Dolines of the Dobrá Voda Karst linked with brittle tectonic structures (Malé Karpaty Mts.)

Alexander Lačný[1,2], Laura Dušeková[3,4], Jozef Hók[2], Michaela Galová[1], Juraj Halama[5] & Ivan Demovič[6]

[1] State Nature Conservancy of the Slovak Republic, Little Carpathians Protected Landscape Area, Štúrova 115, 900 01, Modra, Slovakia; alexander.lacny@sopsr.sk, michaela.galova@sopsr.sk
[2] Comenius University, Faculty of Natural Sciences, Department of Geology and Paleontology, Ilkovičova 6, Bratislava, Slovakia; alexander.lacny@uniba.sk, jozef.hok@uniba.sk
[3] State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Hodžova 11, 031 01 Liptovský Mikuláš, Slovakia; laura.dusekova@sopsr.sk
[4] Institute of Geodesy, Cartography and Geographical Information Systems, Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical University Košice, Park Komenského 19, 04001 Košice, Slovakia; laura.dusekova@student.tuke.sk
[5] Speleoklub Trnava, Ovocná 2839/1, 917 08 Trnava; juraj.halama@gmail.com
[6] Cave group Inovec, Andreja Hlinku 38, 921 01 Piešťany; ivan.demovic1@gmail.com

AGEOS

Abstract: This research is focused on the dolines of Dobrá Voda Karst, which is situated in the Brezovské Karpaty Mts. (north-eastern part of the Malé Karpaty Mts) near the villages of Chtelnica and Dobrá Voda. 263 dolines were identified here and measured in the field, which is presumably the final count. The measured parameters of the dolines were used for morphometric analyses, as well as for finding out the relationships with the geology of the area. The karst is formed in Triassic carbonates of the Považie and Dobrá Voda nappes of the Hronic Unit. Dolines were identified in Neogene basal carbonatic conglomerates (Dobrá Voda Formation) as well. The area of karst rocks is approximately 87.2 km^2. Dolines often tend to be formed in lines with tectonical or lithological predisposition. The most significant lines in the Dobrá Voda Karst are Hlboký Dol, Chtelnické Uhliská, and Cínovec. The origin of dolines can be assumed to the Quaternary Period and related to neotectonics, the development of the relief, and the formation of the river network. This is also confirmed by the trends of the maximum axes of the extension of dolines in the direction N-S, NE-SW and WNW-ESE, which partially correspond to the regional faults. New faults (Hlboký Dol, Cínovec, Bzová) were also identified on the basis of dolines in the lines.

Key words: Western Carpathians, Brezovské Karpaty Mts., Hronicum Nappe, karst, morphometric analyses, neotectonics

1. INTRODUCTION

The scope of our research focuses on the dolines of the Dobrá Voda Karst in the Malé Karpaty Mts., which have been studied in the past by several authors as well (e.g., Droppa, 1952; Mitter, 1983; Šmída, 2008) (Fig. 1.). A few of the dolines were previously known, including several significant ones. However, comprehensive geo-evidence and their parameters, as a basis for more detailed morphometric analysis, have been for the most part absent. It is almost impossible to explore such a vast area for new dolines. Nevertheless, tens of new, undescribed dolines have been revealed using a detailed digital model of the terrain based on LiDAR data. Sufficient data and accurate documentation of properties of these karstic surface forms enable us to reveal further links with the geology and morphology of the study area. Similar research to such an extent in the area of the Dobrá Voda Karst has never been done. The study of dolines allows for more detailed research of underlying rocks, which are often covered by Quaternary deposits and hinder the analysis of geological structures.

Dolines, which are the most distinctive karst surface landforms, represent closed depressions of variable dimensions with slightly-angled or even vertical side walls (Williams, 2004; Sauro, 2012; Waltham et al., 2005 and others). Morphodynamically, dolines represent a basic hydrographic unit, which as a simple catchment area with its system of slopes, drains the water to the lowermost accumulation point (Bondesan et al., 1992; Williams, 2004). The genesis of dolines is influenced by topographic, tectonic, lithological, and morpho-structural predisposition.

Manuscript received 2021-12-8
Revised version accepted 2022-02-04

2. GEOLOGY AND GEOMORPHOLOGY OF THE DOBRÁ VODA KARST

The Malé Karpaty Mts. form the southwestern end of the Carpathian arc in Europe. The mountains are divided, from the south to the north, into the Devínske Karpaty Mts., Pezinské Karpaty Mts., Brezovské Karpaty Mts., and Čachtické Karpaty Mts. Moreover, they belong to the Fatra-Tatra geomorphological area (Mazúr & Lukniš, 1978).

2.1. Geological structure of the Dobrá Voda Karst

The geological structure of the Dobrá Voda greater area was the object of geological and structural mapping (Hók et al., 2018). Pre-Cenozoic rocks comprise only the Hronicum tectonic unit, which is arranged in two thrust sheets with different facial provenience of their sediments and dipping generally to the northwest. The lowermost partial structure contains sediments derived from the basinal part of the Hronicum palaeographic area (the Dobrá Voda Nappe *sensu* Havrila, 2011). The Upper structure of the Hronicum contains carbonate platform facies of Wetterstein Limestone and Wetterstein Dolomite (the Považie Nappe *sensu* Havrila, 2011). The Dobrá Voda nappe is internally imbricated into tectonic slices with the presence of Reifling Limestone and the Lunz Formation.

In the past, problems arose with the stratigraphic affiliation and tectonic position of the carbonate conglomerates in the Dobrá Voda Depression. These were originally dated to the

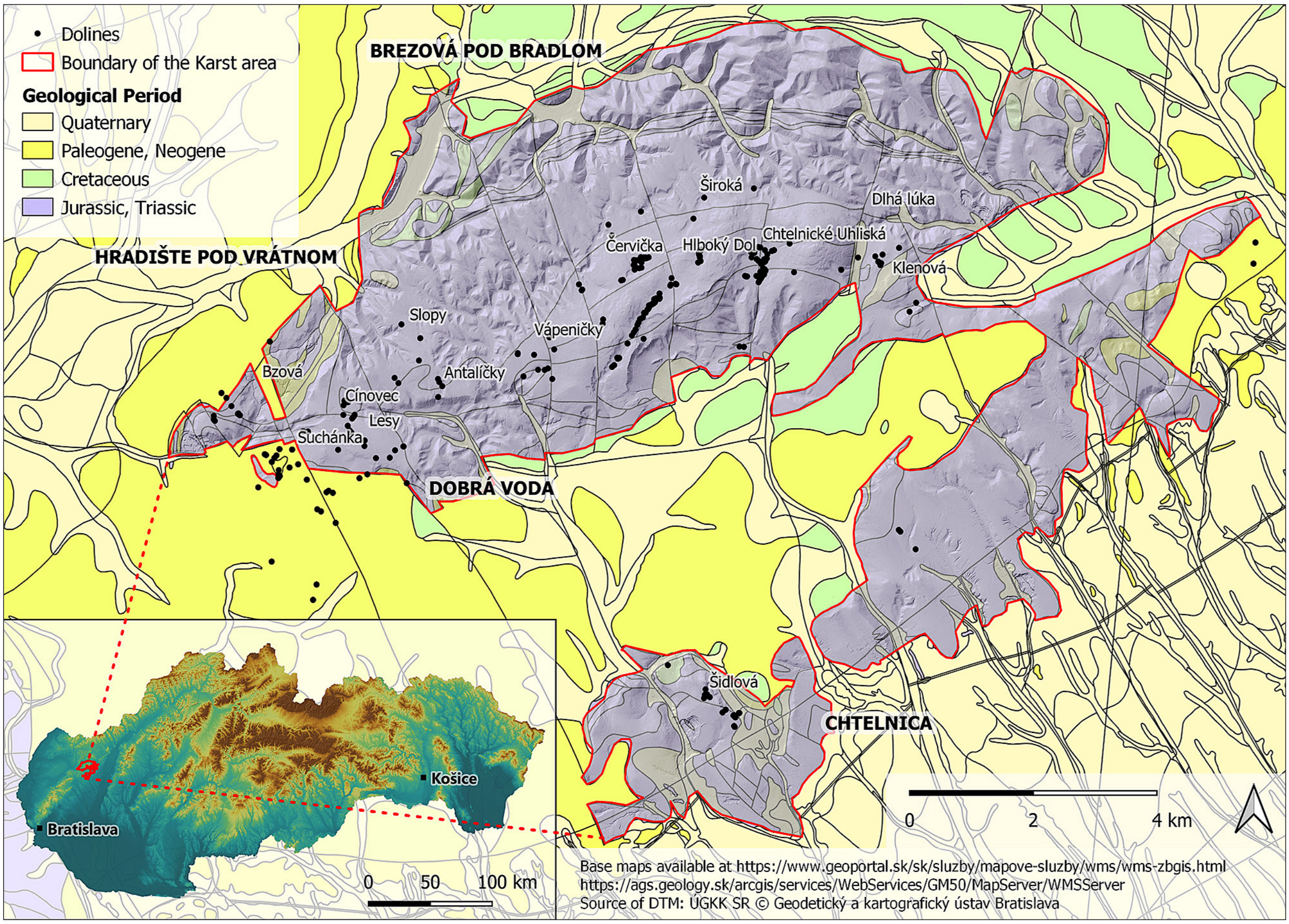

Fig. 1. Schematic geological map of study area with marking of dolines.

Early Miocene (Buday et al., 1962; Buday et al., 1963), and later (Began et al., 1984; Salaj et al., 1987; Michalík et al., 1992; Geological map of Slovakia, 2013) to the Late Cretaceous (Gosau Group). Finally, Kováč et al., (1991) demonstrated that the above-mentioned sediments stratigraphically belong to the Early Miocene (Eggenburgian – Karpatian). Only erosive remnants of the Chtelnica Formation belong to the Upper Cretaceous (Turonian) (Hók & Littva, 2018), representing freshwater massive oncolithic limestones with abundant algae remnants occurring in the Brezovské Karpaty and Čachtické Karpaty Mts. Moreover, the tectonic position of the Upper Cretaceous/Lower Miocene sediments was interpreted (with the exception of Buday et al., 1962; 1963 and Hók et al., 2018) to be in a tectonic footwall of the Mesozoic sediments in the south-verging Dobrá Voda Fault Zone (Marko et al., 1991). The results of geological and structural mapping (Hók et al., 2018) reveal that the Early Miocene sediments either overlay different tectonic slices, or they are tectonically separated from the Mesozoic sediments by normal faults with a negligible oblique component.

