

The Večerná-Čárka cave system (Kuchyňa-Orešany Karst, Malé Karpaty Mountains, Slovakia) – tectonically controlled phreatic speleogenesis in the marginal part of block mountains

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Abstract: The Večerná-Čárka cave system is the longest underground site of the Kuchyňa-Orešany Karst (Malé Karpaty Mountains, western Slovakia). Although its length is only 58 m, it is a site of remarkable interest in terms of speleogenesis that was strongly controlled by tectonic structure of the Middle Triassic limestone (Fatric Unit). Morphologically, the studied cave system represents a branched cave, formed by linear, and in some places intersecting passages. Their direction is strongly linked with two systems of steep parallel and crossing tectonic failures of N–S and NW–SE direction. Phreatic morphologies of passages show that the cave system originated by dissolution of limestone along these tectonic discontinuities, in several places the cave passages were enlarged by the destruction of parallel rock partitions. Probably, waters of deeper circulation ascended along steep tectonic fractures. Since these waters were relatively saturated, limestone mostly dissolved in the zone of mixing with seeping rainwater. A dense network of steep parallel and intersecting tectonic fractures allowed to diffuse groundwater circulation without much concentration of water flow into one or more main conduits. The absence of water table notches, ceiling cupolas as well as blind oval chimneys indicate that the caves formed below or just below the former piezometric surface of groundwater and without its significant oscillations, e.g. in the shallow phreatic zone. The estimated Pliocene (or late Pliocene?) age of the cave system (lying at an altitude of 413–419 m asl.) is determined based on its location above the recent hydrographic network (60 m above the floor of the valley) and by the remains of the Plio-Pleistocene planation surface located at 250–350 m asl. in the adjacent part of the Malé Karpaty Mountains.

Key words: solution cave, non-fluvial phreatic morphology, rock protrusion, rock blade, hydroxylapatite, Western Carpathians

1. INTRODUCTION

In recent years, several caves in the Malé Karpaty Mts. have been explored and documented. After examination of the genesis of the Plavecká Cave and the Pec Cave, it was concluded that both are hypogenic (Bella, 2010; Bella & Bosák, 2012; Bella et al., 2019^a, 2019^b). Detailed geological research, however, has not been carried out in other caves in the Malé Karpaty Mts. These caves are located on the marginal parts of the mountains and are associated with significant fault structures. Such sites include the system of interconnected Večerná and Čárka caves, whose speleological research is carried out by cavers from the regional Plavecké Podhradie group. In this paper, we present the basic geological and geomorphological characteristics of these caves with respect to their genesis.

1.1. Location and general data

The Večerná-Čárka cave system is located approximately 2 km east of Kuchyňa village (Malacky district) in the Modranská skala, which consists of a rock ridge stretching from southwest towards

the northeast in a length of about 500 m (Fig. 1). The entrance to the Večerná Cave lies at an altitude of 419 m asl., 60 m above the current bottom of the Modranská Valley with the alluvium of the Malina brook. The entrance to the cave has been known since time immemorial. Nonetheless the first speleological survey of the Večerná Cave was carried out by cavers from Plavecké Podhradie (M. Velšmid, L. Jánoš, T. Herceg and T. Kožuch) only recently in the year 2010. The entrance to the Čárka Cave is at an altitude of 413 m asl., about 25 m to the southwest of the entrance to the Večerná Cave. The speleological research began in the spring of 2011. Originally the Večerná and Čárka caves were two separate subsurface localities. In 2014, the cavers connected both caves into one genetic unit – the Večerná-Čárka cave system. At present, this system reaches a length of 58 m with a vertical span of 6 m (surveyed by M. Velšmid and T. Kožuch in 2014; Fig. 2) and is the longest cave of the Kuchyňa-Orešany Karst.

1.2. Malé Karpaty Mountains

The Malé Karpaty Mts. are a part of the Tatra-Patra Belt, which forms the outer zone of the Central Western Carpathians (CWC;

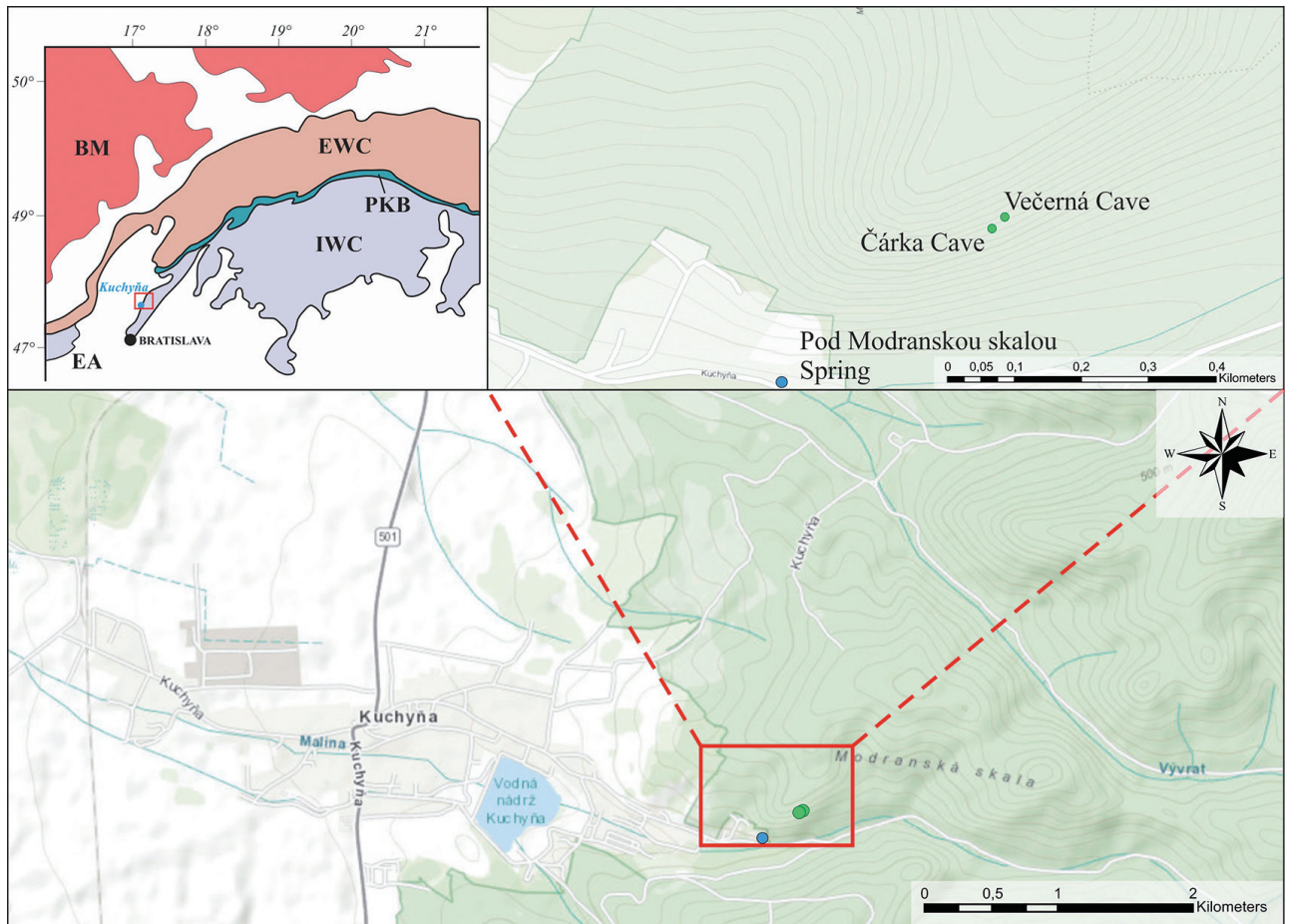


Fig. 1. Location of the Večerná and Čárka caves and Pod Modranskou skalou Spring.

