Geological Control of the Origin of dolines in the Plavecký Karst (Malé Karpaty Mts., Slovakia)

Alexander Lačný[1,2], Rastislav Vojtko[2], Marek Velšmid[3], Laura Dušeková[4] & Juraj Papčo[5]

[1] State Nature Conservancy of the Slovak Republic, Little Carpathians Protected Landscape Area, Štúrova 115, 900 01, Modra, Slovakia; alexander.lacny@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] Cavers of the Plavecké Podhradie o.z., Plavecké Podhradie 284, 906 36 Plavecké Podhradie, Slovakia; mvelsmid@kike.sk
[4] State Nature Conservancy of the Slovak Republic, National Park Malá Fatra, Hrnčiarska 197, 013 03 Varín, Slovakia; laura.dusekova@sopsr.sk
[5] Slovak University of Technology, Faculty of Civil Engineering, Department of Theoretical Geodesy, Radlinského11, 810 05 Bratislava, Slovaka; juraj.papco@stuba.sk

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Abstract: The Plavecký Karst is located in the northern part of the Malé Karpaty Mts. and is exclusively linked to a diverse type of Triassic carbonates of the Hronic Unit, which forms the complex higher nappe system of the Central Western Carpathians. The Plavecký Karst has well-developed underground and surface karstic forms; however, the most typical landforms are dolines. The origin of the dolines in the investigated area is influenced by lithological, tectonic, topographic, and morphostructural predisposition, and they were formed by corrosion, collapses, suffusion, and subsidence processes. In the study area, altogether, 83 dolines and 8 very shallow karstic depressions with muddy bottoms were documented and investigated. Many of them are concentrated in the Biele Hory geomorphological part, as well as the central part of the study area with suitable conditions for doline formation. The dolines are less frequent in the Brezovské Karpaty Mts. and Bukovská Brázda Furrow, where the Plavecký Karst partially extends. Significant dolines were not concentrated directly in the valley bottoms, nor on the karst plateau; however, the dolines follow important lithological boundaries. Most importantly, there are boundaries between predominantly shallow water carbonates of the Middle to Upper Triassic formations and siliciclastic rocks of the Permian to the Lower Triassic in age. In addition to this predisposition, the dolines also follow important lithological boundaries between different types of carbonate rocks, such as boundaries among open marine and shallow water carbonate formations. Furthermore, the dolines have a positive spatial correlation with the faults, having displaced the carbonate formations of the Hronic Unit.

Keywords: morphometric analyses, doline, fault, lithology, Plavecký Karst, Malé Karpaty Mts., Western Carpathians

1. INTRODUCTION

The scope of our research focuses on the dolines of the Plavecký Karst, which have been studied in the past by several authors (e.g., Stankoviansky, 1974; Liška, 1976; Šmída, 2008). In recent years, the dolines have been studied in detail by Šmída (2010). A few of them have been known previously, including several significant ones, which were also documented in great detail. However, comprehensive geo-evidence and their parameters as a basis for more detailed morphometric analysis have been for the most part absent. It is virtually 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 the LiDAR data. In addition, a detailed visualisation of the morphology of larger dolines was the topic of our presented investigation. 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. The study of dolines allows for a more detailed research of underlying rocks, which are often covered by Quaternary deposits, thus hindering an analysis of geological structures. The present study verifies the previous results of geological mapping with the position of the dolines originating in lithological and tectonic discontinuities.

2. DOLINES AND THEIR QUANTITY

Dolines, which are the most distinctive surface forms of the karstic relief, represent closed depressions of variable measurements with slightly angled or even vertical side walls (Bondesan et al., 1992; Williams, 2004; Sauro, 2012; Waltham et al., 2005). Morphodynamically, dolines represent a basic hydrographic unit, which as a simple catchment area with its system of slopes, drain the water to the lowermost accumulation point (Bondesan et al., 1992; Williams, 2004). The genesis of dolines is influenced by topographic, tectonical, lithological, and morphostructural predisposition. Therefore, they can originate through several processes. Four major mechanisms of forming dolines are distinguished: corrosion, collapses, suffusion, and subsidence. However, it is not possible to link the origin of dolines with only one process. Therefore, dolines are considered predominantly polygenetic relief forms. Depending on the process, a variety of doline shapes can be documented; they occur either isolated or in groups. Because the international terminology includes more deep-routed terms for genetic types of dolines, Williams (2004) linked the respective terms with specific genetic processes and thus made the nomenclature more transparent. From the area of the Malé Karpaty Mts., 450 dolines have been mentioned to date (Šmída, 2008). However, this number will likely increase in the

Manuscript received 2020-09-06
Revised version accepted 2020-10-15

future. Typical dolines for this area are structures with a diameter of 10–40 m and a depth of 1–5 m. They are often arranged in lines following tectonic and lithological discontinuities in the host rocks. Within the Plavecký Karst area, Šmída (2010) presented a localization and description of 56 dolines in: Vajarská (1), the Červenica plateau (2), Hrubá-Kržľa (3), the ridge of Kamenná (9), the edge of the Suchá Valley (2), Baborská and surroundings (18) Javorinka (4), Starý plášť (6), Kršlenica (8), Hurtovec (1), north of Buková (2: Prepadlé zvony + 1).

3. GEOLOGY AND GEOMORPHOLOGY

The Plavecký Karst stretches across the Malé Karpaty Mts. in a WSW–ENE direction and includes the triangular shape area among the settlements of Rohožník – Trstín – Prievaly (Mitter, 1983) (Fig. 1). The karst was firstly described by Droppa (1952); however, this description no longer fully represents this definition. Stankoviansky (1974) included the Plavecký Karst along with the Kuchyňa-Orešany Karst and Smolenice Karst in the Karst of the Biele hory. The extent of karst rocks in the area is up to 58.3 square kilometres (Kullman, 1990). The highest elevation point of the region is Záruby hill (767.4 m asl.), which is also the highest hill within the entire mountain range. The geomorphological conditions of the Plavecký Karst were described by Liška (1976). The remnants of the oldest geomorphological cycle are located at altitudes of 450-540 m and form the Midmountain level (Liška, 1976). In addition, with respect to the morphological and genetic properties of the territory of Plavecký Karst, this author divided them into four height grades (150-300 m, 301-450 m, 451-550 m, 551-761 m).

The Plavecký Karst is located in the northern part of the Malé Karpaty Mts. Geologically, the Malé Karpaty Mts. are formed by a variety of pre-Cenozoic units, as well as the unconformable Upper Mesozoic to Cenozoic sedimentary complexes (Maheľ & Cambel, 1972; Polák et al., 2011; Fig. 2). The core of the mountains is composed of a predominantly Variscan basement and its Upper Palaeozoic to Mesozoic sedimentary cover, which belongs to the thick-skinned Tatric Unit. The upper structure consists of detached thin-skinned nappes of the Fatric and Hronic thrust systems. The Fatric Unit is formed almost exclusively by the Vysoká nappe with its typical shallow water sedimentary succession, which developed mainly during the Jurassic. The stratigraphic span of the nappes is from Early Triassic to mid-Cretaceous. The Vysoká nappe is overridden by the structurally highest nappe system of the Hronic Unit, which is composed of the Veterlín and Považie nappes. The lower, Veterlín nappe, is represented by Upper Carboniferous to the Permian volcanic sedimentary complex of the Ipoltica Group lying right on top of the Fatric Unit. The Triassic succession consists of the Lower Triassic siliciclastic sediments, Middle to early Upper Triassic - mainly open marine, basinal succession with generally thicker Lunz deltaic sediments. In contrast, the upper Považie nappe lacks the Ipoltica Group, and the Middle and early Upper Triassic formation are formed predominantly by carbonate platform formations. Both nappes have a well-developed Upper Triassic Haupt dolomite platform. Sediments younger than the Upper Triassic are very scarce.

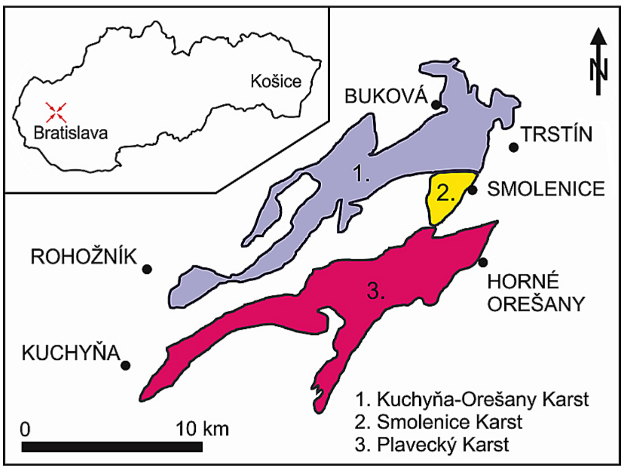


Fig. 1. Schematic figure of karst areas in the central part of the Malé Karpaty Mts. (according to Mitter, 1983).

The nappe structure is an unconformable overlap by the Upper Cretaceous (Gosau) deposits, outcropped in the northern part of the mountains by the Upper Palaeogene deposits in the Bukovská Brázda Furrow. The mountain is bounded by huge Neogene, predominantly middle to upper, sedimentary formations of the Vienna and Danube basins (Fig. 2).

The karst is exclusively linked to a diverse type of Triassic carbonate belonging to both the Veterlín and Považie nappes. The Middle and Upper Triassic carbonate complex is important for the formation of karst (Polák et al. 2011). The non-karstic, siliciclastic parts of the Lower Triassic sediments and the Upper Triassic Lunz Member are contact zones associated with the formation of some dolines. From the southeast, the Plavecký Karst is separated by the non-karstic rocks of the Ipoltica Group and the Lower Triassic formations from the Kuchyňa-Orešany Karst. On the other side, the Bukovská Brázda Furrow divides the Plavecký Karst to the Sološnica-Trstín Karst and the Karst of Plavecké predhorie (Mitter, 1983). Some authors define the Plavecký Karst as a whole without any division (e.g., Hochmuth, 2008; Šmída, 2010). The Karst is formed by scenically arranged, structural monoclinal ridges of the crest and hog-backs type, which originate on an outcropped bedding facies of the NW, inclined mainly by limestone formations; e.g., from SW to NE: Vápenná, Kamenná, Čierna skala, Veterlín, Čelo, Záruba and Havranica (Stankoviansky, 1974). At present, the most comprehensive of all aspects, the Plavecký Karst, was described by Šmída (2010).

Šmída describes the Plavecký Karst as a morphostructural unit with well-developed karst, fulfilling nearly all the attributes of the so-called contact karst in terms of surface karstification. A typical feature of karst is marginal, ponore dolines, ponores, and possibly also relics of marginal poljes or karst plateaus. There are a number of completely genetically different underground localities in the Plavecký Karst. Of the 162 known caves and similar cavities, which are at least a few metres long with a total length of 5258 m, most of them were formed as quasi-slope localities and only local, shorter, and "suspended" drainage of the surface parts of the massif (Šmída, 2010).

