Past surface conditions and speleogenesis as inferred from cave sediments in the Great Cave of Salitrari Mountain (SW Romania)

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ABSTRACT. In one of the passages in the Great Cave of Şălitrari Mountain the floor is completely covered by an alluvial deposit at least 6 m in thickness, ranging from boulders, and cobbles, to sand and clay, topped by a layer of dry bat guano. Sediment and mineral samples collected from six profiles underwent broad analyses to determine their petrological and mineralogical makeup, grain-size distribution, and paleoclimatic significance. The complicated facies alternation suggests frequent changes in the former stream's hydrological parameters, with frequent flooding, leading to the hypothesis that the climate was somewhat wetter than today. Both the mineralogical composition of the sediment (ranging from quartz, mica, gypsum, phosphates, and calcite to garnet, zircon, titanite, olivine, serpentine, tourmaline, sphalerite, pyrite/chalcocopyrite, and feldspars) and the petrological composition of the larger clasts (limestone, sandstone, mudstone, granitoids, serpentinite, amphibolite, diorite, gneiss, quartzite, microconglomerate, and schist) ascribe the potential source rocks to an area with contrasting lithologies, such as amphibolites, felsic and basic metaigneous, and metasedimentary rocks, mixed with a variety of detritic rocks. These rock types are not entirely comprised by the catchment area of the modern Presacina Brook, thus implying that due either to hydrological conditions, or to changes in the base level caused by river down cutting or active tectonics, the former source area was much more extensive. Based on morphological and sedimentological criteria, the cave started under pipe-full flow conditions, and further evolved during a prolonged and complex vadose phase. Evidence to support the existence of hypogene conditions is also present. Once the underground stream left the cave and most of the sediment was removed, speleothem precipitation was initiated. In this contribution we put forward evidence that argue for an extra-basinal origin of some of the alluvial sediments, an uncommon fact documented in few cave environments so far.

Key words: Alluvial sediment, speleogenesis, catchment area, Great Cave of Şălitrari Mt., Cerna Basin, Romania.

INTRODUCTION

The importance of cave sediment studies has been increasingly acknowledged over the last few decades, especially with the augmented reliability and availability of a handful of methods that make dating them possible. Their merit resides in their applicability to a variety of connected research fields: anthropology and archaeology (e.g., Berger et al., 2008), paleoclimatology (e.g., Audra et al., 2007; Polk et al., 2007), paleoenvironment and paleotopography reconstructions, mineralogy (e.g., Polyak and Guven, 2000; Onac et al., 2007), sedimentology and speleogenesis (e.g., Horoi, 1993; Roată, 1993; Häuselmann et al., 2010), as well as several others (e.g., Sasowsky, 2007).

For almost a century the Cerna Valley represented the locus of interest for numerous investigations, initially triggered by the abundant thermal springs and related geological challenges (Povară et al., 1972, 2008; Veliciu et al., 1983; Cosma et al., 1996; etc). This study continues a series of research papers (Onac et al., 2009a, b; Puşcaş et al., 2010; Wynn et al., 2010) documenting various aspects of caves from SW Romania, namely the Cerna River Valley. Our aim is to bring into light

new data concerning the caves developed in the massive Upper Jurassic limestone deposits that flank the Cerna River a few kilometers upstream of the historical spa of Băile Herculane. The purpose of our work is to better constrain the evolution of cave passageways, along with the mode of sediment deposition (directly connected to the direction of the paleoflow and the source area) by combining sediment analysis with observations of passage and cave morphology in the Peştera Mare din Muntele Şălitrari (Great Cave of Şălitrari Mountain, hereafter GCSM). Sub horizontal passages (common to all caves in the proximity) are symptomatic of caves formed near the base level, meander shortcuts making up suitable traps for alluvial sediments (Quinif, 2006). Alternating lithologies are clues for variations in the hydrological regime, which is directly related to changes in surface climate and topography (Häuselmann et al., 2008).

