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Glacial and periglacial relief on the southern slopes of the Western Tatra Mts. (Slovakia) – the results of the first detailed geomorphological mapping of the Žiarska, Jamnicka, Račkova and Bystra Valleys

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Abstract: The article presents the results of the first detailed geomorphological mapping of the Žiarska, Jamnicka, Račkova, and Bystra Valleys, situated on the southern slope of the Western Tatra Mountains. The field work was supplemented by digital topographic as well as statistical analysis of rock glaciers distribution. The author focused on the distribution and morphological features of moraines and rock glaciers. Variability of both sets of deposits strongly reflects topographic influences on debris and snow accumulation. The main factor controlling the geometry of landforms was solar irradiance modified by the influence of the local cirque topography. Two generations of the rock glaciers indicate distinct phases of periglacial conditions during the Late Glacial period.

Key words: deglaciation, moraine systems, relict rock glaciers, morphostratigraphy, Western Tatra Mts.

Introduction

The morphology of many currently deglaciated alpine massifs was strongly transformed during the Late Glacial period by the activity of both glacial and periglacial conditions. The Late Glacial evolution of the alpine type mountains is currently an important issue in many palaeogeographical and palaeoenvironmental studies (Ivy-Ochs *et al.,* 2006; Lotter *et al.,* 2006; Reutcher *et al.,* 2007). They provide information about the conditions and type of deglaciation, the activity of periglacial processes and are an indirect source of information about both regional and local climate fluctuations. The Tatra glacial and periglacial landforms are still major features of valley and cirque floors relief in spite of partial fossilization by Holocene slope activity. Despite the long period of investigations, most geomorphological and palaeogeographical studies were carried out in the High Tatra Mts. (Lukniš, 1973; Klimaszewski, 1988; Baumgart-Kotarba & Kotarba, 1997, 2001). Hence, there is much better understanding of local landforms and their geochronology in this area when compared to the Western Tatra Mts. The earliest comments on glacial morphology of the southern slopes of the Western Tatras date back to the works of Lucerna (1908), who described the moraines of the maximal extent and the system of the glacial troughs in the area between Jalovecka and Kamenista valleys. He distinguished traces of four glaciations and the recessional moraines of the last glaciation, denominated them according to the Alpine terminology of Penck and Brückner (1901–1909). In the study of Szaflarski (1937), on the southern slope, the author distinguished three sets of recessional moraines. In his opinion, the longest ice preservation on the southern slope of the Western Tatra Mts. was in the highest parts of Bystra (Suchy Žadok cirque) and Žiarska valleys. Unfortunately, these two works are lacking in comparative cartographical materials, which make field identification of selected landforms impossible. Apart from the limnological studies of Jamnicke and Bystre Plesa lakes, Młodziejowski (1937) as the first provided a simplified sketch map of the Bystra Valley cirques relief. The most distinctive moraine ridges were marked by the

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above-mentioned researcher in front of the Suchy Zadok and Bystre Plesa lakes cirques.

Lukniš (1964), based on the previous moraine classifications, compared the moraine sequence to his glacial scheme of the High Tatra Mts. The outer and inner moraines of maximal extent were compared with C and D stadial oscillations. Relict rock glaciers were first identified by Nemčok & Mahr (1974); however, in the study area they marked only 3 rock glaciers: one in the Rohacki cirque and two in the cirques of the Bystra Valley. According to their opinion, the formation of rock glaciers in the Tatras started after the complete deglaciation in the periglacial conditions during transitional period between full glacial-Holocene climates.

In 1987, Halouzka mapped Quaternary sediments of the whole Slovak part of the Western Tatras. Unfortunately, these materials are mostly unpublished, preventing spatial comparison. In his subsequent morphostratigraphic scheme, Halouzka (1989) divided moraines which postdate the maximal extent into 3 retreat phases (valley phases) and 3 or 4 final (cirque) phases, the last two of which were formed by the nèvè glaciers (rock glaciers?). This scheme strictly corresponds to the morpho-climatic division of Lukniš (1973). All geological materials of Halouzka (1987) were compiled on the Geological Map of the Tatra Mountains 1:50,000 (Nemčok *et al.*, 1993), but moraine locations are marked in a very schematic and imprecise way, hindering their spatial interpretation.

