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EARLY PLEISTOCENE AGE OF FLUVIAL SEDIMENT IN THE STARÁ GARDA CAVE REVEALED BY ^{26}Al/^{10}Be BURIAL DATING: IMPLICATIONS FOR GEOMORPHIC EVOLUTION OF THE MALÉ KARPATY MTS. (WESTERN CARPATHIANS)

ZGODNJA PLEISTOCENSKA STAROST FLUVIALNIH SEDIMENTOV V JAMI STARÁ GARDA, KI JO JE DALA ^{26}Al/^{10}Be DATACIJA: UPORABNOST ZA GEOMORFNI RAZVOJ NIZKIH KARPATOV (ZAHODNI KARPATI)

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Abstract UDC 551.435.84(234.372.3)

Michal Šujan, Alexander Lačný, Régis Braucher, Peter Magdolen & Aster Team: Early Pleistocene age of fluvial sediment in the Stará Garda Cave revealed by ^{26}Al/^{10}Be burial dating: implications for geomorphic evolution of the Malé Karpaty Mts. (Western Carpathians)

Assessment of vertical movements of tectonically bounded blocks is crucial for determination of geohazards in densely inhabited zones, such as the border zone of western Slovakia and eastern Austria. The morphostructure of the Malé Karpaty Mts. divides the Vienna and Danube basins in the Western Carpathian – Eastern Alpine junction, and its neotectonic activity is of high importance. This study was focused on ^{26}Al/^{10}Be burial dating of fluvial sediment in the Stará Garda Cave, located in the central part of the mountains. The structural research revealed predisposition of forming of horizontal passages in low angle to subhorizontal bedrock stratification together with low-grade metamorphic foliation. Fluvial origin of the passages was inferred from mezoscale erosional features on the bedrock as well as from facies character of the well preserved sedimentary profile. Cave sediment was according to petrographic analysis derived from a watershed comparable to recent one of the Stupavský Potok Stream. Three analysed dating samples provided low values of isotopic concentrations, allowing us only to calculate the minimum burial age of the deposit of 1.72 Ma. Assuming the low position of the cave above recent surface streams, resulting maximum incision rate of 26 m/Ma indicates very low uplift of the mountains horst during the Quaternary. The slow incision of the river network

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Ocena vertikalnih premikov tektonsko omejenih blokov je ključna za določitev geohazardov v gosto naseljenih območjih. Morfostruktura Malih Karpatov deli Dunajski in Donavski bazen na stičišču Zahodnih Karpatov – Vzhodnih Alp in njegova neotektonska aktivnost je zelo pomembna. Študija se je posvetila ^{26}Al/^{10}Be dataciji fluvialnih sedimentov v jami Stará Garda v osrednjem delu gorovja. Strukturna raziskava je razkrila predispozicijo oblikovanja vodoravnih jamskih rovov pod nizkim kotom v odvisnosti od subhorozontalne stratifikacije kamnine ter tudi z nizko stopnjo metamorfne foliacije. Na fluvialno poreklo rovov smo sklepali iz srednje velikih erozijskih oblik na njihovih stenah kot tudi iz lastnosti faciesov dobro ohranjenega sedimentnega profila. Glede na petrografske analize jamski sediment izhaja iz povodja, ki je primerljiv z recentnim povodjem potoka Stupavský. Trije analizirani vzorci so nam dali nizke vrednosti koncentracij izotopov, ki so nam omogočile le izračun najnižje pokopne starosti sedimenta, ki je znašala 1,72 Ma. Če upoštevamo, da leži jama nizko nad recentnimi vodnimi tokovi, dobimo maksimalno hitrost vrezovanja dolin samo 26 m/Ma, kar kaže na zelo majhen tektonski dvig v času kvartarja. Počasno vrezovanje rečne mreže se dobro ujema s široko ohranjenim uravnanim površjem, imenovanim »Srednjegorska uravnava«. V nasprotju pa so sorazmerno visoke

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is in good agreement with a widespread preservation of the planation surface called "Mid-mountain level". In contrast are relatively high values of palaeodenudation rates inferred from isotopic concentrations. Generally, our results indicate that the Malé Karpaty Mts. horst underwent relatively intense but short uplift in the Early Pleistocene, followed by very moderate uplift up to the recent.
Key words: Western Carpathians, Malé Karpaty Mts., fluvial cave sediment, burial dating, Early Pleistocene, neotectonics.

vrednosti hitrosti paleodenudacije, ki izhajajo iz koncentracij izotopov. Na splošno naši rezultati kažejo, da je bil horst Nizkih Karpatov podvržen relativno močnemu, toda kratkemu dvigovanju v spodnjem pleistocenu, ki mu je sledil zmeren dvig do sedanjosti.
Ključne besede: Zahodni Karpati, Nizki Karpati, fluvialni jamski sedimenti, pokopna datacija, starejši pleistocen, neotektonika.

INTRODUCTION

Malé Karpaty Mts., located in the western Slovakia, embody a pre-Cenozoic morphostructure on the westernmost margin of the Western Carpathians (e.g., Hók *et al.* 2014). The horst divides the Danube and Vienna basins filled with successions of mainly Neogene age, which are characteristic by ongoing accumulation during the Quaternary (Maglay *et al.* 1999, 2009; Beidinger & Decker 2011). This is an indication of a possible neotectonic activity of the area. However, neotectonic history of the Malé Karpaty Mts. is still not well known, and this missing piece of information may play a major role for presence of geohazards in this highly inhabited area.

Fluviokarst levels form usually in response to cycles of developing incision of a stream following a base level fall and its stabilisation. Hence, study of timing of their formation could provide a strong proxy for determining vertical movements (e.g., Granger *et al.* 2001; Wagner *et al.* 2010; Calvet *et al.* 2015). Presence of allochthonous sediment deposited by a sinking stream is essential for dating of a cave level formed by fluvial processes.

This study was focused on the Stará Garda Cave, located in the southern part of the Malé Karpaty Mts. The cave contains fluviokarst levels and a fluvial sedimentary profile, which was the subject to facies analysis and cosmogenic burial dating, with aim to determine timing of its formation prior to vertical movements of the Malé Karpaty horst. Considering the geometry of the cave system and its position within the mountains, implications for the Pleistocene geomorphic development of the area were given.

GEOLOGICAL AND GEOGRAPHICAL SETTING

The Malé Karpaty Mts. represent the westernmost exposed segment of the Internal Western Carpathians (Fig. 1a), composed of Tatric, Fatric and Hronic tectonic nappe units. The Tatric unit consists of crystalline basement and its latest Paleozoic to Mesozoic sedimentary cover, while the Fatric and Hronic units are thin skinned nappes comprising latest Paleozoic to Mesozoic sedimentary sequences individualised in the Palaeoalpine tectonic phase (e.g., Hók *et al.* 2014). The area borders with the contact zone of the Eastern Alps and Western Carpathians, which is covered by the Neogene sedimentary sequences of the Vienna Basin.

