Dolines as important indicators of lithology and tectonics: A case study of the Malé Karpaty Mts. (Western Carpathians)

Alexander Lačný[1,2], Rastislav Vojtko[2], Laura Dušeková[3,4] & Lucia Čahojová[1,5]

[1] State Nature Conservancy of the Slovak Republic, Little Carpathians Protected Landscape Area, Štúrova 115, 900 01, Modra, Slovakia; alexander.lacny@sopsr.sk, lucia.cahojova@sopsr.sk
[2] Comenius University, Faculty of Natural Sciences, Department of Geology and Paleontology, Ilkovičova 6, Bratislava, Slovakia; alexander.lacny@uniba.sk, rastislav.vojtko@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] Plant Science and Biodiversity Centre, Institute of Botany, Slovak Academy of Science, Dúbravská cesta 9, Bratislava, 845 23, Slovakia; lucia.cahojova@savba.sk

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Abstract: The Malé Karpaty Mountains in southwestern Slovakia contain more than 650 dolines, mostly arranged along tectonic and lithological boundaries. These dolines serve as important indicators of geological structures and provide valuable insights into the underlying bedrock and rock formations. This study focuses on the spatial distribution and formation processes of dolines in the Malé Karpaty Mts. using advanced methods, such as Digital Terrain Models (DTM) derived from airborne LiDAR data. By combining DTM with field measurements and GIS analysis, the study identifies the tectonic and lithological controls on doline formation and demonstrates their value in interpreting the geological and geomorphological evolution of the area. The results highlight the importance of dolines as markers of subsurface structures and their critical role in understanding karst landscapes.

Keywords: dolines, DTM, LiDAR, lithology, Malé Karpaty Mts., tectonics, Western Carpathians

1. INTRODUCTION

Karst systems cover 10–15% of the Earth's surface and 35% of the European continental area (Goldscheider et al., 2020). On a nationwide scale, carbonates and karst areas which have been defined on them are interesting for the study of karstic processes. In Slovakia, karst areas formed by soluble carbonate rocks cover an area of more than 2,700 km^2, representing approximately 6% of the country, with the largest area in the Slovak Karst (800 km^2). These karst areas are primarily composed of Mesozoic carbonates, with rare occurrences in marbles, magnesites and gypsum (Bella, 2016). Dolines, which are surface forms of the karstic relief, are closed depressions with variable dimensions and side walls that can be slightly angled or vertical (Bondesan et al., 1992; Williams, 2004; Sauro 2012; Waltham et al., 2005, Veress 2020). Morphodynamically, they represent a basic hydrographic unit that drains water to the lowest accumulation point (Bondesan et al., 1992; Williams, 2004). The genesis of dolines is influenced by a topographic, tectonic, lithological, and morphostructural predisposition, as well as climatic factors. Several methodological approaches have been developed for characterizing dolines, including their geometric shape and role as integral components of complex geosystems (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. Williams (2004) identified four major mechanisms for dolines formation: corrosion, collapses, suffosion, and subsidence. In the majority of cases, doline formation/origin cannot be attributed to a single process. Nevertheless, if a dominant formation mechanism was distinguishable, we use the above-mentioned classification in this study.

Depending on the process, a variety of doline shapes can be documented; they occur either isolated or in groups. All genetic types of dolines occur in Slovakia. 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 ring-shaped. They are also categorized by their genesis into solution, collapse, and alluvial dolines. For this study, we consider an alluvial doline to be a doline that has a pronounced inflow line with either an open or half-open bottom, as well as a steep opposite slope (Jennings, 1985). Doline lines formed on lithological and tectonic discontinuities often indicate these structures in the field (e.g., Ćalić, 2011; Veselský et al., 2014[a], 2014[b]; Şener & Öztürk, 2019, Lačný et al., 2020, Telbisz et al., 2024, Petrvalská, 2010).

Our study focuses on the karst areas of the Malé Karpaty Mts. in southwestern Slovakia, where up to a third of this region is composed of carbonate rocks (Lačný et al., 2022a). Our research focuses on dolines as indicators of lithology and tectonics in the region (Fig. 1). The processes of their formation are part of the complexity of these karstic areas. There are up to 650 dolines located across all the Malé Karpaty Mts., which mainly have a linear arrangement corresponding to brittle tectonics or lithological boundaries (Lačný et al., 2022a). These lines on the surface serve as markers for fault interpretation. In some places, due to the presence of dolines, we were able to determine the geological boundaries of individual strata more accurately. Typical dolines in this area have perimeters of 10–40 m and a depth of 1 to 5 m (Lačný et al., 2022a). The study area is predominantly wooded.

Our study of dolines in the Malé Karpaty Mts. uses advanced methods for accurate analysis of these geomorphological

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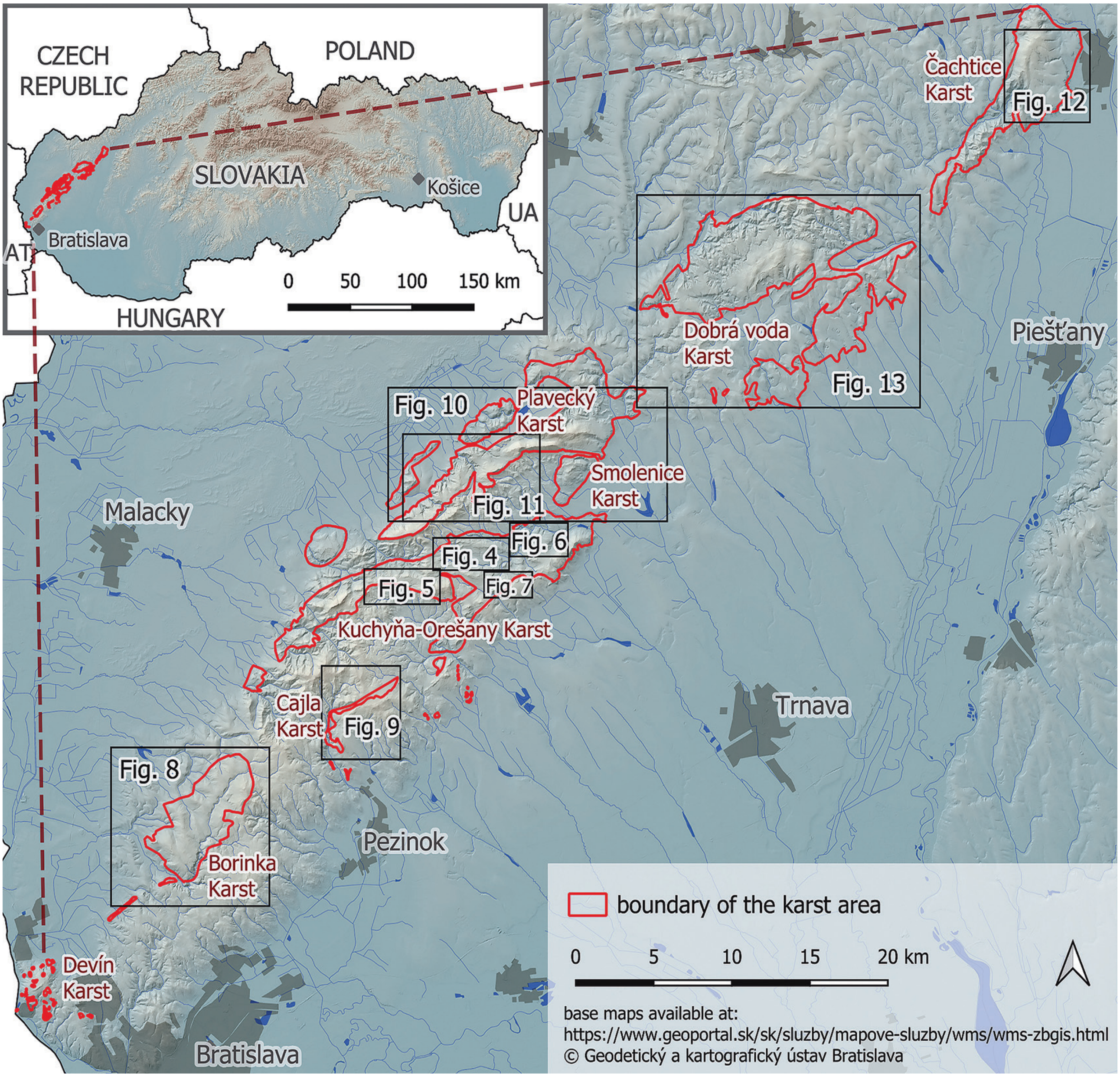

Fig. 1. Schematic map with a marking of the investigated locations (numbers of figures in the article) with the karst areas of the Malé Karpaty Mts. according to Lačný et al., 2022a.

features. Recent advances in digital terrain modelling (DTM) and LiDAR technology have revolutionised the study of dolines by providing high-resolution data that improves both detection and analysis. In particular, LiDAR technology enables accurate characterisation of doline morphology in complex and densely vegetated areas as demonstrated previously by Telbisz et al. (2024), who found that LiDAR-derived doline measurements were more detailed than those derived from topographic maps. Bauer (2015) reviewed different methods for delineating dolines from DTM data, highlighting the variability in results based on different approaches. Ciglič et al. (2022) showed how pre-processing and detection methods affect geomorphometric analysis. In addition, Siart et al. (2013) demonstrated that combining surface and subsurface geospatial data, including LiDAR and geophysical surveys, provides deeper insights into the formation and geometry of dolines. Čarni et al. (2022) used LiDAR data to classify dolines into landform-vegetation units, thereby illustrating the versatility of digital models in ecological and conservation studies. Hofierka et al. (2018) further demonstrated the utility of airborne laser scanning and water flow analysis in identifying karst dolines in forested landscapes. These approaches, combined with GIS methods and geomorphological analysis, allow for more accurate characterization of sinkholes and their impact on the landscape.

We thus set 2 main objectives: i) to summarize the current scientific knowledge of 650 dolines distributed in the territory of the Malé Karpaty Mts; ii) use the analysis of dolines to verify and interpret the geological structures in several places of the territory.

2. STUDY AREA AND METHODS

2.1 Geological settings of study area

The Malé Karpaty Mts., which include the Devínske, Pezinské, Brezovské, Čachtické Mts., are a part of the Tatra-Fatra Belt, forming the outer zone of the Central Western Carpathians (CWC) (Plašienka 2018; Plašienka, 1999) (Fig. 2). The CWC represents a crucial segment in the contact between the Western Carpathians and the Eastern Alps. The structure of the CWC includes Paleoalpine units as well, such as the Tatric, Fatric, and Hronic units. The Tatric Unit comprises a crystalline basement and associated Mesozoic sedimentary cover with features of the Fatric and Hronic nappe units. Upper Cretaceous sediments are represented by the Brezová Group (Salaj et al., 1987) and Paleogene sediments by the Malé Karpaty Group (Buček in Polák et al., 2012).

The Malé Karpaty Mts. extend over 100 km in length and 15 km in width, have an orientation trending SW–NE, and divide the Neogene Vienna and Danube basins. The ridge is 50 km long and 15 km wide in the Pezinské Karpaty Mts., bordered by extensive fault systems of a SW–NE direction. The boundary between the mountains and the Vienna Basin is formed by the Litava fault system which is divided into several segments (e.g. Marko & Jureňa, 1999) and continues as the Dobrá Voda Fault in the Brezovské Karpaty Mountains. The fault limitation against the Danube Basin is referred to as the Malé Karpaty Fault. The present form of the Malé Karpaty Mts. was established in the late Neogene (Minár et al., 2011), with significant Quaternary valley deepening, cave formation, and doline development.

