Extraordinary geology and fault-controlled phreatic origin of the Zápoľná Cave (Kozie chrbty Mountains, Slovakia)

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Abstract: The Zápoľná Cave is located in the SW part of the Kozie chrbty Mountains in the valley of the Čierny Váh River. It is formed in the carbonates of the Gutenstein Formation, right above the décollement plane of the Svarín Partial Nappe (belonging to the Hronic Unit). The rocks bear marks of intensive brittle deformation indicating that the nappe emplacement occurred in relatively cold conditions. The fine-grained sandstone, considerably atypical for the purely carbonate Gutenstein Formation, occurs in the cave. It probably reflects the transition from the underlying siliciclastic Šuňava Formation, which most likely acted as a tectonic lubricant during the nappe translation, and is at present tectonically amputated from the Svarín Partial Nappe. The cave passages follow mainly faults or joints with two general types of orientation – the N–S direction and the E–W directions. Their contribution to the genesis of the cave was not only passive but also active, as they show the signs of the neotectonic activity. Based on the speleomorphological features, the cave evolution is divided into three phases: (I) deep in phreatic zone when the majority of the cave volume was formed by slowly circulating water along the discontinuities (mainly steep faults/joints) in the host rock; (II) in epiphreatic zone characterized by the appearance of the water table in the middle parts of the cave, and followed by its slow fall; and (III) in vadose zone after the water table decline, is characterized mainly by collapse processes. The evidence from cave morphology and fills suggests that there was no ponor through which the Čierny Váh River could enter the cave directly. The phases of the cave evolution, along with the activity of the E–W-trending discontinuities, could be linked to the activity of the Vikartovce Fault located in the south-eastern part of Kozie chrbty Mts., which was active up to Late Quaternary.

Key words: karst, phreatic morphology, Western Carpathians, neotectonics, Hronic Unit, nappe décollement

1. INTRODUCTION

The Zápoľná Cave is located in northern Slovakia, at the south-western part of the Kozie chrbty Mountains (Fig. 1a). The cave is situated in the vicinity of the Svarín village, on the right (northern) side of the Čierny Váh River Valley, approximately 2.5 km downstream from the artificial dam (Fig. 1b). The Čierny Váh River represents a natural boundary between the Kozie chrbty Mountains and adjacent Nízke Tatry Mountains. The cave entrance is located circa 50 m above the bottom of the valley, at altitude 755 m a.s.l. Current length of the cave is 1,813 m, with the vertical span of 59 m, with some parts of the cave being located at altitudes lower than the current riverbed of the Čierny Váh River.

The Zápoľná Cave was declared to be the national natural monument in 2001, but only few scientific studies have been published since its discovery more than 70 years ago. Droppa (1962[a], 1962[b]) mentioned the cave circa 20 years after its discovery, reporting on its accidental discovery during the preparation works for construction of the dam at the Čierny Váh River between 1939–1941. However, both papers describe only a fragment of currently known underground space, calling it Zápoľná Abyss. Substantial amount of the cave spaces was discovered by volunteer cavers during the late nineties, and new findings were reported by Hochmuth (1997), Holúbek (1998), Holúbek & Kráľ (2001), and Bella & Holúbek (2002). Bella and Bosák (2012) described the Zápoľná Cave as the example of the speleogenesis along deep

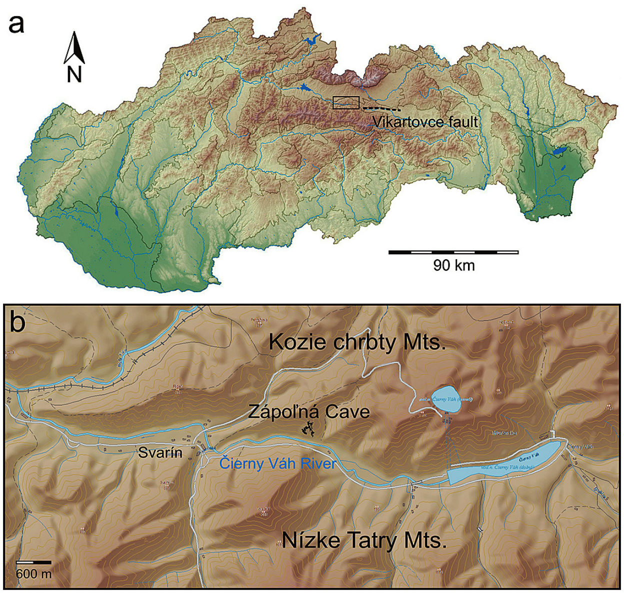

Fig. 1. Location of the Zápoľná Cave marked in the digital terrain model of: a) Slovakia; b) area surrounding the Zápoľná Cave (modified from the ŠGÚDŠ site).

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faults by slowly ascending waters. The published works focused mainly on the description of new discoveries, comments on the morphology and cave genesis. None of them dealt with the detailed description of the cave geology or genesis in wider context of the evolution of the surrounding area. The aim of the article is to fill this gap by presenting new data on tectonics and lithology of the host rocks. It provides also some key insights into its genesis in the context of geomorphological evolution of the cave vicinity.

2. GEOLOGICAL SETTING

The Zápoľná Cave entrance is located in the basal rocks of the Svarín Partial Nappe (Fig. 2) belonging to the Hronic Unit (or Choč Nappe). The rocks of the Hronic Unit cropping out in the cave vicinity are divided into three partial nappes: the Svarín Partial Nappe, Malužiná Partial Nappe, and Boca Partial Nappe (Biely et al., 1997; Havrila, 2011). The stratigraphic sequence of the uppermost Svarín Partial Nappe is composed mainly of the Middle to Upper Triassic formations of the Biely Váh Basin sequence. The occurrence of deep water Reifling Limestone (upper Anisian to lower Carnian cherty limestone) and Lunz Beds (upper Carnian sandstones and shales) represent the characteristic feature of the sequence (Biely et al., 1992). The Svarín Partial Nappe is overthrust on the Malužiná Partial Nappe, which contains Upper Permian to Lower Cretaceous formations. The lowermost Boca Partial Nappe is composed mainly of the Carboniferous to Middle Triassic formations and Upper Jurassic to Lower Cretaceous rocks located on the contact with the Malužiná Partial Nappe (Fig. 2). Lithology of both lower partial nappes indicates that they belong to the sequence of the Čierny Váh Carbonate Platform (Havrila, 2011). While the rocks at the uppermost part of the Malužiná Partial Nappe are intensively folded, the rocks of the Svarín Partial Nappe seem to be remarkably undeformed (Fig. 2).

