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RELATIVE SURFACE DATING OF ROCK GLACIER SYSTEMS IN THE ŽIARSKA VALLEY, THE WESTERN TATRA MOUNTAINS, SLOVAKIA

Abstract. Results of detailed geomorphological analysis and Schmidt-hammer rebound values were used to estimate relative age of relict protalus lobes — rock glacier systems in the glacial cirques of the Žiarska Valley, Western Tatra Mountains, Slovakia. Well developed set of moraine and talus rock glaciers formed during the final phases of cirque glaciers recession. Geomorphological data combined with results of Schmidt-hammer rebound values point to three episodes of rock glaciers formation: RG-1, RG-2 and RG-3. The RG-1 and RG-2 rock glacier systems formed in the valley cirque floors and were genetically linked with glaciers (ice-cored rock glaciers). They have yielded similar mean R-values which suggest relatively small time interval between those episodes and a relatively long period of pronounced cooling without substantial changes of rock weathering conditions. The youngest rock glacier system (RG-3) consists of talus-derived rock glaciers or protalus lobes, suggesting entirely periglacial conditions. The youngest system of rock glaciers represents the most recent cold-stage landforms in the Western Tatra Mts. A similarly developed set of rock glaciers found in different part of the Tatra Mts. may have a similar complex history. Therefore, rock glaciers cannot be seen as rather simple landforms developed during the Late Glacial.

Key words: relict rock glaciers, Schmidt-hammer, Late Glacial, Western Tatra Mountains, Slovakia

INTRODUCTION

Relict rock glaciers are pronounced and characteristic features of thick debris accumulation in alpine environments shaped under harsh, cryogenic conditions. Rock glaciers are formed by slow gravitational deformation of ice-debris mixture in periglacial realm, below the equilibrium line of glaciers (H a e b e r l i 1985, B a r s c h 1988). These are classic examples of site-specific landforms, which formation is controlled by local topo-climatic and geological conditions, favoring accumulation of thick debris of talus and/or till and their succeeding remobilization (H a e b e r l i 1985, B a r s c h 1996, K ä ä b 2007). Rock glaciers flow episodes were attributed to the periods of pronounced cooling which allow permafrost aggradation. Relict rock glaciers represent potentially important indicators of palaeoclimate, reconstruced on the basis of the analogy with the modern relationship between rock glaciers and climate (K e r s c h n e r 1978, 1985; H a e b e r l i 1982, H u m l u m 1998a, F r a u e n f e l d e r , K ä ä b 2000, H u g h e s et al. 2003b).

Dating of rock glaciers and moraines is currently one of the most rapidly developing and methodically advanced issues in glacial and periglacial geomorphology. Precise dating of rock glaciers is difficult and requires integrated approach of relative and absolute age-determination methods (H a e b e r l i et al. 2003, F r a u e n fe l d e r et al. 2005, K e l l e r-P i r k l b a u e r et al. 2008). Reliable radiocarbon dating is impossible due to the lack of suitable organic material (I v y-O c h s et al. 2009). However, extremely limited findings of organic remnants in permafrost cores allowed dating some active rock glaciers (H a e - b e r l i et al. 1999, K o n r a d et al. 1999). Recent studies in the European Alps have shown that relict rock glaciers (Late Pleistocene and early Holocene in age) can be quite successfully exposure-dated with cosmogenic nuclides (I v y-O c h s et al. 2006, 2009). Cosmogenic ages obtained on rock glacier surfaces mark the time of their final stabilization. In contrast, relative surface age-datings of rock glaciers were more frequent and used Schmidt-hammer rebound (N i c h o l a s, B u t l e r 1996; H u m l u m 1998b, F r a u e n f e l d e r et al. 2004, 2005; A o y a - m a 2005, K e l l e r-P i r k l b a u e r et al. 2008) lichenometry (H a m i l t o n, W h a l l e y 1995) as well as weathering rind thickness techniques (N i c h o l a s, B u t l e r 1996; O g u c h i et al. 2001, L a u s t e l a et al. 2003).

The earliest, general comments on the rock glaciers occurrence in the Tatra Mts. date back to the works of J. P a r t s c h (1923) and M. L u k n i š (1973). Further studies focused on identification of rock glaciers morphology on aerial photographs (N e m č o k, M a h r 1974; N e m č o k 1982), geomorphological mapping (K o t a r b a et al. 1987, K a s z o w s k i et al. 1988, L i b e l t 1988, K o t a r b a 1991–1992, 2007), fabric analysis (K o t a r b a 1991–1992) and BTS measurements on rock glacier surfaces testing the potential for permafrost occurrence within thick debris bodies (K ę d z i a et al 2004, K o t a r b a 2007).

