Geographia Polonica
Volume 86, Issue 4, pp. 363–374
http://dx.doi.org/10.7163/GPol.2013.29

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
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PROBLEMS AND POSSIBILITIES OF LICHENOMETRIC DATING IN POLISH MOUNTAINS

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Abstract

The paper presents problems faced when using a new method for defining the growth curves of the thalli of the rocky lichen *Rhizocarpon spp.* in the Polish section of the Tatra and Karkonosze Mountains. Lichenometric curves based on pre-existing data were defined for two climatic-vegetation zones in the Tatra Mountains. These were mainly representative of substrates located in the central parts of these zones. In the new lichenometric curve which was constructed for the Tatra and Karkonosze Mts., the thallus growth curve for the first 100 years was defined in a linear manner in relation to altitude. Therefore the curve can be easily used for dating items located in any part of the altitude zone for which the curve was defined.

The paper also tackles the problem regarding the number of thalli that should be assessed when dating. An approach which assesses a certain number of the largest thalli of a similar diameter seems to be the most suitable for small-scale landforms (with small numbers of thalli) which were formed during one event. The shape of the thallus growth curve is strongly influenced by the landforms (either convex or concave) and the vertical extent of the zone in which the measurement is performed. The presence of multiannual snow patches in close proximity and air pollution also influence thallus growth on the mountains investigated. The geomorphic processes taking place turned out to be a significant problem for proper dating of the items – depending on their interpretation they can either help dating or obscure the reconstruction of the event.

Key words

Rhizocarpon • lichenometry • Tatra Mts. • Karkonosze Mts.

Introduction

The first publication on the basic principles of the method of lichenometric dating was published in 1950 by R.E. Beschel. Since that publication appeared many other papers have presented more and more details of that method, improving its methodology (Beschel 1950, 1957, 1961, 1973; Benedict 1967, 1991, 2008; Locke et al. 1979; Innes 1982, 1985a, b; Kotarba 2001; Armstrong 2002; Bradwell 2004). New lichenometric curves have continuously been created for new areas and lichenometric dating has gained increasing attention, not only among geographers. Along with increasing numbers of studies and papers on that method, new issues appear which take account of both the limitations of using the method and new possibilities for its implementation.

Study area

The Tatra Mountains, whose highest peak is Gerlach in Slovakia (2655 m a.s.l.), form the highest range in the Carpathians. They are more than

Figure 1. Location of the study areas.

50 km long and almost 20 km wide (Fig. 1). The Tatra landscape is of an alpine type (Klimaszewski 1988), the last small glaciers at high elevations melting in Venediger (8.3 ka BP) (Baumgart-Kotarba & Kotarba 2001). Nowadays, the glacial corries are filled with multiannual patches of firn and ice, as well as with inactive, fossil rock glaciers. There is also permafrost in the Tatra Mts., mainly in talus cones, ice caves and numerous debris flows which occur on rockfall-scree slopes. The study area includes the Polish part of the High Tatras and the Western Tatras (from the Rybi Potok Valley to Kopa Kondracka), built up mainly of crystalline rocks (granites, gneisses). The substrates chosen for examination were all man-made (monuments, roads, huts, split boulders) and were located in the altitude range from 1500 to 2134 m a.s.l. on the mountain ridges (including passes), slopes and valley bottoms (Tab. 1). Mean annual air temperature in this area ranges from 2.5 to -1.5°C, and mean annual precipitation oscillates between 1000 and 1450 mm (Hess 1965, 1996).

The first lichenometric curve for the Tatra Mts. and first dating based on that method were produced by Kotarba (1988). Recently, a new lichenometric curve has been constructed, using a new method (Kędzia 2013).

The Karkonosze Mountains form the highest range in the Sudetes (Fig. 1). The range is longer than the Tatras (70 km), while its width is similar (20 km). The highest summit is Śnieżka (1602 m a.s.l.) and it is the only peak in the entire Sudetes which is of a high-mountain type. The Karkonosze Mountains are built of crystalline rocks, mainly granitoids (Czerwiński 1985; Oberc 1985). Nowadays, there are no multiannual firn-ice patches in the Karkonosze and neither has permafrost been detected there. Only the debris flows are numerous, mainly in glacial corries (Parzóch et al. 2008). The study area includes the main ridge of the Karkonosze Mountains from Szrenica Alp to Śnieżka. As dating references the author used man-made structures (buildings, monuments, roads) located along the main ridge and below it on the north-facing slopes at an altitude range of 1168-1602 m a.s.l. (Tab. 2).

