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The depth range and possible continuation of the Havranická jaskyňa cave system revealed by geological methods and electrical-resistivity tomography (ERT), the Malé Karpaty Mts., Slovakia

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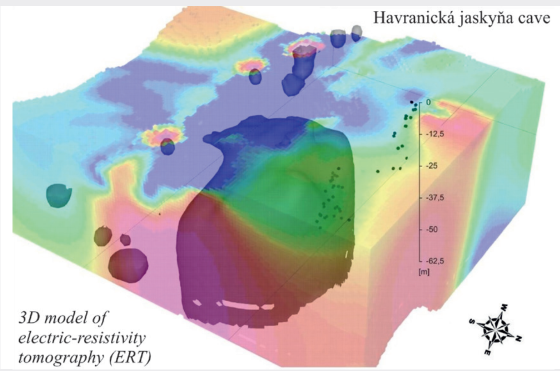
Abstract: Geological (sedimentology, structural geology) and geophysical (electrical-resistivity tomography; ERD) methods were carried out to investigate the possible continuation and depth range of the Havranická jaskyňa cave, situated in the Malé Karpaty Mts. (western part of Slovakia). The origin of the investigated cave is connected with the N–S trending fault, activated during the Pliocene–Quaternary. The cave system is developed in Gutenstein Fm., built dominantly of limestone. According to XRD analyses, the subjacent Gutenstein Fm. dolomite interferes with the cave system in the form of boudins, which modifies the development of the cave in its lower parts. However, the boudins do not affect the course of the cave system. Based on ERT measurement a 3D model of the cave was produced, being complemented by the cave's polygonal traction points. The primary geophysical measurements in 2010 contributed to discovery of new passages in the cave system, so the application of used methodology also in other caves world-wide would be meaningful.

Key words: geological and geophysical research, Havranická jaskyňa cave, the Malé Karpaty Mts., Western Carpathians

Graphical abstract



Highlights

- Multidisciplinary research of Havranická jaskyňa cave system in the Malé Karpaty Mts. indicates the prior origin of the cave on Miocene N-S trending fault, being re-activated and karstified in Plio-Quartenary period.
- New underground spaces indicated by electrical-resistivity tomography (ERT) were confirmed by speleological works

Introduction

More than 300 caves situated in several karst areas are registered in the Malé Karpaty Mts. The karst forms in the studied mountain range have a typical obscure development, so the comprehensive research involving several disciplines is needed to obtain more detail knowledge. The complex methodic approach requires the application of sedimentological (microfacial analyses of carbonatic rocks), structural-geological and geophysical (electrical-resistivity tomography; ERT) methods. Our research was focused on the Havranická jaskyňa cave, situated in the region of the Malé Karpaty Mts. - the Plavecký Karst Area (Šmída, 2010) in the western Slovakia.

The area around the Havrania skala elevation point is characteristic with complicated geological and tectonic setting, being observable on the surface and in the cave system. Since the cave originated due to the corrosive effect of the water, leaking through the fractures, it retained the general direction of the fault structures visible directly in the cave and controlling the shape and direction of its passages. The development of fractures was affected by lithology. For example, preserved slicken slides found on faults in the dolomite, forming rheologically harder material relative to the limestone, have originated due to the relative displacements of the dolomite blocks.

Besides geological methods, the geophysical methods can be beneficial in the karst research - they allow to distinguish properties of the material, filling the voids, and when it is significantly different from the surrounding host rock, they indicate a material contrast (cf. Gibson et al., 2004; Dobečka & Upchurch, 2006; Monchales et al., 2008, as well as Putiška et al., 2012). In our case, we have used the ERT (electrical-resistivity tomography) method, producing the 3D model of the material discontinuities as an output.

Geological setting

The studied area is situated in the Malé Karpaty Mts., app. 1 km northwest of the village of Smolenice. The entrance to the Havranická jaskyňa cave is located only a few meters from the top of the Havrania skala elevation point (599 m a.s.l.), which is a part of the Havranica hill (717 m a.s.l.). This area includes the Považie nappe, being a part of the Hronic nappe system (Polák et al., 2012; Fig. 1). Within the karst regionalization, it is incorporated into the Plavecký Karst Area (Mitter, 1983).

The Havrania skala area is built of the Middle Triassic limestone of Gutenstein Fm., forming 50–100 meters thick bed. The lower part of this formation was correlated with the Annaberg limestone, occurring in the Eastern Alps. This type of limestone was described in the Malé Karpaty Mts. by Bystrický (1972, 1973). The Gutenstein dolomite (Polák et al., 2012), occurring under the limestone, partially interferes into the cave system. A slightly bland position of detrital limestone with a predominance of monotonous micrite (mudstone-wackestone) with rare organodetritic interbeds (foraminiferal-dasykladacea grainstone-packestone) is developed in the upper part of the grey Gutenstein Fm. limestone. The rare fragments of organisms, occurring in the biodetritic interbeds, represent ostracods, segments of crinoids, small gastropods, foraminifers and dasycladacea (Buček, 1988; Buček et al., 1991).

The limestone setting in the Havranica ridge is relatively simple, manifesting bedding with the dip of 60-80° to the north (Maheľ, 1986). Around the cave the bedding has a dip only of 36° to the north.