Similarly as in the world rock glaciers literature (W h a l l e y, M a r t i n 1992 and references therein), vigorous discussion arose over the Tatra's rock glaciers nomenclature and their genetic classification. J. D z i e r ż ek and J. N i t y c h o - r u k (1986) stated that relatively large debris-rock glaciers shaped high valley bottoms in the High Tatra Mts. Those authors suggested three different generations and diverse types of rock glaciers: (i) Oldest Dryas valley floor rock glaciers, (ii) Younger Dryas valley-side rock glaciers and (iii) Little Ice Age protalus lobes. Conversely, K o t a r b a (1991–1992) systematically mapped these features in the Polish High Tatra Mountains and showed that relict rock glaciers are small and less common in this area than suggested by J. D z i e r ż e k and J. N i t y c h o - r u k (1986). A. K o t a r b a (1991–1992) attributed Oldest Dryas valley floor rock glaciers to dead ice and ablation moraine relief which were formed after the recession of debris covered glaciers (K o t a r b a 1991–1992). According to L. K a s z o w s k i et al. (1988) and A. K o t a r b a (1991–1992), the last activity of the Tatra's rock glaciers was connected with a pronounced cooling during the Younger Dryas, as this was the only period of sustained cold conditions following the removal of ice associated with the last glaciation.

In contrast to the High Tatra Mts., still relatively little is known about relict rock glaciers in the Western Tatra Mts., especially on their southern, Slovak part. A. N e m č o k and T. M a h r (1974), L. K a s z o w s k i et al. (1988) and P. L i b e l t (1988) recognized complex rock glacier-like structures (ridges and furrows relief) within northward exposed glacial cirques. Sucessive results of detailed geomorphological mapping yielded evidence of a relatively large number of relict protalus lobes and rock glaciers in the cirques of the south facing Western Tatra's valleys (K ł a p y t a 2009). Studies on the relative age of rock glaciers in the Tatras have so far been limited. However, geomorphological data suggest at least two generations of rock glaciers in the Western Tatra's glacial cirques (K ł a p y t a 2009). The specific objectives of this paper are threefold: (i) to apply Schmid-hammer techniques to the rock glacier systems in the Žiarska Valley, Western Tatra Mountains; (ii) to evaluate the results in relation to the methodology of testing; and (iii) to discuss relict rock glaciers position in relation to the deglaciation history of the Žiarska Valley cirques.

STUDY SITE DESCRIPTION

The research was carried out in the glacial cirques of the Žiarska Valley (V'elké and Malé Závraty cirques) in the southern part of the Western Tatra Mts., northern Slovakia (Fig. 1). The Western Tatra Mountains are ca. 400 m lower and relatively less reshaped by the glacial processes than the High Tatras (L u k n i š 1964). The highest peak in the range, Bystra, reaches 2250 m a.s.l. and a number of peaks exceed 2100 m a.s.l. During major glaciations periods in the Pleistocene, the Tatra Mts. were the most glaciated massif in the Western Carpathians (L u k n i š 1964, K l i m a s z e w s k i 1988), with Alpine-style valley and cirque glaciers and active talus and debris rock glaciers during the final phases of deglaciation. Contemporary climatic snow line lies above the highest summits, and in the Western Tatra Mts. it is about 2500–2600 m a.s.l. (Z a s a d n i, K ł a p y t a 2009). Mean annual air temperature (MAAT) at Kasprowy Wierch (1991 m a.s.l.) which is located on the main ridge of the mountains is –0.8°C, and mean annual precipitation (MAP) is 1742 mm for the period 1951–1960 (K o n č e k, O r l i c z 1974; C h o m i c z, Š a m a j 1974).

The Žiarska valley head is bounded to the north by the main Tatras ridge with altitudes exceeding 2100 m a.s.l. (Banikov 2178 m a.s.l., Hruba Kopa 2166 m a.s.l., Plačlive 2125 m a.s.l.) (Fig. 1). In the western and central part of the Žiarska Valley heads well developed glacial cirques are deeply incised into the common

Tatra type Carboniferous granites and granidiorites (mainly muscovite-biotite granidiorites and biotitic tonalities). In contrast, the eastern part of the Malé Závraty cirque is built of less resistant metamorphic mica-shists (K o h ú t, J a n á k 1994; N e m č o k et al. 1994, P o l l e r et al. 2000, G a w ę d a 2001). Boulder and bedrock lithology in the upper part of the valley is predominantly coarse-grained and produces rough texture after prolonged weathering of minerals.

