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Evolution of the Veternica Cave (Medvednica Mountain, Croatia) Drainage System: Insights from the Distribution and Dating of Cave Deposits

Damir Lacković
Croatian Natural History Museum

Bosiljka Glumac
Smith College, bglumac@smith.edu

Yemane Asmerom
University of New Mexico

Andrej Stroj
Croatian Geological Survey

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Evolution of the Veternica Cave (Medvednica Mountain, Croatia) drainage system: insights from the distribution and dating of cave deposits

Damir Lacković[1], Bosiljka Glumac[2], Yemane Asmerom[3] & Andrej Stroj[4]

[1]Croatian Natural History Museum, Zagreb, Croatia; (damir.lackovic@hpm.hr)

[2]Department of Geosciences, Smith College, Northampton, Massachusetts 01063, USA; (bglumac@smith.edu)

[3]Deptartment of Earth & Planetary Sciences, University of New Mexico, Albuquerque, New Mexico, USA; (asmerom@unm.edu)

[4]Croatian Geological Survey, Zagreb, Croatia; (andrej.stroj@hgi-cgs.hr)

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ABSTRACT

Detailed field examination, U-Th age dating, and stable isotope analysis of Veternica flowstone and shelfstone deposits have been employed in order to unravel details about the geological history of Veternica Cave (Medvednica Mountain, Croatia). The study was carried out in the hydrologically inactive part of the main cave channel, which is developed mainly along the unconformity between Triassic dolostone and Miocene limestone. For 180 m from the cave entrance, (located at 320 metres above sea level (asl)), the morphology of the main channel reflects exclusively phreatic conditions in the cave until the end of its hydrological activity. From 180 to 390 m, the phreatic channel has a secondary vadose entrenchment in the bottom part as marked by massive flowstones at elevations from 306 to 313.5 m asl. From 390 m farther inside the cave (in the upstream direction), the main channel has a tall, narrow cross-section and is of mainly vadose origin. In this part of the cave shelfstone precipitates are observed at 9 different levels ranging from 318.8 to 320.2 m asl, indicating the water palaeolevels in the cave. U-Th dating revealed the age of the highest shelfstone (320.2 m asl) of ~380 kyrs BP, and the age of the lowermost analyzed shelfstone (318.9 m asl) of ~245 kyrs BP. Dating of flowstone deposits, located below the shelfstone level, revealed their formation from ~235 to 205 kyrs BP. A relatively rapid water table lowering and transition from phreatic to vadose conditions occurred within the cave, from ~245 to 235 ka BP, between formation of the youngest shelfstone (representing phreatic conditions below their level) and the oldest flowstone (marking the beginning of vadose conditions). The results provide unique new information about Veternica Cave genesis and geomorphologic evolution of the Medvednica Mountain area.

Keywords: speleogenesis, shelfstone, flowstone, U-Th dating, water table lowering, Veternica Cave, Croatia

1. INTRODUCTION

Veternica Cave is located in the southwestern part of the Medvednica Mountain in the vicinity of Zagreb, the capital of Croatia (Fig. 1). The cave is located in a small isolated karst area, separated from the main Dinaric karst region. The cave has been declared a Geomorphologic Natural Monument and is protected within the Medvednica Nature Park. Veternica was discovered in the 19th century (GORJANOVIĆ-KRAMBERGER, 1899), and is named after a local term for wind (veter or vjetar; i.e. the wind cave), because of the constant air circulation through the cave channels that can be felt near the cave entrance. The first detailed speleological and geological investigations of the Veternica Cave were

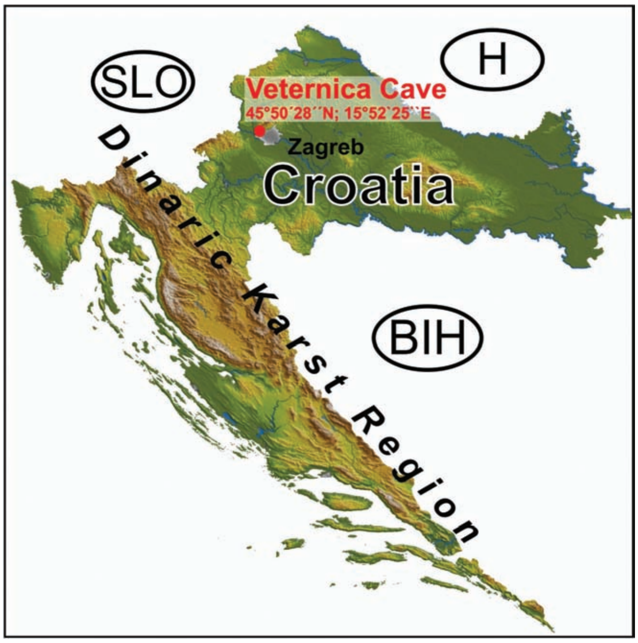

Figure 1: Location of Veternica Cave in the southwestern part of Medvednica Mountain.

performed by POLJAK (1934), and later on by MALEZ (1965), ČEPELAK (1977), PANUŠKA & MARJANAC (1977), SUTLOVIĆ (1991), MARJANAC et al. (2005), and MARJANAC (2007), among others. MALEZ (1965) (a palaeontologist), conducted systematic research on the cave entrance sediments, during which the natural entrance was widened from 0.45 x 0.29 m (HIRC, 1903) to about 4 x 3 m. This research revealed a rich Late Pleistocene fauna and Neanderthal artifacts (MALEZ, 1965). More recent research by MIRACLE & BRAJKOVIĆ (2010) provided a revision of Pleistocene faunal characteristics from the Veternica entrance sediments and their palaeoclimatic implications.

MALEZ (1965) gave a detailed description of clastic deposits at the cave entrance. Analysis of associated fossils suggested the Late Pleistocene age of the deposits, ranging from the end of the Riss glacial to the Holocene. Deposits from the deeper parts of the cave were not described in detail, but MALEZ (1965) documented the channel morphology and made a map and cross-section of the channels up to about 2000 m from the cave entrance. MALEZ (1965) also produced a general interpretation of the cave formation through multiple phases of its geological history. He concluded that during the oldest phase there was an active spring at the present-day cave entrance, and he described a gradual retreat of the water towards the cave interior to its current sink.

