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CONTEMPORARY DEGRADATION OF STEEP ROCK SLOPES IN THE PERIGLACIAL ZONE OF THE TATRA MTS., POLAND

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Abstract

This study presents the results of the first large-area monitoring of steep slopes in the Tatra Mountains. In the research, we used terrestrial laser scanning methods and GIS tools. We also performed crack density measurements. The results obtained demonstrate that the rate of change of slopes under the influence of weathering and rockfall processes is very variable both in time and space. The rate of retreat of 4 steep adjacent granitoid slopes over the same period ranged from 0.00013 ma^{-1} to 0.004 ma^{-1}. The spatial variation in the number and size of cavities was related primarily to the cracks density.

Key words

granitoid slopes • rockfall • climate change impact • terrestrial laser scanning • Tatra Mts.

Introduction

In the periglacial zone of high-mountain areas, the most common processes of decay of steep rock slopes include mechanical weathering (e.g. Eppes & Keanini, 2017), often fostered by chemical weathering (Dixon & Thorn, 2005), resulting in crack propagation (Draebing & Krautblatter, 2019), loosening of rock fragments and their gravitational displacement – free fall, bouncing and rolling (Luckman, 2013). The talus material deposited at the foot of rock slopes forms debris covers modelled not only by paraglacial and periglacial processes, but also by debris flows, runoff and snow avalanches (Kotarba, 1998; Rączkowska, 2006; Rączkowska et al., 2017/2018; Senderak et al., 2019; Rączkowska et al., 2017/2018; Rączkowska & Cebulski, 2022).

Rock slopes differ in their rate of weathering and erosion. These processes depend on both climatic and geological conditions. The thermal (Collins & Stock, 2016) and humidity regimes, freeze-thaw (Matsuoka, 2008) and changes in the thickness of the active layer (Draebing et al., 2017) induce critical and subcritical stresses inside slopes (Eppes et al., 2018). Contemporary climate warming, related deglaciation (Zemp et al., 2015) and the degradation of permafrost (Oliva & Fritz, 2018) in high mountain areas give rise to an increase in rockfall frequency and magnitude (Knoflach et al., 2021). Ongoing climate change also impacts the rock and crack kinematics and, as a result, rockfall patterns at both high and low altitudes (Draebing, 2021). The efficiency of these processes is controlled by the properties of the rock that forms the slope, i.e.: mineral composition, porosity, texture, tensile strength, density of cracks/other discontinuities (André, 1996; Bland & Rolls, 1998; Hall & Thorn, 2010; Lubera, 2014). Thus, the cracking and rockfall processes show great temporal and spatial variability.

In non-glaciated and non-permafrost zones of high mountains, the increase in the risk of rockfall as a result of climate change may be debatable (Sass & Oberlechner, 2012). The results of cosmogenic dating of the colluvia at the foot of rock faces reveal that the greatest rockfalls in the currently non-glaciated Tatra Mountains date back to their deglaciation and, several thousand years later, during the warmer and more humid periods in the Late glacial/early Holocene (e.g. Pánek et al., 2016). Meanwhile, the results of research on modern morphodynamics of slopes and lichenometric dating of the talus deposits have not revealed any trend in rockfall activity in the Tatras over the last 300 years. The processes have generally been of low magnitude, although there have been medium-sized rockfalls (Kotarba et al., 1987; Rączkowska et al., 2017/2018; Rączkowska & Cebulski, 2022). The rockfalls demonstrated the greatest frequency and magnitude in the years 1810-1910, with a peak between 1840 and 1890 (Kotarba & Pech, 2002). Their initiation is currently primarily associated with intense rainfall and snow melting (Lubera, 2014). At the same time, since the beginning of the 1980s, the High Tatras have seen gradual alluviation of talus slopes, which consists of the mobilization of debris as a result of debris flows (Kotarba et al., 1987; Kotarba, 1998; Kotarba et al., 2013; Šilhán & Tichavský, 2016). By contrast, no such tendencies have been found in the Western Tatras (Gorczyca et al., 2014). It cannot be ruled out that the increase in the frequency of debris flows in the High Tatras, especially at the foot of rock faces exposed to the S, may also be associated with an increased supply of talus material as a result of the degradation of the permafrost (Šilhán & Tichavský, 2016).