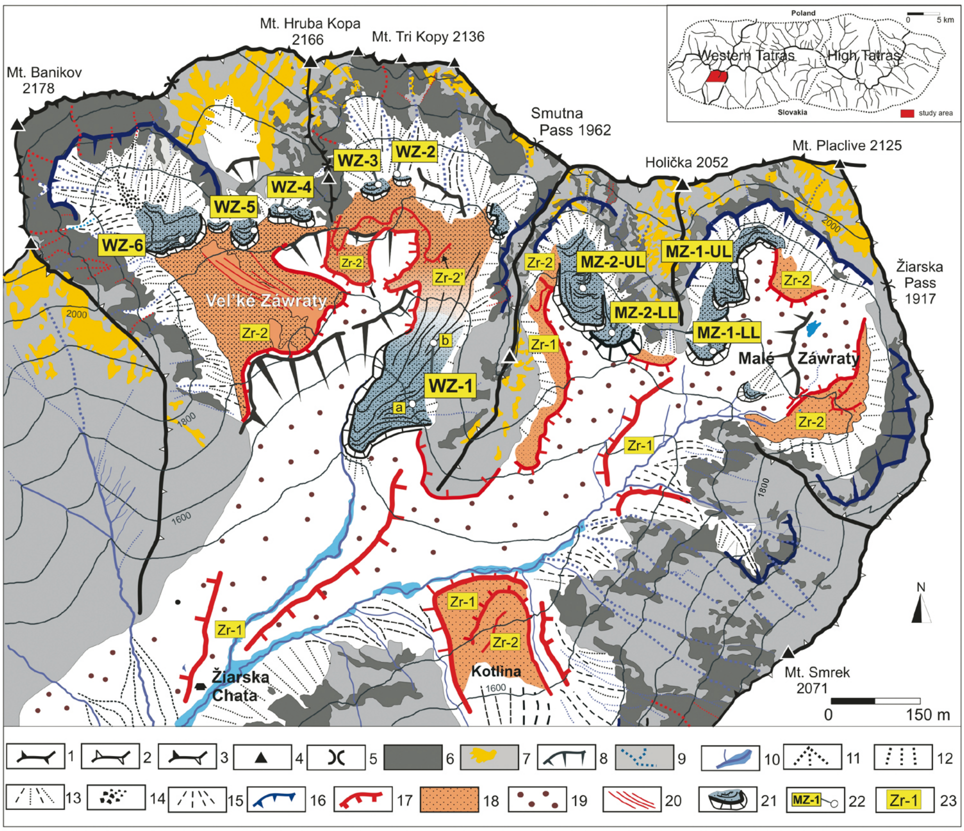

Fig. 1. Geomorphological map of the upper Žiarska Valley (according to P. Kłapyta), 1 — sharp rocky ridge crest, 2 — rounded ridge crest, 3 — asymetmetrical ridge crest, 4 — summits, 5 — passes, 6 — rocky slopes and rockwalls, 7 — debris-mantled slopes, 8 — rock steps, 9 — chutes, debris flow gullies, 10 — stream channels, 11 — rock-fall gravity sorted talus cone, 12 — rockfall gravity sorted talus slope, 13 — alluvial talus slope, 14 — rockfall talus slope-rock slide tongue, 15 — alluvial-avalanche slope and cone, 16 — glacial cirques, 17 — moraine ridges, 18 — ablation moraine covers, 19 — ground moraine covers, 20 — fluted moraine, 21 — relict rock glaciers, 22 — Schmidt-hammer measurement sites, 23 — names of local glacial advances

METHODS

GEOMORPHOLOGICAL MAPPING

GPS-aided geomorphological mapping at 1 : 5000 scale was applied to distinguish distribution and mutual morphostratigraphical relations between glacial and periglacial landforms in the head of the Žiarska Valley. Additionally, Ikonos satellite images, taken in August 2004 by the Tatra National Park, and extensive field observations were carried out to describe rock glaciers microrelief and topographic parameters of rock glaciers (length, width, relative height of frontal slope).

MEASUREMENTS OF SCHMIDT HAMMER REBOUND VALUE

A BN-type Schmidt-hammer (Silver Schmidt) was used to determine the degree of rock surface weathering and relative ages of rock glacier boulders in the Žiarska Valley. The Schmidt-hammer method measures the distance of the rebound of spring-loaded hammer mass impacting on the end of a steel rod held against the test surface (Fig. 2a) (S h a k e s b y et al. 2006). Rebound values (R-values) give a measure of the rock surface hardness, the degree of surface weathering and thus its relative age (S h a k e s b y et al. 2006). R-values range from 10 to 100. A high R-value indicates a less weathered surface (younger relative age), while a low R-value corresponds to a more weathered surface (older relative age) (M a t t h e w s, S h a k e s b y 1984). Schmidt-hammer techniques in conjunction with geomorphological analyses, lichenometry and weathering rind thickness have proved to be a very powerful relative age-dating approach in alpine environments (F r a u e n f e l d e r et al. 2005, M e n t l i k 2006). Although relative dating of landforms does not provide their numerical age, it is success-

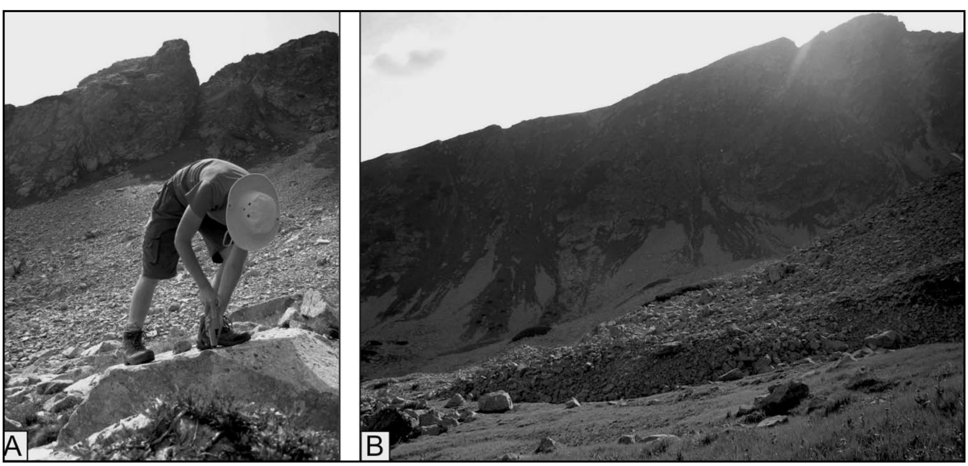

Fig. 2. A — Schmidt-hammer measurements on the surface of the WZ-3 protalus lobe, B — Lobate body of the WZ-5 relict, talus rock glacier in the V'elké Závraty cirque

fully used to distinguish local morphochronological systems in particular areas, and is an inevitable step foregoing terrestrial cosmogenic-nuclide dating (Hughes et al. 2003a, Mentlik 2006).

