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ARE THERE ANY ACTIVE ROCK GLACIERS IN THE TATRA MOUNTAINS?

Abstract. Research on rock glaciers have been conducted in the Tatra Mountains for about 100 years. About 30 years ago, there were papers suggesting that part of the Tatra rock glaciers was formed during the Little Ice Age. About 20 years ago, permafrost was discovered in the mountains. This discovery marked the beginning of research on the activity of rock glaciers. Ten years ago, a study was carried out on the rock glacier near the Velké Hincovo Pleso lake, which excluded any activity of this glacier in the last few hundred years, despite the high probability of the existence of permafrost in it. The following paper presents the results of lichenometric dating conducted for the activity of rock glaciers in the Świstówka Roztocka and the Buczynowa valleys.

Key words: the Tatra Mts., rock glaciers, permafrost, lichenometry

INTRODUCTION AND THE AIM OF THE RESEARCH

The first mention of the rock glacier in studies of the Tatras appeared in a paper by J. Partsch (1923). A description of these formations, located in the Tatra Mountains in Slovakia, first published in 1973, was included in a paper by M. Lukniš. In 1974, A. Nemčok and T. Mahr published their results of research on rock glaciers in the Tatras and the Low Tatras in Slovakia. In total, within the two groups of mountains, they counted as many as 49 fossil rock glaciers, which, according to them, were formed at the end of the last Würm glaciation. The longest rock glacier catalogued by them is located in the Roháčka valley and is 1950 m long and 150 m wide. M. Klimaszewski (1948, 1988) and A. Jahn (1958) wrote about rock glaciers in the Polish Tatras. The first of the cited authors called them debris glaciers, the second defined them as patch rock glaciers. Both authors linked the appearance of these forms with the Pleistocene glaciation, at the same time accepting the modern movement of these forms, but without the participation of permafrost. Another study of rock glaciers in the Polish part of the Tatra Mountains was conducted by J. Dzierżek, L. Lindner and J. Nitychoruk (Dzierżek, Nitychoruk 1986; Dzierżek et al. 1987). The formations, classified by them as rock glaciers, were divided into four types: valley, cirque, subslope and col rock glaciers. They connect the formation of the first three types to the end of the Pleistocene period and the beginning of the Holocene period. Finally, the fourth type — col rock glaciers — was formed, according to the authors, during the Little Ice Age.

In 1986, a paper by A. Kotarba was published. In it, he claimed that there are at least 14 formations which can be considered as rock glaciers in the Polish part of the Tatra Mountains. The most impressive are to be found in the Western Tatras. The largest of them is in the Jarząbcza valley, 1150 m long and 300 m wide. All of these formations are located at an altitude of between 1500 m and 1750 m above sea level. According to A. Kotarba, rock glaciers in the Tatras were created during the Younger Dryas, or even earlier. Then, climatic belts were lowered by about 200–300 m relative to their present position. In his paper, A. Kotarba first drew attention to numerous boulders covered with the *Rhizocarpon geographicum* lichen forming the rock glacier in the Świstówka Roztocka valley. Such a large quantity of lichen proves the long-term stability of the formation. Two years later, another study by A. Kotarba (1988) was published concerning the origin and age of rock glaciers in the Polish Tatras. The author in this states that only formations classified by J. Dzierżek and J. Nitychoruk (1986) as subslope and col rock glaciers are true rock glaciers. He also denies the possibility of any formation of rock glaciers during the Little Ice Age. In yet another paper, dated 1991–1992, A. Kotarba reiterates that rock glaciers in the Polish part of the High and the Western Tatras were formed in the Younger Dryas and are now inactive. The same statement is also to be found in his later papers (e.g. Kotarba 2004).

In 1988, a paper by L. Kaszowski, K. Krzemień and P. Libelt was published on the modeling post-glacial cirques in the Polish Western Tatras. The authors identified two basic types of rock glaciers: deglacial (debris rock glacier according D. Barsch (1996) classification) and niveo-gravitational (talus rock glacier). The emergence of both of these types of glaciers is associated with the Würm deglaciation. At the beginning of the Holocene period, according to these authors, rock glaciers entered a phase of inactivity or even reliction.