Nowadays, there is a great public interest in Veternica. It is the 6th longest cave in Croatia with a total cave channel length of 7128 m (CROATIAN SPELEOLOGICAL SERVER, 2011), and is easily accessible from Zagreb, the largest city in Croatia. The first 380 m of the cave are open for tourists and many speleological schools are held in the cave. The current study aimed at gaining detailed information about the history of the cave that could then be incorporated into tourist guides and shared with visitors, such as the nature and timing of palaeoenvironmental changes associated with a water level lowering in the karst drainage system of the cave. This information was primarily gathered through an in-depth field investigation and a detailed study of the cave flowstone and shelfstone deposits.

Field investigation focused on the morphology of the Veternica Cave conduits and associated alluvial sediments in order to determine hydrological conditions in the cave during its hydrological activity (e.g., BÖGLI, 1980; FORD & WILLIAMS, 1989; PALMER, 2007). Phreatic conduits usually have elliptical to round cross-sections, and as they are formed by pressure flow, their inclination direction is not constrained by flow direction. Vadose channels, on the other hand, are typically vertical shafts or meandering canyons formed by gravity flows, and consequently their inclination direction is uniform and governed by flow direction. Multiple phase channels commonly have phreatic upper parts with vadose trenching in their lower parts (i.e., a typical "keyhole" profile).

This study also focused on the Veternica Cave flowstones and shelfstones because they can provide important information for the detailed reconstruction of cave formation and its palaeoenvironments. The cave flowstones precipitate from thin films of water flowing over subaerially exposed surfaces, and shelfstones, also known as water-table speleothems, are calcite deposits precipitated at the water surface as ledges attached to the cave walls (HILL & FORTI, 1997). These precipitates can be very good indicators of former water levels in caves, as shown by FORD et al. (1993), SZABO et al. (1994), and AULER & SMART (2001). Veternica shelfstones from the "Majmunski prolaz" channel, at about 450 m from the entrance, and the "Kameni slap" flowstones in the "Touristic" part of the cave about 250 m from the entrance (sample locations 1–2 and 3–5; Fig. 2B), were first studied by LACKOVIĆ and HORVATINČIĆ in 1999 (unpubl.), who collected 4 shelfstone samples and 1 sample of the "Kameni slap" flowstone for radiocarbon dating at the Ruđer Bošković Institute in Zagreb. Since the resulting ages were greater than the limit of the ^{14}C technique at that time (>35 kyrs) no further analyses were conducted. The current study reflects renewed interest in the geological history of the Veternica Cave made possible through the use of the modern U-Th radiometric dating method.

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Unlike the rest of the Medvednica Mountain region where carbonate rocks are associated with siliciclastic, metamorphic and volcanic rocks, the western part of Medvednica that hosts the Veternica Cave is made up mainly of carbonate rocks. The oldest rocks in the area are Triassic dolostones, dolomitic limestones, and limestones with interbedded chert, shale and pyroclastic deposits, which are overlain by Miocene dolomitic breccias and conglomerates as well as bioclastic limestones (ŠIKIĆ, 1995). The Veternica Cave passages are of varying morphology and are located mainly