Our results constitute a starting point for future studies aimed at dating the cave alluvium and deciphering the paleoenvironmental context of their deposition. For a detailed discussion regarding the mineralogical assemblage and peculiarities of GCSM, the reader is referred to Diaconu and Lascu (1998), Onac et al. (2009a), Puşcaş et al. (2010).

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LOCATION AND GEOLOGICAL SETTING

The Cerna Mountains are a geographic unit pertaining to the South Carpathians of Romania and are characterized by a series of ridges frequently up to 1500 m in altitude, deeply cut by valleys, resulting in a steep relief especially where limestone outcrops. Oriented NE-SW, the Cerna Valley follows a major dextral strike-slip fault (Berza and Drăgănescu, 1988; Kräutner and Krstić, 2002) through its entire 85 km length, locally with canyon walls carved in granite, schist, and limestone climbing up to 500 m almost vertically (Alexandru et al., 1981). Several smaller strike-slip (both dextral and sinistral) faults striking approximately WNW-ESE, cut the lithologies along the Cerna Valley, while granitic intrusions mapped along the valley are characterized by roughly vertical foliations (Fig. 1, inset B). A subdivision of the Cerna Mountains, Mount Șălitrari flanks the Presacina Brook on the right at its confluence with Cerna, ca. 15 km upstream of Băile Herculane (Fig. 1, inset A; Fig. 2). Along the Presacina Brook, the intrusion of a small granitoid pluton (and its apophyses) disrupted the original strikes and dips of the beds. However, in the cave area the limestone beds still preserve a roughly N-S strike, while dipping ca. 15° to the E.

The major components of the geological puzzle in the research area are the sedimentary formations belonging to the Alpine Danubian nappe system and the metaigneous formations of the Alpine Getic-Supragetic nappe system. The Neoproterozoic Neamțu metamorphic series, outcropping in the SW part of the valley (west of the Băile Herculane Spa) consists of biotite-bearing migmatitic

gneiss, amphibolites, and quartz-bearing micaschists, retromorphosed to green schist facies. Outcropping in the riverbed of both Presacina and Cerna at their confluence and cross cutting the eastern side of Neamțu Series, the Cerna Granite is comprised of quartz, plagioclase, orthoclase, and various amounts of biotite; its predominant color is gray, but at this particular juncture it is bright red (due to its high orthoclase content). Discordant Jurassic detritic deposits in the area of interest belong to the Presacina facies (conglomerates and sandstone at the base, followed by clays and younger sandstone, topped by limestone) pertaining to the Presacina Sedimentary Zone (Năstăseanu, 1980). A geological cross-section through the Presacina Brook reveals the Bogîltin (Pliensbachian-Toarcian; comprised of fine to coarse sandstones with alternating levels of conglomerates, microconglomerates and dark clays), Ohaba (same age as Bogîltin; almost exclusively black clayey schists with sandstone lenses), Ciumîrna (Aalenian; represented by fine-grained to coarse, hard, massive, quartzitic sandstone), and Iuta Beds (Barremian-Aptian; correspond to limestone grading into black schistous mica-bearing marly limestones, capped by conglomerate), followed by the Wildflisch Facies (Upper Cretaceous) and Arjana Beds (conglomerates, coarse sandstone, calcareous sandstone, clayey sandstone, often with schistous structure) (Năstăseanu, 1980). In the modern catchment area of Presacina Brook none of these sedimentary successions incorporate mafic and ultramafic lithologies such as amphibolites and serpentinites.

Fig. 1. Plan and profile view of the cave, showing the location of the studied sections (red stars). Inset A: Location of Băile Herculane; Inset B: Simplified geologic map and location of GCSM (black star) (modified from Năstăseanu and Bercia, 1968); 1, 2: Upper Anteproterozoic (Sebeș-Lotru Series, Amphibolite Facies); 3: Permian (conglomerates, red clays, sandstones, schists); 4: Paleozoic (granitoids); 5: Mesozoic (ultrabasic rocks); 6: Permian (volcanic-sedimentary formations); 7: Lower Jurassic (conglomerates, clayey schists, sandstones); 8: Upper Jurassic-Aptian (Azuga, Sinaia, and Comarnic strata); 9: Turonian-Senonian (sandstones, conglomerates); 10: Albain-Cenomanian (sandstones, limestones, clays); 11: Tithonian-Aptian (limestones, sandstones, conglomerates, dolerites); 12: Upper Cretaceous (sandstones, conglomerates); the dashed blue frame approximately shows the area presented in Fig. 2.