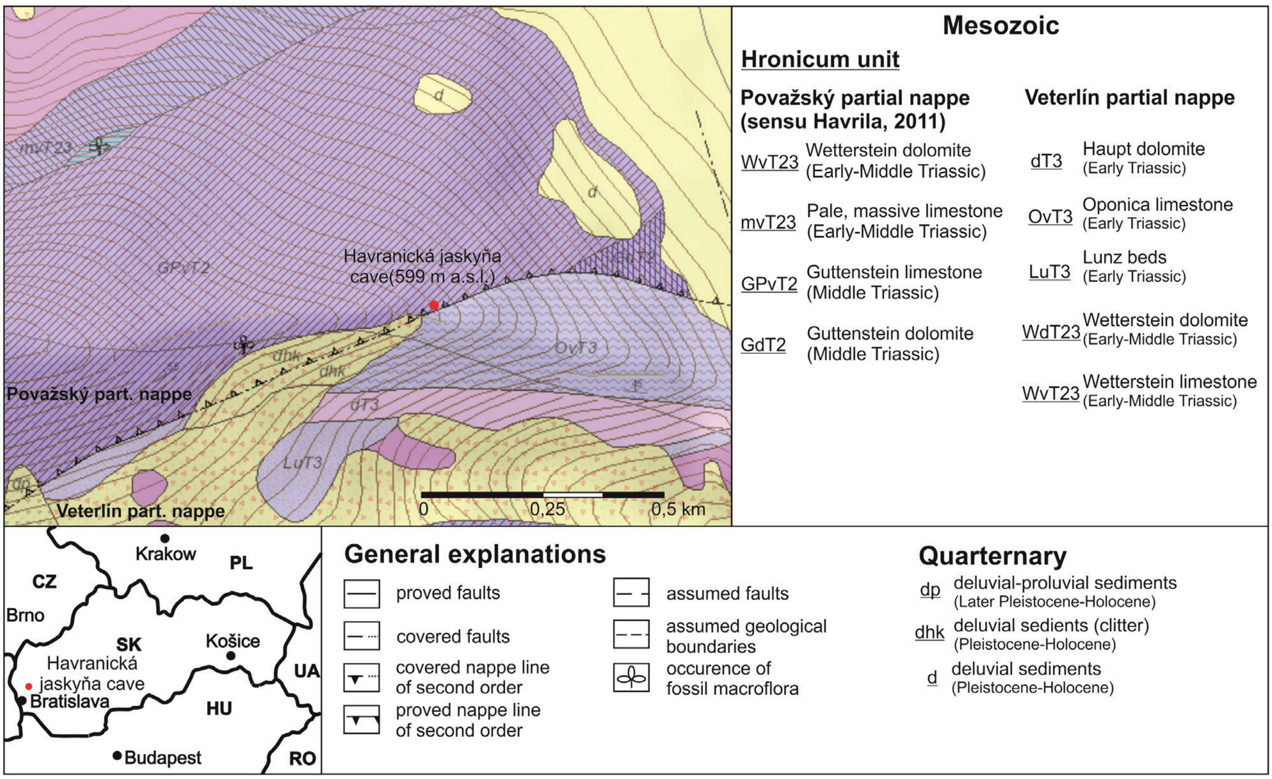


Fig. 1. Geological map of investigated area (taken with permission from the map-server of the State Geological Institute of Dionýz Štúr, Slovakia).

History of research

The Havranická jaskyňa cave is known from the time immemorial. The original entrance was probably destroyed during the World War II, when the Havrania skala hill was under fire. The re-discovery of the cave dates back to 18 September 2004 (Lačný, 2006). After the first mapping work, the cave length was less than 90 meters. However, during 12 years of work, speleologists discovered more than 80 meters of new space, and 14 meters of the depth range. The first exploration work started immediately after the re-discovery of the Zbojnická Chamber, representing the largest hall. As can be seen from the map (Fig. 2), the cave is located in a tectonic dislocation trending N-S. The cave system continues to the north as was confirmed by geophysical measurements in 2010 (Lačný et al., 2012). New exploration work was conducted on the basis of these measurements and new phase of discoveries began in 2013. Speleologists found 15 meters of new passages in the small hall called Michal's chamber. The next discovery came a year later when 30 meters of new passages were found. The current workplace is situated at a depth of -51 meters under the lower earlier discovered part known as the Objavná chamber.

Description of passages

Havranická jaskyňa cave (585 m a.s l.), length: 174.3 m; depth: -51 m

The genetic type of the cave is tectonic-corrosive, while in the lower part we can see passages that were modelled by the water. It is possible that the cave type changes with lithology and increasing depth. During the research, 5 limestone samples were subjected to XRD analysis and petrographic study applying the thin sections. Thin sections of three samples confirmed the presence of dolomite crystals, and the XRD analysis confirmed the occurrence of dolomite and partially dolomitized limestone. The entrance to the cave is situated only few meters from the apical parts of the Havrania skala elevation point (599 m a.s.l.). The first passage is represented by a narrow and steep chimney which leads to the first small chamber of dimensions 4 x 3 m. The atypical air current varies according to the season and wind intensity. Following creep passage is formed of limestone, and partially dolomitized limestone (Fig. 2a, b; sample s1 and s2). Subsequently the passage spreads to Zbojnícka Chamber, the largest hall in the cave (5 x 10 m, 5 m height). This hall was formed on a tectonic dislocation having azimuth 19° and dip 40° (19/40°). Its eastern side is formed of Fe-rich dolomite (Fig. 2, sample s3). From the Zbojnícka Chamber the passage leads to a small tunnel with the azimuth of 250°, reaching the Smoke Chamber (2 x 3 m), situated over it. Then the passage leads from the Smoke Chamber to the small hall (1.5x3 m), representing a vertical joint. The Michal's Chamber, comprised of dolomite with small Ca impurities (Fig. 2, samples s4, s5), is located to the east of the Smoke Chamber. The Objavná Chamber (4 x 7 m), formed on a continued discontinuity of N-S trend, leads to the current workplace at a depth of -51 m, situated below Michal's Chamber.