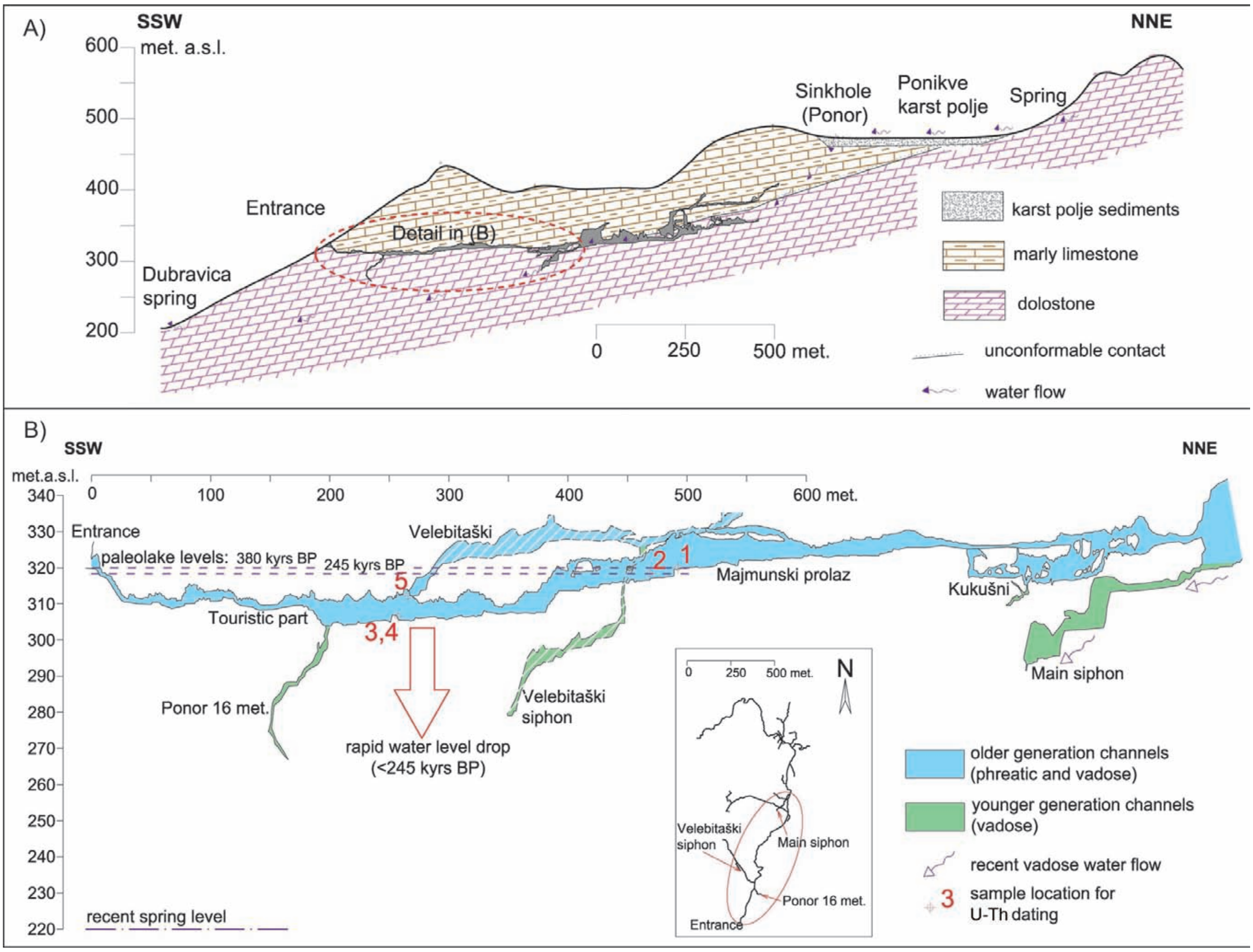

Figure 2: Cross-sections of the main Veternica Cave passages. A) Geological profile illustrating the water drainage pattern from sinkholes along the Ponikve karst polje and through the cave to the Dubravica spring. B) Enlarged area to show detail of the main cave passage and parts of the side channels. Shelfstone (1 & 2) and flowstone (3, 4 & 5) sampling locations are indicated. Reconstructed palaeolake are also shown. Note vertical exaggeration.

along the unconformable contact between Triassic dolostones and Miocene limestones (MALEZ, 1965; ČEPELAK 1977; Fig. 2A). Some of the passages also follow fractures in both of these deposits.

The cave is part of a karst channel system that drains water from sinkholes of the "Ponikve" karst polje and the surrounding karst terrain, through the subsurface to the "Dubravica" spring (MALEZ, 1963; BOŽIČEVIĆ, 1976; ČEPELAK, 1977; Fig. 2A), as confirmed by dye testing (BOŽIČEVIĆ, 1976). There are 9 sinking streams that drain into Veternica. Two of them are located in the Ponikve polje, and the rest are located west of Veternica in the extension direction of the cave lateral channels (Fig. 2B; ČEPELAK, 1977; 1979). There are currently 14 active streams in the cave (ČEPELAK, 1977).

The cave entrance is located 320 m asl, and the cave channels range in elevation from 265 m asl (at the bottom of "Ponor 16 m" channel; Fig. 2B) to 435 m asl, yielding a total elevation difference of 170 m. The cave channels up to approximately 900 m from the cave entrance are hydrologically inactive, but their phreatic and/or vadose morphology is very well preserved owing to an absence of collapse processes and rare speleothem precipitates. From 900 m farther inside the cave, there is an active stream that ends in the "Main siphon" located below the main cave channel (Fig. 2B). Besides this main channel, there are several generally narrower lateral side channels (e.g., "Velebitaški" channel; Fig. 2B). Above the main cave channel with active water flow (approximately at 950 to 1350 m from the cave entrance), dry chambers and passages occur at higher elevation. Steep side channels with vadose morphology are present below the level of the main channel in several places at 180 to 900 m from the cave entrance (e.g., "Ponor 16 m", "Velebitaški siphon" below "Velebitaški" side channel, "Kukušni" channel, channel towards the "Main siphon"; Fig. 2B). The main sinkholes of Ponikve karst polje are at 470 m asl, while the present-day "Main" cave siphon is at 295 m asl, and the cave water surfaces at the Dubravica spring at 220 m asl (Fig. 2A).

3. METHODS

Fieldwork for this study was carried out in 2008 and 2009 in the hydrologically inactive part of the main Veternica Cave channel. The cave shelfstone and flowstone deposits were described and documented in detail and samples for U-Th age dating and stable isotope (oxygen and carbon) analyses were collected. To precisely measure the elevation of various shelfstone and flowstone deposits, a detailed topographic survey from the cave entrance to the "Main siphon" that marks the present-day water level and the contact between the vadose and phreatic zone in the cave was carried out (Fig. 2B). The topographic survey was conducted using a precise compass and clinometer (Suunto types) and calibrated rods. Every measurement of polygonal segments was executed both forward and backward to obtain the maximum survey precision.

The ^{234}U–^{230}Th dating was done at the Radiogenic Isotope Laboratory, the University of New Mexico, USA. Samples were spiked with a mixed ^{229}Th–^{233}U–^{236}U spike. U and Th were separated using conventional anion exchange chromatography. U and Th isotopes were measured using a Thermo Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) which was optimized for U-series analytical work as described by ASMEROM et al. (2006). ^{234}U was measured on a secondary electron multiplier with high abundance filter, while the other isotopes of uranium were measured on Faraday cups with amplifiers that had mixed 10^{10}, 10^{11} and 10^{12} ohm resistors for ^{233}U and ^{236}U, ^{235}U and ^{238}U, respectively. Mass fractionation was monitored using the $^{236}U/^{233}U$ ratio, while SEM/Faraday gain was set using sample standard bracketing. A similar procedure was used for Th isotope measurements. We used an initial $^{230}Th/^{232}Th$ atomic ratio of $4.4x10^{-6}$ assuming a source of Th with a bulk earth $^{232}Th/^{238}U$ ratio of 3.8. The age errors in Table 1 reflect analytical errors and uncertainties in the value of the initial ratio (± 50%). The laboratory U and Th procedural blanks range from 10–40 pg and 5–20 pg, respectively and were not analytically significant. The CRM145 U isotope standard was measured with the samples obtaining the conventionally accepted $\delta^{234}U$ value of –36.5±0.5‰ (CHENG et al., 2000).