The morphostructure of the Malé Karpaty Mts. underwent slow exhumation during the Paleogene to middle Miocene times (Králiková *et al.* 2016). Its tectonic individualisation was connected with a synrift subsidence phase of the Vienna and Danube basins in the middle Miocene, since accumulation of several kilometres thick sequences was associated with activity of faults bounding the Malé Karpaty Mts. from SE and NW (e.g., Kováč 2000). Its present elevated shape is considered to be formed during the Pleistocene (Minár *et al.* 2011), accompanied by deposition of thick Quaternary successions on their both sides (Maglay *et al.* 1999, 2009).

The Borinka Succession crops out in the northwestern part of the Malé Karpaty Mts. and consists of Jurassic marine clastic carbonates deposited in front of an active overthrust (Fig. 1b). The Stará Garda Cave was formed in Prepadlé Formation of the Lower Jurassic age, which comprises gray, massive to thick bedded, occasionally laminated fine-grained carbonates. The cave system assigned to Borinka Karst (Majko 1962; Liška 1982; Mitter 1983; Magdolen 2004; Hochmuth 2008) could be observed in a very specific geological setting, since it rims a thrust of the Tatric crystalline complexes of the Bratislava nappe over the Borinka succession (Fig. 1b).

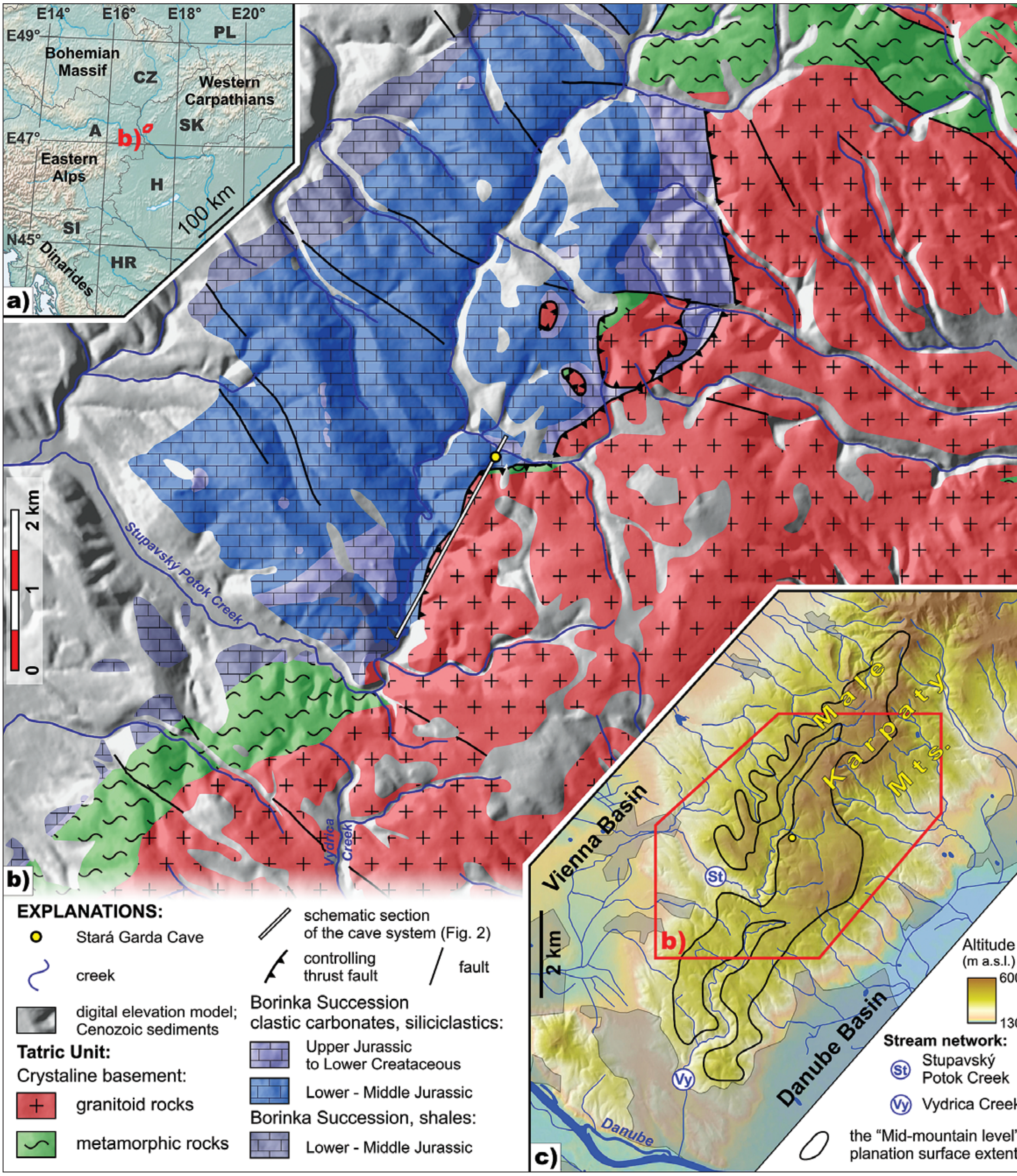

Fig. 1: Location of the study area. a) General location of the southern part of the Malé Karpaty Mts. b) Geological map of the study area according to Polák et al. (2012), simplified. c) Topography of the southern Malé Karpaty Mts. with stream network. The extent of the "Mid-mountain level" planation surface is according to Urbánek (1992).

The contact of both units could be tracked in the generally NE–SW direction (Polák *et al.* 2012).

The area recently belongs to a watershed of the Stupavský Potok Creek (Fig. 1c), but it was proposed that the recent river basin configuration resulted from a stream capture and the NNE–SSW oriented valley parallel to the mountain axis was previously drained by the Vydrica Creek (Lukniš 1955; Urbánek 1992; Sládek & Gajdoš

2014). Morphology of the central part of the mountains is dominated by a well preserved planation surface called the "Mid-mountain level" (Fig. 1c; Urbánek 1992; 2014).

Evolution of the Malé Karpaty Mts. during the Quaternary was until now poorly examined taking into account their vertical movements, what mainly emerged from scarcity of proper geochronological data. This issue was discussed using morphostratigraphy of river terraces on the south-western margin of the mountains (e.g., Šajgalík 1958; Halouzka & Minaříková 1977) and by correlation with planation surfaces (e.g., Lukniš 1964; Jákal 1983; Dzurovčin 1994; Orvoš 2015), but only applying relative dating.