Therefore, bearing in mind global climate change and the related evident increase in rockfall/rock avalanche activity in currently glaciated high-mountain areas as well as the lack or disputability of analogous observations in high-mountain areas which have been unglaciated for thousands of years, we started to monitor large and steep rock faces as the first such exercise in the Tatra Mountains. Our purpose was to quantify the magnitude and spatial distribution of contemporary rockfall processes, as well as their lithological and topographic determinants. We used terrestrial laser scanning (TLS) methods and a GIS tool. We also completed rock slope crack density surveys. The surveys covered the granitoid slopes of Mięguszowiecki Szczyt-Cubryna by Morskie Oko lake. It is the most popular attraction in the Polish mountains, visited by over 700,000 tourists a year and is also an area intensively explored by climbers (Choiński & Pociask-Karteczka, 2014).

Study area

The rock faces and slopes of Mięguszowiecki Szczyt (2438 m a.s.l.) and Cubryna (2375 m a.s.l.) are located on Morskie Oko lake (1395 m a.s.l.) in the upper part of the Rybi Potok Valley in the Polish High Tatras (Fig. 1).

They are mainly composed of Carboniferous granitoids that come apart along joints running in the NW-SE and NE-SW directions. Cataclasites, tectonic breccia and mylonites also occur locally (PGI-NRI, 2021). The alpine relief dates back to several Pleistocene glaciations (e.g. Zasadni & Kłapyta, 2020). In the post-glacial period, sprawling talus fans more than 30-m thick developed at the mouth of gullies formed on SW-NE-oriented faults (Gądek et al., 2016). They are currently mainly modelled by debris flows (Kotarba et al., 2013; Rączkowska et al., 2017/2018; Rączkowska & Cebulski, 2022). Slopes lying above 1900 m a.s.l., that is in moderately cold and cold climatic belts (Łupikasza & Szypuła, 2019), may sporadically be covered by contemporary permafrost (e.g. Dobiński, 2005; Mościcki & Kędzia, 2001; Gądek et al., 2009; Gruber, 2012).

The annual mean air temperature varies from ca. 3°C at Morskie Oko to ca. −2°C on the highest peaks (Łupikasza & Szypuła, 2019). Above 1500 m a.s.l., frosts may occur at any time of year. The annual mean rainfall totals in the study area increase with altitude from 1400 mm to 2000 mm, and the number of days with seasonal snow cover varies from about 150 to over 210 (Ustrnul et al., 2015). There are permanent firn-ice patches in shady and concave landforms where avalanche snow tends to deposit. With the warming climate of the Tatra Mountains and the decrease in the thickness and durability