Fig. 2. Topographic map showing the catchment area of the Presacina Brook and the location of the GCSM. Contour interval 30 m. Topographic map from Jarvis et al., 2008. Hydrology modified from data available at Domogled-Valea Cernei National Park (www.domogled-cerna.ro).

METHODS

Sediment and mineral samples were collected from four out of the six investigated profiles; thorough lithologic columns were drawn at the time of sampling. Profiles were labeled S (Șălitari) followed by consecutive numbers, starting from the mid-section of the NP and continuing toward the cave entrance. Samples were labeled PM followed by a number, in a continuous manner. All sediment levels in Profile S1 and S2 were sampled, while in the other 4 profiles samples were taken only from levels that did not correspond to what we encountered in the previous sequences.

Samples were oven dried at 55°C and color coded using a Munsell Soil Color Chart, weighed and sieved for an average of 5 minutes using standard brass sieves and a W.S. Tyler Rotap RX-29 shaker. The sediment on each sieve was weighed to an accuracy of ± 1 g. Separates from the sand sized fraction (ϕ 2) were washed in DI water to remove clay, and a Franz Magnetic Barrier Laboratory Separator LB-1 was employed to separate zircon and titanite crystals. Following this treatment, mineral grains were identified and quantified by means of stereoscopic microscopy. The ϕ -4 and larger fraction was cut into halves to allow for a better petrological identification of the clasts, in order to ease the identification of the sediment source area. Lithologic columns were created using the software package POLITO 0.3.1 (Stremțan and Tudor, 2010).

Ten samples from the finest material ($\phi > 4$) underwent powder X-ray diffraction (XRD) in the X-ray Powder Diffraction and Thermoanalytical Laboratory (University of Miskolc), to further identify sediment mineralogy. Diffraction spectra were obtained on a Bruker D8 Advance diffractometer under the following operating conditions: CuK α radiation (1.54056; secondary graphite monochromator, Bragg-Brentano geometry, step-scanning mode, 2°-65° (2 θ) range, 0.04° (2 θ) step size, and 2 sec/step detecting time (0.6 mm

anti-scatter and receiving slit, 0.2 mm detector slit). Identification of components was carried out by Search/Match procedure of Bruker Diffraction EVA evaluation module, based on PDF2 (2005) database.

Measurements of cave wall scallops, passage cross-section, and temperature were input into SCALLOPEX 1.0.1, software intended to facilitate the extrapolation of cave stream paleoveLOCITIES (Woodward and Sasowsky, 2009). These features are a proxy for flow velocity, which can be inferred from their length, as well as for flow direction, indicated by the positioning of their steep side. Water viscosity and density, dependant on temperature, as well as passage cross section are the main parameters affecting flow velocity, and thus the resulting scallops.

RESULTS

The succession of the studied profiles heads towards the entrance and their positioning in the cross-section of the cave passage varies. Even though placed within some few meters from each other (Fig. 1), the sites display variations in sedimentary facies. While the overall lithological composition is fairly monotonous, the alternation of sediment sequences is indeed complex (Fig. 3). None of the profiles contain drip- or flowstone (although a stalagmitic crust frequently covers the sediment deposit), but fragments of mammal bones were occasionally found. Plant material was also absent from the alluvial deposit.

Stratigraphic sections are described here from their top to the bottom. Although removed in places, the top layers of the sediment fill from GCSM (outcrops S1 and S2) is very similar to that presented by Foos et al. (2000) in Lechuguilla Cave, New Mexico. Both are topped by dusty gray material, underlain by massive to slightly laminated, dense, brownish-reddish clay, with white deposits filling in a series of crisscrossed fractures within the clay, followed by variably laminated, brown, hard clay. This similarity is supported by the findings of Onac et al. (2009a) and Pușcaș et al. (2010) which, based on stable sulfur isotopes, mineralogy, and passage morphology, argue for the existence of a hypogene stage during this cave's genesis.