2.2. Basic characteristic of the Dobrá Voda Karst

The karstic area in the surroundings of Dobrá Voda in the Brezovské Karpaty Mts. was described and named by Droppa (1952). It covers an area of 87.2 km^2 and includes the elevations of Klenová (585 m a.s.l.), Vrátno (576 m a.s.l.), Slopy (432 m a.s.l.), Orlie skaly (430 m a.s.l.), and Bzová (425 m a.s.l.) (Fig. 1). In the past, this karstic area was called the Brezová Karst (Stankoviansky, 1974). The Mesozoic rocks sequences represent an antiform structure with a NE-SW orientation and distinct Cenozoic depression in the centre of the area (Hók et al., 2018; Šujan et al., 2019). The Mesozoic structure consists of a limestone-dolomitic complex. The north-western part is larger and contains more surface and underground karstic forms than the south-eastern part, which consists largely of dolomites with the exception of the surroundings of the village of Chtelnica where limestones prevail. The karst is built of carbonates of the Hronic nappe with sedimentary sequences of the Middle Triassic up to the sequences of the Jurassic (Salaj et al., 1987; Hók et al., 2018). In the area of interest, Upper and Middle Triasic dolomites, Wetterstein limestones and dolomites, Steinalm Limestone, and Dachstein Limestone are exposed (Salaj et al., 1987; Hók et al., 2018). Some of the karstic forms developed in Neogene basal carbonatic conglomerates as well (Dobrá Voda Formation *sensu* Buday et al., 1962; 1963). Since karstic formations (mostly dolines) are rare in these sediments, they were not included in the total area of the Dobrá Voda Karst. Mitter (1983), however, considered them partially within the area. Moreover, he divided the karst into the northern Brezová Karst and the southern Chtelnica Karst, and between these two, the Dobrá Voda-Prašník Karst, which had developed on Neogene conglomerates, was recognised.

Dolines are typical surface karstic forms. Significant doline lines are located in the area of Hlboký Dol, Chtelnické Uhliská, and Cínovec. As many as 263 dolines were recognised here, although Šmída (2008) suggested the presence of only ca. 170 dolines. Some of them had been opened by exploratory works by speleologists. In the doline at Chtelnické Uhliská no. 13 ("Trinástka" or Cave C13), a depth of 22 m was documented, whereas in doline no. 18 ("Osemnástka" – Cave C18), a depth of 30 m was documented. Another ponor cave located on the doline line of Hlboký Dol is Cave D46 (length = 75 m; depth = 32 m), which terminates with a siphon. The Ponor doline Pod Širokou, which is partially similar to Cave D46, has the character of a semi-blind valley, while it functions as an occasional ponor. At the bottom is the entrance to the Jaskyňa pod Širokou Cave (depth = 17 m). It is important to mention the underground karstic forms, such as the Slopy Cave (length = 75; depth = 42 m), Klenová Cave (depth = 18 m), and the vertical Jaskyňa pod Vrátnom Cave (depth = 18 m). Archaeologically, the Veľká pec Cave is also quite interesting. The longest cave of the Dobrá Voda Karst is located in the Chtelnica part – Zbojnícka jaskyňa Cave (length = 190 m; depth = 22 m). The Jaskyňa v Chrášťí Cave is also located in this part, into which a smaller stream flows (length = 60 m). A new addition to this list is the Hradisko D10 Cave (length = 62 m; depth = 14 m) above the Dobrá Voda quarry. In the entire karstic area, corrosive caves dominate. The area represents a seismically-active zone with active tectonics. From the surface karstic forms, it is also important to mention karren. Locally, they occur throughout the entire karstic area. A larger number of karren is located at Orlie skaly in the surroundings of Slopy, on the platforms of Malá Pec and Veľká Pec at Kamenec, as well as in the area of Kresaná skala above the village of Chtelnica. At the locality in the area of Hodinková veža, parallel solution runnels are developed extensively on the rock wall. Solution hollows and fissure karren dominate. The Dobrá Voda Karst is rich in profuse karstic springs, such as Mariáš, Hlávka, Stratený stok, and Vítek.

The extent of tufas and travertines is also noteworthy. In this respect, the studied area was documented in detail by Briestenský (2008). He located and documented 201 springs in total here. 32 of them are linked with the recent development of tufas and travertines. The reason for documentation of these forms was the presumption of their connection with significant active lines. The occurrences are largely connected with Triassic dolomites and limestones. The best-known occurrence of such tufas in the Dobrá Voda Karst is the locality of Ľahký kameň, which received the status of a natural reserve in 1993. Significant accumulations of lithified travertines can be found close to the state road from the village of Hradište pod Vrátnom to the town of Brezová pod Bradlom, between the localities of Michaličkov mlyn and Holdošovský mlyn. The locality represents the frontal part of a travertine terrace, which had been quarried parallel to the road. The exposed quarry wall, with a length of 20 m and a height of ca. 6 m, represents multigenerational sedimentation of travertines. The terrace itself attains a length of 300 m. In addition to active quarries, many disused quarries are located in limestones and dolomites across the entire area.

3. METHODS

Several methodological approaches have been developed so far, both for the characterisation of ideal parameters for geometric shape and for the characterisation of dolines as an integral part of a complex geosystem in relation to geological, geomorphological, hydrological, climatic, pedologic, and biogeographic properties of the land (e.g., Cvijić, 1893; Segre, 1948; Williams, 1972; Castiglioni, 1991; Bondesan et al. 1992; Faivre & Rieiffsteck, 1999; Basso et al., 2013; Šegina et al., 2018; Mihevc & Mihevc, 2021; Garasic, 2021).

Therefore, they can originate through several processes. Four major mechanisms of forming dolines are distinguished: solution, collapses, suffosion, and subsidence. However, it is not possible to link the origin of dolines with only one process. Depending on the process, a variety of doline shapes can be documented; they occur either isolated or in groups. Since the international terminology includes more deep-rooted terms for genetic types of dolines, Williams (2004) linked the respective terms with specific genetic processes, and thus made the nomenclature more transparent.

On the basis of their shape, dolines were classified in Slovak terminology according to Jakál (1975). With regards to the inclination of their walls, dolines can be divided into four categories: funnel-shaped, cup-shaped, kettle-shaped, and well-shaped. Jakál (2008) distinguishes three types of dolines in the Slovak Karst based on their genesis: solution dolines, collapse dolines, and alluvial dolines. In our article, we consider an alluvial doline to be a doline with a pronounced inflow line with an open or half-open bottom and a steep opposite slope (see Fig. 9). This type can be considered an alluvial streamsink doline according to Jennings (1985). Doline lines formed on lithological and tectonical discontinuities are often an indicator of these structures in the field (e.g., Ćalić, 2011; Veselský et al., 2014[a]; 2014[b]; Lačný et al., 2020).

For locating dolines, as well as for providing the historical context of speleological works in the dolines, cooperation with local speleologist groups (OS Inovec, Speleoklub Trnava) was required. Several tools were used during the field research, including a GPS toolkit, laser rangefinder, inclinometer with compass (Leica Disto D3), measuring tape, geological compass, and a camera.

Several previously published case studies were examined, which were focused on the karstic areas of the Malé Karpaty Mts. (e.g., Veselský et al., 2014a; 2014b; Lačný et al., 2019; 2020; 2021). Moreover, in each exact location of the dolines, we documented several directly measurable attributes as well: localization, altitude, perimeter, depth, the longest axis passing through the smallest point of the doline (LAXI), the shorter axis (perpendicular to the longest axis – WAXI) according to Bondesan et al. (1992), azimuth of the longest axis, and the inclination of the walls, vertical shape of the doline, lithology, bottom character, genetical type, and hydrology. The dolines were categorised in the field based on their shape in map view as round, oval, or irregular.

The geographical coordinates of the dolines obtained from our fieldwork were transformed and recorded in a geographical information system (GIS). Visualizations were made using the QGIS Desktop 3.16.3 "Hannover" with GRASS 7.8.5 (QGIS.org, 2021). The final maps illustrate the relevant parameters of the dolines, such as perimeter, depth, and orientation of the longest axis, all of which were depicted on hillshaded DTM (Digital Terrain Model), which had been created from processed and classified LiDAR data. The data were acquired within the National project for aerial laser scanning of the Slovak Republic (Leitmannová & Kalivoda, 2018).

Tab. 1: Count and percentage of dolines divided into several altitude ranges.

altitude [m a. s. l.]	count of dolines	percentage of dolines [%]
250–300	10	3,8
300–350	25	9,5
350–400	63	24,0
400–450	71	27,0
450–500	59	22,4
500–550	33	12,5
550–600	2	0,8

4. RESULTS

4.1. Morphology and morphometric analysis

The final number of dolines in the Dobrá Voda Karst area is 263. They are located mostly at 350–500 m a. s. l. The percentage of dolines in 50 m-ranges can be seen in Tab. 1. Since the graphical view of the altitudes of dolines did not show any significant horizons in which dolines are more frequent but the altitude of dolines has nearly equal representation instead, the regular intervals were chosen.

In the Dobrá Voda Karst, dolines formed mainly in the areas with a slope of 3 degrees and no more than 7 degrees, although a few of them had been formed on steeper slopes (Fig. 2). As many as 60 dolines have an inflow line, which is approximately 23 % of the total amount. Inflow lines are usually present in funnel-shaped alluvial or solution dolines. In some cases, the lines reach more than 15 m, the longest of which are in the dolines D052 (2 inflow lines of 35 and 25 m), D094 (35 m), D097 (2 inflow lines of 35 and 30 m) D148 (50 m), D117 (2 inflow lines of 70 and 45 m), and D146 (120 m); however, in other cases, they are usually shorter, being no more than a few meters long. In most cases, the inflow lines are oriented in the direction of the maximal axes of the dolines, and they are the result of infiltration of precipitation from the ground to underground spaces.

From the total count of the known and measured dolines to date, according to the classification of Jennings (1985), solution and subsidence genetic types of dolines are predominant (45 % both) with the rest of the dolines being alluvial streamsink