Mean annual air temperature in this area ranges from 0.4 to 3.0°C, and mean annual precipitation is 1500 mm (Kwiatkowski & Hołdys 1985). The study area is located in the cool and very cool climatic zones (Migała 2005).

The first lichenometric curve for the Karkonosze Mts. has recently been constructed by Kędzia (2011). The lichenometric dating of debris flow levées and gullies is currently being carried out.

Table 1. Location of reference structure in the Tatras.

Reference structure	Altitude [m a.s.l.]	Structure creation date [year]	Lichen factor [mm/100 years]
Shelter ruins at Krzyżne	2134	1880	29.8
Shelter ruins near Kopa Kondracka	1859	1889	34.4
Debris flow near Zielony Staw	1820	1988	35.5
Debris flow near Zielony Staw	1710	1988	38.4
Shelter ruins of Gienkowe Mury	1707	1941	37.9
Shelter ruins near Mały Staw Polski	1651	1932	38.0
Pavement to Strażnicówka shelter	1650	1946	38.5
Shelter at Czarny Staw	1628	1930	39.5
Monument of Karłowicz	1530	1909	41.7
Boulders near Murowaniec hut	1500	1951	41.7

Table 2. Location of reference structures in the Karkonosze Mts.

Reference structures	Altitude [m a.s.l.]	Structure creation date [year]	Lichen factor [mm/100 years]
Boulders on Śnieżka peak	1602	1967	33.8
Droga Jubileuszowa (road)	1570	1964	34.7
Droga z głazów (pathway)	1570	1852	37,7
Stake near Wielki Szyszak	1503	1946	36.3
RGV bench	1422	1906	37.0
Ruins of Prinz-Heinrich-Baude	1415	1880	37.4
Boulders near Szrenica hut	1359	1921	37.6
Boulders near Szrenica hut	1359	1949	37.7
Monument of Kalmanov	1352	1930	37.5
New hut near Łabski Szczyt	1168	1938	39.6

Number of thalli

The number of thalli which it is recommended should be assessed when carrying out lichenometric dating differs according which of various authors one refers to. Usually it is recommended that the 5 largest thalli should be selected, however, only those ones which are circle-like should be selected (e.g. Birkenmajer 1980, 1981; Innes 1984, 1985a; André 1986, 1990; Sioberg 1990; Evans et al. 1999; Pech et al. 2003; Sołomina et al. 2010; Angiel & Dąbski 2012).

If the thalli with the maximum diameter are similar in size and they are numerous, their mathematical average will be roughly the same. In this case the number of thalli measured does not influence the results, no matter if it is the 5 or 10 largest lichen patches that are taken into consideration. Such a situation can be exemplified by one of the reference structures (with a known date of origin) in the Karkonosze Mts. (Tab. 3). The average diameter calculated on the basis of the first 5 thalli is 23.1 mm, while the average diameter of all 10 thalli is 22.8 mm. The difference between the results is only 0.3 mm and it is smaller than the accuracy of the measurement, which is 0.5 mm.

A great conformity in size of thallus is observed when comparing the 5 largest thalli. Only one thallus differs from the others by 0.5 mm, which is also the accuracy of the measurement. When we compare the size of the 10 largest thalli, the difference between the smallest and the largest one is 1.5 mm. However, the remaining 8 thalli are 22.5-23.0 mm in diameter. Therefore even in this

Table 3. The diameter of the 10 largest thalli on two reference structures.

Ordinary number	Thalli diameter of the first reference structure	Thalli diameter of the second reference structure
	10 largest thalli [mm]	10 largest thalli [mm]
1.	23.5	38.5
2.	23.0	38.5
3.	23.0	38.0
4.	23.0	35.0
5.	23.5	35.0
6.	23.5	35.0
7.	22.5	34.0
8.	22.5	33.0
9.	22.5	30.0
10.	22.0	30.0
Difference between the smallest and the largest thalli [mm]	1.5	8.5
Average diameter (the first 5 thalli) [mm]	23.1	38.3
Average diameter (10 thalli) [mm]	22.8	34.7

case the difference between most of the thalli is only 0.5 mm.

On the second reference structure the average diameter for the 10 largest thalli is 34.7 mm, while for the first 5 largest thalli – 38.3 mm (Tab. 3). In this case the difference between these two measurements is 3.6 mm, while the difference between the smallest and the largest thalli is as much as 8.5 mm. The thalli sizes can be classified into three distinct classes: 30.0 mm; 33.0-35.0 mm; 38.0-38.5 mm. Their difference is 3.0 mm.