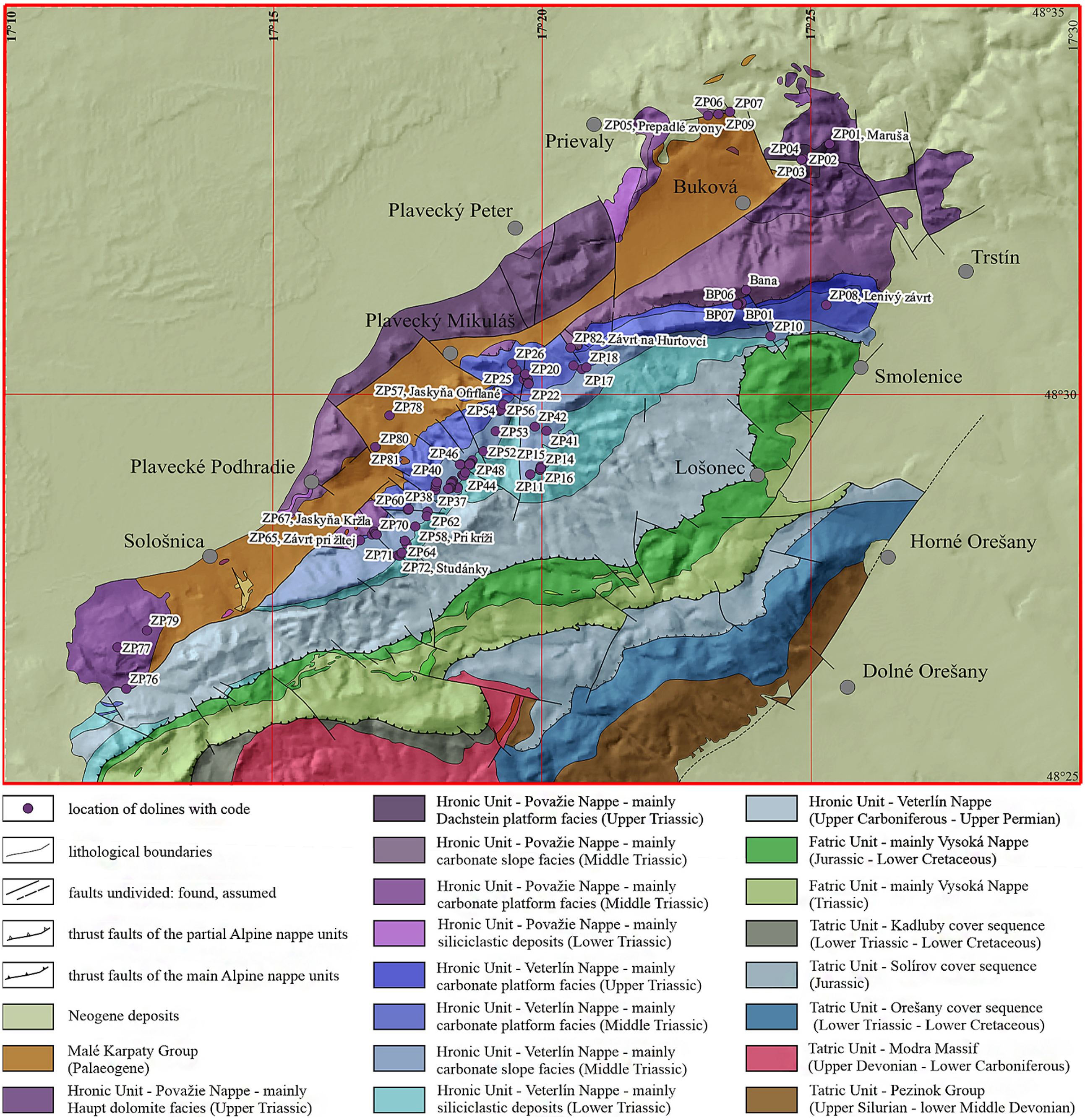


Fig. 2. Schematised tectonic map of the Malé Karpaty Mts. with the mapped dolines (according to Mahel' & Cambel, 1972; Polák et al., 2011; modified).

4. METHODS

For locating dolines, as well as providing the historical context of speleological works in the dolines, cooperation with a local speleologist group (Cavers of the Plavecké Podhradie) 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.

During the morphometric analysis, several previously published case studies were followed, including those by Veselský et al. (2014a, 2014b) and Lačný et al. (2019a), which focused on the Malé Karpaty Mts. area, as well as the studies done by Petrvalská (2010), who studied the dolines of the Jasovská Plateau.

In addition to the exact location of the dolines, we also documented several directly measurable attributes: elevation, perimeter, depth, the longest axis, azimuth of the longest axis, and the inclination of the walls. The dolines were categorized in the field based on their top view as round, oval or irregular (cf. Petrvalská, 2010).

On the basis of their shape, dolines were classified according to the work of 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. In funnel-shaped dolines, the inclination of walls attains 30–45°, and there may be an active submersion on their bottom. In cup-shaped dolines, the inclination of walls attains 12–15°, and the bottom can be blocked. Kettle-shaped dolines represent a transitional type between funnel-shaped and cup-shaped dolines, and their walls may incline up to 30°; their bottom is relatively wide and flat. Ring-shaped dolines are shallow, being up to 4 m deep and attaining a perimeter of up to 50 m; their walls are nearly vertical.

The form of dolines is derived from the basic geometric shapes. Starting with Cvijić (1893), a number of researchers noticed two basic attributes in particular. The first was their diameter (D) and depth (H), and secondly, their proportion (D/H), from which principal forms were derived (Bondesan et al., 1992). However, the boundary of a doline commonly has an irregular shape and it is often not possible to compare it with any geometric shape. Therefore, the average diameter of the doline is not simple to determine for each doline. The diameter of a doline was calculated from the average perimeter of the doline itself by the following steps: The average perimeter of the doline was obtained from the calculated perimeter using the longest axis, which was calculated together with the mapped perimeter of the doline. Finally, the partial result was averaged, and the diameter was computed by a known formula for calculating circles. Based on the D/H ratio, the authors divided dolines into four geometrical forms (trunk of cone, hemisphere, cone, cylinder).

A digital terrain model was created from processed and classified LiDAR data. Raw LiDAR data were acquired within the National project for aerial laser scanning of the Slovak Republic (Leitmannová & Kalivoda, 2018) in a low vegetation period, mostly during autumn 2017 and spring 2018 (Source of ALS data: ÚGKK SR). The data were provided in an unclassified point clouds form, with vertically and horizontally aligned flight strips. The average density of all return points was approximately 60 points/m2. The position of the points was primarily determined in the ETRS89 coordinate system, Transverse Mercator projection (TM34, EPSG code 3046) and ellipsoidal heights (ellipsoid GRS80). These data were transformed using the PROJ4 tool (https://proj.org/) into the National position system S-JTSK, realisation JTSK03 (EPSG code 8353) and the National height system Bpv, realisation 1957 (EPSG code 8357). The classification into 9 standard ASPRS LiDAR classes (with great emphasis on the ground class) (ASPRS, 2013) was realized in the software package Trimble INPHO SCOP++ v. 5.6.1 with a robust hierarchical filtering strategy Lidar DTM using a 14-step iteration algorithm. Parameters of the filters and statistical tests were individually set and analysed for selected areas and subareas. The average density of the ground points was 22 points/m2. From the processed ground points, an initial digital terrain model was subsequently created. This model was manually checked, and artefacts (steep local hills or holes) were identified and reclassified as a noisy class. The final digital terrain model was created from final ground points in the Surfer v.16 software using the Kriging interpolation method (default parameters implemented in the software). Grid step was selected to 50 cm due to the large average density of the ground points per m2. Internal cross validation on 10000 points

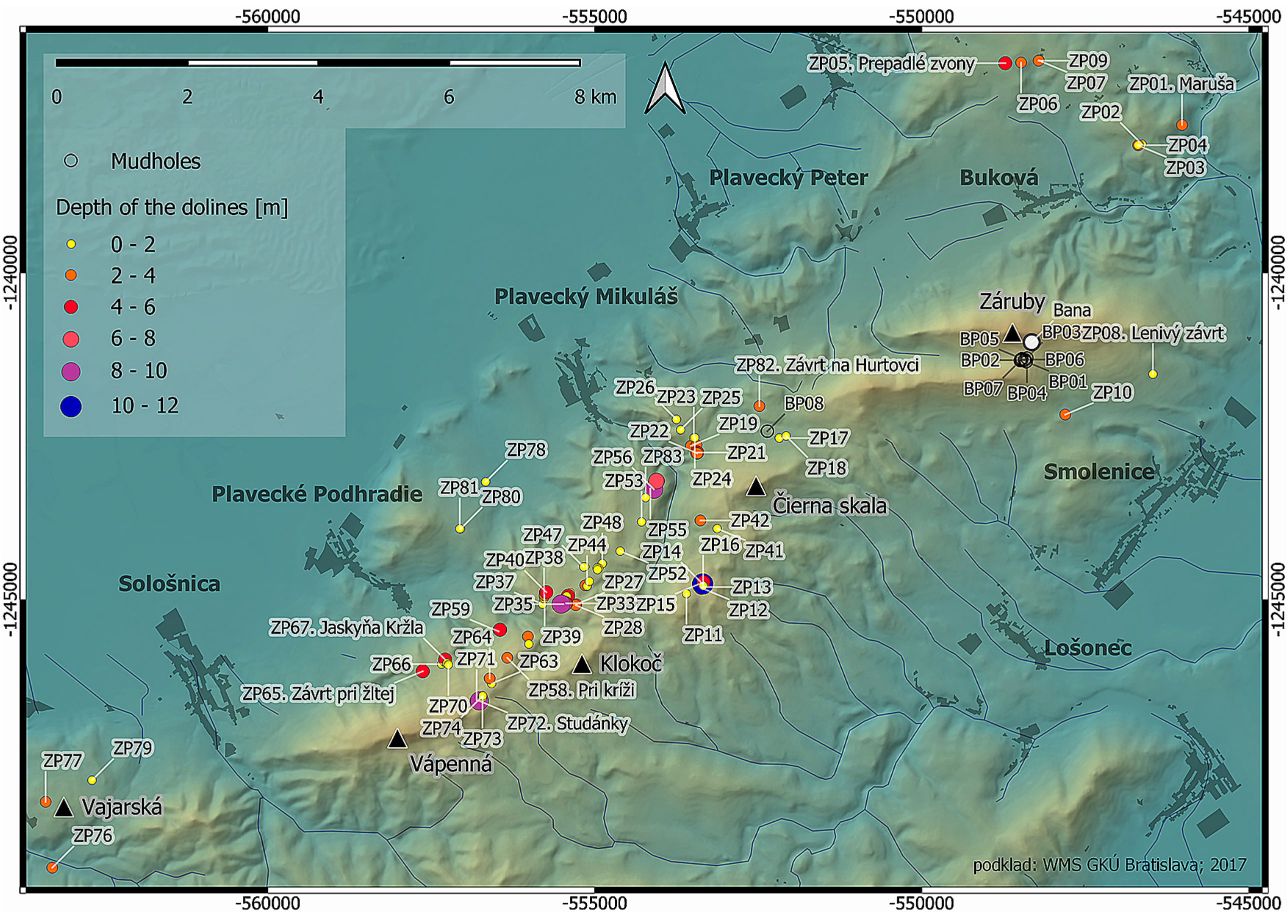


Fig. 3. Location and a depth of the investigated dolines in the Plavecký Karst.