Schmidt-hammer test is a relatively new exposure-age dating technique, which has been used since 1980 as a method for relative-age dating of moraines (Matthews, Shakesby 1984; Evans et al. 1999, Mentlik 2006, Shakesby et al. 2006), rock glaciers (Frauenfelder et al. 2005, Keller-Pirklbauer et al. 2008), glacially scoured bedrock (McCaroll, Nesje 1993; Matthews et al. 1996, Winkler 2003) and rock avalanche deposits (Clark, Wilson 2004). In the case of calibration by local control points of known age, this method is known as Schmidt-hammer exposure age dating (SHD) (Matthews, Winkler 2011).

Apart from many advantages for geomorphological research, Schmidt-hammer method has some limitations. Results of Schmidt-hammer tests can be affected by local geological and geomorphological conditions and other environmental factors that influence weathering rates. Sampling of boulder surfaces makes this technique sensitive to post-depositional disturbances which could bring relatively young boulders to the surface (Matthews, Winkler 2011). In such a situation, mean R-values are treated as the minimal ages of the tested surface (Matthews, Shakesby 1984). On the other hand, lichen and soil cover may enhance rock surface weathering as much as 25–50 times (McCaroll, Viles 1995; Shakesby et al. 2006). In this study measurements were made on rock glaciers ridge crests to minimize the possible influence of late-lying snow patches (Ballantyne et al. 1989), and on stable, dry and near-horizontal boulder surfaces (Fig. 2a), free of large lichens and cracks (Sumner, Nel 2002). Test sites were kept as small as possible and the largest boulders exceeding 25 kg were randomly chosen. At each measurement site 150 readings were recorded on the surfaces of common Tatra-type granite boulders. At each of the five boulders 30 measurements were made, and the mean was calculated. Five values deviating most from the mean were excluded and the remaining 125 values were used for the evaluation of the mean R-value with 95% confidence interval as well as standard deviation, coefficient of variation and skewness (Matthews, Shakesby 1984, Hubbard, Glasser 2005).

RESULTS

RELICT ROCK GLACIERS OF THE ŽIARSKA VALLEY- THE FIELD EVIDENCE

The studied rock glacier bodies have been identified at the valley head (V'elké and Malé Závraty cirques) of the 17,5 km^2 large, southward trending Žiarska Valley (Fig. 1). In this part of the valley, 11 rock glaciers and protalus lobes — situated between 1515 and 1890 m a.s.l. — formed in the cirque bottoms and at the

Table 1

Topographical data for the studied rock glaciers in the Žiarska Valley

Rock glacier	Type	Debris source	Plan form	Aspect	Altitude [m a.s.l.]		Altitude range [m]	Lenght [m]	Width [m]
					Head	Front			
MZ-1	polymorphic	moraine	tongue-shaped	S	1890	1748	142	238	138
MZ-1-LL		moraine	tongue-shaped	S	1856	1748	111	119	65
MZ-1-UL		moraine	tongue-shaped	SSE	1890	1834	56	180	110
MZ-2	polymorphic	moraine	tongue-shaped	SSE	1880	1745	135	198	118
MZ-2-LL		moraine	tongue-shaped	SE	1780	1745	35	80	56
MZ-2-UL		moraine	tongue-shaped	S	1880	1757	43	165	76
WZ-1	monomorphic	moraine	tongue-shaped	SSW	1640	1515	125	530	310
WZ-2	protalus bulge	talus	rampart	S	1835	1822	13	40	70
WZ-3	protalus lobe	talus	lobate	S	1830	1820	10	90	90
WZ-4	protalus lobe	talus	lobate	S	1840	1831	9	40	70
WZ-5	monomorphic	talus	lobate	S	1830	1810	20	80	100
WZ-6	monomorphic	moraine/talus	tongue-shaped	SE	1845	1825	20	200	220

Fig. 3. Lower lobe of the Malé Závraty-1 rock glacier (MZ-1-LL) in the eastern part of the Malé Závraty cirque

base of talus slopes, eight from which were the subject of detailed studies. Morphological and altitudinal characteristics of the rock glaciers are listed in Table 1, and the rock glacier localities are numbered in Fig. 1. All studied features are relict (*sensu* B a r s c h 1988) as indicated by subdued surface topography, large melt-out depressions between frontal slope and rock glaciers surface, as well as soil and vegetation cover with patches of *Pinus mugo*.