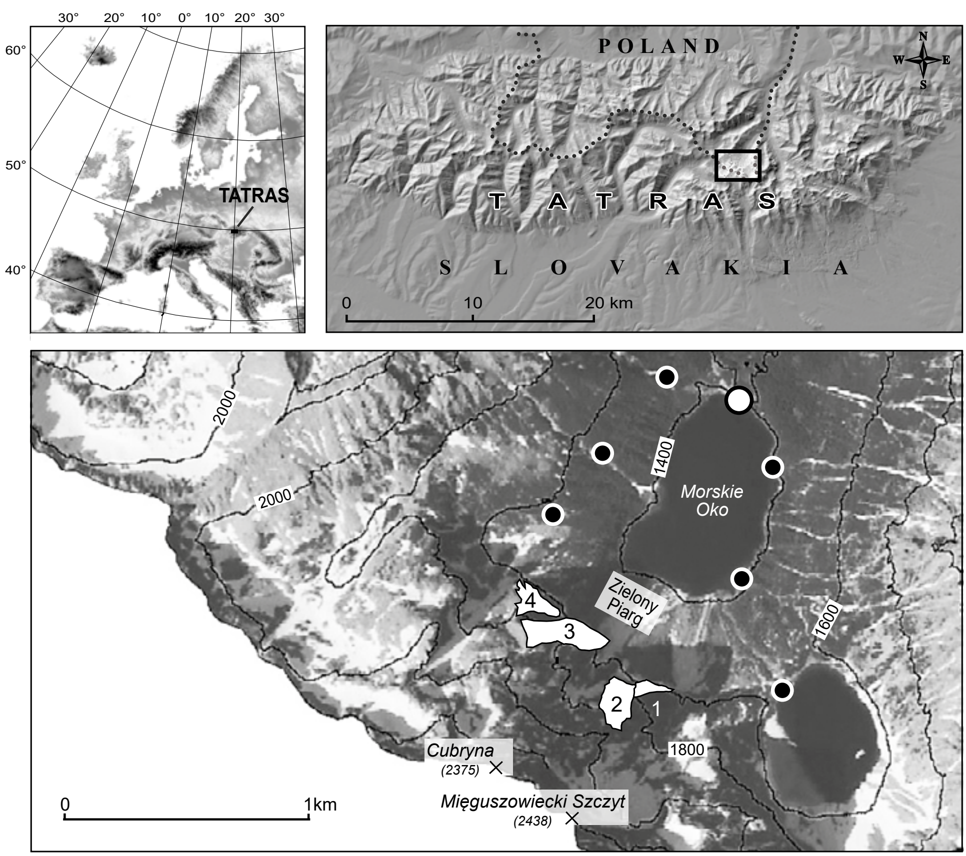

Figure 1. Study area. White dot – location of the main measurement site, black dots – locations of additional spots, polygons 1-4 – rock slopes studied (test surfaces)

of snow cover, the number and size of these patches have decreased noticeably in recent decades (Gądek, 2014).

Methods

TLS Surveys

A Riegl VZ-2000 laser scanner fitted with a Nikon D810 camera and a GPS receiver was used to measure the changes on the study slopes. The surveys were carried out on 27 October 2016 and 26 June 2019. On the first date, measurements were taken at 7 spots around Morskie Oko (Fig. 1). Based on the results of an analysis of the distribution and area of the so-called 'blind spots' (covered areas), we established the optimal position for the surveying site from which the maximum amount of spatial data could be obtained. On the second date, measurements were only made from that spot. It lies on the northern end of Morskie Oko (ϕ = 49°12'02"N; λ = 20°04'19"E), 1 km from the slopes surveyed (Fig. 1). The frequency and range of the laser light were 50 kHz and approx. 2 km, respectively.

The measurements took into account the prevailing weather conditions (air temperature and relative humidity, as well as atmospheric pressure) based on data obtained from the Institute of Meteorology and Water Management which was recorded at Morskie Oko by means of an automatic weather station.

Processing of scanning data

The scanning data obtained was processed into high-resolution numerical terrain models and a differential elevation model using the RiSCAN PRO v. 2.4 software. The point clouds registered during both measurement sessions were given natural colours, and subsequently were mutually oriented and fitted with an accuracy of ±1 cm. The planes of adjustment were differently oriented and evenly distributed over the surface of the rock slopes. The dimensions of these planes ranged from 0.25 m to 65 m, and their number exceeded 4000. False points were eliminated with the 'reflectance gate', 'deviation gate' and 'octree' filters. On the basis of the dataset thus acquired, four test polygons with areas ranging from 19.6 thousand m^2 to 49.3 thousand m^2 were drawn (Figs. 1, 2). 'Blind spots' represented no more than 10% of the areas surveyed. Numerical models of these areas with a resolution of 0.1 m x 0.1 m were created by the triangulation method. The differential elevation models generated on their basis revealed changes in the surface of the slopes over the 3-year inter-measurement period. They were visualised in planes parallel to the sections of the slope examined. During the first session of measurements (October 2016), the Pinus mugo were burdened with remnants of snow from the period preceding the laser scanning (snow no longer lay on the rock slopes). This made it easier to identify spots overgrown with dwarf mountain pine on the differential elevation model, because during the second round of measurements (June 2019) the straightened shrubs were usually a dozen or so centimetres higher. The places overgrown with *Pinus mugo* were eliminated from the differential elevation model.

GIS methods

In the ARC GIS 10.6 software environment, the previously created numerical terrain models were processed into exposure, inclination and hypsometric maps as well as a differential elevation model showing changes in the test rock surfaces in the horizontal plane. In the first case, 4 basic exposure classes were adopted (N, E, S, and W), in the second, 4 classes of inclinations (< 45°, 45°-65°, > 65°-80° and > 80°), and in the third 4 altitude classes (< 1600 m, 1600-1700 m, > 1700-1800 m and > 1800 m a.s.l.). A simplified differential elevation model which consisted exclusively of pixels indicating places of loss of rock material was superimposed on these maps. In the various classes of exposure, inclination and altitude, the percentage share of the area of registered rock cavities was determined. The distribution of the data obtained and the (Pearson) correlation between the morphometric features of the slopes examined and the cavities were also checked. The statistical significance of the correlation was determined using the t-test.

Crack density measurements

The surface density (D_s) of the cracks within the test slopes was determined on the basis of photographs using to the following equation (Liszkowski & Stochlak, 1976):

$$D_s = \frac{\sum l}{P}$$

where:
$\sum l$ – sum of crack lengths,
P – area of test polygon.