Till the present study, neither a detailed geomorphological map, nor an authoritative morphostratigraphic scheme of deglaciation for particular valley systems has existed for the southern slope of the Western Tatras. Especially the last period of glacial-periglacial activity is poorly recognized, despite its clear imprint on the morphology of the cirques.

Study area

The study area comprises three valley systems: Jamnicka, Račkova, Bystra and the uppermost section of Žiarska, which are situated in the Slovak Western Tatra Mountains in their highest, central part (Fig. 1). The area is bordered from the north by the main Tatra ridge ranging from Mt. Banikov (2,178 m a.s.l.) to Mt. Blyšt (2,155 m a.s.l.). From the south, it is bordered by the young, Neogene Subtatric fault, along which the Tatra massif had been highly rotationally uplifted above the Palaeogene flysch of the Liptov intermountain basin (Janak, 1994). The study area is built of crystalline and metamorphic rocks, mainly by granites, mica-schists, para- and orthogneisses and migmatites, which belong to the Tatricum-type crystalline basement (Janak, 1994). The highest summits rise above 2,150 m a.s.l. (Bystra 2,250 m a.s.l., Jakubina 2,194 m a.s.l.), and are ca. 400 m lower than in the High Tatras (Lukniš, 1964). The glacial cirques lay at an altitude of about 1,700–1,850 m a.s.l. (Halouzka, 1987) and comprise well developed glacial and periglacial landforms. Asymmetrical uplift of the southern part of the Tatra massif caused an intensive linear and backward erosion along with the partial rejuvenation, which led to the formation of deep and steep valley profiles in the middle and lower valley sections. The valleys of this range are more deeply incised than those in the High Tatras, whereas relatively large non rejuvenated surfaces were preserved in the uppermost sections of the valleys (especially in the Bystra, Gaborova, Žiarska and Kamienista valleys).

Materials and methods

Detailed geomorphological mapping at the scale of 1:10,000 was performed to obtain information about glacial and periglacial landform distribution. Additionally, 1:5,000 mapping was applied to distinguish complicated sets of moraines and rock glaciers in the glacial cirques, which point to complex patterns of deglaciation. Rock glaciers were identified on the basis of the occurrence of typical morphological indicators (frontal slope, ridge-and-furrow relief, orientation of longitudinal axis of boulders). Within the rock glaciers' frontal slopes, core zones altitudes, longitudinal axis orientations and aspects were measured. The fieldwork was supplemented by optical remote sensing, including 1-m Ikonos images and 0.75-m colour orthophotomap of the Tatra Mts.

Statistical analysis of K-means clustering was applied to identify the altitude distribution of the relict rock glaciers fronts, with the help of the R Project for statistical computing software. A total number of 39 measurements of rock glacier fronts elevation were arranged increasingly and tested for possible aggregations, which would suggest occurrence of different rock glacier generations.

Glacial morphology of the Žiarska, Jamnicka, Račkova and Bystra valleys

Glaciers of the Last Glaciation in the Western Tatra Mountains had a considerable extent (Fig. 1). The largest glacial system was formed in the Jamnicka Valley. The highly asymmetrical glacier system was nourished mostly from the western slopes by the ice from seven firn-basins: Jamnicke Plesa Lakes, Jakubina, Rohacki, Smrek, Puste, Maselne and Repa cirques. The glaciers terminated at an altitude of ca. 1,000 m a.s.l., but frontal moraines have not been preserved and granite-derived accumulation cover deposited on bedrock built by mica-schists marks the maximal glacial position. Terminal moraines have