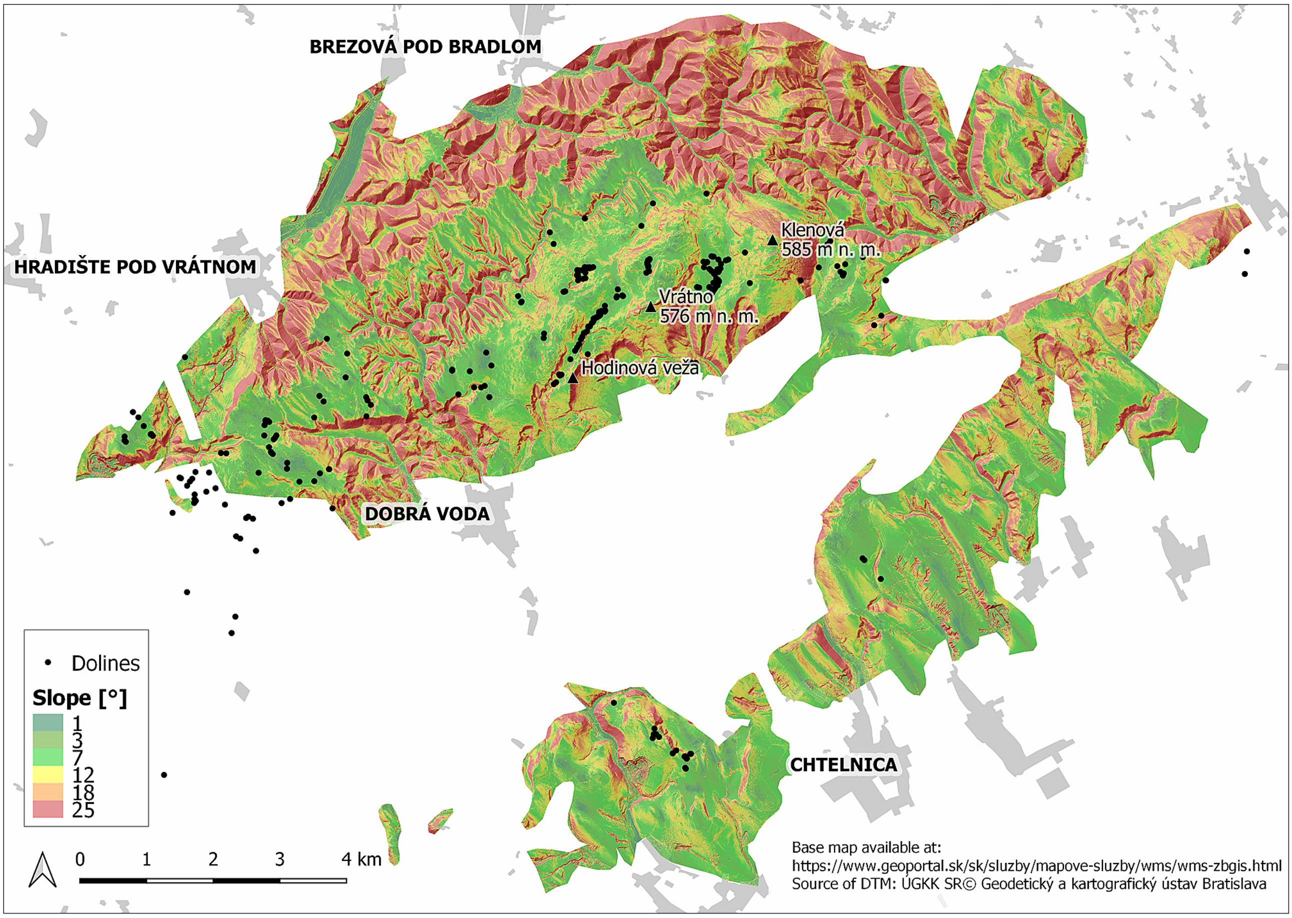

Fig. 2. Map of slopes with marked dolines.

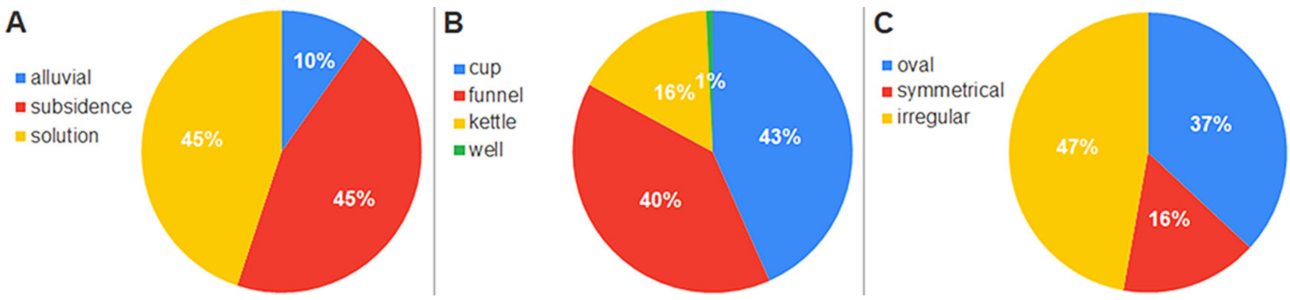

Fig. 3. Graphs of genetic type (A) and morphology of dolines (B – based on the slopes of the dolines, C – based on the footprint of dolines).

dolines (10 %) (Fig. 3A). Solution and alluvial streamsink dolines are predominant at the bottom of the valleys, on the lines with tectonical or lithological predisposition, where the dewatering of precipitation from adjacent slopes is more intensive (Cínovec, Hloboký Dol, Chtelnické Uhliská). In contrast, the subsidence type of dolines is more frequent in areas with a lower slope, and these dolines are usually isolated and not concentrated into larger groups. According to Jakál (1975), cup-shaped (43 %) and funnel-shaped (40 %) forms dominate in the morphology of dolines followed by kettle-shaped dolines (16 %). Minor representations have well-shaped dolines (1 %) (Fig. 3B). The funnel and kettle-shaped types of dolines are linked to alluvial and solution genetic types, while cup-shaped dolines are in most cases of a subsident type. The methodology of Petrvalská (2010) was used to differentiate the shapes of dolines based on their footprint (Fig. 3C) to irregular (47 %), oval (37 %) and symmetrical – round dolines (16 %). Some dolines are so close to each other that their footprint is similar to the number 8, (D2, D15, D36, D59, D104, D153, D204) while some are parasitical to others – a secondary doline located in original one (D58, D59, D108, D125, D141, D143, D181, D186, D187, D199). This is the result of active infiltration of precipitation. Such cases are typical for solution funnel-shaped dolines.

More than half of the dolines have a perimeter in the range of 20–40 m, with 26 % between 7–20 m, 14 % between 40–60 m, and almost 4 % are in the range of 60–80 m (Fig.4, 5A) Only four dolines have a perimeter of 80–100 m, and just three of them are more than 100 m (maximum D187–118 m).

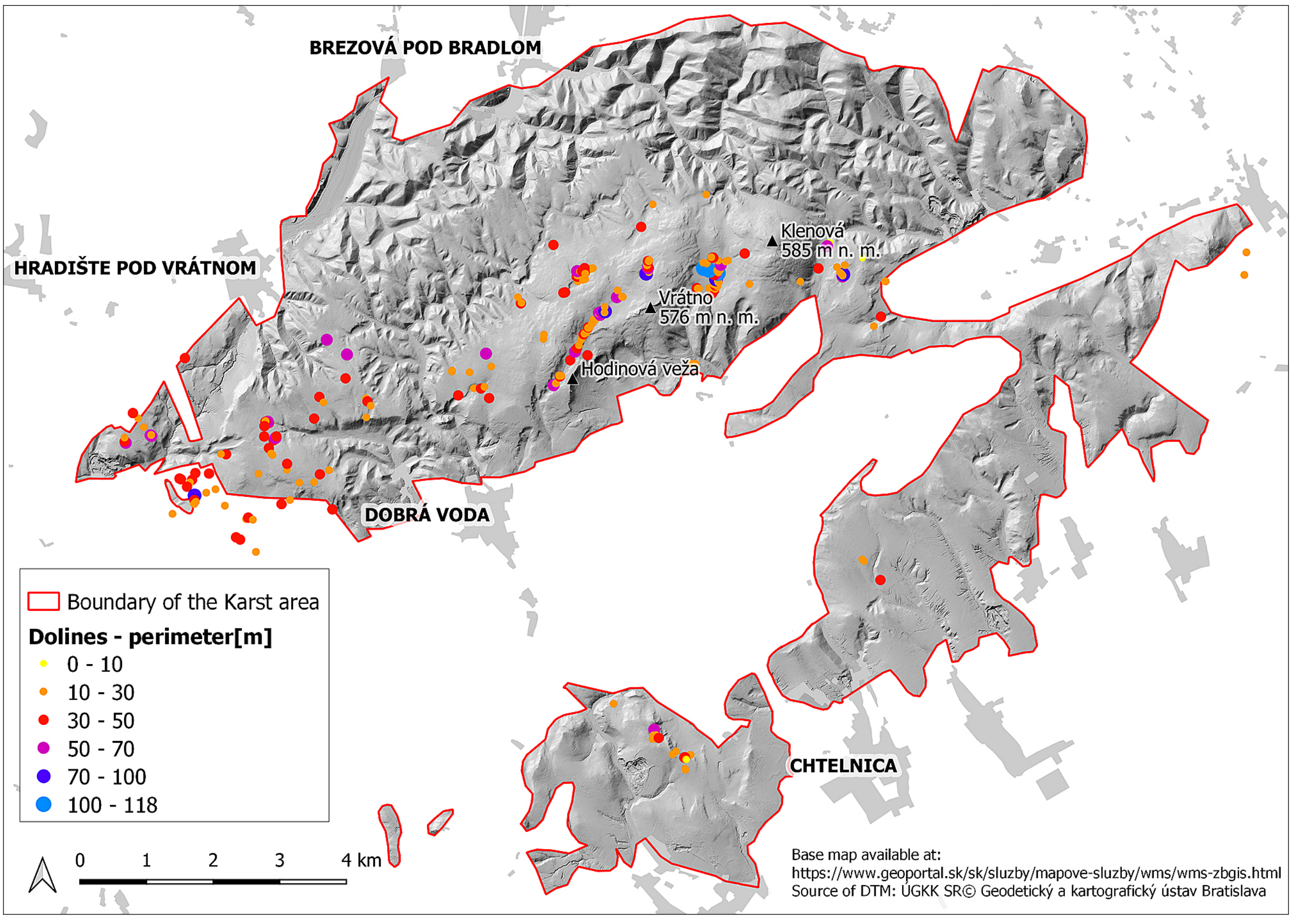

Fig. 4. A map of Dobrá Voda Karst illustrating the perimeter of the dolines.

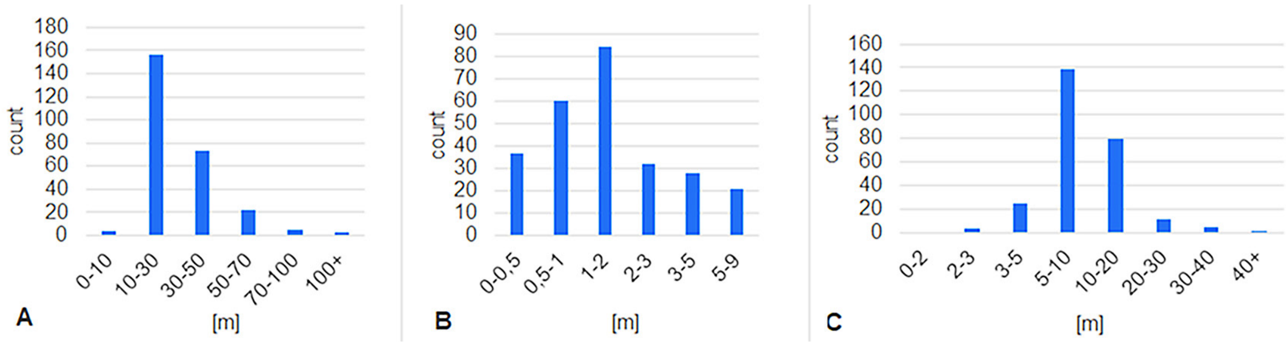

Fig. 5. Graphs of perimeter (A), depth (B) and the length of the longest axes (C) of the dolines.

The majority of dolines, which is almost 70 %, have a depth in the range of 0.5–2 m. 12 % of the dolines reach a depth in the range of 2-3 m and more than 15 % in the range of 3–6 m. Only 8 dolines are deeper than 6 m (the deepest is D146 – 9 m) (Fig. 5B). Deeper dolines are mostly situated on significant lines with a tectonical predisposition or formations (Hlboký Dol, Chtelnické Uhliská, Červíčka, Cínovec), while shallow ones are mostly isolated or located on the periphery of more numerous lines or formations instead (Fig. 6).