In 1994, W. Dobiński (1996, 1997), in the context of research on permafrost in the Tatra Mountains, performed twenty nine BTS measurements (bottom temperature of the winter snow cover), covering the whole sediment-covered bottom of the Świstówka Roztocka valley, including the rock glacier there (Fig. 1). And it is on the surface of the rock glacier that W. Dobiński registered the lowest values of temperatures of –4°C. According to the assumptions of this method, such low temperatures support the presence of permafrost (Haeberli 1973). Apart from the BTS method, W. Dobiński also applied electro-resistivity sounding on the rock glacier in the Świstówka Roztocka valley. The most interesting result was obtained on the glacier tongue. Namely that, at a depth of 1–4 m, there was a layer of resistance detected at the level of 1MOhmm, suggesting "the presence of buried ice or ice-rich permafrost" (Dobiński 1997). Electro-resistivity sounding was also applied by W. Dobiński on the rock glacier in the Buczynowa valley (Fig. 1), but the result of the probing was not as clear as in the Świstówka Roztocka valley.

In the period 2003–2005, B. Gądek installed a digital temperature recorder on the surface of the rock glacier in the Świstówka Roztocka valley (Gądek, Kędzia 2008; 2009). Ground surface temperature measurements were carried out from autumn to spring. During both winters, temperatures at the floor of snow cover fluctuated around the value of –1.5°C. Despite the fact that the previous BTS measurements (patrol) and electro-resistivity sounding conducted by W. Dobiński (1996, 1997) suggested the existence of permafrost at depths of 0.5 to 3.0 m, but monitoring of the ground surface temperature has not confirmed this.

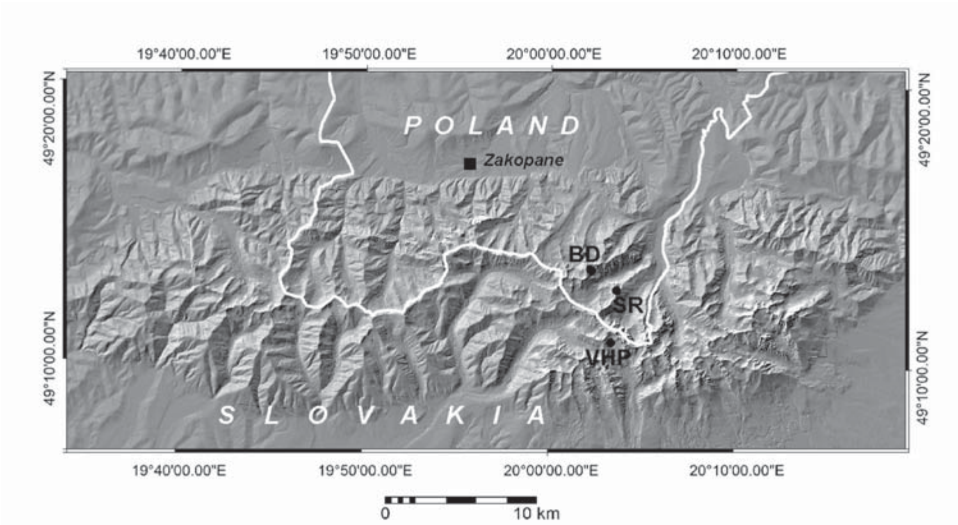

Fig. 1. Map of the Tatra Mountains with the selected research objects: BD — the Buczynowa valley, SR — the Świstówka Roztocka valley, VHR — the Velké Hincovo pleso lake

In 2000–2001, Ł. Ostrowski (2002) carried out precise measurements of rock material movement on the rock glacier in the Świstówka Roztocka valley, using GPS. As the study period was only one year, the values of displacements obtained from these measurements in most cases did not exceed the values of measurement errors. Therefore, the results obtained cannot be considered reliable. In 2008, measurements on the rock glacier in the Świstówka Roztocka valley were conducted one more time by members of the Scientific Society of Geographers, University of Silesia (Ciepły 2011). Fig. 2 shows a numerical terrain model of the valley with the rock glacier in it. Numbers represent the measurement locations and arrows show the direction of movement. Numbers without arrows indicate a lack of movement. The largest displacement, which was about 6 m, was registered at station No. 7. At station No. 1, it was about half as big, and the smallest displacement occurred at station No. 3 — approximately 10 cm. M. Ciepły considers the presence of permafrost as the most likely cause of the movement (Ciepły 2011).

