entire succession was subsequently reinterpreted through an allostratigraphic approach: the recognition of an important erosional surface, associated with a significant change in sedimentation, allowed the distinguishing of two main allounits labelled MG1 and MG2. Furthermore, the different kinds of sediments collected in the cave were analysed using the XRF and XRD techniques, in order to establish their chemical and mineralogical compositions.

The integration of lithological, sedimentological, allostratigraphic and mineralogical data permits formulation of an interesting hypothesis about speleogenetic processes that influenced the cave, with particular reference to the processes capable of generating the underground space. In this context, most of the current available space results from a complex interplay between different processes: disintegration of a particular lithofacies of the bedrock, consequent production of sediments and deposition into a subterranean lake. These sediments were removed from the cave during some non-depositional and erosive phases, which led to a positive balance in the available space.

1. Introduction

In the last decades several studies on cave sediments have been performed. However, they were generally focused on chemical sediments that are formed in place, precipitated from solution. This kind of deposit is an excellent source of information for paleoclimatic reconstructions.

In contrast to the widespread interest in chemical sediments, only in the last years have geoscientists paid attention to clastic sediments (Bosch and White, 2004; Sasowsky and Mylroie, 2004; White, 2007). These deposits are mainly made of clasts or particles that are moved mechanically before the deposition and can be subdivided into autochthonous and allocthonous sediments (White, 2007). The first derive locally within the cave and often correspond to the insoluble component of the bedrock, while the latter are composed of sediments transported into the cave from outside (White, 2007 and reference therein).

Clastic sedimentary fills are usually studied because they may give information concerning the evolution of the surrounding territory: for example changes in the deposition in a cave are very sensitive to landscape erosion or flood-related events, which are often directly connected with the climate evolution of the area (Bosch and White, 2004; Springer, 2005; White, 2007; Auler et al., 2009). Furthermore, this kind of study has important implications also in archaeology and palaeontology, whose finds are usually inside cave-fills (Brandy and Scott, 1997; Ghinassi et al., 2009).

Some authors hypothesize that clastic sediments in caves may be a source of information about speleogenesis (Springer, 2005), but in spite of the increasing number of papers dealing with these deposits, only few of these have focused on their implications in speleogenetic processes and, in particular, on the creation of the underground space. Only recently some authors (Vergari and Quinif, 1997; Tognini, 1999; Häuselmann and Tognini, 2005; Quinif et al., 2006; Audra et al., 2007; Quinif, 2010) have described a new speleogenetic process ("phantomisation", or rock-ghost weathering), in which the study of cave clastic sediments provides important information concerning the evolution of karst systems in impure limestone and dolostone rocks. Similar processes have been already described, with different terms, for caves developed in quartz-rich rocks (Piccini and Mecchia, 2009 and reference therein). According to this hypothesis, the bedrock was firstly affected by an incomplete dissolution during a long-term stability of the base level (autochthonous phase *sensu* Quinif, 2010). This condition allowed the insoluble materials to remain in place,

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preserving the structure of the parent rock (phantoms or rock-ghosts). Generally the dissolution is strongly influenced by rock discontinuities (fractures, joints and faults) and that is the reason why the rock-ghosts are spatially delimited inside the rock massif (Häuselmann and Tognini, 2005; Quinif, 2010). The partial dissolution causes a dramatic increase in rock porosity and consequently in hydraulic conductivity. Residual and unconsolidated materials can be eroded and removed by seepage waters (piping processes), forming small cavities or conduits. These conditions can facilitate the development of an underground drainage network, with a greater capacity to remove the weathered part of the bedrock (fluviatile phase *sensu* Quinif, 2010). This kind of karst evolution can continue until the unconsolidated material is completely removed; at this point it would not be possible to recognize the evidence of the ancient ghost-rocks and the evolution of the caves could just have occurred through classical karst processes (Audra et al., 2007).

This paper deals with the study of the sedimentary fill of the Mugnano Cave (Tuscany, Italy) which shows unique and interesting features. A sedimentological analysis was performed and used in conjunction with an allostratigraphic interpretation of the entire succession, in order to understand the relationships between the sediments and speleogenesis.

2. Geological setting

The Montagnola Senese is composed of a series of N–S aligned hills west of Siena (Tuscany, Italy) and is located in the inner Northern Apennines; a fold-thrust chain formed during the Tertiary in response to the interaction between the Adria and Corso-Sardinian microplates (Carmignani et al., 2001 and references therein).

The present structural setting of this sector of the Apennines is the result of two major deformation episodes: the first one, characterized by a compressive tectonic regime, was associated with the convergence between the European margin and the Adria micro-plate which occurred between the Cretaceous–Late Oligocene and Early Miocene (Carmignani et al., 1995). A second deformation episode was related to the regional extension that concerned inner Northern Apennines since the Early–Middle Miocene (Carmignani and Kligfield, 1990; Jolivet et al., 1991; Elter and Sandrelli, 1994). This stage was realized through two main extensional events: the older one (Early–Middle Miocene) was characterized by the action of low-angle normal faults and caused a stretching of 120% or more (Carmignani and Kligfield, 1990; Brogi, 2003, 2004) and the exhumation of the originally deeply buried rocks (now outcropping, for example, along the Middle Tuscan Ridge that structurally includes the Montagnola Senese area). The younger extensional event (Early Pliocene–Quaternary) was dominated by the development of high-angle normal and transtensional faults (Brogi, 2003) that caused a lower stretching (about 10%) and gave rise to the present "Horst and Graben" structure of inner Northern Apennines (Carmignani et al., 2001).

