Glacial geomorphology and Pleistocene glacier reconstruction in the Demänovská Valley, Low Tatra Mountains, Slovakia

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Abstract: In the Western Carpathians, clear evidence of the Pleistocene glaciations only occurs in two mountain massifs – the Tatra and Low Tatra Mountains. The Low Tatra Mountains (2043 m a.s.l.), contrary to the higher and more strongly glaciated Tatra Mountains (2654 m a.s.l.), have previously been much less attractive for scientific research. Hence, in these mountains both glacial landforms and chronology, together with a detailed reconstruction of glacier geometry and resulted equilibrium line altitude (ELA), are poorly documented. The aim of this paper is to characterize the glacial relief and reconstruction of geometry and ELA of the Zadná voda glacier in the Demänovská Valley system which belongs to the category of the largest Pleistocene glaciers on the northern slope of the Low Tatra Mountains. The mapping results show that a freshly shaped, massive terminal moraine of maximal ice extent (MIE, likely formed during the global Last Glacial Maximum – LGM) occurs 4.3 km distance down-valley from the glacial cirque backwalls. There is no evidence of deposits from older glaciations beyond the terminal moraine down the valley. The terminal zone of the MIE features a fresh morainic landscape with hummocky topography with kettle hollows and the only known morainic lake in the Low Tatra Mountains – Vrbické pleso. During the MIE, the Zadná voda glacier covered 7 km^2 of the area and featured a mean thickness of 48 m. The ELA of this glacier was 1433 m, determined by the area-altitude balance ratio (AABR) 1.6 method, which is a similar value to the LGM ELA calculated in the Western Tatra Mountains. The recessional stages were only recognized in the cirques area, where one or two generations of debris-covered glaciers and rock glaciers mark the final deglaciation of the study area.

Keywords: Low Tatra Mountains, glacier reconstruction, ELA (equilibrium line altitude), glacial cirques, rock glaciers, LGM (Last Glacial Maximum)

INTRODUCTION

In the Carpathians, there are no present-day glaciers, but traces of Pleistocene glaciations can be found in more than 30 mountains massifs (Pawłowski 1936, Kłapyta et al. 2022, Urdea et al. 2022). In the Western Carpathians, evidence of the valley-type glaciation during the Pleistocene only occurs in two mountain massifs – the Tatra and Low Tatra Mountains (Fig. 1). The Tatra Mountains are the highest (Gerlachovský štít, 2654 m a.s.l.) and northernmost located. This massif is the coldest and features one of the best-developed glacial landscapes in the entire Carpathian arc. Since the discovery of traces of Pleistocene glaciations in the Tatras (Zejszner [Zeuschner] 1856), these mountains have been the focus of the attention of researchers, resulting in significant advances in knowledge about glacial morphology and glacial chronology (Kłapyta & Zasadni 2017/2018). During the Last Glacial Maximum (Clark et al. 2009), the largest glaciers in the Tatras reached over 10 km in length and were up to 400 m thick, often expanding beyond the mountain front as a piedmont glacier (Zasadni & Kłapyta 2014, Makos et al. 2018, Zasadni et al. 2021). Glacier erosion has significantly transformed the massif, creating a well-developed alpine landscape with deeply incised glacial troughs, compound and staircase glacial cirques with common overdeepening basins, filled in the present-day with lakes. There are also glacial thresholds up to 400 m high and the advanced stage of glacier backward erosion has transformed ridges into sharp arêtes (Lukniš 1973, Klimaszewski 1988, Zasadni & Kłapyta 2014, Kłapyta et al. 2016). To date, the glacial chronology and postglacial landscape evolution are constrained by more than 300 cosmogenic exposure ages (summarized in Kłapyta & Zasadni 2017/2018), with well-defined LGM glacier expansion (26–18 ka) (Engel et al. 2015, 2017, Makos et al. 2013a, 2014, 2016, 2018) and its several recessional stages until the Younger Dryas (Engel et al. 2015, Makos et al. 2018, Zasadni et al. 2020). Considerable effort has been expended in the development of 3D surface reconstructions of glaciers (Makos & Nowacki 2009, Zasadni & Kłapyta 2014) and paleoclimate interpretations of glacial landforms and rock glaciers (Dzierżek et al. 1986, Kotarba 1988), including the estimation of the former equilibrium line altitude of glaciers (Makos et al. 2014, 2018, Engel et al. 2015, 2017, Zasadni & Kłapyta 2016, Zasadni et al. 2020).

In the much lower Low Tatra Mountains (Ďumbier, 2043 m a.s.l.), the degree of glacial imprint on the landscape and the inventory of glacial landforms are less well developed and represented. As a consequence, this massif has been less attractive for researchers and knowledge about glacial geomorphology is much less advanced in comparison to the Tatras (Vitásek 1924, Lukniš 1964, Gajdoš & Klaučo 2010, Gajdoš & Anstead 2013). Glaciation in the Low Tatars was N-S asymmetric with most of the glaciers located on the northern slope of the massif in the highest Ďumbier group (Lukniš 1964). The Low Tatras glaciers were also relatively small, with a maximum length ranging between ~4–5 km (Lukniš 1964).

The traces of the Pleistocene glaciers in this massif were first described by Roth (1885), who indicated glacial morphology landforms in the Bystrá Valley and Ludárova Valley (on the northern slopes of the Low Tatra Mountains). Since then, maximal moraines have been mapped by many authors, but there are still doubts about the extent of the glaciers in the individual valleys due to inaccurate mapping and the degradation of post-glacial forms (Volko-Starohorský 1943, Louček et al. 1960, Lukniš 1964, Droppa 1972, Škvarček 1980, 1986). General pictures of MIE in the entire massif have been presented by Vitásek (1924), Louček et al. (1960) and Lukniš (1964, 1972). However, individual reconstructions differ from each other by several hundred meters in terms of the length of glaciers. This is exemplified by the variety of glacier extent presented for the Demänovská Valley (Fig. 2). The description of glacial deposits in the Low Tatra Mountains was also presented by Lukniš & Plesník (1961), Mazúr & Kvitkovič (1980), Mazúr et al. (1980, 2002), Halouzka et al. (1997), Maglay & Pristaš (2002), and Maglay et al. (2009, 2011). The problem of glaciation in the Low Tatra Mountains was reviewed by Gajdoš & Klaučo (2010) and Gajdoš & Anstead (2013). Thus far, no attempts have been made to produce a detailed reconstruction of the 3D ice surface or an ELA reconstruction based on a modern approach in the Low Tatras. The ELA of several glaciers on the northern slope of Mt. Ďumbier group was estimated in the range 1410–1460 m a.s.l. (average of 1430 m) by Vitásek (1924). These ELA estimates use the simple Höfer method, which is considered too inaccurate today as it is strongly sensitive to glacial hypsometry (Benn & Lehmkhul 2000).

Similarly, there is still relatively little knowledge on the number, extent and chronology of post-LGM recessional stages in the massif. Nemčok & Mahr (1974) recognized large relict rock glaciers in the Demänovská Valley glacial cirques using an interpretation of aerial images. It should be emphasized that this was the first description of rock glaciers in the Carpathians.

The aim of this paper is to characterize the glacial land system: cirques, maximal and recessional moraines/rock glaciers, and document the glacial morphology in the western part of the Demänovská Valley (Zadná voda Stream valley), based on detailed mapping and analysis of a high-resolution digital elevation model (DEM), the reconstruction of the geometry and equilibrium line altitude (ELA) of this glacier and the determination the stages of glacial recession. In the study, the 3D ice-surface geometry of the Low Tatras Pleistocene glacier is presented for the first time together with an estimation of glacier ELA during the MIE, using the modern area-altitude balance ratio method (AABR 1.6), to compare the "degree of glaciation" to other glaciated massifs during the LGM.