Plašienka et al., 1997; Plašienka, 1999). The study area represents an important segment of the CWC in the junction zone between the Western Carpathians and the Eastern Alps. Paleozoic units of the Tatric, Fatric, and Hronic units participate in their structure. Tatric Unit is built by Palaeozoic crystalline basement and by the associated Mesozoic sedimentary cover; which is exposed mainly in the southern and central parts of the mountain range (cf. Polák et al., 2012). The northern part of the range is mainly composed of the Fatric and Hronic nappe units. The post-nappe Upper Cretaceous sediments are represented by the Brezová Group (Salaj et al., 1987). Palaeogene sediments are represented by the Malé Karpaty Group (Buček in Polák et al., 2012), located in the northwestern part of the territory.

The Malé Karpaty Mts. are more than 100 km long and 15 km wide and a SW–NE-trending mountain range, which separates the Neogene Vienna and Danube basins. Within the Pezinské Karpaty Mts., the ridge is 50 km long and 15 km wide and is limited by extensional fault systems of NE–SW direction. From the northwest, the boundary between the mountains and the Vienna Basin is formed by a lower Miocene to Quaternary Vienna Basin Transform Fault (VBTF) divided into several segments (Decker et al., 2005; Beidinger & Decker, 2011; Hinsch & Decker, 2011). Towards the northwest, the VBTF continues to the Brezovské Karpaty Mts. as the Dobrá Voda fault. The fault limitation against the Danube Basin is referred to as the

Malé Karpaty fault. It is assumed an early Neogene to Quaternary normal fault (Marko & Jureňa, 1999). The caves of the Kuchyňa-Orešany Karst are associated with fault structures of the N–S, NW–SE, and NE–SW directions (Lačný, 2013). The Malé Karpaty Mts. gained their present form in the late Neogene (Minár et al., 2011), when the mountains became fully tectonically and morphologically separated from the Neogene basins. However, their exhumation history is slightly older (cf. Danišík et al., 2004; Králiková et al., 2016).

1.3. Kuchyňa-Orešany Karst

The Kuchyňa-Orešany Karst is located in the northern part of the Pezinské Karpaty Mts. stretching from the WSW to ESE across the mountain range between Kuchyňa and Horné Orešany villages, with a partial offset to Píla village (Stankovičský, 1974). It is formed by Mesozoic complexes of the Fatric and Tatric units (Polák et al., 2012). The units have band-like structure, with alternating carbonate and non-carbonate units limiting the development and extent of the karst, including the size of the caves. The known caves do not exceed 60 m in length. The western part of the Orešany Karst is built by the Fatric Unit, which is composed of the Vysoká and Zliechov successions. A substantial part of the Fatric Unit in the Malé Karpaty Mts. is built by the Vysoká succession, which is mostly composed of

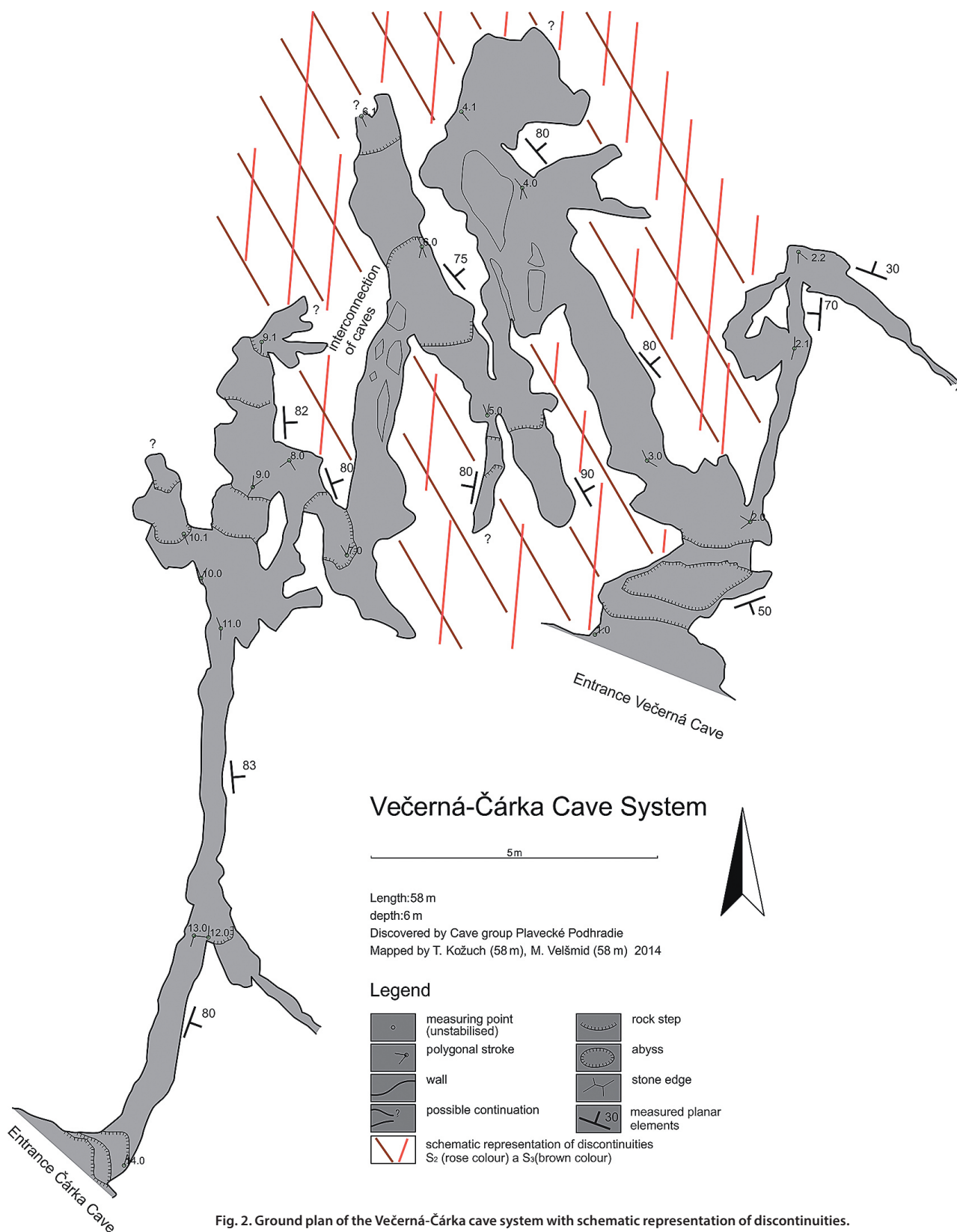


Fig. 2. Ground plan of the Večerná-Čárka cave system with schematic representation of discontinuities.