The Stará Garda Cave was discovered by a team of professional cavers led by Ján Majko in February 1958 after a one month excavating of debris from a sinkhole. The entrance was buried soon after the early reconnaissance by rock blocks in April, the same year. The re-discovery of the cave happened in June 1991 and during the next 20 years some new passages were attached along with continuation at the very end. The key advance was done in 2011, when extensive horizontal labyrinth was reached and the cave was connected with two other near-by caves thus creating the Borinka Cave System.

METHODS

CAVE SURVEY: MAPPING, STRUCTURAL RESEARCH AND SEDIMENTOLOGY

The survey of the cave was done in the years 2003–2004 by the members of speleological club Speleo Bratislava. Individual geodetic points were assayed by the mine surveying method using a hanging compass, mine inclinometer and steel or fibreglass measuring tape. All values of bearings were measured two times (both in forward and back orientations). The plan of the cave was generated using polyline that connects all geodetic points and station points as well. The side projection was constructed in the same way using calculated coordinates of all station points.

Structural investigations were carried out by the classic field-based methods of structural analysis. The fundamental structural elements (bedding, brittle discontinuities) were measured during the field work and visualized with the software for structural geology OpenStereo (Grohmann & Campanha 2010). 20 structural elements were measured in the Stará Garda Cave and near surface.

Analysis of lithofacies is based on principles of fluvial sedimentology (Miall 2000; 2006) with emphasis on specifics related to depositional processes in caves (e.g., Bosch & White 2004; White 2007; Farrant & Smart 2011). A detailed vertical lithological log was constructed with aim to record temporal changes in depositional processes. The sandy material of grain size 0.5–1.0 mm was subject to petrological analysis in two thin sections using polarisation microscope. Erosional features of passage walls were interpreted according to Bretz (1942), Curl (1966), Bögli (1980), Lauritzen (1981), Ford & Williams (2007), Palmer (2007), Klimchouk (2007) and Farrant & Smart (2011).

$^{26}Al/^{10}Be$ BURIAL DATING PRINCIPLES

The $^{26}Al/^{10}Be$ burial dating method was applied to three sandy samples taken from vertical succession of the studied sedimentary log. The dating is based on assumption, that clastic material containing quartz grains was exposed at the ground surface to cosmic rays in the source area and then transported in a stream followed by a burial in a cave. Interaction of cosmic rays with quartz material causes production of radionuclides ^{26}Al and ^{10}Be by nuclear reactions with a stable spallation production ratio of 1:6.75. After deposition in a cave passage, the quartz material is shielded from cosmic rays and the $^{26}Al/^{10}Be$ ratio will decrease due to radioactive decay of the two elements (e.g., Goose & Phillips 2001; Granger & Muzikar 2001). The measured ratio can thus be used to determine the minimum burial age. This age can also be considered to the minimum age of the cave formation, providing that cave was formed by fluvial processes and dated sediment could be clearly interpreted as allogenic and deposited by a stream. Assuming that no post production occurred after deposition, the data also allow determining the maximum denudation rate that prevailed at surface before burial (von Blanckenburg 2005). Coordinates of studied cave, which were applied in calculations, are following: Lon – 17.13365; Lat – 48.27864; Alt – 442 m. The studied sedimentary profile appears in the depth of 58 m.

TREATMENT OF THE BURIAL DATING SAMPLES

Three samples of sand were taken from vertical succession. Samples of purified quartz were sieved to fraction 0.25–1 mm and ca. 70 g of material underwent sequential leaching in HF for decontamination of the grains from atmospheric ^{10}Be. The pure decontamined quartz was spiked with ~100 µl of a (3025±9) ppm of 9Be carrier solution and totally dissolved in HF. An aliquot for ICP-OES measurements of concentrations of stable aluminium was taken after evaporation of the solution. Al and Be were separated using standard procedures of ion exchange chromatography (Merchel & Herpers 1999). Beryllium and aluminium hydroxides were oxidized and cathoded with metal powder (Niobium for Be and Silver for Al) for AMS measurements, which were performed at French national facility ASTER (CEREGE, Aix-en-Provence).

RESULTS

GEOMETRY OF THE BORINKA CAVE SYSTEM AND THE STARÁ GARDA CAVE

The Borinka Cave System consists of four caves, from which three are connected (Fig. 2). Active stream occupy several levels and leaves the system at the elevation of 343 m a.s.l. (Stará Garda Cave) or 335 m a.s.l. (Jubilejná Cave). A connectivity to the resurgence located ca. 2.5 km to the SWW on the elevation of 299 m a.s.l. was proved by a tracer test. Hence, the studied sedimentary profile in the Stará Garda Cave is located approximately 45 m above the modern piezometric level recently occupied by a recent stream.

The uppermost passage of the Stará Garda Cave is reached by an artificial shaft 6 m deep (Fig. 3). A gently dipping hall is followed by a network of vertical 2 to 5 m deep wells with vertical levels arranged in a spiral framework. These passages reach the Chamber of Bats in the depth of 50 m. Here appears a horizontal passage oriented to the east with inflow of a stream. The horizontal passage is after 15 m modulated by a vertical 7 m deep shaft and opens to a spacious N–S oriented hall containing rockfall material. The Fragment of Meander Passage follow on its end, which is 1.5 to 2 m high and 1 to 1.5 m wide and was originally completely filled by fluvial deposits. The passage is accessible in a length of 20 m thanks to excavation works. The main passage continues from the Chamber of Bats by a vertical shaft on the level of 60 m depth, where it branches to two sinking fissure passages. Than the Stará Garda Cave connects towards the north to the extensive complex of passages of the Borinka Cave System. Original Stará Garda Cave follows the western direction and opens to the most spacious segment – the Great Chamber. Narrow fissure passages continue from the bottom of the hall to the lowermost level of the Satrá Garda Cave in the depth of 96 m (343 m a.s.l.). The cave terminates here by a narrow, low and impassable passage, were is located an outflow of the stream.

STRUCTURAL PREDISPOSITION OF THE STARÁ GARDA CAVE

Orientation of the cave passages in the Stará Garda Cave appears as parallel to major planar discontinuities. These are mostly primary stratification planes and planes of fissures associated with faults. Measurements of orientation of stratification S_0 directly in the cave as well as on the surface in close vicinity shows their orientation to W–NW and E–SE with dip reaching 20–35° (Fig. 4a, c).

