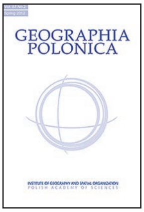

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LICHENOMETRIC CURVE FOR THE SOUTHERN SLOPE OF THE TATRA MOUNTAINS (SLOVAK TATRAS)

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Abstract

This paper presents the first lichenometric curve of *Rhizocarpon geographicum* for the southern slope of the Tatra Mts (Slovak Tatras). The curve was developed based on measurements carried out in the years 2018-2019. The curve was constructed using measurement results from 9 objects of known time of origin, situated in the Tatra Mts. at an altitude of 1,250-1,900 m a.s.l. On each of them, the diameter of the 5 largest thalli was measured. Their average diameter was assigned an age value and then the lichen factor was calculated and a classical lichenometric curve was developed, as well as a modified curve taking into account the effect of altitude on the rate of thallus growth. The lichen factor is in the range between approx. 34.5 mm/100 years at 1,900 m a.s.l. and 44 mm/100 years at 1,250 m a.s.l. No significant differences were found in the rate of thallus growth between the southern and northern slopes of the Tatra Mts.

Key words

lichenometric dating • *Rhizocarpon geographicum* • Tatra Mountains

Introduction

Since the time when the work by R.E. Beschel (1950), presenting the basics of the lichenometric dating method, appeared in the literature in the 1950s, many publications in this field have been published, which have made the principles of using this method more detailed and increased the accuracy of dating (Beschel, 1961, 1973; Jochimsen, 1973; Armstrong, 1976, 1978, 1981, 1983, 2002, 2006, 2013, 2015, 2016; Lock, Andrews, & Webber, 1979; Innes, 1982, 1983, 1984, 1985a,b, 1988; Coxson & Kershaw, 1983; Benedict, 1990, 1991, 2008, 2009; Karlèn & Black, 2002; Armstrong & Bradwell, 2001, 2010a,b, 2015; Bradwell, 2004; Trenbirth & Matthews, 2010). They have demonstrated, among other things, that an essential precondition for the accuracy of dating by this method is a properly constructed lichenometric curve (Kędzia, 2015). Moreover, it has been proven that the lichenometric curve for a specific mountain area varies depending on the altitudinal zones or with respect to the individual parts of the area (e.g. Beschel, 1961; Kotarba, 1988; Armstrong, 2016). Due to the low cost intensity and simplicity of the method, lichenometric dating is used in various sciences; it is particularly common in geomorphology (Denton & Karlén, 1973; Karlén, 1973; Webber & Andrews, 1973, Matthews, 1974; Birkenmajer, 1981, 1982, 1991; Innes, 1983, 1984, 1988; 1985b; Kotarba, 1988, 1989, 1991, 2001; Dąbski, 2002, 2007; Bradwell, 2009; Armstrong & Bradwell, 2010a; Sołomina, Ivanov, & Bradwell, 2010).

Although more than half a century has passed since the first applications of this method, it is often disregard. The reason for this is mainly the difficulty in developing a lichenometric curve for a particular area. It is not always possible to find a sufficient number of objects that would meet the requirements of this dating method and thus guarantee its accuracy. Typically, it proves impossible to meet the basic criteria for such objects, i.e. known date of their formation, the presence of thalli with undisturbed growth (e.g. by high vegetation or roofing) and an appropriately large number of objects having these features in a certain range of altitudes (applies to mountains). It is not uncommon that, only two or three out of 50 pre-selected objects meet all the requirements of this dating method.

In the Tatra Mts., the first growth curve of *Rhizocarpon geographicum* thalli for their northern slope was developed by A. Kotarba over 30 years ago (Kotarba, 1988). The lichen factor (thallus growth in mm in the first 100 years) determined at that time was 32.5 mm for the temperate cold zone (1,850-2,200 m a.s.l.) and 38.1 mm for the very cool zone (1,550-1,850 m a.s.l.). In the following years, based on the factors determined, the first lichenometric dating of the debris slopes in the Sucha Woda Valley was carried out (Kotarba, 1989, 1991, 1992, 1997, 2001, 2004; Jonasson, Kot, & Kotarba, 1991; Kotarba & Pech, 2002). Since then, this dating method has been used in many studies in the field of geomorphology and cryosphere research (Kędzia, 2010, 2011, 2013a, b, 2014, 2015a,b; Gądek, Grabiec, Kędzia, & Rączkowska, 2016). All these works concerned exclusively the northern slope of the Tatra Mts., i.e. mostly the Polish part of these mountains. Due to the climatic differences between the northern and southern parts of the Tatra Mts., mainly with respect to the distribution of temperature and precipitation (Hess, 1965, 1974; Ustrnul, Walawender, Czekierda, Šťastný, Lapin, & Mikulová, 2015), the lichenometric curve developed by A. Kotarba was not used for the southern slope of the Tatra Mts.