RELICT ROCK GLACIERS IN THE MALÉ ZÁVRATY CIRQUES

Two tongue-shaped, polymorphic rock glaciers (*sensu* Frauenfelder and Kääb 2000), termed 'Malé Závraty-1' (MZ-1) and 'Malé Závraty-2' (MZ-2) were formed at the bottom of the amphitheatre Malé Závraty cirques (Figs. 1 and 3). Thick rock glacier bodies facing south to south-east are located at the foot of the talus below a 100-150 m in height cirque walls, built from resistant granitoides. Rockfalls from the headwalls of the cirques provided most of the debris input. At least two individual generations of rock glacier lobes with distinct steep fronts (lower lobe/LL and upper lobe/UL) can be distinguished at each of the two landforms. The lobe fronts represent separate phases of rock glacier formation, and the ages of these lobes may represent succeeding cool climate periods (K i r k b r i d e, B r a z i e r 1995; A o y a m a 2005). MZ-1-LL and MZ-2-LL belong to an older rock glaciers generation (Fig. 3), and unit MZ-1-UL and MZ-2-UL to a younger one. The fronts of MZ-1 and MZ-2 rock glaciers are situated at similar altitudes (1745 m a.s.l.).

In the eastern part of the Malé Závraty cirque, the typical MZ-1 rock glacier microrelief with linear and arcuate ridges up to 2–5 m high slowly grades into the arcuate terminal moraine of ZR-2 stade, to create a distinct bilobed morphology (C h e u c a, J u l i a n 2004). In the uppermost parts of the western Malé Závraty cirque, MZ-2 rock glacier body has almost completely overriden the terminal moraine of Zr-2 glacial advance. As cirque moraines exist together with the rock glacier and appear to be of the same age, it is probable that the cirque glaciers and rock glacier existed contemporaneously. This indicates that debris for the formation of MZ-1 and MZ-2 rock glaciers was mainly transported by Zr-2 stade glaciers and the landforms are former ice-cored rock glaciers.

RELICT ROCK GLACIERS IN THE V'ELKÉ ZÁVRATY CIRQUES

Two altitudinal systems of relict rock glaciers occur in the vast cirque of the V'elké Závraty (Fig. 1). In the eastern, lowest part of the cirque, a well-developed tongue-shaped rock glacier extending down to 1515 m a.s.l is preserved. The rock glacier, termed WZ-1, covers 0.076 km^2, and is the largest one in the study area. The main source of rock glacier debris originated from the densely fissured headwalls of the subsidiary cirque below the Smutna Pass (1962 m a.s.l.). The feature has a distal frontal slope up to 20–30 m in height with an apron of debris, and a collapsed boulder-covered surface which is organized into linear ridges up to 2–5 m high. In its uppermost parts, the rock glacier body grades into a distinct terminal moraine of ZR-2 stade (Fig. 1). This indicates that debris for the formation of WZ-1 rock glacier tongue was mainly transported during Zr-2 glacier

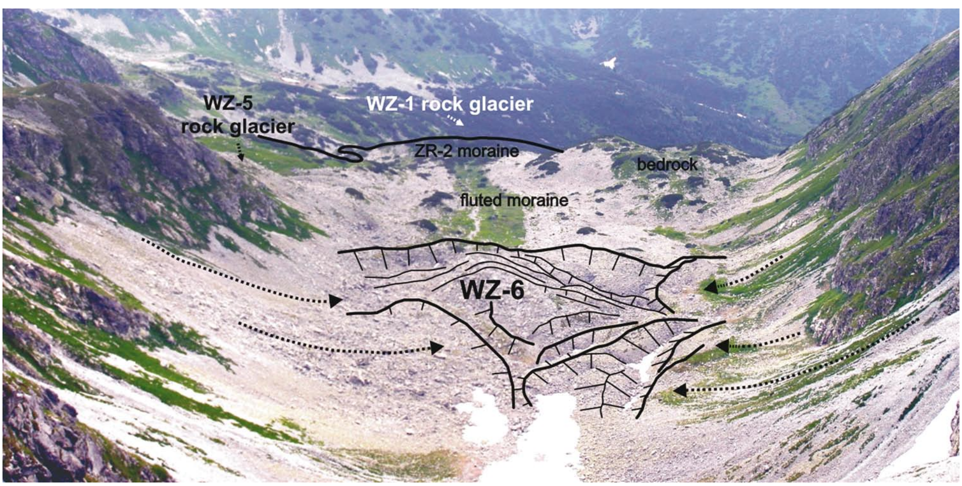

Fig. 4. Massive tongue of the WZ-6 rock glacier in the glacial cirque under the Mt. Banikov. View from the Mt. Banikov (2178 m a.s.l.). Arrows indicate main directions of debris supply

advance, and the landform is a former ice-cored rock glacier. High thermal insulation of debris cover caused WZ-1 rock glacier to advance about 180 m lower in the valley than the surrounding glaciers in the western part of the V'elké Závraty cirque.

The upper part of the V'elké Závraty cirque contains seven relict rock glacier bodies in the form of small monomorphic protalus lobes or rock glaciers (Figs 1, 2b and 4), five of them are the focus of this study (WZ-2, WZ-3, WZ-4, WZ-5, WZ-6) (Tab. 1). No glacial moraines are present in the upper parts of the cirque. Steep frontal slopes extend down to ca. 1820-1830 m a.s.l. Rockfalls from the south-facing headwalls of the cirque were the main source of debris input. All landforms (with the exception of WZ-6) extend from the base of large scree slopes and it would therefore appear likely that they are talus-derived rock glaciers (Fig. 2b). All these landforms are characterized by one pronounced arcuate frontal rampart and collapsed debris body. Transverse ridges are not so well developed as in the WZ-6 although they can still be discerned. They represent initial examples of talus landforms created as the result of slow deformation of rock/ice mixture: protalus bulges (*sensu* L u c k m a n 2007) and protalus lobes (*sensu* W h a l l e y 2004, H a r r i s o n et al. 2007).