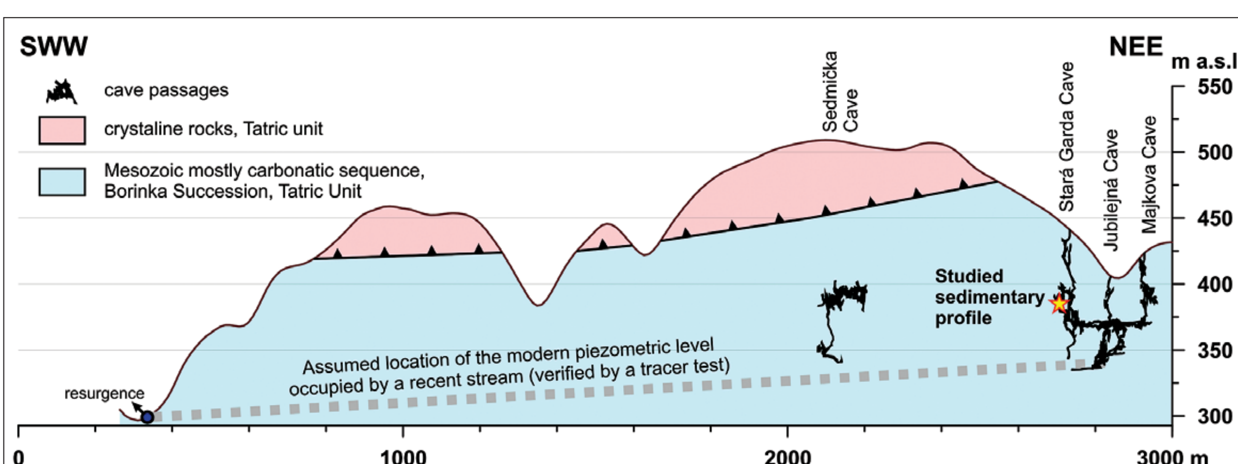

Fig. 2: Schematic section of the Borinka Cave System depicting its position related to topography and recent stream network.

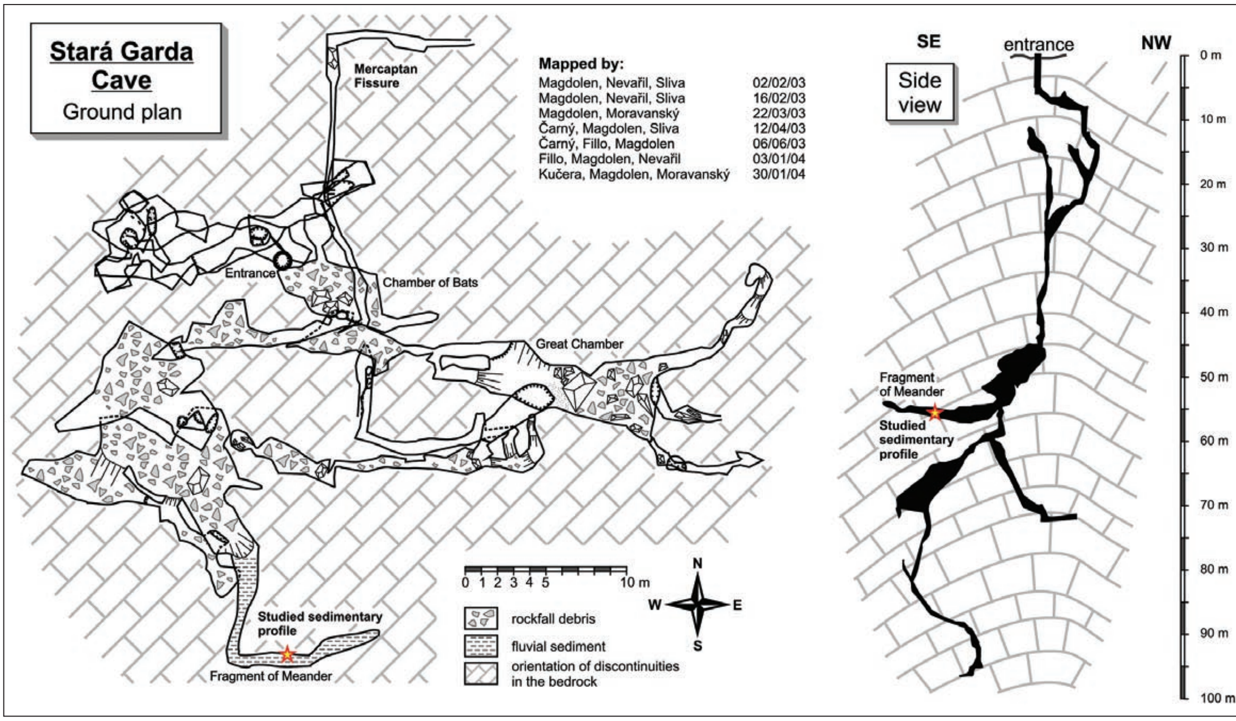

Fig. 3: Ground plan and side view of the Stará Garda Cave with indication of main structural elements of the bedrock.

While the orientation of bedding planes is in accordance with the data gained in general geological mapping of the area (Polák *et al.* 2012), steeper dipping of the Borinka Succession is much more common in the Malé Karpaty Mts. than observed low angle inclination. A low grade metamorphic foliation S_1 connected with the overthrust of the Bratislava nappe was observed as sub-parallel to stratification S_0. Abovementioned planar inhomogeneities S_{01} affected formation of horizontally oriented domes and passages present in lower altitudes of the cave, such as the passage with studied sedimentary profile.

Subvertical to vertical fissures S_2 represent another observed system of major plane discontinuities, oriented generally in ESE–WSW direction (Fig. 4b, c). These fissures played a major role during corrosive to fluvial erosive processes of forming of passages in the upper part of the cave up to depth of 40 m, what is well observable on the map view on Fig. 3. Similar structures were considered as important for origin of several other caves of the Borinka Karst (Magdolen & Sliva 2003).

The planes S_{01} are inclined towards W–NW and E–SE, forming limbs of folds. Plašienka (1987) declared, that original geometry of S_{01} planes was overprinted by subsequent Palaeoalpine transpressive event, which led to a mezo- and macroscale symmetric and slightly asymmetric folding. Foliation associated with this event represent a cleavage of subvertical fold axial planes, which are common feature in the area, but were not observed directly in the studied cave. Movement of the dextral SW-NE oriented transpressional zone caused rotation of fold axes not only on dextral Riedel Shears R_1, but also on sinistral shears R_2 in a counter clockwise direction (Plašienka 1987). This rotation is expected to be responsible for the present orientation of folds of S_{01} planes as well as of S_2 fissures.