Until now, the lithology of the Zápoľná Cave was not studied in detail. Droppa (1962[a], 1962[b]) described the entrance section of the cave, formed in Anisian grey blue limestone interwoven with

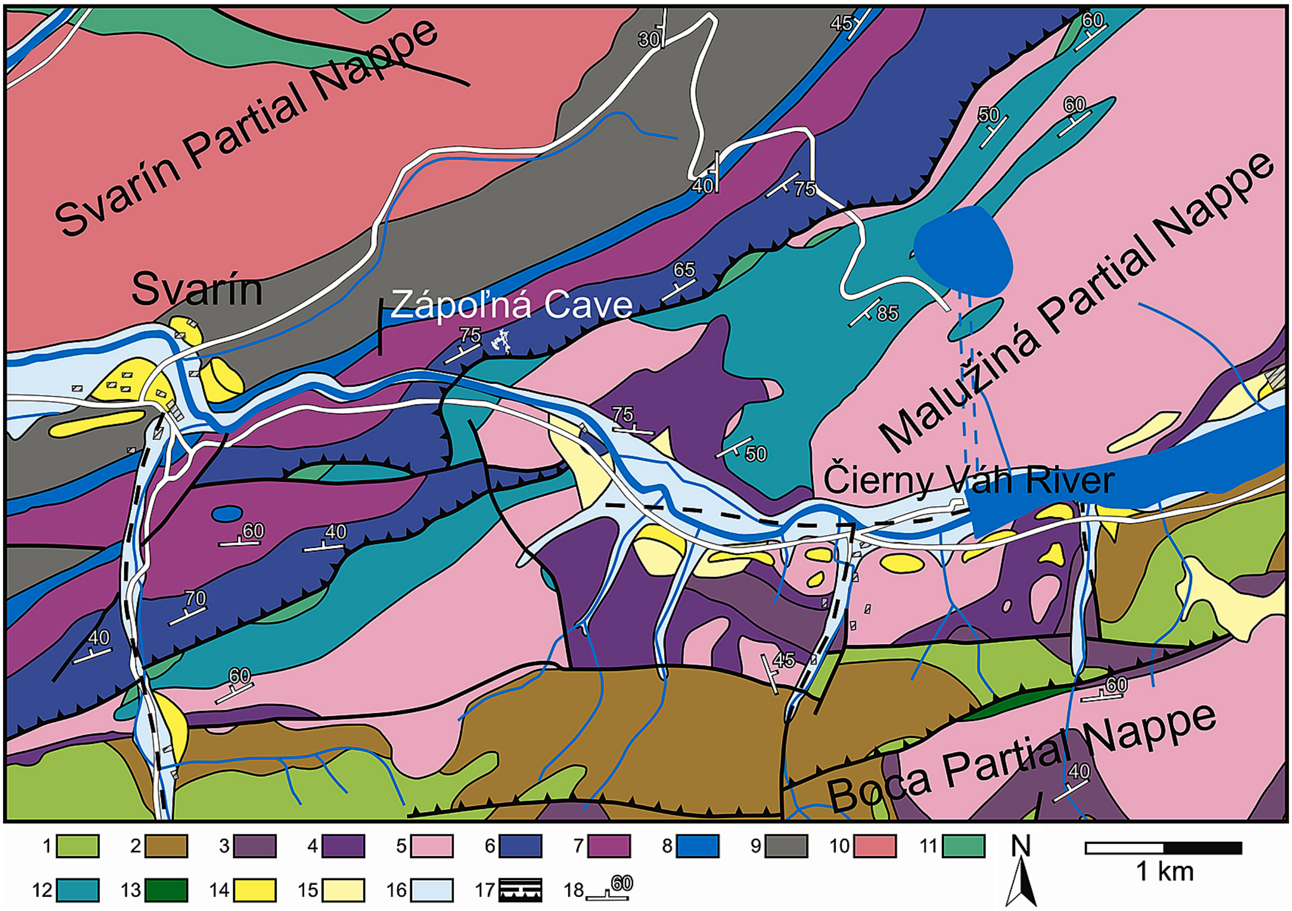

Fig. 2. Geological map of the area surrounding the Zápoľná Cave (based on Biely et al., 1992, 1997; Havrila, 2011). 1. volcanites of the Malužiná Formation (tholeitic basalts and andesites, Upper Permian); 2. sediments of the Malužiná Formation (variegated sandstones and shales, Upper Permian); 3. Benkové Formation (sandstones, sandy and clayey shales, Lower Triassic); 4. Šuňava Formation (sandstones, clayey and sericitic shales, limestones, marly limestones, Lower Triassic); 5. grey dolomites (Middle – Upper Triassic); 6. Gutenstein Formation (black to dark grey limestones, Middle Triassic); 7. Ramsau Dolomite (grey dolomites, Middle Triassic); 8. Reifling Limestone (grey cherty limestones, Middle – Upper Triassic); 9. Lunz Beds (sandstones with black shales, Upper Triassic); 10. Haupt dolomite (light grey dolomites, Upper Triassic); 11. Fatra Formation and Dachstein Limestone (light grey and pink limestones, Upper Triassic); 12. grey limestones with nodules of silicites (Lower Jurassic); 13. light grey and beige muddy limestones (Upper Jurassic – Lower Cretaceous); 14. river terraces (Quaternary); 15. deluvial sediments (Quarternary); 16. alluvial plains (Holocene); 17. faults (from top to bottom): observed, expected, nappe thrust lines.

dense lattice of secondary calcite veins. Bella & Holúbek (2002) mention that the majority of the cave is formed in the Gutenstein Limestone (Gutenstein Formation in the revised terminology, see Havrila, 2011). This Middle Triassic formation is composed mainly of black to dark grey, bedded or massive micritic limestone, with occasional layers of dolomite (Biely et al., 1997).