2.2 Malé Karpaty Karst

The first comprehensive definition of the Malé Karpaty Mts. Karst was provided by Beňovský (1951), followed by the subsequent works of Stankoviansky (1982) and Mitter (1983), who geomorphologically divided the karst areas into units and subunits. Stankoviansky (1982) distinguished eight karst units: Čachtice Karst, Brezová Karst, Plavecký Karst, Smolenice Karst, Kuchyňa-Orešany Karst, Borinka Karst, Cajla Karst, and Devínská Kobyla Karst; whereas Mitter (1983) recognized four main areas: the karst regions of the Devínske Karpaty Mts., the Pezinské Karpaty Mts., the Brezovské Karpaty Mts., and the Čachtické Karpaty Mts., which are further divided into 14 units. This subdivision, which was identified by Mitter (1983), has proven less useful for complicated allocation and has therefore not been adopted in speleological or geomorphological literature. On the other hand, the division identified by Hochmuth (2008), which is based on the division devised by Stankoviansky (1982), has been adopted and is commonly used in current studies (Čachtice

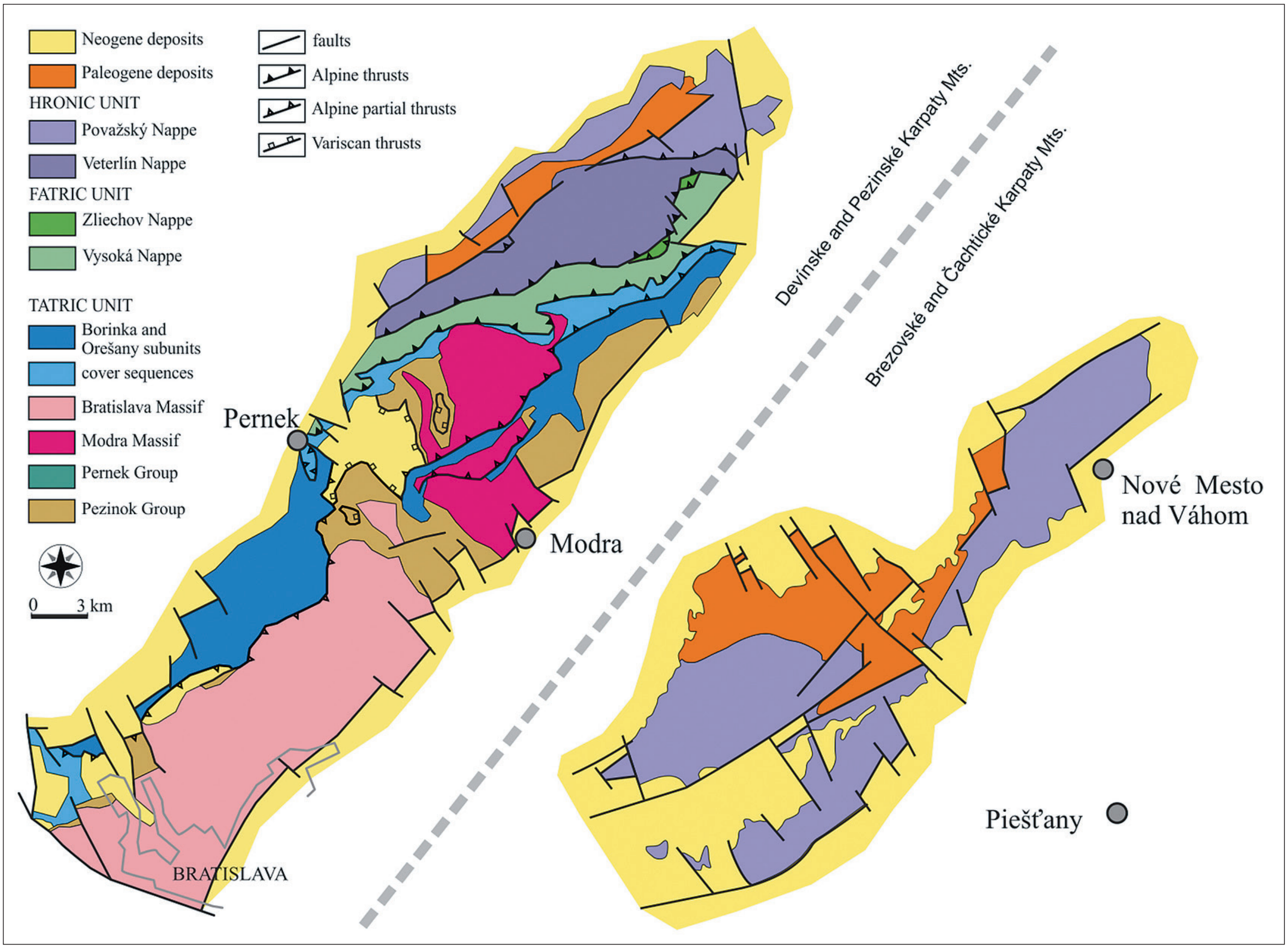

Fig. 2. Tectonic map of the Malé Karpaty Mts. modified according to geological maps (Polák et al., 2011) & (Began et al., 1984).

Karst, Dobrá Voda Karst, Plavecký Karst, Smolenice Karst, Kuchyňa-Orešany Karst, Borinka Karst, Cajla Karst, and Devín Karst). This division has also been further adopted by Lačný et al. (2022a) (Fig. 1). Šmída (2010) recognized the same karstic areas as well. Instead of the Kuchyňa-Orešany Karst, he prefers and uses the name "Orešany Karst" for this karst area. Jakál (1993) defines karst in the Malé Karpaty Mts. as dissected karst of massive ridges, horsts, and combined fold-fault structures, including dissected karst of monoclinal crets and ridges (Tab 1.) with partly-developed to well-developed exo- and endokarst.

From a geological point of view, the Hainburg Hills are a continuation of the Malé Karpaty Mts. Here, too, karst is exposed, where 25 caves of interesting genesis can be found (Neuhuber et al., 2021). At present, 362 caves are registered in the Malé Karpaty Mts. (Source: Slovak Museum of Nature Protection and Speleology, status as of 29.9.2021), and when including caves across the border in Austria, the number of caves reaches 387.

2.3 Field Measurements and Documentation

Measurements of lithological plane elements and brittle structures in the study area were carried out using standard geological survey methods with the Freiberg geological compass. All dolines were identified and documented in the field, and their coordinates were recorded using the coordinate system WGS 84. For planiography of these elements, we used source data (partially supplemented) published in the literature (Veselský et al., 2014a,b; Lačný et al., 2018, 2019a, 2020, 2021, 2022b,c; Lačný & Csibri, 2020).

The geographical coordinates obtained from our fieldwork were transformed and recorded in a geographical information system (GIS). Visualizations were created using the QGIS Desktop 3.16.3 "Hannover" with GRASS 7.8.5 (QGIS.org, 2021).

For identification and delineation of the dolines, we used the Digital Terrain Model (DTM), which is based on airborne LiDAR data. The DTM was created from processed and classified LiDAR data acquired within the National project for aerial laser scanning of the Slovak Republic (Leitmannová & Kalivoda, 2018). The detailed model revealed many new, previously undescribed dolines, increasing the sum from 450 (Šmída, 2008) to 650 (Lačný et al., 2022a) (Table 1). We can therefore assume that our research covered all size-significant dolines in the Malé Karpaty Mts, considering the level of identification of the techniques used. The majority of dolines are arranged in ordered lines that follow the faults and lithological boundaries beneath the surface. Some of the dolines, unfortunately, are flooded (Fig. 3A), thus complicating a detailed study. Collaboration with local speleologist groups was essential for locating dolines and providing historical context.

3. RESULTS

3.1 Documentation of dolines in the Devín Karst and Smolenice Karst.

In the Smolenice Karst, not a single doline was found. Based on the DTM, we identified only very shallow, rather unmeasurable depressions, in the area of Prielohy above the Village of Smolenice. The original doline shaft through which the Driny Cave was discovered was also unmeasurable, since it is now covered with concrete levelled with the surface.

To date, it appears that no dolines in the Devín Karst have been identified. Our research was conducted in the northern part of the Devínská Kobyla Hill (452 m a.s.l.). We focused specifically on two locations: Psie Skaly and Biele Skaly. At the Psie site, anthropogenic depressions with excavations and coals were found, suggesting that they were lime pits. Morphology of anthropogenic depressions according to the DTM was described by Dušeková et al. (2020). At the Biele Skaly site, we found four depressions in an approximately N–S direction. Again, there was coal at the bottom, and the terrain was slightly reshaped. However, the bottoms of these depressions were dry, which may indicate infiltration of surface precipitation into the subsurface. Thus, the origin of these depressions remains questionable. In

Tab. 1. Numbers of identified dolines in karst areas of the Malé Karpaty Mts. with characteristics of karst areas.

Name of karst area	Area (km^2) (Lačný et al. 2022a)	Min altitude (m a.s.l)	Max altitude (m a.s.l)	Number of dolines	Average Size of dolines (m)		Geological characteristics of karst area	Geomorphological type of karst (Jakál, 1993)
					depth	diameter		
Čachtice Karst	34,5	194	588	86	3,23	58,88	Hronic Unit, neogene deposits	A
Dobrá Voda Karst	87,2	256	586	263	2,11	31,81	Hronic Unit, neogene deposits	A,B
Plavecký Karst	57,4	198	768	92	2,02	43,9	Hronic Unit, neogene deposits	A,B
Smolenice Karst	5,2	260	483	0			Fatric Unit	A
Kuchyňa-Orešany Karst	58,1	244	759	115	1,26	29,19	Fatric Unit, Tatric Unit	A,B
Cajla Karst	3,2	326	590	50	2,54	56,2	Tatric Unit	B
Borinka Karst	26,3	241	650	44	2,56	34,27	Tatric Unit	B
Devín Karst	1	171	444	0			Tatric Unit, neogene deposits	A

A Dissected karst of massive ridges, horsts and combined fold-fault structures

B Dissected karst of monoclinal crets and ridges

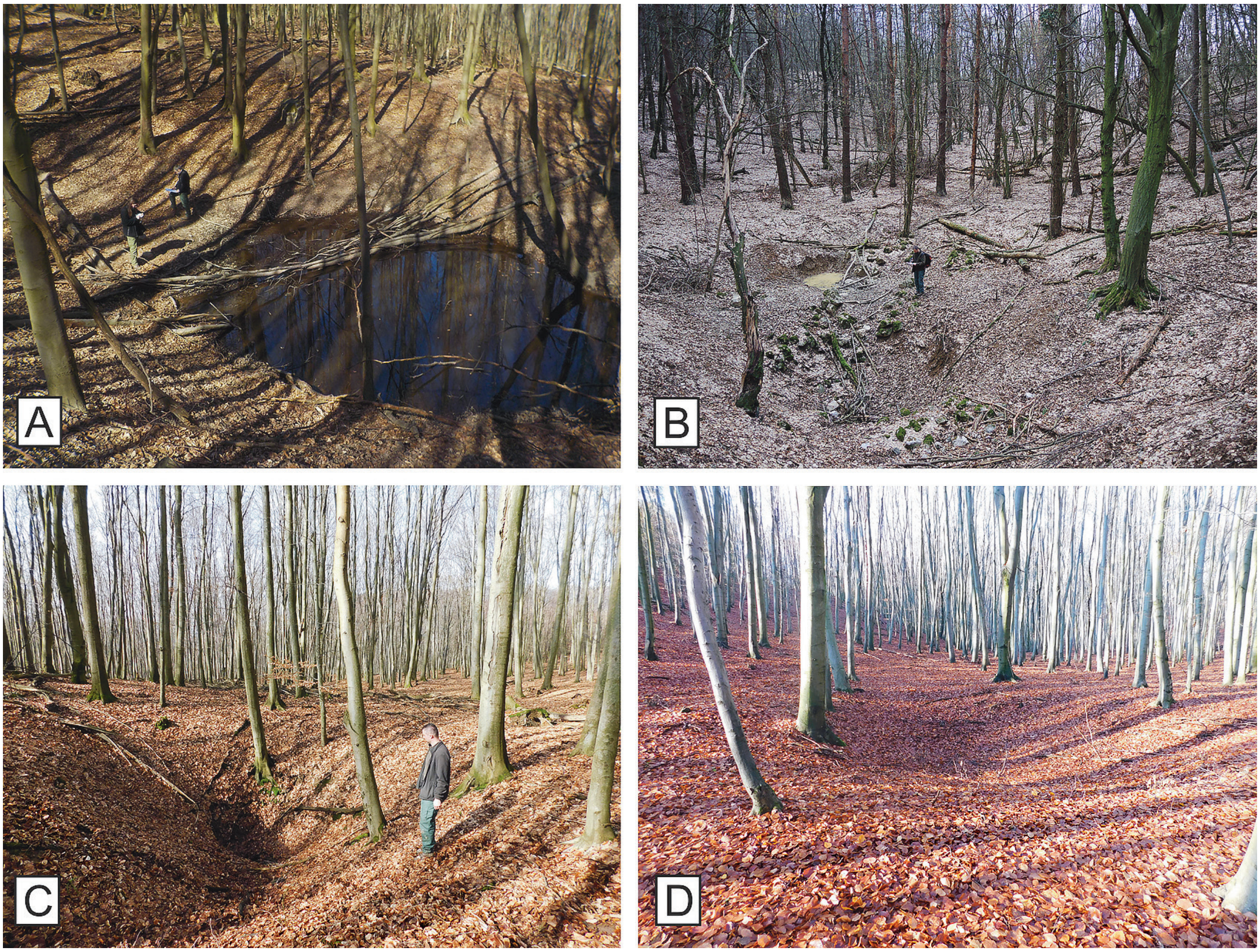

Fig. 3. A) Flooded doline near Godova skala Rock (Kuchyňa-Orešany Karst). Photo: A. Lačný; **B)** Linear arrangement of dolines on the Čachtice Platau. Photo: L. Kubičina; **C)** Solution doline in the Dobrá Voda Karst. Photo: M. Fuňová; **D)** Shallow subsidence doline (Dobrá Voda Karst). Photo: A. Lačný

general, the northern slopes and valleys of the Devínska Kobyla Hill are literally dotted with pits of anthropogenic origin. We cannot exclude that some of the anthropogenic pits may have been dolines in the past, especially those found at the contact of karstic and non-karstic rocks. However, there is little hard evidence at present. The low frequency of dolines in these karst areas is also caused by the small size of these areas.

