Triggers of present-day rockfalls in the zone of sporadic permafrost in non-glaciated mountain region: the case study of Turnia Kurczaba (the Tatra Mts., Poland)

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Abstract: In recent decades there has been growing evidence of the impact of ongoing climate warming on the frequency of rockfalls. However, these are not adequately documented, especially in non-glaciated, high mountain regions of middle latitude. This study comprehensively documents the Turnia Kurczaba rockfall, one of the most significant rockfalls recorded in recent decades in the Tatra Mountains. The precise projections of the volumes and distribution of rock losses and deposits, the determination of the trajectories, modes and speeds of movement of rock material, as well as information on the geological, morphological, and meteorological conditions behind the Turnia Kurczaba rockfall form a unique dataset. The data documents a spectacular episode in the contemporary development of a complex slope system in the Tatras in an all-encompassing way and can be used to validate and calibrate existing models and improve numerical simulations of other rockfalls, both for hazard and risk assessment and slope evolution studies. Moreover, in the context of archival data, they demonstrate that in the Tatra sporadic permafrost zone, only relatively small rockfalls have been recorded in recent decades. Their cause was not the degradation of permafrost but freeze-thaw processes with the co-participation of rainwater and meltwater. The largest of these occur within densely fractured cataclysites, mylonites, and fault breccias. The impact of rockfalls on the morphodynamics of talus slopes is uneven in the storied arranged rock-talus slope systems. Even colluviums belonging to the same slope system can differ in their development rate and regime, and different thermal and wetness drivers can control their evolution.

Keywords: rockfall, natural hazards, high mountains, impact of climate change, Tatra Mts.

INTRODUCTION

Rockfalls and rock avalanches are common in high mountain areas. The term rockfall comprises the fall of a rock mass after it breaks away from a very steep rock slope, its disintegration, and subsequent motion, which may involve downslope bouncing, rolling, or sliding (Evans et al. 2006). Large rockfalls that generate the extremely fast displacement of dry debris are referred to as rock avalanches (Cruden & Varnes 1996). Typically, rock avalanches involve flow-like rapid movement of large-volume fragmented rocks, which can travel up to several kilometres and reach the opposite slope of the valley (Hermanns 2013, Hungr et al. 2013).

Literature on the subject abounds in descriptions of large rockfalls and rock avalanches with volumes exceeding 10^6 m^3 that have taken place in the European Alps (Deline 2001, Noetzli et al. 2003, Crosta et al. 2004, Fischer 2006, Oppikofer et al. 2008, Walter et al. 2020), and in the Yosemite Valley (Wieczorek et al. 1992), the Pyrenees (Corominas et al. 2005), the Caucasus (Haberli et al. 2004) British Columbia (Geertsema et al. 2006), and the Southern Alps of New Zealand (Allen et al. 2011). Smaller rockfalls have been described less frequently, although they are more common, as exemplified by events observed in the European Alps during the hot summer of 2003 (Gruber et al. 2004, Ravanel et al. 2017).

The environmental conditions behind the loss of stability of high-mountain rock slopes can be very complex (Ballantyne 2002, Gunzburger et al. 2005, Evans et al. 2006, Fischer et al. 2012). A key role is played by the rock mass quality/bedrock fabric, especially the density, direction, gradient, and size of structural discontinuities (Fischer et al. 2012, McColl 2012, Luethi et al. 2015, Mair et al. 2020, Sala et al. 2020). The importance of the thermal dynamics and moisture content of rocks has been highlighted by Allen & Huggel (2013) and Mair et al. (2020). Topographic conditions such as the height, gradient, shape, and roughness of the slope determine the likelihood, mode, direction, and velocity of motion of the released material and the runout distance (Evans & Hungr 1993, Azzoni et al. 1995, Crosta & Agliardi 2004, Frattini et al. 2008).