Several peculiar features in the geomorphology and arrangement of Quaternary deposits are visible in the area near the Zápoľná Cave. Wide alluvial plain of the Čierny Váh River narrows down significantly in the cave vicinity, and then broadens again near the Svarín village. Both sides of the valley are composed of practically identical rocks, yet the right (northern) side of the valley is considerably steeper, and its drainage is much less developed (Fig. 1b). In a similar way, the Quaternary deposits including river terraces and deluvial sediments are located almost exclusively on the left side of the valley (Fig. 2). The development of the accumulations on the right side of the valley in the Fig. 2 was probably induced by left-bank tributary located outside of the displayed area but visible in Fig. 1b.

Due to high fissuration, the rocks at the lowermost parts of the nappe do not tend to crop out frequently. Therefore, the Zápoľná Cave could potentially serve as a well-suited place for the observation and study of rocks near basal parts of the Svarín Partial Nappe. Moreover the arrangement of the Quaternary sediments near the cave, especially the fluvial terraces, points out to some degree of Quaternary tectonic activity occurring in the area. Therefore the evaluation of the data concerning the genesis of the Zápoľná Cave could help to decipher the neotectonic evolution of the area. Neotectonics in the Western Carpathians were defined as post-Miocene tectonic processes (Hók et al., 2000).

3. METHODS

Several surveys of the cave were carried out with the focus on mapping of the cave lithology including the measurements of bedding planes and faults. The survey was also focused on the identification of key morphological features important for the evaluation of the cave genesis. Ten rock samples were taken from various places of the cave (marked in Fig. 3) in order to represent the broadest possible stratigraphic interval. An acid test with 5% hydrochlorid acid was performed on every sample. Nine thin sections were prepared by Geoanalytical Laboratory of State Geological Survey of Dionýz Štúr. The thin sections were analyzed in petrographic microscope for observation of the texture, minerals, fossils, and other microfacial characteristics. The samples were chemically analyzed in the laboratory of State Geological Survey of Dionýz Štúr, mainly in order to determine the ratio of MgO to CaO, and to detect the occurrence of other constituents. Commonly used classification of limestone-dolomite series (e.g., Petránek, 1963) was used for identification of the rock samples; MgO content from 21.9 to 19.7 %, 19.7 to 10.9 %, and 10.9 to 2.2 % are considered as dolomite, limy dolomite, and dolomitic limestone respectively.

4. RESULTS AND DISCUSSION

4.1. Lithology

The limestones of the Gutenstein Formation in the Zápoľná Cave are bedded and have dark grey colour. The bed thickness varies from 2 to 20 cm with occasional occurrence of thinner bedding or lamination (Fig. 4a). Due to the strong deformation, the rocks are brecciated at several places (Fig. 4b); e.g., in the middle of the Upper Passage (Fig. 3, Z-4 sample). In brecciated rock, the calcite veins often separate fragments with profoundly different microfacies indicating that movements of great magnitude occurred within the rock (Fig. 4c). The recrystallization or microbrecciation is also observable under the microscope; Z-1, Z-3, and Z-6 samples (Fig. 3) were identified as partially recrystallized microsparite with occasional poorly preserved bioclasts (ostracode shells could be reliably identified, Fig. 4d). Z-1 sample also contains remnants of evaporite pseudomorphoses ('bird eyes'), and sparite in Z-6 sample shows remnants of layered texture.

The limestones contain various admixtures of dolomite or directly transition into calcitic dolomite with MgO content around 15–18 % (Tab. 1). Dolomite with the higher content of the MgO (19.7–21.9 %) was not identified in chemical analyses, and probably does not occur in the cave. Thick-bedded grey to dark grey

Tab. 1. Chemical analyses of samples from the Zápoľná Cave. The values are percentual.

chemical components	sample Z-2 breccia	sample Z-5 sandstone	sample Z-7 limey dolomite	sample Z-8 limey dolomite	sample Z-9 limey dolomite	sample Z-10 limestone
SiO_2	5.61	86.3	2.08	7.11	5.54	1.73
Al_2O_3	1.87	1.81	0.72	2.06	1.79	0.67
Fe_2O_3	0.77	2.84	0.28	0.91	0.87	0.40
CaO	37.6	3.74	39.8	31.6	30.3	52.0
MgO	11.4	0.28	12.1	15.7	17.8	1.99
TiO_2	0.09	0.08	0.03	0.10	0.09	0.03
MnO	0.02	0.37	0.08	0.02	0.02	<0.01
K_2O	0.73	0.42	0.29	0.85	0.66	0.29
Na_2O	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
P_2O_5	0.06	0.05	0.06	0.05	0.04	0.03
loss on ignition	41.7	3.97	44.3	41.3	42.8	42.7