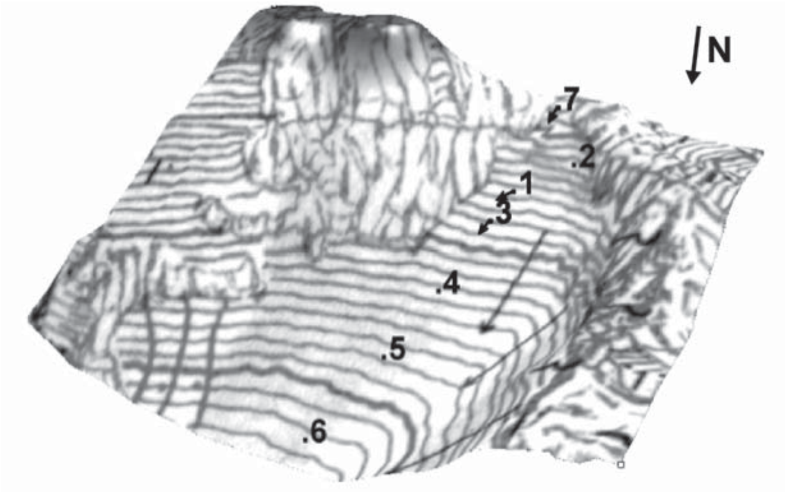

Fig. 2. A numerical model of the rock glacier in the Świstówka Roztocka valley with the selected measurement points. Arrows indicate the direction of movement of the measurement points (Ciepły 2011)

In 2011 and 2013, papers by P. Kłapyta were published on the Schmidt hammer dating of the rock glaciers in the Western Tatras. The author defined three periods of the formation of rock glaciers, connecting them to the last glaciation.

In 2014, S. Kędzia conducted lichenometric measurements on the rock glacier in the Świstówka Roztocka valley and the rock glacier in the Buczynowa valley. The aim of this study was to prove, using lichenometric dating, whether these rock glaciers show movement characteristic of active forms filled with ice.

STUDY AREA

The rock glacier in the Świstówka Roztocka valley is one of the best formed in the Polish part of the Tatra Mountains (Fig. 3). It is behind a small glacial, two-level, hanging valley, open to the north-east. Its length is about 730 m and its width is up to 200 m (Klimaszewski 1988). The valley is surrounded, on the south side, by the Opalony Wierch peak, (2115 m a.s.l.), on the west side, by Kopa peak (1855 m a.s.l.), and on the east side, by the Opalone ridge. The Świstówka Roztocka valley falls with a step of about 400 m to the Roztoka Valley. Lichen measurements were carried out in the range of between about 1800 to about 1970 m a.s.l.

The Buczynowa valley, similarly to the Świstówka Roztocka valley, is a two-level hanging glacier cirque with a length of about 950 m and a width of up to 400 m, open to the south-east. The bottom of the upper level of the valley is located at a height of about 1790–1800 m a.s.l., and the bottom of the lower level is located at a height of 1695–1740 m a.s.l. The valley is surrounded by rockwalls

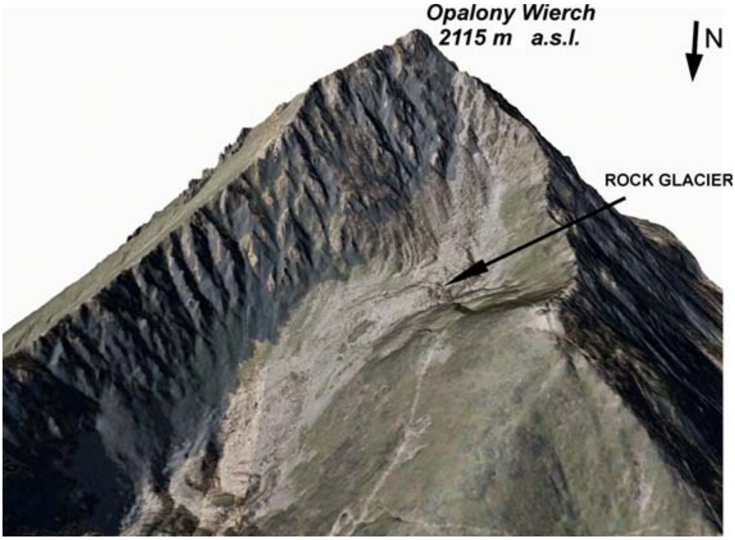

Fig. 3. The rock glacier in the Świstówka Roztocka valley

of the Kozi Wierch peak (2291 m a.s.l.), the Czarne Ściany peaks, the Granaty peaks and the Buczynowe Turnie peaks. The Buczynowa valley hang with a rocky step at a height of about 260 m to the Roztoka valley (Klimaszewski 1988). Lichenometric measurements were carried out on the rock glacier boulders on the upper level of the valley.