MEZOSCALE EROSIONAL FEATURES OF THE CAVE BEDROCK MORPHOLOGY

The surface morphology of the bedrock carbonate in front of the passage with studied sedimentary profile shows horizontal erosional zones (Fig. 5a), which are considered as indications of notching process. These developed by corrosion during episodes of nearly static water body in a vadose passage with an open channel. Several zones of notches in vertical arrangement mirror gradual filling of the passage with sediment (aggradation) and consequent rising of a water table (Farrant & Smart 2011). In contrast, spoon-shaped scoops are present just on opposite side to the sedimentary profile (Fig. 5b), which are comparable to scallops. Scallops are formed by dissolution in a turbulent flow (Bretz 1942; Curl 1966; Ford & Williams 2007). Another erosional features of sub-vertical orientation observable on Figure 5c are interpreted as half tubes or as wall grooves (Bögli 1980; Lauritzen 1981; Ford & Williams 2007; Palmer 2007; Klimchouk 2007). These develop typically by dissolution under phreatic conditions by vertically flowing water in a passage, that has become filled by sediment, what leads to upwards

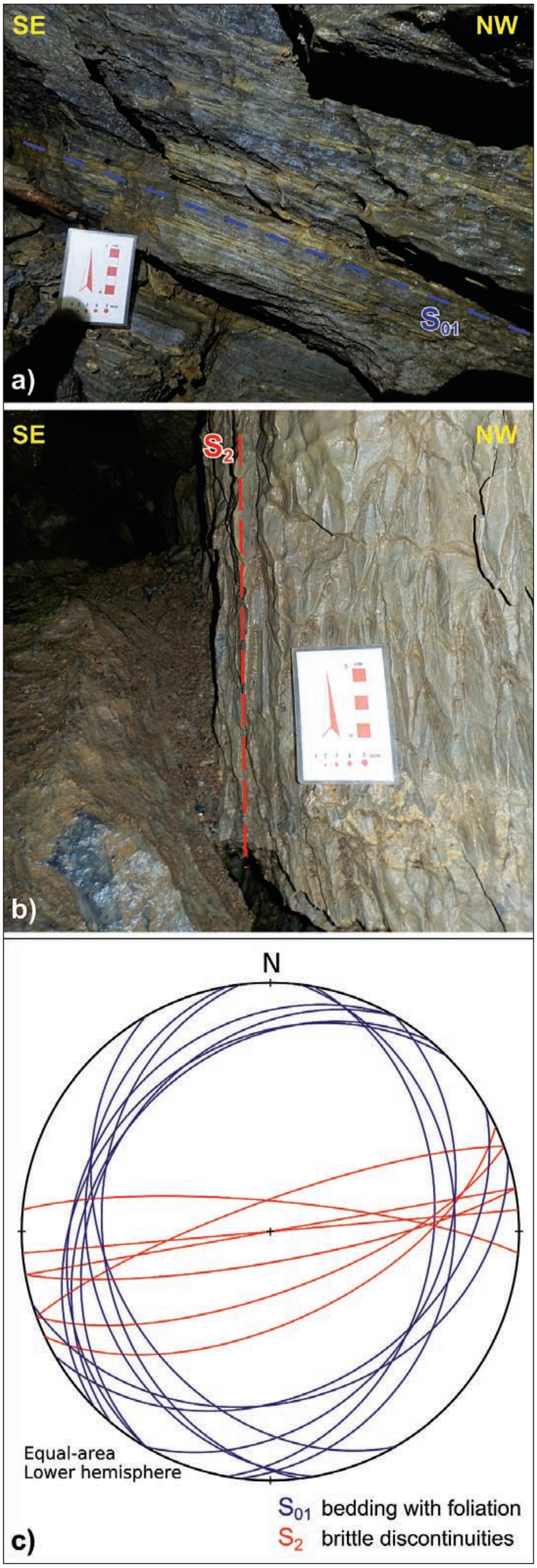

Fig. 4a: Example of the bedrock stratification plane associated with metamorphic foliation (S_{01}). b) Example of fissure S_2 related to transpressive event. c) Stereographic projection summarizing orientation of S_{01} and S_2 discontinuities. (Photo: A. Lačný).

orientation of dissolution (Ford & Williams 2007; Klimchouk 2007). Combination of these structures indicates alternating of highly turbulent stream with standing water conditions, and presence of mostly vadose but also phreatic setting during formation of the passages.

STRATIGRAPHY OF THE CAVE FLUVIAL INFILL

Description

The sedimentary profile in the Fragment of Meander passage contains several distinct lithotypes, depicted on the log on Fig. 6. Fine grained lithotype is represented by mud and muddy sand, which mostly occurs in 0.5 to 1 cm thin laminae, in lower part of the log reaching 2–3 cm. Mud is usually laminated and forms continual layers, which divide sandy units. Boundaries are mostly sharp and planar, in several levels scoured (105 and 122 cm), indicating erosion

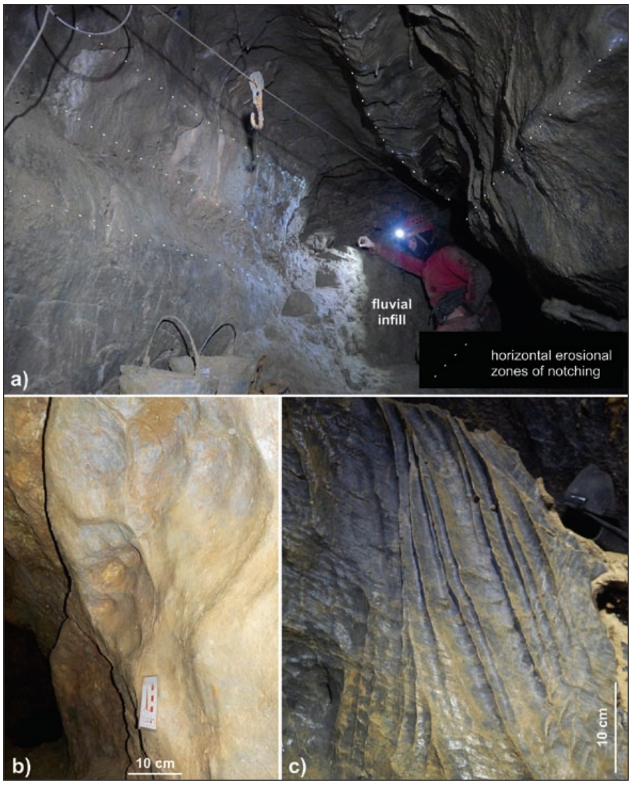

Fig. 5: Erosional features on the cave bedrock surface. a) Horizontal erosional zones, which represent notching during process presence of nearly static open channel water body. b) Spoon-shaped scoops formed by turbulent flow. c) Half tubes/wall grooves formed by vertically flowing water under phreatic conditions (Ford & Williams 2007; Klimchouk 2007; Photos: N. Filipčíková and T. Lanczos).