STUDY AREA

The Low Tatra Mountains are located within the central part of the Western Carpathians, south of the Tatra Mountains (Fig. 1). The main ridge stretches latitudinally at a distance of 100 km from Revúca Valley on the west to Hnilec Valley to the east. It culminates in the Mt. Ďumbier (2045 m a.s.l.) group in the west, and the Mt. Kráľova hoľa (1946 m a.s.l.) group in the east. The highest parts of the massif are built with crystalline rocks, dominated by granodiorites, and to a lesser extent – tonalites and granites (Kettner 1927, Biely et al. 1992). Granites predominate on the southern slopes of the Mt. Ďumbier group, while mainly granodiorites of the Ďumbier type with higher biotite content occur on the northern slopes (Biely et al. 1992).

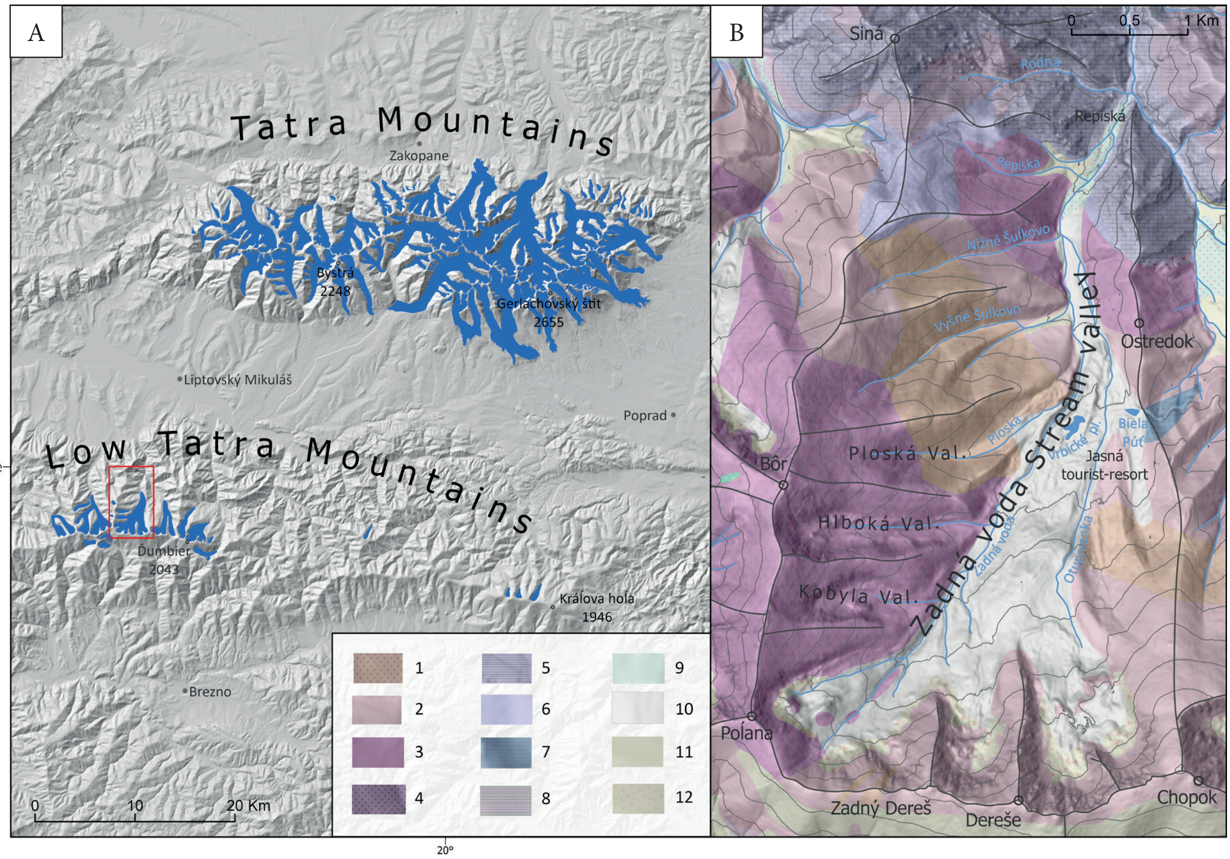

Fig. 1. *Study area: A) location of the Zadná voda Stream valley (red rectangle) in the context of glaciated massifs of the Western Carpathians; the map shows LGM glacier extent in the Tatra Mountains (Zasadni & Kłapyta 2014) and the Low Tatra Mountains (Lukniš 1964); B) geological map of the Zadná voda Stream valley (based on Biely et al. 1992): 1 – leucocratic granite; 2 – biotite tonalites and granodiorites of Ďumbier types; 3 – biotite granodiorites with K-feldspar; 4 – dolomites and breccias; 5 – Gutenstein Formation: dark gray and black limestones; 6 – Lúžňany Formation: light gray, pink and red quartzites, quartz sandstones, arkosic sandstones and conglomerates; 7 – Carpathian Keuper: quartz sandstones, arkoses, conglomerates, dolomites; 8 – Ramsau dolomites; 9 – fluvioglacial deposits; 10 – glacial drift; 11 – deluvial sediments; 12 – talus and debris flow deposits*

The Zadná voda Stream valley is the western part of the Demänovská Valley system, located on the northern slope of the Low Tatra Mountains. The valley is 15 km long and ranges in elevation from 720 m a.s.l. to 2024 m a.s.l. at the Chopok summit. The middle and upper part of the valley are cut entirely in the Ďumbier type granodiorites. In the study area the only natural, glacial-origin lake of the Low Tatra Mountains is to be found – Vrbické pleso (Volko-Starohorský 1943, Louček et al. 1960).

The lake has an area of 0.56 ha, is 8 m in depth and is located in the central part of the valley, near to the Jasná tourist-resort, at an elevation of 1115 m a.s.l.

Among the first descriptions of the postglacial relief in the study area were provided by Roth (1885) and Sawicki (1910). Most previous studies have estimated the extent of the Zadná voda glacier to be 5–6 km long. The shorter extent (4–4.5 km) was proposed by Vitásek (1924) and Lukniš (1964) on the base of distinct moraines located 900 m down the valley from the Vrbické pleso (Fig. 2). According to the two earliest studies (Vitásek 1924, Volko-Starohorský 1943) the Zadná voda glacier was fed by two tributaries from the Kobylá and Hlboká cirques (Fig. 2). In contrast, more recent studies (Lukniš 1964, Halouzka et al, 1997, Maglay et al. 2009) largely ignore the presence of glaciers in these cirques (Fig. 2).

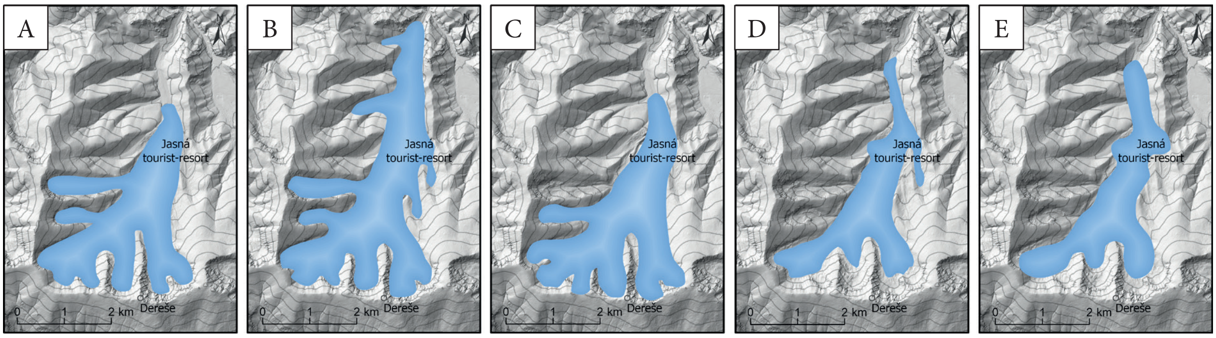

Fig. 2. *Extent of the Zadná voda glacier during the LGM according to the previous studies: A) Vitáshek (1924); B) Volko-Starohorský (1943); C) Lukniš (1964); D) Halouzska et al. (1997); E) Maglay et al. (2009)*

METHODS

Geomorphological mapping

The spatial distribution of glacial landforms and sediments was mapped through field-based and remote-sensing approaches (Chandler et al. 2018). Landform delineation was conducted with the use of a high resolution (1 m) digital elevation model (DEM) (source: ÚGKK SR, geoportal.sk) and the analysis of aerial orthoimages (Google Earth), orthophotomaps (geoportal.sk), particularly useful for interpretation of landforms located above the tree line (ca. 1450 m a.s.l.) in glacial cirques. The extent of the maximum moraines was mapped in detail with a GPS receiver to trace the distribution of glacial sediment cover and single glacial boulders in a densely forested area.