This paper presents the first lichenometric curve of *Rhizocarpon geographicum* for the southern slope of the Tatra Mountains located entirely in the territory of Slovakia, developed as a result of several years of research in this area.

Study area

The study covered the southern slope of the Tatra Mountain, located in the Velická Valley, the Velká Studena Valley and the Skalnatá Valley (Fig. 1). It is an area formed of granite and granodiorites (Piotrowska et al., 2015), with an alpine relief (Lukniš, 1973), located within the climate zones ranging from subalpine to subnival (Hess 1965, 1974). The mean annual temperature range from 3.6°C at Štrbské Pleso (1,360 m a.s.l.) to 2.7°C at Skalnaté Pleso (1,763 m a.s.l.) and mean annual precipitation from 968 mm at Štrbské Pleso (1,360 m a.s.l.) to 1,421 mm at Skalnaté Pleso (1,763 m a.s.l.) (Hlavatá, Škvarenina, & Čepčeková, 2011; Bičárová & Holko, 2019). The research was conducted on objects whose location is marked in Figure 1.

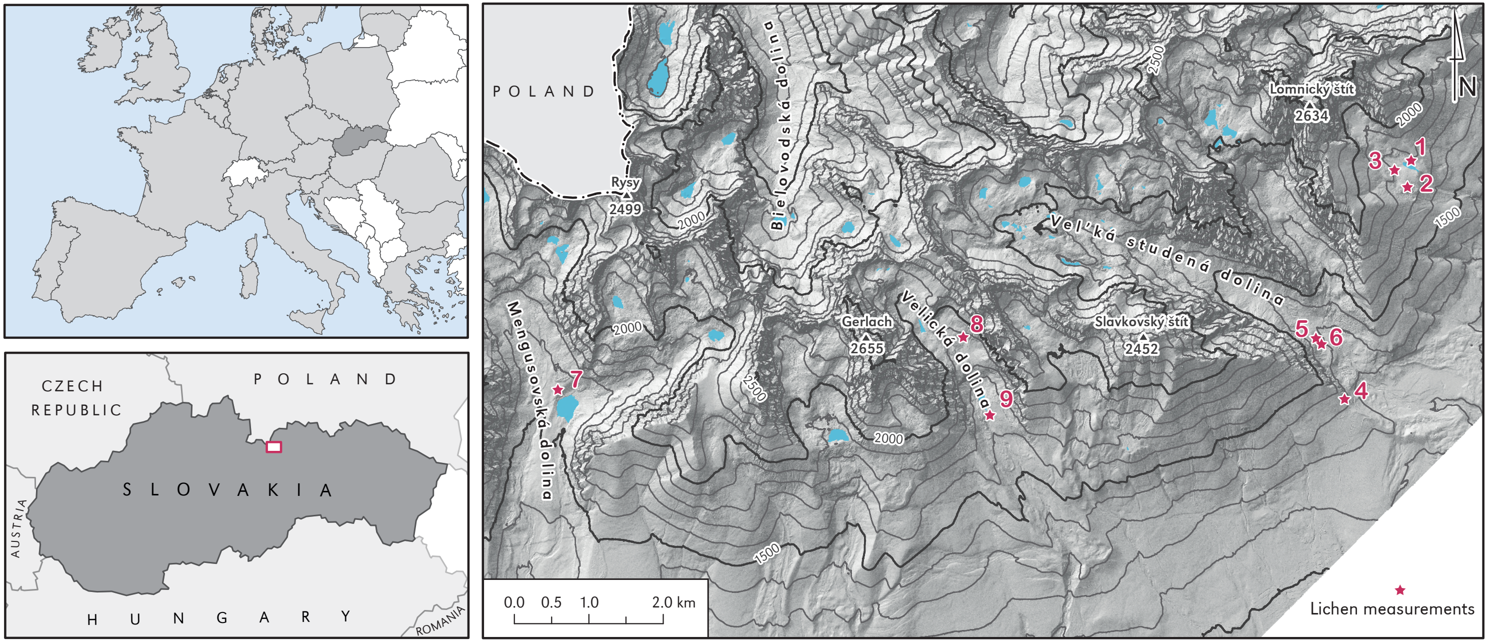

Figure 1. Location of study area. Map with measurement points: 1 – Vikend chata, 2 – Meteorological station (Skalnatá dolina), 3 –Skalnatá chata, 4 – Bilíkova chata, 5 – Rainerova chata, 6 – Chata Kamzík, 7 –Popradské pleso, 8 – Kvetnica, 10 – Blásyho chata. Hillshade DEM is based on aerial laser scanning data; ALS product

Source: ÚGKK SR.

Methods

The measurements were carried out on *Rhizocarpon geographicum* lichens growing on the surface of granitoid boulders. The study was carried out in 2018 and 2019 on 50 objects, of which only 9 met the requirements and were used to construct the lichenometric curve. All the objects were located in concave forms, i.e. valley bottoms or on the lower parts of valley slopes. The valleys with the studied objects open out to the south or close to the southern direction. The altitude of the objects was determined using a Garmin Oregon GPS unit and topographic maps.