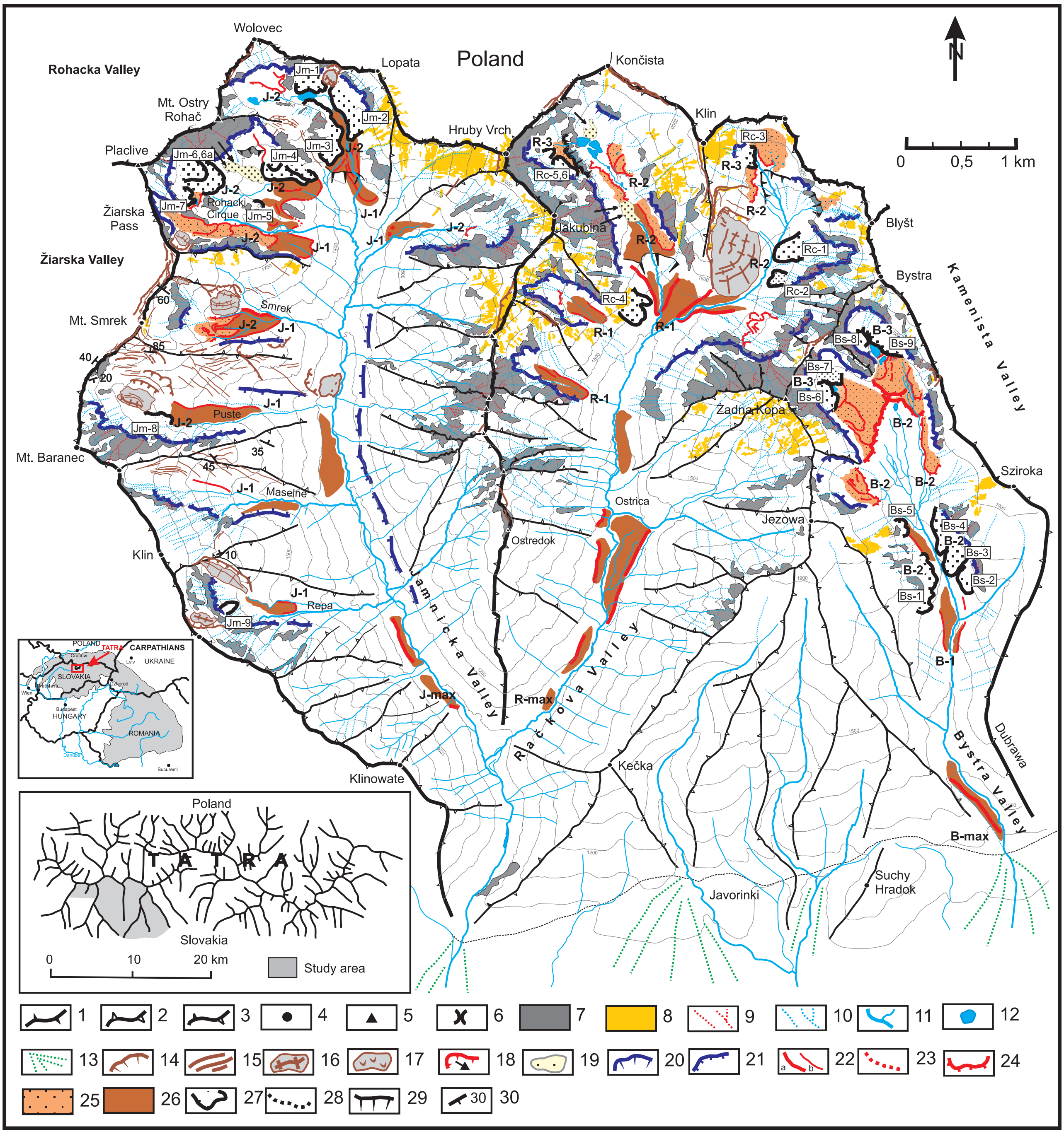

Fig. 1. Map of the Western Tatra Mts. landforms within the Jamnicka, Rackova and Bystra valleys, according to the author. Morphosystems mentioned in the text: J-max – maximal moraines in the Jamnicka Valley, R-max - maximal moraines in the Račkova Valley, B-max – maximal moraines in the Bystra Valley, J-1 - first morphosystem in the Jamnicka Valley, J-2 – second morphosystem in the Jamnicka Valley, R-1 – first morphosystem in the Račkova Valley, R-2 – second morphosystem in the Račkova Valley, R-3 – third morphosystem in the Račkova Valley, B-1 – first morphosystem in the Bystra Valley, B-2 – second morphosystem in the Bystra Valley, R-3 – third morphosystem in the Bystra Valley.