3.2 Dolines of the Kuchyňa-Orešany Karst

The Kuchyňa-Orešany Karst is situated in the northern part of the Pezinské Malé Karpaty Mts. between the villages of Kuchyňa and Horné Orešany (Fig. 1). It is characterized by a significantly striped structure with alternating carbonate and non-carbonate formations. This limits the development and extent of the karst processes. It is also reflected in the size of the caves which, at present, do not exceed 60 meters in length. In this area, horizontal caves dominate. The Kuchyňa-Orešany Karst itself developed in the rocks of the Vysoká Nappe that belong to the Fatric Unit, as well as in the Mesozoic sedimentary complexes of the Tatric Unit (Lačný et al., 2022a).

The Kuchyňa-Orešany Karst is characterized by the presence of dolines, and it currently contains 115 of them. This means that based on the number of dolines, it ranks second among the karst areas of the Malé Karpaty Mts. after the Dobrá Voda Karst, which contains 263 dolines (cf. Lačný & Csibri, 2020). The dolines in this area are arranged linearly. Solution dolines occur in the largest amount, and there are also shallow subsidence dolines, which are present further from the main doline lines. The area is dominated by three karst plateaus: the Dlhý Vrch Hill, the Komberek Hill, and the Biela Skala Rock, where detailed geomorphological research has previously taken place (Dušeková et al., 2020). Since this area is characterized by the great lithological variability of the rocks (i.e., the formation of dolines at lithological boundaries) and the dominant formation of dolines on fault structures and near-fault structures, it was therefore studied in great detail.

3.2.1. Karst Plateau Dlhý vrch Hill

The area of Dlhý Vrch Hill (481 m a.s.l. and 474 m a.s.l.) is situated on the northern edge of the karst plateau of the same name with an area of 0.29 km^2 (Fig. 4). The geological bedrock is composed of Triassic carbonates, which belongs to the Fatric Unit (Polák et al., 2011). Intensive research has also been carried out in this karst plateau since 2011 (Lačný, 2011). The most important results of the geological and geomorphological research of this karst region are summarized in the work of Veselský et al. (2014a), where 26 dolines are registered. Research has also shown a tectonic predisposition of the main W–E doline line, reactivated on the lithological boundary (18 dolines). Some dolines also occur at the lithological contact of the Carpathian Keuper sediments with underlying Main Dolomite. They are located northwest of the doline line.

The "Orešanská sonda" doline originated in the Vysoká Limestone and, based on excavation work, reaches a depth of 20 m; it can therefore be classified as a solution doline. The formation of the "Orešanská sonda" doline is predominantly connected to the NW-SE oriented fault zone, on which the "Orešanská Spring", "Orešanská sonda", and two shallow dolines located 300 m to the northwest of the "Orešanská sonda" are situated (Potočný et al., 2016).

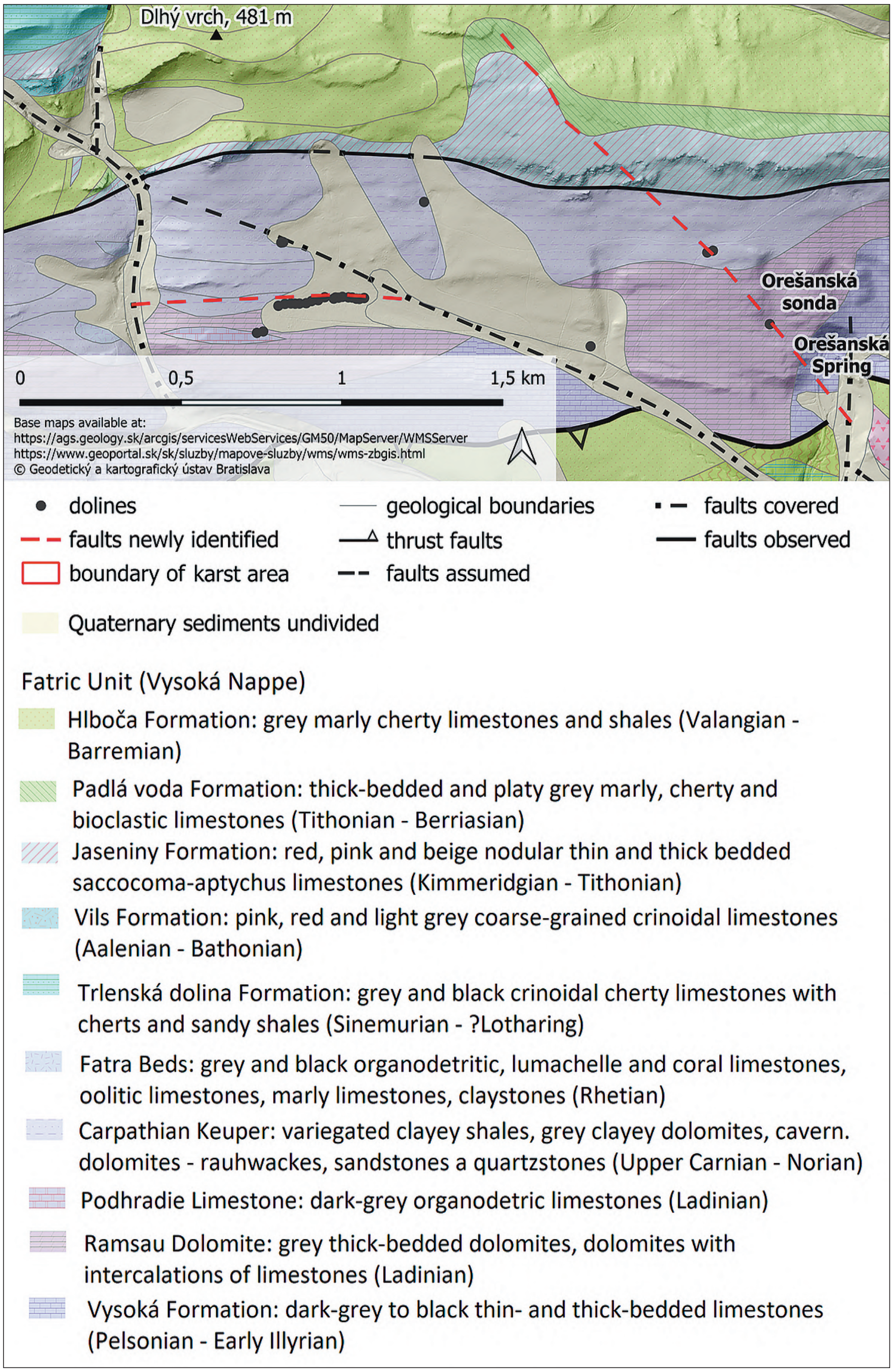

Fig. 4. Geological map of Dlhý Vrch Hill (Kuchyňa-Orešany Karst) (Polák et al., 2011) with the markings of dolines and new faults.

3.2.2. Karst Plateau on Biela skala Rock

Near the Biela Skala Rock (561 m a.s.l.) (Fig. 5), which is situated to the northwest of the Village of Píla, approximately 40 dolines have been observed (Veselský et al., 2014b). They were found in a shallow valley 350 m north of Biela Skala Rock (Fig. 5). These dolines are distributed along a 1450 m long line and oriented to the northwest, in some places immediately adjacent to each other. The largest of them is 8 m long and reaches a depth of 4 m. The average diameter of the dolines in this area is 3–6 m; the average depth is 0.3–4 m. Four of the dolines contain an inflow line and an active solution doline with an open bottom. The bedrock consists of Vysoká Limestone. The dolines originate predominantly on a distinctive NW–SE fault structure, which significantly manifests itself on the surface morphology as well.

There is one more doline and several shallow depressions near the spot height of Sedlo Skalka (525 m a.s.l.), about 2 km east of Biela Skala Roch (561 m a.s.l.), which can also be considered a part of the site. The doline itself originated at the lithological boundary of the Ramsau Dolomite and the Carpathian Keuper of the Vysoká Nappe (Fatric Unit). It is elongated in an ESE–WSW direction and follows the discontinuity between inhomogeneous formations (Veselský et al., 2014b). There is a shallow doline with a mud slough in its immediate proximity and, on the line eastwards, there are several very shallow dolines following the contact zone of karst with non-karst.

3.2.3 Karst Plateau on the Komberek Hill

Komberek Hill (Kŕč) (409 m a.s.l.) (Fig. 6) lies near the Village of Horné Orešany, in the area of Majdánske. The hill is surrounded by a karst plateau, which contains several dozens of dolines and lime pits (Fig. 6). There are also very shallow dolines with mud sloughs in the middle we marked as mudholes (many parameters are immeasurable here). For further research, 76 depressions