In the zone of terminal moraines, particular attention was paid to discerning the difference in morphology and landform preservation, which is the key feature in distinguishing fresh, young LGM moraines from degraded, older pre-LGM moraines in the Tatra Mountains (Zasadni & Kłapyta 2014, Zasadni et al. 2021).

The stratigraphic position of the recessional moraines and rock glacier fronts is determined by their relative distance between maximum moraines and cirque headwalls (Palacios et al. 2020). In this study, both the horizontal and vertical distance is taken into account.

$$D3D = \sqrt{L^2 + H^2},$$

where: $D3D$ is the 3D distance, L is the distance between the given moraine/rock glacier front and the foot of the cirque headwall, H is the elevation difference between the given moraine/rock glacier and the cirque headwall.

Cirque morphometry

Glacial cirques were identified using the definition of Evans & Cox (1974). The cirque crest and cirque floor were drawn in the GIS using a slope map and contour lines generated the base of the DEM. The boundary between the cirque floor and headwall was drawn at a gradient of about 27° (Mîndrescu & Evans 2014). Basic morphometric parameters of both cirque size (length, width, cirque / bottom area) and shape (maximum and minimum cirque slope) were measured using a 25 m DEM. Additionally, the maximum elevation of cirque crests were determined, together with the minimum and maximum elevation of the cirque floor. The difference between cirque floor and cirque crest elevation herein served as a measure of vertical cirque relief. The median aspect of the cirque axis was measured in the outward direction from the headwall to the threshold along the line dividing the cirque area into two halves. Cirque development was classified using five qualitative grades according to Evans & Cox (1995) and Mîndrescu & Evans (2014). Cirque floor status was estimated using five qualitative categories: major rock basin lake, major bog, minor lake / bog, drift, and outsloping (Mîndrescu & Evans 2014). The vector of the mean aspect of glacial cirques (central tendency) and strength of asymmetry (the degree of concentration of directions around the mean) was plotted as a sum of lines with appropriate directions and lengths proportional to the numbers at a given aspect in a clockwise order. Connecting the lines, the start and the end of points served as the resultant of the vector, giving the mean direction and vector strength (Evans 2021). Previous analyzes used the tenth percentile (P10) of the lowest floor elevation to exclude outliers and extremes, and to estimate the lowest ELA for the maximum glaciation in the given area (Federici & Spagnolo 2004, Mîndrescu & Evans 2014, Kłapyta et al. 2021a, 2021b), and comparison the results with AABR ELA. In the case of the Zadná voda Stream valley, the number of cirques does not allow the P10 method to be applied. Therefore, the P20 method was used, considering the 20^{th} percentile of the cirque floor elevation.

Reconstruction of glacial geometry and ELA

The 3D surface position was reconstructed in a GIS environment based on the mapped distribution of the landforms of glacial accumulation (frontal and lateral moraines, scattered erratic boulders and glacial till covers) and erosional features (trimlines) (Benn et al. 2005). Ice thickness was assessed along the flowline using glacier profile models (Benn & Hulton 2010) provided in the Pellitero et al. (2015) toolbox with the use of 50–100 kPa basal shear stress values (Cuffey & Paterson 2010). To calculate the ELA of the glacier, the area altitude balance ratio – AABR (Furbish & Andrews 1984, Osmaston 2005, Rea 2009, Pellitero et al. 2015) with a ratio of 1.6 was used. This value was recently applied in the Carpathians (Zasadni et al. 2020, Kłapyta et al. 2021a, 2021b), and in the Alps (Le Roy et al. 2017, Federici et al. 2017, Scotti et al. 2017). To account for the errors in the ELA calculation, a range of AABR values from ~1.0 to ~3.0 (Rea 2009) was considered. The basic morphometric and hypsometric parameters were calculated: length, aspect, area, maximum and average ice thickness, minimum and maximum, median (accumulation-area ratio – AAR 0.5) and mean elevation (AABR 1) (Zasadni et al. 2020).

The upper parts of rock glaciers have a similar paleoenvironmental significance. A moraines and rock glaciers do not form until below the ELA, thus the ELA must be above the highest frontal or lateral moraines (Haeberli 1985, Humlum 1988, Benn & Lehmkuhl 2000). The RILA (rock glacier initiation line altitude), defined by Humlum (1988, 2000), represents the altitude from which the rock glacier creeps out from the slope above. The value of RILA is therefore the minimum ELA value for the recessional stages.

RESULTS

Glacial cirques

There are five cirques in the upper part of the Zadná voda Stream valley: Veľký Dereš, Medzi Veľkým a Zadným Derešem, Poľana, Kobylá and Hlboká (Figs. 3, 4) The two larger ones, Veľký Dereš (Dereše E and Dereše W) and Poľana (Zadný Dereš, Sedlo Poľany, Solisko) are similar to complex cirques, while the remaining three are simple ones. All cirques were classified to the 2^{nd} quality class according to Evans & Cox (1995) and Mindrescu & Evans (2014) (Tab. 1).