The maximal prolongation of the longest axis of doline could be caused by more significant discontinuity, however, as is claimed by Petrvalská (2010), it depends on the orientation of the slope and could be caused by microclimatic processes or other physical-geographic conditions. The longest axes in the Dobrá Voda Karst are mostly 10 to 20 m long, with longer ones being really rare – the longest axis, which is longer than 40 m, has just one doline. (Fig. 5C). Based on the ratio of the minor and major axes of the dolines, the eccentricity (ellipticity) can be computed as follows (Doctor & Young, 2013).

where a and b are half of the major and minor axes, and the eccentricity reaches the values from 0 to 1. According to the results, 9 dolines are perfect circles (e = 0), 2 are very close to the shape of a circle (very close to zero), 15 dolines are not very significant ellipses, although the majority of dolines have an elliptic shape (closer to value 1). The results may be a little confusing because of the irregular shape of many of the dolines, but

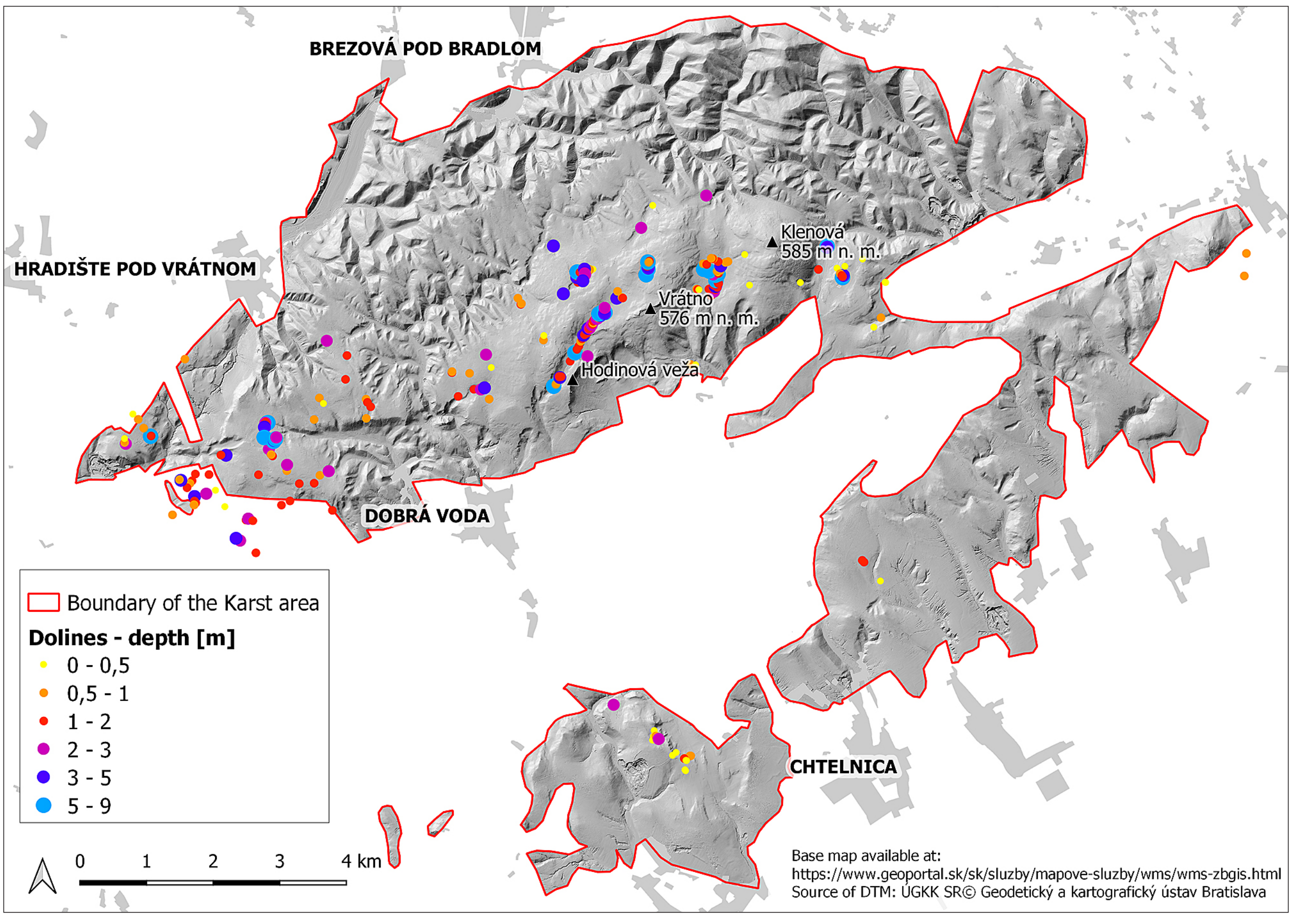

Fig. 6. A map of Dobrá Voda Karst illustrating the depth of the dolines.

they confirm that the oval dolines categorized during the field research predominate over the rounded (symmetrical) ones.

According to the azimuth of the longest axis of doline, several more frequent directions can be recognised: N-S, NE-SW and WNW-ESE. This measured parameter will be analysed in detail in the chapter *5. Interpretations of fault structures according to the bedding and brittle tectonic.*

4.2. Dolines and lithology

Representation of dolines in individual strata is as follows: Steinalm Limestone (99), Ramsau Dolomite (40), Wetterstein Limestone (38), Neogene conglomerates of Dobrá Voda Formation (34), Wetterstein Dolomite (31), Raming Limestone (13), Reifling Limestone (5), Main Dolomite (3).

The greatest range in the central part of the Dobrá Voda Karst consists of Steinalm Limestone. Significant doline lines, such as Hlboký Dol, Široká or an area of dolines in the region of Šidlová were formed here. There are a total of 99 dolines. Apart from the good solubility of limestones, tectonics proved to have markedly high representation in them. Moreover, the Hlboký Dol valley is significant, since part of the territory is drained through the dolines.

Up to 40 dolines are situated in the Ramsau Dolomite, where they occur predominantly in the area of Chtelnické Uhliská. They form a footwall of Steinalm Limestone located in the north. For the most part, fault structures create the predisposition for doline formation.

Wetterstein Limestone extends in the overburden of Steinalm Limestone. There are 38 dolines in them. These include suitable carbonates with good solubility as well, and thus contain many dolines. Dolines in the area of the Bzová, Cínovec, Červíčka, or Vápeničky locations are related to these rocks.

There are up to 34 dolines that appear in the neogene conglomerates of the Miocene Epoch. These Neogene conglomerates are not attributed to the Dobrá Voda Karst territory, since there is only minimum underground karst phenomena. If these rocks were attributed to the karst, its area would increase excessively in size. In the past, for example, Mitter (1983) classified a part of the conglomerates in the Dobrá Voda Karst. The material consists of various Mesozoic carbonates, which lithologically correspond to their immediate footwall. These are primarily Wetterstein dolomites and limestones, as well as a few Steinalm and Anaberg limestones of the Triassic age or Cretaceous sandstones. Furthermore, they include more assorted clastics of crystalline rocks or quartzites. Where clastics of carbonates prevail, common karst processes also occur. When mapping the dolines, underground premises with smaller caves at the bottom of some of them were observed. The more externally they were from the karst area, the less frequent such phenomena occurred. The prevalence of subsidence dolines of cup shapes is visible. This could be presumed that the prevalence of the subsidence of rocks is due to subgrade, carbonate rocks.

The largest size range of the Dobrá Voda Karst consists of Wetterstein Dolomite. In this regard, there are up to 31 dolines, despite the fact that the solubility of dolomites is lower compared to limestones. Dolines are rather isolated here and do not form significant doline lines. Larger dolines appear in these strata in the area of Dlhá lúka and the Klenová gamekeeper's lodge. Extension of dolines in other types of rocks is minimum. However, limestones prevail over dolomites here as well.

Significant lines

In the Dobrá Voda Karst, there are plenty of dolines; however, some of them create significant, numerous formations or lines, which can indicate faults or other discontinuities. In this chapter, such lines or formations of dolines are described. The locations of dolines were chosen because of their significant depth, perimeter, or high number of dolines in a small area. In addition to the formations described below, the locations near the elevation point at Bzová (425 m a. s. l.), Červíčka (to N and W from Hlboký Dol line), and between the elevation points Klenová (585 m a. s. l.) and Skala (397 m a. s. l.) are also significant.

Hlboký Dol

The most numerous dolines are formed on the line of Hlboký Dol, which is located approximately 2 km NE from the village of Dobrá Voda. The line was formed on a tectonically predisposed line in a NE-SW direction and contains 55 dolines in the length of 2.4 km (Fig. 7, 8). Here, the dolines are located at an altitude between 439 to 564 m a. s. l. Most of them have a depth in the range of 1–2 m (46 %); while other categories are similar in count, none of the dolines of this line have a depth shallower than 0.5 metres. 12 % of the dolines have a depth in the range of 5–9 m, however, just one of them is deeper than 8 m. Here, the majority of dolines have a perimeter in the range of 10–30 m (69 %). Only 2 dolines have a perimeter larger than 70 m, and there is no doline in the category that is 0–10 m in perimeter. The longest axes of the dolines may correspond in some cases with fault structures in the NE-SW and NW-SE direction, as well as with bedding planes oriented in the NE-SW direction. In this line, solution funnel-shaped dolines are predominant. The shape of the dolines is the consequence of the occurrence of a significant tectonic line, through which intensive infiltration of groundwater to the underground occurs. The most significant doline in the Dobrá Voda Karst (D146) was identified here (D46 in speleological evidence), in which an intensive speleological survey had been done in the past. On the vertical profile (Fig. 9), it can be seen that one slope is much steeper than the others. This is a typical alluvial doline with a long inflow line.

Chtelnické Uhliská

The second significant line of dolines is located 1km SW from the top of Klenová (585 m a. s. l.) and 48 dolines were formed here (Fig. 10). They are divided into 2 significant lines predisposed by faults with an NE-SW and NW-SE direction. Three of them reach more than 100 m in perimeter – D181 (C15), D186 (C18) and D187 (C19) and have been surveyed by speleologists in the past. Most of the dolines of this line have a depth in the range between 0,5–2 m. 42 % of dolines reach a depth of 1–2 m and 27 % have a depth in the range of 0.5–1 m. Only one is deeper than 7 meters, and just 2 are shallower than 0.5 m.

Dolines are located at an altitude of 424 to 472 m a. s. l. The area is formed by Ramsau dolomites and Steinalm limestones.

They are also found in the line of Hlboký Dol. Due to the location on the crossroad of 2 faults, solution funnel-shaped dolines dominate here as well. Most of the dolines are oval in the footprint category. In this line, orientations of the longest axis of the dolines with a direction of N-S, ESE-WNW and E-W are more frequent.

Cínovec

The line is located approximately 3 km NW from the village of Dobrá Voda, between the elevation points at Vysoká skala (440 m a. s. l.) and Lesy (443 m a. s. l.) (Fig. 11). Dolines are situated at an altitude of 378 to 400 m a. s. l. 15 dolines were formed here. Orientation of their longest axis is dominant in a NE-SW and NW-SE direction. The majority are irregular in shape. Since the dolines are located on the fault where it is predisposed to the Horná Blava valley and the infiltration of groundwater here is intense, solution funnel shaped dolines are predominant. The depth of the dolines is significant here as well, reaching more than 5 m in 4 cases. Each doline is deeper than 0,5 m, with many of them more than 1 m. In most cases, perimeters range from 30 to 50 m, the largest value is 70 m in just one case.