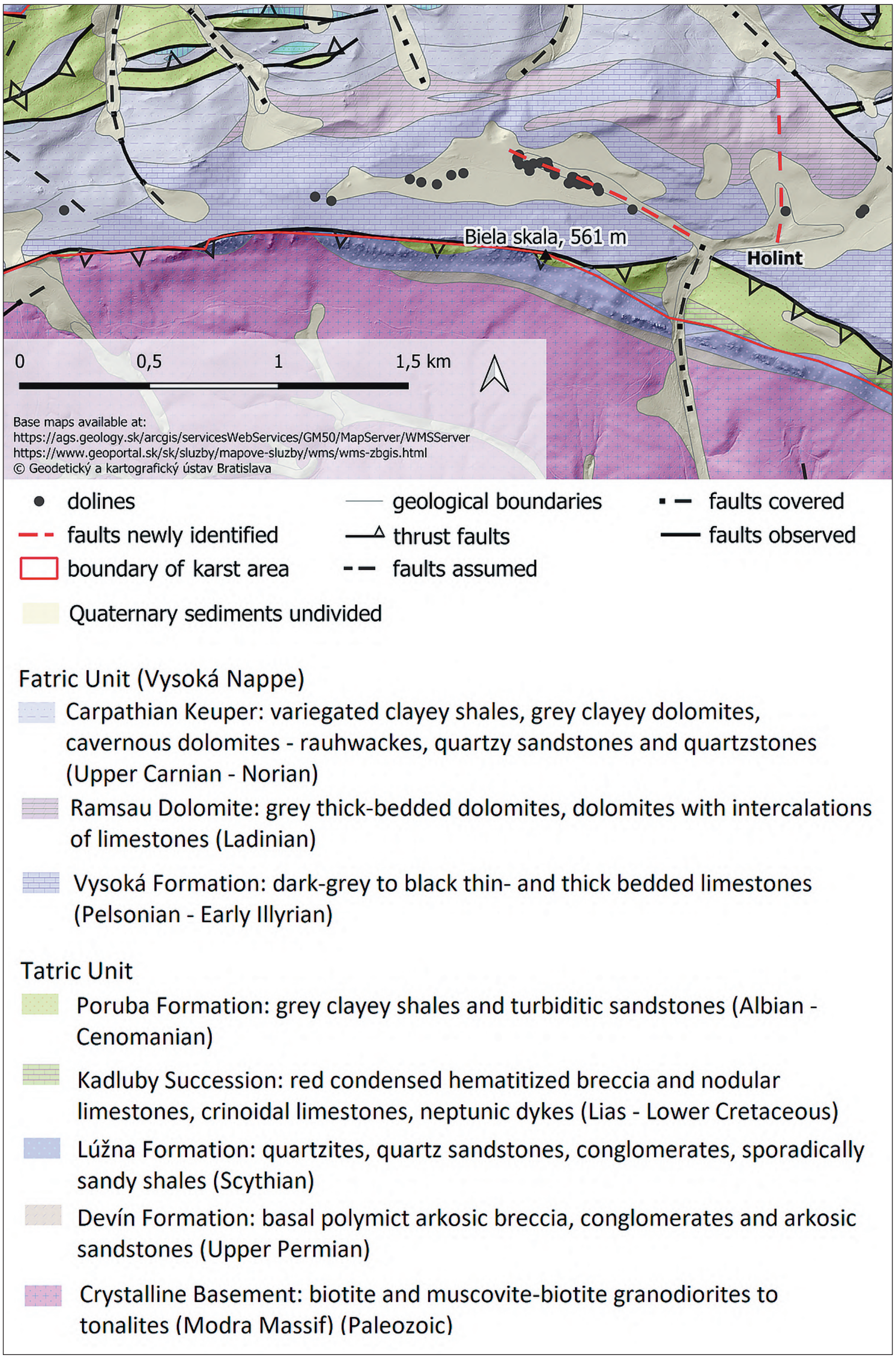

Fig. 5. Geological map of Biela Skala (Kuchyňa-Orešany Karst) (Polák et al., 2011) with the markings of dolines and new faults.

were documented. The majority of them are dolines, although so-called lime pits were also observed (sites containing charcoal and traces of lime). The presence of lime pits on Komberek Hill poses a problem when identifying the dolines. Since dolines are natural depressions, it is possible that some of them were used as lime pits in the past. This has also been confirmed by geophysical research – magnetometry performed on several dolines near the doline line (Putiška et al., 2014). The average length of dolines in this area is 4–11 m with depths of 0.5–3 m. However, there are also larger dolines with an average diameter of 26 m and an average depth of 6 m. From the point of view of genesis, these are predominantly solution dolines. They were formed by the gradual dissolution of carbonates that took place at lithological and tectonic interfaces. Based on Electric Resitivity Tomography, we examined the subsoil (only subsoil or subsurface) of the dolines, and the measurement results also confirmed the original interpretations of the formation of dolines (Lačný et al., 2018). The main doline line originated on a prominent fault of a N–S direction (Fig. 6). On the basis of research conducted further away from the doline lines where solution dolines dominate (Lačný et al., 2018), shallow, cup-shaped forms of dolines formed on the plateaus, resulting from subsidence and referred to as subsidence doline. Several dolines were also formed at the lithological interfaces among the Middle Triassic carbonates, such as the rauhwackized carbonate and Carpathian Keuper. There are 35 karst depressions (21 dolines and 14 mudholes) excluding anthropogenic depressions.

3.2.4 Dolines west of Godova Skala Rock

The last line is situated in the area of Godova Skala Rock (Fig. 7) and is part of Klokočina Hill (550 m a.s.l.), north of the Village of Doľany. This line of six dolines (Fig. 7) is located at the contact of karst and non-karst rocks, or more precisely, quartzites of the Lúžna Formation, with bench limestones and silicites of the Slepý Formation, both belonging to the Orešany cover sequence of the Tatric Unit (Polák et al., 2011) (Fig. 3A). The entire area is covered by slope sediments containing non-karstic material (dominantly sediments of the Lúžna Formation). We managed to locate 6 dolines and one shallow depression (Lačný & Csibri, 2020). Northeast of the last doline, there are three more depressions of unknown origin. We assume that they are of anthropogenic origin, based on their shape and location.

The dolines in this area are relatively shallow, with a slope inclination angle of up to 33°. They are irregularly elongated in shape in a NE–SW direction, following the karst interface. These are solution dolines formed by intermittent atmospheric precipitation and draining to the NE.

3.3 Dolines of the Borinka Karst

The Borinka Karst (formerly known as the Pajštúnsky Karst) (Fig. 8) is situated in the southwestern part of the Malé Karpaty Mts. and is bound to the Mesozoic limestones of the Borinka Unit (Plašienka, 1999). The Mesozoic limestones are present on both sides of the Stupava Stream, whose source is under the elevation point of Konské hlavy (653 m a.s.l.) and further flows through the Prepadlé Valley, which is parallel to the axis of the mountain. The stream then turns northwest across the Village of Borinka and continues towards the town of Stupava. The Stupava Stream flows through carbonates (so-called Borinka limestones in the part of the valley below the Banské elevation point) and reaches the non-karst bedrock near the settlement of Medené Hámre.

As a part of our research, 44 dolines were located in the Borinka Karst (Lačný et al., 2022b). The linear arrangement of the dolines can be observed in the localities of Staré Hájne, Ostrovec, and Banské (Fig. 8). The locality Staré Hájne (495 m a.s.l.) contains up to 14 dolines and two shallow depression forms. The main part is composed of a doline line in a flatter valley with a NW–SE direction. This doline line is 650 m long. The longer axes of the dolines correspond with the direction of the valley that stretches up to the wall of the quarry. Several dolines have inflow lines directed into them, and dolines here reach depths of 5–9 m. These are significant values by the standards of the Borinka Karst. Dolines are located in the Borinka limestones, and speleological excavations were performed at the bottom of two of them.

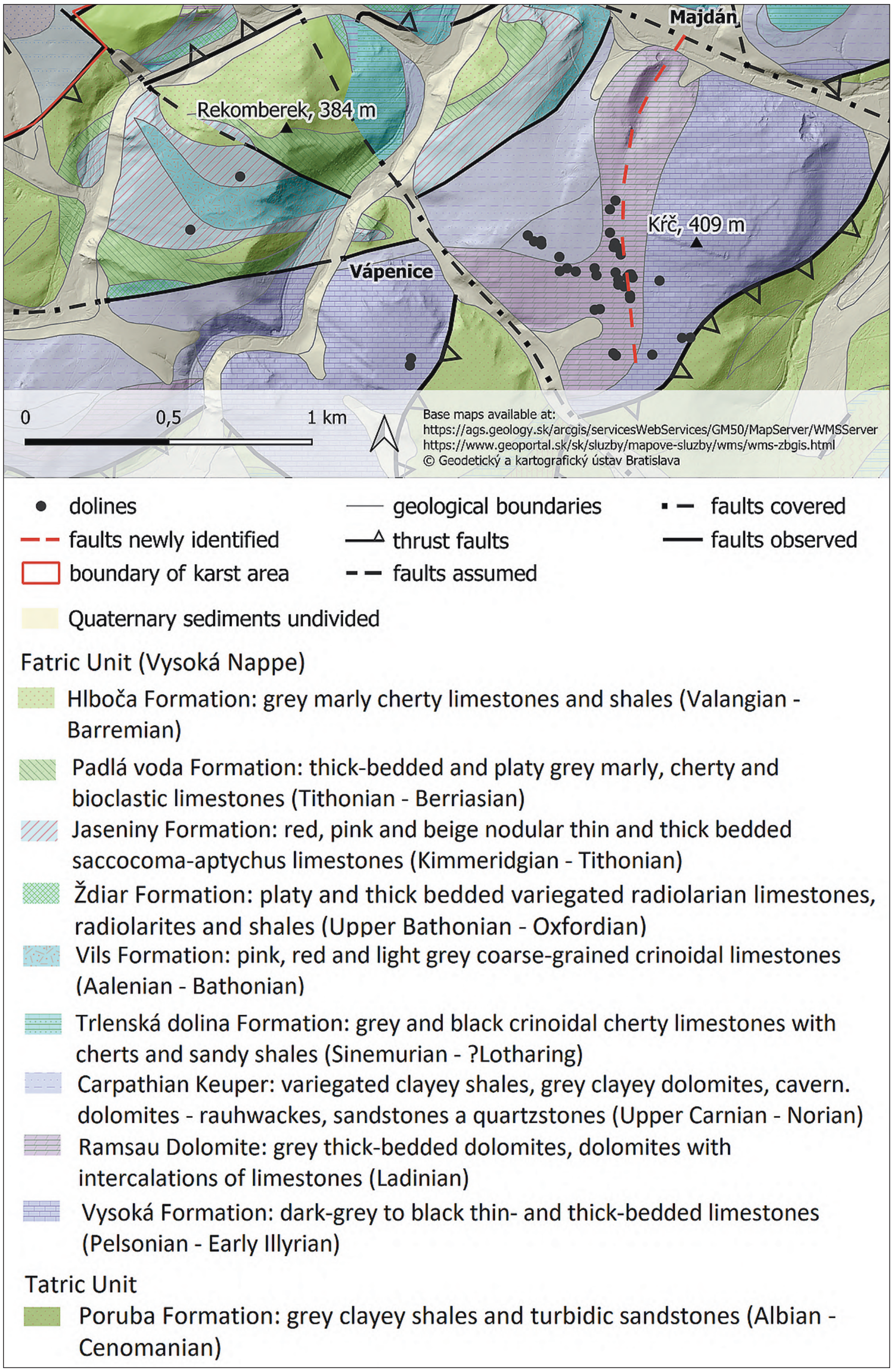

Fig. 6. Geological map of Komberek (Křč) Hill (Kuchyňa-Orešany Karst) (Polák et al., 2011) with the markings of dolines and new faults.

Another locality where indications of doline lines can be observed is the locality of Ostrovec. These dolines are located 770 m southeast of Ostrovec (468 m a.s.l.). They are located on a gentle slope and there are several anthropogenic pits nearby. Here, we measured 10 dolines. Based on the maximum axes of elongation and the location of the dolines, three parallel lines with approximately W–E direction can be considered (Lačný et al., 2022b).

Relatively well-developed dolines with a line arrangement located in a valley can be found 360 m southeast of the spot height of Banské (531 m a.s.l.). This is one of the side valleys that connects to the Prepadlé Valley in its upper part. Four of the dolines are in the NW–SE line, in which another shallow depression had previously been identified. The azimuths of the maximum axes of elongation correspond to the course of the valley. The largest of the dolines of this line reaches a depth of up to 6 m, and a probe was excavated by speleologists on the bottom. There is an active parasitic doline with a partially-open bottom, currently situated at its bottom. The dolines originated in the Borinka limestones.