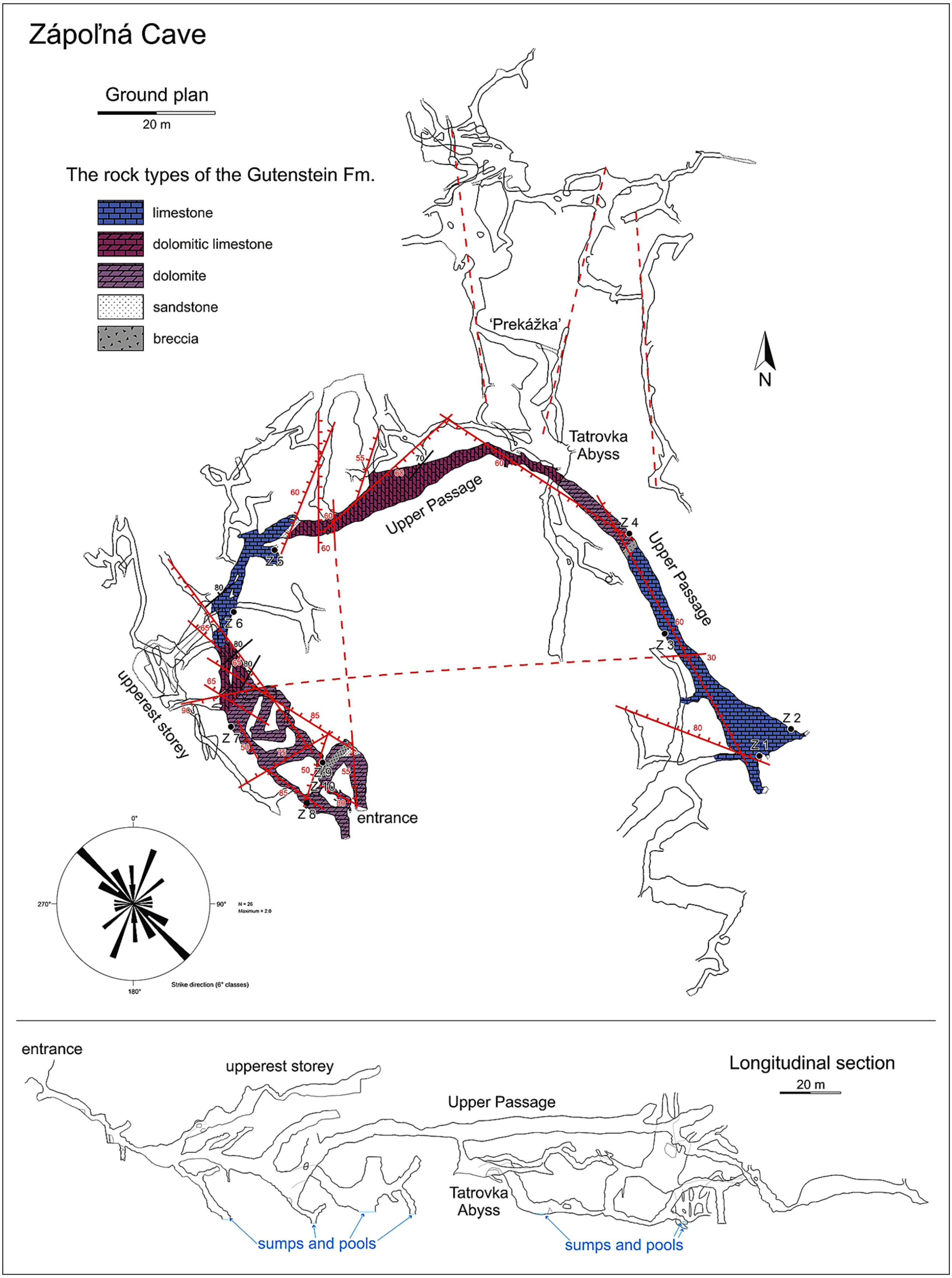

Fig. 3. Ground plan and longitudinal profile of the Zápoľná Cave. The ground plan contains mapped rock types, marked places of sample collection (black dots from Z-1 to Z-10), orientation of the bedding planes (black lines), mapped (ticked lines) and expected (dashed lines) faults. The orientation of discontinuities measured in the Zápoľná Cave is shown in the rose diagram created by Stereo32 software (Röller & Trepmann, 2003).

dolomites occur mainly in the middle parts of the Upper Passage. Dolomites are often brecciated and/or tectonically perturbed by calcite veins. They are represented by partially recrystallized dolomicrosparites, with remnants of evaporite pseudomorphoses (Fig. 4e). Near the entrance, within the zone of intensive tectonic fracturing, the dolomites contain silty admixture, which