There are many potential rockfall triggers (McColl 2012). The key ones, sometimes acting simultaneously, include: (a) seismic activity (Kobayashi et al. 1990, Deparis et al. 2008, Kargel et al. 2016), (b) exposure and debuttressing of rockwalls as a result of glacier retreat (Ballantyne 2002, Fischer et al. 2006, Oppikofer et al. 2008, Ravanel et al. 2017, Knoflach et al. 2021), and (c) degradation of permafrost (Gruber & Haeberli 2007, Harris et al. 2009, Ravanel et al. 2010, 2017, Fischer et al. 2012, 2013, Sala et al. 2020, Savi et al. 2020, Knoflach et al. 2021). Major rockfall triggers also include heavy precipitation events, rapid snow melt, and thermal anomalies (Eberhardt 2006, Allen & Huggel 2013, Luethi et al. 2015, Paranunzio et al. 2016, 2019, Sala et al. 2020). Thermal and precipitation anomalies have been identified as the cause of contemporary rockfalls in non-glaciated areas of the Italian Alps (Paranunzio et al. 2016, 2019).

In order to improve the risk management associated with rapid mass movements, there is a need to both enhance our knowledge about the conditions and course of the detachment, the transport and deposition of the released rock masses, as well as developing an improved regional and local understanding of the susceptibility of slopes to instability. It can be expected that ongoing climate change, which is manifested by the intensification of thermal and precipitation anomalies, will be increasingly conducive to rapid mass movements in the future (Schlögel et al. 2020). Increased rockfall hazards are observable in both glaciated and non-glaciated high mountains with permafrost, whereas in other high mountain areas the impact of present-day climate change on rock slope dynamics is questionable (Kenner 2019, Hendrickx et al. 2020, Mainieri et al. 2023).

Rockfalls are one of the key processes that shape the relief of the Tatra Mountains today (Rączkowska 2006, Rączkowska & Cebulski 2022), although their activity was much greater at the time of the Pleistocene deglaciations (Pánek et al. 2016) or during the Little Ice Age (Kotarba & Pech 2002, Kotarba 2004, Rączkowska 2006). However, as a consequence of ongoing climate change, increasing temperatures and the frequency of heavy precipitation (Niedźwiedź et al. 2015, Łupikasza & Małarzewski 2023), the activity of rockfall may increase. In the last decade, tourist routes within a small area in the Polish High Tatras have been repeatedly closed due to damage caused by rockfalls and the subsequent instability of rockwalls. This is one of the reasons why the monitoring of the talus and rock slopes (Rączkowska & Cebulski 2022, Gądek et al. 2023) and continuous meteorological measurements have been carried out for many years in the cirques of the Morskie Oko and Czarny Staw pod Rysami lakes (Fig. 1), where the tourism carrying capacity (TCC) is sometimes exceeded (Choiński & Pociask-Karteczka 2014). Thanks to this, the course, causes and geomorphological impacts of the most recent dangerous rockfall, which occurred around 4:40 pm on 22 October 2021 on the Turnia Kurczaba peak, were precisely recorded. Further insights into the event were provided by two video records of people who witnessed it. The materials have been used to: (i) determine accurately the location, geometry, and size of the rockfall starting zone and the volume of the rock mass released, identify (ii) its topographic, (iii) geological, and (iv) hydrometeorological controls, (v) determine the velocity and trajectory of the transport of debris, and (vi) determine the distribution of rock deposits within the complex slope system.

The main goal of this paper is to identify the causes of the Turnia Kurczaba rockfall in the context of contemporary climate warming and permafrost degradation in non-glaciated mountains and to collect data for the validation and calibration of numerical models that can be implemented in the next stages of the research for hazard and risk assessment and slope evolution studies.

STUDY AREA

The rockfall in question occurred in the upper part of the Rybi Potok Valley in the Polish High Tatras (Fig. 1). The area is built up of Carboniferous granitoids that disintegrate along joints running in the NW-SE and NE-SW directions, and in the fault zones there are also cataclysites, mylonites, and tectonic breccias (Piotrowska 1997, Piotrowska et al. 2015a, 2015b).