Samples for stable isotope analysis represent a small amount of carbonate powder collected from flowstone and shelfstone specimens using a microdrill mounted on a binocular microscope. The flowstone samples were mainly drilled along stratigraphic horizons that represent a series of thin laminae made up of finely to medium crystalline calcite. The shelfstone samples were also drilled along distinct stratigraphic horizons composed of coarse to very coarse crystalline calcite with only faint laminations visible in some specimens. All samples were heated at 400°C for one hour to remove volatile organic components. At the University of Massachusetts at Amherst, USA, samples were reacted with 100% anhydrous phosphoric acid (H_3PO_4) for ten minutes and analyzed using an on-line automated carbonate preparation system (Kiell III) linked to a Finnigan-MAT DeltaXL+ ratio mass spectrometer. Standard isobaric and phosphoric acid fractionation corrections were applied to all data. Internal analytical precision, monitored through daily analysis of carbonate standards, is better than or equal to 0.1‰ for both carbon and oxygen isotope values. Stable isotope results are expressed as $\delta^{13}C$ and $\delta^{18}O$ values in ‰ relative to the Vienna PeeDee Belemnite standard (VPDB).

4. RESULTS

4.1. Field investigation

The first part of the main Veternica channel, from the cave entrance to 180 m (Fig. 2A) is characterized by wide, circular to elliptical conduits with basal fills of clastic alluvial sediments (Fig. 3B). Alluvial sediments at the bottom of the cave channels have been partly dug out by cavers during early cave explorations and also later on to ease tourist access (Fig. 3A). The overall channel shape and the gently undulating surface morphology of the basal alluvial sediments characterized by the absence of uniform slope direction and the lack of evidence for any vadose downcutting, all indicate the presence of phreatic or epiphreatic flow conditions in this part of the cave until the end of its hydrological activity.

At 180 to 390 m from the cave entrance, the initially phreatic channel is characterized by secondary vadose entrenchment with a uniform downstream slope direction. This vadose entrenchment ends at the beginning of the "Ponor 16 m" side channel at 180 m from the cave entrance, and the main cave channel contains flowstone deposits at 250 m from the entrance (Fig. 2B; sampling sites 3, 4 and 5).

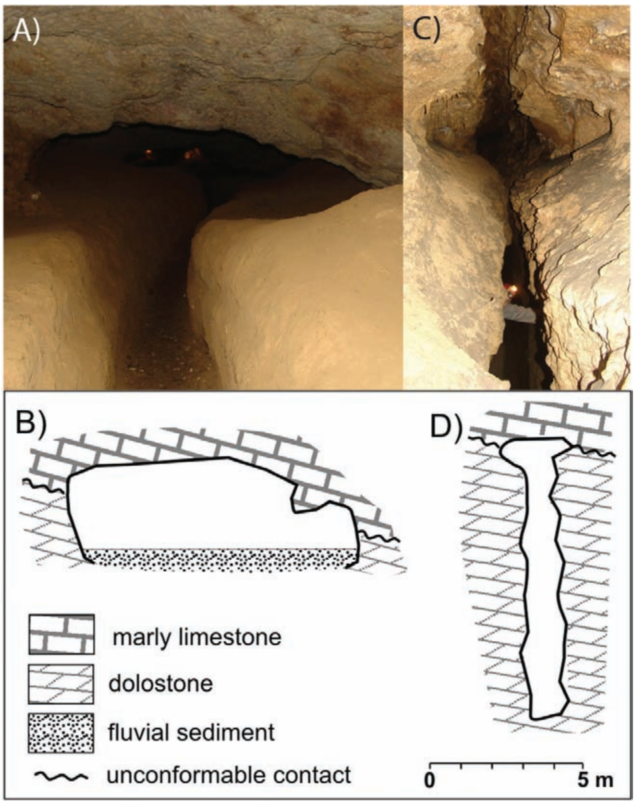

Figure 3: Characteristic morphology of the cave channels. A) Photograph of a phreatic channel (located 75 m from the cave entrance), covered with clastic sediment in the basal part (the cut through the sediment is man made); B) Sketch of a phreatic channel (located about 130 m from the cave entrance; modified after MALEZ, 1965); C) Photograph of a typical vadose morphology channel (located at 550 m from the cave entrance); D) Sketch of a channel with phreatic roof and tall, narrow vadose trenching morphology (located about 500 m from the cave entrance; modified after MALEZ, 1965).