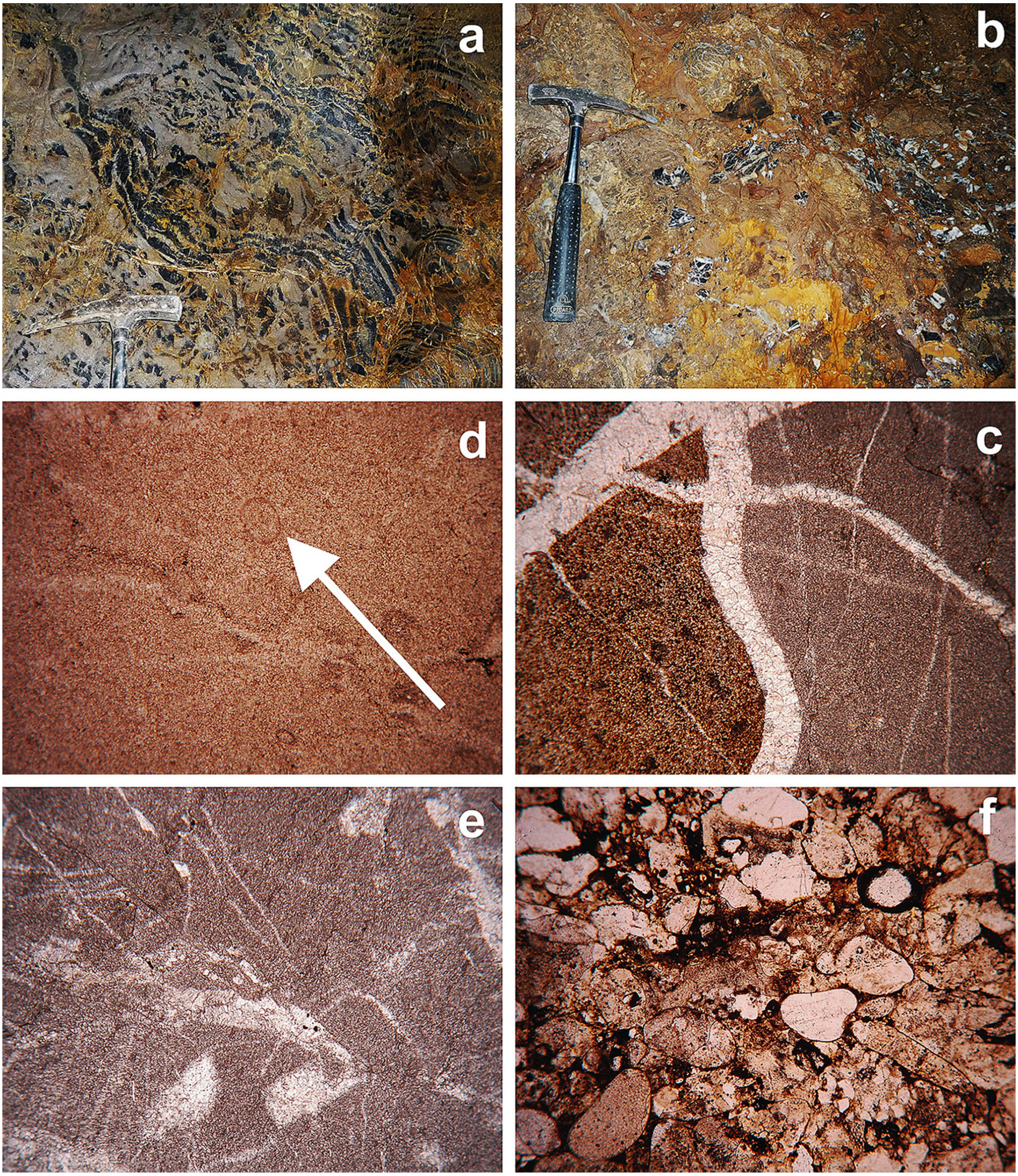

Fig. 4. a) Laminated rocks of the Gutenstein Formation cropping out at the cave wall. Increased content of siliciclastic material was observed in grey layers. Note that due to the shape of the walls, the rock appears to be folded. b) Dolomitic breccia in the middle parts of the Upper Passage. c) Breccia fragments separated by calcite veins (sample Z-4). The fragment at the right is impregnated by iron oxide. Magnification approximately 30x. d) Ostracode (marked white arrow) in microsparite of Gutenstein Formation (sample Z-3). Magnification approximately 30×. e) Pseudomorphoses after evaporite in dolomitic breccia (sample Z-4). Magnification approximately 40×. f) Well-rounded quartz grains in the limey sandstone (sample Z-5). Magnification approximately 30×, plane polarized nicols. Photo: Ľ. Gaál.

macroscopically changes their colour to grey brown (Z-8 and Z-9 samples). The dolomites contain small angular grains of quartz (about 0.05 mm), occasional pyrite, and iron hydroxides. Higher SiO_2 content was also detected in chemical analyses of Z-7, Z-8, and Z-9 samples (2.08 to 7.11 %). Near the entrance, the layer of brecciated limestone (Z-10 sample) with clasts of light brown colour occurs within the dolomites. It contains clastic admixture, with slightly increased silty content (1.73 % SiO_2).

At several places (e.g., under the entrance to the Upper Passage) thin lenses of fine, dark brown quartz arenite are emplaced within the Gutenstein Formation. Thanks to the selective chemical erosion, the sandstone starkly protrudes from the cave walls. It is composed of both angular and well-rounded quartz grains (grain size about 0.6 mm), with occasional fan-shaped chalcedony crystals, and spicules of siliceous sponges (Fig. 4f). Matrix is siliceous, and locally impregnated by red-brown iron hydroxides. Most of the rock is made up of SiO_2 (86 %), with CaO and Fe_2O_3 (making up 3.74 and 2.8 % respectively, Tab. 1).

The Zápoľná Cave is situated in limestones and dolomites of the Gutenstein Formation. The intercalating beds of the limestone and dolomite lend the credence for usage of the term 'Gutenstein Formation' rather than 'Gutenstein Limestone' (cf. Havrila, 2011). Numerous calcite veins occur in the rock, presumably as a result of strong fracturing due to its proximity to the décollement plane. Strong tectonic influence is also indicated by frequent occurrences of breccias and microbreccias, as well as partial limestone recrystallization. The primary micritic matrix is often recrystallized to sparite, and the original fossil material is obscured.

The presence of terrigeneous admixture, not typical for the lagunar rocks of Gutenstein Formation, represents one of the most peculiar features in the Zápoľná Cave. The admixture occurs in two forms: as the layers and lenses of fine-grained sandstone, or as increased content of silt in the calcitic dolomite. The siliciclastic material is more typical for the stratigraphically older (Lower Triassic) Šuňava Formation (Biely et al., 1997). The formation is absent in the Svarín Partial Nappe, due to the expected tectonic amputation from the overlying Gutenstein Formation during the thrusting. The horizons with the admixture of siliciclastic material therefore most likely represent lowermost parts of the Gutenstein Formation, implicating that the contact between both formations is gradational. Considering that the Šuňava Formation probably served as tectonic lubricant for the movement of the Svarín Partial Nappe, it cannot be ruled out that at least some sandstone lenses were tectonically wedged among the beds of the Gutenstein Formation.

4.2. Geological structures

The beds in the cave generally dip steeply (~80°) towards the NE (azimuth ~320°). Similar orientation of the beds, albeit with less steeper (~60°) dip, was also measured from the surface outcrops of the Gutenstein Formation near the cave. At several places, the rocks appear to be folded; however the seeming folding is just a projection caused by the shape of corroded cave walls (Figs. 4a and 5a). The lens of the fine-grained sandstone located near the cave entrance seems to be tectonically emplaced in its position, rather than being part of the original coherent sedimentary sequence (Fig. 5b).

Several brecciated zones can be observed in the cave (Figs. 4b and 5c). Their orientation corresponds with the orientation of the thrust line of the Svarín Partial Nappe. One such zone is located near the cave entrance, dipping at relatively shallow angle (~20°) northwestwards. It crosses the middle part of the Upper Passage along another significant brecciated zone with similar orientation. The latter is filled with fault gouge, and is located at the end of the passage. Strong rock fracturing, as well as numerous calcite veins (Fig. 5d), also probably result from the close proximity of the cave to the sole of the Svarín Partial Nappe. These structures are most likely genetically related to the décollement plane of the Svarín Partial Nappe, and their brittle character reveals that the nappe emplacement occurred in relatively cold conditions.

A number of tectonically induced faults and joints disturbing the rock massive can be observed within the cave. The location, orientation, and dip of the mapped faults are marked in Fig. 3. Most numerous of them are the NW–SE- to NNE–SSW-trending faults, while the E–W- to NE–SW-trending faults are less frequent (see rose diagram in Fig. 3). Due to steep dip of the bedding planes, it is entirely possible that they could also be reactivated as planes of movement during suitable stress conditions. Fractured flowstones systematically concentrated near the faults and joints striking towards N–S and NW–SE point out to their relatively young activity.

4.3. Cave morphology and genesis

The genesis and development of the Zápoľná Cave was influenced by several factors that had also a profound impact on the evolution of the surrounding area. The extensive karstification played an important role across the entire area of the Kozie chrbty Mountains and the north-eastern part of Nízke Tatry Mountains. The evidence for karstification is supported by cavities observed in borehole HK-4 (Hanzel, 1977), but also by the occurrence of numerous karst landforms (*cf.* Droppa, 1962[a], 1962[b]). The karst landforms are strongly linked to the tectonic setting; numerous karst landforms, such as dolines, ponors, and karst resurgences, occur in the proximity of faults (Droppa, 1962[a],1962[b]). The research of the Važec Cave (Bella et al., 2016) located to the northeast of the area, also revealed the close relationship between karst and tectonics.