1 – sharp rocky ridge crest, 2 – rounded ridge crest covered with debris and vegetation, 3 – asymmetrical ridge crest (steep rocky slope from one side and debris-vegetation one from the other), 4 – rounded summits covered with debris and vegetation, 5 – sharp rocky summit, 6 – passes, 7 – rocky slopes and rockwalls, 8 – block slopes with debris covers, 9 – chutes cut in solid rock, 10 – debris flow gullies, levees cut in debris covers, 11 – stream channels, 12 – lakes, 13 – fluvioglacial cones, 14 – landslide niche, 15 – system of fissures, 16 – landslide packets, 17 – colluvia, 18 – rock-slide niche, 19 – rockfall talus slope-rock slide tongue, 20 – glacial cirques, 21 – glacial troughs, 22 – moraine ridges; a – moraines of maximal glacial extent, b – moraines of recessional stages, 23 – poorly exposed moraine ridges 24 – massive fronts of moraines of distinct glacial readvance, 25 – ablation moraine covers, 26 – ground moraine covers, 27 – relict rock glaciers, 28 – south Tatra boundary, 29 – rock steps, 30 – dips of metamorphic schist complex

The codes of rock glaciers listed in Table 1 are marked on the map.

been deposited within narrow, steep valley section and thus were rewashed by postglacial fluvial erosion and covered by slope deposits. In the Račkova Valley, glacier snout terminated at 1,050 m a.s.l. This terminal position is marked as the lower edge of the large granite boulder accumulation. Massive lateral moraines mark the maximal glacier tongue extent up to the Ostrica meadow. Ice from the two main cirques: Zadna Račkova and Gaborova Valley as well as from two tributaries from the west cirques: Wyżna Kotlina and Jakubina fed the valley glacier of Račkova Valley.

In the Bystra Valley (Fig. 1), the glacier had its accumulation area in three highly-elevated firn basins of Suchy Zadok, Bytre Plesa Lakes, and a smaller basin located under the Jezova. High elevation of cirque bottoms resulted in large alimentation surface and considerable extent of the Bystra glacier.

In the Jamnicka and Račkova valleys, moraines of the maximal glacial extent were deposited within the Tatra massif and did not extend into the foreland. There is no geomorphological evidence for confluence during the last glaciation either, as suggested in the literature (Lucerna, 1907; Szaflarski, 1937; Lukniš, 1964; Nemčok, 1993; Halouzka, 1987). Only in the Bystra Valley the glacier tongue in its maximal extent did reach the neighborhood of the Tatra foreland, what is marked by the prominent (1 km long) right lateral moraine ridge in the mouth of the valley (Fig. 1).

The first system of recessional moraines was formed in the upper valley position in the Bystra (B-1, 1,350 m a.s.l.) and Rackova Valley (R-1, e.g. Polana Pod Klinom 1,430–1,450 m a.s.l.), whereas in the Jamnicka Valley they were preserved under the mouth of the cirques (J-1, Fig. 1). They represent massive, subdued ridges and locally (Puste cirque, Rohacki cirque) ablation moraine covers indicate that some glacier termini were debris-covered.

The next morphosystem (J-2, R-2, B-2, Fig. 2), indicates an outstanding readvance, marked by the similar pattern of massive, debris morainic ridges with numerous dead ice depressions in the terminal part of former glacier tongues. The 20–30 m high, steep moraine ridges mark the onset of the deglaciation dominated by heavy debris input, well imprinted in the cirque relief. This morphological system was formed as a continuum of landforms, from debris-covered terminus, through debris covered glaciers, to valley floor rock glaciers (ice-cored rock glaciers). Such relief is particularly well developed in the cirques of Žiarska Valley (Welke Zawraty, Fig. 2; Zr-1 rock glacier) and suggests that glacier-derived rock glaciers have also developed during this period. The best-developed regular pattern of glacial-periglacial landforms is recorded in the Bystra Valley cirques (B-2, Fig. 1). The morphology of this valley consists of highly elevated, non-rejuvenated valley bottom, and twin cirques of similar aspect and altitudes, with cirque head-wall relief. Altogether, they provide a unique opportunity for distinguishing landform arrangement connected with ice decay. Topographical and structural factors led to the long preservation of the glacial ice. In addition, thick debris cover protected the ice core from melting, which was intensified by heavy solar irradiance at the southern cirque aspect. Climate-induced individual glacial fluctuations are clearly imprinted in the morainic arrangement. On the proximal side of the readvance moraine ridges, two recessional moraines of minor sub-oscillations occur. They constitute distinct morainic ridges in the inner part of debris-covered zone, which could have originated as a result of the successive remobilization of ice cores in the following stadials. Their geometry has been characterised by the decreasing width against similar length and topographical clustering under the shaded rock walls and rocky slopes. The pattern described above is very well imprinted in the Suchy Zadok and Bystre Plesa lakes cirques (Fig. 1). On the proximal side of these moraines, large dead ice depressions have been formed. In the Bystra Valley they are filled with waters of Velke Bystre Pleso and Anitine Očko Lakes (Fig. 1).