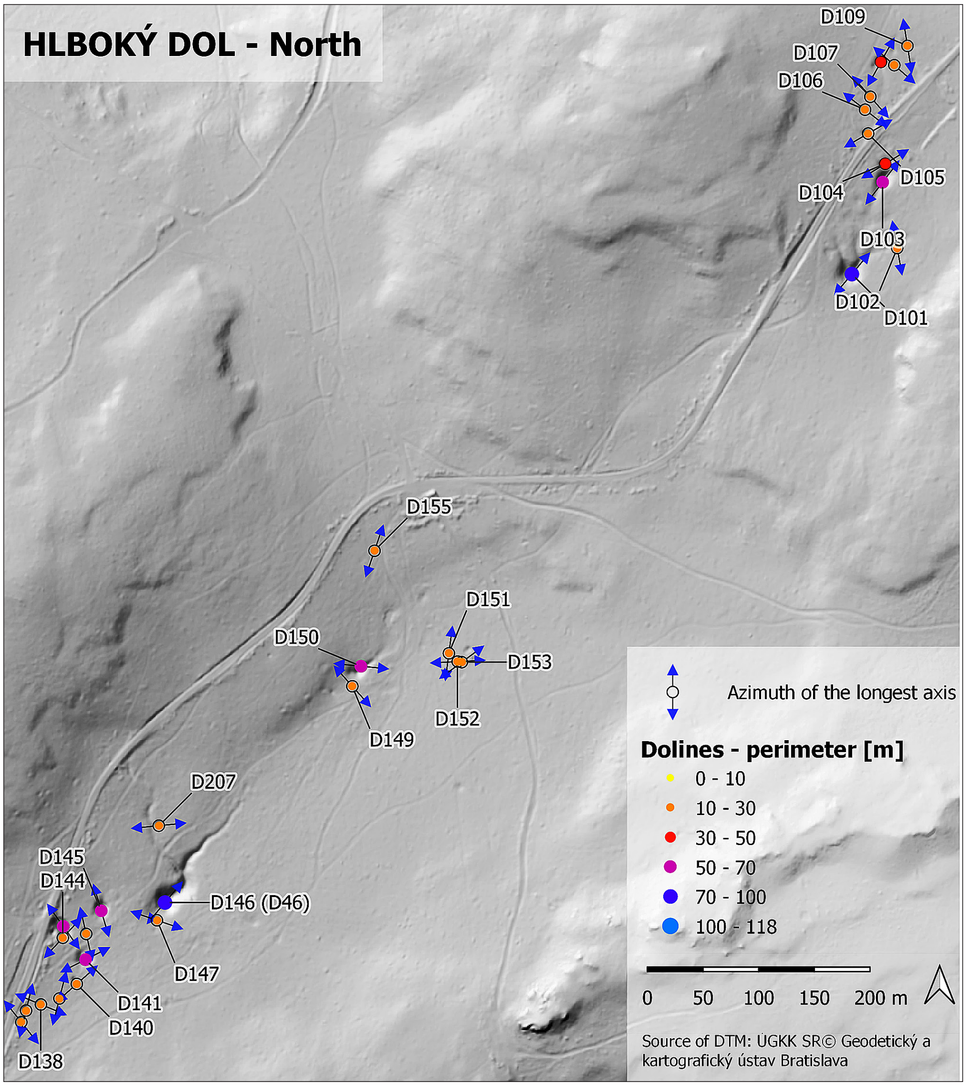

Fig. 7. Location of dolines in the Hlboký Dol valley (north part).

5. INTERPRETATIONS OF FAULT STRUCTURES ACCORDING TO BEDDING AND BRITTLE TECTONIC

The formation of dolines on significant doline lines encourages the interpretation of fault structures. However, this is not always possible. This is because a part of dolines may also be formed on various near-fault structures or lithological interfaces. As it appears, in relation to the relatively monotonous lithology in the Dobrá Voda Karst, which is free of significant lithological interfaces of karst and non-karst rocks, the dolines are represented in this way only exceptionally, i.e., on the interface of limestones and dolomites. Thus, the prevalence of doline lines based on the neotectonic structures that can be dated back to the Quaternary Period is proved. These frequently appear in dry to semi-dry valleys, and they are significant infiltration areas of surface precipitation.

A significant fault can also be predicted in the area of Hlboký Dol, continuing up to Široká in the NE-SW direction (Fig. 12). This is further documented by several maximum axes of extension of more striking dolines in this direction. One typical example is the doline No. D146 (Cave D46) or the dolines in the location of Široká. Smaller dolines prove the orientation of maximum axes of dolines in the NW-SE direction, i.e., perpendicularly to the valley, which may be related to detailing due to the infiltration from the valley slopes. This fault was outlined in the study by Hók et al. as well (2018).

Another possible significant fault can be situated in the NW-SE direction, which is a ramp on which larger dolines were formed in the area of Chtelnické Uhliská. This is indicated also by the maximum extensions of the doline axes of some of them. The fault can be determined based on the change of relief of the rock ridge north-west of the location as well (Fig. 12).

Dolines in the Cínovec locality encouraged the interpretation of the WNW-ESE fault, a part of which is a continuation of the already mapped fault in this area (Fig. 12). The valley extending out to these dolines contributed to its determination.

The fault in the Bzová location, which runs parallel with the

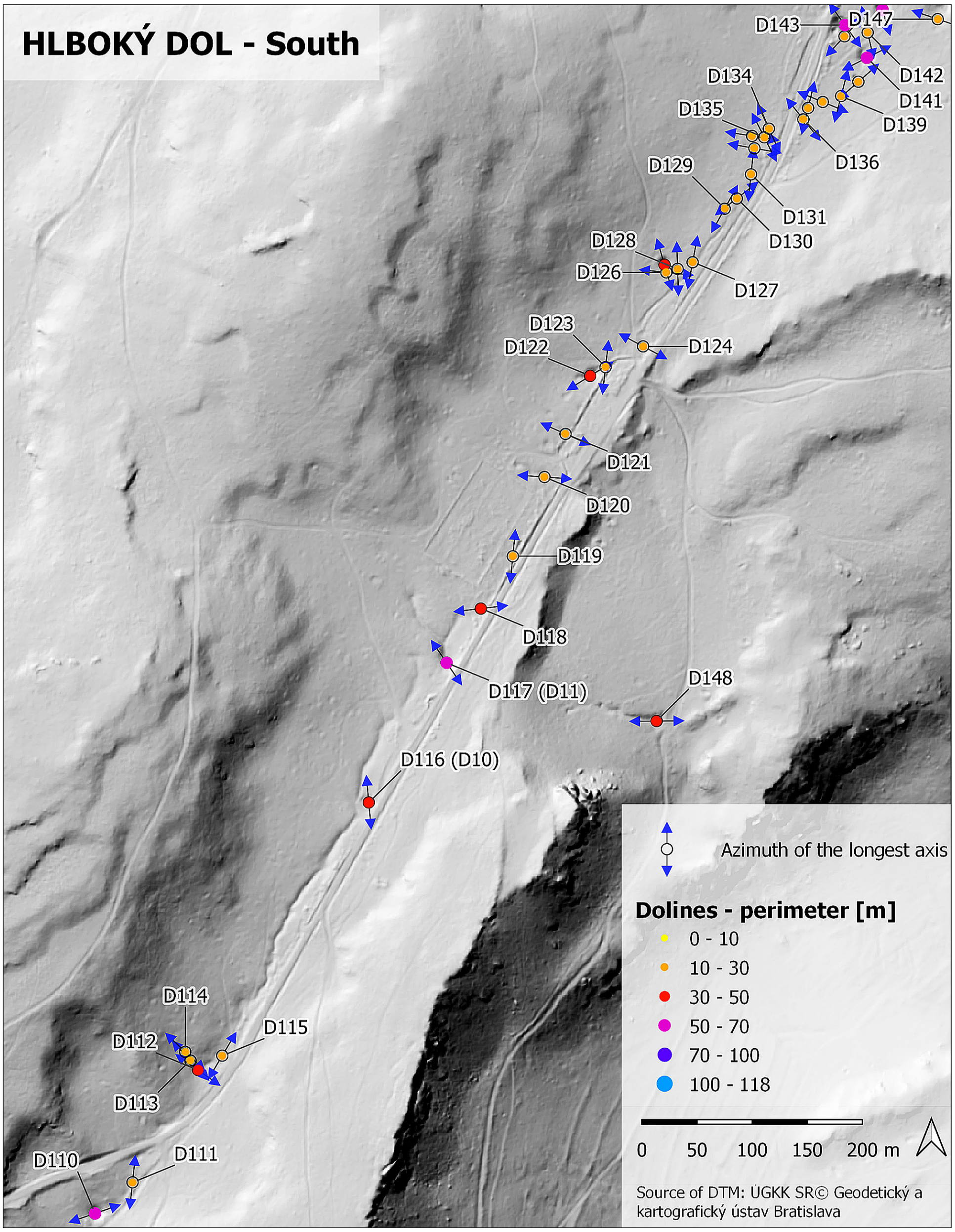

Fig. 8. Location of dolines in the Hlboký Dol valley (south part).

already mapped system of faults in the NW-SE direction and further continues under the Neogene conglomerates, can be considered the last mapped fault by means of the doline line (Fig. 12).

Perhaps the most important data in terms of tectonic interpretation are azimuths of the longest axes of dolines. The longest axis of the dolines should indicate a prevalent structure on which it was formed. Some dolines in the valley bottoms elongate in the direction of these valleys. However, this is not always the case, and it is possible to come across the situation when the azimuth of the longest axis of the doline does not correspond with the valley direction in which it was formed. The results are not so unambiguous, however, since three important directions contributing to the doline formation can be marked. These include the N-S, NE-SW and WNW-ESE directions (Fig. 13). These directions are represented on the territory by faults and by reflection of Neotectonics; they markedly remodel the morphology of the concerned territory as well. The Dobrá Voda Karst consists of an antiform structure of the NE-SW direction with a significant depressed area in the middle of the territory. It is divided by cross faults in the direction of the NW-SE and NNE-SSW affinity. There is less frequent representation of W-E directions of faults. Perhaps the most significant fault of the NE-SW direction was recorded in the Hlboký Dol valley. Therefore, it can be assumed that the dolines are bound to these fault structures, and their maximum axes of extension reflect the fault tectonics under the ground. The three previously described doline lines can be mentioned as a suitable example. The line in the Cínovec location was formed at the fault in the WNW-ESE direction, Hlboký Dol at the NE-SW fault, and the dolines in the Chtelnické Uhliská location were formed on the fault structure of the N-S direction with a side branch reflecting the fault extending in the NW-SE direction. A part of the dolines exists on the tectonized lithological boundaries of limestones and dolomites as well.

Apart from the mapping of new faults, accurate measurement of dolines enabled the verification of the ones originally interpreted. These include the locations of Chtelnické Uhliská, Vápeničky, Antaličky, and Červíčka, where dolines are situated above them. Their identification is very important because they are covered by the Quaternary sediments precisely on the flat parts of the territory, thereby making the geological research complicated.