The longitudinal profile of the Zápoľná Cave is markedly irregular, composed of variously steep looping passages, abysses, and blind chimneys (Fig. 3). Some of the long straight passages are guided by faults, joints, or bedding planes. The entrance branch of the cave passages begins roughly 50 m above the current level of the Čierny Váh River, descending steeply towards the NW. The branch terminates with water sumps at the lowest part of the cave, approximately at the level of the alluvial plain of the Čierny Váh River (steep flooded tubes leading downward). Above the entrance passage, the uppermost storey of the Zápoľná Cave is located at 750–755 m a.s.l. At the lower level, the so-called Upper Passage (Horná chodba, at 735 m a.s.l.) represents the largest passage and is kinked at several places, following the course of the NW–SE- and NE–SW-trending faults. The southeasternmost part of the passage is located near the surface, ending with collapse choke, while the SW part descends towards the lower parts of entrance passage. In the middle part, the passage is crossed by narrow N–S-oriented passage. This type of orientation is typical for the entire northern section of the cave, with the passages following N–S striking faults.

Considerable number of morphological phreatic features in the Zápoľná Cave was formed by water ascending along the faults, joints, or bedding planes. Among them, cupola-like and chimney-like cavities are observed mainly in the upper parts of the cave (height about 15 to 20 m, up to 30 m), and smaller half-spherical cavities reminiscent of ceiling pockets and holes (Fig. 6a–c). The latter are more frequent, occurring in the bottom parts of Tatrovka Abyss and parts located under the Upper Passage. Most pronounced cavities formed along the N–S-trending faults. In the lower part of the entrance branch, the natural windows and/or parallel passages separated by several centimeter-thin wall partitions also points out to the intensive solutional shaping of the cave.

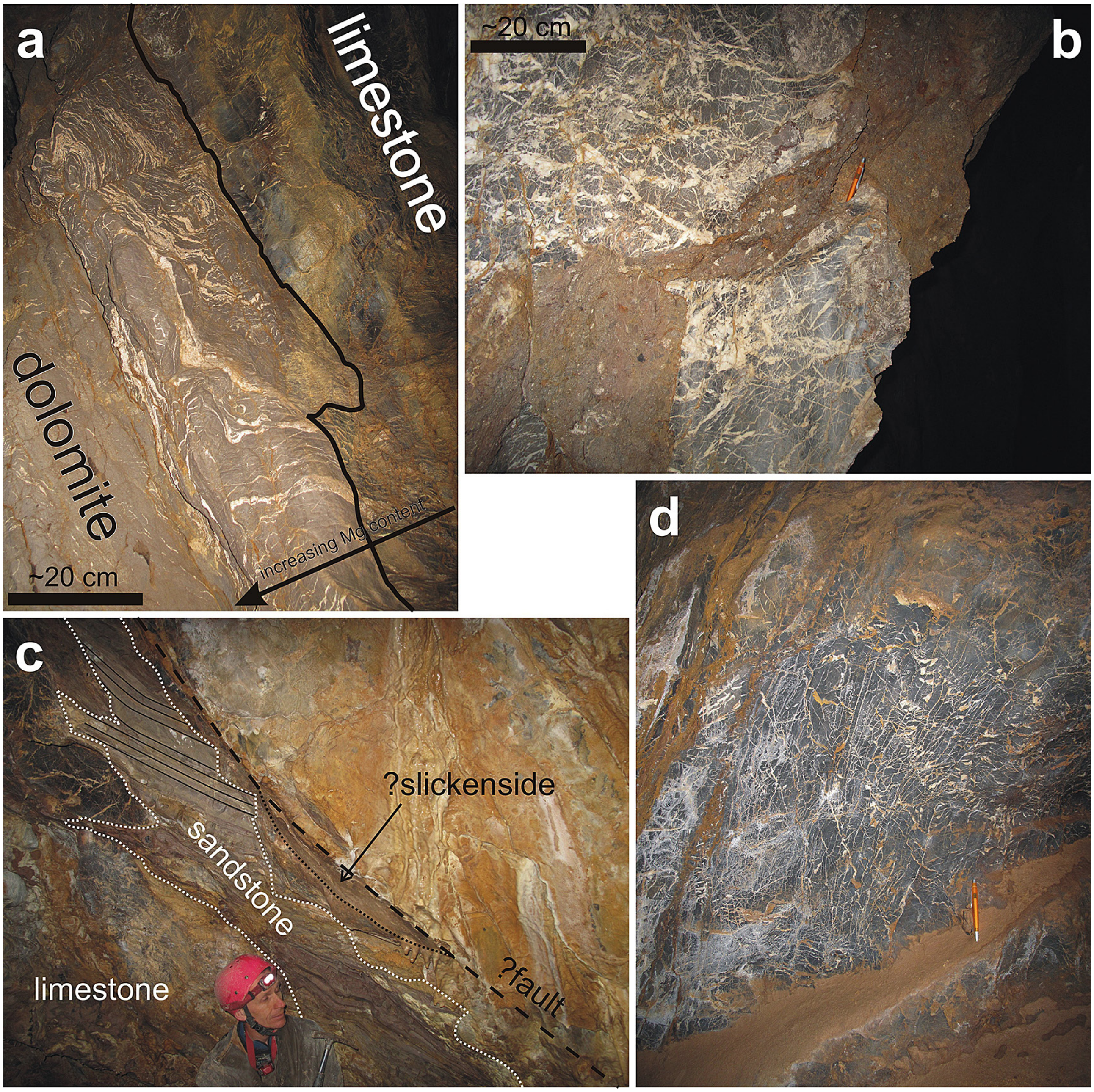

Fig. 5. a) Rheological differences between the layers of the Gutenstein Formation. Note that the shape of the walls creates the illusion of folded calcite veins. b) Transition of strongly fractured rock into tectonic breccia. c) A lens of layered sandstone that seems to be tectonically wedged into the rocks of Gutenstein Formation along what appears to be a thrust fault covered by the flowstone. Slight folding is observed in parts of the sandstone lens. This could represent drag folds formed during the fault movement. d) A rock laced with dense network of calcite veins – a common phenomenon throughout the entire cave. Photo: P. Bella.