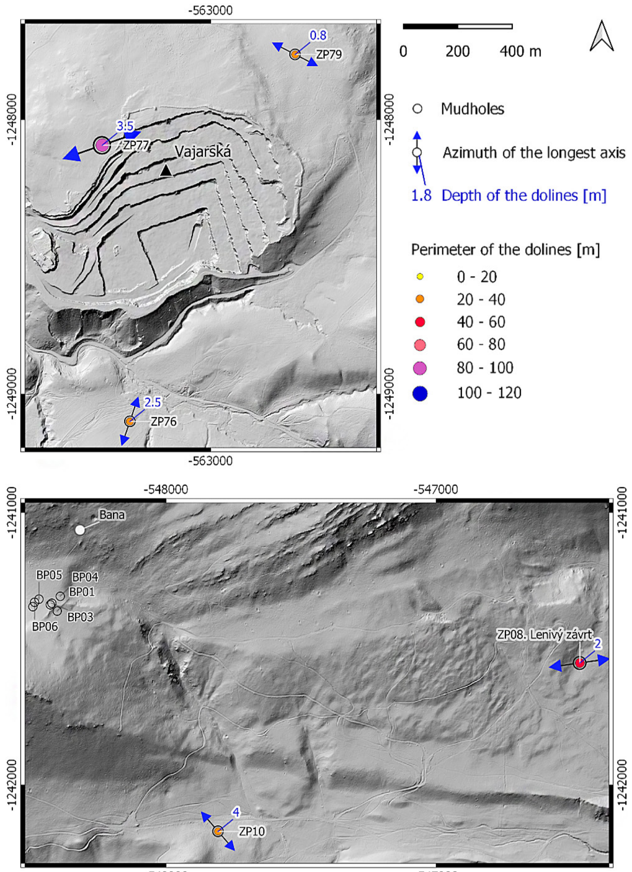


Fig. 4. Location of dolines on Vajarská (ZP76, ZP77, and ZP79) and Záruby (ZP08 and ZP10) sites.

shows very high internal accuracy (standard deviation in vertical direction is below 10 cm) of the final model. This model was used in the search for field depressions, which were subsequently verified by our field research.

The geographical coordinates of the dolines obtained from our fieldwork were projected onto a geographical information system (GIS). Visualizations were made using QGIS Desktop 3.12.1 with GRASS 7.8.2 (QGIS.org, 2020; GRASS Development Team, 2020). The final maps illustrate the four parameters of dolines: a) a perimeter; b) a depth; c) an orientation of the longest axis; d) an overview of location of the dolines with description of the lines.

5. RESULTS

5.1. Localization of dolines

Within the entire Plavecký Karst, altogether, 83 dolines (Fig. 3; Tab. 1) and 8 very shallow karstic depressions (Tab. 2) with muddy bottoms were localised and documented (Fig. 2). For a better understanding of the relationship between the dolines and their rock substrate, the dolines were visualised (Figs. 4–9). Visualisation was based on the digital model of the terrain developed by our team using GIS. The Bana locality, southwest of Záruby (768 m asl.), was also localised and it most likely represents a larger, collapsed, anthropogenically processed underground cavity (Lačný et al., 2019b; Fig. 4). In the proximity of the dolines, anthropogenic depressions, mostly limepits, were also identified at several places. The largest number of limepits was found in the area of Havranica Hill (714 m asl.). However, we excluded anthropogenic

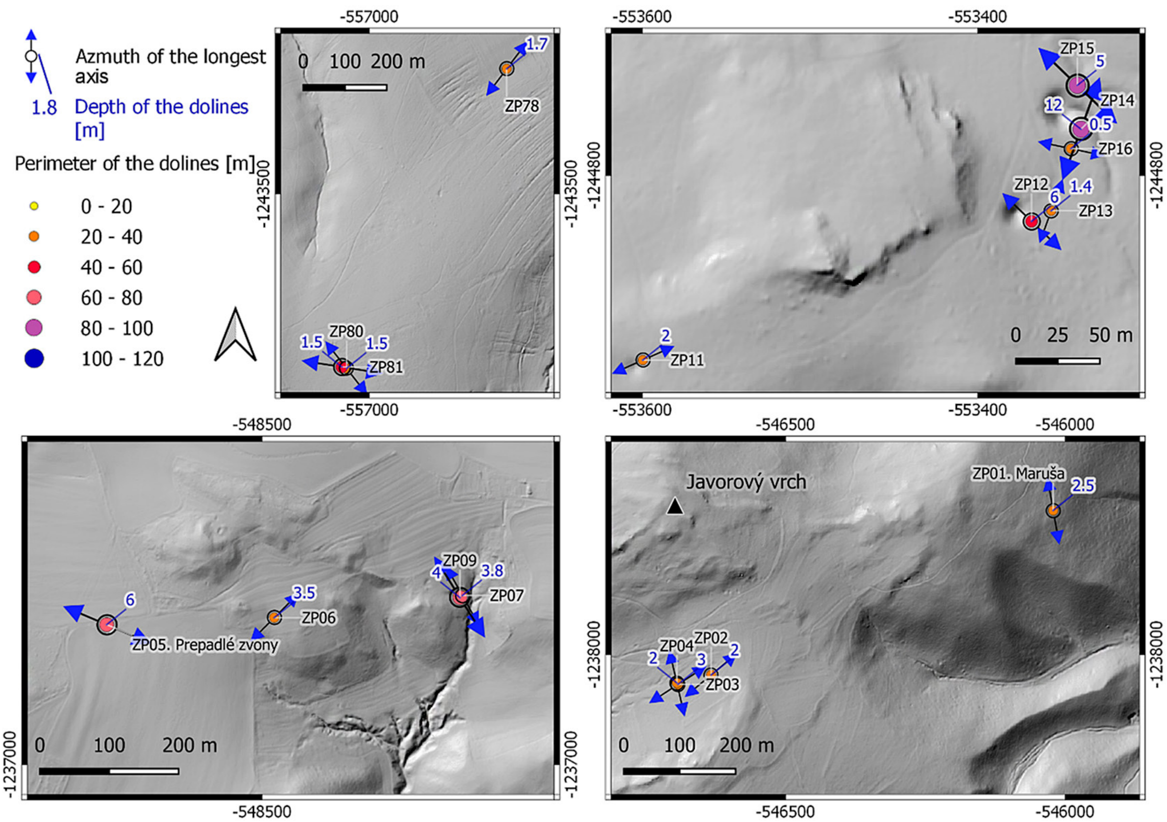


Fig. 5. Location of dolines on sites east of the village of Plavecké Podhradie (ZP78, ZP80, and ZP81), Starý plášť (ZP11–ZP16) and north of the village of Buková (other sites).

Tab. 1. Attributes of the dolines in the Plavecký Karst.

Doline Designation	Latitude	Longitude	Altitude [m asl.]	Perimeter [m]	Depth [m]	Longest Axis [m]	Azimuth of Longest Axis [in degrees]	Inclination [in degrees]	D/H Ratio	Geometrical form	Category
ZP01. Maruša	48.554269	17.422327	380	25	2.5	7.1	350	35	3.01	hemisphere	irregular shape
ZP02	48.551099	17.414463	422	29	2	8.13	50	31	4.34	hemisphere	irregular shape
ZP03	48.550894	17.413685	419	35	3	10.5	57	21	3.61	hemisphere	irregular shape
ZP04	48.550917	17.413653	421	21	2	5.3	347	32	3.00	hemisphere	irregular shape
ZP05. Prepadlé zvony	48.560361	17.384640	429	76	6	23	293	39	3.93	hemisphere	irregular shape
ZP06	48.560663	17.387887	431	34	3.5	8	225	38	2.69	hemisphere	oval shape
ZP07	48.561187	17.391504	415	32	3.8	9.3	331	41	2.56	hemisphere	irregular shape
ZP08	48.519774	17.421316	417	44	2	8.9	82	22	5.73	trunk of cone	irregular shape
ZP09. Lenivý závrt	48.561157	17.391460	402	79	4	23	148	37	6.02	trunk of cone	irregular shape
ZP10	48.513069	17.404060	373	35	4	12.37	139	35	2.94	hemisphere	oval shape
ZP11	48.483470	17.329669	602	34	2	9.72	246	26	5.14	trunk of cone	oval shape
ZP12	48.484416	17.332680	595	52	6	15.9	314	40	2.70	hemisphere	oval shape
ZP13	48.484483	17.332830	592	23	1.4	5.5	20	18	4.58	hemisphere	irregular shape
ZP14	48.484934	17.333004	581	90	10	37	200	50	3.28	hemisphere	irregular shape
ZP15	48.485167	17.332940	583	87	5	29	314	35	5.67	trunk of cone	irregular shape
ZP16	48.484825	17.332939	588	21	0.5	5	282	7	11.68	trunk of cone	irregular shape
ZP17	48.506022	17.345633	443	34	1.7	11.05	269	34	6.43	trunk of cone	irregular shape
ZP18	48.506403	17.346994	449	38	1.1	11.52	280	25	10.73	trunk of cone	irregular shape
ZP19	48.503858	17.327637	458	49	3.5	12.6	14	42	4.03	hemisphere	irregular shape
ZP20	48.503863	17.328787	463	42	2.5	12.76	259	41	5.23	trunk of cone	irregular shape
ZP21	48.503061	17.329053	462	61	5.5	14	249	39	3.04	hemisphere	irregular shape
ZP22	48.502865	17.329115	464	22	2.7	5.6	273	37	2.33	hemisphere	irregular shape
ZP23	48.504914	17.328019	467	33.5	1	12.5	69	14	11.58	trunk of cone	irregular shape
ZP24	48.504956	17.328122	468	20	0.5	5.8	86	10	12.17	trunk of cone	irregular shape
ZP25	48.505819	17.325279	485	23	1.7	6	269	35	3.92	hemisphere	oval shape
ZP26	48.507191	17.324077	494	54	1.4	13.6	135	12	11.00	trunk of cone	irregular shape
ZP27	48.480752	17.307186	533	51	2.2	14.26	255	23	6.93	trunk of cone	irregular shape
ZP28	48.480492	17.307190	533	46	2.2	15.92	302	39	3.82	hemisphere	oval shape
ZP29	48.482039	17.305720	527	61	1.8	20.6	208	21	11.12	trunk of cone	irregular shape
ZP30	48.481806	17.305449	532	27	1.5	8.44	149	21	5.68	trunk of cone	oval shape
ZP31	48.481570	17.305431	533	58	5	15.7	281	41	3.42	hemisphere	irregular shape
ZP32	48.481511	17.305127	535	15	0.5	3.95	289	26	8.72	trunk of cone	round shape
ZP33	48.480520	17.305099	536	57	5.5	16.7	74	38	3.17	hemisphere	oval shape
ZP34	48.480615	17.304838	538	44	5	13.7	209	31	2.77	hemisphere	oval shape
ZP35	48.480442	17.304538	538	80	8	20.5	12.4	35	2.87	hemisphere	oval shape
ZP36	48.480347	17.304255	537	82	10	27	172	39	2.66	hemisphere	irregular shape
ZP37	48.480102	17.300271	532	39	1.5	10.4	17	17	7.60	trunk of cone	oval shape
ZP38	48.480868	17.300453	540	41	1.5	13.9	175	13	8.98	trunk of cone	irregular shape
ZP39	48.481304	17.300506	538	65	3	20	200	24	6.78	trunk of cone	irregular shape
ZP40	48.481781	17.300783	531	44	4.5	12.27	342	37	2.92	hemisphere	irregular shape
ZP41	48.492793	17.334676	538	26	2	7.38	260	33	3.91	hemisphere	oval shape
ZP42	48.493682	17.331067	522	35	3.5	8.6	96	32	2.82	hemisphere	oval shape
ZP43	48.483340	17.308661	541	38	3.5	10.74	280	33	3.26	hemisphere	irregular shape
ZP44	48.483177	17.309069	540	25	1.2	8.16	351	18	6.72	trunk of cone	irregular shape
ZP45	48.483850	17.309546	541	20	0.5	6.4	26	16	12.77	trunk of cone	irregular shape
ZP46	48.485577	17.308187	536	62	1.8	21	234	17	11.32	trunk of cone	irregular shape
ZP47	48.485570	17.307912	535	30	0.5	7.2	114	15	16.75	trunk of cone	irregular shape
ZP48	48.486465	17.311732	531	56	2	17.15	276	20	8.74	trunk of cone	irregular shape