Within the Jamnicka and Račkova drainage basins, a deeply incised, narrow valley system with relatively small cirques prevails. Such topography caused an earlier rise of local glaciers equilibrium lines above the cirque bottoms; thus, the sequence of glacial landforms is incomplete, lacking in the youngest debris landforms in comparison with the spacious corries of the Bystra or Žiarska valleys.

The third morphosystem consists of relict rock glaciers, which appear in the highest part of Banikov Račkova and Bystra valley cirques (R-3, B-3; Fig. 1). They are in considerable spatial separation from the previously described landforms. They are very prominent, massive and relatively freshly shaped structures, located below rock walls in the shaded parts of the cirques (Figs. 1–2).

Glacial and periglacial landform assemblage on the southern slopes of the Western Tatras stands out clearly from the moraine sequences on the northern slopes (Klimaszewski, 1988; Kaszowski *et al*., 1988). Variability of both sets of deposits reflects strong topographic influences on debris and snow accumulation, which is apparent from their geometry. The cirque moraine sequences occupied the most favourable zones for ice preservation; thus they are concentrated in the lateral zones of the corries, near the rock walls (Žiarska Valley cirques, Rohacki cirque). The central parts of the glaciers were dominated by ice and mostly unprotected from ablation by insulating debris cover. The central sun-drenched part of the cirques was ice-free and the moraines were deposited much higher, in the inner corrie zone. The