On each studied object the diameters of largest lichens were measured. The method of measuring of the largest lichen thallus diameter, i.e. the diameter of circle circumscribed around the lichen thalus (Fig. 2) was applied, as it had been in lichenometric research in the Tatra Mts. since the beginning. Measurements were made using a transparent ruler. Thalli with a small diameter (several millimetres) were measured with an accuracy of approx. 0.5 mm while thalli with a diameter of several tens of millimetres were measured with an accuracy of approx. 1 mm. The accuracy of measurement was determined by the shape. The small thalli had a more regular shape, which allowed more accurate measurement. The shape of the large thalli was less regular, which made it difficult to measure them. The measurement error was between 2% and 10%.

Based on the measurements, the average diameter of the five largest thalli (5LL) was calculated for each object. The only exception was the Blásyho chata measurement object where only 4 large thalli could be found, and those were used to calculate the average value. Knowing the age of the object, the age of the thallus with the calculated average diameter was determined. The lichen factor was then determined based on the ratio of the average diameter to the age.

Results and discussion

Characteristics of the study objects and results of the measurements

1. Vikend chata
   This wooden house was built in 1936 for the workers constructing the cable car to the Lomnický štit peak (Konieczniak, 2010) and is situated at an altitude of 1,760 m a.s.l. The study was carried out on sites of rock surfaces exposed from under the soil cover when the ground was being levelled in preparation for construction

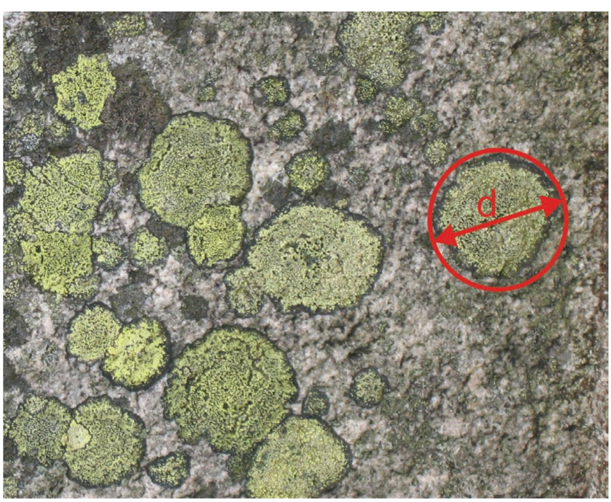

Figure 2. Measurement of the largest thallus diameter using the circumscribed circle method

of the chalet. Some of the boulders uncovered at that time were not overgrown with vegetation so some thalli were preserved on them, and those were used to create the lichenometric curve. The largest thalli had a diameter of approx. 31.5 mm (Tab. 1).