Profile S1 is the least complex, displaying clear limits from one facies to the next, with continuous horizontal beds. Profile S2 is the thickest (ca. 4.65 m) and in its upper third mimics section S1, although transitions are somewhat less explicit and numerous sand lenses are visible. An interesting feature is the 50 cm thick conglomerate level with heavily weathered, brittle clasts (sandstone, limestone, mudstone, gneiss) and white, altered carbonate cement. Poorly sorted levels of variously colored sand and gravel prevail in the bottom two thirds of S2. Ten meters down-stream, outcrop S3 is a thick pile of sediment (2.5-3 m) with visible horizontal layering and distinct granulometry (sand and gravel predominate), leaning against the cave wall in the inner curve of a bend. On the opposite wall, S4 is sheltered from erosion in an alcove, and displays sediment levels common to sections S1 through S3. Further downstream S5 comprises alternating levels of sand and gravel admixed with sand. In the bottom third of the alluvial deposit we encountered sediment sequences that were slightly indurated due to the presence of concentrated carbonate solutions, sometimes resulting in poikilitic calcite cement made up of large clear crystals (up to 1 cm). Similar observations were

reported by Bosak et al. (2000). The last profile, S6, can be linked to the bottom half of S5, and consists of a mixture of gravel, sand, and coarse sand, with no trace of clay.

Only 7 out of the 24 sediment samples held ϕ -4 and larger fraction that allowed for a macroscopic and microscopic petrographic study of the clasts. One or two rock types, with minor additions, dominate each of them. The main participants are dark limestone (subangular to subrounded), light limestone (subangular to rounded), sandstone (angular to rounded), mica-rich mudstone (generally subrounded), and granitoids (subrounded to rounded). Minor constituents were found to be serpentinite (always angular), amphibolite (subrounded), diorite (subrounded to rounded), gneiss (subrounded), quartzite (angular to rounded), microconglomerate (rounded), and schist (subrounded to rounded). Several of the above-mentioned clasts carry pyrite, sphalerite, and chalcopyrite grains, while muscovite, biotite, and quartz are also frequent constituents. Most of these pebbles are flattened and/or elongated and some are weathered and brittle.

The mineralogy of the sediment samples allows for some constraints to be put on their probable source area. The complete mineralogical composition of the fine-grained sediments collected from GCSM is presented in the Supplementary Online File 1. All of the twenty analyzed samples showed different concentrations of garnet (light to dark brown and dark pink, probably spessartine and almandine), zircon (transparent to light yellowish, with some very well preserved elongated prisms, characteristic for magmatic zircons (Pupin, 1980), titanite (transparent to light yellowish-brown flat prism fragments), olivine (dark green and brown fragments), tourmaline (dark brown and green), sphalerite (dark golden-brown), pyrite/chalcopyrite (dark golden splinters), and pyrite (golden, with some well preserved cubes).

Powder XRD results come from samples taken from three of the sediment profiles (S1 through S3). Quartz and muscovite are omnipresent, and samples from the top layers of S1 and S2 are rich in phosphates (hydroxylapatite, taranakite, leucophosphite, and tinsleyite). Feldspars are also common in most samples (sanidine, microcline, albite, and anorthite) giving important clues about the source rock for these sediments. Diffractions were not targeted to identify clay minerals, thus our findings are restricted to kaolinite and vermiculite. Gypsum is a regular occurrence in fine-grained sand and clay lenses. A remarkable presence is that of nordstrandite, a common weathering product in bauxitic soils derived from limestone (Anthony et al., 1997), but an unusual cave mineral (Polyak and Provencio, 2001; Merino et al., 2009).