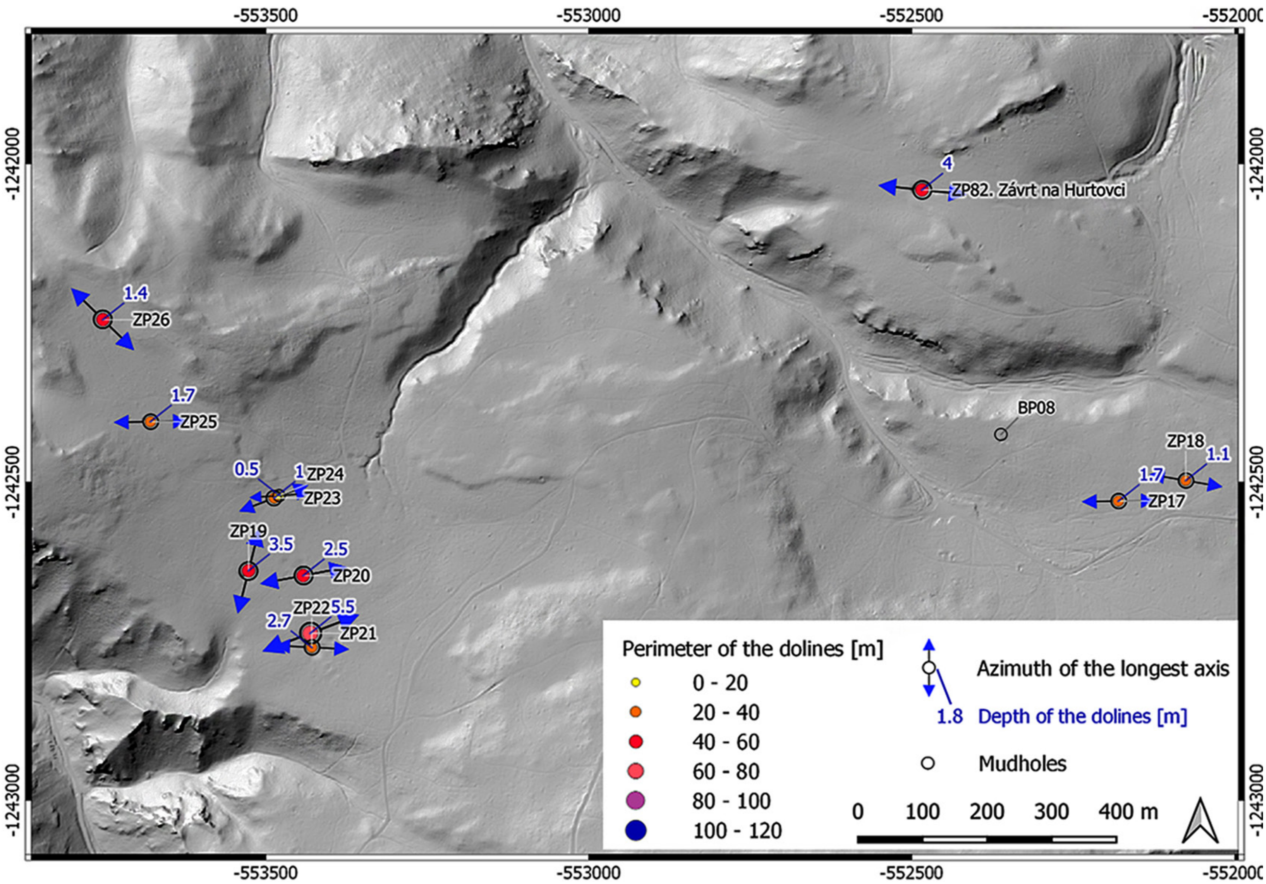
Tab. 1. Attributes of the dolines in the Plavecký Karst (continued).

Doline Designation	Latitude	Longitude	Altitude [m asl.]	Perimeter [m]	Depth [m]	Longest Axis [m]	Azimuth of Longest Axis [in degrees]	Inclination [in degrees]	D/H Ratio	Geometrical form	Category
ZP49	48.485805	17.311201	535	29	2	7.3	176	28	4.13	hemisphere	irregular shape
ZP50	48.485825	17.310883	535	23	2	7.4	200	34	3.68	hemisphere	irregular shape
ZP51	48.485603	17.310897	536	26	2	7	117	33	3.82	hemisphere	irregular shape
ZP52	48.488398	17.315170	544	83	1.5	26.5	117	15	17.64	trunk of cone	irregular shape
ZP53	48.492703	17.318970	494	31	1.7	10.9	111	21	6.11	trunk of cone	irregular shape
ZP54	48.497054	17.320180	468	25	2	9	83	37	4.24	hemisphere	irregular shape
ZP55	48.497302	17.320205	466	30	2.5	9.5	183	35	3.81	hemisphere	irregular shape
ZP56	48.497325	17.320838	466	91	9	25	208	45	3.00	hemisphere	irregular shape
ZP57. Jaskyňa Ofrflané	48.498434	17.321374	452	66	8	19.8	350	46	2.55	hemisphere	irregular shape
ZP58. Pri kríži	48.472280	17.294086	598	113	4	40	319	30	9.50	trunk of cone	irregular shape
ZP59	48.475836	17.291937	520	23	0.5	5.9	261	10	13.22	trunk of cone	oval shape
ZP60	48.475874	17.291805	518	72	4	19.3	91	29	5.28	trunk of cone	irregular shape
ZP61	48.476022	17.292031	515	46	5.6	12.2	257	38	2.40	hemisphere	irregular shape
ZP62	48.475469	17.297897	522	85	4	24	225	32	6.38	trunk of cone	oval shape
ZP63	48.468534	17.291393	612	67	1.5	20	343	18	13.78	trunk of cone	irregular shape
ZP64	48.469224	17.290879	607	92	3	32	313	22	10.21	trunk of cone	irregular shape
ZP65. Závrt pri žltej	48.469291	17.276961	518	50	5	12.8	185	40	2.87	hemisphere	irregular shape
ZP66	48.470522	17.280715	541	16	0.4	6.7	311	10	14.74	trunk of cone	oval shape
ZP67. Jaskyňa Kržla	48.471190	17.281335	514	50	4.5	15.1	284	37	3.45	hemisphere	irregular shape
ZP68	48.470672	17.281718	521	24	2	8.5	335	32	4.03	hemisphere	irregular shape
ZP69	48.470728	17.281768	521	14	0.5	4.6	113	20	9.06	trunk of cone	oval shape
ZP70	48.470520	17.282116	523	18	1.5	6.1	78	30	3.94	hemisphere	oval shape
ZP71	48.466088	17.288644	646	81	3	23	345	25	8.13	trunk of cone	irregular shape
ZP72. Studánky	48.465993	17.289224	647	115	9	39	324	47	4.20	hemisphere	irregular shape
ZP73	48.466429	17.289904	646	29	0.4	9.11	291	12	22.93	trunk of cone	oval shape
ZP74	48.466672	17.289950	643	65	1.5	25	176	18	15.23	trunk of cone	oval shape
ZP75	48.474451	17.297668	577	20	0.6	6	215	12	10.31	trunk of cone	oval shape
ZP76	48.437360	17.204774	337	27	2.5	6.5	199	30	3.02	hemisphere	oval shape
ZP77	48.446278	17.202053	463	98	3.5	29.5	71	32	8.67	trunk of cone	irregular shape
ZP78	48.496067	17.286050	327	31	1.7	9	217	27	5.55	trunk of cone	oval shape
ZP79	48.449872	17.211156	354	35	0.8	11.9	117	17	14.40	trunk of cone	irregular shape
ZP80	48.489283	17.281836	433	38	1.5	13	142	14	8.37	trunk of cone	irregular shape
ZP81	48.489303	17.281678	432	42	1.5	14	279	12	9.12	trunk of cone	irregular shape
ZP82. Závrt na Hurtovci	48.510583	17.342111	447	41	4	15	276	40	3.51	hemisphere	irregular shape
ZP83	48.495833	17.319167	523	30	1.7	7.5	20	25	5.01	trunk of cone	oval shape

depressions, and a morphometric analysis was carried out only in the natural karstic dolines. More such dolines were localised by us north of the village of Buková, occurring on cultivated fields or close to the farmsteads (Fig. 5). Distribution of the dolines is bound to flat terrain features. The largest number of dolines was found on the plateaus with maximum slope inclination of a few degrees (usually up to 3–5°). Therefore, these are not ideal conditions for doline formation in the entire area of the Plavecký Karst. However, there are isolated areas with dolines that do exist, and they are restricted to the north of the village of Buková around the spot heights of Javorový vrch Hill (480 m asl.) and Trnkový

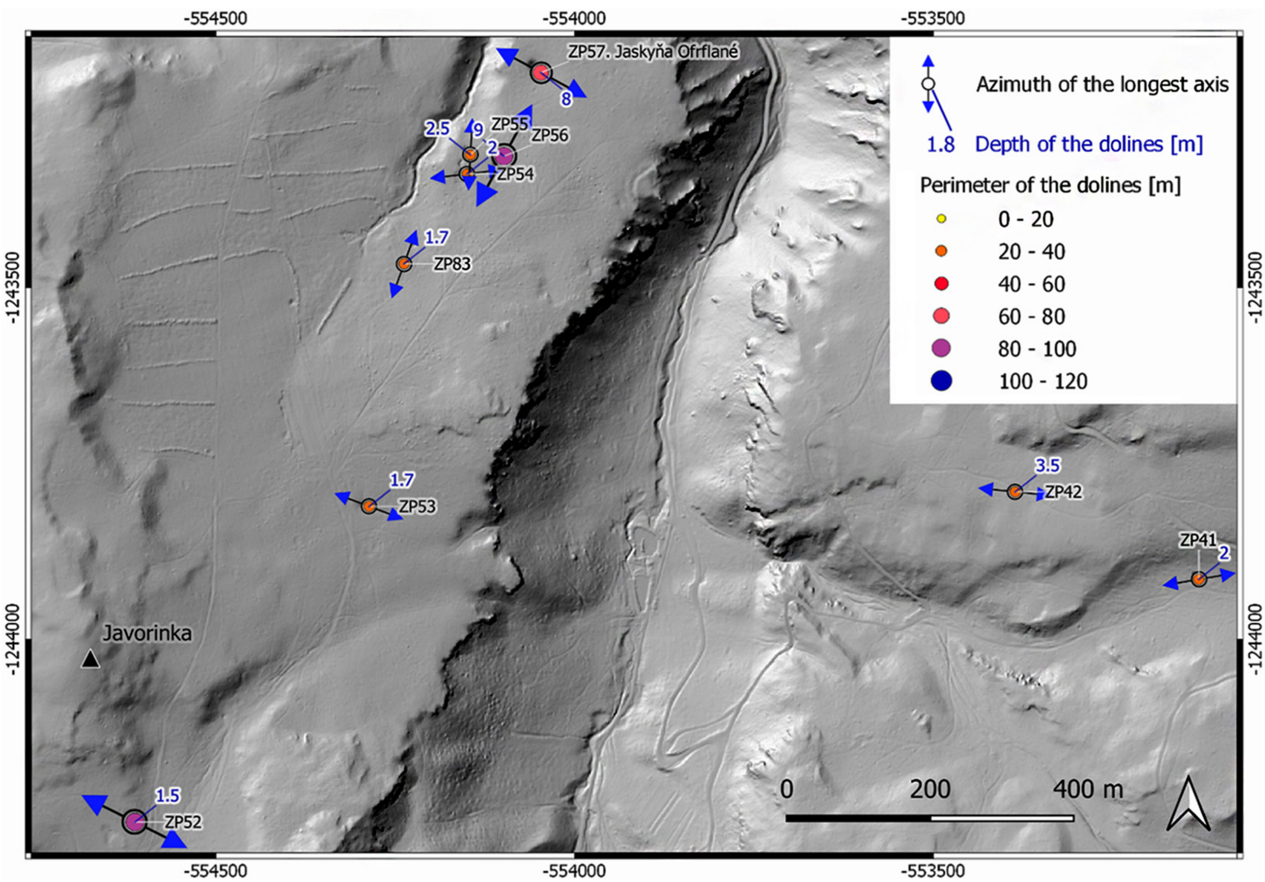
Tab. 2. Shallow depressions with mudholes in the Plavecký Karst.