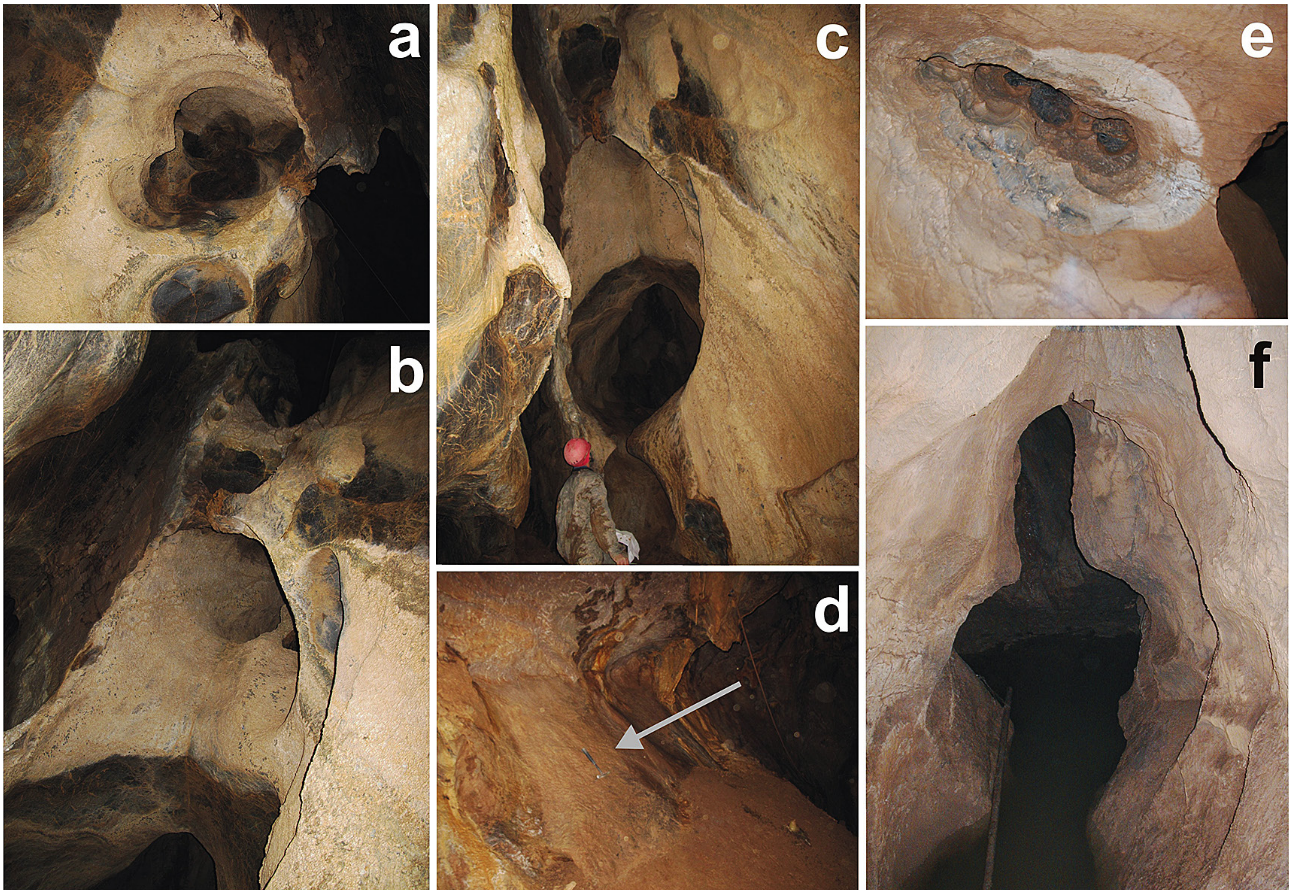

Fig. 6. Phreatic morphology of the Zápoľná Cave. a) Cupola-like cavity (upward view). b) Chimney-like cavity and holes controlled by steep bedding planes (upward view). c) Phreatic tube and wall holes. d) Solution facets (planes of repose) in the Upper Passage. e) ceiling pocket under the Tatrovka Abyss (air trap formed during occasional floods of the lower part of the cave, upward view). f) Flooded bottom of phreatic passage in the lower part of the cave. Photos: P. Bella.

Above-mentioned morphological features indicate that cave has formed in phreatic conditions with slow circulation and convection of water (Bella & Holúbek, 2002) ascending along the faults located in the cave proximity (Bella & Bosák, 2012). The morphological features do not show marks of fluvial sculpturing, and fluvial fills are absent. When coupled with the complete absence of the river channels in the cave, it can be concluded that no significant underground stream flew through the cave. Clastic sediments are predominantly composed of yellow-brown clay (Holúbek, 1998). This could represent allochthonous sediments transported into the cave, or the autochthonous insoluble residua from the dissolved rock. In a similar vein, occasional fine-grained sand could be either transported into the cave, or originate from the sandstones located in the cave.

Other features of the cave point out to periods of groundwater level stagnation, followed by the episodes of water table decline. At the western margin of the Upper Passage, the *planes of repose* (Lange, 1963) are visible. These solution inward-inclined smooth wall surfaces (facets), generally maintain a slope of approximately 40–45°, independent of bedding planes inclination on the walls (Fig. 6d). They are formed in the conditions of slow water circulation, when the accumulation of insoluble residues created a barrier for widening the floor and sloping walls in flooded part of cavities. Lateral wall notches also occur in the Upper Passage, and solution flat ceiling above the Tatrovka Abyss, corresponding to the past water table. The Upper Passage is located roughly 30 m above the alluvial plain of the Čierny Váh River (Bella & Holúbek, 2002). Half-spherical cavities on the ceiling located in the lower parts of the entrance branch, Tatrovka Abyss, and adjacent passages bear marks of the water table oscillation. Their edges are trimmed by clayey residua deposited during the flooding of the lower parts of the cave, but their centers show clean rocky surfaces. This suggests that the cavities were filled by air bubbles preventing their complete filling by water (Fig. 6e). This suggestion is further supported by occurrence of the mud "bands" under the ceiling of the side passage leading to the space behind the rocky threshold called 'Prekážka' (Bella & Holúbek, 2002).