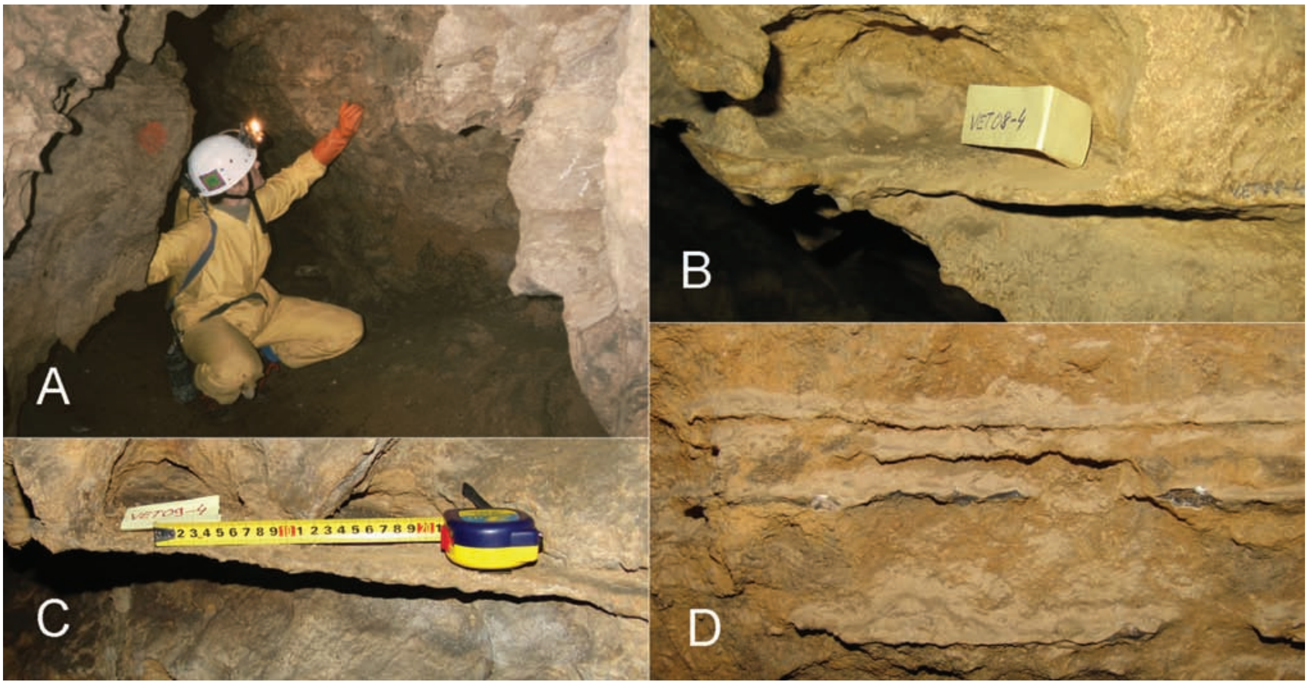

Figure 4: Field photographs of the Veternica Cave shelfstone deposits. A) Speleologist pointing at multiple shelfstone deposits, about 1 cm thick, along the sidewalls of the "Majmunski prolaz" channel. B) Close-up of the 1 cm thick shelfstone shown in (A) and the location of sample VET08-4 at sampling site 1 (Fig. 2B). C) A ~1 cm thick shelfstone remnant and location of sample VET09-4 at sampling site 2 (Fig. 2B). D) Close-up photograph showing the distribution of shelfstones at 4 different levels. Each shelfstone is about 1 cm thick.

The third part of the main channel extends farther inside the cave (beyond 390 m), and has a tall, narrow shape with phreatic roof and vadose trenching morphology (Fig. 3D). In this part of the cave, called the "Majmunski prolaz" channel, at 410 to 475 m from the cave entrance there are 9 different levels of shelfstone deposits (Fig 2B; sampling sites 1 and 2). The shelfstones are located along the channel sidewalls and extend towards the middle of the channel from barely noticeable 0.1 cm thick precipitates (Fig. 4A) to a 105 cm long shelfstone bridging the entire width of the channel. The thickness of individual shelfstones varies from 1 to 30 mm, with an average of about 5 mm. The highest and the lowermost shelfstone levels are 20 cm above and 120 cm below the bottom of the present-day cave entrance, respectively.

The lateral extent and level of the Veternica shelfstones mark the position of a free surface palaeolake. According to the observed channel elevation as well as a major (vadose to phreatic) change in channel morphology, the palaeolake ended in the downstream direction at a distance of 390 m from the cave entrance. From that point, all the way to the present entrance, the cave channels were phreatic during the existence of the palaeolake. Therefore, the formation of the vadose entrenchment at 180 to 390 m as well as the flowstone deposition at 250 m from the cave entrance both postdate the palaeolake period. In the upstream direction, the palaeolake extended to 475 m from the cave entrance (Fig. 2B). From that point upstream and farther inside the cave, the channel bottom is at higher elevation than the highest observed shelfstone level.

The flowstones at the focus of this study are located approximately 250 m from the cave entrance, at an elevation of 306 to 313.5 m asl (Fig. 5). They are below the entrance to a fracture-related side channel ("Velebitaški"), which was the source of the palaeowater flow responsible for precipitation of the flowstone known as "Kameni slap" at the elevation of 306 to 312 m asl (Fig. 2B: sampling sites 3 and 4; Fig. 5B). The known thickness of the "Kameni slap" flowstone is 55 cm and its aerial extent is about 20 m^2. The surface of the flowstone is covered with karren and small dissolution scallops (Fig. 5B), and there is a 40 cm deep erosional cut in the middle part of the flowstone (Fig. 5C). Clastic deposits cover the lower part of the flowstone and its base. Excavations of these deposits during cave maintenance in 1990 revealed bones of a cave bear (*Ursus spelaeus*; MALINAR & LACKOVIĆ, unpublished data). During the winter of 2008/2009 a detailed field study of the "Kameni slap" flowstone was carried out, and specimens for U-Th age dating were collected by drilling a 15 cm deep core in the deepest part of the naturally eroded cut, through the flowstone at sampling site 3 (Figs. 2B, 5D and E). The core, however, did not reach the oldest "Kameni slap" flowstone precipitate. Sampling site 4 is on the surface of the flowstone (Figs. 2B and 5C). Besides the "Kameni slap" flowstone, a sample from an eroded flowstone above "Kameni slap" (sampling site 5; Figs. 2B and 5A), from the entrance to the "Velebitaški" channel at 313.5 m asl was also collected. However, it was not possible to correlate the erosional remnants of this flowstone to the nearby "Kameni slap" flowstone deposits.

4.2. U-Th age dating

Shelfstone samples from the highest level, or 20 cm above the bottom of the cave entrance (sampling site 1 at 320.2 m asl; Figs. 2B and 4B), and from 110 cm below the bottom of the