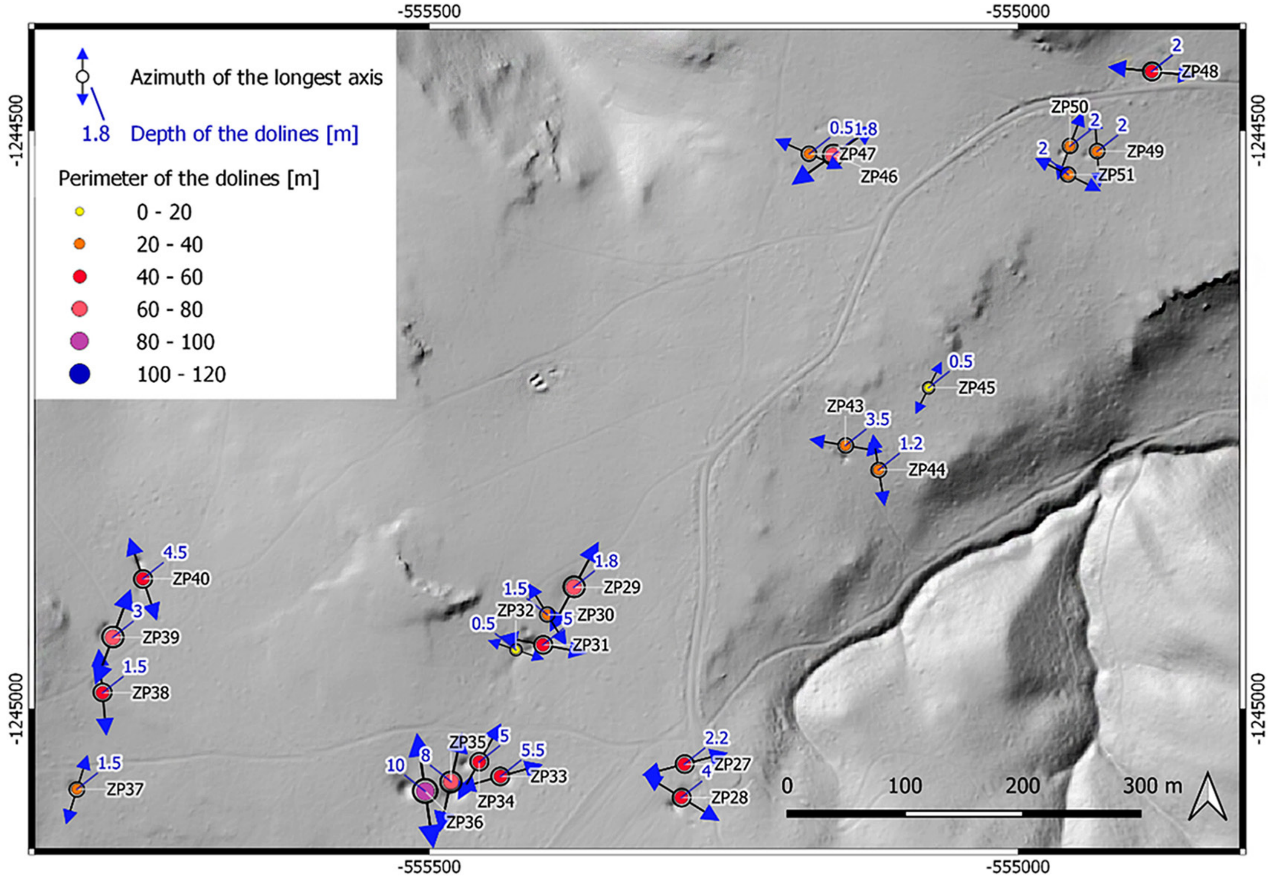
designation	altitude (m)	latitude	longitude	perimeter (m)	depth (m)
BP01	640	48.519791	17.394961	9.5	1
BP02	644	48.519975	17.394586	5	0.5
BP03	644	48.520029	17.394657	22	1.5
BP04	643	48.520285	17.395043	12	0.5
BP05	644	48.520122	17.393993	8	0.5
BP06	645	48.520006	17.39379	19	1
BP07	645	48.519855	17.393723	31	1.2
BP08	427	48.5068	17.343044	36	1.5



▲ **Fig. 6.** Location of dolines at the Kršlenica and Hurtovec sites.

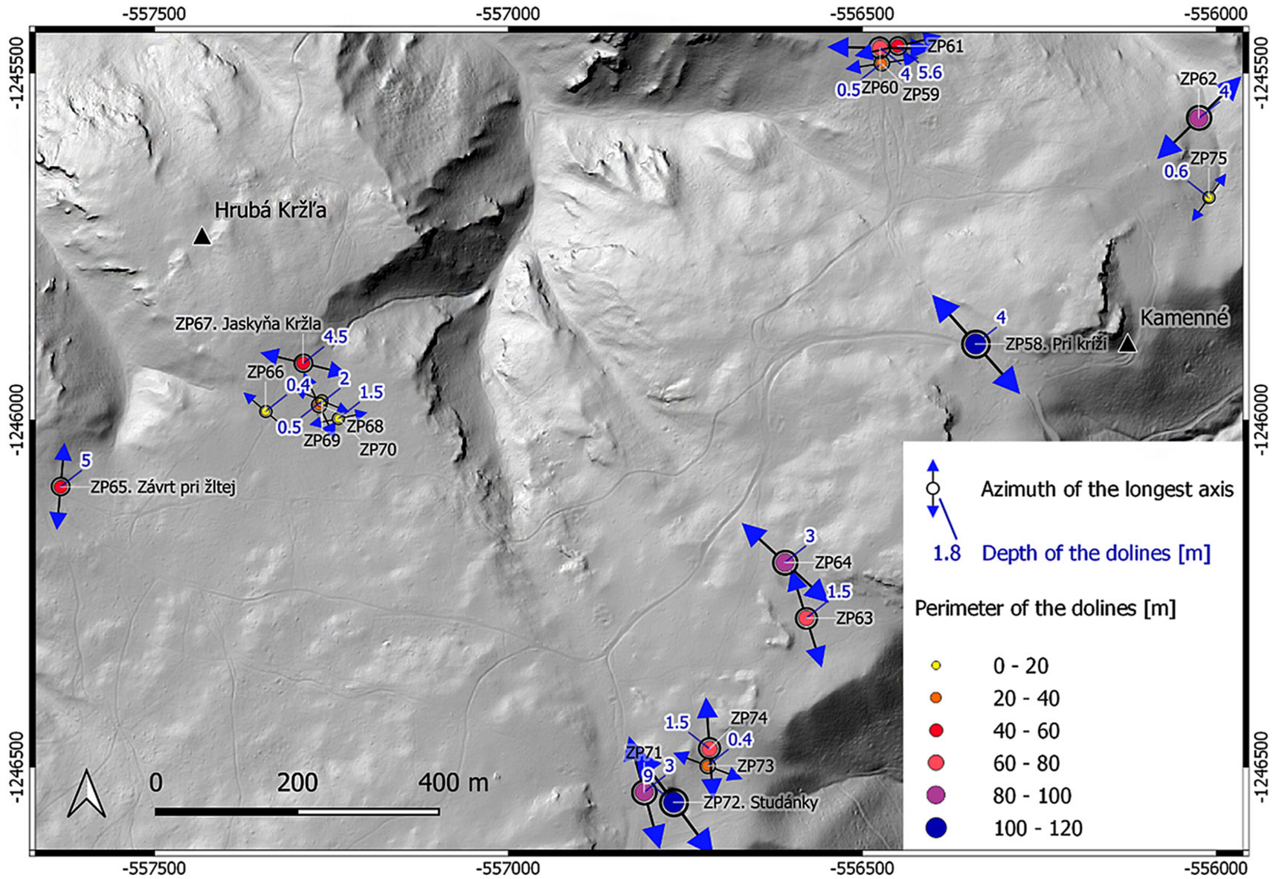
▼ **Fig. 7.** Location of dolines at the Javorinka and Čierna skala sites.





▲ **Fig. 8.** Location of dolines at the the Baborská site.

▼ **Fig. 9.** Location of dolines at the Vápenná and Hrubá Kržľa sites.