The Middle Tuscan Ridge is mostly made of Late Paleozoic to Mesozoic formations (Monticiano–Roccastrada Unit) that include clastic (Verrucano group) and carbonate lithologies (e.g. "Montagnola Senese Marbles Formation") (Giannini and Lazzarotto, 1970), affected by a green-schist facies metamorphism. The Monticiano–Roccastrada Unit was locally overlapped by the non-metamorphic Tuscan and Ligurian Nappes (Giannini and Lazzarotto, 1970).

The Tuscan Nappe in the studied area is represented only by the "Calcare Cavernoso" formation that widely crops out on the northern sector of Montagnola Senese.

2.1. The "Calcare Cavernoso" formation

The name "Calcare Cavernoso" means vuggy limestone, but the formation mainly consists of clast- to matrix-supported dolomitic limestone with a characteristic vacuolated texture (Passeri, 1979; Gandin et al., 2000; Lugli, 2001; Lugli et al., 2002). This formation crops out diffusely in southern Tuscany where it is present at the same stratigraphic level as the Triassic evaporites of the Burano Anhydrite Fm. that represents the base of the non-metamorphic Tuscan Nappe.

During the last century many geoscientists focused their attention on the Calcare Cavernoso in order to understand its origin, which for a long time has been related to the transformation of the original Burano Anhydrite Fm. as a consequence of syn- and post-orogenetic events. These events include the break-up of the brittle dolomitic layer, anhydrite fluidification and hydration–dissolution cycles of the sulphates after exhumation (Signorini, 1946; Merla, 1952; Trevisan, 1955; Giannini and Lazzarotto, 1967). The importance of hydration and dissolution processes on the development of the Calcare Cavernoso was understood a long time ago, since it was observed that the original evaporitic–dolomitic lithotypes are preserved only where an impermeable cover has prevented sulphate dissolution (Signorini, 1946; Signorini and Pieruccini, 1968). This impermeable cover was made of shale of the Ligurian Nappe. Despite this observation for a long time the origin of Calcare Cavernoso was predominantly related to tectonic brecciation.

Recently Gandin et al. (2000) demonstrated that the Calcare Cavernoso is a completely new rock that was formed as a consequence of the dissolution of sulphates and destabilization of the original brecciated dolostone. The same authors suggest that it is incorrect to consider this rock as a breccia because it maintains traces of its past brecciated features locally.

A particular lithofacies of the Calcare Cavernoso Formation is the so-called "Cenerone" (Passeri, 1975): it is made up dark grey, powdery or sandy dolomite that forms masses or lenses characterized by a poor degree of cohesion (Gandin et al., 2000; Lugli, 2001). The origin of this incoherent lithofacies is attributable to weathering processes that affected the remnants of the original dolomitic clasts (Gandin et al., 2000; Lugli, 2001). Weathering acted in recent times (post-Miocene according to Lugli, 2001) and was favoured by the intense tectonic fracturating of dolomitic layers, which facilitated the percolation of waters. The mechanical features of this lithofacies are similar to the weathering-derived residual sediments, observable in other karst areas (Burger, 1989; Vergari and Quinif, 1997; Tognini, 1999; Quinif et al., 2006; Quinif, 2010).

Very similar to the Calcare Cavernoso is the "Breccia di Grotti", a formation introduced by Signorini (1966) and then described by Giannini and Lazzarotto (1967, 1970), that was made up of continental breccias and sandstones with a dominance of Calcare Cavernoso elements. The deposition of "Breccia di Grotti" occurred during the Neogene in palaeo-morphological depressions in an alluvial fan setting. It is often very difficult to distinguish the two formations, but it is important to note that in the "Breccia di Grotti" lithofacies similar to "Cenerone" are lacking.

3. Cave location and description

The Mugnano Cave (T/SI 258 in the Tuscan register of caves) is located in the Siena district (Fig. 1a,b,c), and has its opening at an altitude of 306 m in the Fungaia area (Montagnola Senese). The region is hilly, the highest altitude is represented by Monte Maggio (671 m a.s.l.), and is bounded to the north and south by two plains, respectively "Pian del Lago" and "Pian del Casone" (both about 280 m a.s.l.). In detail, "Pian del Lago" appears as a large and closed depression delimited by karst terrain (Calcare Cavernoso and Breccia di Grotti Fms.), that has generally been interpreted as a polje (Pascucci and Bianciardi, 2001; Pascucci, 2004). The sedimentary infill of this polje is generically attributed to the Quaternary (Costantini et al., 2009), but an older age for the formation of this depression cannot be excluded. A different origin is conceivable for "Pian del Casone" that, according to Capezzoli et al. (2009) and Capezzuoli and Sandrelli (2004), is interpretable as a portion of a palustrine–lacustrine tectonic basin, developed in response to the regional Middle Pleistocene uplift of the Northern Apennines (Bartolini,