shallow-water sediments. Its range is from the Lower Triassic to the Upper Cretaceous. The Zliechov succession is represented only inferiorly and ranges from the Lower Jurassic to the Upper Cretaceous. Some caves are also bound to the Tatric Unit, more precisely to its Mesozoic carbonate complexes in the range

from Middle Triassic to Lower Cretaceous. The relief of the western part of the Kuchyňa-Orešany Karst is formed by a set of monoclin ridges formed on the layer fronts of the dolomitic-limestone complex (Stankoviánsky, 1982). Originally, the eastern part of Kuchyňa-Orešany Karst was considered as a part of the

Smolenice Karst (Droppa, 1952). However, Stankoviansky (1974, 1982) and Mitter (1983) have identified the Kuchyňa-Orešany Karst as a separate geomorphological karst unit, what has been late widely accepted (cf. Lačný, 2007; Hochmuth, 2008).

2. METHODS

Measurement of structural elements on the surface, as well as in the underground was performed by methods of structural geology, using a Freiberg-type geological compass. OpenStereo software was used to analyze and plot measured structures (Grohmann & Campanha, 2010).

Detailed inventory and documentation of corrosion rock shapes as well as whole morphology of passage and their spatial arrangement in relation to tectonic discontinuities enabled to clarify the natural conditions and processes of cave system formation. Using the documentation of the Večerná-Čárka cave system, the degree of connectivity of passages was determined based on graph analysis applied to the cave topology according to Howard (1971).

Dark coatings occurring on the walls of the cave passages and limestone blocks were examined microscopically and by X-ray diffraction analysis (XRD).

3. GEOLOGICAL SETTING OF THE CAVE SYSTEM

3.1. Lithology

The Večerná-Čárka cave system was formed in the Vysoká Formation consisting of dark grey to black, well-bedded limestone (Pelsonian – early Illyrian). The limestone of the Vysoká succession appears in a continuous lenses stretching from Kuchyňa village to Majdánske settlement. The limestone is a variety of the Gutenstein Formation, from which it differs only by the abundance of bioclastic limestones (Polák et al., 2012).

The Ramsau Dolomites appear in the overburden. The Upper Triassic deposits are characterized by a massive development of the Carpathian Keuper, which crops out in the northwestern part of the surveyed area (Fig. 3). In the southeastern part, the Vysoká succession is back-thrust onto the cover sequence of the Tatric Unit, represented by the Poruba Formation (Albian–Cenomanian).

3.2. Structural analysis

The area in scope excels in its good outcropping conditions, as it is located directly in the distinctive Modranská Skala rock ridge. A total of 26 planes were measured, of which 13 were measured directly in the caves. Based on the field research, the measured planes have been classified into four categories (S_0 , S_1 , S_2 , S_3), partly taking into account their genetic and temporal relationship (Fig. 4). The S_0 surfaces represent the bedding (blue arcs). They generally dip to the NW, with an average inclination of about 50°.

The S_1 planes (red arcs) are perpendicular to the S_0 surfaces. They yield similar dips as the S_0 surfaces, but their orientation

is opposite with dip direction towards S–SE. These planes are very commonly encountered on the surface. Sometimes the S_1 planes are more pronounced than the bedding itself. These may be cleavage planes (or jointing cleavages) measured, for example, in the northeastern part of the Plavecký Karst (Csibri & Lačný, 2014). It can be assumed that the planes originated during the early Miocene south-vergent overprint of the original north-vergent setting (Marko et al., 1991).

The third category consists of discontinuities with a N–S to NNE–SSW direction (S_2 , pink arches). They are steeply dipping to the west or east respectively. Such planes are commonly identified across the whole Malé Karpaty Mts. and they were important in the origin of caves of the Kuchyňa-Orešany Karst as well as in the Plavecký Karst (Lačný, 2013; Lánčzos et al., 2013; Csibri & Lačný, 2014).

The Malé Karpaty Mts. are expected to be in active compressional settings of N–S direction (Kováč et al., 2002), if the pure shear model is applied and, reactivation of fault structures must take place. This can be confirmed by long-term measurements in the Driny Cave (Briestenský et al., 2011). In this model, dilatation on N–S-trending faults should take place. Furthermore, horizontal displacements should take place on NW–SE- and NE–SW-trending faults. To the east of the studied cave system, a similar fault with the mentioned direction may be affinity (Fig. 3).

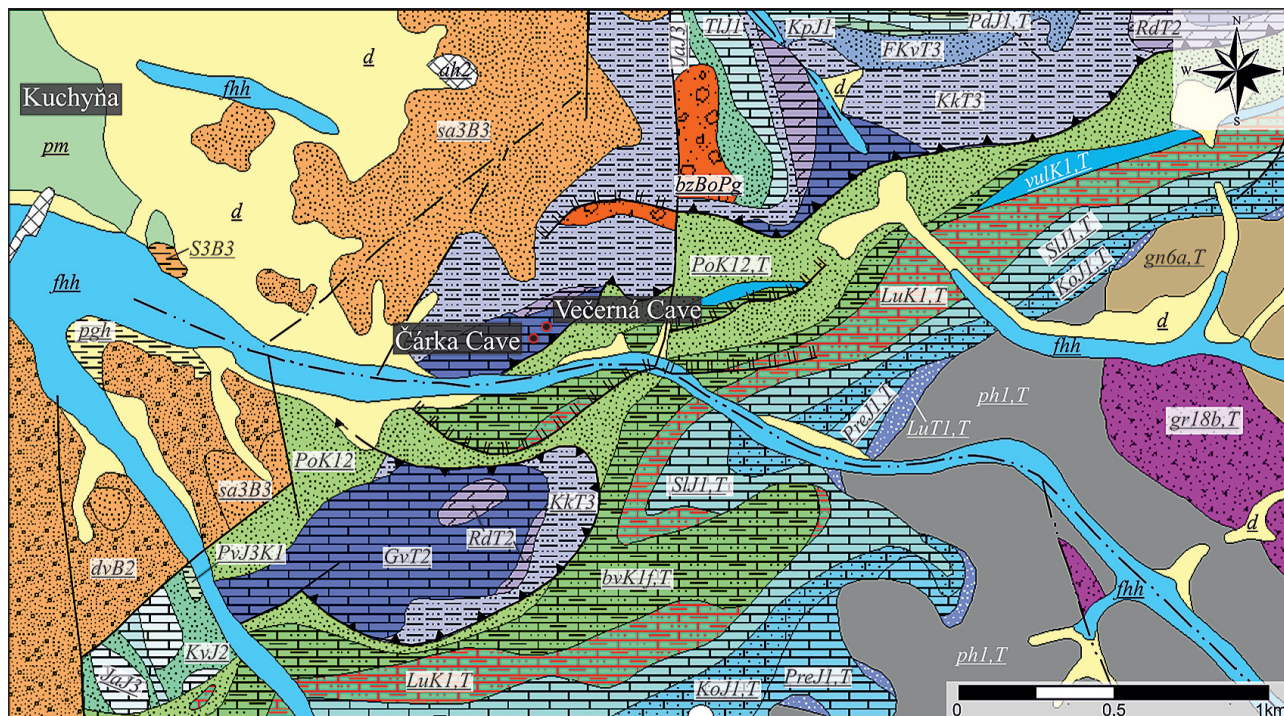
The fourth category consists of NW–SE-trending planes, which are almost sub-vertical (S_3 , brown arcs) and are bound to significant fault structures of this direction in the entire Malé Karpaty Mts. In the Kuchyňa-Orešany Karst, most cave spaces as well as the most important sinkhole lines seem to be controlled by them (Lačný, 2013; Lačný et al., 2018; Veselský et al., 2014^a, 2014^b).