METHOD

To estimate the age of *Rhizocarpon geographicum* lichens, a lichenometric curve was used, as drawn for the Polish part of the Tatra Mountains by S. Kędzia (2013, 2014). The measurement was performed to an accuracy of 2–3 mm using a transparent ruler. The largest lichens with a circular shape were selected for measurement. Secondary generations of lichens were found on the overwhelming majority of boulders. Many large lichens were joined with other lichens, making them unsuitable for measuring (Fig. 4). For this reason, lichens which met the requirements of lichenometric dating were usually not the oldest. This means that the given age of the occurance of boulders is the minimum. The actual period of the occurance of boulders' in a given location can be many times longer.

RESULTS AND INTERPRETATION

The surfaces of the boulders forming the rock glaciers in the Świstówka Roztocka valley and the Buczynowa valley are covered with very numerous and old *Rhizocarpon* species of lichens that cause a dark green hue of the glacier visible from a distance (Fig. 5). The diameter of the largest *Rhizocarpon geographicum*

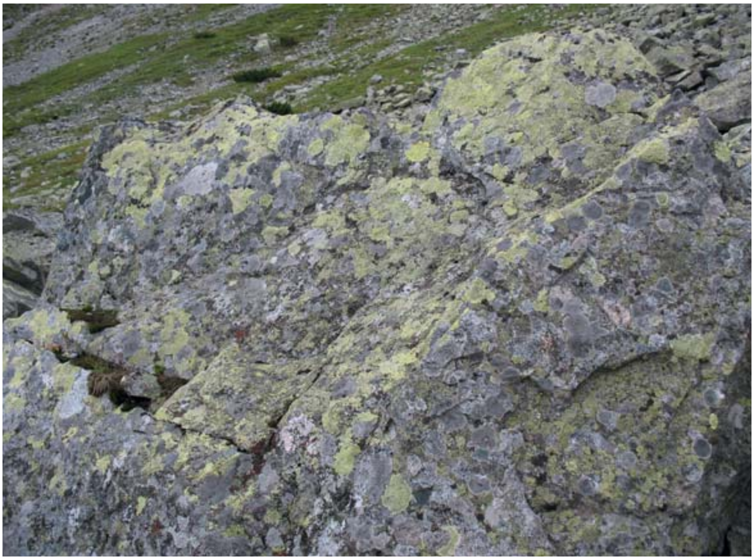

Fig. 4. Boulders of the rock glacier in the Świstówka Roztocka valley with several generations of lichens (by S. Kędzia, 1/07/2014)

Fig. 5. The surface of the rock glacier in the Świstówka Roztocka valley (by S. Kędzia, 1/07/2014)

lichens reached about 110–140 mm. The lichen factor for the height interval in which the measurements were made is between 33 to 36 mm / 100 years, assuming that the lichens in these glacial cirques grow as fast as on the flat or convex forms of the slopes for which the lichenometric curve has been drawn. For the largest measured lichens, we can deduce ages, depending on the altitude, from about 360 to 420 years. At the same time, as stated above, the largest lichens were not the oldest. Currently, the existing living lichens on rock surfaces are of a subsequent generation.

For lichens to be able to colonize a rock surface and grow on it, they must receive, inter alia, the right amount of light and water. Changes in the position of the surface of rocks lead to disturbances in the growth of lichens and, in the case of large restriction of the amount of light and water, will cause their death (Haeberli et al. 1979). On active rock glaciers, the rock material forming the glacier is bonded with ice and subject to movement. Boulders on the surface of the glacier change their position, move in different directions, and are reoriented (Jahn 1970; Kotarba 1991–1992). Assuming that the age of the largest measured lichens is approximately 400 years old, it is difficult to believe that during such a long period of time, the boulders on the surface of the active rock glacier have not changed their position. Given that the largest measured lichens were not the oldest, not only the contemporary activity of rock glaciers should be considered unrealistic, but also the theory concerning their formation during the Little Ice Age (LIA).

The movement of boulders on the upper level of the rock glacier in the Świstówka Roztocka valley, as reported by M. Ciepły (2011) is not evidence of glacial activity. Both on the rock glacier in the Świstówka Roztocka and the rock glacier in the Buczynowa valley, single boulders, or clusters of a few boulders can be found to be completely or partially devoid of lichens. The closer to the slopes of the valley, especially chutes and talus cones, the more devoid of lichens the boulders occur.