Jaskyňa v Havranej skale cave (574 m a.s.l.), length: 20 m

Jaskyňa v Havranej skale cave is situated in close vicinity to the Havranická jaskyňa cave, as the entrance to this small cave is located 15 meters southwest of the Havranická jaskyňa cave. It is formed on a remodeled discontinuity (105/76°), which is 0.5 to 1 meters wide and 2 to 6 meters high (Šmída, 2010). However, the connection of these caves should be considered as the vertical difference is only 10 meters, and a notable air draught occurs at the end of the Jaskyňa v Havranej skale cave.

Structural research

Both caves (Havranická jaskyňa cave and Jaskyňa v Havranej skale cave; Fig. 3) were formed on the same sub-vertical discontinuity trending N-S, which can also be seen on the surface at the cave entrance. Fractures of this trend are characteristic in the entire area around the cave. The beginning of the cave origin features another important system of discontinuities - the bedding with 36–76° dip northward (Fig. 4A, B). We have to note that the caves overlap each other in different depths. The N-S trending sub-vertical discontinuities dominate in the Plavecký Karst Area and can often be found in other karst areas of the Malé Karpaty Mts. The direction of cave passages has a connection with faults of N-S affinity, being accompanied with those of NW-SE trend, so they were formed on a paired system of discontinuities.

The discontinuities trending N-S have contributed to karstification process by allowing the penetration of atmospheric rainfalls through the carbonatic massif and dissolution of carbonate, as well as allowing subsequent water corrosive effects. The current compression is approximately of N-S direction (Kováč et al., 2002). The earlier tectonic research, based on tensometer measurements of relative movement of blocks in the Driny cave, located ca 10 km ENE of the Havranická jaskyňa cave in similar tectonic conditions (Briestenský et al., 2011), revealed the dextral displacements on the NW-SE trending discontinuities and sinistral displacements on NNE-SSW trending discontinuities. Authors deduce that the current stress field is represented by a compression of NNW-SSE direction, applying the pure shear model for the origin of N-S trending faults, where the NW-SE and NE-SW discontinuities