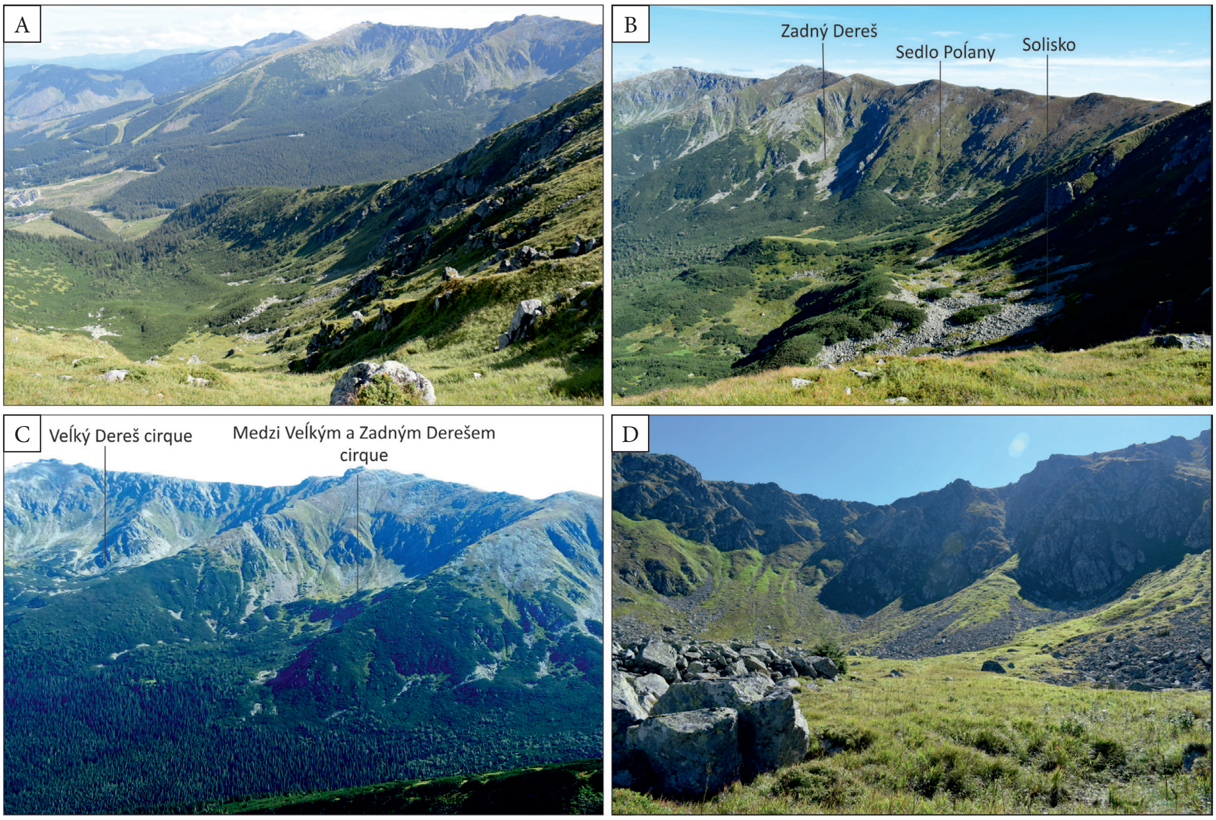

Fig. 3. *Glacial cirques in the Zadná voda Stream valley: A) Hlboká cirque; B) Poľana cirque: Zadný Dereš, Sedlo Poľany and Solisko; in the foreground is talus rock glacier of Solisko; C) Veľký Dereš cirque and Medzi Veľkým a Zadným Derešem cirque; D) cirque floor with talus sediments in the Veľký Dereš cirque*

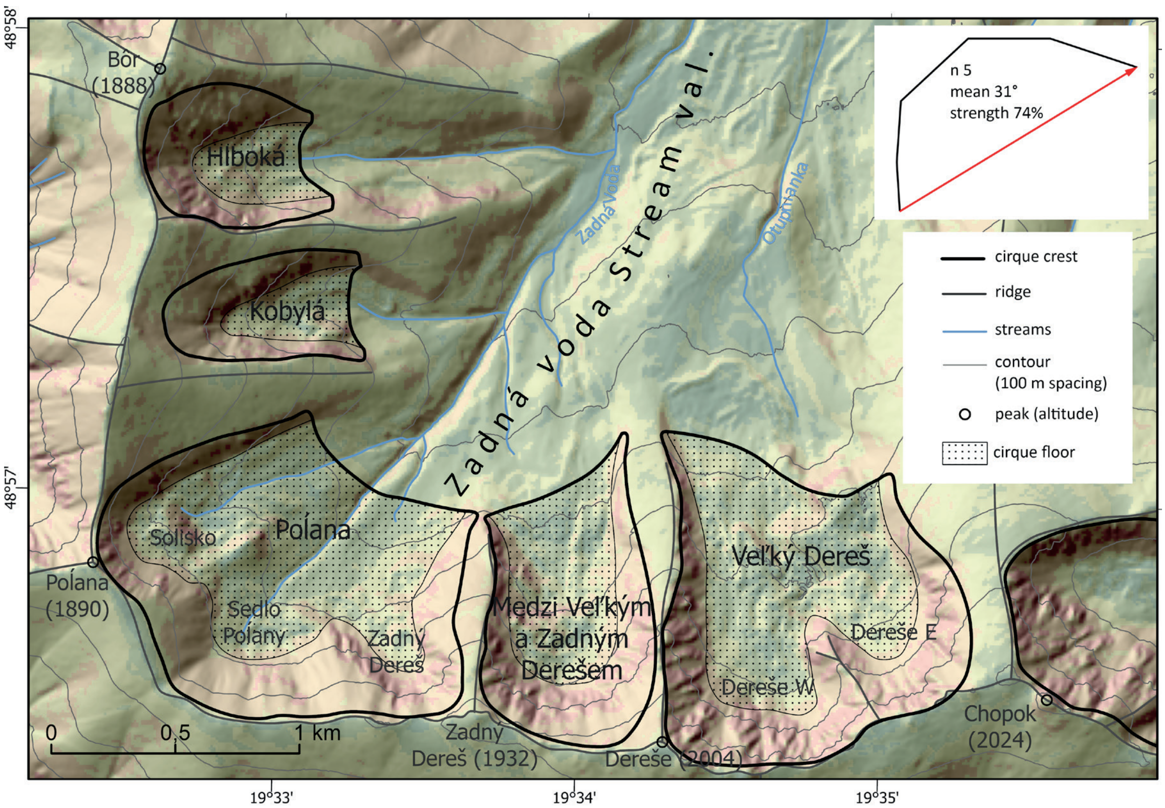

Fig. 4. *Maps of cirques in Zadná voda Stream valley and the mean aspect of the vector axis*

Table 1
Basic morphometric parameters of the sizes and shapes of glacial cirques in the Zadná voda Stream valley

Number and cirque name	Length [m]	Width [m]	Elongation [L/W]	Area [ha]		Floor area / cirque area [%]	Median aspect of cirque axsis [°]	Maximum gradient [°]	Minimum gradient [°]	Maximal altitude of cirque crest [m a.s.l.]	Minimal altitude of cirque floor [m a.s.l.]	Mean altitude of cirque floor [m a.s.l.]	Vertical dimension [m]	Length / height range	Grade	Lake status entire of floor
				entire cirque	cirque floor											
(1) Veľký Dereš	1131	1288	0.88	122.8	67.1	54.6	342	51.9	12.6	1986	1452	1616	534	2.12	2	drift
(2) Medzi Veľkým a Zadným Derešom	1025	695	1.47	63.7	32.9	51.7	0	49.4	0.8	1940	1454	1573	486	2.11	2	drift
(3) Poľana	1127	1511	0.75	134.5	77.4	57.5	43	47.0	2.7	1878	1445	1587	434	2.60	2	outsloping
(4) Kobylá	747	406	1.84	28.9	11.2	38.7	86	45.1	9.1	1811	1463	1540	348	2.15	2	outsloping
(5) Hlboká	630	561	1.12	33.3	12.1	36.3	93	38.3	12.5	1873	1520	1597	353	1.78	2	outsloping

The median axis aspect of the cirques in the Zadná voda Stream valley is in the azimuth range 345–93° with mean aspect 31°. Cirque floors are at heights 1445 to 1968 m a.s.l. with an average of 1583 m a.s.l. The average elevation of cirque floors is 1583 m a.s.l., and the crest surrounding the cirques is on average 1898 m a.s.l.

Moraines and rock glaciers

The maximum moraine of the Zadná voda glacier is located at an elevation of 1060 m a.s.l., 650 m north of Vrbické pleso, near the Jasná tourist resort settlement (Fig. 5). The latero-frontal moraine distal slope is 40 m in height.