From the genesis point of view, the Večerná-Čárka cave system was affected by two directions of brittle discontinuities of NW–SE (S_3) and NNE–SSW (S_2) directions (Fig. 2). The largest cave spaces originated at the intersections of the NW–SE and NNE–SSW oriented networks. The NW–SE direction seems to be the most dominant. The S_0 and S_1 planes play only a minor role in the cave genesis, and were identified in the horizontal parts of the cave. The surfaces inclined to the NW at an angle of 40°–50° probably influenced the karstification only marginally

4. CAVE MORPHOLOGY

4.1. Spatial pattern of cave passages

The entrance abyss-like part of the Večerná Cave at the depth of 6 m branches into two passages of NW–SE and NNE–SSW directions. These two passage directions also occur in other parts of the Večerná Cave as well as in the Čárka Cave (Fig. 2). These two systems cross in the northwest part of the Večerná Cave and the adjacent northern part of the Čárka Cave. The passages are wider (usually 1.5–2 m), and usually higher (up to 2.5 m) at the intersections of these two different directions. In the other parts of the caves, the passages are usually 0.5–1 m and in some places up to 1.5 m wide. Most of the passages are wedge-shaped upwards, and the bottom is covered by fine-grained sediments (Fig. 5A; in



Quaternary

- anthropogenic fillings
Recent - Subrecent, ah2
- deluvial sediments
Pleistocene/Holocene, *d*
- fluvial sediments
Late Pleistocene/Holocene, *fhh*
- deluvial-polygenetic sediments
Pleistocene/Holocene, *pgh*
- proluvial sediments
Middle Pleistocene, *pm*

Neogene (Viena Basin)

- Studienka Fm.**
Upper Badenian, *S3B3*
- Studienka Fm., Sandberg Mb.**
Upper Badenian, *sa3B3*
- Devínska N. Ves Fm.**
Middle Badenian, *dvB2*

Paleogene

- Borové Fm.**
Paleocene/Oligocene, *bzBoPg*

General explanations

- Assumed faults
- Faults
- Overthrust faults
- Nappe boundary identified
- Nappe boundary covered

Fatricum

- Kopienec Fm.,** Lower Jurassic (Hettangian-Sinemurian), *KpJ1*
- Fatra Fm.,** Kössen Mb. Upper Triassic (Rhaetian), *FKvT3*
- Carpathian Keuper Fm.** Upper Triassic (Norian), *Kkt3*
- Ramsau dolomites** Middle Triassic (Anisian-Ladinian), *RdT2*
- Gutenstein Fm.,** Annaberg lim. Middle Triassic (Anisian), *GvT2*

- Poruba Fm.,** Upp./Low. Cretaceous (Albian-Cenomanian), *PoK12*
- Padlá Voda Fm.,** Upper Jurassic-Low. Cretaceous (Tithonian-Berriasian), *PvJ3K1*
- Jaseniná Fm.,** Upper Jurassic (Kimmeridgian-Tithonian), *JaJ3*
- Sandy-krinoidic lim.** Middle Jurassic (Aalenian-Bathian), *KvJ2*
- Prístodolka Fm.** Lower Jurassic (Pliensbachian), *PdJ1.T*
- Trlenská Fm.** Lower Jurassic (Sinemurian), *TlJ1*

Tatricum

- Koreneč Fm.,** Lower Jurassic (Hettangian?), *KoJ1.T*
- Lúžna Fm.** Lower Triassic (Scythian), *LuT1.T*
- Bt-paragneisses** with flaky graphit, Upper Silurian-Lower Devonian, *gn6a.T*
- Graphitic-sericitic fylites,** Lower Paleozoic?, *ph1.T*
- Bt-granodiorites, tonalites** Paleozoic, *gr18b.T*

- Poruba Fm.,** Upp./Low. Cretaceous (Albian-Cenomanian), *PoK12.T*
- Organodetritic and sandy lim.** Lower Cretaceous (Barremian-Albian), *bvK1f.T*
- Vývrat Fm.,** alkali-basalts Lower Cretaceous (Bareman-Aptian), *vulK1.T*
- Lučivná Fm.,** Lower Cretaceous (Valanginian-Hauterivian), *LuK1.T*
- Slepý Fm.** Upper Jurassic (Oxfordian), *SlJ1.T*
- Prepadlé Fm.,** Lower Jurassic (Pliensbachian-Toarcian), *PreJ1.T*

Fig. 3. Geological map of the study area (after Polák et al., 2011).

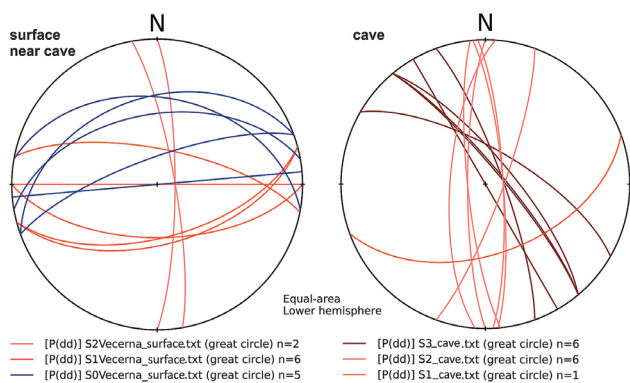


Fig. 4. Structural diagrams of the measured planar elements

some places they are protruded by longitudinal rocky spurs or narrow cavities which cannot be explored). Except from the entrance part, the other parts of the Večerná Cave are almost horizontal, similar to the passages of the Čárka Cave. The main passage of the Čárka Cave leads from the entrance towards the NNE and intersects with the other passages mainly in the northern parts.

Based on graph analysis applied to the topology of the horizontal caves (Howard, 1971), the ground plan of the Večerná-Čárka cave system represents a network of branched and intersecting passages with a low degree of interconnection (parameters: $\alpha = 0.041$; $\beta = 1.037$; $\gamma = 0.373$ / alternative parameters: $\alpha = 0.034$; $\beta = 1.031$; $\gamma = 0.367$). In the case of caves with several loops and a predominant dendritic pattern of passages, the valid parameters are: $\alpha = 0$, $\beta = 1$, $\gamma = 1/3$.