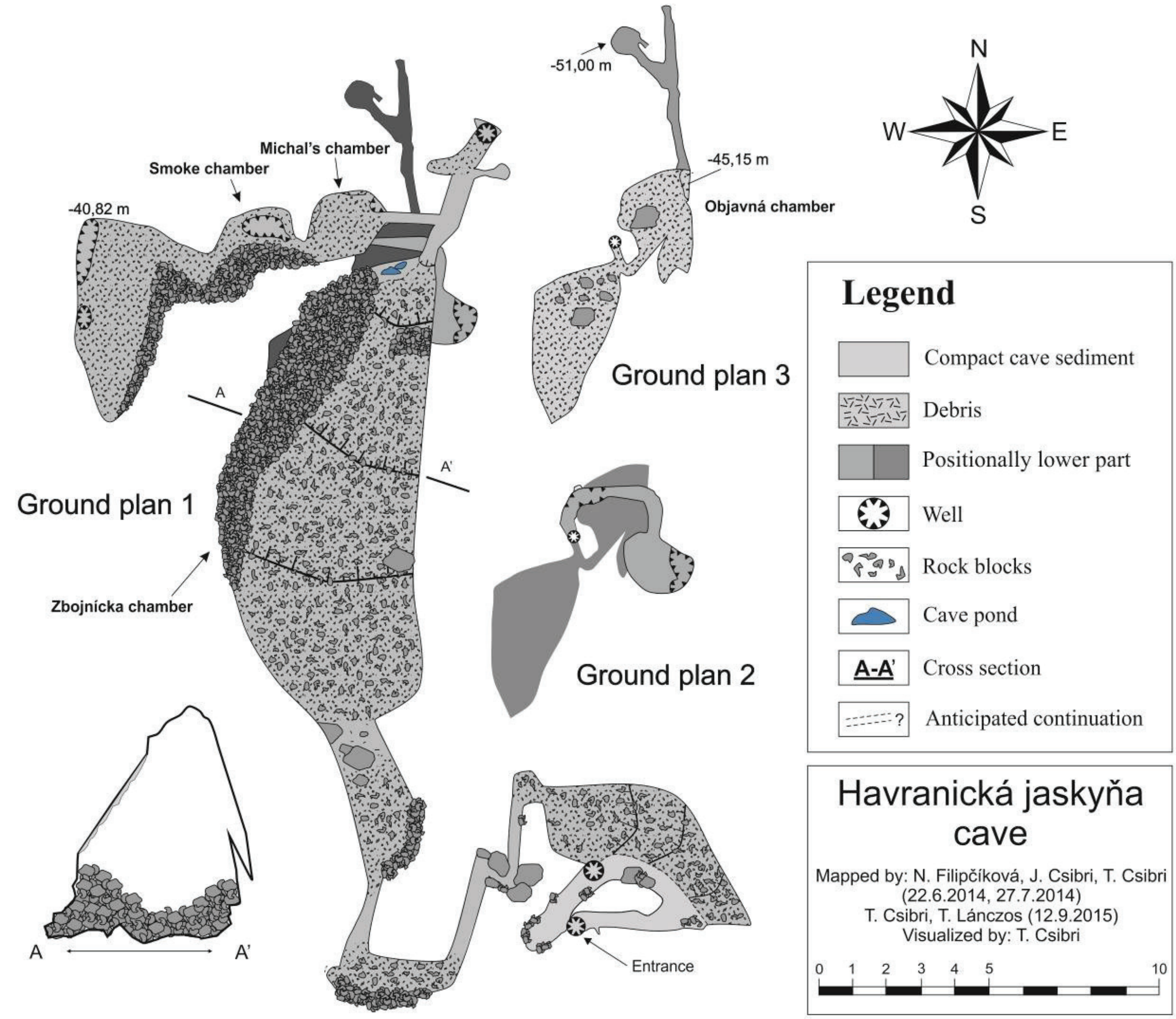


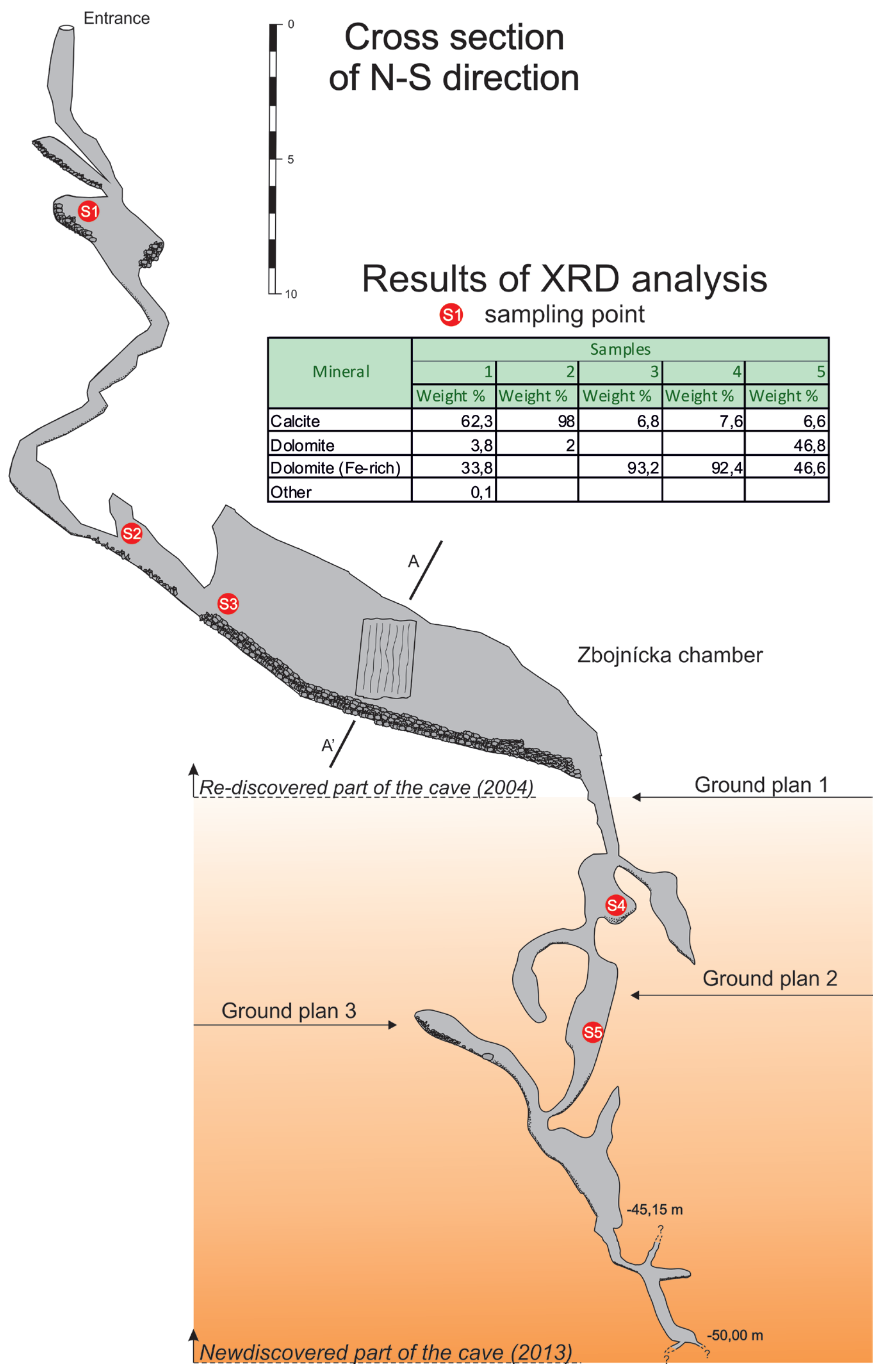
Fig. 2a. Ground plan of the Havranická jaskyňa cave.

represent the paired system of faults. These results correspond to mechanism of recent stress field in the region of the Malé Karpaty Mts. (cf. Kováč et al., 2002).

Applying the current compression field and the pure shear model, there should be reactivated also earlier existing N-S trending structures. Revealed shifts on geological discontinuities indicate that they represented the sinistral faults also in the past, forming paired system to the dextral faults of NW-SE trend. Later, during the middle Miocene compression of N-S direction they were reactivated as normal faults, being associated with opening of the Badenian deposition centre of the Vienna Basin (Marko & Jureňa, 1999).