Since the photographs were taken using central projection, in which the geometric distortions increase with distance from the main point, they were framed so that the walls examined were in their central area. The terrain resolution of the photographs used (pixel size) was 0.1 m. However, homogeneous linear features, by influencing the colour and brightness of pixels, become visible in the images even if their width is smaller than the pixel size. The length of the cracks identified was determined on the basis of measurements taken on the photograph and an averaged scale calculated based on the area of the polygons in the pictures and their actual area. The latter was measured on numerical models of the rock walls in the RiSCAN PRO software.

Results

Morphometry of rock slopes

Selected morphometric features of all the rock surfaces tested are presented in Fig. 2 and Table 1. The height of the slopes examined ranges from 207 m to 320 m. Steep slopes with N exposure prevail. The share of areas exposed in other directions is 38%, of which areas with E and W exposures account for 29% and 5%, respectively. Typically, the inclination of the test surfaces ranges from 45° to 65° (38%). About 15% of the surfaces have a slope of < 45°. Slopes in the classes > 65°-80° and above 80° account for 27% and 20% of the test surfaces respectively.

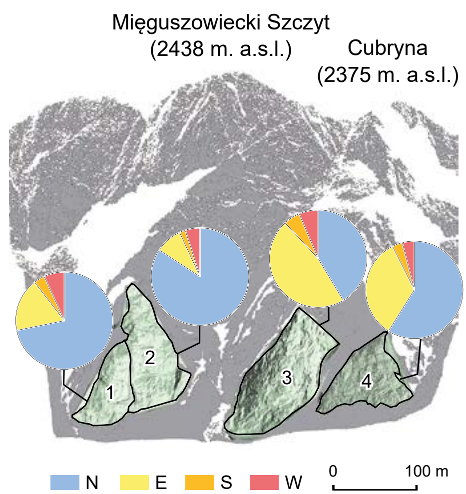

Figure 2. Northern slope of the Mięguszowiecki Szczyt and Cubryna peaks (point cloud) and test polygons 1-4 (DEMs), pie charts: aspect of test surfaces

Table 1. Morphometric characteristics of the rock slopes studied

Test poligon No	Length [m]	Width [m]	Area [thousands of m^2]	Inclination [°] Min. Max. Mean			Altitude [m a.s.l.] Min. Max.	
1	235	106	19.6	0.2	89.6	65.4	1599	1808
2	310	140	36.7	0.2	89.6	61.3	1632	1949
3	320	180	49.3	0.6	89.9	66.2	1575	1878
4	207	170	29.6	0.1	89.4	49.9	1618	1818

Changes in the surface of rock slopes

The changes in the rock slopes in the period from October 2016 to June 2019 are presented in Figure 3. Over the three-year period, rock slopes with an area of 135.2 thousand m^{-2} lost at least 1003 m^3 of rock material. Therefore, the average rock face recession rate could be close to 0.0025 ma^{-1}. These changes varied from one test polygon to another. The smallest number of cavities was recorded on test polygon 1, while the greatest was on test polygon 4. The cumulative volumes of cavities on these slopes were close to 8 m^3 and 365 m^3, and their retreat rates were 0.00014 ma^{-1} and 0.004 ma^{-1}, respectively. On test polygons 2 and 3, the cumulative loss volumes were close to 282 m^3 and 348 m^3, and the rock face recession rate was 0.0025 ma^{-1} and 0.0023 ma^{-1}, respectively. Usually, the depth of individual rock recesses registered during the research did not exceed 0.4 m.

Importance of exposure, inclination and altitude

The spatial distribution of the rock cavities identified is presented in Table 2. The greatest number of cavities was found on locations with N exposure (63%), and the least on those with W exposure (3%). Only on test polygon 3, were most of the cavities found in its E sector. In general, on each of the 4 polygons, the sums of the loss surfaces and the slope areas in the individual exposure classes were proportional to each other, with the exception of rock surfaces with W exposure, where the cavities were less significant than would be expected given the size of the sector.

Among the altitude ranges adopted in the study, the greatest number of rock cavities was registered in the > 1700-1800 m a.s.l. zone (42%), and the lowest below 1600 m a.s.l. (1.5%). In each case, the sums of loss areas were proportional to the surface area of the altitude zone.

Among the slope inclination categories, the greatest number of rock cavities were identified in areas with a slope of 45-65° (42%), while the smallest were found in areas with an inclination of < 45° (13%). Also in this case, the aggregate loss areas and the slope areas within the various inclination categories were generally proportional to each other, save that there were slightly fewer cavities on rock faces with an inclination > 80° than should be the case given the size of these walls.