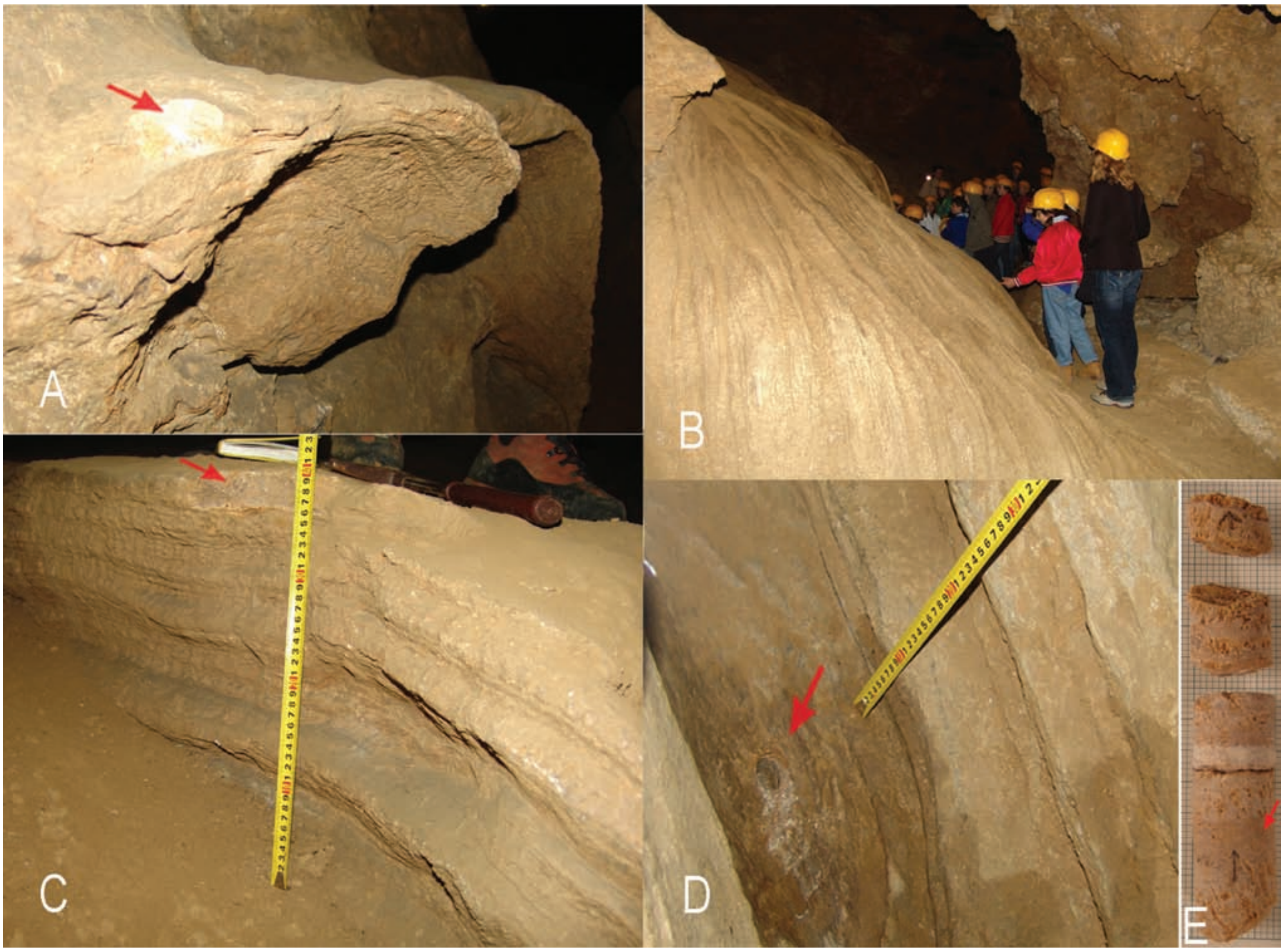

Figure 5: Veternica Cave flowstone deposits. A) Location of sample VET08-5/1 at sampling site 5 from an eroded flowstone at the entrance to the "Velebitaški" channel (Fig. 2B). B) "Kameni slap" flowstone in the "Touristic" part of the cave (sampling sites 3 and 4). Karren and small dissolution scallops characterize the surface of the flowstone. C) Location of sample VET08-5/2 at sampling site 4 (Fig. 2B) on flowstone surface on top of the erosional cut through the "Kameni slap". D) Arrow marks the location of sampling site 3 (Fig. 2B), which is a coring site on the bottom of the erosional cut through the "Kameni slap" flowstone. E) Photograph of the core from sampling site 3, with an arrow indicating location of sample VET08-5/3/1.

cave entrance (sampling site 2 at 318.9 m asl; Figs. 2B and 4C) were dated, because the lowermost shelfstone (10 cm below the analyzed one) is relatively small and poorly preserved. The highest shelfstone gave an age of 379.8 ± 15.5 kyrs BP, and the age of the lowermost analyzed shelfstone is 244.6 ± 3.6 kyrs BP (Table 1).

The flowstone at the elevation of 313.5 m asl (sampling site 5; Figs. 2B and 5A) gave an age of 234.6 ± 9.1 kyrs BP (Table 1). The oldest "Kameni slap" flowstone sample from the bottom of the drill core, at the elevation of 306 m asl, formed at 212.4 ± 8.1 kyrs BP (sampling site 3; Figs. 2B, 5D and 5E), whereas the youngest sample (sampling site 4; Fig. 2B and 5C) formed at 205.7 ± 10.9 kyrs BP (Table 1).

4.3. Stable isotope analysis

The results of preliminary stable isotope analysis of 7 flowstone and 3 shelfstone samples are included in Table 2 and illustrated in Figure 6. In general, the samples analyzed have

Table 1: Uranium-series data for selected Veternica Cave flowstone and shelfstone samples.

Material: Site (sample)	^{238}U (ng/g)	^{232}Th (pg/g)	^{230}Th/^{232}Th activity ratio	^{230}Th/^{238}U activity ratio	measured δ^{234}U (‰)	Initial δ^{234}U (‰)	uncorrected age (yrs BP)	corrected age (yrs BP)
Flowstone:								
4 (VET08-5/2)	828 ± 2.4	345737 ± 1236	7.30 ± 0.04	0.996 ± 0.005	125±1	223±7	216073 ± 3411	**205692 ± 10880**
3 (VET08-5/3/1)	699 ± 1.9	211121 ± 498	9.98 ± 0.04	0.986 ± 0.004	110±1	200±5	219968 ± 3009	**212400 ± 8105**
5 (VET08 5/1)	787 ± 1.9	318073 ± 813	8.60 ± 0.03	1.138 ± 0.004	216±1	419±11	243227 ± 3273	**234644 ± 9144**
Shelfstone:								
2 (VET09-4)	924 ± 2.2	35260 ± 102	87.25 ± 0.39	1.089 ± 0.004	171±1	341±4	245477 ± 3549	**244646 ± 3623**
1 (VET08-4)	651 ± 1.5	284977 ± 662	8.15 ± 0.03	1.168 ± 0.005	149±1	435±20	389005 ± 13183	**379776 ± 15528**

Yrs BP = years before present, where present = AD 2009.