Our research results confirmed that the Havranická jaskyňa cave was formed on a significant fault trending N-S. There is a presumption of later re-activation of this fault in the Plio-Quaternary period. The role of tectonic discontinuities of the earlier period at the cave formation can not be excluded, because similar structures of this affinity are registered in the Malé Karpaty Mts. from the middle Miocene. The uplift of the Malé Karpaty Mts. (except of the earlier Upper Cretaceous-Paleogene event) took place in the Upper Miocene, so the karstification should occur only after the Miocene time. Therefore we assume, that the main phase of karstification should be associated with a Plio-Quaternary period.

For comparison there is worth to mention the tectonic result of the research in the eastern part of the Western Carpathians (Németh in Gaál et al., 2017; cf. Fig. 10 ibid.), being focused on the caves developed in magnesite bodies along the contact zone of Veporic and Gemeric units). The



Mineral	Samples				
	1	2	3	4	5
	Weight %	Weight %	Weight %	Weight %	Weight %
Calcite	62,3	98	6,8	7,6	6,6
Dolomite	3,8	2			46,8
Dolomite (Fe-rich)	33,8		93,2	92,4	46,6
Other	0,1				

Fig. 2b. Cross section of Havranická jaskyňa cave.

research has revealed that the origin of a system of N-S trending faults is a consequence of the post-Upper Cretaceous subhorizontal displacements on conjugate NE-SW (sinistral shearing) and NW-SE (dextral shearing) trending faults and the generally N-S trending faults represent the synthetic faults related to both systems (l.c.). In the Malé Karpaty area, located in the western limb of the Western Carpathian arc, the sinistral shearing on NE-SW trending faults is much more dominant.

We can find calcified terra rossa in the discontinuities on the cave walls. Autochthonous clastics of carbonates, which are differently rounded (0.5 to 2.5 cm), occur in the terra rossa. Sharp-edged fragments are interpreted as products of tectonic processes. In a smaller amount we identified also well rounded pebbles, their roundness is related to their transport. Despite we have not found shapes created by erosion, their existence in the past cannot be excluded. They were probable erased by the corrosive effect of percolating water or the destruction of the walls, related to younger tectonic processes. As one example of such processes we interpret the origin of the Zbojnícka Hall. Below this hall, Šmída (2010) assumes that there was a larger corrosion hall, which after the neotectonic and gravitational movements has collapsed. The wedge-shape profile of the Zbojnická Hall (Fig. 5) represents a result of this event. The cave system continues northward, and the passages become more vertical (70-80°).

Geophysical research

Seven 2-dimensional, direct-current electrical-resistivity traverses were carried out. Electrical resistivity tomography (ERT) prospecting was performed using an ARES (GF Instruments) multi-electrode system with a set of 48 electrodes evenly spaced for every 5.5 m. A dipole-dipole array configuration was used with a geometrical factor of "$k = 2\pi n (n+1) a$", where "**a**" is the dipole length and "**n**" is the dipole separation. For surveys with this array, the "a" spacing is initially fixed at the smallest unit electrode spacing and the "n" factor is increased from 1 to 2 to 3.

In the first phase of the geophysical survey we re-measured three sections: the first profile (pf-1-09) was situated just behind the largest known chamber in the Havranická jaskyňa cave; the other two sections: pf-2-09 and pf-3 09 (Fig. 6) were outlined parallel to the first profile in the direction of the expected continuation of the cave system. An

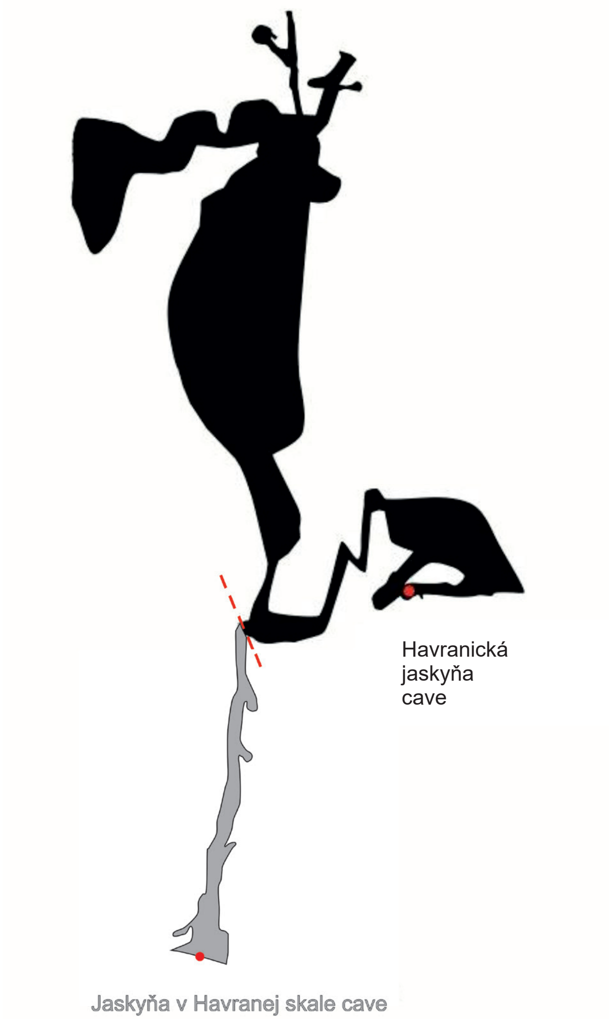


Fig. 3. Position of the Havranická jaskyňa cave and Jaskyňa v Havranej skale cave in the Havrania skala massif (599 m a.s.l.). Orientation of figure corresponds with that in Fig. 2a, which re- presents the northern (black) part of Fig. 3.