One significant finding is that the maximum extensions of dolines, especially in the case of smaller dolines, is more dependent on surface factors affected by topography, terrain inclination, and subsequent direction of surface precipitation flow. In contrast, larger dolines are more related to subsurface discontinuities and the connection with their maximum axes of extension on the surface are visible. These subsurface discontinuities (stratification, fault structures) are those which are subsequently dissolved and disintegrated and have even more influence on the final shape of the doline.

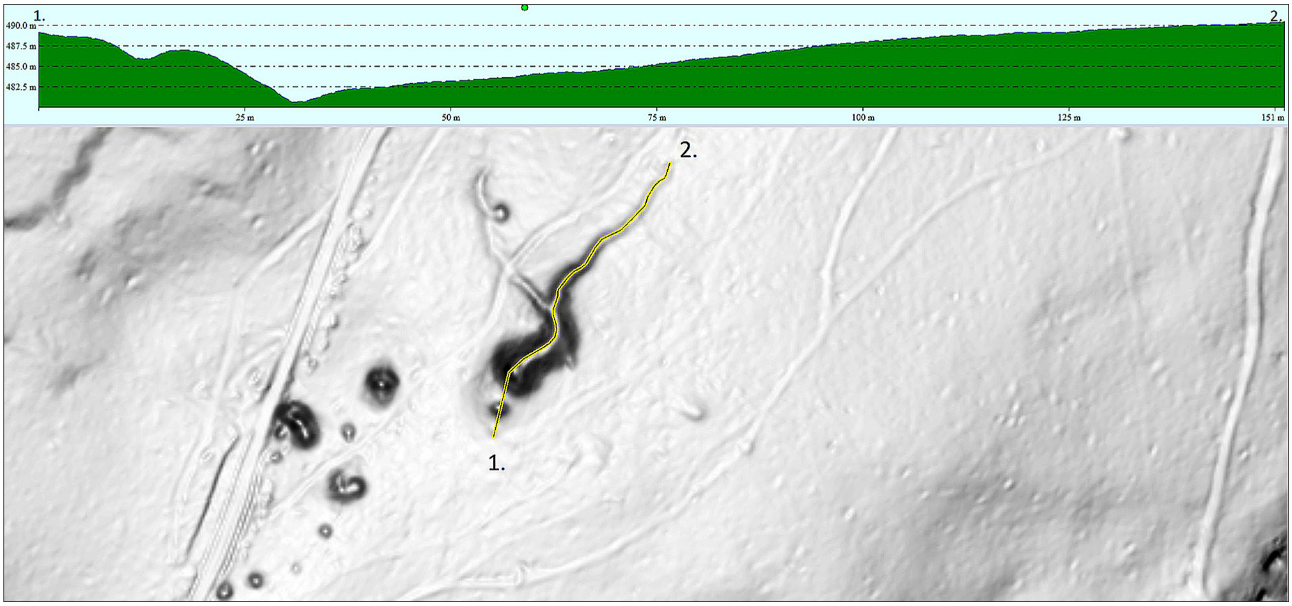

Fig. 9. The most significant alluvial streamsink doline of the Dobrá Voda Karst - D146 - viewed on the hillshaded DTM with vertical profile in the upper part.

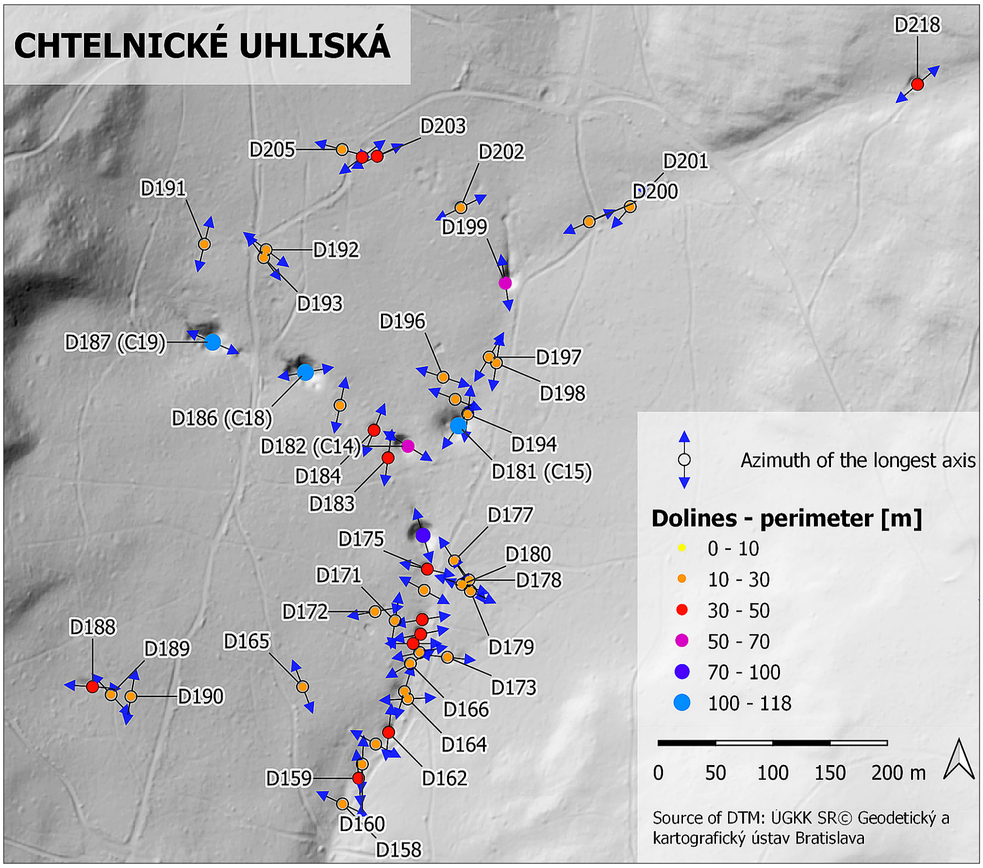

Fig. 10. Location of dolines at the Chtelnické Uhliská site.

Finally, based on the earmarking of new fault structures, wider relations concerning the drainage of the studied karst territory can be presumed. Some of our findings verify the current knowledge on the hydrology and hydrogeology outlined previously by Droppa (1952). It is assumed that drainage of the significant Hlboký Dol doline line as an infiltration area will be related to the captured karst springs at Dobrá Voda village, which are brought here through the network of fault structures. The "Stratený stok" karst spring at Vyvieračka Pod Bachárkou will be partially subsidized from that area. Similarly, dolines in the area of Lesy and Cínovec will contribute to a stream at Mariáš along young fault structures. Further significant grouping of dolines at Chtelnické Uhliská will be an infiltration area of the stream at Vítek. However, additional facts of this character would require further hydrogeological research.

6. DISCUSSION

The doline edge definition or defining the longest axis of dolines is subjective. In the case of the longest axis, LiDAR data serves for verification appropriately. At alluvial dolines with a cranking inflow line, a problem arises where the doline boundary must be artificially terminated, since the doline is to be closed from all sides. If we included a longer inflow line, for example, one with a perimeter or the longest doline axis, disproportions against other dolines may occur during statistical evaluation. Therefore, we didn't

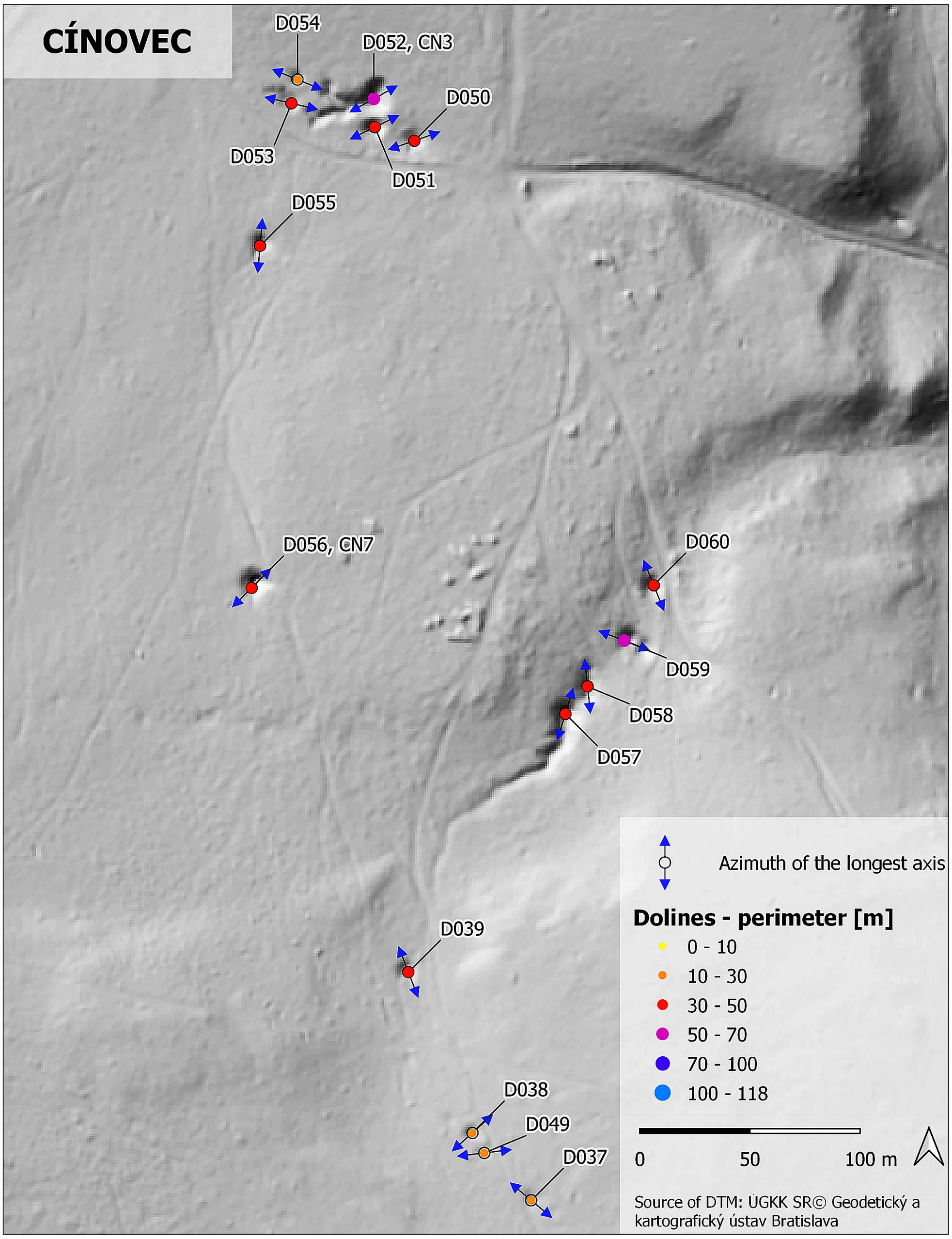

Fig. 11. Location of dolines at the Cínovec site.

cannot exclude that a part of these anthropogenic pits were originally dolines.