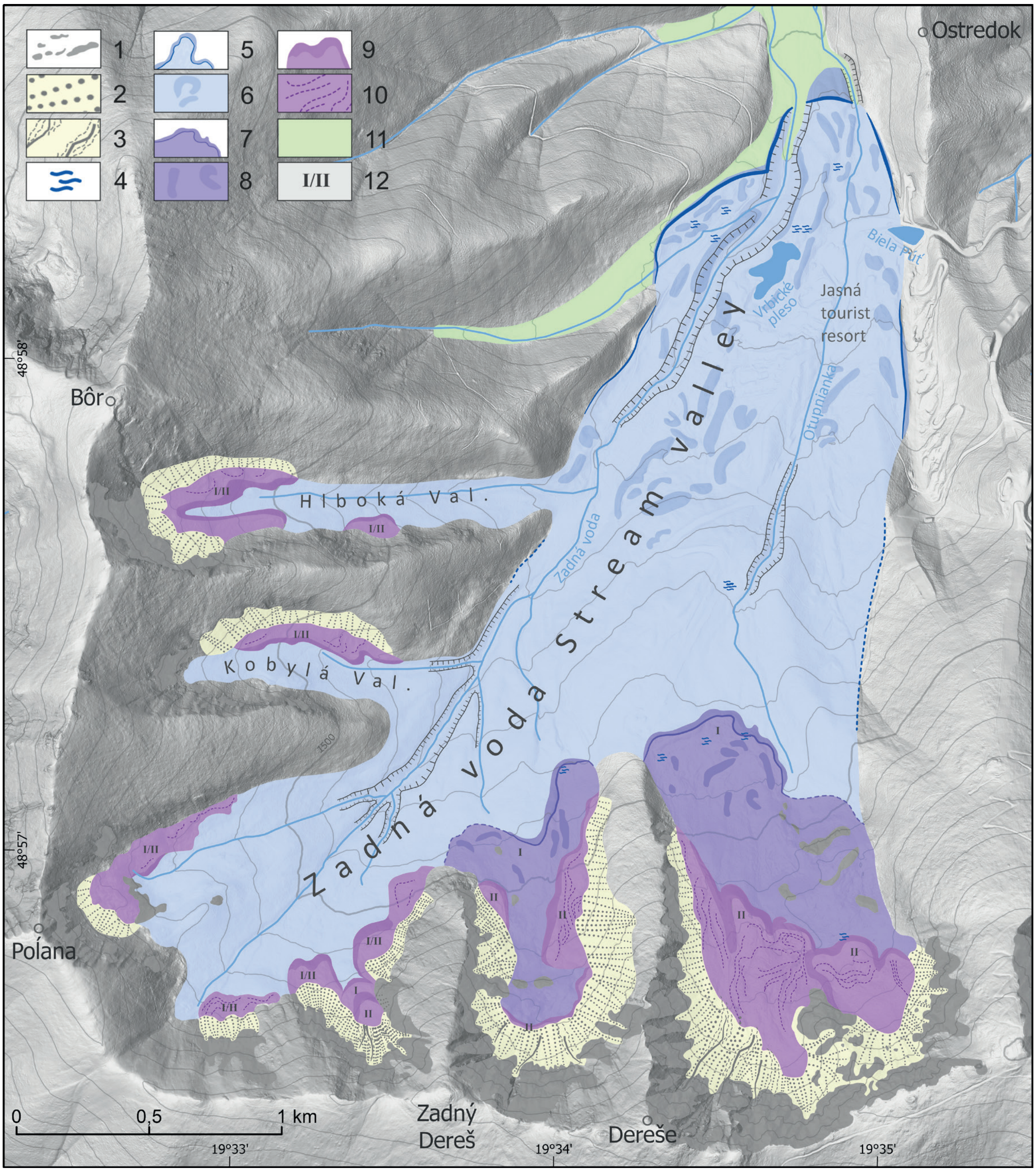

Fig. 5. Geomorphological map of the Zadná voda Stream valley, contour lines with 50 m spacing: 1 – bedrock and rock walls; 2 – talus deposits; 3 – erosion channel and debris flow; 4 – peat bog; 5 – moraines with areas covered with passively transported boulders; 6 – hummock moraines; 7 – moraines of debris-covered glacier; 8 – area of a debris-covered glacier with distinct hummocky moraines; 9 – rock glaciers (debris rock glaciers and talus rock glaciers) and rock glacier fronts; 10 – rock glacier area with marked surficial ridges; 11 – alluvial and fluvioglacial deposits; 12 – stage of recession

The moraine front is deeply (9–15 m) cut by the Zadná voda and Otupnianka stream channels. The right lateral moraine was partially destroyed as a result of the levelling of the terrain for ski runs and the creation of the Biela Púť artificial water reservoir. The maximum height of the proximal slope of the moraine in this part of the valley is 3 m. In the western part of the valley, at the mouth of the Ploská Valley, a distinct 3.5 m high frontal-lateral moraine is visible (Fig. 6).

This moraine ridge is cut by the Ploská stream flowing out of the side valley. The vast scale of the terminal moraine zone, which extends from the end moraine ca 1.5 km upvalley, features hummocky moraine topography with the common presence of dead-ice depressions. The largest of them is filled with Vrbické pleso lake water. The glacial transported boulders are sized between 2–4 m and are widely scattered on the moraine surface.

In the Zadná voda Stream valley, one or two stages of deglaciation are recorded in the moraine-rock glacier sequence. All landforms of deglaciation occur in the higher part of the valley, in the cirque floors (the lowest at an altitude of 1415 m a.s.l. in the Veľký Dereš cirque). There are landforms which are connected with the recessional stages in all cirques. In the largest cirques (Veľký Dereš, Medzi Veľkým a Zadným Derešem, Zadný Dereš) are two stages of glacial recession, while only one stage is visible in smaller cirques. Two major landforms connection with the recessional stages can be distinguished in the Zadná voda Stream valley: debris-covered glacier (in the two eastern cirques) and rock glacier in the other cirques.

The debris-covered glacier is characterized by moraines, which do not show a viscous flow morphology (Clark et al. 1994) and formed longitudinal ridges with depression on the proximal side. An exposure of glacially moulded bedrock is observed in the Veľký Dereš and Medzi Veľkým a Zadným Derešem cirques. The boulders observed on the surface were glacially transported, with sizes varying between 2–5 m, and they are partially embedded in the glacial till. On the other hand, fields of openwork boulders typical of relict rock glacier surfaces are rare in this area.