Table 2: Carbon and oxygen stable isotope data for selected Veternica Cave flowstone and shelfstone samples.

Material: Sampling site (sample)	δ13C (‰ VPDB)	δ18O (‰ VPDB)
Flowstone:		
5 (VET 08 5/1)	–11.78	–10.31
4 (VET 08 5/2 a)	–11.43	–9.94
4 (VET 08 5/2 b)	–2.38	–8.55
4 (VET 08 5/2 c)	–7.07	–8.89
3 (VET 08 5/3/1 a)	–11.83	–9.12
3 (VET 08 5/3/1 b)	–10.85	–9.23
3 (VET 08 5/3/1 c)	–11.35	–9.48
Shelfstone:		
1 (VET 08-4)	–11.11	–9.35
2 (VET 09-4 b)	–11.26	–8.45
2 (VET 09-4 c)	–11.23	–9.06

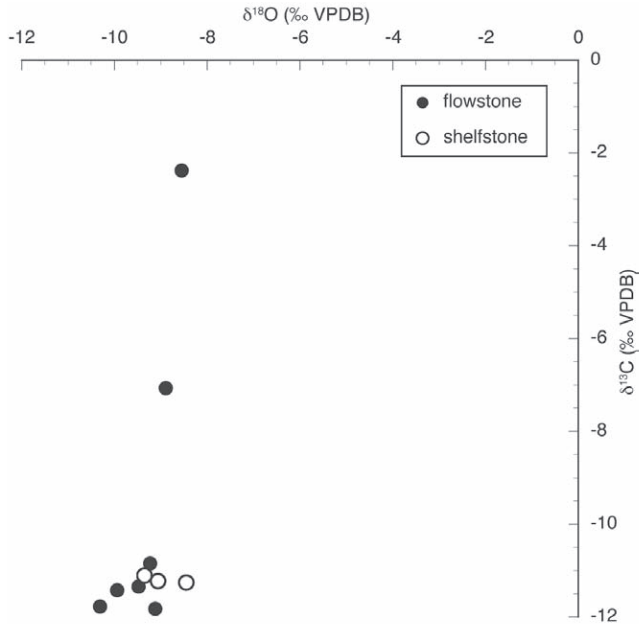

Figure 6: Results of preliminary stable isotope analysis of the Veternica Cave flowstone and shelfstone deposits.

relatively invariable oxygen, and highly variable carbon isotope values, characteristic of meteoric precipitation. Five of the flowstone samples (three from sampling site 3 – deeper section of "Kameni slap" flowstone; one from sampling site 5 – flowstone at the entrance to "Velebitaški" channel; and one from sampling site 4 – surface layers of "Kameni slap" flowstone), cluster towards the most negative carbon and oxygen values measured, and partially overlap with the compositional field defined by shelfstone samples, which on average have slightly less negative oxygen isotope values (Fig. 6). The remaining two flowstone samples (both from sampling site 4 – surface layers of "Kameni slap" flowstone) have substantially less negative carbon isotope values (Fig. 6).

5. DISCUSSION

Field observations and age determination of the "Majmunski prolaz" shelfstone (sampling sites 1 and 2; Fig. 2B) yielded information about the timing and lateral extent of vadose and phreatic conditions in the Veternica Cave during the time period of shelfstone formation. Since shelfstones generally form in quiet subsurface lakes and pools, their presence in Veternica is related to the occurrence of standing water marking a significant decrease in water flow intensity. As the age of both analyzed shelfstone samples (~380 and ~245 kyrs BP) coincides with the Riss glacial maxima (OIS 8 and 10; SIEGERT, 2001), it is likely that the decrease in water flow through the cave was related to cold and dry glacial climatic periods. Since the study area was located in a periglacial environment without any substantial evidence for major glaciations of the Medvednica Mountain and nearby areas (ŠIKIĆ, 1995), the main influence of Pleistocene climatic oscillations on Veternica Cave hydrology was probably in terms of changing precipitation rates. It is also possible that during shelfstone formation, the "Majmunski prolaz" channel was a hydrologically less active part of the cave system, and that the main water circulation was taking place in other lateral side channels or in channels at different elevations. Given that the elevation difference between the 9 observed shelfstone levels is only 1.4 m, but their age range is at least 135 kyrs (age difference between the second lowest and the highest shelfstone), the period of shelfstone formation represents a relative stagnation in water level within this karst terrain. Particular shelfstone levels probably reflect water levels during periods of diminished water circulation alternating with more hydrologically active periods. The elevation difference between the shelfstones could be a consequence of the changing morphology of a palaeospring, or of very slow gradual karstification.

Precipitation from stagnant palaeolake water of rather constant composition is also supported by the relatively uniform stable isotope values of the examined shelfstone samples (Fig. 6). These values overlap in part with a group of flowstone samples suggesting similar environmental conditions for precipitation of some of these cave speleothems. The slightly less negative oxygen isotope values of one of the shelfstone samples may be related to evaporation or temperature variations of the palaeolake waters (Fig. 6). On the other hand, the substantially less negative carbon isotope values of the two examined flowstone samples (Fig. 6) suggest a greater variability in the composition of the water percolating through the cave under vadose conditions.