4.2. Smaller rock morphologies

In the Večerná Cave and in the northern part of the Čárka Cave (in the sector of their speleological interconnection), narrow rock walls separate parallel fissure passages (Fig. 5B,C). In places where rock partitions were destroyed, mostly at places of crossing tectonic discontinuities, elongated rock spurs hanging from the ceiling and upstanding from the floor are preserved (Fig. 5D). Rock spurs, which are narrow and reach from the ceiling or floor significantly into the cave passage, named rock blades (cf. Slabe, 1995). Because plate-like, pointed or rounded protruding rock shapes, arranged in a line, morphologically resembling a curtain dividing wall; in Czech and Slovak literature they are designated as 'coulisses' (Kunský, 1950 and others).

Rock partitions as well as elongated ceiling and floor rock spurs are perforated by numerous corrosion holes (Fig. 6A,B). The diameter of tubular rock holes is usually 10–15 cm, the largest holes are up to 25 cm in diameter. Floor rock spurs are rounded in places, probably due to 'below-sediment' corrosion (cf. Slabe, 1995; Bella & Urata, 2002).

Rock partitions (rock dividing walls; Bella, 2008) in both investigated caves are structurally conditioned by steep parallel tectonic discontinuities, formed by the same limestone as other parts of the caves. Although rock partitions are typical mostly for corrosion network of cave labyrinths (cf. Palmer, 1975, 1991; White, 1988), they also occur in branched caves predisposed by a dense network of parallel tectonic discontinuities. However,

rock partitions in some caves are conditioned lithologically, i.e. they are associated with narrow stripes of less soluble or harder insoluble rocks (cf. Osborne, 2005 and others).

In addition, numerous ceiling rock holes, also controlled by steep tectonic discontinuities, resulted from an intense karstification of limestone in the area of studied caves (Fig. 6C). Mixed corrosion contributed to their formation (rainwater seeping along a steep tectonic discontinuity was mixed with more saturated water filling the cave). Irregular rock holes or spongwork-like cavities deepened into the ceilings are less frequent and they are visible in the northwest part of the Večerná Cave (Fig. 6D).

5. CAVE DEPOSITS

The floors of both caves consist mainly of accumulations of clastic sediments of various grain sizes, which fill the lower parts of the cave spaces. The sub-angularly rounded blocks formed by carbonates of the Vysoká Formation are dominant. The clasts are of various sizes, usually decimeter dimensions. Between them clays occur, which were transported into the cave from the surface. Dark debris with osteological remains of recent animals occur in several places on the floors. Typical dripstone formations are hardly found in the cave system. Thin calcite coatings and crusts were precipitated on some sloping rock wall surfaces.

The Večerná Cave is also interesting for its black coatings on the rock walls and on the carbonate blocks forming its clastic fill (Fig. 7). Microscopic analysis confirmed the assumption that this was a secondary coating on the limestone surface (Fig. 8). The XRD analysis showed that this coating contained hydroxylapatite – $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$ (Fig. 9).

6. DISCUSSION

6.1. Origin and evolution of the cave system

Following the morphological classifications of caves (White, 1988; Palmer, 1991, 2000), the Večerná-Čárka cave system can be considered a branched cave formed by linear, intersecting passages, which strictly follow two systems of steep parallel and intersecting tectonic discontinuities. It has a phreatic origin, as evidenced by numerous well-preserved corrosion rock shapes (oval ceiling and wall holes, elongated ceiling and floor rock spurs). Its origin was controlled by numerous steep tectonic discontinuities, which cross in several places. Along them, the waters of deeper circulation ascended upwards. Since these waters were relatively saturated, limestones dissolved mostly in the zone of mixing with the seeping rainwater. The absence of water-table notches on the rock walls, ceiling cupolas and oval blind chimneys indicates that the caves formed more or less just below the piezometric surface of groundwater and without its significant oscillations, i.e. in the shallow phreatic zone. Due to the parallel arrangement of tectonic discontinuities, narrow rock walls between adjacent fissure passages gradually thinned and were disrupted by rock holes and windows, in some places they were fully destroyed (only elongated rock spurs protruding