This suggests that these 10 thalli appeared on the reference structure at different times. It can be assumed that progressive development of the thalli was observed in that location. The first thalli to colonize the surface are the ones with a diameter of 38-38.5 mm and only after around 10 years did the next thalli develop (the ones with a diameter of 33-35 mm). It is probable, that there were more thalli in the first stage of the colonization, however, they became connected to other thalli afterwards and as such, they do not meet the requirement for that method of dating.

This example shows, that only three thalli from the range 38-38.5 mm should be considered for calculating the average diameter. Taking into consideration a larger number of thalli from other size classes leads to obscuring the results and increases the dating error. This proves that only the oldest thalli, which do not differ much in size, should be considered for calculating the average diameter. If the thalli diameters are of the same or almost the same size, the number of thalli measured does not influence the results of the calculation.

The size-frequency approach method introduced by Benedict (1967) and applied by many researchers (e.g. Lock et al. 1979; McCarroll 1993; Bradwell 2001, 2004, 2009; Dąbski 2007; Orwin et al. 2008; Golledge et al. 2010; Roberts et al. 2010; Angiel & Dąbski 2012) could not be applied in this study because (i) all the dating reference structures were developed in a short period of time (up to a few months), (ii) the area and number of thalli on some structures were small, (iii) dating reference structures were of a young age (usually several decades).

Straight or curved?

Various shapes of thalli growth curve are presented in the literature. Some of them are straight lines for their entire length, while others are straight only for the first dozen or so, or several dozen years and other curves do not form any straight lines at any stage (Denton & Karlén 1973; Calkin & Ellis 1980; Orombelli & Porter 1983; Kotarba 1988; O`Neal & Schoeneberger 2003; Pech et al. 2003; Solomina & Calkin 2003; Wiles et al. 2010). This issue has been analysed for the thallus growth curve in the Karkonosze Mts.

The reference structures were composed of crystalline rocks (mainly granitoids) and they were located on the main ridge and on a dissected slope with a Northern aspect, and within the altitude range from 1168 up to 1602 m a.s.l. (Tab. 2). This was in contrast to the Tatra Mts. where some structures were located within convex landforms (mountain ridges) and others within concave landforms (floors of deeply incised valleys) (Tab. 1). Therefore differences in mean annual temperature at the reference sites in the Karkonosze are mainly due to the altitude difference and are not additionally influenced by the type of relief and landforms.

The thalli growth curve for the Karkonosze Mts. is presented in Figure 2. It was constructed on the basis of all the 10 reference structures, which cover an altitude range of 434 m and refer to two climatic zones: cool and very cool (Migała 2005). The curve is a second grade polynomial and is arch-shaped.

The thalli growth curve for an altitude range of 335 m (from 1168 m a.s.l. up to 1503 m a.s.l.) is presented in Figure 3. It is also a second grade polynomial. However, its shape differs substantially to the curve presented in Figure 2, as it forms an almost straight line.

When comparing these two curves, it can be stated that their shapes were highly influenced by the altitude range. Its contraction by 100 m resulted in a total change of the shape of the thalli growth curve from an arched line into an almost straight line.

Such a situation can be explained by the difference in mean annual air temperature at the locations of the reference structures. The larger the altitude difference between the highest and the lowest elevation of the reference points, the bigger the difference in mean annual temperature. The rate of thallus growth is highly dependent on temperature and the resulting period of occurrence of snow cover (Coxson & Kershaw 1983; Iwafune 1997; Trenbirth & Matthews 2010), therefore the rate of thallus growth changes according to changes in altitude.

The results prove that only thalli from a narrow range of altitude, where the differences in thallus size are negligible, should be taken into consideration when constructing the thalli growth curve.

The shape of the thallus growth curve is also influenced by the type and shape of landform where the reference structures is located. It can be exemplified by the thallus growth curve which was constructed for the Tatra Mts. using the new method (Kędzia 2013).