In light of the data obtained, exposure, altitude and slope do not, in general, appear to influence the intensity of the rockfall processes. The values of Pearson correlation (r) between the slope area and the sum of the areas of rock loss in the individual classes of morphometric features of the slope ranged from 0.97 to 0.99. The correlations were significant ($p < 0.05$), but the size of the statistical sample was small, and the distribution of the features investigated was not normal. The step-like longitudinal profiles of the slopes

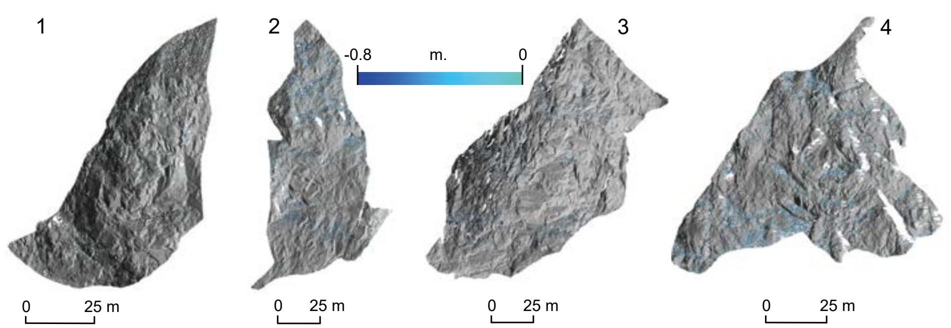

Figure 3. Differential elevation models for polygons 1-4 (view in a plane parallel to the slope). The blue-green colors indicate rock cavities, which originated in the period between October 2016 and June 2019

Table 2. Surface area of test slopes v. cumulative rock loss area in the various classes of exposure, altitude and inclination

Slope properties		Polygon no 1		Polygon no 2		Polygon no 3		Polygon no 4	
		slope [%]	cavities [%]	slope [%]	cavities [%]	slope [%]	cavities [%]	slope [%]	cavities [%]
Aspect	N	71.8	73.7	84.2	87.4	41.4	39.1	58.9	55.2
	E	17.7	18.4	8.9	7.7	46.7	51.3	33.7	38.9
	S	3.7	4.8	2.0	3.6	5.5	4.9	3.4	2.9
	W	6.8	3.1	4.9	1.3	6.4	4.7	4.0	3.0
Altitude [m a.s.l.]	< 1600	0.0	0.0	0.0	0.0	5.5	5.7	0.0	0.0
	1600-1700	46.6	42.1	17.3	16.9	47.1	47.1	55.5	54.7
	> 1700-1800	52.5	56.5	38.8	38.4	39.2	39.0	43.2	44.0
	> 1800	0.9	1.4	43.9	44.7	8.2	8.2	1.3	1.3
Inclination [°]	< 45	16.0	15.8	13.0	13.2	12.0	8.7	19.4	18.5
	45-65	30.3	34.6	47.3	50.6	32.8	37.5	38.4	39.9
	> 65-80	24.0	25.4	25.8	25.6	27.9	30.0	29.2	29.6
	> 80	29.7	24.2	13.9	10.6	27.3	23.8	13.0	12.0

under study imply, however, that the steepest fragments of the slopes are more resistant to decay. There is a clear relationship between the slope retreat rate and the share of rock faces with an inclination > 80° in their total surface area (see section 4.4.).

Importance of crack density

The crack density (D_s) identified within the test polygons in the images of rock slopes did not show very high variability. The values ranged from 0.21 m^{-1} (polygon 1) to 0.38 m^{-1} (polygon 4), and the weighted average was 0.28 m^{-1} (Fig. 4).

The rock slope within polygon 1 was characterised by both the lowest crack density and the slowest retreat, while polygon 4 was characterised by the highest crack density and the fastest recession. In the other two test polygons, both the crack density and the rate of slope retreat were similar. On test polygon 2, where the crack density was 0.25 m^{-1}, the rock face retreat rate was 0.0002 m^{-1} higher than on test polygon 3 (see section 4.2), where the crack density was 0.27 m^{-1} (Fig. 5A). At the same time, on polygon 2, rock faces with an inclination of > 80° constituted a smaller proportion of the surface area than on test polygon 3 (Tab. 2, Fig. 5B).