Formation of dolines can be dated back to the Quaternary Period, and this was related to neotectonics, relief development, and the formation of a river network. Furthermore, this is confirmed by the trends of maximum axes of doline extensions in the N-S, NE-SW and WNW-ESE directions, which partly correspond with regional tectonics. The Quaternary Age is also assumed on the basis that the phenomena of paleokarst have not yet been recorded in the Brezovské Karpaty Mts. Liška (1982) also assumed a Quaternary Age of the dolines from the territory of the Malé Karpaty Mts. (Borinka Karst). A part of the dolines was formed on tectonized lithological boundaries as well. As for the doline genesis, 45 % of them belong to solution, 45 % to subsidence and 10 % to alluvial types. The solution and alluvial streamsink dolines are concentrated in significant tectonic lines, where fast infiltration of surface precipitation occurs. In contrast, subsidence dolines are frequently located as isolated or in fading parts of faults and lithological boundaries. Shape heterogeneity of the dolines is visible on the entire territory based on the manifoldness of the measured attributes. More than half of the dolines have a perimeter in the range of 20–40 m. The majority of dolines, almost 70 %, have a depth ranging from 0.5–2 m, and they are typical dolines of the Malé Karpaty Mts. They are located mainly at an altitude of 350–500 m a. s. l. and were formed mostly in the areas with slopes of 3 degrees (maximum 7 degrees), with just a few of them being formed on steeper slopes.

Based on the location and size of the dolines, Dobrá Voda can be determined in terms of the geomorphic evolution of karst as a young type karst (*sensu* Grund, 1914). This can be seen by the underground karst formations - caves in which a majority

measure the longer inflow line (tens of meters) to the circumference of the doline. A smaller, flat inflow line located mainly in the direction of maximum extension of a doline is not problematic and forms a part of the doline measurement.

7. CONCLUSIONS

The dataset of 263 dolines provided deeper knowledge of the Dobrá Voda Karst with prevalence of these surface karst forms. Moreover, this frequency makes it predominant amongst all karst territories of the Malé Karpaty Mts. The research, however, was hindered by the occurrence of various anthropogenic pits, mostly lime pits, which are also related to carbonate rocks. We

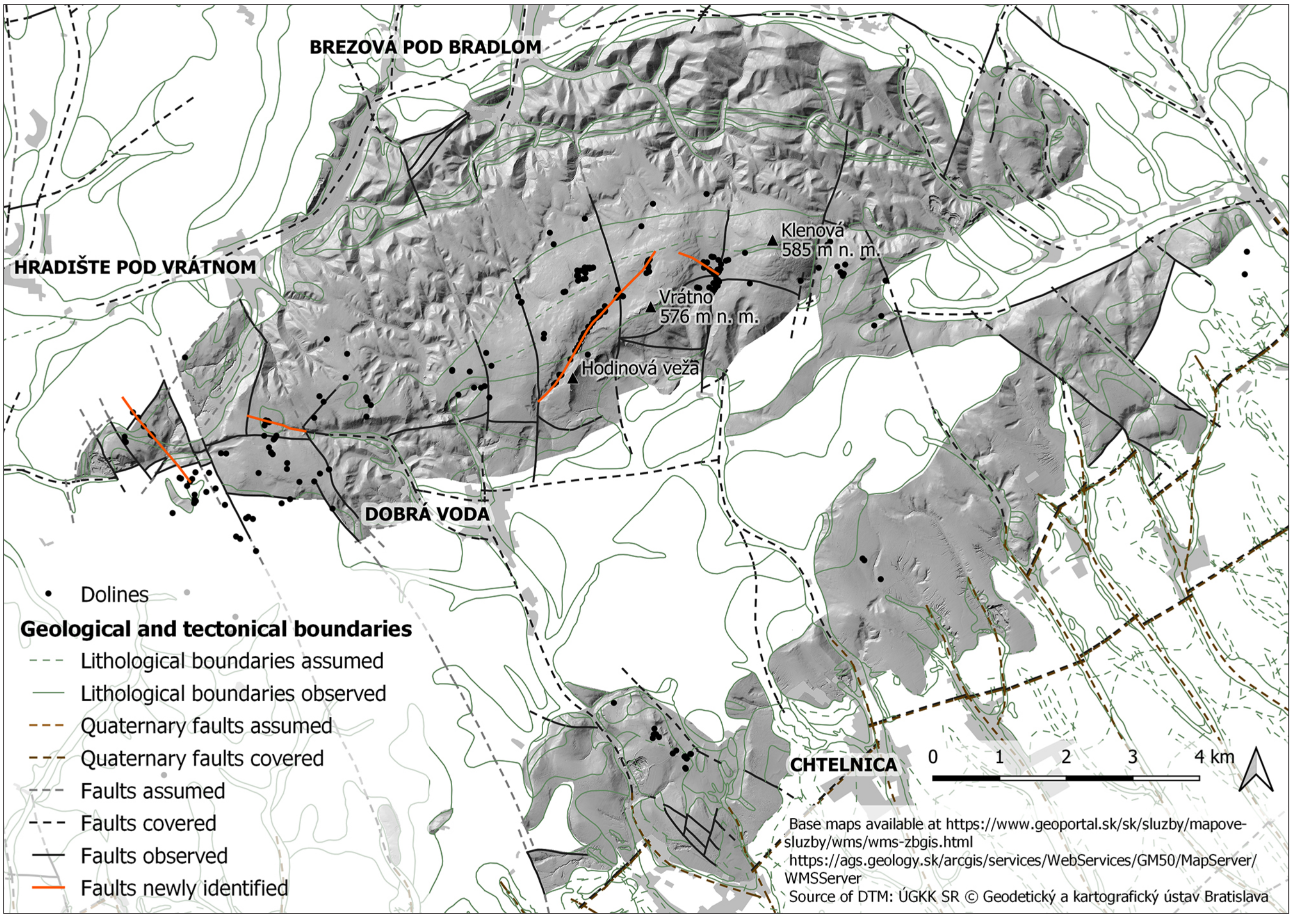

Fig. 12. A map illustrating the faults and lithological boundaries and new faults in the Dobrá Voda Karst.

reach only several tens of meters, and most of them are related to dolines.

The largest number of dolines is located in the north-west block of the karst territory, which is formed by the limestone-dolomitic complex. The dolines are bound here to the highly soluble Steinalm Limestone and Wetterstein Limestone. The most significant doline lines, such as Hlboký Dol, Cínovec, or Červíčka were formed here. There is a prevalence of solution funnel-shape dolines, while even alluvial dolines were formed in some places. Their drainage is assumed in harnessed karst springs in the villages of Dobrá Voda, Mariáš, Pod Bachárkou and Vítek. It is interesting to note that a significant concentration of dolines in the area of Chtelnické Uhliská in the Ramsau Dolomite was also formed. The predisposition for their formation includes fault structures. Lithological boundaries took a minor share in their origin, since a significant lithological contrast of strata is absent.

There are comparably fewer dolines in the south-east block with the prevalence of dolomites. The majority of them were localized in the area of Šidlová, which is again formed by limestones.

Subsidence cup-shaped dolines appear more frequently in isolated positions on the flat parts of the terrain, or along the continuation of doline lines. Such dolines prevail in the Neogene conglomerates as well, where dissolution of footwall carbonates is considered.

Acknowledgement: The geological and geomorphological research was carried out within the framework of the scientific grant projects: APVV-16-0146, VEGA - 1/0115/18, VEGA - 1/0340/22 and the Plan of main tasks of the State Nature Conservation of the Slovak Republic for 2020. Special thanks to our colleagues Nikola Kušniráková and Erika Žitňanská for assistance with the field research. We thank the editor Doctor Tomáš Lánczos, as well as the reviewers Professor Mladen Garašić and Associate Professor Pavel Bella for their valuable advice and comments.

References:

Basso A., Bruno E., Parise M. & Pepe M., 2013: Morphometric analysis of sinkholes in a karst coastal area of southern Apulia (Italy). Environmental Earth Sciences, 70,6, 2545–2559.

Began A. (ed.), Hanáček J., Mello J. & Salaj J., 1984: Geologická mapa Myjavskej pahorkatiny, Brezovských a Čachtických Karpát 1: 50 000 [Geological map of the Myjavská pahorkatina, Brezovské Karpaty and Čachtické Karpaty Mts in scale 1: 50 000]. GÚDŠ, Bratislava [in Slovak].

Bondesan A., Meneghel M. & Sauro U., 1992: Morphometric analysis of dolines. *International Journal of Speleology*, 21 (1–4), 1–55.

Briestenský M., 2008: Indikátory zlomovej aktivity Brezovskej časti Malých Karpát [Fault activity indicators of the Malé Karpaty Mts. Brezová part]. *Geomorphologia Slovaca et Bohemica*, 1/2008, 16–25. [in Slovak]

Buday T., Cambel B., Kamenický J., Maheľ M., Brestenská E., Kamenický L., Kullman E., Matéjka A., Salaj J. & Zaťko M., 1963: Vysvetlivky k

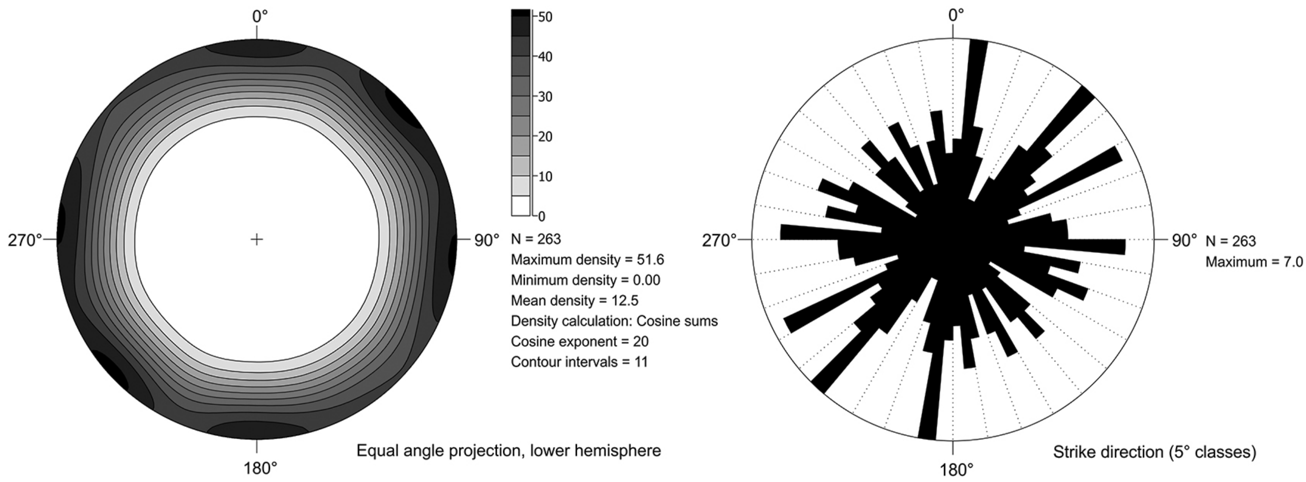

Fig. 13. Contour and rose diagram illustrating the orientation of the longest axis of the dolines.

prehľadnej geologickej mape Geologická mapa ČSSR, 1:200 000 [Explanations to the overview geological map of the Czechoslovak Socialist Republic] M-33-XXXVI Bratislava, M-33-XXXV Wien. Geofond, Bratislava, 248 p. [in Slovak].