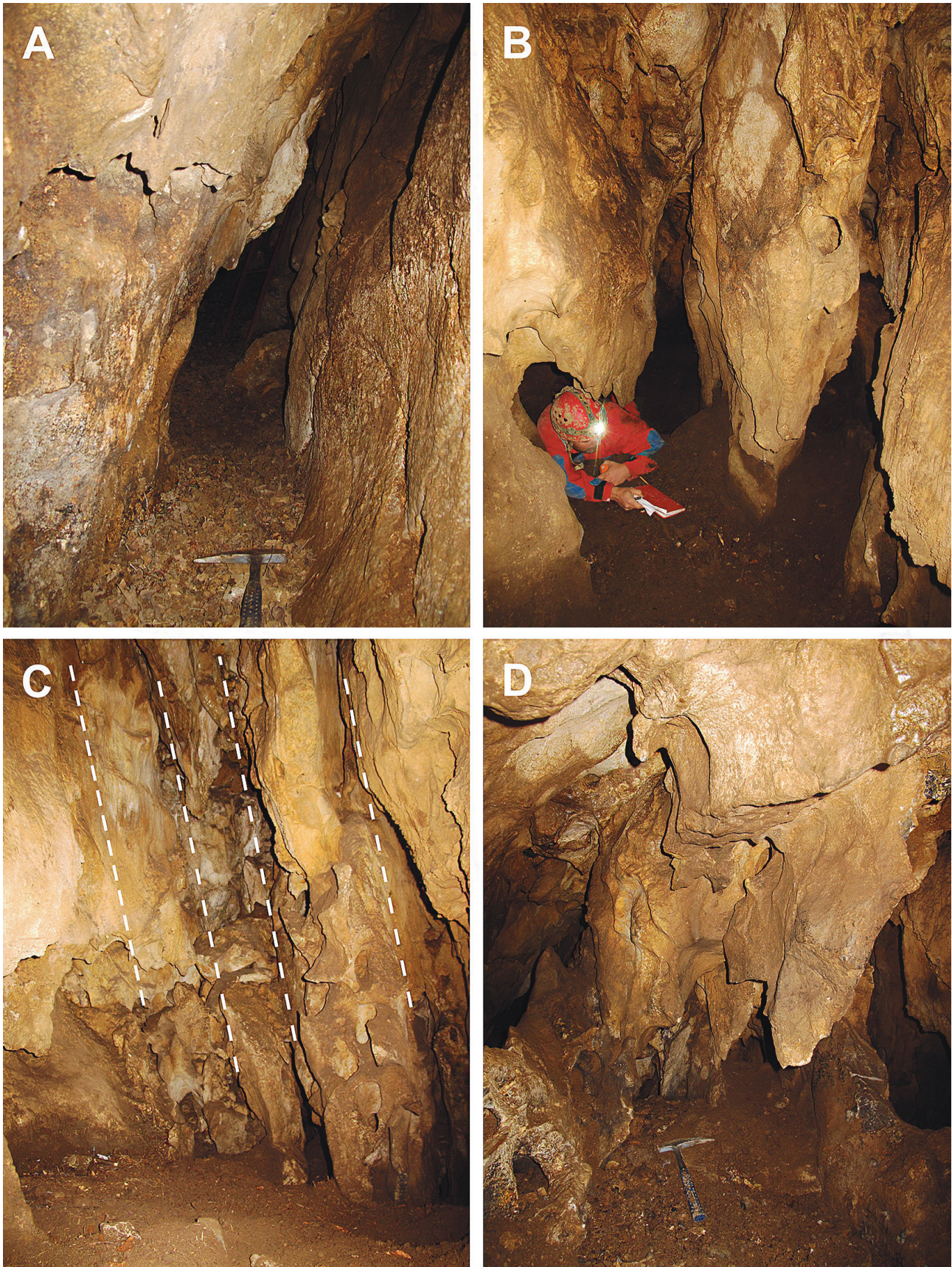


Fig. 5. Major morphology of cave passages: A – narrow fissure passage controlled by steep tectonic discontinuity, B – passage partly divided by a vertical rock partition, C – parallel steep fissures enlarged by the dissolution of limestone between rock partitions, D – ceiling and floor elongated rock protrusions as remains of the destruction of rock partitions. Photo: P. Bella

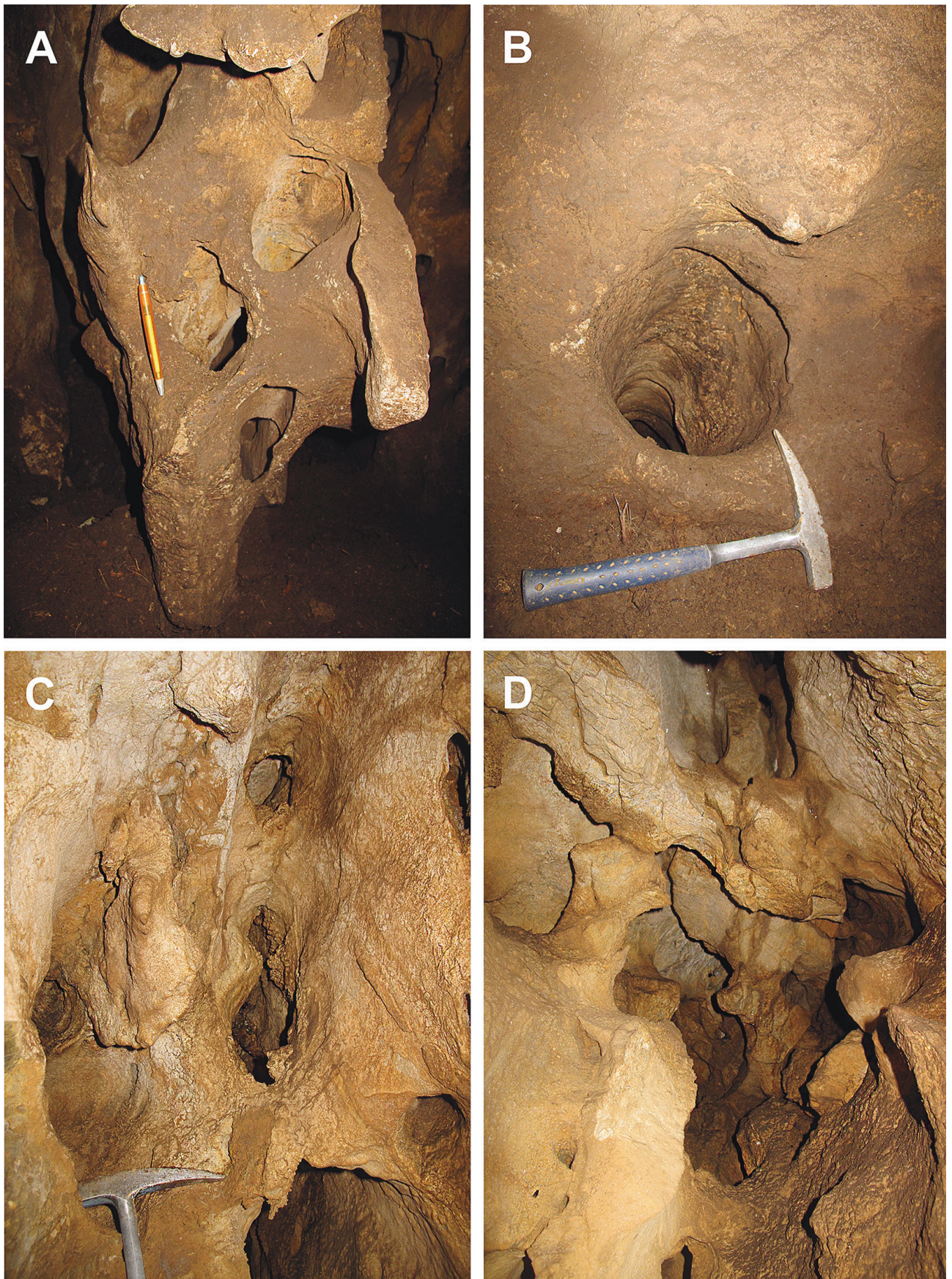


Fig. 6. Small-scale deepened solution forms: A – tube-like hollows leading through a rock partition, B – tube-like hollow in the rock wall, C – ceiling pockets controlled by a steep tectonic discontinuity, D – spongework-like hollows on the cave ceiling.,. Photo: P. Bella



Fig. 7. Coated carbonates. Photo: A. Lačný

from ceilings and floors remained; Fig. 10). Rock partitions were mostly destroyed at the intersections of tectonic discontinuities, where the passages are usually widest.

A dense network of steep parallel and intersecting tectonic discontinuities allowed diffuse groundwater circulation without much concentration of water flow to one or more main conduits (the studied cave system has not features typical for a river branch drainage system). Following the continuing incision of the bottom of the valley, the groundwater level dropped and the caves reached the vadose zone. The water seeping from the surface into the caves only slightly renewed the original phreatic morphology of the passages, in which ceiling fissures were enlarged. Calcite

coatings and crusts were precipitated at the places where they run down the sloping rock walls. The original phreatic cavities were largely filled with fine-grained sediments washed down from the surface. Some steep, corrosion fissures have been completely filled with sediments (mostly in the lower and presumed, lower-lying cave parts). The slope sediments, including debris, fill the eastern edge of abyss-like fissure in the entrance part of the Večerná Cave.

The occurrence of black hydroxylapatite-containing coatings in almost the entire cave may indicate that it was used as a wintering place for bats in the past. Its parts, which are currently covered with washed clay, were previously free spaces.