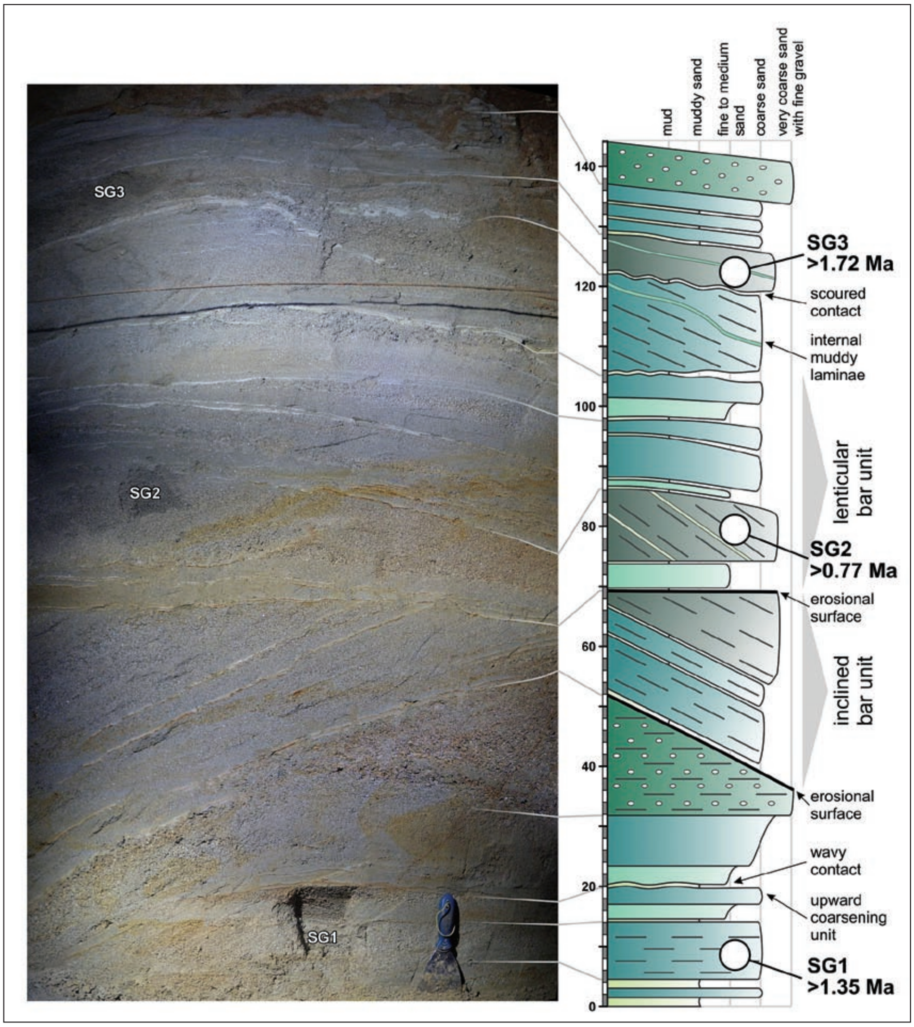

Fig. 6: Photomosaic of the studied sedimentary section in the Fragment of Meander passage with corresponding lithological log, its interpretation and position of burial dating samples. Since the passage is narrow, relative dimensions of layers are affected by compilation of photographs.

preceding their deposition. Wavy laminae were deposited above positive sandy forms, which may represent current ripples (Fig. 7b).

Fine to medium sand appears as massive. Commonly overlies muddy laminae and continuously passes upward to coarse sand. Coarse sandy layers could be observed either as weakly stratified or massive individual layers 5–10 cm, up to 20 cm thick, or together with fine to medium sands in upward coarsening units (Fig. 7b). These layers locally contain gravel reaching 0.5 cm in diameter (intervals 32–52 cm; 137–144 cm). Coarse sands

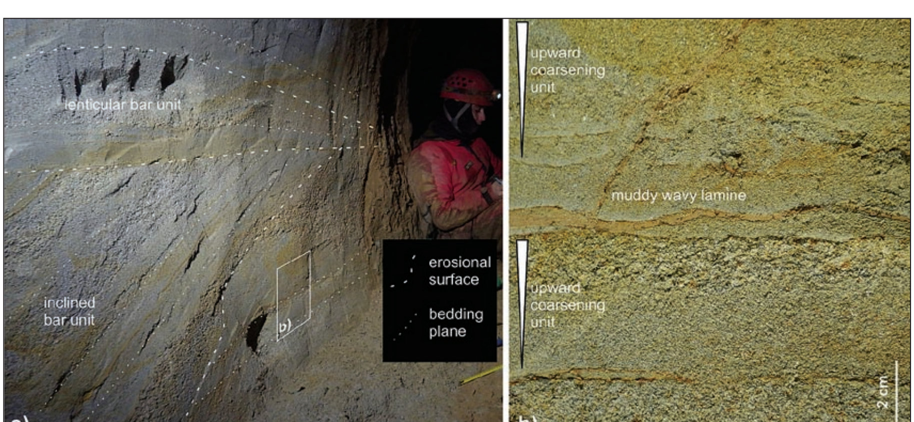

Fig. 7a: Side view of the sedimentary profile with marked stratification and main bounding surfaces. b) Detail of the lithofacies with presence of upward coarsening units and muddy laminae of wavy shape. (Photos: N. Filipčíková and T. Lanczos).

could be found with internal muddy laminae of planar or wavy shape.

Two major erosional surfaces appear in the log on 52 and 69 cm, marked by angular contacts between layers (Fig. 7a). The succession in interval 0–52 cm is subhorizontally arranged with general upward coarsening trend. Interval in 52–69 cm is inclined with dip of 25° towards the west. The above situated layers up to 105 cm form a lenticular convex horizon with slightly upward decrease in grain size (Fig. 7a). Topmost part is characteristic with wavy boundaries and generally coarse grained appearance.

Interpretation of depositional processes

Dominantly sandy layers were deposited by an unidirectional traction current in a channel, what is implied by character of sorting as well as by geometry of the strata (e.g., Bosch & White 2004). Variable grain size (heterolithic pattern) resulted from frequent change in the flow transport capacity. Common presence of continual muddy laminae arose from significant decrease in transport capacity leading to deposition from suspension. These events could represent episodes of slackwater deposition, when the passage was fully water-filled (Bosch & White 2004; White 2007).