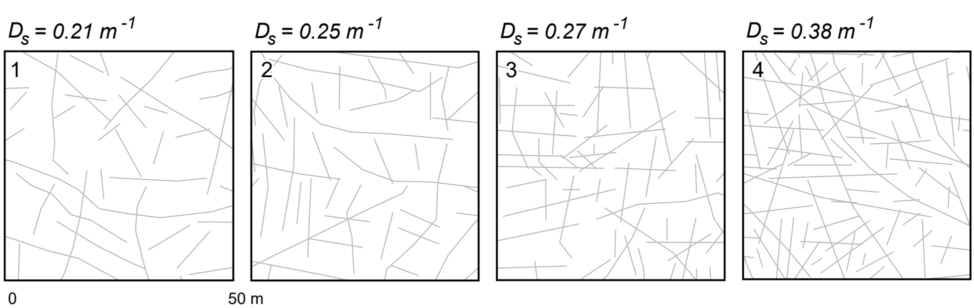

Figure 4. Crack density (D_s) identified in the imagery – example sections of test polygons 1-4

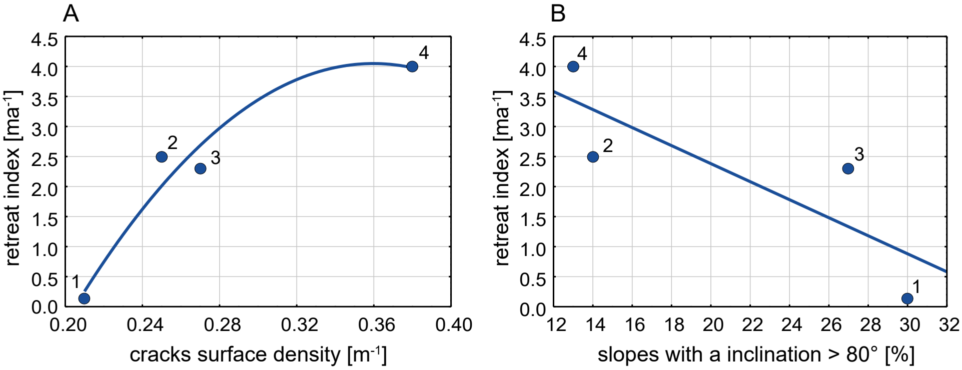

Figure 5. Relationship between the retreat rate and (a) crack density and (b) the proportion of rock faces with an inclination > 80° in the total area of test polygons 1-4

On all test polygons, the rock cavities recorded were concentrated along the most distinct and longest cracks.

Discussion

The degradation of the slopes progressed as a result of weathering and the detachment of small rock fragments (*single block falls*). However, the rate of rock face recession that we recorded within the test polygons was at least an order of magnitude greater than the values established previously by other authors who had studied contemporary decay of granitoid slopes in the Tatra Mountains (Rączkowski, 1981; Kotarba et al., 1983, 1987). The published data also demonstrate that in other high-mountain areas the rate at which granitoid slopes recede often does not reach 0.001 ma^{-1} (Galibert, 1965; Coutard & Francou, 1989; Strunden et al., 2015), but it can also be close to or higher than 0.002 ma^{-1} (Francou, 1988; Haeberli et al., 1999). However, these results are not comparable because they have been produced by different methods, at different places and at different time periods. All of them provide evidence for a large variability in time and space in the intensity of degradation of rock slopes (including granitoid ones). It is notable that, in classical studies, calculations of the contemporary rate of slope retreat are primarily based on the volume of rock material deposited over several years on measuring nets distributed at points (e.g. Bechtt, 1995) or cavities on painted rock surfaces (e.g. Matsuoka et al., 1998). In such situations, the representativeness of the sample is particularly important. To a large extent, this may be related to the correct registration of the supply of thick rock fragments as it is these that may have a decisive impact on the growth in the volume of the talus slope (Rapp, 1960; Luckman, 2008).

It follows from the latest results of TLS monitoring of the Zielony Piarg talus fan (Rączkowska et al., 2017/2018; Rączkowska & Cebulski, 2022), which is partially fed with material falling off test field 3, that its volume increased by 2576 m^3 in 2017-2019. Thus, the average rate of retreat of the feeding slope, which has an area of 271,000 m^2, could have been close to 0.0047 ma^{-1} over the period. In the same period, the average retreat rate of test slope 3 was 50% slower, except that in the upper section of the Zielony Piarg slope system, in addition to granitoids, there are also cracked and weathered mylonites.