The predominant phreatic morphology of the underground spaces (especially in places almost completely corroded rock walls, numerous oval rock holes and cavities), parallel and intersecting cave passages predisposed by steep tectonic disturbances, as well as a slightly elevated water temperature in the nearby spring under the Modranská skala points to possible hypogenic speleogenesis of the investigated caves. The water temperature in this spring reaches more than 12 °C; the water temperature in the other permanent springs of the Kuchyňa-Orešany Karst is on average around 8 °C (Lačný, 2012). The hypogenic origin of the caves with slightly heated waters ascending along the faults at the tectonic boundary of the Malé Karpaty Mts. and Vienna Basin was confirmed near the Plavecké Podhradie village (Bella, 2010; Bela & Bosák, 2012; Bella et al., 2019^a, 2019^b).

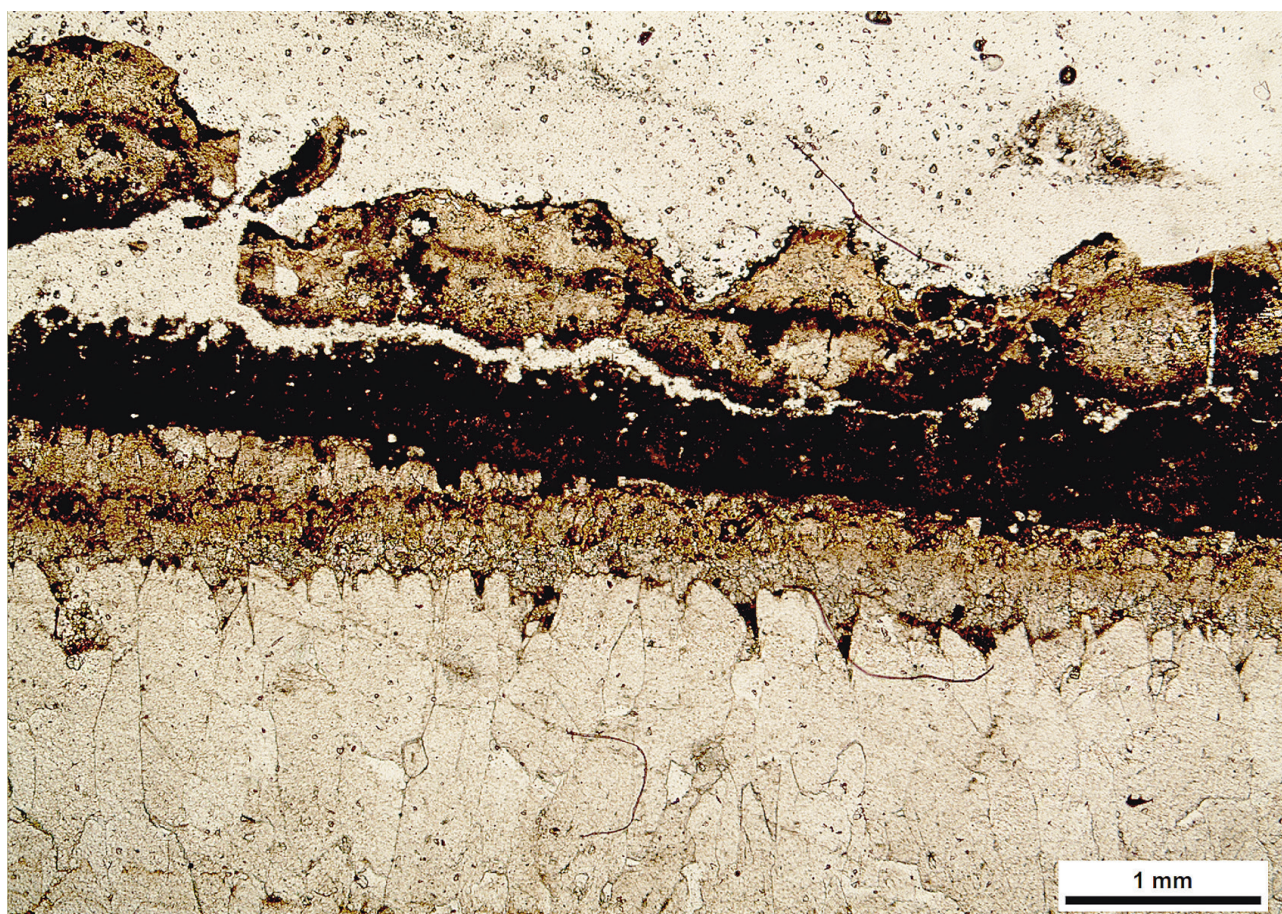


Fig. 8. Oxidation coating, IIN. Photo: A. Lačný

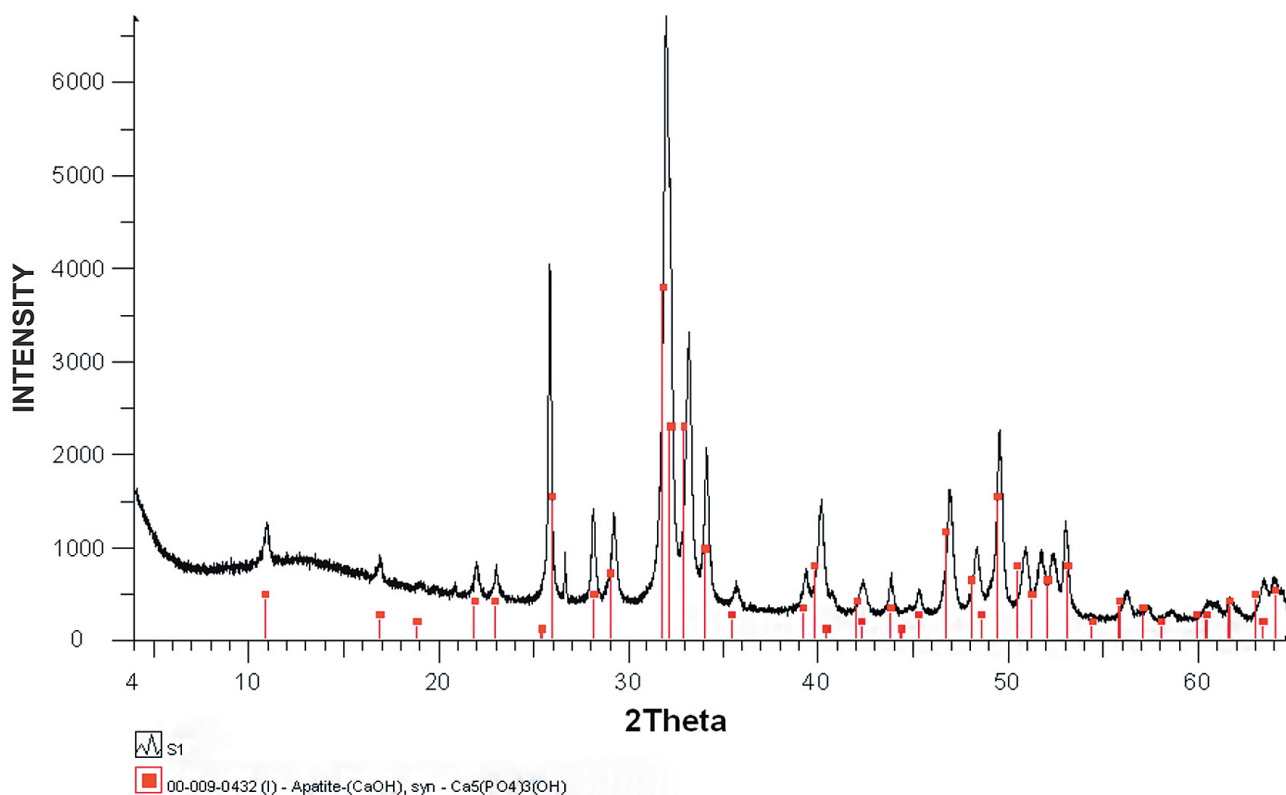


Fig. 9. X-ray record from the analyzed black coating containing hydroxylapatite

6.2. Estimated age of the cave system

The time of the cave system origin can be approximately determined based on its height position in view of height positions of the recent hydrographic network and the surrounding planation landforms. In the southern part of the Pezinské Karpaty Mts., in the Borinka Karst, a horizontal, river-modelled section of the Stará Garda Cave, located about 45 m above the present bottom of the Stupavský brook valley, was formed in the Early Pleistocene (proven by dating of allochthonous fluvial sediments

using cosmogenic nuclides ¹⁰Be and ²⁶Al; cf. Šujan et al., 2017). If neotectonic movements in the Borinka Karst and the Kuchyňa-Orešany Karst were not significantly different, the Večerná-Čárka cave system (413–419 m above sea level; at 54–60 m above the bottom of the valley) could probably be older than the mentioned part of the Stará Garda Cave. Probably, it could be formed in the Pliocene (Late Pliocene).

At the time of the phase of phreatic development, the studied caves were probably just below the level of the valley bottom. Remnants of the Plio-Pleistocene river level along the periphery

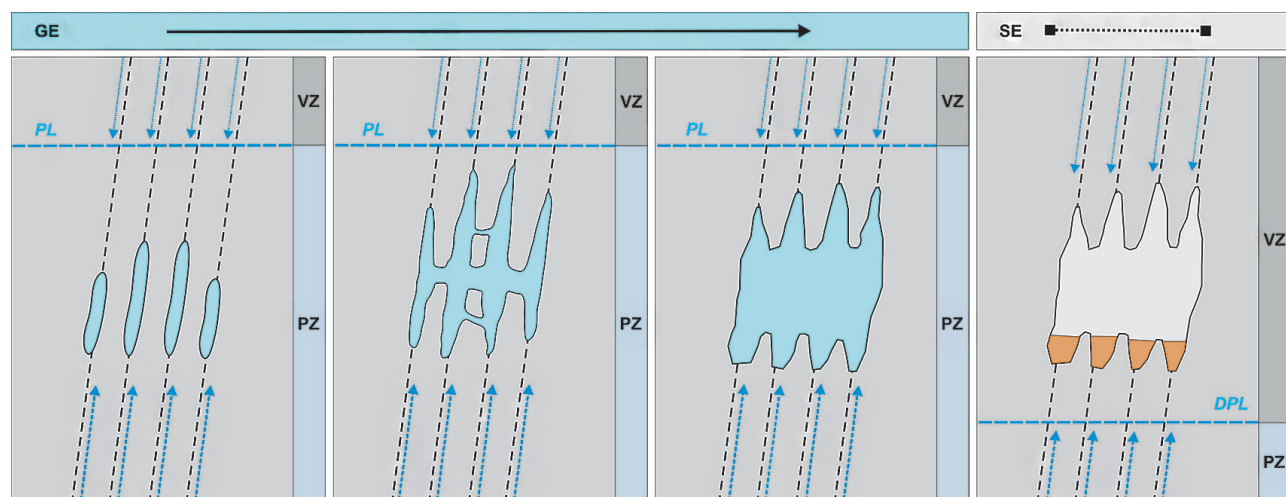


Fig. 10. Sketch of the origin and development of cave passages by the gradual corrosive destruction of parallel limestone partitions: PZ – phreatic zone, VZ – vadose zone, PL – piezometric surface of groundwater, DPL – decreased piezometric surface of groundwater due to the lowering of the local base level of erosion (e.g. the incision of valley), GE – phases of gradual enlargement of passages in the phreatic zone, SE – ended corrosive enlargement of passages in the vadose zone

of the southern part of the Malé Karpaty Mts. are preserved at altitudes of 250–350 m (Urbánek, 1992).

6.3. Implications from the hydroxylapatite occurrence for the nature conservation