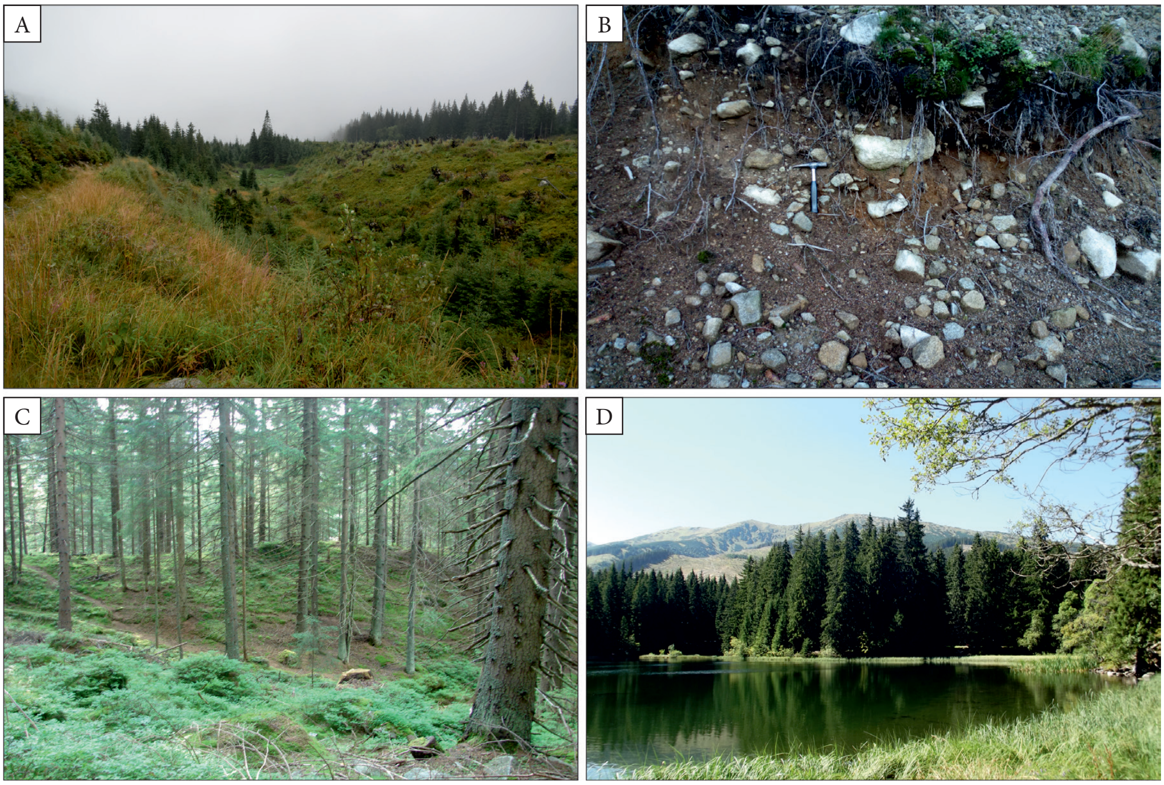

Fig. 6. *Accumulation forms in the Zadná voda Stream valley: A) frontal moraine and hummock moraine near Ploská Valley; B) glacial deposits of lateral moraine near the Biela Pút; C) ablation moraine with hummocky moraines near the Vrbické pleso; D) Vrbické pleso*

The fossil landforms (Fernández-Fernández et al. 2017) left by debris-covered glaciers are found in the largest cirques – Veĺký Dereš and Medzi Veĺkým a Zadným Derešem cirques. The glacier enjoyed good accumulation conditions there due to the shaded position of the cirque floor, the supply of debris, snow avalanches and snow blowing, and the extent of the glacier in this stage was ca. 24–36% to MIE (Figs. 5, 7).

Following the Barsch (1996) classification, the debris rock glacier and talus rock glacier were distinguished. The debris rock glacier is only observed in Veĺký Dereš cirque. This landform is characterized by steep and high fronts (25 m high and 40° slope), pronounced ridge and furrows which are perpendicular to the past flow direction (Clark et al. 1994). The boulders 6–8 m in size and openwork boulders, are often deposited without fine sediments. In smaller cirques there are talus rock glaciers, forming a type of aprons, occurring at a short distance from the rock walls (100–150 m), which is only 3–4% of the distance to the MIE.

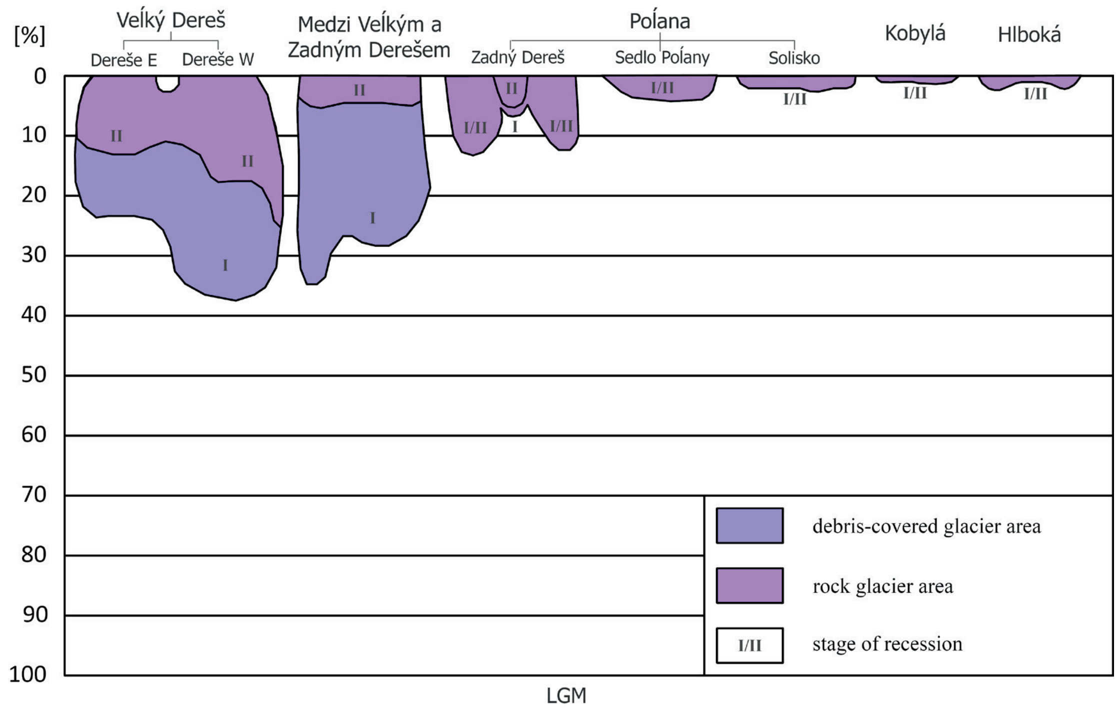

Fig. 7. *The ratio of distance 3D of recession stages to the maximum moraines. The 100% is the maximum ice extent (MIE) of the Zadná voda glacier and 0% is the foot of the cirque headwall where deglaciation ends*

Glacier reconstruction and ELA estimation

The reconstructed Zadná voda glacier surface geometry during MIE and its ELA is presented in Figure 8. The glacier was 4350 m long and covered 7 km^2 in area. Its maximum thickness was 135 m. The average thickness of the reconstructed glacier area was 48.1 m. The area of the greatest thickness of ice is located in the confluence of ice from Medzi Veĺkým a Zadným Derešem, Poĺana, Kobylá and Hlboká cirques. P20 of the floor elevation as an estimate of the lowest previous ELA during maximum glaciation (Mîndrescu & Evans 2014) is 1647 m. The difference between the highest peak (Dereše, 2004 m a.s.l.) and P20 is 438 m. It is near the value that Mîndrescu & Evans (2014) considered as the minimum for nested cirque development. The analysis of DEM shows that the ELA rose by about ca. 270 m (1433 m calculated by AABR 1.6 method, for the glacier during the MIE up to 1700 m – it is the highest value of RILA of the rock glacier in the Veĺký Dereš cirque). The RILA determined for the older stage of recession is 1590 m, and for the younger stage is 1640 m (maximum 1700 m in the Veĺký Dereš cirque).