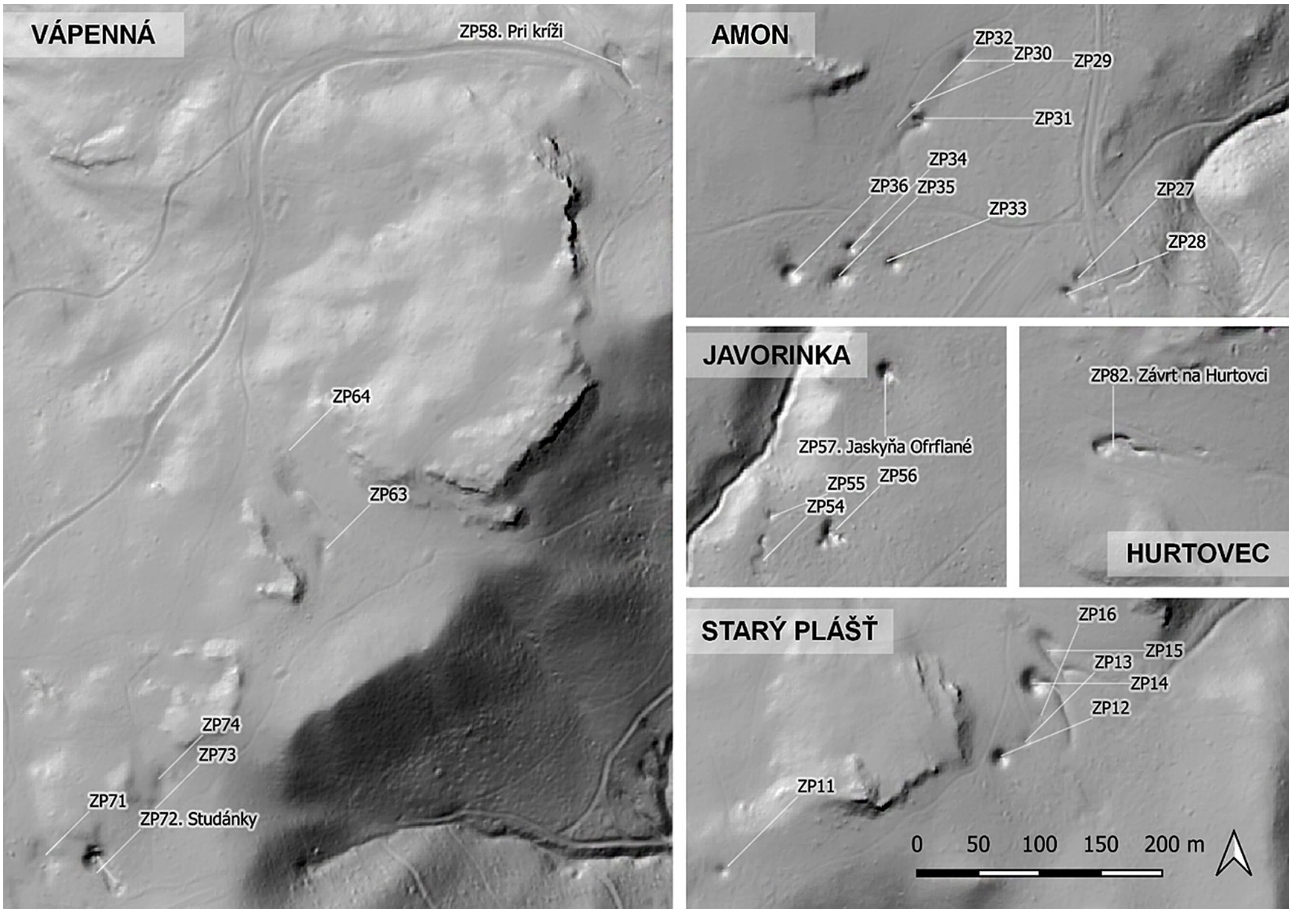


Fig. 10. Digital terrain model with significant dolines.

vrch Hill (453 m asl.) (Fig. 5), and at the Vajarská site (420 m asl.) (Fig. 4). Two dolines and seven mudholes were identified, isolated in the eastern part of the Plavecký Karst in the Saddle of Záruby (625 m asl.), south of Havrania skala (554 m asl.), and in the proximity of Vlčiareň (752 m asl.) (Fig. 4). Otherwise, the dolines were located in a continuous belt from below the north-western slopes of the hill of Vápenná (752 m asl.) to the plateau on Hurtovec (448 m asl.) east of Plavecký Mikuláš (Figs. 5–9). Holes on the Pohanská Plain (495 m asl.) were not suitable for morphometric analysis, since an important ancient fortified settlement occurs there. We are inclined to concur with Šmída (2010), who described them as holes of an unspecified origin. Even if they represented genuine karstic features, they were most likely anthropogenically processed.

Geomorphologically, all dolines are located in the Malé Karpaty geomorphological unit and most are localized in the Pezinské Karpaty subunit (Mazúr & Lukniš, 1978). Their largest number is concentrated in the Biele Hory geomorphological part, which is the central area of the Plavecký Karst with suitable conditions for doline formation. In the geomorphological subunit of the Brezovské Karpaty, where the Plavecký Karst still occurs, we found eight dolines. These landforms were located north of Buková. In the geomorphological part of the Bukovská Brázda Furrow, six dolines were identified. Three of them were located NW of the village of Plavecké Podhradie and a further three in the area of Vajarská (420 m a.s.l.).

5.2. Morphometric analysis of dolines

Several methodologic approaches have been developed, both for characterisation of ideal parameters for geometric shape and for 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). Genetically, most of the dolines of the Plavecký Karst can be considered polygenetic forms, in which the corrosive effects of surface precipitation, sometimes concentrated into inflow lines, are dominated over collapsed weakened ceilings of the caves. Based on the inclination of sidewalls, dolines that are funnel-shaped (41) and kettle-shaped (29) dominate in the Plavecký Karst, whereas cup-shaped dolines (13) are the least represented (following Jakál's division). The documented areal shape of dolines is highly influenced by the interpretation of respective mappers. There was only one ideally round doline (ZP32) in the studied area; 24 dolines were oval in shape, and the rest can be described as irregular (cf. Petrvalská, 2010).

Based on the methodology of Bondesan et al. (1992), the trunk of cone (similar object – plate) and hemisphere (similar object – bowl) dominate as the geometrical forms. Other types (cone, cylinder) are not represented. Shallow forms are located on the plateaus. The geometrical form trunk of cone has 43 dolines and the hemisphere geometrical form contains 40 dolines.

Except for the rock substrate, the shape of the dolines is influenced by surface factors, as well as a variety of shaped deluvial coverage. No less than 13 dolines contained inflow lines, through which the atmospheric fall penetrates below the surface. In this respect, interconnected dolines can also be observed. Most of them represented a group of two dolines; based on their shape, such forms are regarded as "eight-shaped" (ZP39, ZP46, and ZP63). Some dolines can be identified as mother-and-daughter dolines, which are sometimes called parasitic dolines or depressions. The best example is the doline ZP56 on the Javorinka plateau (Fig. 7), which contains three additional parasitic (daughter) dolines (Fig. 10).

The dolines originate on plateaus where the inclinations differ in degrees only. However, there were sites where the dolines were concentrated close to valleys or plateau edges with a higher inclination, although occurrences of dolines on significantly inclined surfaces were rare within the studied area. Such dolines could be related to collapse structures as well (e.g., the Bana locality). The most conspicuous doline of this type was identified in a distinctly cut valley north of Kamenná (618 m asl.). It consisted of a significant depression with a perimeter of 85 m and a depth of 4 m (ZP62) (Fig. 9). There were three indistinct depressions higher in the line.

The size of the measured dolines was relatively heterogeneous. While the largest doline forms dominated on the contact of distinct lithological boundaries – the Ipoltica Group and overlain carbonates – further from the line, "middle-sized" and smaller forms prevailed in the Malé Karpaty karst area. Dolines with a perimeter of 21–50 m and a depth of 1–4 m are the most common (Fig. 11A). The largest perimeters were attained in the dolines ZP72 – Studánky (115 m) (Fig. 12) and ZP58 – Pri kríži (113 m). The situation is similar in the Plavecký Karst as well, especially when the depth of dolines is concerned; many of them were 1–4 m deep (Fig. 11B). Deeper dolines were concentrated in the previously mentioned distinct lithological boundary. The deepest dolines were those at Starý plášť (ZP14 – 10 m deep) and ZP36 with a similar depth, which are located on Amonova lúka (560 m asl.). The latter doline originated on the lithological boundary of Lower Triassic quartzites and overlain dolomitic limestones (Šmída, 2010). The most heterogeneous group of dolines were obtained when the longest axis was taken into account; dolines with the longest axis of 3–16 m were the most common (Fig. 11C).

A visualisation of the dolinesś heights above sea level in ascending order brought some interesting results (Fig. 13). A fitting constellation of geological and geomorphological processes resulted in the largest number of dolines (n = 37) being formed in the heights of 514–544 m asl.

Because the mapping was carried out in the winter months of 2020 onward, thawed surface with vaporization was identified at the locality of Maruša (ZP01) (Fig. 5). In other places, especially where the dolines were connected with the caves (Ofrflané, Studánky, and Kržľa), no air flow nor any thawed doline bottoms were identified.

The dolines occurring in the southernmost part of the Plavecký Karst in the area of Vajarská are also noteworthy (Fig. 4). As mentioned by Šmída (2010), a number of dolines were destroyed by active mining at the Vajarská quarry. In this area, two dolines close to the quarry

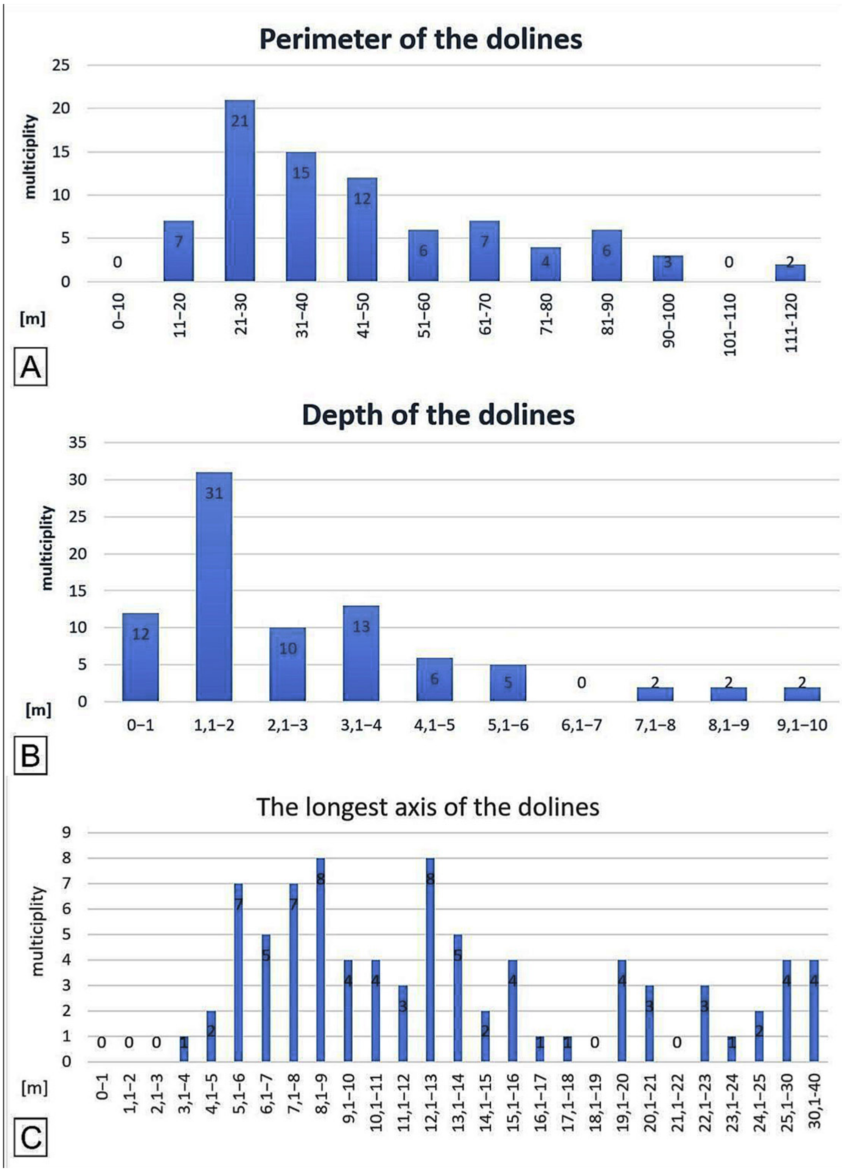


Fig. 11. A – Graph showing the multiplicity of dolines based on their perimeter; B – Graph showing the multiplicity of dolines based on their depth; C – Graph showing the multiplicity of dolines based on their longest axis.