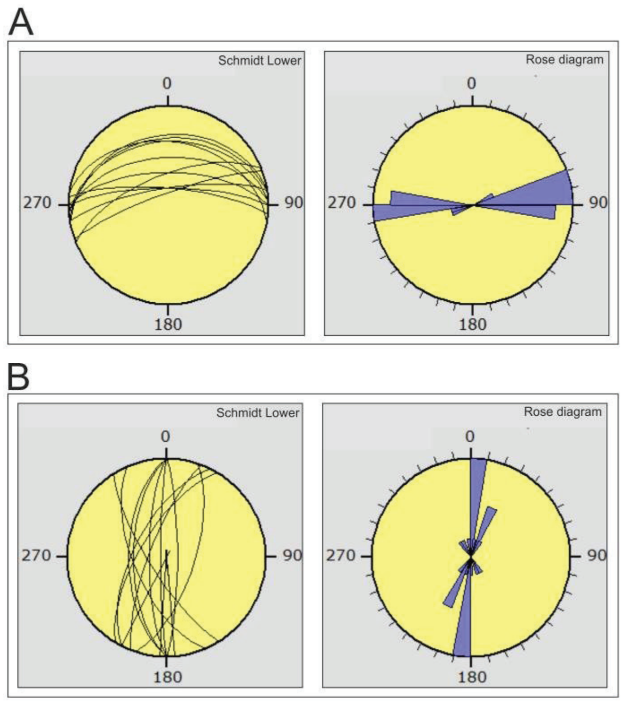


Fig. 4. Tectonograms: **A** – bedding in the Havranická jaskyňa cave and its surroundings. **B** – discontinuities measured in the Havranická jaskyňa cave, the Havrania skala hill and surrounding.

Fig. 5. The wedge-shape profile of the Zbojnická Chamber in the Havranická jaskyňa cave. Photo: A. Lačný.

inversion model of these profiles demonstrates considerably high resistivity anomalies – greater than 21 000 Ωm, which highlights the great cavities (caves). On the basis of these results, we added new ERT measurements. These new profiles were measured due to thickening and the dissemination of information on the locality. Four other sections were also measured on this site. The first profile (pf-0-10) was situated above the already known part of the Havranická jaskyňa cave. The second profile (pf-4-10) was situated 44 m from the pf-0-10 profile. The next two profiles: pf-5-10 and pf-6-10 (Fig. 6) were situated perpendicular to the previous profiles. Thus, we created a network of measurement points 44 m x 264 m with a density of 11 m x 5.5 m. Such density measurements allowed us to create a detailed 3D visualization of the results (Fig.7).

Geophysical results

The main purpose of the geophysical survey was to find the direction of the possible continuation of the cave system. According to the spatial distribution of resistivity values, a significant area with a high resistivity value is visible in the central part of the studied area (Fig. 7). In this area, we anticipate the occurrence of other karst formations. The system of fractures and smaller cavities in the rock environment increases the overall resistivity of

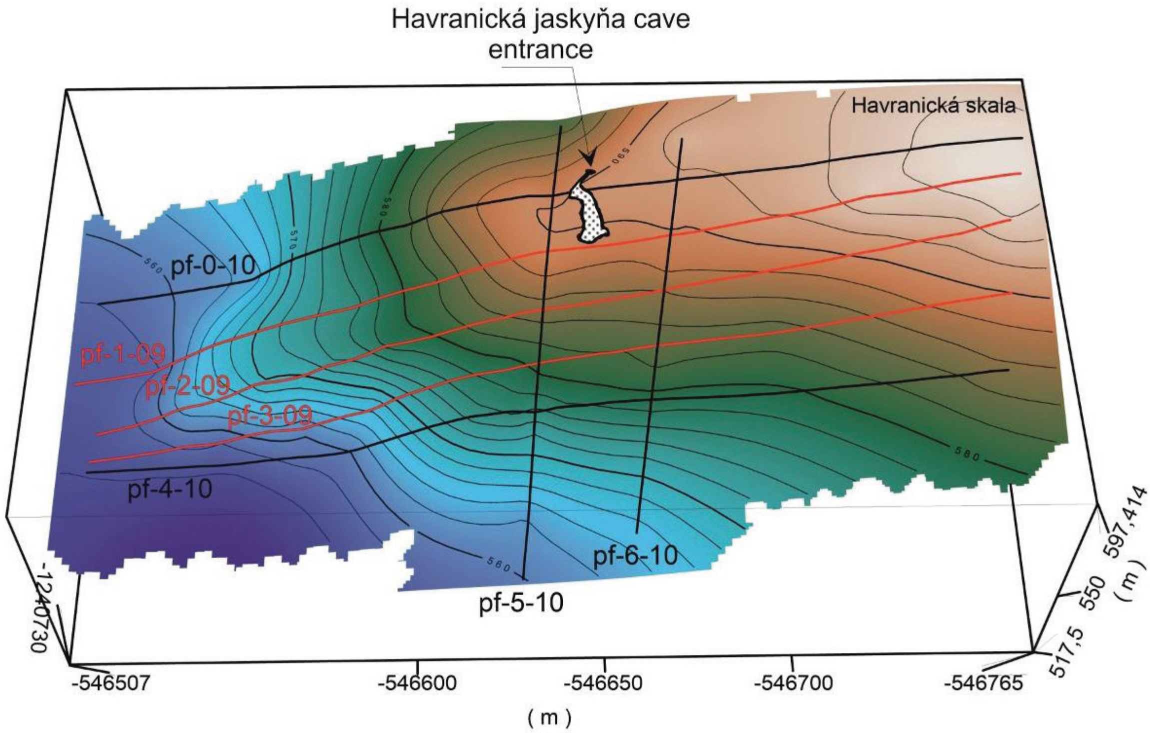


Fig. 6. Position of profiles around the Havranická jaskyňa cave (S-JTSK GPS coordinate system).