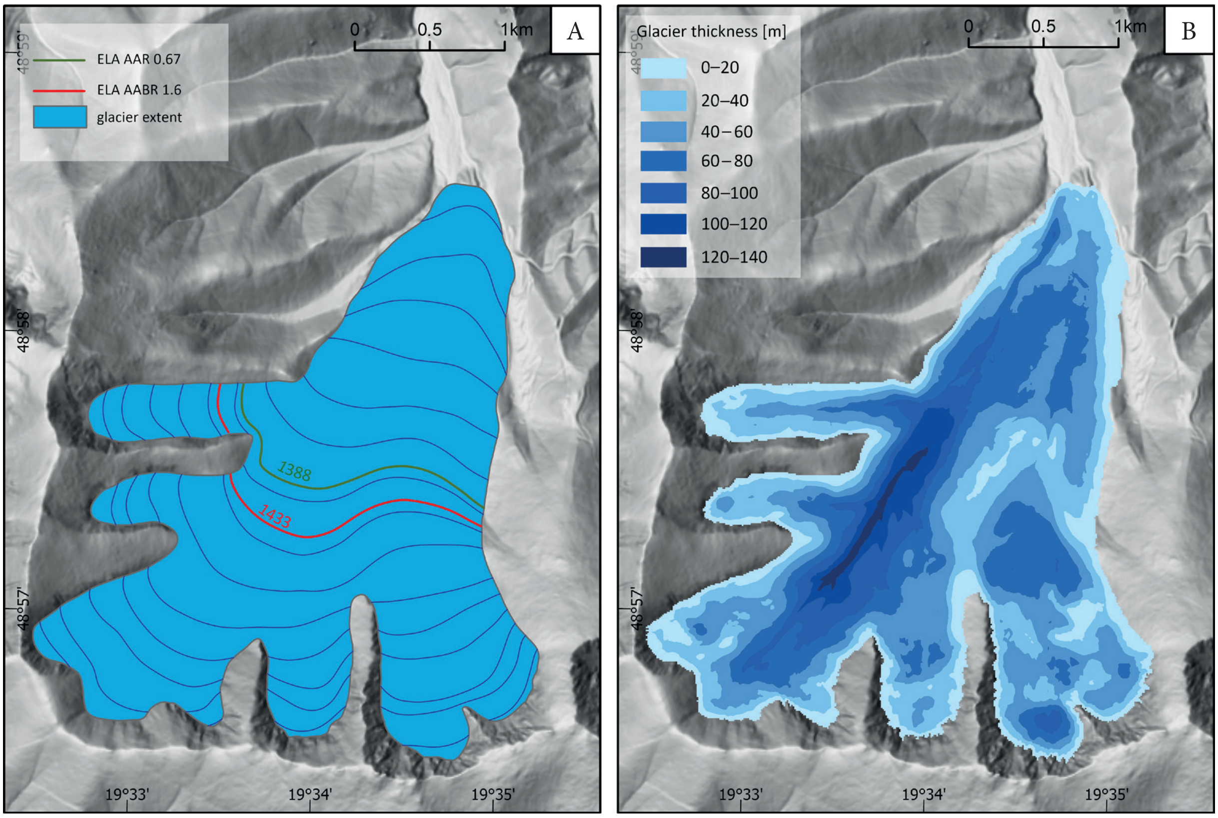

Fig. 8. *Glacier of Zadná voda: A) glacier and equilibrium line altitude reconstruction of the LGM advance; glacier contour lines with 50 m spacing; B) glacier thickness of the LGM advance*

DISCUSSION

The morphometric parameters of cirques in the Zadná voda Stream valley do not differ significantly from the results obtained in the most glaciated massifs of the Carpathians. All cirques in the Zadná voda Stream valley were defined as the 2nd-grade, which is similar value as in the Chornochora and Svydovyets massifs (3.09, Kłapyta et al. 2021b) and Romanian Carpathians (2.67, Mîndrescu & Evans 2014). However, in the stronger glaciated High Tatra Mountains, the presence of the top 1st-grade cirques with overdeepenings and cirque lakes is common. This grade of cirque development is not observed in the Western Carpathians outside the High Tatra Mountains.

The mean slope of the cirque floor in the study area (22.9°) shows slightly higher values in comparison to the values obtained in the Chornohora and Svydovyets massifs (13.5°, Kłapyta et al. 2021b), which suggests less developed cirques. However, the average ratio of length to height range (2.15) is similar to the other Carpathian massifs (2.10 in Romania, Mîndrescu & Evans 2014; 1.87 in the High Tatra Mountains, Křížek & Mida 2013) and this parameter is considered a measure of glacial cirque development.

In the Tatra Mountains, the results of dating by means of the TL (Butrym et al. 1990, Lindner et al. 1993), TL and OSL (Baumgart-Kotarba et al. 2001) and the cosmogenic isotope methods (Dzierżek et al. 1999, Makos et al. 2013, 2014, 2016, 2018, Engel 2015, 2017) prove that well-preserved maximal latero-frontal moraines were formed during the LGM, between 26 and 18 ka. By analogy to the Tatra Mountains, it is assumed that the maximal moraines in the Low Tatra Mountains are also LGM in age.

The presented maximum extent of the Zadná voda glacier and its 3D surface reconstruction is based on a very distinct terminal moraine at an altitude of 1060 m a.s.l. Nevertheless, the presented maximum extent of the glacier is 100 to 2000 m smaller than in previous estimations (Vitáshek 1924, Volko-Starohorský 1943, Lukniš 1964, Halouzka et al. 1997, Maglay et al. 2009).

Glacial sediments downvalley of the distinct terminal moraine are not mapped. As shown in the inventory of boulder size distribution in the Białka Valley (Zasadni et al. 2021), large surficial boulders, up to 5 m in size, may occur in the neighbouring Tatra Mountains both in LGM and degraded pre-LGM till covers. In the study area downvalley of the terminal moraine, oversized boulders typical for moraines and glacial sediments are not observed. Hence the absence of older moraines beyond the MIE glacial limit is inferred. This confirms previous research results in the Low Tatra Mountains, where older glaciations moraines have never been reported (Vitáshek 1924, Lukniš 1964, Gajdoš & Klaučo 2010, Gajdoš & Anstead 2013). In the Carpathians, moraines of older glaciations only occur in the most glaciated massifs: the Chornohora and Svydovyets massifs (Kłapyta et al. 2021b), Rodna Mountains (Kłapyta et al. 2021a) and the High Tatra Mountains (Zasadni & Kłapyta 2014, Zasadni et al. 2021, 2022a). In this regard, moraine development in the study area and LGM is similar to the less glaciated part of the Tatras: the Western and Bielskie Tatras where the pre-LGM moraines are not observed (Zasadni & Kłapyta 2014, Zasadni et al. 2022a).

In the studied valley, the MIE glacier left a well-developed and massive latero-frontal moraine with a distinct hummocky topography with chaotic ridges and depressions in the inner zone of the moraine (1000 m wide). Such a landform assemblage in the area of the former glacial terminal zone is linked in the neighboring High Tatra Mountains with the presence of debris covered glaciers (Zasadni & Kłapyta 2014, Zasadni et al. 2022b). The insulating effect of surficial moraine cover on glaciers promoted dead ice block conservation which turned into a circular depression after deglaciation. One such depression filled with lake water is the Vrbické pleso in the study area. In the Tatra Mountains, morainic lakes are common (e.g. Toporowy Staw Niżni or Štrbské pleso; Kłapyta et al. 2016) but only Vrbické pleso has such an origin in the Low Tatra Mountains. It suggests that the Zadná voda glaciers were similar to the largest glaciers in the High Tatra Mountains and had debris cover, at least in the lower part of the glacier terminal zone.

The reconstruction of the Zadná voda glacier in this study, with a length of 4.3 km and an area of 7 km^2, is one of the largest in the Low Tatra Mountains. According to Vitáshek (1924), Volko-Starohorský (1943) and Kele (2007) only four glaciers on the northern slope of the massif, the Lúčanka, Ludárovský, Bystrá and Krížanka, were slightly longer (ca. 5–6 km of length). The length of the Zadná voda glacier is similar to the average length of the glaciers on the northern slope of the Tatra Mountains (Tab. 2) (Zasadni & Kłapyta 2014). However, the size of glaciers in the Low Tatra Mountains differs significantly from the largest glaciers of the Tatra Mountains. Similarly, the thickness of these glaciers is lower to compare in the largest glaciers in the neighboring Tatra Mountains (e.g. the Białka glacier is up to 400 m thick, Zasadni & Kłapyta 2014). This means that the largest glaciers in the Low Tatra Mountains had much lower erosive potential than the glaciers in the High Tatra Mountains. In such large glaciers, the rate of glacial erosion is strong enough to erode and lower the glacier bed in successive glaciations. This leads to decreasing size and altitude of glacier accumulation area and limits the size of glaciers during the glacial maxima.