Two main angular contacts in the sedimentary profile are of erosional origin, indicating high dynamics of the stream. The inclined strata in 52 to 69 cm of the log, reaching up to 70 cm in thickness towards the left side (west), could be considered as a channel bar. Thus, the dip direction towards the west indicates palaeoflow direction. Overlying cross-stratified coarse sand together with the strata up to 105 cm is of lenticular convex shape and probably represents cross section of a point bar. Several ca. 6–8 cm thick units with upward-coarsening character resulted from pulses of increased flow strength. Despite the variation in a transport capacity, the flow was relatively perennial, what is indicated by generally stable upper limit of gain size, good sorting and organization of strata into channel bars without presence of gravity flow deposits.

PETROLOGY AND PROVENANCE OF THE DATED SEDIMENT

Petrology of the sands from samples SG1 and SG3 was studied in thin sections. Percentual content of each observed clast type is summarized in the Tab. 1. Mineral clasts are represented by quartz, K-feldspar, microcline, muscovite, sericitized biotite and sericitized plagioclase (Fig. 8a-h). Lithoclasts of carbonates, shales and granites showed relatively high abundance, while sandstone lithoclasts were less common. Most of the mineral clasts were poorly rounded (Fig. 8a, b), while higher roundness was observed in shale lithoclasts (Fig. 8e, f). Percentage content of individual clast types does not differ significantly between SG1 and SG3 samples.

All mineral clasts and granite lithoclasts are expected to be derived from granitic rocks, which form the recent drainage basin of the Stupavský Potok Creek. An exception could represent some well-rounded quartz clasts, which could originate from shales. Lithoclasts of shales were most probably sourced from erosion of Lower Jurassic of the Borinka Succession, while fine grained sandstones are present in the Lower-Middle Jurassic of the succession. Summarizing the mentioned information, sources of all documented clast types are present in the recent drainage basin of the Stupavský Potok Creek and their appearance indicate short transport. Material of metamorphic rocks, which crop out more to the north, was not observed.

Tab. 1: Percentage content of clast types observed in thin sections of samples SG1 and SG3.

Clast type	***SG1 [%]***	***SG3 [%]***
Quartz	25.5	22
K-feldspar	14	12
Microcline	9.5	7
Muscovite	4	6
Sricitized plagioclase	3	7.5
Sericitized biotite	8.5	5
Carbonate lithoclast	6	11.5
Shale lithoclast	18	10.5
Granite lithoclast	8.5	13
Sandstone lithoclast	3	5.5

BURIAL DATING, INCISION AND PALAEODENUDATION RATES

Lithofacies analysis proved fluvial origin of the profile in question. Moreover, study of morphological features of erosional origin on cave passage walls imply that stream corrosion and dissolution were main processes controlling origin of the passages in the lover part of the cave. Thus, burial dating of samples taken from this profile should mirror age of the cave formation.

All three measured samples provided relatively low concentrations of both ^{10}Be and ^{26}Al (Tab. 2). Considering the low $^{26}Al/^{27}Al$ sample ratios (ranging from 3.3×10^{-15} to 4.58×10^{-15}) compared to the processional blank $(2.2 \pm 1.92) \times 10^{-15}$ the most rigid approach was applied with taking into account only the upper limit for the ^{26}Al concentrations. This will thus yield to minimum burial ages.

Resulting minimum burial age of sedimentary profile is 1.72 Ma, since sample SG3 is on the top of the pro-

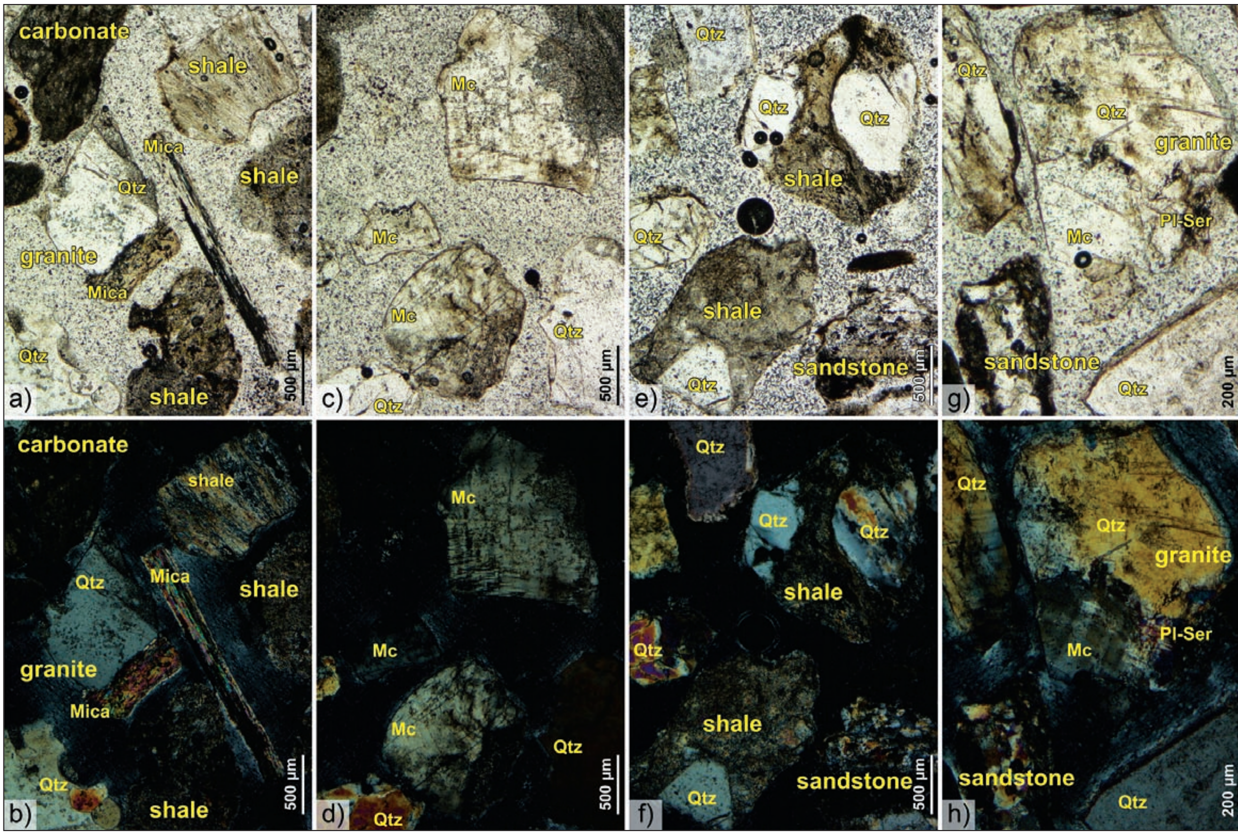

Fig. 8: Most common clast types observed in thin sections. Upper photos represent plane polarized light, lower photos cross polarized light. Abbreviations: Qtz – quartz; Mc – microcline; Pl-Ser – sericitized plagioclase. Mica represents altered biotite. Shale, granite and sandstone indicate lithoclasts.