The hydroxylapatite is phosphate mineral of organic origin and is the direct reaction product of the bat guano and limestone (due to the neutralization of the acidic solution at the contact with limestone). Therefore, it is the most common phosphate mineral in caves. It was firstly identified by Shepard (1882) who named it 'monite' according to the Island Mona, Puerto Rico. It is stable at pH 6.2–6.6. The hydroxylapatite is known from many caves of the world (Shepard, 1882; Schadler, 1929; Dunn & White, 1957; Kaye, 1959; White & Dunn, 1962; Hill & Forti, 1997; Audra et al., 2019 and others).

The hydroxylapatite occurrence proves that the Večerná Cave was a significant chiropterological site. We observed some bats in the Večerná Cave also during our field research in September 2019. In the Večerná-Čárka cave system, more regular observations of bats are needed as they are protected species.

7. CONCLUSIONS

The morphology of the Večerná-Čárka cave system points to their origin under phreatic conditions when the underground spaces were completely filled with water. The waters ascended along significant steep tectonic discontinuities. They were gradually enlarged by limestone dissolution. This process was the most intensive in the mixing zone of rising largely saturated waters with more aggressive waters seeping from the surface. At the places of denser parallel or intersecting oblique tectonic discontinuities, the separating rock partitions were completely eroded by corrosion that expanded the underground spaces laterally. Cave formation was strongly predetermined by steep tectonic disturbances of N–S and NW–SE direction. In the vadose phase of the development, after the groundwater level dropped due to the incision of the bottom of the valley below the level of the caves, the water seeping from the rain or melting snow only non-significantly influenced the cave morphology. However, they caused the precipitation of calcite coatings and crusts on some parts of the cave walls and the transport of fine-grained sediments from the surface into the caves. It may be assumed that most of the cave spaces are currently filled with clay, partly also with limestone blocks and debris. Local cavers have largely removed this material from the caves. Thereby the extent of their explored parts has been significantly enlarged. This made it possible to formulate a more comprehensive view of the origin and development of underground spaces.

The research results to date indicate that the Večerná-Čárka cave system is a remarkable and important site in the karst of marginal parts of the Malé Karpaty Mts. The investigated part of the Kuchyňa-Orešany Karst is located near a significant discontinuity, which separates the Malé Karpaty Mts. and the Vienna Basin. The results of this research complement the existing knowledge about the specific conditions and speleogenetic

processes (ascending phreatic speleogenesis) in the marginal parts of the Malé Karpaty Mts. and raise challenges for further research on similarly located caves.

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