Table 2
Relation between the morphometric parameters of the reconstructed glacier in the Zadná voda Stream valley and the reconstructed glaciers in the other Carpathians Massifs (N slopes)

Parameter	Average values for N slope glacier				
	Zadná voda	Tatra Mts. (Zasadni & Kłapyta 2014)	Chornohora Mts. (Kłapyta et al. 2021b)	Svydoviec Mts. (Kłapyta et al. 2021b)	Rodna Mts. (Kłapyta et al. 2021a)
Glacier length [km]	4.30	4.20	2.89	2.69	2.80
Glacier area [km^2]	7.00	6.30	2.23	2.30	1.81
Glacier thickness [m]	48.10	–	28.00	25.50	28.00

In consequence, this produces a sequence of moraines where LGM moraines have an inner position (Kaplan et al. 2009, Anderson et al. 2012, Pedersen & Egholm 2013). The small glaciers of the Low Tatra Mountains probably did not have such erosive force, which is why the self-limiting effect of glaciations did not occur. This explains why pre-LGM moraines are not observed in the Low Tatra Mountains. However, it cannot be excluded that older pre-LGM moraines and sediments were completely eroded on steeper valley slopes as a result of strong solifluction reworking during the glacial climate which featured in the Carpathian Mountains (Zasadni et al. 2021).

I have distinguished two recessional stages of the Zadná voda glacier. The development of debris-covered glaciers was in this place, where the conditions of accumulation were favorable: a shaded position of the cirque floor, the high supply of debris, and the presence of snow avalanches. These landforms are more difficult to identify than rock glaciers during the geomorphological mapping and the DEM analysis. The boulders are mostly embedded in glacial till, and openwork boulders are rarely occur. Currently, only relict rock glaciers are observed. The calculated distance 3D parameter shows that they were relatively large (24–36% in relation to MIE). In the best development cirque in the Zadná voda Stream valley were debris rock glaciers (Veĺký Dereš, size of debris rock glaciers was 11–15% to MIE). The parameters of the 3D distance show that the size of talus rock glaciers was similar in most cirques of the Zadná voda Stream valley (3–6% in relation to MIE). The surface of rock glaciers features a typical ridge and furrow topography, and openwork boulders are common on the glacier surface.

A gradual difference is visible from east to west and is connected with the quantity and type of glaciers. In the two eastern cirques (Veĺký Dereš cirque and Medzi Veĺkým a Zadným Derešem cirque) two types of landforms are found: debris-covered glaciers (stage I of recession) and rock glaciers (II stage of recession). The debris rock glaciers connected with stage II of the recession were in Veĺký Dereš cirque and the talus rock glaciers connected with stage II of the recession were in Medzi Veĺkým a Zadným Derešem cirque. The two landforms developed as talus rock glaciers, connected with stages I and II of deglaciation in the Zadný Dereš cirque.

In the other smaller cirques there is only one single landform of the talus rock glacier. It is likely that their climatic oscillations were filtered out into single rock glacier generation.

The lower altitude of debris-covered glacier fronts is in the range of ca. 1415–1480 m, and for the rock glacier fronts ca. 1500–1600 m in the Zadná voda Stream valley. A similar altitude and morphological position are enjoyed by large rock glaciers in the northern slope of the Western Tatra Mountains dated by Engel et al. (2017) from 13.4 ±0.5 to 11.9 ±0.5 ka with cosmogenic 10 Be method.

ELA reconstruction was performed using several methods. The result obtained by the P20 method, analogous to the Mîndrescu & Evans method (2014), gave a very high result for ELA – 1647 m. Perhaps it is not a reliable indicator for such a small number of cirques and should not be compared with the ELA results obtained by the P10 method for the other massifs (Tab. 3).

Table 3
Relation between the results of ELA for the reconstructed glacier in the Zadná voda Stream valley and the reconstructed glaciers in the other Carpathians massifs

Study area	**ELA [m]**		
	P20 or P10	**AABR 1.6**	**AAR 0.67**
Zadná voda	1647	1433	1388
Tatra Mts. (Zasadni & Kłapyta 2014)	–	1580	1502
Western Tatra Mts. (Zasadni et al. 2018)	–	1450	–
Chornohora Mts. (Kłapyta et al. 2021b)	1432	1516	1490
Svydovyets Mts. (Kłapyta et al. 2021b)	1382	1401	1408
Rodna Mts. (Kłapyta et al. 2021a)	1580	1697	1690

The ELA calculated by the AAR 0.67 method (1388 m), gave a lower value than for the selected glaciers in the High Tatra Mountains (1460–1640 m using the AAR 0.63–0.67 method; Engel et al. 2015, Makos et al. 2018, Zasadni & Kłapyta 2018). Using the AABR method which is recommended in the literature (Rea 2009, Oien et al. 2022) both ELAs: in the Zadna voda glacier (1433 m) and in the Tatra Mountains (1580 m, Kłapyta & Zasadni 2018) are higher, but the difference is similar – in the Low Tatra Mountains, the ELA is ca. 150 m than in the Tatras.

A similar, relatively low ELA to that of the study area is also estimated in the Western Tatra Mountains (~1450 m, Zasadni et al. 2018) and in the northern part of the Eastern Carpathians (Ukraine): Chornohora and Svydovyets massifs (~1400–1500 m; Kłapyta et al. 2021b), but the obtained result is much higher than the lowest ELA in the entire Carpathians (1280–1350 m obtained in the Borzhava massif, located in the northern part in the Ukrainian Carpathians; Kłapyta et al. 2022). However, the ELA calculated for the Zadná voda glacier is lower by ca. 260 m than the highest ELA of the Eastern Carpathians obtained in the Rodna Mountains (Kłapyta et al. 2021a) and much lower than the highest ELA of the Southern Carpathians (1700–1850 m in the Retezat Mountains; Ruszkiczay-Rüdiger et al. 2016, 2017).

The ELA result obtained for the Zadná voda glacier, which is close to the ELA calculated for the Western Tatra Mountains, would fit well with the general increase in the ELA trend, determined for the southern transect north of the Alps. There is a general increase of LGM ELA towards the east of the Vosges Mountains, through the Bohemian Massif, Krkonoše Mountains, Tatra Mountains, and the Rodna Mountains in the location which is furthest east (Heyman et al. 2013, Mentlik et al. 2013, Engel at al. 2014, Zasadni et al. 2018, Kłapyta et al. 2021a).

CONCLUSIONS

Detailed geomorphological mapping in the western part of the Demänovská Valley allowed the determination of the maximum extent and recessional stages of the Zadná voda glacier attributed to LGM. The glacier terminus descended to an elevation of 1060 m a.s.l. The length of the glacier was 4.3 km. The presence of hummocky topography and dead ice-depressions in the terminal moraine complex indicate that during the LGM the terminus of the Zadná voda glacier was debris-covered.

The distinguished recessionary stages were associated with the development of a debris-covered glacier or rock glacier in the cirque parts of the valley. There is a visible gradual change in the type of glaciers from east to west. In the easternmost largest cirques, which provided the best conditions for glacier development, two different types of glaciers are observed: debris-covered glaciers and rock glaciers. Debris-covered glaciers in the Veĺký Dereš cirque and Medzi Veĺkým a Zadným Derešem cirque are associated with stage I of deglaciation, while the debris rock glaciers in the Veĺký Dereš cirque and talus rock glaciers in the Medzi Veĺkým a Zadným Derešem cirque represent stage II. Two talus rock glaciers (I and II stage) developed in the Zadný Dereš cirque, while in the westernmost cirques there is only one visible deglaciation stage (I/II), which developed as a talus rock glacier.

The reconstructed ELA of the Zadná voda glacier during the MIE gave a result of 1433 m calculated by the AABR 1.6 method. The ELA during the last stage of deglaciation was above 1640 m. The glacial relief of Zadna voda Stream valley is one of the best-developed in the Low Tatra Mountains. On the other hand, there is a less glacial transformation of the landscape in comparison to the High Tatra Mountains. The relief of this valley, the absence of sediments related to pre-LGM, the cirque-valley nature of the glaciers and no overdeepending in the cirques, together with the similar ELA and height of the massif, permits the conclusion that the glaciation in the Zadna voda Stream valley is comparable to the glaciation in the Western Tatra Mountains.

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