Tab. 2: Upper limit of ^{26}Al concentrations, ^{10}Be concentrations, calculated minimum burial ages and maximum denudation rates for the 3 studied samples from the Stará Garda Cave.

Sample	*$^{26}Al_{upper\ limit}$ (kat/g)*	*^{10}Be (kat/g)*	*$^{26}Al_{upper\ limit}/^{10}Be$*	*Minimum burial age (Ma)*	*Maximum denudation rate (m/Ma)*
SG1	18.74	5.075 ± 0.53	3.69	1.35	475.42
SG2	18.68	3.831 ± 0.42	4.88	0.77	840.70
SG3	21.17	6.994 ± 0.70	3.03	1.72	281.18

file. The cave infill was deposited most probably during the Gelasian age of the Early Pleistocene.

Incision rate could be inferred according to position of the Stará Garda Cave in the Borinka cave system (Fig. 2). The position of the dated profile ca. 45 m above the lowermost cave level occupied by an active stream imply average maximum incision rate ~26 m/Ma during the last 1.72 Ma.

Obtained concentrations yielded catchment-averaged maximum palaeodenudation rates ranging from 281.2 to 840.7 m/Ma. These values are very approximate due to high uncertainty in ^{26}Al concentrations. It is worth nothing to mention, that palaeodenudation rates represent only a few tens of thousands of years long time slice, during which is quartz grain exposed to cosmic rays, eroded, transported and deposited in a cave passage (von Blanckenburg 2005).

DISCUSSION

The obtained dating result of the Stará Garda Cave allochthonous fluvial sediment proves, that the Malé Karpaty Mts. horst was in elevated morphological position similar to recent already during the Early Pleistocene and river incision into carbonate complexes of the Borinka Succession was already active. Calculated maximum incision rate of ~26 m/Ma in the southern part of the Malé Karpaty Mts. represent significantly lower value comparing with case studies focused on the Quaternary incision rates in the Transdanubian Range Mts. (60–160 m/Ma; Ruszkiczay-Rüdiger *et al.* 2016) or in the Eastern Alps (~100 m/Ma; Wagner *et al.* 2010). The value of 30–40 m/Ma implied by the results of Bella *et al.* (2014) for the Internal Western Carpathians is much closer to presented study. The southern Malé Karpaty Mts. are characteristic by moderate relief with low average slope inclination ranging in 6–14°, indicating minor intensity of recent erosion (Polák *et al.* 2012; Urbánek 2014). The highest flat-shaped parts of the relief were considered to be remnants of the pre-Pliocene initial planation surface called "Mid-mountain level" (e.g., Mazúr 1976; Minár *et al.* 2011) and are well preserved across the area (Fig. 1c; Urbánek 1992; 2014). Our results imply, that uplift of the Malé Karpaty Mts. reached low intensity during the Quaternary, what led to moderate incision of streams and wide preservation of the planation surface.

Although the obtained palaeodenudation rates are very approximate, they provide important insight into topographic conditions of the Malé Karpaty Mts. during the Early Pleistocene. The values are an order of magnitude higher comparing with other case studies focused on mountain cave systems in the Europe (e.g., Wagner *et al.* 2010; Calvet *et al.* 2015 and reviewed data therein). Moreover, obtained values are two orders of magnitude higher than $^{26}Al/^{10}Be$ result from Internal Western Carpathians (Bella *et al.* 2014) and calculations based on ^{10}Be depth profiles in the Transdanubian Range (Ruszkiczay-Rüdiger *et al.* 2016). On the other hand, studies of ^{10}Be concentrations in recent river sediments in Apennines, Southern and Eastern Alps revealed denudation rates ranging from 150 to 550 m/Ma in watersheds not affected by Pleistocene glaciations (Norton *et al.* 2011; Wittmann *et al.* 2016). However, all these localities exhibit much higher relief than the Malé Karpaty Mts. Thus, the increased denudation rates during the Early Pleistocene might have resulted from a short episode of increased uplift related to forming of recent morphostructure of the mountains.

The beginning of Quaternary is characteristic by significant cooling and shift to continental climate with high seasonality and oscillations in mean annual temperatures and precipitation in the Central and Eastern Europe (e.g., Meyers & Hinnov 2010; Kahlke *et al.* 2011). The climate change resulted in increased intensity of erosion processes, what probably affected the relatively high Early Pleistocene denudation rates observed in the studied area. A more detailed study is needed to determine a precise history of denudation rates in the Malé Karpaty Mts., as well as to examine their major control factors.

Low measured isotopic concentrations are expected to be a consequence of fast erosion and transport to the cave passage, with short time of exposure. The cave sediment was according to petrographic analysis transported to a short distance and probably derived from the area comparable to the recent drainage basin of the Stupavský Potok Creek. Absence of the metamorphic minerals in the cave sediment suggest, that the palaeo-watershed did not exceed further to the north. Thus, river basin pattern remained generally unchanged in the studied locality. Low uplift rate left the valley in the central part of the Malé Karpaty Mts. relatively unaffected by the headward erosion.

CONCLUSIONS

The study revealed fluvial origin of lower passages of the Stará Garda Cave (Malé Karpaty Mts.), considering mezoscale morphological erosional features on the bedrock surface and facies of the sedimentary infill. Analysis of ^{26}Al and ^{10}Be concentrations from three fluvial sediment samples provided low isotopic values, allowing us only to calculate minimum burial age of 1.72 Ma. Low concentrations of both isotopes probably resulted from short transport and exposition. A short transport of the sandy material in a river basin of extent comparable to actual one of the Stupavský Potok Creek is indicated by petrographic character of the cave sediment. The dated sedimentary profile is located only ca. 45 m above the river bed of the recent stream network, what imply a slow incision rate lower than 26 m/Ma. This value together with the widespread preservation of the "Mid-mountain level" planation surface was interpreted as a result of slow uplift of the mountains and associated low base level fall during the Quaternary. High palaeodenudation values calculated from isotopic concentrations indicate episode of intense uplift during the earliest Pleistocene, when the river network incised into the planation surface to elevation level of the studied sedimentary profile in the Stará Garda Cave. The vertical movement was negligible since the early Quaternary uplift episode up to recent.

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