During the formation of shelfstone in the vadose environment of the "Majmunski prolaz" channel, the lower part of the cave (Fig. 2B) was characterized by phreatic conditions. Timing of the onset of the flowstone formation in the upper part of the channel at 250 m from the entrance (Figs. 2B and 5A, sampling site 5), prior to ~235 kyrs BP, indicates that the transition from phreatic into vadose conditions happened during a relatively short time period of less than ~10 kyrs. This relatively fast lowering of the water level in Veternica could have been caused by rapid advance of downward karstification as a consequence of the base level lowering due to enhanced tectonism and uplift of the western Medvednica Mountain relative to the Sava river valley (regional base level). The present-day distribution of Quaternary deposits in the area suggests a total Quaternary uplift of about 350 m along the southern flanks of Medvednica Mt., including the late Pleistocene and Holocene (the last 130 kyrs) uplift of about 60 m (KUK et al., 2000). This supports active tectonism during the late Quaternary, when Veternica experienced rapid water table fall. During the period of enhanced vertical karstification, those formerly phreatic channels ("Touristic" part, Fig. 2B) first became epiphreatic or only occasionally flooded, and then completely dried out as the drainage capacity of the channels in dolostone deposits at lower elevations increased.

The ages of "Kameni slap" flowstones from the lowermost part of the "Touristic" part of Veternica indicate the end of significant hydrologic activity at the entrance area of the cave. As it was not possible to sample the oldest "Kameni slap" flowstone deposits, we could not determine the exact onset of flowstone formation, but we established that it started before ~212 kyrs BP (sampling sites 3 and 4; Fig. 2B). The tectonic uplift first reactivated a vadose flow through the "Majmunski prolaz" channel. This flow eroded most of the sediment from the lower parts of the channel, as supported by the presence of vadose downcutting of the channel bottom in the "Touristic" part of the cave, from the "Majmunski prolaz" channel downstream to "Ponor 16 m" (Fig. 2B). This downcutting was likely coeval with the formation and subsequent partial erosion of the "Kameni slap" flowstone (sampling sites 3 and 4; Figs. 2B and 5C). At that time, the "Ponor 16 m" was probably the main drainage channel for vadose flow, and part of the cave from "Ponor 16 m" downstream to the cave entrance became completely dry as it is today. The preserved phreatic shape of the channel and the bottom sediments surface morphology between the cave entrance and "Ponor 16 m" (Fig. 2B), indicate phreatic conditions in this part of the channel until the cessation of hydrologic activity (e.g., PALMER, 2007). The reconstructed timing of the end of hydrologic activity at the cave entrance is in agreement with previous studies indicating that the oldest clastic sediments at the cave entrance were deposited after hydrologic activity ceased at the end of the Riss glaciation (prior to 130 to 150 kyrs BP; MALEZ, 1963).

After formation of the youngest "Kameni slap" flowstone (sampling site 4; ~205 kyrs BP), water flow from the "Velebitaški" channel temporarily increased. This is reflected in both erosional and corrosional forms present throughout the entire flowstone surface and in a 40 cm deep erosional cut through the flowstone (Fig. 5). Today, water flows only in the deeper part of the "Velebitaški" channel, where it sinks into the "Velebitaški siphon" (Fig. 2B).

The results of detailed GPS measurements suggest that the Medvednica region is still being actively uplifted (PRIBIČEVIĆ et al., 2007). Present-day cave morphology indicates that lowering of the groundwater circulation level is an ongoing process, gradually advancing upward from the downstream end of the karst system. The morphology of younger generation Veternica Cave channels (Fig. 2B) reflects this advance: steep inclination of the hydrologically active channel towards the "Main siphon", and the presence of abandoned generations of channels and siphons, which were, during past karstification phases, draining water from the main channel to the lower levels (e.g., "Ponor 16 m", "Kukušni channel", Fig. 2B).

To improve reconstruction of the geological history of the Veternica Cave, future studies should include the dating of the oldest flowstones as well as shelfstones from all different levels, in addition to detailed sedimentological analyses and dating of clastic alluvial deposits from the cave channels. Such multifaceted studies can provide unique and interesting information about the cave history that can then be shared with the public. Numerous visitors are attracted annually to the Veternica Cave, not only because of its easy access and proximity to the large metropolitan area of Zagreb, but also because this is one of the longest caves in Croatia, rich in cave formations, while its deposits have yielded cave bear remains and Neanderthal artifacts. This public interest in the cave is a perfect opportunity to disseminate the results of up-to-date scientific research on Veternica, but it also necessitates the need for preservation and protection of this delicate cave system.

6. CONCLUSIONS

1) The study of cave deposits from the hydrologically inactive part of the main channel in Veternica Cave documented the morphological evolution of the cave and surrounding area.

2) The cave entrance is at 320 metres asl. For 180 m from the entrance, there were phreatic conditions in the main cave channel until the end of its hydrological activity, while the main channel at 180 to 390 m from the cave entrance shows phreatic morphology with later vadose entrenchment. In this part of the channel there are flowstone precipitates at 250 m from the cave entrance at elevations ranging from 306 to 313.5 m asl.

3) Part of the channel that is farther inside the cave and higher upstream, has a tall, narrow morphology of vadose origin. Nine different shelfstone remnants were observed in this part of the channel at elevations ranging from 318.8 to 320.2 m asl. These shelfstones mark the position of a free surface palaeolake that extended from 390 to 475 m from the present cave entrance.

4) U-Th dating revealed the age of the highest shelfstone (from 320.2 m asl) of ~380 kyrs BP, and the age of the lowest analyzed shelfstone (from 318.9 m asl) of ~245 kyrs BP. Dating of the flowstones in the downstream part of the cave indicates their formation from ~235 to 205 kyrs BP.

5) The time interval between formation of the youngest shelfstone (representing phreatic conditions below their level), and the oldest flowstone (marking the beginning of vadose conditions) represents a period of relatively fast water table fall between ~245 and 235 kyrs BP and the consequent transition from phreatic to vadose conditions in the "Touristic" part of the cave. This fast water table lowering resulted in the preserved phreatic characteristics of the channel between the cave entrance and "Ponor 16 m" (or for about 180 m from the cave entrance) according to the major change in channel and sediment morphology.

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