2. Meteorological station (Skalnatá dolina)
   A brick building at an altitude of 1,778 m a.s.l. in which there is a meteorological and astronomical observatory. The construction was completed in 1943. Prior to the construction that was commenced in 1939, the surface was levelled and railway tracks were laid to transport building materials and equipment from the railway station at Skalnaté pleso (Skalnaté Lake) to the site. The thalli were measured on boulders exposed during the construction of the railway tracks. Their maximum diameter was approx. 30 mm (Tab. 1).
3. Skalnatá chata
   The shelter is situated at an altitude of 1,725 m a.s.l., it was the first shelter for tourists climbing Lomnický štit. Initially, it was a rock shelter, which was repeatedly extended in subsequent periods (Konieczniak, 2010). In 1877, during extension work, some large boulders were moved and are now located on the western side of the chalet. The rock surfaced uncovered at that time became overgrown with thalli, the largest of which reached a diameter of approx. 50 mm (Tab. 1).
4. Bilíkova chata
   The shelter was built in 1934 and then extended in 1935-1936 (Konieczniak, 2010). Unfortunately, the chalet itself, like other facilities of this type, is not suitable for lichenometric dating due to the lack of a surface with thalli meeting the requirements of this dating method. The thalli were measured just outside the chalet, on boulders lying at an altitude of 1,255 m a.s.l., the surface of which was unearthed in 1936 during restoration of the tourist route. The diameter of the largest thalli was approx. 32 mm. It is the lowest-lying of all the objects based on which the lichenometric curve was created (Tab. 1).
5. Rainerova chata
   One of the oldest shelters and at the same time the smallest one; it was built in 1865 at an altitude of 1,305 m a.s.l. (Konieczniak, 2010). Thalli were measured on some boulders marking the path built in 1997 and leading to the chalet. Their maximum diameters ranged from 9 to 10 mm (Tab. 1).
6. Chata Kamzík
   A large shelter right next to the Rainerova chata shelter, built in 1884 and demolished in 1980. The foundations of this

Table 1. Description of measurementpoints

Number	Measurement points	Altitude [m a.s.l.]	Year of formation/ construction	Age [years]	Mean max. diameter (5LL) [mm]	Lichen factor [mm/100 years]
1	Chata Vikend	1760	1936	83	31.5	37.8
2	Meteorological station (Skalnatá dolina)	1778	1939	80	30.0	37.5
3	Skalnatá chata	1725	1877	142	50.0	35.0
4	Bilíkova chata	1255	1946	73	32.0	43.8
5	Rainerova chata	1305	1997	22	9.5	42.7
6	Chata Kamzík	1303	2007	12	5.0	41.7
7	Popradské Pleso	1520	1922	89	34.5	38.6
8	Kvetnica	1900	2002	16	5.5	34.4
9	Blásyho chata	1670	1929	90	34.0	37.7

shelter were dismantled and taken away only in 2006 (Konieczniak, 2010). However, some of the boulders were left around the chalet, and it was on their surfaces, exposed during the demolition, that thalli were measured. The maximum diameter of these thalli was approx. 5 mm (Tab. 1).

7. Popradské pleso
   The first shelter was built there in 1879. It was repeatedly extended and rebuilt e.g. in 1922, and is the mountain hotel now (Konieczniak, 2010). Thalli were measured on boulders situated just by the retaining wall surrounding the square in front of the chalet. Their maximum diameter ranged between 34 and 35 mm (Tab. 1).
8. Kvetnica
   Debris flows with known age are some of the best objects for measuring purposes. The studied debris flow track is located in Velická dolina (Velická Valley) at a place called Kvetnica, at an altitude of approx. 1,900 m a.s.l. (Kapusta, 2015). The levée of debris flow from 2002 were identified. The diameters of the largest thalli on this levée were in the range of 5-6 mm. The larger thalli also occur in several parts of this debris flow tracks, on landforms of older debris flows, but of unknown date of formation (Tab. 1).
9. Blásyho chata
   This shelter was built in 1871-1872 at Velické pleso lake at an altitude of 1,670 m a.s.l. Unfortunately it was destroyed by a snow avalanche in 1874, and in later years demolished (Konieczniak, 2010). At present, only some fragments of the boulders from which it was built are left. The diameters of the largest thalli were in the range of 33-35 mm (Tab. 1).