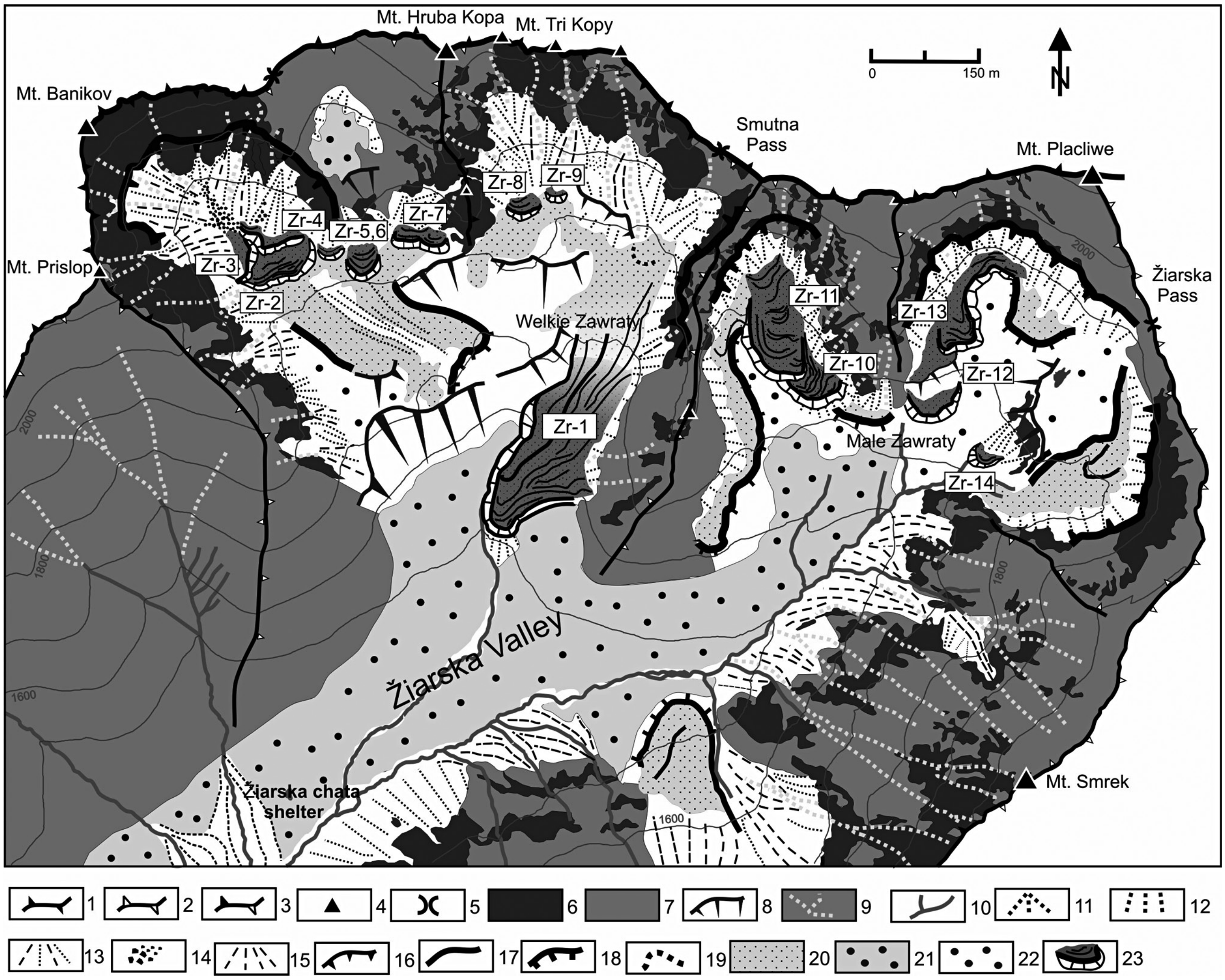

Fig. 2. Geomorphological map of the uppermost section of the Žiarska Valley, Western Tatra Mts., according to the author. 1 – sharp rocky ridge crest, 2 – rounded ridge crest covered with debris and vegetation, 3 – asymmetrical ridge crest (steep rocky slope from one side and debris-vegetation one from the other), 4 – summits, 5 – passes, 6 – rocky slopes and rockwalls, 7 – Richter denudation slope, stabilized by vegetation, 8 – rock steps, 9 – chutes, debris flow gullies, levees cut in debris covers, 11 – stream channels, 11 – rockfall gravity sorted talus cone, 12 – rockfall gravity sorted talus slope, 13 – alluvial talus slope, 14 – rockfall talus slope-rock slide tongue, 15 – alluvial slope, 16 – glacial cirques, 17 – moraine ridges, 18 – massive fronts of moraines of distinct glacial readvance, 19 – poorly exposed moraine ridges, 20 – ablation moraine covers 21 – ground moraine covers, 22 – rock valley bottom covered by weathered discontinuous moraine covers 23 – relict rock glaciers. The codes of rock glaciers listed in Table 1 are marked on the map.

spatial variability of debris accumulation zone of the former glacier surface was preserved in the relief of Banikov cirque, where thick zone of ablation moraine cover concentrates on the cirque sides, whereas its central part is debris-free.

The main factor controlling the geometry of glacial and periglacial landforms was solar irradiance modified by the influence of the local topoclimate variables (shading, snow and debris production). A common situation in the studied cirques was that glacial body split into the two lateral minor debris-covered tongues, which were protected from insolation by the shade and debris may have reached a considerable distance down the cirques. Such a specific geometry of glacial forms was also identified on the southern slope of the High Tatras in the valleys of Krivan massif (Ksandr, 1954; Za ko, 1961).