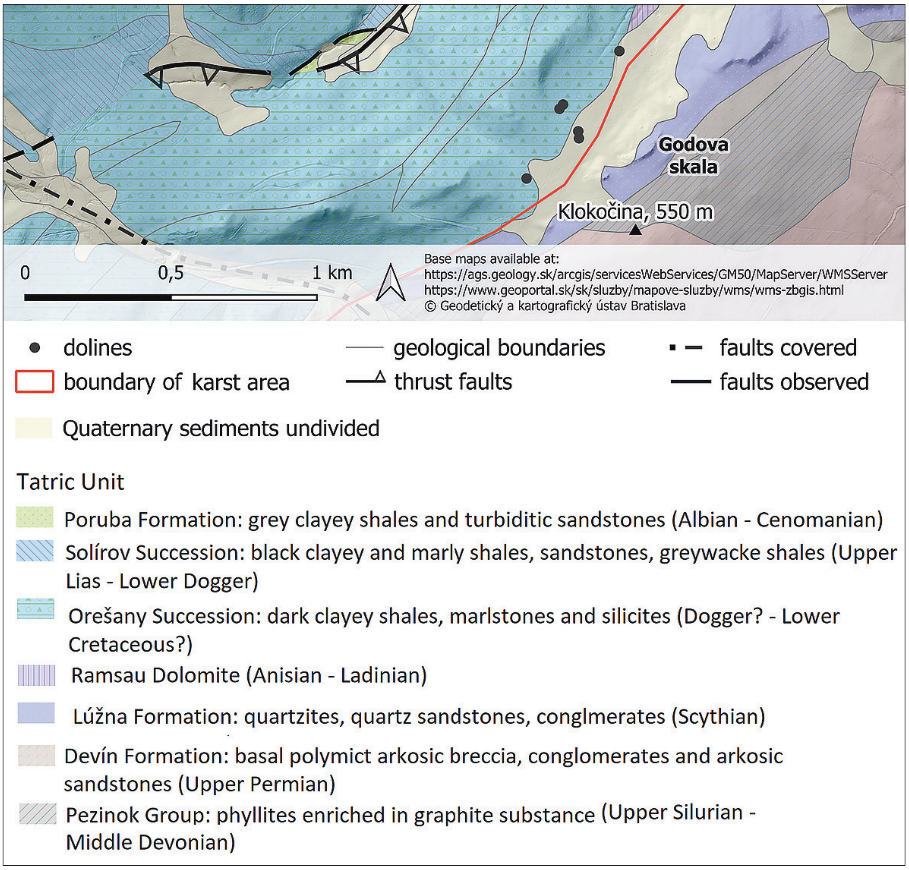

Fig. 7. Geological map of Godova Skala Rock (Kuchyňa-Orešany Karst) (Polák et al., 2011) with the markings of dolines.

Dolines are also scattered in the Okopanec Massif (531 m a.s.l.). The Okopanec Massif is characterized by the presence of the limestones of the Prepadlé Formation, and they extend to the largest area here. This is also the area where the endokarst is most widespread, and it is represented by the Borinka Cave System and other important caves, such as the Sedmička Cave, Silnického Cave, and Vlčie Jamy Cave. There are also several anthropogenic pits, which are a byproduct of the lime industry, since the quality raw material for quicklime production is found in this area. Dolines were formed along the perimeter of the massif near the contact of Borinka limestones with granites to granodiorites of the Bratislava Nappe (Fig. 8). Some have been described previously by Liška (1982) as marginal karst pits, which are formed when soluble karst rocks come into contact with insoluble rocks. Finally, there is one more phenomenon found here. Since we know the course of several caves underground, and several dolines and depressions are located on steep slopes above the network of underground spaces, we can conclude that these are not corrosive dolines, but collapse dolines (above the Borinka Cave System, Vlčie Jamy Cave) (Lačný et al., 2022b). The doline "Žulový Závrt" can also be considered an example of a collapse doline on a slope. It is located in Zbojnícky Jarok, opposite the Zbojnícka Cave, 780 m northwest of Medené Hámre (290 m a.s.l.).

Dolines predominantly occur in the well-developed karst of Borinka limestones or on contact with non-karst rocks, especially granitoids, sandstones, or quartzites (Fig. 8). In addition to occurring in contact zones, their genesis is also linked to faults in NE–SW, NW–SE, and NNW–SSE strikes with solution dolines dominating here (Lačný et al., 2022b). These directions also corresponded with the measured data of the maximum axes of doline elongation and can be partially correlated with regional neotectonics (Lačný et al., 2022b). A similar link to preferential directions has also been observed in other karst areas of the Malé Karpaty Mts. (Lačný et al., 2019a; 2020). The valleys, but also the doline lines of Staré Hájne and Banské, which are situated in flatter valleys of this direction, are linked to NW–SE-striking fault zones.

In summary, when compared to other karst areas of the Malé Karpaty Mts., three characteristic features can be observed in the Borinka Karst concerning the dolines. The first one is the direct contact with the Tatric crystalline basement. In the area of Okopanec, solution dolines were formed almost directly on the contact, and Liška (1982) refers to them as marginal karst dolines, as well as dolines with a tributary groove formed by intermittent surface water flow, which are also known as alluvial dolines. The second phenomenon is the greater occurrence of collapse dolines. Such dolines can be found above known parts of caves and reflect the course of underground cave spaces. In contrast, in the central part of the Borinka Karst, on the flatter parts of the area, clusters of solution dolines arranged in lines were formed, which can be seen at the localities of Staré Hájne, Ostrovec, and Banské. The third phenomenon comprises anthropogenic pits, which are several times higher than regular dolines. These are lime pits, charcoal burning pits, or various pits created to verify raw materials by the local population. It is possible that some of the dolines were also used for this purpose. The formation of the dolines can be dated to the end of the Pleistocene, as evidenced by their periglacial filling proven by Liška (1982).

3.4 Dolines of the Cajla Karst

The Cajla Karst has developed on the intricately folded limestones and dolomites on the N-NW rim of Cajlanská Veľká homoľa Hill (516 m a.s.l.) (Fig. 9) (Mitter, 1983). A belt of karstic rocks is also present from the locality of the Rybníček site towards the Veľká Homoľa Hill (709 m a.s.l.) and to the Tisové Skaly, where the observatory of Comenius University is located. The karst is covered with slope sediments (Bizubová et al., 2000). This belt continues towards the Village of Píla at the base of the Kukla

Hill (564 m a.s.l.). On the eastern slopes, the terrain is divided by deep valleys of hillside streams expanding from the ridge of the southern part of the Malé Karpaty Mts. belonging to the Modra Granodiorite Massif. The lithology for karstification consists of Gutenstein Limestone and Dolomite (Anisian–Ladinian) of the Tatric cover sequence, whereas in the area of Modra-Harmónia, Paleozoic marbles and erlans of the Pezinok Group are karstified as well (Polák et al., 2011).

In the studied area, as many as 50 dolines have been identified, located at the contact of quartzites of the Lúžna and Gutenstein formations (Lačný et al. 2021) (Fig. 9). Karst, where the doline line is located, is covered by slope deposits. Their thickness attains several tens of meters and contains small debris, but also occasional larger blocks of quartzites, which had been transported from a nearby ridge of the Veľká Homoľa Hill (709 m a.s.l.). In the debris slope, Gutenstein carbonates are also present, usually as occasional debris, although larger blocks with a diameter of several metres have also been observed. In other areas, carbonates are exposed as small "islands". They are exposed especially in the surrounding of the elevation point of Vápenka (590 m a.s.l.), located north of the Veľká Homoľa Hill (709 m a.s.l.). Here, a large number of anthropogenically processed pits are located as well, which are used for limestone mining and its subsequent processing of lime. The majority of anthropogenically processed pits are in the vicinity of Vápenka (590 m a.s.l.), where carbonates are exposed at the surface. According to historical maps, several quarries had been located there.

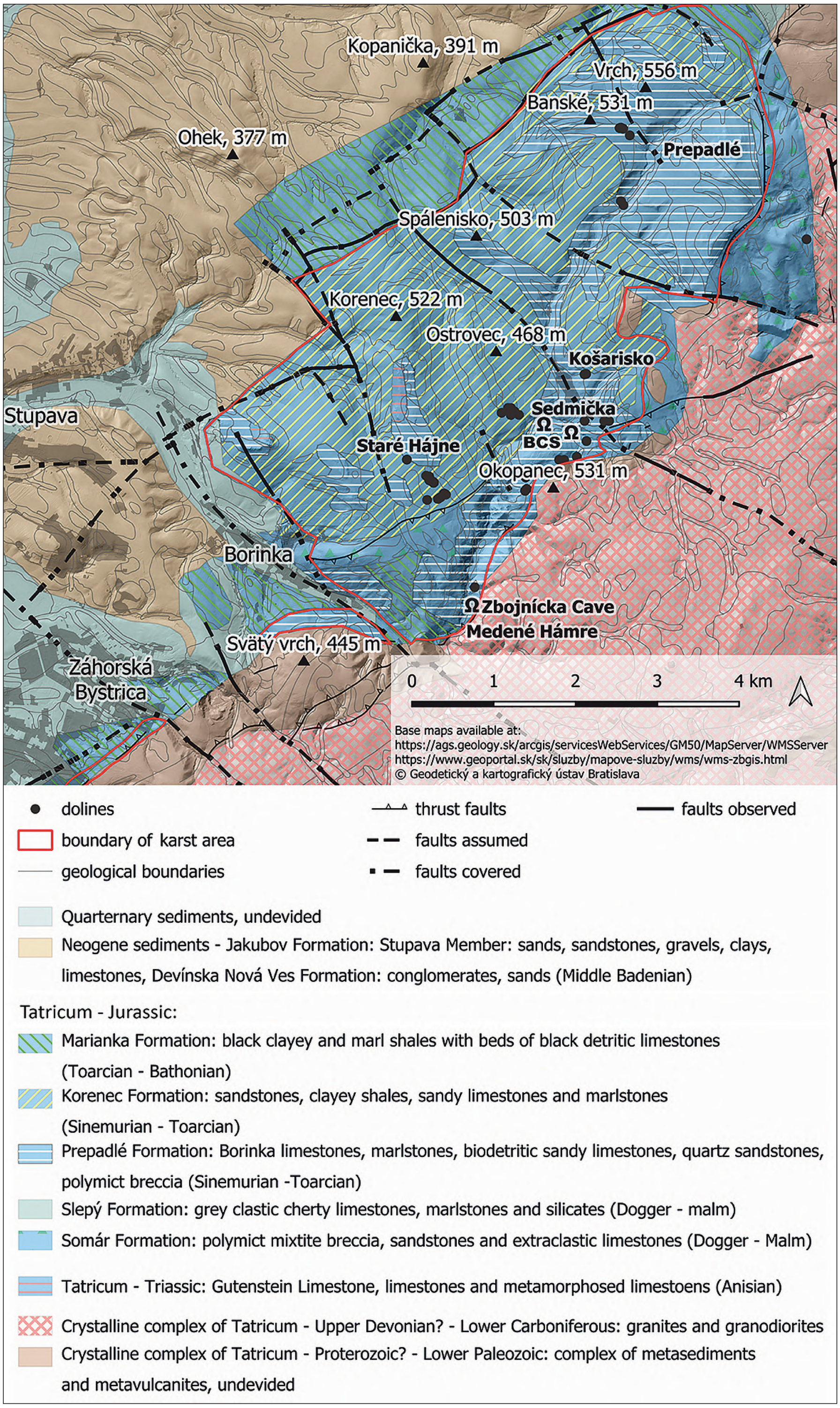

Fig. 8. Geological map of Borinka Karst (Polák et al., 2011) with the markings of dolines.

As many as 49 dolines are arranged in the line (except for Braňov Závrt). They were formed on a tectonic dislocation on the contact of quartzites of the Lúžna Formation and overlying carbonates of the Gutenstein Formation (Fig. 9). In general, dolines are located on a slightly inclined platform in the range of 1–5°. Near the contact between quartzites and limestones with intensive atmospheric water drainage, funnel-shaped formations dominate, sometimes with semi-open to open bottoms where solution geneses dominated. Further from the main line, cup-shaped dolines with flat bottoms dominate, some of them contain bottom mudflats. Some of them can be described as subsidence dolines.

In as many as 11 dolines inflow lines were identified, or their bottoms had active submersions, which drained the water into the underground during increased atmospheric precipitation (Lačný et al., 2021).