Lichen curves for southern slopes of the Tatra Mountains

The first measurements of thalli on objects with a known date of origin based on which A. Kotarba determined the first lichenometric curves for the Tatra Mts. showed that the lichen factor changes with altitude. As the altitude increases, the thallus growth decreases. Therefore, A. Kotarba (1988) developed two lichenometric curves for the northern slope of the Tatra Mts., one for the very cool zone and one for the temperate cold zone (Fig. 3).

The use of two lichenometric curves increases the accuracy of the measurement, but creates a problem when measuring objects with high vertical extension, e.g. debris flows, because two growth curves cannot be used for one object. For this reason,

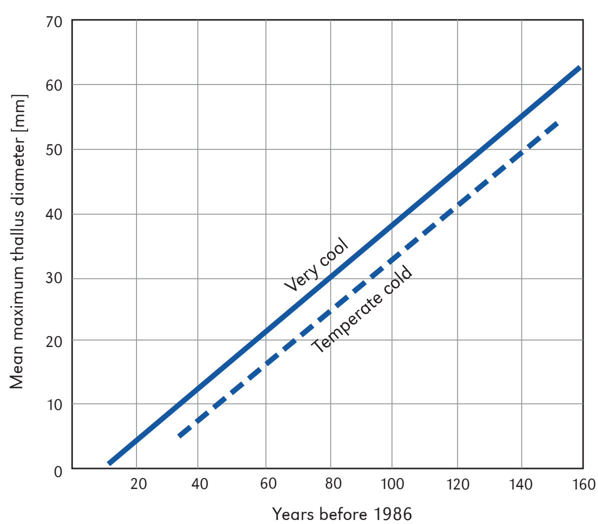

Figure 3. Lichenometric curves for the temperate cold and very cool climatic belts (Kotarba, 1988)

when developing the lichenometric curve for the southern slope of the Tatra Mts., it was decided to determine two curves.

The first curve was created in the traditional way, i.e. based on thalli measured on objects located at different altitudes, from approx. 1,250 m to approx. 1,900 m a.s.l. (Fig. 4). It is described by the equation:

$$y = -0.0007x^2 + 0.4618x - 0.7383$$

where: $R^2 = 0.9928$.

As can be seen in Figure 4, not all average diameters of the largest thalli of a particular object lie exactly on the lichenometric curve. This is not only due to the accuracy of the measurements of the thalli but also to the altitude and the associated different rate of thallus growth. When determining the lichenometric curve, the highest accuracy is achieved if objects of different ages and at different altitudes available. Unfortunately, this is rarely the case. The course of the upper part of lichenometric curve for the southern slope of the Tatra Mts. (Fig. 4) was strongly affected by the thalli measured on boulders at the Skalnata chata station (the highest point on the lichenometric curve), i.e. located on one object only. In order to increase the accuracy of the lichenometric curve, there should be more such objects, as is the case in its central and lower course. Unfortunately, it was not possible to find more objects older than 100 years and with thalli that would meet the requirements of this dating method. Therefore, the rate of lichens growth, determined by course of the lichenometric curve shown in Figure 4, may slightly differ from the actual rate of their growth at individual heights and age ranges.

When using this curve for lichenometric dating, it should also be borne in mind that all objects used for its construction were located in the bottom of valleys or on the lower parts of their slopes. In the case of dating objects situated on convex landforms (ridges or peaks) characterised by climatic conditions different from valley bottoms, the growth rate of thallus on such landforms may differ from the growth rate determined from the lichenometric curve (Kędzia & Parzóch, 2016). Thus, the accuracy of dating with this method will be reduced. The same applies to objects located significantly below or above the altitudinal range for which the lichenometric curve was constructed.

When lichenometric dating is used for objects at low altitude (below the range for which the curve was constructed), the effect of air pollution on thallus growth must also be taken into account (Haffner, Lomsky, Hynek, Hallgren, Batic, & Pfanz, 2001).