Distribution of relict rock glaciers

Rock glaciers are morphological indicators of periglacial conditions in the mountains; their occurrence is controlled primarily by climatic, topographic and geological factors (Barsch, 1996), thereby their position could be spatially diversified. Basing on air photos interpretation, Nemčok & Mahr (1974) identified numerous relict rock glacier-like structures in the Western Tatra Mts., mostly on the northern slope, in the shaded cirques of Zuberska Valley. The current field work allows the author to identify several new relict rock glaciers on the southern slope of the Tatras, whose location is numbered on the geomorphological map (Figs. 1–2) and described in Table 1. Most of the identified landforms are initial and small debris bodies, which in 75% are talus-derived, lobate forms, located under rocky slopes and rockwalls. Some rock glacier tongues (e.g. Zr-1, Zr-10, Zr-11, Zr-13 in the Žiarska Valley) developed in the cirques with clear spatial and morphological connection with the moraines, what suggests both their glacial and periglacial origin.

They were formed beneath small cirque glaciers, which retreated into cirques and became buried owing to high debris supply resulting from the frost-shattering of the surrounding rockwalls (see Johnson, 1980, 1987; Benn & Evans, 1998).

Many relict rock glacier surfaces collapsed, but still retain much of their microrelief: longitudinal, arcuate and transverse ridges and furrows. Steep frontal slopes are still well developed and preserved as a distinct parabolic ramp, which resembles massive moraine ridges but retain debris accumulation body on the proximal side. Rock glacier orientation is strongly diversified, over half of the total rock gla-

Table 1. Distribution and basic morphological characteristic of relict rock glaciers in the study area (according to author). Rock glaciers location depicted in figures 1 and 2

Rock glacier code	Localization	Front elevation (m a.s.l.)	Debris source	Aspect	Morphology, shape	Other features
Račkowa Valley						
Rc 1	Gaborova valley	1,690	moraine	SW	tongue shaped	distinct fronal ramp, collapsed surface
Rc 2	Gaborova valley	1,650	talus	W	lobe with initial tongue	colapsed internal surface
Rc 3	Zadnia Gaborova	1,860	talus	E	lobate	initial, discordant to the moraine cover
Rc 4	slope of Rackova valley	1,470	talus	SE	lobe with initial tongue	welll developed ridges and furrows
Rc 5	Zadnia Rackova cirque	1,815	talus	NE	lobate	initial, partly fossilized by debris flows
Rc 6	Zadnia Rackova cirque	1,815	talus	NE	tongue shaped	initial, partly fossilized by debris flows
Jamnicka Valley						
Jm 1	Jamnickie Lakes cirque	1,736	talus	S	lobate	welll developed ridges and furrows
Jm 2	Jamnickie Lakes cirque	1,652	talus	SW	lobate	distinct frontal ridge, very wide
Jm 3	Jamnickie Lakes cirque	1,625	talus	NE, E	lobate	very wide, encircle the talus slope
Jm 4	Rohacki cirque	1,555	talus	S	lobate	complex of 2 lobes generation
Jm 5	Rohacki cirque	1,640	talus	NE	lobate	small, distinct frontal ridge
Jm 6	Rohacki cirque	1,765	moraine	E	tongue shaped	distinct frontal ridge, large boulders
Jm 6a	Rohacki cirque	1,780	moraine/talus	E	lobate	inside the debris mass of Jm 6 form
Jm 7	Rohacki cirque	1,780	moraine	E	lobe with tongue	discordant to the moraine
Jm 8	Puste cirque	1,650	talus/moraine	NE	lobate	distinct frontal ridge, partly fossilized
Jm 9	Repa cirque	1,630	talus	NE	lobate	surface covered by dwarf-pine
Bystra Valley						
Bs 1	slopes of Bystra valley	1,485	talus	E	lobate	distinct frontal ridge, very wide
Bs 2	slopes of Bystra valley	1,474	talus	SSW	lobate	surface covered by dwarf-pine
Bs 3	slopes of Bystra valley	1,510	talus	SSW	tongue shaped	surface covered by dwarf-pine
Bs 4	slopes of Bystra valley	1,565	talus	SSW	lobate with tongue	surface covered by dwarf-pine

cier number favouring SW (28%) and NE (23%) aspects (Table 1). The lowest position of the fronts of talus rock glaciers could be interpreted as the potential zone of permafrost distribution (Haeberli, 1985). In the study area, relict rock glacier Rc-4 in the Račkova Valley and the Bs-1, Bs-2, Bs-3 forms in the Bystra Valley descended to 1,480–1,470 m a.s.l. (Fig. 1, Table 1). Hence, the altitude of 1,470 m a.s.l. marks the potentially lowest boundary conditions for permafrost creep.