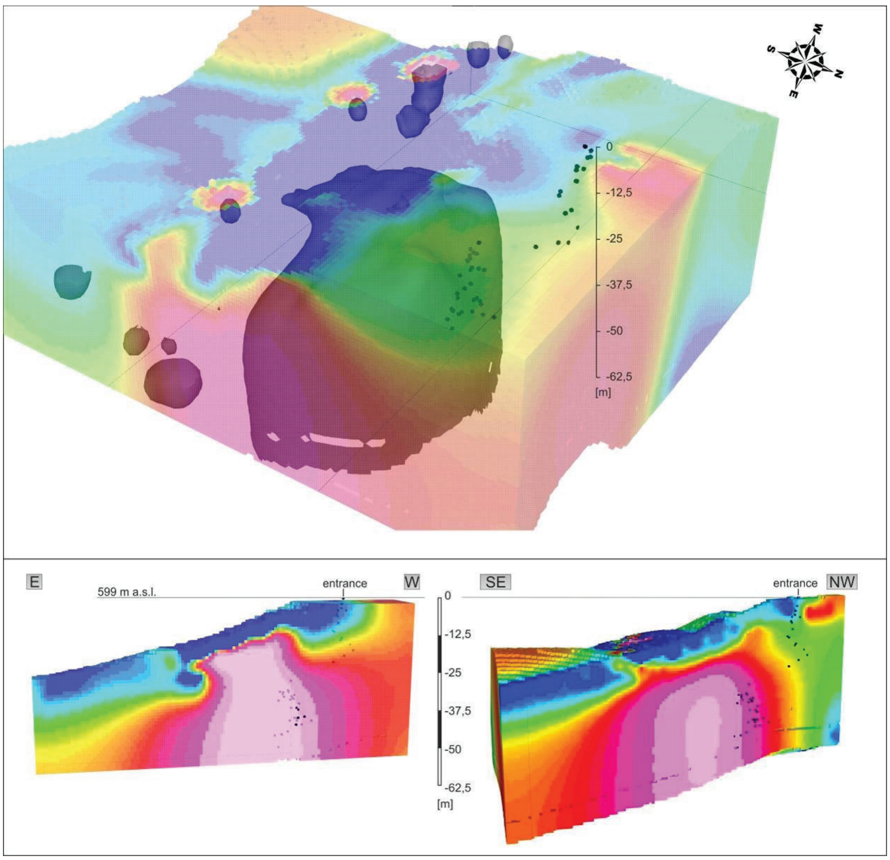


Fig. 7. The 3D models of ERT surveys with the polygonal traction points of the Havranická jaskyňa cave (A – iso-surface's value – 12 000).

the environment. According to the results of ERT measurements and subsequent 3D visualization, the highly resistive anomalous region of the concentric shape is followed and its continuation can be traced downwards (in depth). Based on these findings, we continued to consider the continuation of the cave system only to depth. Subsequent speleological studies confirmed the prerequisites of the geophysical survey, and new cave areas were discovered up to a depth of -50 m (Fig. 2). The course of newly discovered spaces was geodetically oriented and confronted with the results of geophysical research. The correlation between the high resistivity area and the black dots has confirmed the original assumption that the cave system continues downwards (Fig. 7).

Conclusion

During the research of Havranická jaskyňa cave the geological (sedimentology, structural geology) and geophysical (electrical resistivity tomography – ERT) survey methods were combined to detect possible lateral and depth continuation of the cave system.

The Havranická jaskyňa cave was formed on a sub-vertical discontinuity trending N-S. At the beginning of the cave formation, the primary limestone bedding with the dip of 36–76° to the north has played an important role. The lithological research has revealed the dolomitized parts in the lower parts of the cave. These dolomite boudins interfered into the cave system and affected the karstification; however the course of the cave system remained unchanged, which was confirmed also by the geophysical measurements.

During the geophysical research, seven 2-dimensional, direct-current electrical-resistivity traverses were carried out. Overall, we re-measured seven profiles. The results show that a significant area with a high resistivity value is visible in the central part of the studied area. From the spatial distribution of the resistivity values, it is evident that the system of fractures and smaller cavities in the rock environment increases the overall resistivity of the environment. According to the results of ERT measurements and subsequent 3D visualization, the highly resistive anomalous region of the concentric shape is followed and its continuation can be traced downwards (in the depth). This model, which was geodetically referenced and completed by the measured points during the cave mapping, convincingly proves the presumptions of the geophysical survey.

Subsequent speleological and structural geological studies confirmed the continuation of the cave system, but only downward. Based on the results of the geophysical survey and new cave spaces were discovered down to a depth of -50 m. The results of the geophysical ERT measurement were confirmed by speleological work; however, speleologists are still working in the deepest parts of the cave – still finding new until unknown cave spaces.

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Hĺbkový rozsah a možné pokračovanie jaskynného systému Havranickej jaskyne, zistené geologickými metódami a elektrickou odporovou tomografiou (ERT), Malé Karpaty

V krasových územiach pohoria Malé Karpaty sa nachádza viac ako 300 registrovaných jaskýň. Krasové formy tohto územia je potrebné študovať z viacerých hľadísk v spolupráci s viacerými vednými disciplínami. Tento komplexný metodický postup vyžaduje aplikovať sedimentologické (mikrofaciálna analýza karbonatických hornín), štruktúrnogeologické a geofyzikálne (elektricko-odporová tomografia – *electrical-resistivity tomography*; ERT) metódy. Uvedené metódy výskumu sme aplikovali na Havranickú jaskyňu, ktorá sa nachádza v Plaveckom krase v centrálnej časti pohoria Malé Karpaty.