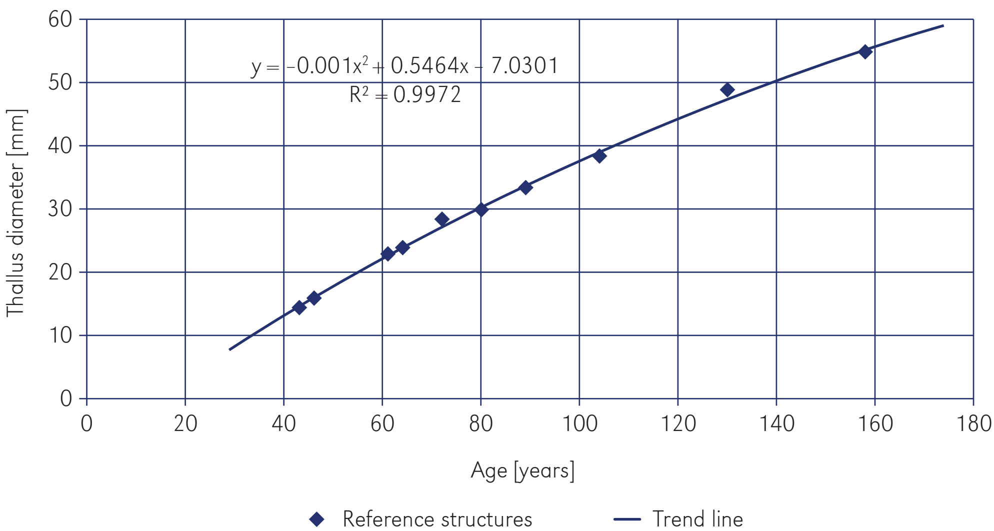

Figure 2. Thalli growth curve for the Karkonosze Mountains for cool and very cool climatic zones.

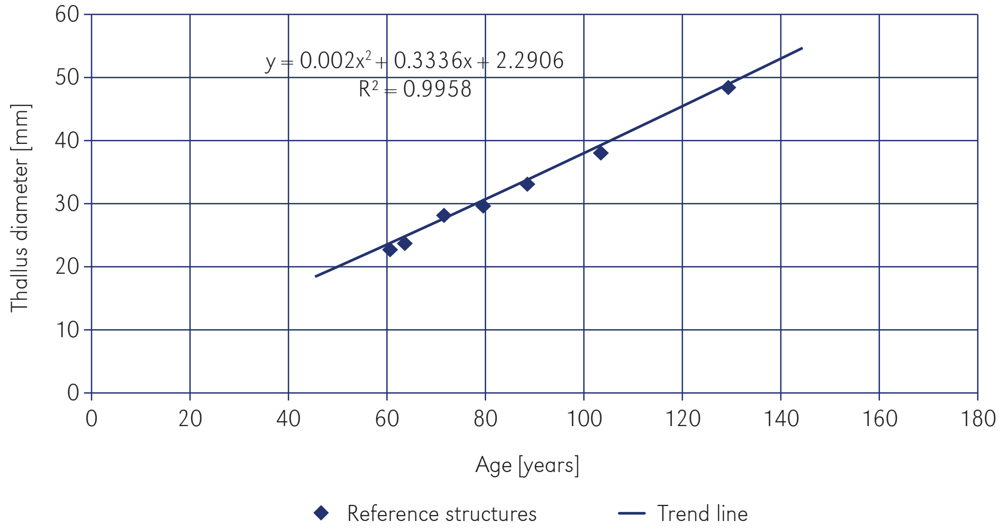

Figure 3. The thallus growth curve for the Karkonosze Mountains for the cool climatic zone alone.

The highest located reference structures are situated on mountain ridges (convex landforms). Thermal inversion is thus not observed in such places and the snow cover is usually thin due to wind blow. In contrast, most other reference structures are located within the large valley floors where thermal inversion is quite frequent and the snow cover is much thicker than on the ridges.

As a result, the difference in mean annual air temperature between mountain ridges and valley floors is smaller than the difference in altitude would suggest. Therefore the rate of thallus growth which can be observed on the reference structures located within the valley floors is slower than that observed on mountain ridges located at the same altitude above sea level. In this case the thallus growth curve forms an almost straight line. Unfortunately, the role of thallus age and its connection with thallus growth in influencing the shape of the curves (McCarthy 2003; Bradwell & Armstrong 2006; Bradwell 2009, 2010) could not be observed in either of the mountain regions investigated as the period of the investigation was not long enough.

The impact of snow patches

The mass balance of multiannual snow patches, in the same way as that of glaciers, is an important indicator of climate change. Therefore the largest snow patches on the Tatra Mts. have been under constant monitoring for around 30 years (Wiśliński 2002).