Buday T., Cambel B., Kamenický J. & Maheľ M. 1963: Geologická mapa ČSSR, mapa predštvrtohorných útvarov [Geological map of the Czechoslovak Socialist Republic, map of the pre-Quaternary formations] 1:200 000; M-33-XXXV list Bratislava; M-33-XXXVI list Wien. [in Slovak]

Ćalić J., 2011: Karstic uvala revisited: Toward a redefinition of the term. *Geomorphology*, 134, 1–2, 32–42.

Castiglioni B., 1991: Some morphometric and environmental aspects of dolines in Berici Hills (Vincenza, Italy). *In:* Proceedings of the International Conference on Environmental Changes in Karst. Areas-IGU-UIS, Quaderni del Dipartimento di Geografia nr. 13, Universita di Padova, 143–155.

Cvijić, J.,1893: Das Karstphanomen. Versuch einer morphologischen Monographie. *Geographischen Abhandlung*, Wien V, 3, 218–329.

Droppa A., 1952: Kras na juhovýchodnej strane Malých Karpát. In: Virsík M. et al. [eds.]: Kras a jaskyne Malých Karpát [The Karst on the southwestern part of the Malé Karpaty Mts. *In:* Virsík M. et al. (Eds.): The karst and caves in Malé Karpaty Mts.]. Sprievodca Slovakotouru. Tatran, Bratislava, 63–138. [in Slovak]

Doctor D. H., Young J. A., 2013: An evaluation of automated GIS tools for delineating karst sinkholes and closed depressions from 1-meter lidar-derived digital elevation data. *In:* Land, L., Doctor, D. H., Stephenson, J. B. (Eds.) Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, National Cave and Karst Research Institute, 449–458.

Faivre S. & Reiffsteck P., 1999: Measuring strain and stress from sinkhole distribution, Example of the Velebit mountain range, Dinarides, Croatia. In: Beck, B. F., Pettit, B. F. & Herring, J. G. (Eds.): Proceedings of the Seventh Multidisciplinary Conference on sinkholes and the engineering and environmental impacts on karst. Rotterdam: A. A. Balkema, Rotterdam, Brookfield., 25–30.

Garasic M., 2021: Introduction to Karst and Geology of Croatia. ln: The Dinaric Karst System of Croatia - Speleology and Cave Exploration. Cave and Karst Systems of the World. Springer, Cham. 437 p.

Geological map of Slovakia M 1: 50 000, 2013: [online] Bratislava: Štátny geologický ústav Dionýza Štúra, Available online: http://mapservergeology.sk/gm50js

Grund A., 1914: Die Geographische Zyklus im Karst. *Gesellschaft für Erdkunde*, 52, 621–640.

Havrila, M., 2011: Hronikum: paleogeografia a stratigrafia (vrchný pelsón – tuval), štrukturalizácia a stavba [Hronicum: Paleogeography and stratigraphy (Upper Pelsonian - Tuvalian), structuring and construction]. *Geologické Práce*, 117, 7–103. [in Slovak]

Hók J., Littva J., Šujan M., Šamajová L., Šujan M. & Šipka F., 2018: Geological structure of the Dobrá Voda seismoactive area (western Slovakia). *Acta Geologica Slovaca*, 10, 2, 143–150

Hók, J. & Littva, J., 2018: Chtelnické súvrstvie – nová litostratigrafická jednotka sladkovodných vápencov vrchnej kriedy v Brezovských Karpatoch a Čachtických Karpatoch (západné Slovensko) [The Chtelnica Formation – a new lithostratigraphic unit of the Upper Cretaceous freshwater limestones in the Brezovské Karpaty Mts. and Čachtické Karpaty Mts. (Western Slovakia)]. *Geologické práce, Správy*, 132, 53–58. [in Slovak with English summary]

Jennings J. A. 1985: Karst geomorphology, second edition. Oxford, Basil Blackwell, 293 p.

Jakál J., 1975: Kras Silickej planiny [Karst of Silica Plateau]. Osveta, Martin, 149p. [in Slovak]

Jakál J., 2008: The Surface Morphology of Karst Landscape. In Jakál J. & Bella P. (Eds.): Caves of the World Heritage in Slovakia, State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Liptovský Mikuláš, 37–46. [in Slovak]

Kováč M., Baráth I., Šútovská K. & Uher P., 1991: Zmeny v sedimentárnom zázname spodného miocénu v dobrovodskej depresii [Lower Miocene events in the sedimentary record of the Dobrá Voda Depression]. *Mineralia Slovaca*, 23, 3, 201–213. [in Slovak with English abstract and summary]

Lačný A., Kubičina L. & Csibri T., 2019: Morfometrická analýza závrtov Čachtickej planiny [Morphometric analysis of sinkholes on the Čachtická Plain]. *Slovenský kras*, 57/2, 147–164. [in Slovak with English abstract]

Lačný A., Vojtko R., Velšmid M., Dušeková L. & Papčo J., 2020: Geological control of the origin of dolines in the Plavecký Karst (Malé Karpaty Mts., Slovakia). *Acta Geologica Slovaca*, 12, 2, 137–152.

Lačný A., Putiška R., Vojtko R., Dušeková L., Mojzeš A., Brixová B., Zvara I., Andrássy E. & Magdolen P., 2021: Study of dolines of the Cajla Karst originated on covered karst landform (Malé Karpaty Mts., Western Carpathians). *Acta Geologica Slovaca*, 13, 2, 170–190.

Leitmannová K. & Kalivoda M., 2018: Projekt leteckého laserového skenovania Slovenskej republiky [Aerial Laser Scanning Project of the Slovak Republic]. *Geodetický a kartografický obzor* 64/106, 101–104 p. [in Slovak with English abstract]

Liška M., 1982: Výskum Borinského krasu a jeho ochrana [Investigation of the karst formations at Borinka and its protection]. *Výskumné práce z ochrany prírody*, 4, Bratislava, 3–73. [in Slovak with English summary]

Mazúr E. & Lukniš M., 1978: Regionálne geomorfologické členenie SSR [Regional geomorphological division of the Slovak Socialist Republic]. *Geografický* časopis, 30, 2, 101–125. [in Slovak]

Marko F., Fodor L. & Kováč M., 1991: Miocene strike-slip faulting and block rotation in Brezovské Karpaty Mts. *Mineralia Slovaca*, 23, 3, 189–200.

Mihevc A. & Mihevc R., 2021: Morphological characteristics and distribution of dolines in Slovenia, a study of a lidar-based doline map of Slovenia. *Acta Carsologica*, 50, 1, 11–36.

Michalík J., Broska I., Franců J., Jendrejáková O., Kochanová M., Lintnerová O., Masaryk P., Papšová J., Planderová E., Šucha V. & Zatkalíková, V., 1992: Štruktúrny vrt Dobrá Voda DV-1 (1 140,8 m) (Dobrá Voda - Konča Skaliek) v Brezovských Karpatoch [Structural borehole Dobrá Voda DV-1 (1 140,8 m), (Dobrá Voda - Konča Skaliek) in Brezovské Karpaty Mts]. *Regionálna geológia Západných Karpát,* 27, 152 s. [in Slovak with English summary]

Mitter P., 1983: Geomorfologická rajonizácia krasu Malých Karpát [Geomorphological regional division of the Malé Kapaty Karst]. *Slovenský kras*, 21, 3–34. [in Slovak with Russian abstract and English summary]

Petrvalská A., 2010: Morfometrická analýza závrtov na príklade Jasovskej planiny (Slovenský kras) [Morphometric analysis of dolines on the Jasovská Plateau example (Slovak Karst)]. *Geomorphologia Slovaca et Bohemica*, 1/2010, 33–44. [in Slovak with English abstract]

QGIS.org, 2020: QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.org

Salaj J. (ed.), Began A ., Hanáček J., Mello J., Kullman E., Čechová A . & Šucha P., 1987: Vysvetlivky ku geologickej mape Myjavskej pahorkatiny, Brezovských a Čachtických Karpát [Explanation to the Myjavská pahorkatina upland, Brezovské and Čachtické Karpaty Mts.]. Geologický ústav Dionýza Štúra, Bratislava, 181 p. [In Slovak]

Sauro U., 2012: Closed Depresions in Karst Area. In White W.,B. & Culver., C.: The Encyclopedia of Caves (third edition), 140–155.

Segre A. G., 1948: I fenomeni carsici e la speleologia del Lazio. Pubblicazioni dell 'Istituto di Geografia dell'Universita di Roma, 7, 239 p.

Stankoviansky M., 1974: Príspevok k poznaniu krasu Bielych hôr v Malých Karpatoch [Contribution to the knowledge of the Biela hora karst in the Malé Karpaty Mts.]. *Geografický* časopis, 26, 3, 241–257. [in Slovak with English abstract]

Šegina E., Benac Č., Rubinič J. & Knez M., 2018: Morphometric analyses of dolines – the problem of delineation and calculation of basic parameters. *Acta Carsologica*, 47, 1, 22–33.

Šmída B., 2008: Krasové jamy (závrty) Západných Karpát: štúdium ich morfológie a genézy. [Dolines of the Western Carpathians: the study of the morphology and genesis] Minimum thesis, Faculty of Natural Sciences, Comenius University in Bratislava, 113 p. [in Slovak]

Šujan M., Braucher R., Šujan M., Hók J., Povinec P., Šipka F., Team Aster, Rugel G. & Scharf A., 2019: The tectono-sedimentary evolution of a major seismogenic zone with low slip rate activity: A geochronological and sedimentological investigation of the Dobrá Voda Depression (Western Carpathians). *Sedimentary Geology*, 383, 248–267.

Veselský M., Lačný A. & Hók J., 2014a: Závrty na Dlhom vrchu: modelová štúdia ich vzniku na lineárnych diskontinuitách (Malé Karpaty) [Dolines on Dlhý vrch hill: case study of doline evolution on linear discontinuity (Malé Karpaty Mts.)]. *Acta Geologica Slovaca*, 6, 2, 59–168. [in Slovak with English abstract and summary]

Veselský M., Ágh L., Lačný A. & Stankoviansky M., 2014b: Závrty na krasovej plošine Biela skala a ich morfometrická analýza, Kuchynsko-orešanský kras, Malé Karpaty [Sinkholes on the karst land of Biela skala and morphometric analyses, Kuchyňa-Orešany Karst, Malé Karpaty Mts.]. *Slovenský kras*, 52, 2, 127–139. [in Slovak with English abstract and summary]

Waltham T., Bell F. & Culshaw M., 2005: Sinkholes and subsidence. Series Karst and Cavernous Rocks in Engineering and Construction, Springer, Berlin, 382 p.

Williams P.W., 1972: Morphometric analysis of polygonal karst in New Guinea. *Geological Society of America Bulletin*, 83, 3, 761–796.

Williams P., 2004: Dolines. In: Gunn J. (Ed.): Encyclopedia of Caves and Karst Science. Taylor and Francis Group, London, 304–310.