The large spatial variation of the decay rate among the rock slopes studied was mainly associated with local crack densities, lithology and inclination. The largest number and magnitude of cavities registered over the study period on test polygon 4 correspond to the close proximity of a large fault and the presence of xenoliths (Gawęda & Szopa, 2011; A. Gawęda, personal communication, 4 February 2021). The role of lithology and rock fracture in weathering and rockfall processes is obvious (Matsuoka & Sakai, 1999; Matsuoka, 2008). However, the results of our measurements did not confirm the significance of exposure, as had been previously noted, inter alia, by Matsuoka et al. (2003). We also found no relationship between the elevation of the terrain and the rock slope decomposition rate (e.g. Kotarba et al., 1987). Probably, the importance of these factors has not been revealed due to the predominant influence of geological factors. The lower susceptibility to weathering of the rock faces with a slope > 80° that were monitored may be related to (a) lower crack density, (b) rapid surface runoff of rainwater and meltwater, which are, apart from rock temperature (gelation cycles), the key factor behind weathering processes (e.g. Matsuoka & Murton, 2008) and (c) the solely primary nature of rock detachment (Rapp, 1960; Luckman, 1976). Vertical or nearly vertical granitoid walls may be more prone to disintegration during periods of rock mass expansion, including deglaciation (e.g. Ballantyne & Benn, 1996; Senderak et al., 2020) and as a result of tectonic shocks (Reznichenko et al., 2017), degradation of permafrost (Haeberli, 2013) and reduced friction on internal high-dip discontinuities.

In recent years, there have been growing efforts to identify past climate change and the evolution of talus slopes on the basis of their internal structure imaged by electroresistivity and GPR methods (Sass, 2006; Onaca et al., 2016; Senderak et al., 2020). In the light of the results of the monitoring of rock slopes in the Tatra Mountains, it seems advisable that in interpreting the geophysical data, account should be taken of the density of cracks in rock slopes and not just the size, relief and lithology of the feeding areas (Gądek et al., 2016).

Contemporary global climate change, which is manifested by an increase in air temperature and in many high-mountain and polar areas also by a rise in the frequency of rainfall and thaw (e.g. Łupikasza et al., 2019), may contribute to large rock avalanches and acceleration of rockfall processes (e.g. Deline et al., 2011; Ravanel & Deline, 2011). In connection with the observed climate change in the Tatra Mountains, which gives rise, inter alia, to an increase in ground temperature and the degradation of sporadic permafrost (Gądek & Leszkiewicz, 2012; Gądek, 2014), this region is also likely to experience an increase in the magnitude of rock face decay, especially in fault zones where cataclasites, fault breccias and mylonites are additionally present, and where the density of rock mass fractures is significant. The series of *mass falls* (10^2-10^5 m^3) observed in the last decade over a small area of the Polish part of the High Tatras (Fig. 6), and the damage to tourist routes caused by them, seem to confirm the above view. However, these events occurred only in the autumn and spring seasons, and the trigger was gelivation. Moreover, they were formed in fault, cataclysite-mylonite zones (Kajdas et al., submitted). Therefore, in places where the geological structure, fractures and morphology of slopes contribute to the formation of rockfalls, it is reasonable to combine regional records of meteorological conditions with local monitoring of changes in the surface of rock slopes and their stability. The classification of slopes and the development of regional warning systems for such hazards would facilitate risk management in high mountain areas.

The advantages of the TLS method which we use in monitoring changes in rock slopes include, above all, the ease, speed and precision of acquiring a large number of pieces of spatial data from a single location, which is particularly important in high-mountain environments where the working conditions are difficult and change rapidly. Moreover, TLS data are not burdened with errors resulting from the randomness of measurement, uncertainty of the time interval, or a small random sample. However, using the TLS method to study rockfall processes entails the problem that it does not provide data on small rock cavities and the inevitable occurrence of blind spots in mountainous terrain (Błaszczyk et al., 2022). Notwithstanding the above, the fact that we were able to capture