However, the reconstruction of their former surface and thickness from years prior to this period, for example from the end of the Little Ice Age, is very difficult. The reason for that is the negligible, compared to glaciers, change in the extent of the snow patches and, usually, a lack of distinct landforms, like moraines. One of the methods which permits one to estimate the dimensions of snow patches is lichenometric dating (Benedict 1991; Iwafune 1997; Golledge et al. 2010). It is difficult to date the extent of snow patches, but this is, in contrast, possible for the glacial moraines. Estimation is thus a better term to use than dating in the case of the snow patches. Most glaciers show a constant trend of recession since the end of the Little Ice Age, often on a large scale. Some of the ice fronts have receded by several hundred metres or even more (Zemp et al. 2008).

In contrast, the changes in the extent of snow patches do not usually exceed several or dozen or so metres due to their small size. The old nival moraines are overlaid by frequent oscillations. The maximum thickness of the snow patches is much easier to reconstruct than their surfaces. It can be determined from measurements of the lichen thalli overgrowing the rock walls. However, dating the maximum extent of the snow patches using the same method can give false results, as thallus growth is influenced by the close proximity of the snow patch.

According to research carried out by Rączkowska (1995) in the Tatra Mts., the impact of the snow patch on air temperature can extend as much as several dozen or so metres from the patch. Therefore the thalli which grow in close proximity to a snow patch have a slower growth rate than thalli occurring at a larger distance (several dozen or more metres). That impact is also enhanced by the occurrence of a long period of seasonal snow cover around the snow patches (Iwafune 1997; Trenbirth & Matthews 2010). The slower rate of thallus growth has the effect that the thalli are attributed a much younger age than their true age. Unfortunately, that error in dating is very difficult to eliminate, as it requires that reference structures be located in close proximity to a snow patch.

Dating and slope processes

The lack of thalli or the occurrence of mainly very young thalli on the surfaces of debris-rockfall cones is usually interpreted as an intense supply of debris material from rock walls. In many cases such an interpretation is correct. However, in some cases the lack of the thalli is the result of processes which only occur within the talus, with no additional influence of any material supply from the rock cliffs. If the upper part of the talus is overgrown by a wide belt of dense dwarf mountain pines, only snow avalanches, large debris flows and large boulders can overcome such a barrier. The remaining weathering material is trapped within the dwarf mountain pines zone. Only during very snowy winters, when the dwarf mountain pines are completely covered with snow, can the fine material be easily transported along the entire talus (Kędzia 2010).

A small part of a talus cone of debris-rockfall origin, which is located in the Tatra Mts., is presented in Figure 4. There is a visible lack of thalli on the debris surrounding a boulder. However, the boulder itself is overgrown by thalli from all sides. The same applies to another boulder which is partly visible in its vicinity. Such a situation can easily be explained by the constant and intense fresh supply of debris from the rock wall. The fresh surfaces of debris are covered by new debris before they can become colonized by lichen. However, detailed investigation of the boulder's surface suggests a different conclusion. The lower part of the boulder is entirely devoid of thalli. There are no signs of movement or rotation, neither of the boulder nor of the other boulders nearby. This

Figure 4. A boulder with an uncovered, thallus-free lower section.

suggests, that the entire surface of the boulder has been exposed quite recently, as lichen has not yet managed to colonize it .

The exposure of the surface may be the result of the movement down the talus of the finer material which formerly surrounded the boulder. According to the measurement of the distance between the ground surface and the line of the thalli on the boulder, one can determine the thickness of the debris cover which was transported down the talus. The reason for triggering the talus instability and the movement of the debris is another question.

In the Karkonosze and more frequently in the Tatra Mts., there are numerous boulders which used to be deeply submerged in the debris cover and which were later exposed, for example during repeating episodes of debris flow within the same gully. As a result, thalli of various sizes are found on the surfaces of the boulders depending on the time when the debris flow occurred. Such boulders not only permit the reconstruction of the dates of various episodes of geomorphic processes, but also the estimation of the amount of eroded material from these sites.

Pollution

The construction of four large mining and energy industry centres was commenced in the 1950s at the junction of the borders of Poland, Czechoslovakia and Germany. They had a large impact on environmental conditions in the Western Sudetes due to pollution, additionally enhanced by the unfavourable circulation of air masses which approach the area from the west. The gas and dust emissions were the main reasons for the ecological disaster which occurred in some parts of these mountains. In spite of the limitation of the pollution in the later period (due to the introduction of modern technologies and the closure of many of the industrial estates), the remaining industry still influences the natural environment of that part of the Polish mountains.