These observed morphological features are indicative of the subsequent water table decline interrupted by oscillations, probably as a response to the incision of the Čierny Váh River Valley. As the lowest parts of the cave are still flooded, and only partially explored by speleodiving, their phreatic evolution is still ongoing. The lowermost cave parts below the water level of Čierny Váh River are flooded by phreatic water, forming several sumps and pools with various depths (Figs. 3, 6f). The water level fluctuates seasonally, with maxima in summer and minima in winter.

Extensive recent phreatic karstification is still active in the limestones underlying the valley of the Čierny Váh River. Water gains and losses of the Čierny Váh River have been observed in the narrowed section of the river valley (Hanzel, 1973; Šalaga et al., 1985). The amount of gained/lost water ranged from less than 100 up to almost 600 $l.s^{-1}$. Karst features were found also in the deeper part of phreatic zone at depth of 70 m under the current riverbed in borehole HK-4, located southeast of the area approximately 20 km upstream of the Čierny Váh River (Hanzel, 1977).

Some phreatic cavities originally formed by dissolution, were subsequently remodeled by the frost weathering and collapse processes (Bella & Holúbek, 2002) e.g. in near-entrance parts, side passages of the entrance branch, southeastern ending part of the Upper Passage, and others. The passages are often terminated by collapse chokes here, and collapsed rock blocks are scattered on the floor. The planes of division on the walls, ceiling, and collapsed blocks bear no signs of solutional shaping. Sharp-edged morphologies originated by frost weathering and breakdown processes in the vadose zone, after the water table decline. Breakdown processes were enhanced by intensive freezing (Droppa 1962[a], 1962[b]).

4.4. Neotectonics

Two types of faults observed in the cave (NW–SE to NNE–SSW- and E–W to NE–SW trending faults) seem to play not only passive, but also active role in the evolution of area. The N–S-trending faults (Fig. 2) predispose the direction of the river tributaries, and are also probably responsible for the widening and narrowing of the valley. The E–W to NE–SW-trending faults predispose the course of Čierny Váh River (Fig. 2), and are probably related to the reactivational movements along the Svarín Partial Nappe thrust line. They are also probably responsible for the differences in the topography and drainage pattern between the right (northern) and the left (southern) side of the valley, as well as for the distribution of the Quaternary deposits. Higher rock resistance of the Svarín Partial Nappe is not sufficient to explain the valley narrowing, as some of the highest peaks in the area are made by the rocks of the underlying partial nappes. The same is true for the differences between the Čierny Váh River Valley sides, as practically the same rock types crop out on the left (southern) and the right (northern) side.

The topographical evolution of the area, as well as the cave evolution, seems to be linked to the neotectonics. Supposed isolated phreatic evolution of the cave without any contact with the surface river, together with other already mentioned facts, points out to the asymmetric uplift of the valley sides with the E–W-oriented fault, prompting more pronounced uplift of the right (northern) bank, during the Čierny Váh River incision. These results are contrary to the results of Maglay et al. (1999), where the opposite sense of movement is reconstructed. However the detected sense of movement is consistent with the movement mode of the nearby E-W striking Vikartovce fault (Fig. 1a), which was active until 135 ±14 ka (Vojtko et al., 2011[b]). The neotectonic activity of the N–S trending faults is attested not only by the above-mentioned facts, but also by the faulted flowstone found in the proximity of these faults.

The determination of the age succession of the fault activity is problematic. Sůkalová et al. (2012) in the area near the Zápoľná Cave identified the W–E-trending faults (and the corresponding N–S-oriented extension) as the youngest. However, Littva & Hók (2014) designated the N–S-trending faults (and the corresponding E–W-oriented extension) as the youngest. The latter implies very recent stress field change, the former contrasts with the results from other parts of the Western Carpathians (Hók et al., 2007; Kováč et al., 2011; Pešková et al., 2009; Vojtko et al., 2008, 2010, 2011[a], 2012). Since the area represents one of the geomorphologically anomalous parts of the Western Carpathians (Minár et al., 2011), more research is necessary in order to resolve these discrepancies.

5. CONCLUSIONS

The Zápoľná Cave is developed in limestone and dolomites of the Gutenstein Formation situated just above the sole of the Svarín Partial Nappe, belonging to the Hronic Unit. The rocks carry signs of the intensive brittle tectonic deformation, including occurrence of dense vein lattice, breccias, and fault gouges. This indicates that the conditions near the nappe décollement were sufficient for the semi-ductile deformation of the limestone at best. Layers and lenses with siliciclastic admixture localized within the Gutenstein Formation are probably a result of the gradual transition from the underlying Šuňava Formation, which was tectonically amputated, probably during the nappe translation. Therefore, tectonically induced emplacement of some layers of the Šuňava Formation might also be possible.

The morphological features in the cave indicate that the cave evolution proceeded in three phases. The majority of the cave was formed by water dissolution along faults, joints, and occasionally bedding planes deep in phreatic conditions, without any contact with the surface. The next phase is denoted by the formation and slow water table decline, interrupted by the episodes of its oscillation or stagnation. Final phase started in the exposed parts of the cave by localized collapses induced mainly by freezing processes.

Two principal types of tectonic brittle structures were identified as playing the key role in speleogenesis of the cave: the NW–SE- to NNE–SSW-, and the NE–SW- to E–W- trending faults. They acted not only as the passive conduits for the groundwater circulation, but probably also actively contributed to the evolution of the topography, and consequently also to the evolution of the cave. Although the activity of the NE–SW- to E–W-trending faults could be linked to the activity of the Vikartovce Fault, dated to be active as far as 135±14 ka (Vojtko et al., 2011[b]), the temporal succession of the fault types is uncertain.

Since only few works dedicated to the Zápoľná Cave have been published, provided results represent significant contribution to the state of knowledge. The results show high potential of the cave for the future research. The data point out to the extensive karstification in the area, implying that some parts of the cave are yet to be discovered. Thanks to its geologically unique position, the cave is suitable for study of the rock structures at the basal parts of the Svarín Partial Nappe. Future, more detailed tectonic research of the rocks in the Zápoľná Cave could reveal a lot of important data, not only about the Svarín Partial Nappe alone, but also about the basal nappe parts and/or nappe emplacement mechanisms in general. The cave also presents elementary component in understanding the geomorphological and neotectonic evolution of the surrounding area. More research is needed to address some problems, in particular the research aimed at studying the terraces of the Čierny Váh River and incision phases of its valley, and at resolving the order of the fault activity in the area.

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