The fact that a local fault guided the dissolution of the Main Passage is visible in several locations, and could be a clue as to why the cave passages are linear. The only place along the Main Passage where scallops could be clearly observed is at the entrance of the cave, on a passage length of approximately 8 m, where the ceiling is less than 8 m high. Successive generations of scallops can be observed on the ceiling and upper half of both walls, the more recent being superimposed on the older ones, and considerably smaller (<1 cm), all indicating that the paleoflow direction was towards the valley of the modern Presacina Brook. Based on 20 measurements of the older generation of large scallops, we calculated the paleovelocity of the subterranean stream to have been 0.32 m/s. The fact that current

markings are present in such an odd location, where they are usually destroyed by frost shattering, is rather difficult to explain. One possibility is that this is the only sector in the cave where they were formed, due to hydrological peculiarities. Other plausible explanations are that they do exist elsewhere in GCSM but are too high up on the walls to be observed, or that they were erased by erosion, as signs of heavy mechanical weathering are visible throughout the cave. Also, the limestone at the cave entrance seems to belong to a different sedimentary facies than that in the rest of the cave, although we did not carry out thorough facies analysis.

DISCUSSIONS AND CONCLUSIONS

Sediments in GCSM are directly connected to conditions in the catchment area (petrography, vegetation cover, rainfall, uplift and stream down-cutting) and are of both allochthonous and autochthonous origin. The identified processes at work range from massive collapse to fines transported as suspended load. Along the entire length of the Main Passage it is clear that at least during one stage the void was almost completely filled with sediment (patches of detritus on the walls, meandering ceiling channels, and pendants). Unfortunately, there is no hard evidence to allow an estimation of the amount of sediment removed through stream erosion as compared to that extracted for manufacturing gunpowder in historic times.

The cross-section of the passages suggests that pipe-full flow was a major genetic stage, while the shallow canyon upstream of the NP (Fig. 1) implies a lowering of the base level after the sediment was removed. A fairly simple cave pattern, with limited branching, no meandering or significant side passages, and the steeply inclined floor of the Final Passage might advocate an organized recharge (ponor-fed type cave) (the profile of the Speotimiş Passage is rather flat). The fact that the general passage trend is almost perpendicular to the flow of the present surface stream (Presacina Brook; Fig. 2), together with the presence of current markings (indicating that the cave was discharging water into the brook), and the tilting of the cave passages toward Presacina (profile view in Fig. 1) suggest that GCSM was carved by one of the springs feeding this brook, and further on, both brook and cave must have been at approximately the same elevation at the time. Auler et al. (2009) found that the lack of dripstones, while flowstone is virtually omnipresent, may be explained through repeated cycles of sediment deposition and removal. We believe that our similar findings in the NP may be due to analogous conditions, as well as to the present dryness of this passage.

The cobbles made of sedimentary rocks (various types of limestone, sandstone, mudstone, conglomerate and microconglomerate) are most probably sourced from the Presacina Sedimentary Zone. The mineralogical composition of the fine-grained sediments is consistent with felsic (granitoids, ortho- and paragneiss) as well as mafic (amphibolites and mafic metaigneous rocks) source rocks. The presence of serpentine in sample PM 83 and olivine in samples PM 83 and PM 72 is a strong evidence that the source area contained mafic lithologies, such as the Sebeş-Lotru amphibolites that outcrop NE from our study site. The felsic lithologies that supplied the sediments were most probably ascribed to Lainici-Păiuş type metasediments

Fig. 3. Tentative stratigraphic correlation of the detailed lithologic columns for the six profiles described from the Nitrate Passage. Profile locations as shown in Fig. 1.

(Liégeois et al., 1996; Iancu et al., 2005). Thus, we conclude that the original catchment area was probably larger than the modern one, although we are unable to set more precise confines. An essential conditioning factor in the evolution of the Cerna River (and its tributaries) is the continuous activity of Cerna fault. Reactivated during Alpine orogeny (middle Cretaceous), the dextral strike-slip fault has been active (with subsequent lull periods) since and based on field and map studies, a minimum separation of 30 km is assumed. The tectonic activity of a fault has an important impact on the evolution of sedimentary basins situated along its strike and can dramatically change the sedimentation rate, as well as the area that supplies sediments. It worth mentioning that a separation of 30 km assumed for Cerna fault would have greatly impacted Presacina Brook as well, thus modifying its catchment area and imprinting great heterogeneities in the sediment sources.