Well developed tongue of WZ-6 rock glacier occurs in the bottom of a deep glacial cirque under Mt. Banikov (2178 m a.s.l.) (Fig. 4). The feature has a steep distal front slope up to 10 m in height and a surface which is characterized by regular boulder-covered transverse ridges. WZ-6 covers 0.037 km^2 and is the largest feature within the youngest rock glaciers generation. The surface clasts are larger, more angular and lack interstitial fine materials in comparison with

Table 2

Statistical parameter of Schmidt-hammer results: mean R-values with 95% confidence limits (R value), number of measurements (N), standard deviation (SD), coefficient of variation (V) and skewness (SK)

Site	Altitude (m a.s.l.)	R-value	N	SD	V	SK
rock glacier						
MZ-1-LL	1760	52.14 ± 1.1	125	6.21	6.54	0.10
MZ-1-UL	1870	53.96 ± 1.3	125	7.21	15.55	0.06*
MZ-2-LL	1730	55.0 ± 1.2	125	6.52	1.77	-0.22
MZ-2-UL	1765	56.33 ± 1.3	125	7.28	13.0	-0.15*
WZ-1-a	1630	54.1 ± 0.8	125	3.83	2.92	-0.04
WZ-1-b	1650	53.34 ± 0.9	125	3.49	3.14	0.49
WZ-2	1830	61.80 ± 0.7	125	3.48	0.44	-0.93
WZ-3	1820	62.15 ± 0.4	125	2.70	1.08	-0.25
WZ-4	1840	61.57 ± 0.7	125	4.88	3.88	-1.22
WZ-5	1820	61.54 ± 0.7	125	4.68	3.91	-1.38
WZ-6	1830	61.82 ± 0.7	125	3.95	3,48	-0.67

* Bimodal

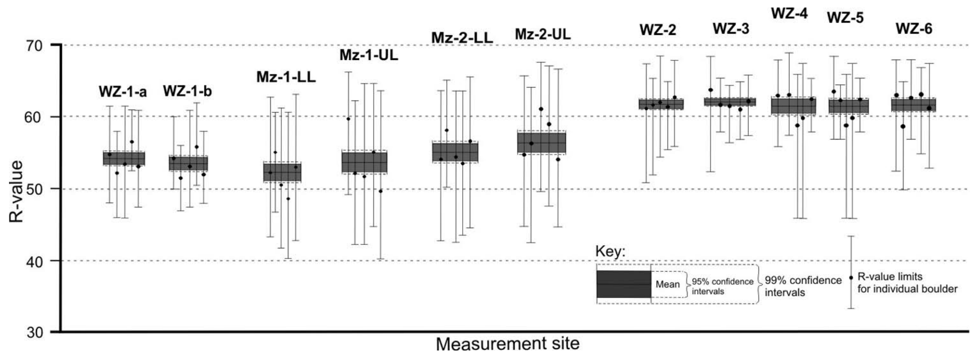

Fig. 5. Results of the Schmidt-hammer rebound (R-value) measurements in the Žiarska Valley. Mean R-values with 95% and 99% confidence intervals are shown for individual sites. Numerals in the graph refer to measurement locations in Fig.1

those on protalus lobes, suggesting that catastrophic rock falls from the 200–260 m high cirque walls had an important role in the rock glacier formation (Fig. 4). At the proximal part of the WZ-6 rock glacier body, deep, irregular depressions are preserved, produced probably by the melting of the internal ice lenses. Geomorphological characteristics of this landform suggest that its formation was complex. It must have formed as a result of debris overloading of a retreating small glacier in a high-walled cirque and succeeding creep of ice/debris mixture owing to permafrost.

ROCK SURFACE WEATHERING

Mean R-values with 95% confidence intervals associated with particular sites are shown in Table 2. Figure 5 shows, the statistical significance of the difference between the mean values by indicating the extent to which the confidence intervals overlap. The mean R-values range from 52.14 (MZ-1-LL) to 62.15 at the surface of WZ-3 rock glacier (Fig. 5, Tab. 2). The 95% confidence intervals are generally low and go from ±0.4 (WZ-3) to ±1.3 (MZ-1-UL, MZ-2-UL). Two clear statistical populations of mean R-values could be distinguished with the local data sets: one which ranges from 52.14 to 56.33 and the other ranging from 61.54 to 62.15 (Fig. 5). The differences between the means for the two populations are statistically significant. The R-values of both MZ-1 and WZ-1 rock glacier sites are very consistent and are not statistically different. Only the MZ-2 rock glacier sites show slightly higher values in comparison with both MZ-1 and WZ-1 values. The mean R-values for the individual rock glaciers lobes in the Malé Závraty cirque (MZ-1-LL/UL and MZ-2-LL/UL) do not differ significantly (Fig. 5). In the case of the MZ-1 and MZ-2 rock glacier lobes difference in mean R-values between lower and upper lobes are 1.22 and 1.33, respectively. There is a fairly clear difference in mean R-values for the rock glacier surfaces in the lower and the upper part of the V’elké Závraty cirque. Mean R-values for the protalus lobes-rock gla-