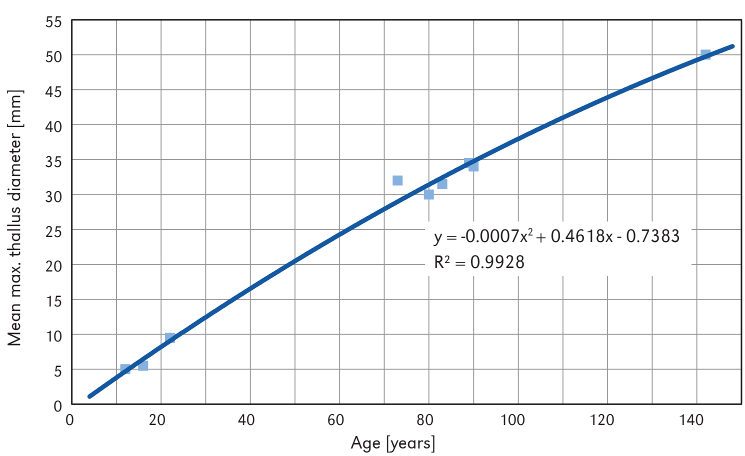

Figure 4. Lichenometric curve for the southern slope of the Tatra Mts. constructed based on the average of the largest thallus diameters

It was not possible to find *Rhizocarpon geographicum* thalli below an altitude of approx. 1,000 m a.s.l. when the first lichenometric curves for the Polish part of the Tatra Mts. was elaborated. The reason was the high air pollution that persisted in the inversion layer over the town of Zakopane (Kotarba, oral information). A similar situation may occur in the Slovak part of the Tatra Mts. where there are numerous localities also at the foot of the mountains.

Figure 5 presents the lichenometric curve for the northern slope of the Tatra Mts. developed by S. Kędzia (2015) and the curve for their southern slope. A comparison of both curves demonstrates that the rate of growth of *Rhizocarpon geographicum* thalli on both sides of the Tatra Mts. is very similar. Unfortunately, it cannot be clearly stated whether the differences visible in the course of the curves, especially their upper parts, are the result of inaccuracy of measurements or climatic differentiation. In order to do so, it would be necessary to carry out detailed research aimed at finding objects formed in the same period on both sides of the Tatra Mts., situated at the same altitude and in similar terrain forms.

An important problem in lichenometric dating, which has been demonstrated in many studies, is the decrease in the rate of thallus growth, resulting from the changes in climatic conditions with increasing altitude (Beschel, 1961; Coxson & Kershaw, 1983; Benedict, 1990, 1991; Armstrong, 2002, 2005, 2006, 2013, 2015, 2016; Solomina & Calkin, 2003; Armstrong & Bradwell, 2010b, 2015; Hansen, 2010; Trenbirth & Matthews, 2010). Therefore, another curve was constructed based on the collected data, showing the variability of the lichen factor depending on the altitude (Fig. 6). It is described by the equation:

$$y = -1.9485x^2 + 83.36x - 1,297.3$$

where $R^2 = 0.8975$.

With this curve, the error resulting from using the same value of lichen factor for objects located at different altitude can be avoided. Consequently, the accuracy of the lichenometric dating is increased. Unfortunately, even this curve has its disadvantages. As the research to date has shown, the growth rate of thalli is related to their age (e.g. Bradwell & Armstrong, 2007; Bradwell, 2010). For thalli that reached a diameter of approx. 40 mm, the growth rate decreases. In the case of the curve in question, it was only on one object that the average diameter of the largest 5 thalli exceeded 40 mm.

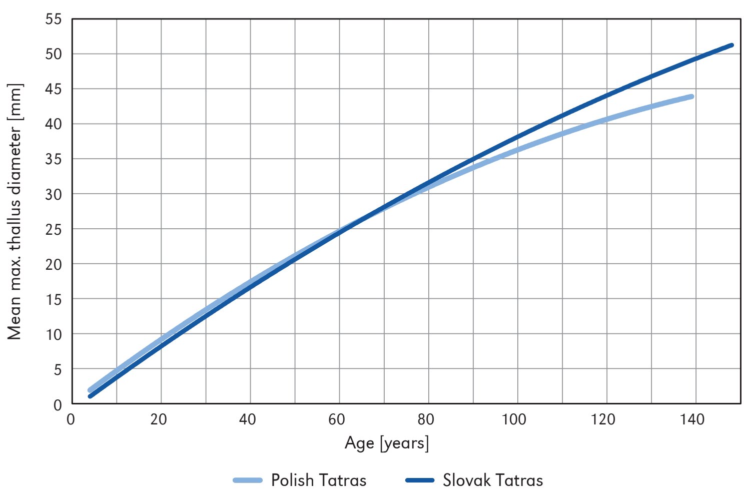

Figure 5. Lichenometric curve for the northern and southern slopes of the Tatra Mts. based on the average of the largest thallus diameters