Figure 6 shows the edge of the rock rubble with a rock glacier visible in the background. In the foreground, there are the remains of a snow patch, very old

Fig. 6. Fresh rocky boulders at the limit of debris cover in the bottom of the Buczynowa valley (by S. Kędzia, 2/07/2014)

rocks covered with lichens, and two small boulders without any lichens, with very fresh surfaces. These fresh boulders are the result of the process of rockfall off the rock walls and deposition. After the falling boulders rolled down a steep slope (largely covered with alpine meadows) and stopped at the first boulders of the rock debris cover the valley bottom. Such a situation occurs when there is no snow cover, or it is very thin. In winter and spring, when the snow cover is sufficiently thick and hard, we have to deal with the situation shown in Figure 7. Both large and small boulders that have fallen off the rock wall, slide on the smooth and hard snow cover not only on the steep slopes, but also at the bottom of the valley. In the case of very thick snow cover, covering large depressions, material passes even onto the top of the tongue of the rock glacier (Fig. 8). Large boulders rolling down a rocky slope and snow avalanches hitting the boulders forming a rock glacier, can make them move. Such situations are presented in Figure 9. The boulder on the right has been rotated by about 180°. Its upper part covered with lichens turned up at the bottom, and the bottom of the boulder, devoid of lichens due to the lack of sunlight, was exposed and was on the top.

The lack of lichens on the surface of boulders may not always be due to a supply of fresh material from the slopes, or the movement of material forming the rock glacier. Figure 10 shows a place with a residual snow patch. In places where snow is overdue, the colonization of rock surfaces by lichen is very difficult, and sometimes impossible (Haeberli et al. 1979). In the place shown in the picture, every year, or every few years, snow remains long enough to prevent

Fig. 7. Photos present boulders on the surface of a snow patch in the Buczynowa valley (by S. Kędzia, 2/07/2014)

Fig. 8. A fresh boulder at the back of a rock glacier tongue in the Świstówka Roztocka valley (by S. Kędzia, 1/07/2014)

Fig. 9. A rotated and moved large boulder on a rock glacier in the Świstówka Roztocka valley (by S. Kędzia, 1/07/2014)

Fig. 10. Places devoid of lichens due to a long-lasting snow patch in the Buczynowa valley (by S. Kędzia, 2/07/2014)

colonizing the surface of boulders by lichens. A lack of lichens is therefore not the result of a movement caused by gravity or freezing. It results only from a prolonged period of snow cover.

CONCLUSIONS

Lichenometric dating indicates that the rock glaciers in the Polish Tatras were formed before the LIA. Unfortunately, due to a relatively rapid growth of the lichens, the exact time period of their formation is, however, impossible to determine. The rock glaciers, most probably, began to develope, as most authors claim, at the turn of the late Pleistocene period and the beginning of the Holocene period. Some rock glaciers could still be active, or even form during the Venediger period, when the last high-altitude marginal glaciers of the Tatras melted (Baumgart-Kotarba M., Kotarba A. 2001 a, b). An analysis of the spatial distribution of lichens and their age shows that, during the LIA, rock glaciers showed no movement characteristic of this type of active forms including the ice. Any movement of individual boulders, or even a group of boulders, forming a rock glacier, does not need to be associated with the permafrost. Due to hitting by snow avalanches and material falling from the slopes, boulders forming a rock glacier can be rotated and moved. It most often happens in the marginal parts of a glacier, especially in contact with debris-flow cones. Also, in steeply sloping places, rock material, under the force of gravity, may show slight movement, especially when it is freshly deposited and very loosely packed.

Although research by B. Gądek and S. Kędzia (2008, 2009) ruled out the existence of contemporary permafrost on the rock glacier in the Świstówka Roztocka valley, it cannot be excluded that such permafrost exists in some rock glaciers in the Tatras. In 2001–2003, S. Kędzia, A. Kotarba and J. Mościcki conducted, research into the rock glacier at Velké Hincovo pleso in the Slovak part of the Tatra Mountains (Kędzia et al. 2004). The results of these studies suggest the presence of permafrost, but within only a small part of the glacier. However, the presence of permafrost in the studied glacier does not cause any movement. On the surface of the glacier, lichens with a diameter of several centimeters were measured, demonstrating no movement for at least a few centuries.

According to the studies conducted so far, there is no evidence of rock glacier formation during the LIA, nor their activity both during the said cooling and the present.

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