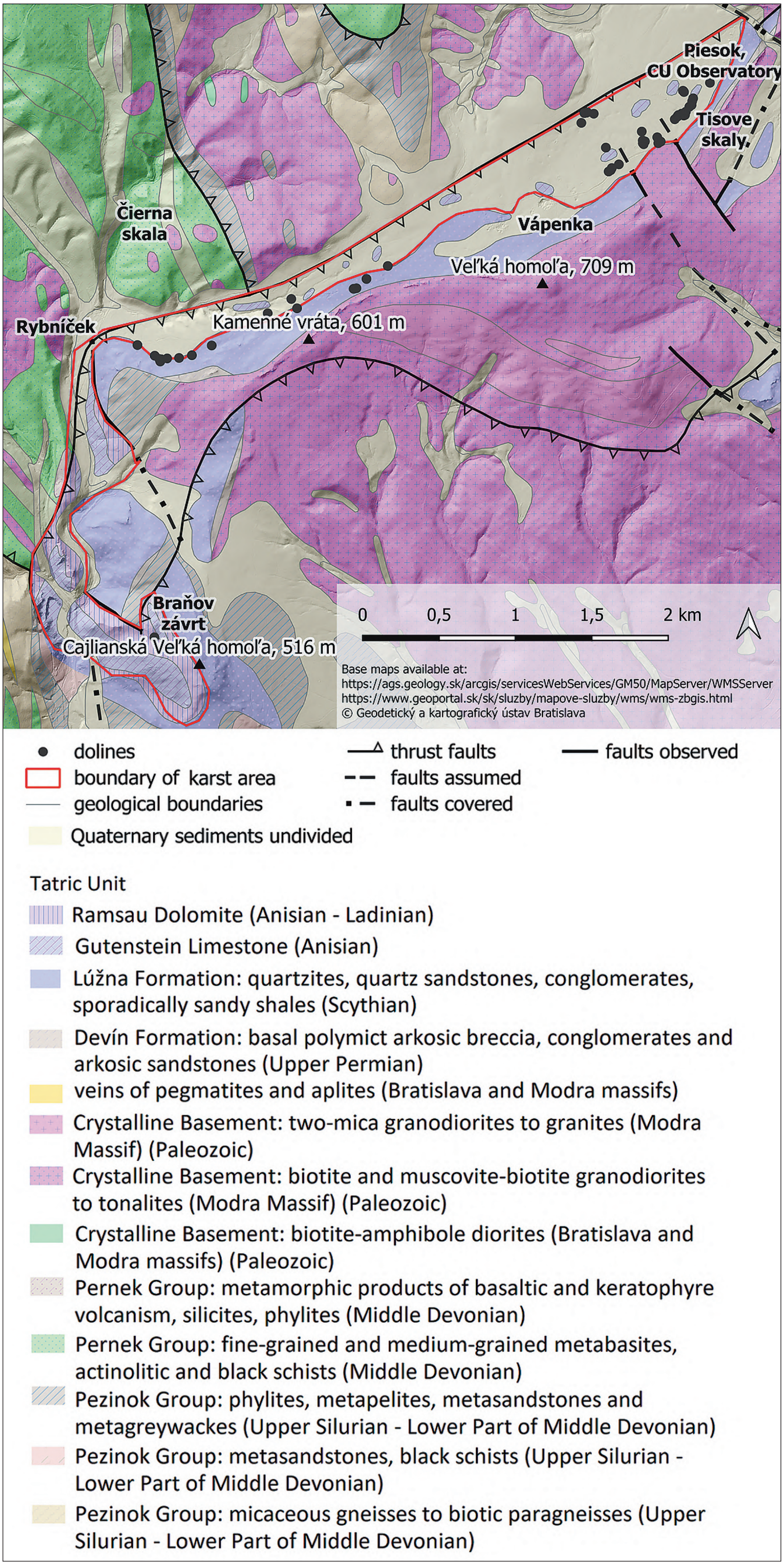

Fig. 9. Geological map of Cajla Karst (Polák et al., 2011) with the markings of dolines.

According to Lačný et al. (2021), azimuths of the doline's longest axes plotted in the rose and contour diagrams indicate two main directions. The NE–SW direction is the dominant one, while the other is a NW–SE direction (Lačný et al. 2021). The NE–SW direction follows the main doline line, which is a tectonized zone of the lithological boundary between quartzites and carbonates (Fig. 9). The maximum elongation of the axes of the studied dolines in this direction may be caused by surface water outflow and subsequent draining from the highest spot (629 m a.s.l.) in the direction towards the NE into the area of Tisové Skaly and to the SW into the area of the Rybníček site. In addition, several inflow lines follow this direction.

The second, NW–SE direction of maximum elongation of the doline axes influenced the water outflow underground from the main ridge of the Veľká homoľa Hill (709 m a.s.l.), which was built up by quartzites and located SE of the doline line. Upon contact with carbonates, a significant infiltration and morphology of dolines in this direction can be observed. This kind of orientation may also be due to the brittle tectonic structures of such affinity occurring in the area (Fig. 9).

In the area of the Comenius University Observatory, several significant depressions showed signs of anthropogenic activity (excavation work). In addition, the carbonates in this area were covered by a greater thickness of slope sediments containing blocks of quartzite of different sizes and clays. Carbonates are not fully exposed here. Geophysical research was conducted to explore the possibility of these forms being dolines (Lačný et al., 2021). Based on the number of geophysical methods that were used (electrical resistivity tomography, seismic refractive tomography, and radon manometry), the occurrence of carbonates on the fault structure under the debris slope sediment layer was confirmed.

Since such comprehensive

research on the covered karst has not yet been carried out, the phenomenon of covered or concealed karst has been described here for the first time based on Veress (2016) in Slovakia (Lačný et al., 2021).

3.5 Dolines of the Plavecký Karst

The Plavecký Karst (Fig. 10) extends across the Malé Karpaty Mts. in a WSW–ENE direction and includes the area in the approximate triangle of Rohožník – Trstín – Prievaly (Mitter, 1983). It was first described by Droppa (1952), although his definition does not represent the current state of knowledge. Stankoviansky (1974) included the Plavecký Karst together with the Kuchyňa-Orešany Karst and the Smolenice Karst into the Karst of Biele Hory. The surface area of karstic rocks is up to 58.3 km^2 (Kullman, 1990). The highest peak of the area is the Záruby Hill (768 m a.s.l.), which is also the highest elevation point of the mountain range (Fig. 10). The karst is bound exclusively to the carbonates of the Hronic Unit. The central part is formed by the Veterlín Nappe (*sensu* Havrila, 2011), whereas the northern part is formed by the Považie Nappe. A sedimentary succession of Middle to Upper Triassic carbonates is important for the formation of the karst (Polák et al., 2011). The non-karstic parts of the Lower Triassic Šuňava and Benkovský Potok formations, as well as the Upper Triassic Lunz Member are contact zones associated with the formation of some dolines. From the southeast, the Plavecký Karst is separated from the Kuchyňa-Orešany Karst by a strip of non-karstic rocks of the Upper Paleozoic, so-called Ipoltica Group of the Hronic Unit.

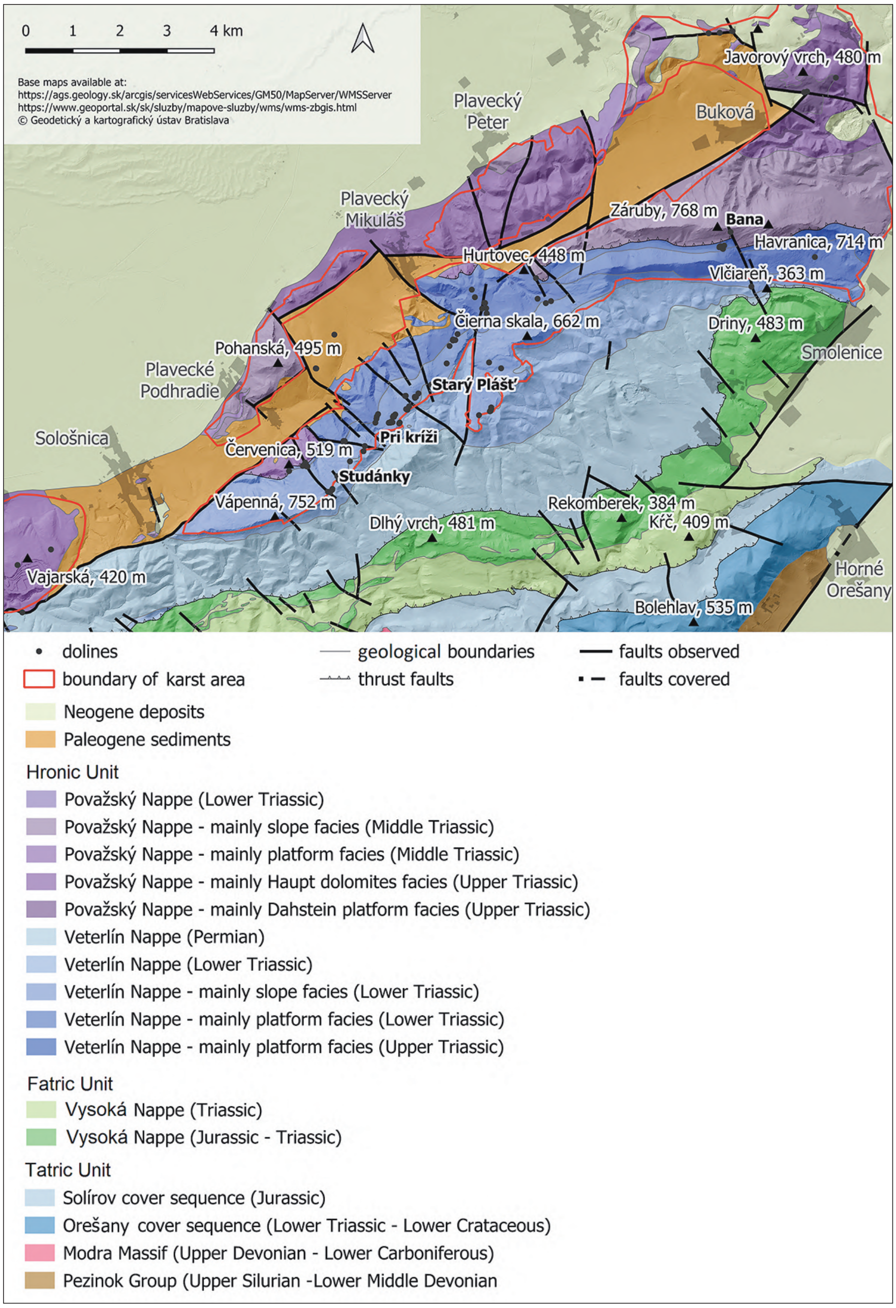

Fig. 10. Geological map of Plavecký Karst (Polák et al., 2011) with the markings of dolines.

Within the entire Plavecký Karst, 83 dolines and 8 shallow depressions of karstic origin with muddy bottoms were localised (Lačný et al., 2020). In addition, the locality of Bana was identified, which lies southwest of Záruby (768 m a.s.l.); it likely represents a larger collapsed underground cavity (Lačný et al., 2019b). In the vicinity of dolines, anthropogenic depressions – most often lime pits –were also identified in several places. The largest number of lime pits was identified in the area of Havranica Hill (714 m a.s.l.). One of the conditions for the morphometric analysis is to exclude anthropogenic reprocessing of the original doline. So far, we have identified several such dolines north of Buková Village, located in cultivated fields or next to settlements. The distribution of dolines is tied to flat terrain features. The majority of dolines are located on platforms with slopes of no more than a few degrees. Therefore, the entire area of the Plavecký Karst does not have ideal conditions for the formation of dolines, although there are isolated areas with dolines, which can be found north of the Village of Buková (around Javorový Vrch Hill (480 m a.s.l.), as well as at Vajarská Hill (420 m a.s.l.)). Two isolated dolines and seven mudholes were identified in the eastern part of the Plavecký Karst at the elevation point of Sedlo Záruby (625 m a.s.l.), south of Havranica (714 m a.s.l.) and near Vlčiareň (363 m a.s.l.). Otherwise, the dolines are in a continuous strip from the northwestern end of the Vápenná Hill (752 m a.s.l.) to the Plateau at Hurtovec (448 m a.s.l.), east of the Village of