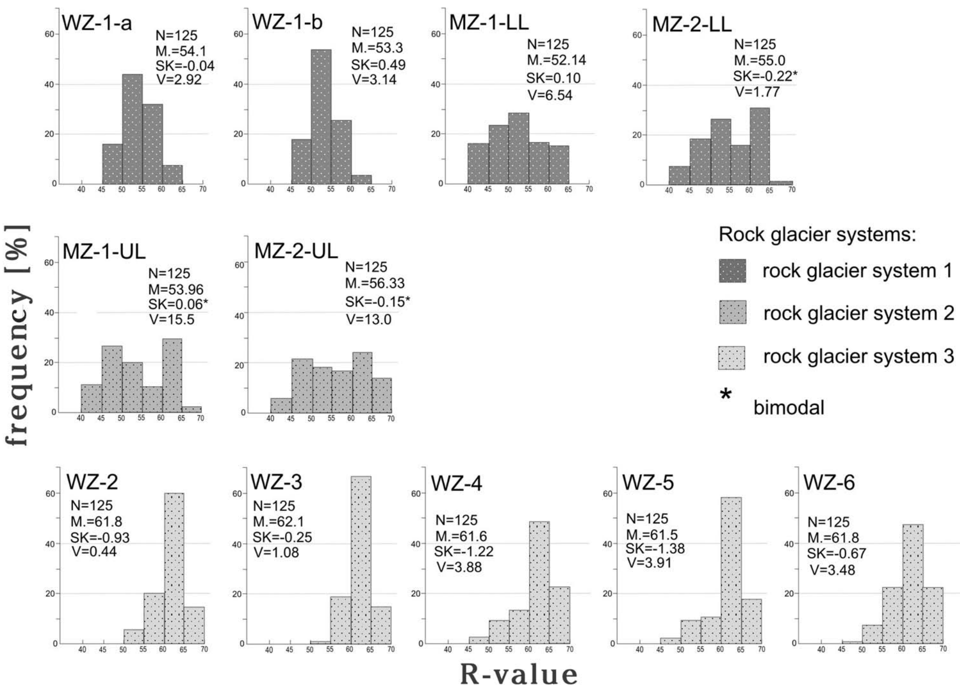

Fig. 6. Frequency histograms of R-values measured in the Žiarska Valley: N — number of measurements, M — mean R-value, SK — skewness, V — coeficient of variation. Numerals in the graph refer to measurement locations in Fig.1

cier system (WZ-2, WZ-3, WZ-4, WZ-5 and WZ-6) are significantly different and show together comparable results (Fig. 5). Their 95% confidence intervals overlap and are low (from ±0.4 to ±0.7). The frequency distribution for most of the samples is unimodal (Fig. 6). Bimodal distribution peaks are seen in the data from both two upper lobes of the MZ-1 and MZ-2 rock glaciers (Fig. 6, Tab. 2). The frequency distributions of MZ-1-UL and MZ-2-UL are strongly tailed. The lowest skewness values were calculated for WZ-1a, and MZ-1-LL sites, with near symmetrical frequency distribution (Tab. 2). All sites in the upper part of V'elké Závraty cirque (WZ-2, WZ-3, WZ-4, WZ-5, WZ-6) exhibit slight negative skewnesss which may point to a somewhat lower mean R-value than observed. (Tab. 2).

DISCUSSION

The Schmidt-hammer measurements in the glacial cirques of the Žiarska Valley reveal mean R-values in the range of 52.14 to 62.15 (δ = 10.01), with generally low 95% confidence limits (Fig. 5). The increase of mean R-values from the lower to the upper part of the valley is observed. R value differences above 10 suggest time periods of some thousands to some tens of thousands of years, even in resistant rocks such as gneiss (A o y a m a 2005, F r a u e n f e l d e r et al. 2005, S h a k e s b y et al. 2006, K e l l e r-P i r k l b a u e r et al. 2008). Schmidt-hammer rebound values indicate a long formation history of the rock glaciers in the Žiarska Valley and combined with geomorphological data point to the three episodes of rock glaciers formation: RG-1, RG-2, RG-3.

The oldest rock glacier episode in the Žiarska Valley (RG-1) indicate the bodies of the MZ-1-LL, MZ-2-LL and WZ-1 rock glaciers. They are present in the lowest geomorphological position and show the lowest R-values. However, R-values results obtained at the MZ-2 rock glacier are slightly higher from those from WZ-1 and MZ-1 features (Fig. 5). In fact, this small anomaly might result from: (i) lithological and mechanical differences between massive granites which built the western part of the Malé Závraty cirques (MZ-2 locality) and more crushed rocks in the eastern part (MZ-1 locality), where common Tatra type granitoides contact with mica-shists of the metamorphic zone; (ii) increase of calculated total mean R-value due to measurements on boulders of higher R-value. This may be the case of the MZ-2-UL feature, where two boulders show significant higher R-value readings (Fig. 5).