Two morphosystems exist within the set of relict rock glaciers. Statistical methods were applied to determine altitude variability and potential clustering, which in connection with morphological relations suggest several landform generations. Among the total of 39 relict rock glaciers, K-means clustering shows two aggregations. 15 lowest values of altitude (up to 1,690 m a.s.l.) clusters around the mean value of 1,582.8 m a.s.l., and 24 highest values (above 1,720 m a.s.l.) clusters around the mean value of 1,811.167 m a.s.l. (Fig. 3). Two generations of rock glaciers were formed in the cirques of Bystra and Žiarska valleys. In the remaining valleys, because of small size and narrow cirque bottoms, this spatial relation was poorly developed. The first group of talus rock glaciers was formed on the slopes of massive debris morainic ridges, which mark the prominent readvance. In the Žiarska Valley, a clear morphological transition between massive moraine ridges and valley-floor rock glacier body exists (Male and Welkie Zawraty cirques; Fig. 2). This is a classic example of glacial-periglacial landform continuum. The second group of rock glaciers marks the last stage of deglaciation (Fig. 1). Their position suggests that their formation was controlled by the presence of rock walls and rocky slopes, which were the source of snow avalanches and provided shade. Statistical

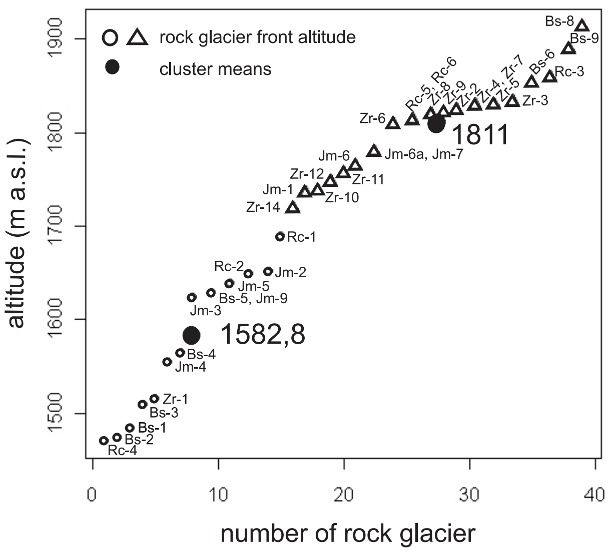

Fig. 3. K-means clustering of relict rock glaciers fronts elevations based on R Project statistical analyses

analysis and morphological relations confirm the presence of two generations of rock glaciers and indicate two distinct phases of periglacial conditions on the southern slopes of the Tatra Mts. during the Late Glacial.

Conclusions

The glacial and periglacial landforms of the Western Tatras are indicators of palaeoenvironmental changes controlled mainly by climate. Geomorphological mapping of the Žiarska, Jamnicka, Račkova, and Bystra valleys indicates the significant and well preserved glacial and periglacial landform assemblage on the southern slopes of the Western Tatra massif. Apart from the maximal Würm moraines, three sets of landform systems were distinguished. The second of them points to the prominent readvance of debris-covered glaciers, marked by the 20–30 m high, steep moraine ridges. The last two stages of the Würm glaciation were fixed in the Western Tatras relief as the continuum of talus and glacial-derived landforms: moraine ridges, ablation moraines, and rock glaciers. Clear morphological coincidence of such features, like moraines and rock glaciers suggest also their temporal coexistence. The variability of both sets of deposits reflects strong topographic control on the debris and snow accumulation; particularly, landform geometry was heavily reliant on the topoclimatic conditions, which determined the style of deglaciation. Morphological and statistical relations indicate two distinct phases of periglacial conditions linked with rock glaciers formation. The third, rock glacier-dominant, morphosystem suggests pure periglacial conditions during the ice decay. Because of clear morphological relations, the study area is particularly suitable for further study of the morphology and morphochronology of the Last Glaciation in the Tatra Mts.

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