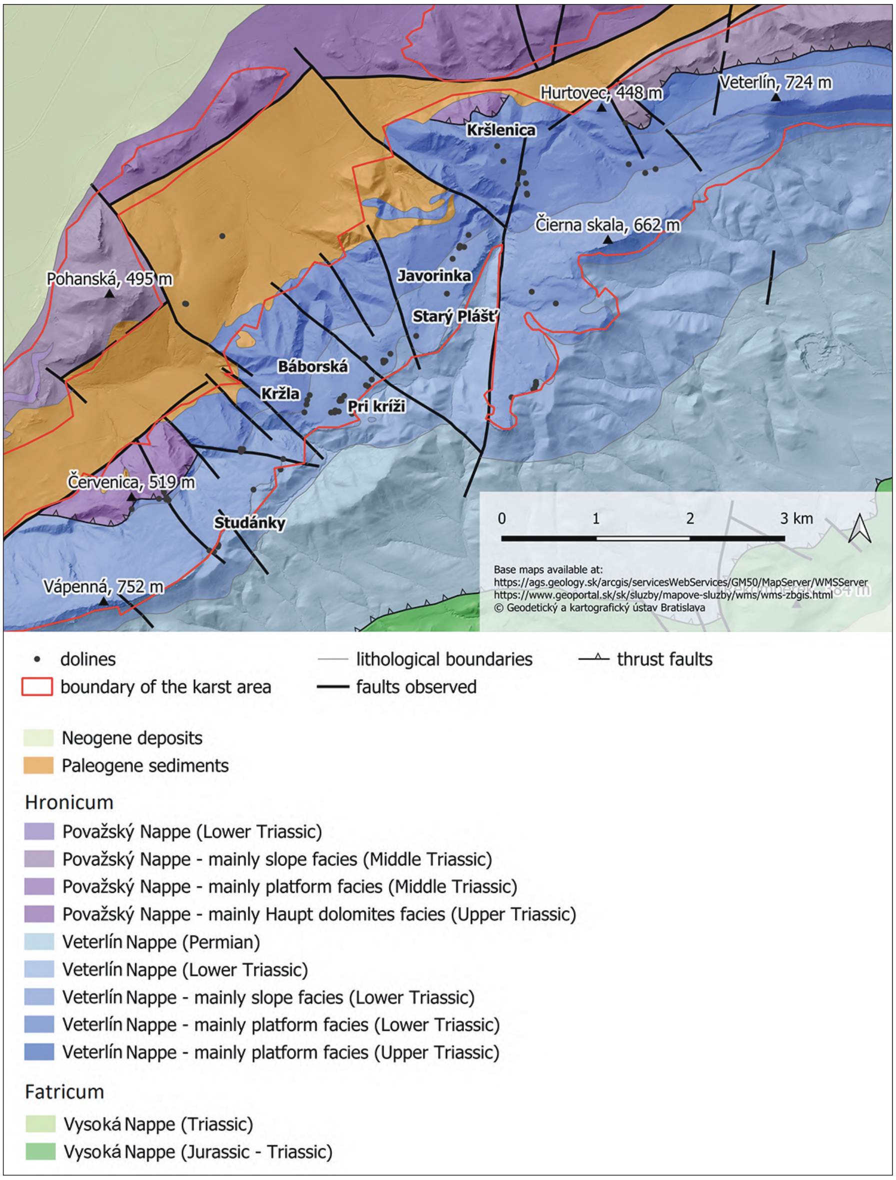

Fig. 11. Geological map of the central part of Plavecký Karst (Polák et al., 2011) with the markings of dolines.

Plavecký Mikuláš. We do not consider the pits on the Pohanská Plateau (495 m a.s.l.) to be suitable for morphometric analysis because of the presence of important fortified settlements. We agree with the opinion of Šmída (2010), who describes them as pits of uncertain origin. Even if they were of karstic origin, they were likely reshaped anthropogenically.

Dolines on karst plateaus are mostly concentrated in lines. However, they are not as pronounced as, for example, in the adjacent Kuchyňa-Orešany Karst (Lačný & Csibri, 2020) or on the Čachtice Plateau (Lačný et al., 2019a). In these karst areas, the dolines are largely concentrated in major fault zones. In the Plavecký Karst, this happens to a lesser extent and the variability of fault zones from which they originate differs. The dolines of the Plavecký Karst are dominated by lithological boundaries (Fig. 10). The largest of the dolines of the Plavecký Karst formed as significant alluvial stream sink dolines (Studánky, Starý Plášť, and Pri kríži), which occur near the distinctive lithological boundaries of the Benkovský potok Formation and consist mainly of quartzites, arkoses, and graywacke (Lower Triassic), as well as overlying carbonates of the Gutenstein Formation (Aegean – lower Pelsonian) or the Lunz Mb. (Závrt na Hurtovci) (Polák et al., 2011). Important alluvial stream sink dolines can also be found on the sites of Javorinka, Baborská, Kršlenica, and Kržla.

Pronounced dolines are not concentrated directly in the valley bottoms, but rather on their edges. This indicates the dynamics of the processes occurring in the most active parts of the valleys, where dolines can often be destroyed or never form. A similar case of the absence of dolines in a major valley is also observed in the Čachtice Karst in the Hlboká Dolina Valley (Lačný et al., 2019a).

The measured maximum axes of doline elongation have trends in the W–E and NE–SW directions (Lačný et al., 2020). These directions are correlated with the course of discontinuities beneath the surface. The Plavecký Karst itself is elongated in the NE–SW direction, dominated by dolines at lithological boundaries (Fig. 11). The W–E direction dominates in the central plateau parts of the Plavecký Karst and is related to regional tectonic structures to which the doline lines are also tied. Just like in the previous karst areas, there are corrosive dolines near the doline lines and shallow depressions in several places (e.g., at Sedlo Záruby 625 m a.s.l.), which can be attributed to subsidence dolines. As mentioned above, especially at the lithological boundaries, so-called alluvial stream sink dolines with pronounced inflow lines are formed.

In terms of hydrology, the water is generally drained from the south-east to the north-west through the valleys. Based on some doline lines, they likely also follow a similar course underground.

3.6 Dolines of the Čachtice Karst

The Čachtice Karst is the northernmost karst area of the Malé Karpaty Mts. The karst area is located on both sides of the antecedent canyon, the Višňové stream breach (Hochmuth, 2008). Here, the karst is linked to the Mesozoic carbonates of the Hronic Unit. Jakál (1993) described this karst area as segmented karst composed of massive ridges, horsts, and combined fold and fault structures, with partially to well-developed endokarst and exokarst.

The most dominant part of the Čachtice Karst is undoubtedly the Čachtice Plateau (Fig. 12). It covers an area of 21 km^2 with the highest point of Salašky (588 m a.s.l.). The Čachtice Plateau is dominated by dolines, which are often arranged into lines. Most dolines do not exceed 20 m in width and 5 m in depth. However, there are also dolines of larger dimensions with widths of 140–195 m, even up to 257 m, and a depth of up to 30 m. It should be noted that the longest cave of the Malé Karpaty Mts., the Čachtice Cave, with a length of 3865 m and a depth of 110 m (List of caves of Slovakia. Status as of 31. 12. 2017) is located in the Čachtice Plateau. It was discovered through one of the dolines on the surface of the plateau.

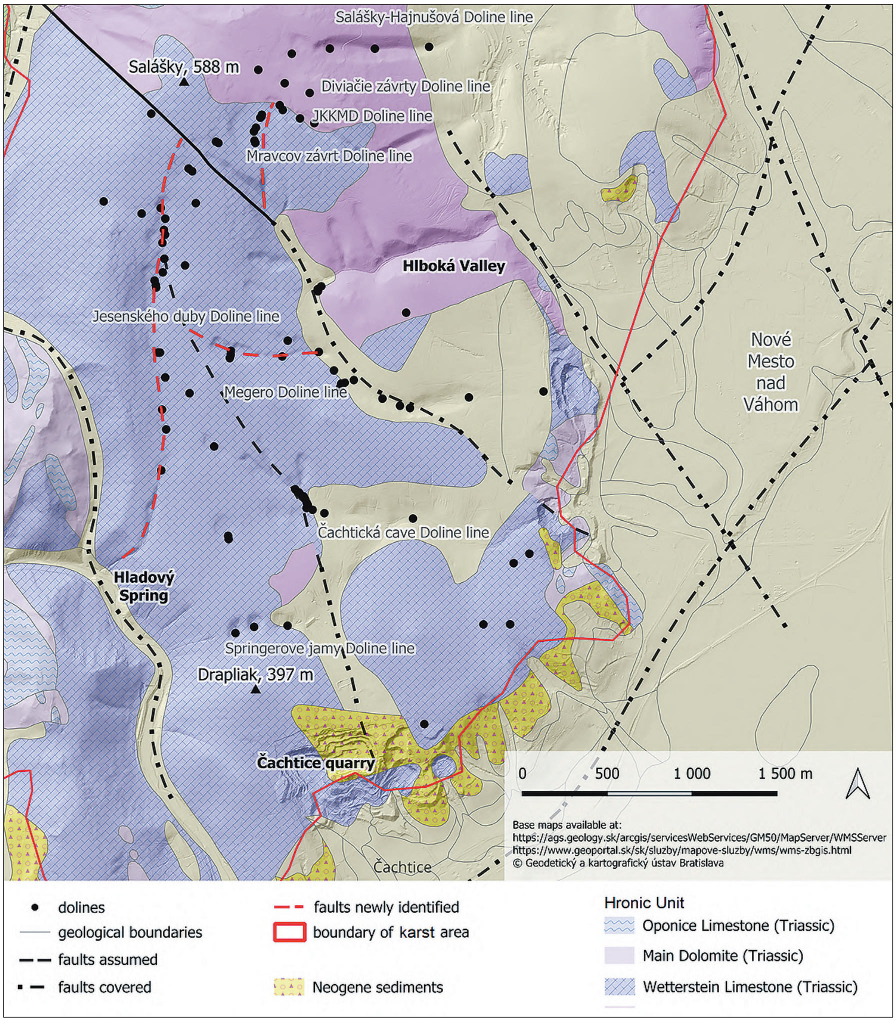

Fig. 12. Geological map of Čachtice Plateau (Čachtice Karst) (Polák et al., 2011) with the markings of dolines and new faults.

As a part of our research, 85 dolines were located and mapped on the Čachtice Plateau (Fig. 12) (Lačný et al. 2019a) (*note: one doline was mapped later in 2021, N48.754815, E17.77546). Dolines rarely occur individually, they are mostly arranged in lines (Fig. 3B), mainly on dry valley bottoms at the edges of a plateau, or on tectonically predisposed lines directly on the plateau. They often contain inflow lines. Connected dolines are also present here, and in most cases, these occur in pairs. Several dolines are referred to as maternal dolines with a daughter doline, which are also referred to as parasitic dolines or depressions. The best example is the Megero Doline, with a perimeter of up to 606 m, with eight daughter (parasitic) dolines. There are also dolines outside the main lines, which were difficult to locate, and we consider them as valuable data. Their measured attributes are even more valuable because they complete our overall knowledge of the dolines of the Čachtice Plateau.

Perhaps the most important data from the point of view of tectonic interpretation are the azimuths of the longest axes of dolines. Some dolines in valley bottoms are elongated in the direction of these valleys. However, this is not always the case, and there are also cases where the azimuth of the longest axis of the doline does not correspond to the direction of the valley in which it was formed (Špringerove jamy pits, etc.). Based on our data, we can describe three dominant directions that participated in the formation of the dolines of the plateau (Lačný et al., 2019a).

Probably the largest number of dolines is present in the WNW–ESE direction (Lačný et al., 2019a). This likely resulted from several factors. One of them is the fact that the dataset probably captured two structural discontinuities that dominated the doline formation. These may be subvertical discontinuities in the NW–SE direction dominant in the formation of valleys and river networks and discontinuities in the W–E direction, which may be related to areas of bedding planes with a dip of 30 to 50° to the N and S respectively (measured in the central part of the plateau), thereby indicating a fold-scale structure. The layering areas of bedding planes were likely later tectonized. However, the soil cover around the dolines prevented us from studying the observed structures and their possible division more closely. The fold structure is also documented in the quarry in Čachtice. The sedimentary deposit forms an anticlinal structure. The axis of the anticlinal runs in a WNW–SSE direction in the area of the Draplák elevation point (Salaj et al., 1987).

Another important direction in terms of the genesis of dolines is the N–S direction (Lačný et al., 2019a). It is represented mainly by the Jesenského Duby Line, beginning from the spring of Hladový Spring and ending below the Salašky, or the line of the "Mravcov závrt" doline (Fig. 12). The link between Hladový Spring and the line of Jesenského Duby has also been demonstrated using stable carbon isotopes by Mareková et al. (2020).