Although calculated based on present temperatures rather than paleotemperatures and taking into account only the older generation of current markings, plotting paleoflow velocities calculated using ScallopEx 1.0.1 on a Hjulström diagram (Fig. 4) shows that at the point of exit from the cave the current was still strong enough to erode and transport fine grained material, but it would have already deposited coarse alluvium.

Fig. 4. Hjulström diagram with dashed line showing the flow velocity calculated in ScallopEx.

The mineralogical and petrologic study of the sediment deposit indicates that mostly allogenic waters carved the cave. As pointed out by Palmer (2001), in the case of allogenic streams most of the cave growth takes place during flood events, which are usually restricted to certain periods in the hydrologic cycle. During peak levels debris carried by the floodwaters can dam the underground stream, resulting in slack water. Normal flow and flood conditions, as well as slack waters, can be deduced in GCSM from the sediment pile deposited in the NP. Alternating levels of gravel, sandy gravel, fine to coarse sand, and clay imply frequent variations in flow energy (repeated cycles of normal flow interrupted by flooding, damming, and ponding) inherent to ponor-related caves, which are quick to respond to even relatively small discharge fluctuations. Most pebbles are sub-rounded to well rounded, elongated and/or flattened, and habitually positioned on their flat side, parallel to the paleocurrent, indicating regular high-energy flow conditions. However, some sediment levels show no clast orientation, clearly depicting flood conditions.

On the basis of morphological clues, sedimentary facies and mineralogical and petrographical makeup of the alluvium we argue that the major speleogenetic phases involved were as follows: 1. epiphreatic regime (suggested by the quasi tubular cross-section of the passages); 2. vadose flow with repeated depositing and removal of significant volumes of sediment (implied by the ceiling pockets, ceiling channels and residual patches of fine sediment on the walls); 3. removal of the sediment from the entire cave, with the exception of the NP (our initial working hypothesis -the rerouting of the cave stream toward underlying cave passages, following the base level lowering- although supported by the presence of breakdown that could mask the existence of passages capable of removing important volumes of sediment and the occurrence of cave entrances a few tens of meters below the openings of GCSM, was contradicted by the meager size of the aforementioned caves, and the complete absence of sediment therein. We believe that the preservation of the alluvium in the NP, could be due to a particularity of the bedrock morphology -a concave segment- in this sector of GCSM); 4. deepening of the local base level followed by massive collapse; 5. dripstone growth in the final sector of the Main Passage, and flowstone throughout the cave.

The main processes at work in GCSM (sediment input, sediment erosion and speleothem precipitation) hold paleoenvironmental value; the large mass of alluvium deposited here suggesting a prolonged period of wet climate, punctuated by frequent flooding. Dating this sediment would enable us to establish whether the floods were more common than in today's climate, as well as the time interval during which the sediment was deposited. The presence of nordstrandite, which occurs mostly in regions that benefit from a warm and moist type of weather (Hathaway and Schlanger, 1965; Dani et al., 2001), identified in a sandy gravel stratum could point to such climate conditions. Nordstrandite was also reported to precipitate within caves under hypogene conditions (Onac et al., 2009c; Spilde et al., 2009). As of now we are unable to discriminate between a primary or secondary origin for this unusual mineral.

The subterranean stream left this cave (making room for drip- and flowstones) either because of tectonics (valley down-cutting as a result of uplift), a change in climatic conditions leading to a somewhat cooler and dryer stage, or a combination of both. The absence of wood debris in the sediment profiles is probably due to their incompatibility on a long term with the cave environment. Although not yet completed, our study opens the door for future research in the area, including multiple dating possibilities (pollen, quartz pebbles, flowstone, dripstone, sediment) and assessments of valley down-cutting rates in the region.

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