The oldest rock glacier system (RG-1) evolved beneath small cirque glaciers (ice-cored rock glaciers), and advanced beyond the limits of glaciers position overriding their terminal moraines. Ice-cored rock glaciers in the Žiarska Valley most probably formed during deglaciation when glaciers retreated into a high-walled cirque and became buried due to high debris supply from frost-shattering of the surrounding rockwalls. The presence of small cirque glaciers above rock glaciers suggests that although precipitation must have been low enough to preclude glacier extension to lower altitudes, it was not so low as to inhibit glacier formation entirely. Considering the fact that MZ-1, MZ-2 and WZ-2 rock glaciers were ice-cored, their creep was initiated during glacier expansion episodes and their activity could be attributed to the continuous supply of moraine debris (K i r k b r i d e, B r a z i e r 1995). Therefore, it is assumed that WZ-1, MZ-1-LL and MZ-2-LL were coeval with the cirque glaciers that formed in the Žiarska Valley during the Zr-2 stade (Fig. 1).

The second rock glacier episode in the Žiarska Valley (RG-2) is indicated by two upper lobes of the MZ-1 and MZ-2 rock glaciers, which were preserved in the Malé Závraty cirques (MZ-1-UL and MZ-2-UL). Schmidt-hammer measurements on the MZ-1 and MZ-2 polymorphic rock glaciers suggest relatively short time gap between the two lobe generations. Instead of their clear geomorphological individuality, both lower and upper lobe of MZ-1 and MZ-2 rock glaciers indicate similar R-values. This may imply a relatively long period of cryogenic conditions without substantial changes of rock weathering conditions. Observations on active rock glaciers suggest that minimal time period of cryogenic conditions for rock glaciers formation is in the range of 100 to 1000 years (B a r s c h 1996). The upper lobes of MZ-1 and MZ-2 rock glaciers are probably contemporaneous with the small cirque moraine ZR-2’ that formed in the eastern part of the V’elké Závraty cirque (Fig. 1). Strongly tailed, bimodal frequency distribution of MZ-1-UL and MZ-2-UL suggests that this data sets contain more than one statistical population (Fig. 6) (Matthews, Owen 2010). Bimodal frequency distribution is likely to express the occurrence of boulders of younger age within the debris of upper lobes. This may be explained by: (i) transport of anomalous boulders onto rock glacier as a results of snow-avlaching or rockfall, or more likely (ii) the reactivation of rock glacier creep in the highest part of Malé Závraty cirques during the RG-3 episode. This may have brought relatively young boulders to the rock glacier surface (Matthews, Winkler 2011).

The youngest system of rock glaciers (RG-3) represents talus-derived rock glaciers and protalus lobes (WZ-2, WZ-3, WZ-4, WZ-5, WZ-6), which were preserved only in the highest part of the V’elké Závraty cirque (Fig. 1). Slight negative skewnesss values of the RG-3 sites indicate that the obtained Schmidt-hammer readings are somewhat higher than original rock surface hardness. This might result from measurements on pegmatite bedrock surface which could produce higher readings than a rougher one. Nevertheless, the highest Schmidt-hammer measurements indicate that the studied features are the most recent cold-stage landforms in the Žiarska Valley and on the southern slope of the Western Tatra Mts. It is likely that these features formed during the final stage of the Late Glacial as talus rock glaciers, however, presence of a small cirque glacier above the body of WZ-6 couldn’t be ruled out. The presence of talus-rock glaciers suggests periglacial conditions during the final stage of cirque deglaciation. Many relict rock glaciers in the Tatra Mts. may have a similar complex history (Dzierżek, Nitychoruk 1986, Kaszowski et al. 1988, Kotarba 1991–1992) and as such they cannot be seen as rather simple landforms developed during the Late Glacial.

CONCLUSIONS

The presence of well developed relict rock glaciers in the cirques of Žiarska Valley in the Western Tatra Mountains provides information regarding Late Glacial relief evolution in this area. Three episodes of rock glaciers formation in the cirques of Žiarska Valley (RG-1, RG-2, RG-3) can be clearly distinguished by use of geomorphological data and Schmidt-hammer measurements. The oldest rock glacier system (RG-1) has evolved beneath small cirque glaciers (ice-cored rock glaciers) and advanced beyond the limits of glacier position during the Zr-2 stade. The second phase of rock glacier activity (RG-2) was attributed to pronounced cooling which caused formation of the upper lobes of MZ-1 and MZ-2 rock glaciers as well as ZR-2’ glacial advance in the highest part of the Žiarska Valley cirques. During the last period of rock glacier creep activity a well developed system of debris features formed in the highest part of V’elké Závraty cirque

(RG-3), and reactivation of the rock glacier creep in the western, highest part of Malé Závraty cirques might also have taken place. The debris features of V'elké Závraty cirque are of periglacial origin and can be classified, according to D. B a r s c h (1988, 1996), as talus rock glaciers. The presence of such landforms implies that during the most recent cold-stage in the Western Tatra Mountains, periglacial conditions were predominatant. The obtained results of Schmidt-hammer measurements confirm that relative age estimation based on this method can be effectively used for Late Glacial rock glacier features. Schmidt-hammer rebound values could postulate local basic morphochronological systems in glaciated cirques and valleys, and enable direct comparison of the results in neighboring valleys of similar lithology, climate, exposition and glacial history.

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