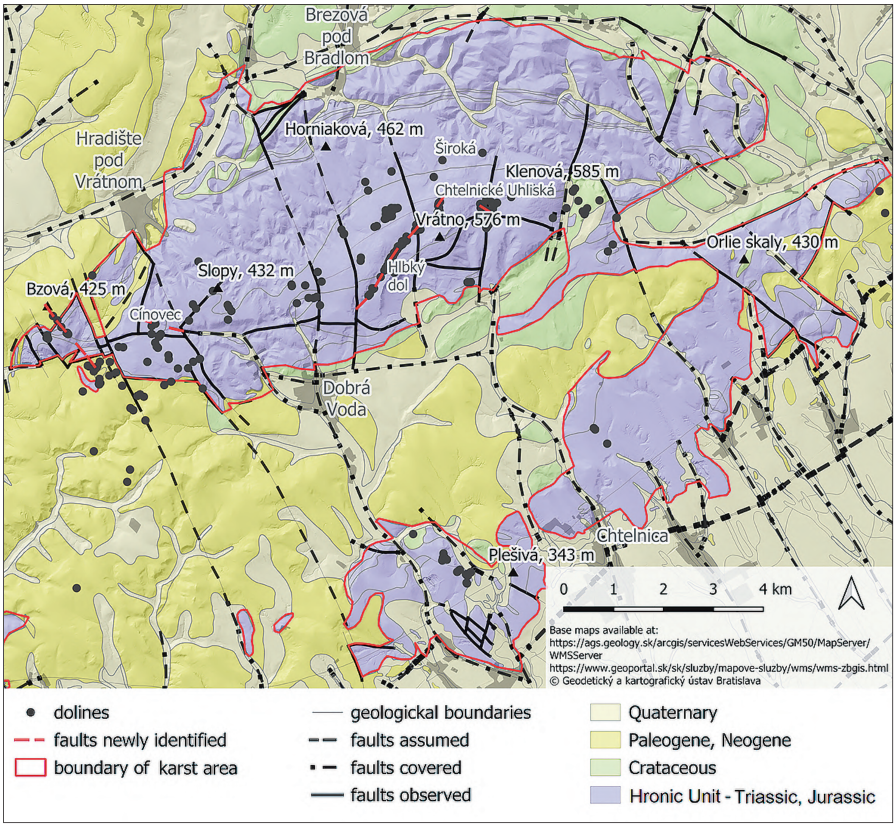

Fig. 13. Geological map of the Dobrá Voda Karst (Polák et al., 2011) with the markings of dolines and new faults.

We assume a connection with significant faulting in this direction, representing, for example, a significant marginal fault in the western part from Višňové to Hrušové.

The last of the significant directions of the longest doline axes is the NE–SW direction (Lačný et al., 2019a). This direction is important from the point of view of speleogenesis of the caves of the Čachtice Plateau (Čachtická Cave, Hladový Spring). Near the Hladový Spring and also in the Hladový Prameň Cave, the surfaces of these discontinuities are oriented generally in a NE–SW direction and are steeply inclined to the NW or SE. We assume their reactivation. They may be related to recent neotectonic movements – extension during the Late Pleistocene to Holocene (Vojtko et al., 2008; Littva et al., 2015).

Lithological boundaries play only a minor role in the formation of dolines, since the limestones mostly exhibit homogeneous nature, although we admit some variability within strata.

It has also been shown that the direction of the elongation of a doline is not always the same as the direction of the structure (valley) to which it is linked. This means that dolines form at the junction of multiple discontinuities in the massif. Therefore, it depends on the significance of the fault and its depth location and later, of course, on what the final shape of the doline will be (depending on surface factors). The most numerous directions of the longest doline axes (WNW–SSE) correspond to the fault system to which valleys and surface flows are tied. Other major directions involved in the formation of dolines are N–S and NW–SE. These are trends that speleologists can expect even in underground cave spaces, whether discovered or still undiscovered.

3.7 Dolines of the Dobrá Voda Karst

The karstic area in the surroundings of the Village of Dobrá Voda in the Brezovské Karpaty Mts. was first described and named by Droppa (1952) (Fig. 13). It covers an area of 86.5 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.). In the past, the Dobrá Voda Karst was also referred to as the Brezová Karst (Stankoviansky, 1982). Divided into two parts, it represents an anticlinal structure in a NE–SW direction, with a distinct depression located in the centre of the area. The north-western part, which is built by a limestone-dolomitic complex, is larger and contains more surface and underground karstic forms than the south-eastern part, which is built mainly by dolomites, except for the area near the Village of Chtelnica where Triassic limestones prevail. Here, the karst is built of carbonates of the Hronic Unit. The stratigraphic span of the nappe is from the Lower Triassic to the Cretaceous (Salaj et al., 1987). Characterised by shallow-water limestones, exposed strata are dominated by the Main Dolomite, organogenic and reefal Wetterstein limestones and dolomites, pink nodular Schreyeralm Limestone, Dachstein Limestone, and the so-called Oponice Member (Salaj et al., 1987). Some of the karstic forms developed in Neogene basal conglomerates as well, i.e., the Jablonica Member. (Salaj et al., 1987). The conglomerates are predominantly carbonatic, composed of clasts derived from Triassic and Jurassic limestones, and to a lesser extent, also from various largely Upper Cretaceous sandstones. They rarely derive from quartz, arkose, porphyroids, or gneisses. Since karstic forms (especially dolines) are rare in these rocks, they were not included in the total area of the Dobrá Voda Karst. However, Mitter (1983) considered them to be partially within the area. He divided the karst into the northern Brezová Karst and the southern Chtelnica Karst, and then, between these two, the Dobrá Voda-Prašník Karst, which originated in Neogene conglomerates.

In the Dobrá Voda Karst, dolines are typical surface karstic forms. Significant doline lines can be found in the area of the Hlboký Dol Valley, Chtelnické Uhliská, and Cínovec sites. Up to 263 dolines have been documented here (Lačný et al., 2022c), although Šmída (2008) suggested the existence of only about 170 dolines. Some of them were excaveted by speleologists.

The dolines in the Dobrá Voda Karst are often formed in lines with a tectonic or lithological predisposition. The largest number of dolines was formed in the line of Hlboký Dol, about 2 km NW of the Dobrá Voda Village. The doline line, 2.4 km in length, originated on a tectonically-predisposed line in the NE–SW direction and contains 56 dolines. The longest measured doline axes may, in some cases, correspond to faults with a NE–SW and NW–SE direction (Lačný et al., 2022c). In this linear arrangement, funnel-shaped (solution and alluvial stream sink) dolines predominate.

Another important line of dolines is located 1 km SW of the peak of Klenová Hill (585 m a.s.l.), where 48 dolines were formed on two lines, predisposed by faults of the N–S and NW–SE directions (Fig. 13). The Ramsau Dolomite and Steinalm Limestone are exposed in the area. Similar to the locality of Hlboký Dol Valley, solution dolines are present here.

The doline line at Cínovec is located about 3 km NW of the Village of Dobrá Voda, between the elevation points of Vysoká Skala Rock (440 m a.s.l.) and Lesy (443 m a.s.l.) (Fig. 13). Fifteen dolines were formed here; the orientation of their longest axes is predominantly in the NE–SW and NW–SE directions. Most of them are irregular in shape. Again, dissolution dolines dominate (Fig. 3C).

Based on the maximum axes of doline elongation, three important directions contributing to the formation of dolines and doline lines can be identified: N–S, NE–SW, and WNW–ESE (Lačný et al., 2022c). In this area, these directions are represented by faults and reflections of neotectonics and significantly change the geomorphology of the affected area (Fig. 13). The Dobrá Voda Karst is characterised by a pronounced depression in its centre, which is a NE–SW antiform structure. The depression is divided by intersecting faults of the NW–SE and NNE–SSW directions. W–E faults are less common. Perhaps the most significant fault in a NE–SW direction was identified in the Hlboký Dol Valley.

It can therefore be assumed that the dolines are linked to these faults and that their maximum elongation axes reflect the fault tectonics of the bedrock. The three doline lines described above are a good example of this. The line at the Cínovec site originated on the fault of the WNW–ESE direction, Hlboký Dol Valley on the fault of the NE–SW direction, and the dolines at Chtelnické Uhliská were formed on the fault structure of the N–S direction with the lateral branch of the NW-SE fault. Some dolines are also found on tectonized lithological boundaries, especially limestones and dolomites.

4. DISCUSSION AND CONCLUSIONS

Research of 650 dolines of the Malé Karpaty Mts. brought new results concerning surface and endokarst forms and contributed to the interpretation of faults. In several places, it clarified the lithological boundaries of individual strata. It can be stated that the Malé Karpaty Mts. are, from the point of view of doline research, the most precisely studied territory in Slovakia to date. The dolines in the Malé Karpaty Mts. are concentrated in lines and rarely isolated. Based on the location and size of the dolines, karst areas can be determined in terms of the geomorphic evolution of karst as a young type and rare as adolescent karst (sensu Grund, 1914)

In addition, the so-called covered karst was described in the Cajla Karst using dolines and geophysical methods (Lačný et al., 2021). Dominant doline lines occurred on reactivated fault systems in the NW–SE and NE–SW directions, and the directions N–S and W–E had a smaller representation. The fault structures of the NW–SE and NE–SW can be dated back to the Miocene with their reactivation to the present. Faults of the NW–SE direction originated in the Karpatian-Badenian period. Together with the NE–SW sinistral faults, they form a pair system. In the Driny Cave, there is activity on these fault structures at present – their reactivation (Briestenský et al., 2011). When compressing approximately in the N–S direction, the reactivation of extensive N–S structures in the pure shear model should be observed. Offsets of the geological boundaries suggest that in the past, they also functioned as sinistral directional faults, forming a pair system with NW–SE dextral faults. Later, under the influence of the Mid-Miocene compression stress of the N-S direction, they were reactivated as normal faults, associated with the pull-apart mechanism of the opening of the Badenian depocenter of sedimentation of the Vienna Basin (Marko & Jureňa, 1999). Doline lines also came into being at the lithological boundaries of individual strata. The most widespread rocks where dolines originated are carbonates of Middle to Upper Triassic sequences of respective units exposed in the Malé Karpaty Mts. This is mainly due to their significant wide distribution in the Malé Karpaty Mts. and suitable conditions for their dissolution. Only the dolines in the Borinka Karst are also linked to Jurassic sequences (especially Borinka limestones of the Prepadlé Formation), as well as some of the dolines in the Kuchyňa-Orešany Karst. These are mainly dolines in the area of Godova Skala Rock, where the doline line originated on the contact of quartzites of the Lúžna Formation with bedded limestones with the silicites of the Slepý Formation (Middle-Upper Jurassic?), both belonging to the Orešany cover sequence of the Tatric Unit. Within the Dobrá Voda Karst, part of the isolated dolines was also formed to a lesser extent in Neogene basal conglomerates, which are also called Jablonica Mb. (Miocene). Conglomerates are predominantly carbonate, and the process of dissolving carbonate clasts also dominates here. Since the Malé Karpaty Mts. have a so-called striped structure, elongated in a NE–SW direction, some directions of doline lines correspond to this. In addition, tectonic or lithological contact among karstic and non-karstic rocks enhances the effect of dissolution, as confirmed by our study, where significant doline lines were observed to be concentrated on these discontinuities (Plavecký Karst, Borinka Karst). Morphologically, valleys were linked to the faults, which allowed even better concentration and draining of surface water into the underground in the form of dolines. Near the doline lines with intensive atmospheric water drainage, solution dolines were formed by slowly-dissolving carbonate at fault structures and lithological boundaries. Further away from the doline lines (for the most part), shallow cup-shaped forms of dolines formed on the plateaus, resulting from subsidence and referred to as subsidence dolines (Fig. 3D). Several dolines have been identified as collapse dolines based on the existence of subsurface cavities, the shape of the dolines, and the geophysical work carried out (e.g., Lačný et al., 2019b). Several dolines can be referred to by the non-genetic name of alluvial stream sink dolines. Doline lines are also related to the draining and flow of groundwater, which is later trapped in karst springs, thus the results of our research may be of further use to experts in hydrogeology.

The actual exhumation of the Malé Karpaty Mts. (except for the Late Cretaceous-Paleogene period, cf. Danišík et al., 2004; Králiková et al. 2016) took place since latest Miocene, and so the formation of karst and dolines could have taken place only after this phase, at the earliest in the Pliocene (Neuhuber et al., 2021). According to this assumptions, we assign the main karst phase to the Pliocene-Quaternary period with a different climate from the present one (Šujan et al., 2017).

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