Fig. 12. The largest doline in Plavecký Karst ZP72 – Studánky with a perimeter of 115 m. Photo: M. Velšmid.

were documented – ZP77 (close to the quarry wall) and ZP79 (shallow valley NE of the Vajarská quarry). Depressions localised south of the Woodsman house, Baďura, which is situated at the beginning of the Rohožnícka valley, were especially difficult to evaluate (Fig. 4). For instance, Šmída (l.c.) did not consider them holes of karstic origin, but as limepits. However, Škvarček (1966) considered them dolines. We consider at least one of them to be a potential doline, since it originated at the boundary of karstic and non-karstic rocks that are covered by Quarternary debris.

The value of density of the dolines in the Plavecký Karst is 1,5 dolines per square kilometer. Density in the central part (which contains dolines near Vápenná, Hrubá Kržľa, Amón, Javorinka, Čierna skala, Starý plášť, Kršlnica and Hurtovec) is a little higher - 5,6 dolines per square kilometer, which is more similar to the

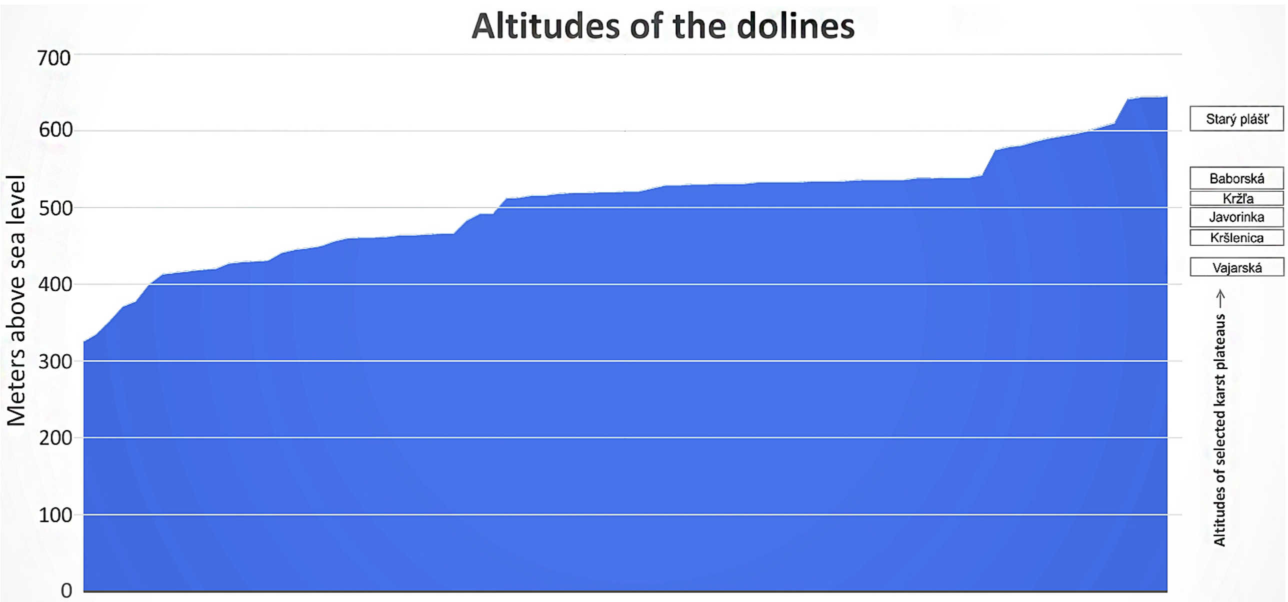


Fig. 13. Graph representing the altitudes of the dolines arranged from the lowest to the highest altitude.

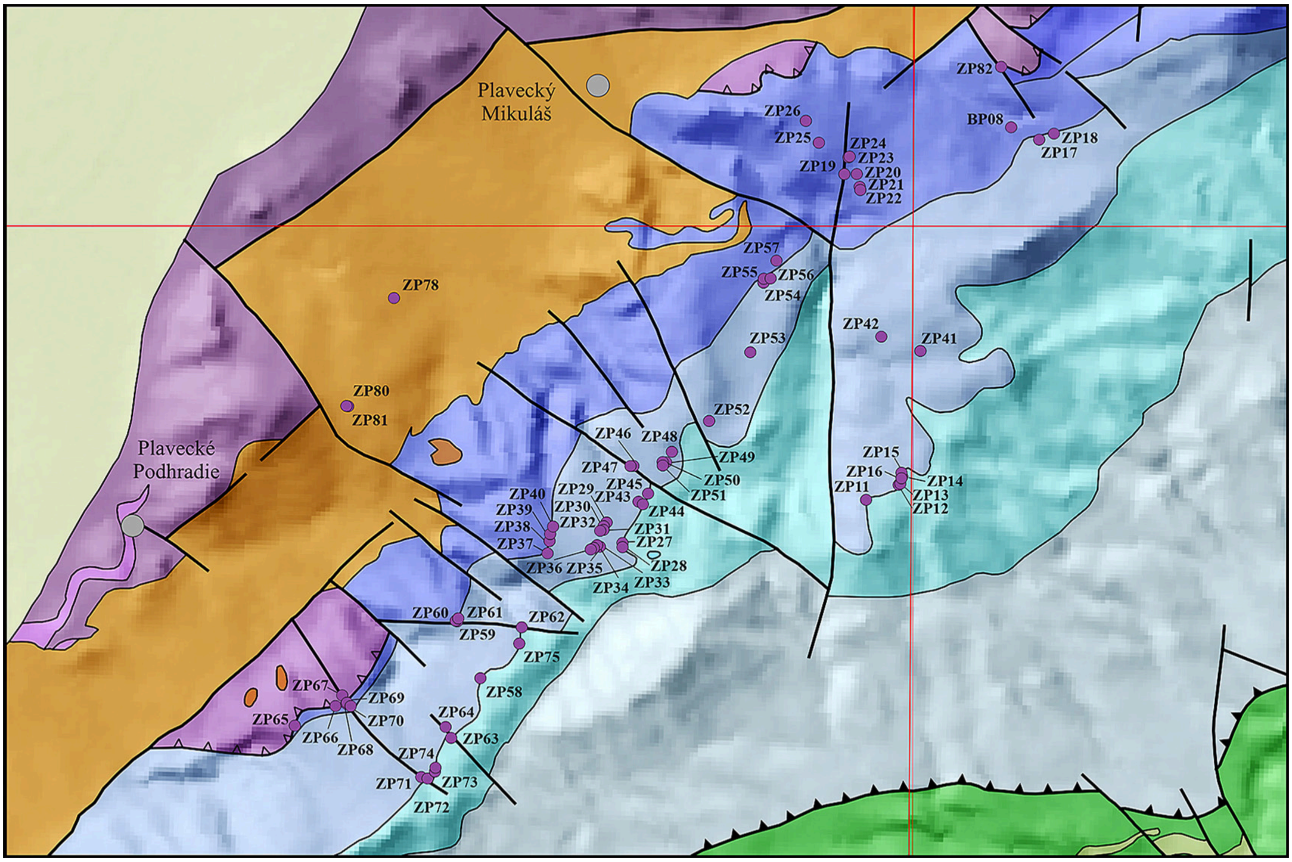


Fig. 14. Schematised tectonic map (a detail) of the Malé Karpaty Mts. with the mapped dolines (according to Mahel' & Cambel, 1972; Polák et al., 2011; modified).

density on the Čachtická plain - 4 dolines per square kilometer (Lačný et al., 2019a). However, in comparison with the Koniart plain - 15 dolines per square kilometer, Plešivecká plain - 45 - 50 dolines per square kilometer or Silická plain - 55 dolines per square kilometer (Hochmuth, 2004) is in our case, a low value.

5.3. Relationship among geological structure and dolines

The dolines are usually concentrated in line structures on karstic plateaus. In the Plavecký Karst, this occurs to a lesser extent and the variability of the disjunctive structures where they originated is different. However, the research clearly shows that dolines, those which are arranged in lines, mimic underlying structures (Figs. 2, 14). Some of these structures are also reflected in landforms, for example, in the form of valleys. For instance, the ZP62, ZP63, and ZP64 dolines (Fig. 9) are connected to valleys, because the orientation of the longest axes of these dolines is parallel to the course of the valley. At the edges of the plateaus, there are dolines formed by the continuation of the dislocation structures by which the valleys are connected (for example the ZP19 doline) (Fig. 6). In contrast, other, indistinct lithological and tectonic structures, which do not clearly appear on the surface, can be identified based on a linear distribution of the dolines.

In terms of spatial and genetic analysis of dolines, the research also includes measurements of the spatial orientation (azimuth) of the longest axis of the dolines. These data are important from the point of view of the genesis of the doline and its link to the subsurface lithological or structural discontinuity, respectively. Based on the spatial analysis, the directions of W–E to NE–SW dominate (Fig. 15). These directions are a combination of several discontinuities on which the dolines were formed.

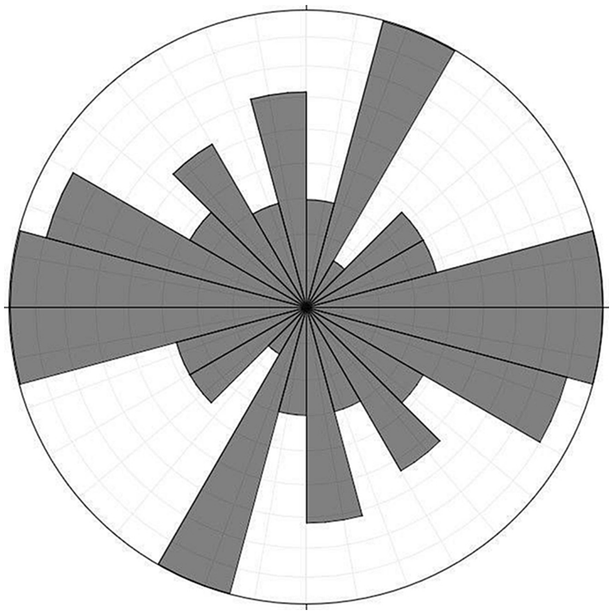


Fig. 15. Rose diagram of measured 83 azimuths of the longest doline axes with 15°class. Max value is 7.23% between the azimuth 111° and 120° with circular variance 0.8329.