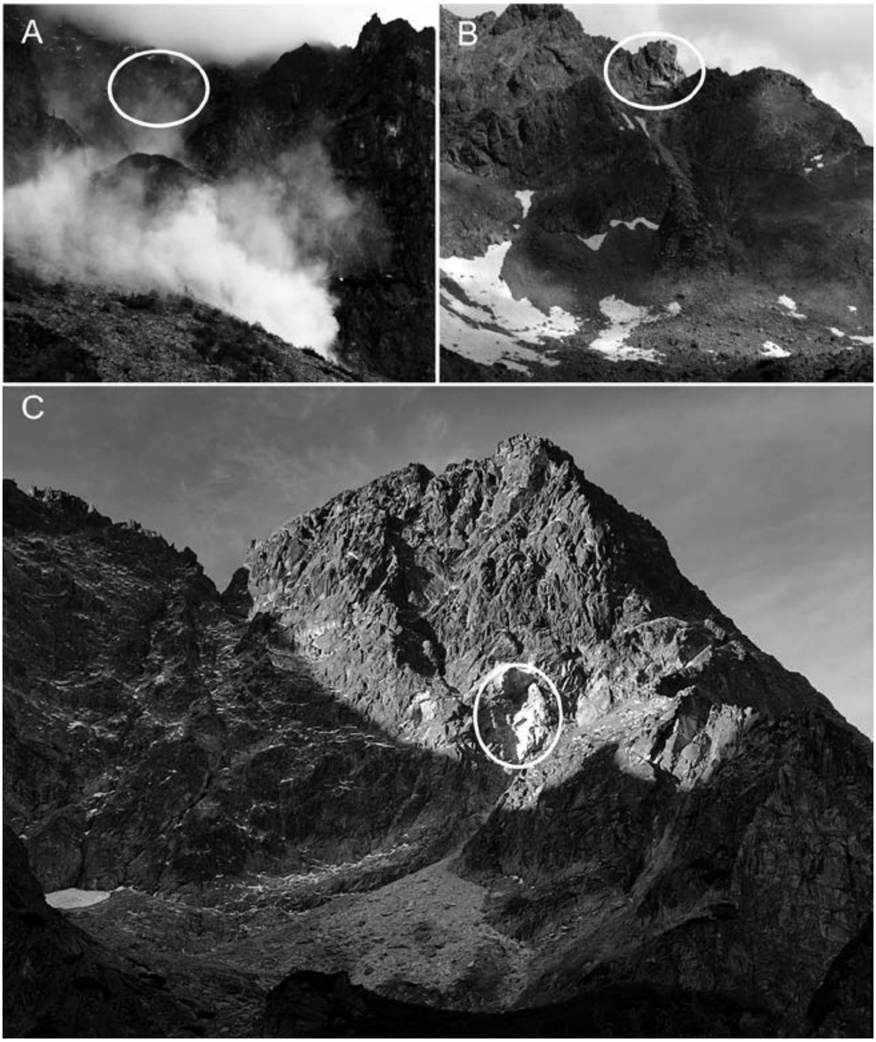

Figure 6. Mass falls (10^2-10^5 m^3) in the Polish part of the High Tatras: (A) Cubryna slope on 23 September 2012 (photo by R. Kaczka), B) Niebieska Turnia on 21 May 2018 (photo by M. Szumny), C) Turnia Kurczaba on 22 October 2022 (photo by B. Gądek). The ellipse indicates the rockfall release area

the following: (a) changes in dwarf mountain pine related to it being burdened by snow remnants, (b) high correlation of the rock cavities registered with crack density, and (c) realistic values of measurements of the rate of rock face retreat verified by an independent team with measurements of the mass balance of the talus fan (Rączkowska & Cebulski, 2022), provides evidence of the usefulness of the methodology deployed.

Conclusions

In high-mountain areas, the rate of changes in granitoid slopes under the influence of weathering and detachment processes is very variable, both in time and space. It can vary by an order of magnitude and even more on the surfaces of adjacent rock slopes. Over the 3 years when the slopes of Mięguszowiecki Szczyt – Cubryna were monitored, the pace of their retreat within the 4 large polygons surveyed ranged from 0.00013 ma^{-1} to 0.004 ma^{-1}.

The spatial variations in the number and size of cavities within granitoid slopes developing under the same climate conditions was related primarily to the density of the cracks. The influence of morphometric features such as inclination, exposure and altitude of rock faces may not be noticeable. Data on the cracking of rock slopes should therefore also be taken into account when studying the evolution of slope systems (including talus slopes).

In the Tatra Mts., which have not been glaciated for thousands of years, the greatest threat may currently be posed by rock faces in the periglacial zone, which, at the same time, on account of the lithology and density of cracks, show the greatest tendency to disintegrate under gelivation conditions. In the granitoid part of the Tatra Mountains, these include slopes located in the fault/mylonite zones in the moderately cold and cold climatic belts. At the same time, due to the progressive climate warming, the possibility of medium- or large-sized rockfalls caused by the degradation of permafrost cannot be ruled out. However, the events should not be frequent due to the sporadic occurrence of permafrost in the Tatras.

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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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