Havranická jaskyňa je situovaná približne 1 km západne od obce Smolenice, pričom vchod sa nachádza iba pár metrov od kóty Havrania skala, ktorá je súčasťou vrchu Havranica (717 m n. m.). Jaskyňa bola známa od nepamäti, pričom počas druhej svetovej vojny bol pôvodný vchod zasypaný. Jaskyňu znovu objavila jaskyniarska skupina Speleoklub Trnava 18. 9. 2004 (Lačný, 2006). Jaskyňa bola prvotne dlhá približne 90 m. V roku 2010 tu boli vykonané geofyzikálne merania, ktoré potvrdili pokračovanie jaskynného systému. Na základe týchto meraní jaskyniari začali s výkopovými prácami. V roku 2013 došlo k novým objavom v jaskyni na základe geofyzikálnych modelov z roku 2010. Havranická jaskyňa má momentálne dĺžku 174,3 m s celkovou hĺbkou –51 m.

Študovaná jaskyňa je vytvorená prevažne v gutensteinských vápencoch hronika, resp. v jeho čiastkovom príkrove – považskom čiastkovom príkrove (Polák et al., 2012). Na základe mikrofaciálnej analýzy a röntgenovo-difrakčných analýz sa potvrdilo, že jaskynný systém tvoria vo vyšších častiach čiastočne dolomitizované vápence, pričom smerom do hĺbky dominujú dolomity s vysokým obsahom Fe. Najnovšie objavené časti jaskyne sú tvorené vápencami až dolomitickými vápencami (obr. 2b).

Zo štruktúrnogeologického hľadiska Havranická jaskyňa vznikla na subvertikálnej diskontinuite s.-j. smeru, ktorá je sledovateľná aj na povrchu pri samotnom vchode. Sklon vrstvovitosti variíruje medzi 36 – 76°, pričom sa lavice skláňajú na sever (obr. 4). Najaktuálnejšie výsledky z pohľadu recentnej tektoniky prináša práca Briestenského et al. (2011). Na základe svojich výsledkov sa domnievajú, že v súčasnosti na sz.-jv. štruktúrach dochádza k dextrálnym pohybom a na ssv.-jjz. poruchách k sinistrálnym pohybom. Autori dedukujú, že súčasné napätie je ssz.-jjv. kompresia. Vychádzajú z predstavy čistého strihu, kde sz.-jv. a sv.-jz. poruchy tvoria párový systém. To korešponduje s predstavou a mechanizmom recentného napätia v oblasti Malých Karpát (Kováč et al., 2002). V modeli čistého strihu by mali vznikať, resp. sa reaktivovať aj extenzné s.-j. štruktúry. Preto sa domnievame, že súčasná kompresia môže mať vplyv aj na staršie zlomové štruktúry s.-j. smeru. Z posunov na geologických rozhraniach vyplýva, že v minulosti fungovali aj ako sinistrálne smerné zlomy, ktoré so sz.-jv. dextrálnymi zlomami tvorili párový systém. Neskôr pri pôsobení strednomiocénneho kompresného napätia s.-j. smeru sa reaktivovali ako poklesy súvisiace s mechanizmom (*pull-apart*) otvárania bádenského depocentra sedimentácie Viedenskej panvy (Marko a Jureňa, 1999).

Výsledky štruktúrnogeologického výskumu potvrdili, že Havranická jaskyňa vznikla na významnej zlomovej poruche práve s.-j. smeru. Predpokladá sa neskoršia aktivácia v pliocénno-kvartérnom období. Nie je však vylúčené ani tektonické porušenie v skoršom období, keďže zlomy s touto afinitou registrujeme v oblasti Malých Karpát v strednom miocéne. Samotné vynorenie Malých Karpát (s výnimkou vrchnokriedovo-paleocénneho eventu) sa udialo vo vrchnom miocéne, preto krasovatenie mohlo nastať až po tejto fáze, najskôr v období pliocénu. Podľa našich predpokladov hlavnú fázu krasovatenia priraďujeme do pliocénno-kvartérneho obdobia s klímou odlišnou od súčasnej.

Počas geofyzikálnych meraní sa vyhotovilo 7 dvojdimenzionálnych profilov metódou ERT. Pri meraniach sa využil multielektródový systém ARES (GF Instruments). Celkovo sa použilo 48 elektród v intervale 5,5 m, pričom meranie prebehlo v konfigurácii dipól – dipól. Prvé profily boli vedené nad systémom Havranickej jaskyne (obr. 6), neskôr boli doplnené ďalšie profily. Na základe 2D profilov sa vyhotovil 3D model jaskynného systému, doplnený bodmi polygónového ťahu, ktoré sa využívajú pri mapovaní podzemných priestorov (obr. 7). Jaskynný systém na obr. 7 preukazuje vysoký odpor v centrálnej časti študovanej jaskyne.

Nové priestory definované multidisciplinárnym výskumom Havranickej jaskyne potrvdili speleologické práce a nové objavy až do hĺbky –51 m. Speleologický výskum pokračuje na najhlbšom mieste jaskyne, kde jaskyniari neustále nachádzajú nové nepoznané miesta.

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