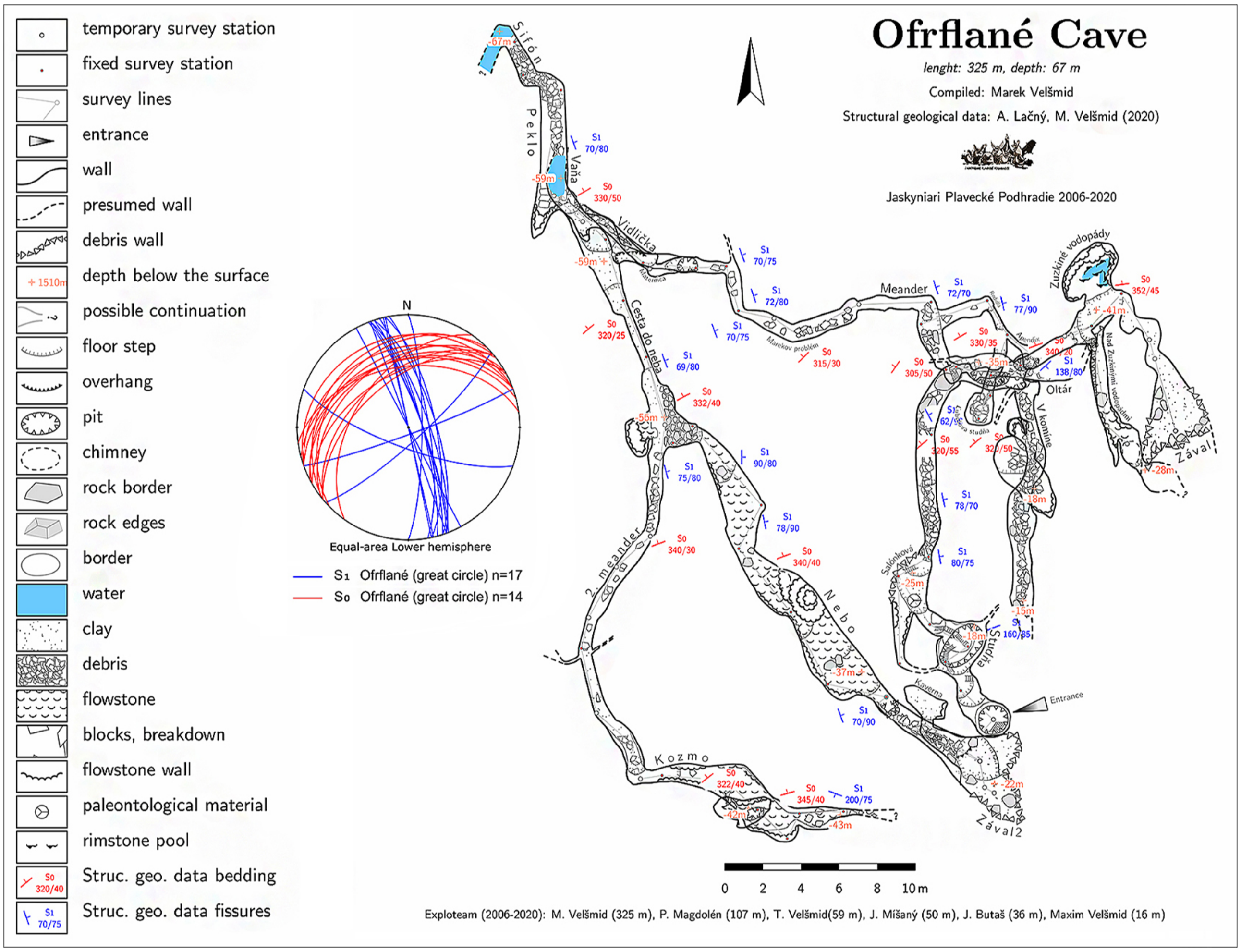


Fig. 16. Map of the Ofrflané Cave.

By comparing the known geological structure, the shape of the relief, our measurements, and origin, the dolines were divided into several categories. Lithological boundaries unequivocally dominate in the Plavecký Karst. In the Veterlín nappe, the majority of dolines were formed at the lithological boundary between the Lower Triassic siliciclastic deposits and Middle Triassic carbonates (Gutenstein Fm. and Ramsau Fm. respectively). This is the area of the largest dolines of the Plavecký Karst, which were formed as distinct ponore dolines (Studánky, Starý Plášť, Pri kríži; Fig. 10) in the central part of the study area (Fig. 14). The second significant lithological boundary where the dolines originated, is formed between the Middle Carnian sandstone and siltstone of the Lunz Member and under- and overlying Upper Carnian and Norian limestone and dolomite generally belonging to the Hauptdolomite – Dachstein facies (e.g., Závrt na Hurtovci doline). Significant dolines were also found in the area of Javorinka, Baborská, Kršlenica, or Kržla (cf. Fig. 14). The third, genetically different dolines were formed along fault structures. In the Veterlín nappe, the dolines are in line with the NW–SE trending faults and seldom with faults of different orientation.

In the Považie nappe, the dolines are generically related to the discontinuities. The most frequent position of the dolines is linked with the generally W–E oriented regionally important faults (ZP02–07 and ZP09) (Fig. 5), which form the boundaries among the Triassic carbonates of the nappe and the Cenozoic sedimentary complexes (especially Upper Palaeogene deposits of the Malé Karpaty Group or Neogene deposits of the Vienna Basin (Fig. 2). Additionally, the dolines were also found in close proximity to the sole of the Považie nappe (ZP65 and ZP66) and at NW–SE trending faults (Bana, ZP67, ZP82). The dolines originated at the NE–SW striking faults (ZP76) and occasionally at the lithological boundaries (for example, ZP01 – Maruša doline). Some of the dolines were also found in the Palaeogene deposits of the Bukovská Brázda Furrow. We assume that the Palaeogene deposits are most likely absent in these places (ZP 78, ZP80, and ZP81).

5.4. The Ofrflané Cave

The link between the dolines as a karstic surface form and the structures underneath could be observed in the northern part of the Javorinka karstic plateau (561 m asl.) (Fig. 7). In this part, the plateau ended abruptly in two distinct valleys: the Mokrá Valley in the eastern part and a distinct unnamed valley in the western part. Both valleys were oriented in a NE–SW direction and originated at significant faults with the same orientation. Several dolines were also identified there. Two of them were represented by significant surface depressions: ZP54 with daughter dolines and ZP57 with an inflow line, where there was an entrance on its bottom to the Ofrflané Cave (Fig. 10). The cave was discovered during the digging works by speleologists from Plavecké Podhradie in 2005. Today, the cave attains a length of 325 m and a depth of 67 m (Fig. 16). It was formed in the dark, muddy limestones of the Guttenstein facies with a transition into the Reifling Limestone. The doline above the cave attained a perimeter of 66 m and a depth of 8 m. The doline was moderately elongated in a NNW–SSE direction (azimuth 350°) in the length of 19.8 m. The inflow line with the length of approximately 12 m entered the doline from the SE. During the field research, we focused on measuring the structural elements of the cave; specifically the planar structural elements related to the cave corridors. Based on their orientation and genetic relationships, they were classified into two categories: Primary bedding S0 was identified with 14 measurements, and fissures S1 contained 17 measurements (Fig. 16). The measured bedding planes S0 consisted of a homogeneous data group with a NW–SE orientation and were 30–50° inclined northeastward. The fissures did not represent such homogeneous grouping, but they held the trend of subverticality (70–90°) with a general NNW–SSE direction. Based on speleogenesis, the formation of the cave corridors was concentrated on both discontinuities, as well as their combination. Underground structures, including the inflow line from the SE direction, corresponded with the prolongation of the doline in the NNW–SSE direction. Interestingly enough, discontinuities of the orientation of the surrounding valleys in the NE–SW direction were not recorded in the cave. Apparently, this orientation was important for the formation of the ZP56 and ZP86 dolines with the longest axis corresponding to this direction. In the line of the same orientation, the ZP54 and ZP55 dolines were also localised.

6. INTERPRETATION AND DISCUSSION

Multidisciplinary morphostructural, geological, and speleological research improve the knowledge of the dolines in the Plavecký Karst. However, there are also several unanswered questions and remarks that deserve additional investigation in the future. Some of them are discussed in the text below.

Significant dolines were not concentrated directly in the valley bottoms, but on their edges (the line of dolines at Javorinka; Fig. 7) or in the continuation of the bottoms on the plateau parts (the line of dolines ZP37–40 at Baborská; Fig. 8). As far as the valleys were concerned, this referred to the dynamics of processes occurring directly in the most active valley parts, where the dolines could often be destroyed or never formed. A similar case of the absence of dolines in a distinct valley was observed in the Hlboká valley of the Čachtice Karst (Lačný et al., 2019a). We have a typical example at one site. The dolines on the Javorinka plateau (ZP53–57 and ZP83; Fig. 7) are an important phenomenon. A steep, eroded valley with a NE–SW azimuth runs parallel with the line of dolines; however, no dolines are observed in the bottom of the valley. The dynamics of the environment are most likely the reason for the absence of the dolines in the valley bottom.

Hydrologically, drainage of waters in the form of valleys generally occurred northwestward. Such development can be expected on the surface in the form of dolines, but also underground. The pattern of dolines is not as distinct as it is, for example, typical for the neighbouring Kuchyňa-Orešany Karst (cf. Lačný & Csibri, 2020) or on the Čachtice Plain (Lačný et al., 2019a). In these karstic areas, the dolines are concentrated in most cases along significant fault boundaries. However, the dolines of the Plavecký Karst are quite often related to the lithological boundaries among the Lower Triassic siliciclastic deposits, Middle Triassic shallow-water carbonates, Upper Triassic siliciclastic sediments, and Upper Triassic carbonates (cf. Figs. 2, 14). The general strike of the lithological boundaries of the Hronic Unit have a NE–SW direction, and the dolines are often linked with such boundaries.

Some of the dolines have a maximum extension axis parallel to the direction of the valley, while others have this axis oriented differently. The reason may be that dolines are usually formed at the intersection of various discontinuities (see the map of the Ofrflané Cave at Fig. 16), which form a network of joints, faults, and bedding planes under the doline. This depends on the significance of the failure and its depth location, as well as on the surface factors that determine the final shape of the doline.

7. CONCLUSION

During the research, 83 dolines and 8 shallow depressions were identified (Tabs. 1, 2). Therefore, 35 more karstic depressions than previously described by Šmída (2010) were found and documented. As far as the occurrences of dolines in the karstic areas of the Malé Karpaty Mts. are concerned, the area of the Plavecký Karst appears to be slightly above average. Based on morphometric analysis, the dolines of the Plavecký karst can be considered typical dolines of the Malé Karpaty Mts. The largest extent being dolines with a circumference from 21 m to 50 m and a depth from 1 to 4 m.

The dolines are concentrated in line structures, and the research clearly shows that the dolines, which are arranged in lines, mimic the underlying structures. In the Plavecký Karst, the lithological boundaries between the siliciclastic deposits and carbonates are the most significant geological structures where the dolines were formed. The faults, however, are less significant, but nonetheless, they are still frequent, geological boundaries where the dolines were formed.

As for the Ofrflané Cave, its parts that are known to date suggest the development of nearly parallel corridors, which cross the corridors of the perpendicular orientation. Based on the evolution of the underground spaces (vertical shafts ended with roof falls), it can be postulated that more of these parallel structures were once, and still related to the surface, through which atmospheric precipitation is drained into the underground. Specifically, the roof drops in the upper parts of the corridors close to the surface, which suggests that it is only a matter of time when the corrosion will weaken the caved-in parts once more, resulting in the formation of a surface depression. Alternatively, the doline itself could be destroyed due to the roof drop of the respective cave part and the subsequent cover of deluvial sediments. These processes may occur within the next tens of hundreds of years, especially when smaller forms are concerned.

Acknowledgement: The geological and geomorphological research was carried out within the framework of the scientific grant project APVV-16-0146, VEGA 2/0100/20, and the Plan of main tasks of the State Nature Conservation of the Slovak Republic for 2020. Special thanks to our colleagues Michaela Galová, Peter Puchala, and Richard Zipser from the Little Carpathians Protected Landscape Area for help with the field research. We thank the editor and reviewers for their valuable advice and comments.

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