The differences in matching the mean values of the largest thallus measured on individual objects to the lichenometric curve at Figure 6 result from the accuracy of the thallus measurement. Small thalli with a diameter of e.g. 5 mm were measured with an accuracy of approx. 0.5 mm, which gives an error of 10%. On the other hand, large thalli, e.g. with a diameter of 50 mm, were measured with a slightly greater inaccuracy of approx. 1 mm, which is only 2% error regarding their diameter. The conclusion is the younger the thalli were measured, the greater error in determining the lichen factor were.

When comparing the lichenometric curve for the southern slope of the Tatra Mts with the curves developed for different parts of the Alps, it can be concluded that in terms of the thallus growth rate, the differences between the Tatra Mts. and some parts of the Alps are rather small. Lichen factor of approx. 43 mm was determined for the southern flanks of the Mont Blanc massif (Orombelli & Porter, 1983). P. Pech et al. (2003) developed a curve for the Massif des Ecrins (French Alps) with a lichen factor of approx. 30 mm, using a large number of measuring points situated well above 2,000 m a.s.l., while H. Blijenberg (1998), who also carried out research in the French Alps determined a lichen factor of approx. 38 mm. M. Czempiński and M. Dąbski (2017) obtained a curve with a lichen factor of approx. 28 mm in Ötztal Alps at an altitude of approx. 2,000 m a.s.l. O. Sass (2010), on the other hand, determined a curve with a lichen factor of approx. 34 mm for the Stubai Alps (Austrian Alps). Also in the Austrian Alps, S. Winkler and R.A. Shakesby (1995) obtained an even greater lichen factor of approx. 38 mm. However the above demonstrates not only similarities in the thalus growth rates, but also the relatively great local variability of these rates among particular parts of Alps.

Conclusions

The lichenometric curve developed for the southern slope of the Tatra Mts. is applicable for lichenometric dating in the altitude range from 1,250 to 1,900 m a.s.l. When dating objects outside this range, reduced dating accuracy must be taken into account. Lichen factor decreases with altitude. At an altitude of 1,250 m a.s.l. it is almost 44 mm/100 years, while at 1,900 m a.s.l. it is approx. 34.5 mm/100 years. Despite the climatic differences between the southern and northern slopes of the Tatra Mts., the growth rate of *Rhizocarpon geographicum* thallus on both sides of the Tatra Mts. is almost equal. Slight differences occur at higher altitudes.

All of the thalli used to determine the lichenometric curve grew on rock surfaces

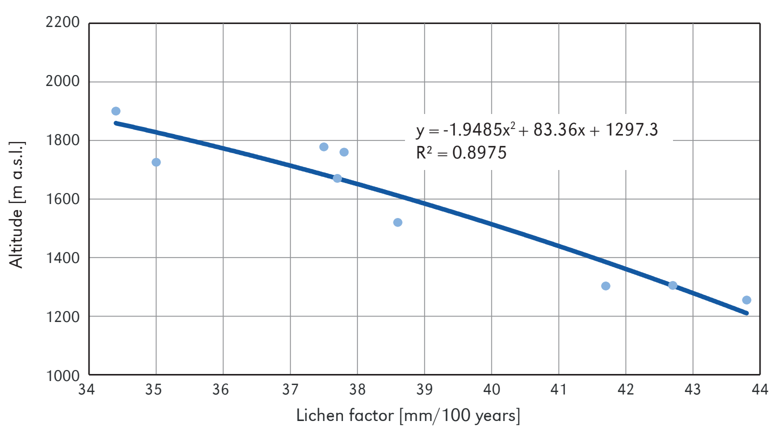

Figure 6. Lichenometric curve for the southern slope of the Tatra Mts. determined based on the lichen factor

of granitoids; therefore, the curve can only be used to date objects built of granitoids. There is a need for further research to provide new data to refine the developed lichenometric curves, and to determine the thallus growth rate on the other types of rocks.

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

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