The field work revealed a substantial difference in the number of thalli of the lichen species *Rhizocarpon* between the Karkonosze and the Tatra Mts. The most distinct difference was observed for the youngest population of thalli. In the Tatra Mts. the freshly exposed rock surfaces are colonized by lichen within a few years, while in the Karkonosze Mts. the colonization is retarded and the overall number of thalli is much smaller. Therefore the lichenometric dating in the Karkonosze is much more difficult and less precise than in the Tatra Mts.

A large amount of pollution emitted by the mining and energy industries influences not only the rate of lichen colonization and the number of thalli, but certainly also the rate of thallus growth (Jonasson et al. 1999; Haffner et al. 2001; Jovan 2008). It can be assumed that the growth was slower over the last 50 years than in the previous period. This assumption does not influence the accuracy of the dating of items which are several dozen years old. However, the dating of items which are much older than the oldest reference point may result in a high level of error.

Conclusions

The problems of lichenometric dating presented in this paper do not affect the two mountain ranges to the same extent. As far as the number of thalli is concerned, the problem is more significant in the Karkonosze Mts., which is due not only to a higher level of pollution, but also to a more rapid expansion of the vegetation cover which overgrows the landforms being dated much faster than is the case in the Tatra Mts. In the Karkonosze Mts. many debris flows (for example in the Łomniczka Corrie) end in the upper forest zone, while in the Tatra Mts. most of the debris flows finish in the alpine or subalpine zone. The much smaller number of thalli occurring on the old landforms in the Karkonosze, such as gullies and levées of debris flows, can thus be connected with their being more rapidly overgrown by vegetation. The number of thalli, as mentioned above, is also influenced by the level of pollution. This problem mainly affects the Karkonosze Mts., however, it also occurs in the Tatra Mts. While constructing the first lichenometric curve for the Tatras, there was a big problem in finding thalli at an altitude lower than approx. 1000 m a.s.l. This situation was explained by the inversion of temperature and build up of pollution over Zakopane, which is a town situated in the foothills of the Tatra Mts. (Jonasson et al. 1991).

The discussion on the number of thalli presented above refers to the landforms and structures which formed or were built over a short period of time, such as debris flows, rockfalls, monuments. Their surface is usually not very large and thus the number of thalli is small. For large landforms, which were formed during a longer period of time and are composed of material of various ages (such as glacial moraines), a different method is more suitable, namely the size-frequency approach developed by Benedict (1967). However, the youngest glacial moraines in the Tatra Mts. are as old as the beginning of the Holocene and the use of lichenometric dating is not possible because of the relatively fast and abundant colonization of the surface of the rock and the high growth rate of the lichen. The biggest thalli found in the Tatra Mts. which meet the criteria of the dating method were about 20 cm in diameter, which means they were about 500-600 years old. The same problem applies to the rock glaciers. Only the protalus ramparts around the multiannual firn-ice patches can be dated by the use of the size-frequency approach.

The problem of the impact of the location of the reference structures on the shape of the thallus growth curve mainly occurs in the Tatra Mts. The influence of relief on variations in temperature is substantial due to the location of some of the reference structures within the valley floors and some others within the upper parts of the mountain ridges. In the Karkonosze Mts. the differences in temperature between the reference locations resulted mainly from the differences in altitude, as they were all located on slopes, mountain ridges or summits. Such a location of the reference points is connected both to the general relief of the mountains and to human impact, mainly tourism and grazing.

The problem of the influence of snow patches on the rate of thallus growth mainly applies to the Tatra Mts. because the multiannual snow patches only occur in these mountains. The biggest of them are called glacierets. There are snow patches in the glacial corries in the Karkonosze Mts. as well, however, they are much smaller in size and – in contrast to the Tatras – they are not multiannual and no annual layers are preserved.

The impact of slope processes on lichenometric dating should be considered in both mountain ranges. Nevertheless, it is much more often observed in the Tatra Mts. This is mainly due to the relief and to the temperature, which is mostly determined by altitude above sea level.

The problems of lichenometric dating in the Polish mountains, which are presented in this paper, are most crucial for proper and accurate dating. On the other hand, the problems presented in this paper are not only typical for Polish conditions but may also apply in other regions of similar relief and environmental characteristics across the world.

Acknowledgements

I wish to express my gratitude to Prof. Adam Kotarba, Dr Agnieszka Latocha, Dr Krzysztof Parzóch, Dr Joanna Remisz, The Board of the Tatras National Park and Karkonosze National Park for help in collecting data, conducting field studies and discussions on the manuscript.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

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Article first received • July 2013
Article accepted • October 2013