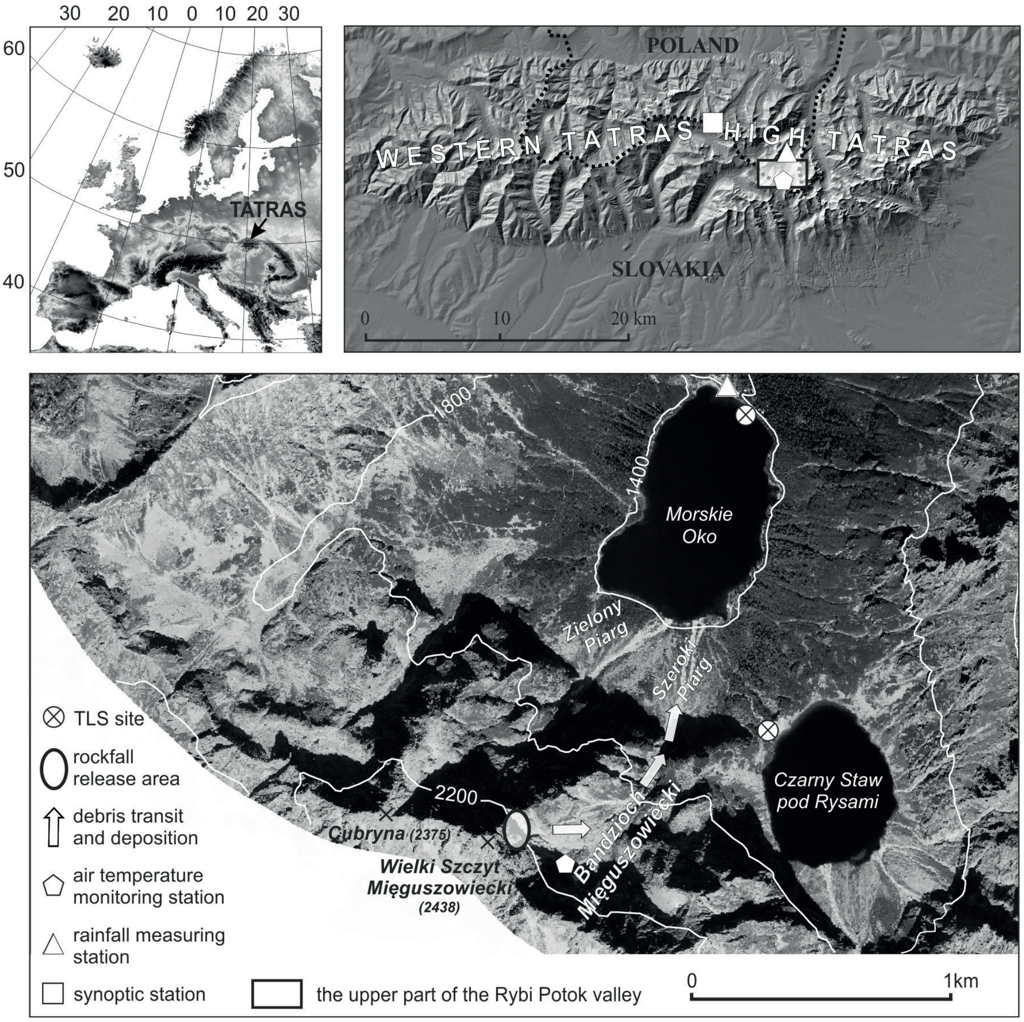

Fig. 1. *Location of the study area and measuring sites*

The high-mountain relief of this area dates back to a series of Pleistocene glaciations (Klimaszewski 1988, Rączkowski et al. 2015, Zasadni et al. 2022). In the post-glacial period, extensive talus cones with a thickness exceeding 40 m developed at the mouths of gullies (Gądek et al. 2016). Today, they are mainly modelled by debris flows (Rączkowska et al. 2018, Rączkowska & Cebulski 2022). The research comprised the complex slope system of the Wielki Szczyt Męguszowiecki peak (2,438 m a.s.l.) – the Morskie Oko lake (1,375 m a.s.l.), on which the Turnia Kurczaba peak fell on 22 October 2021, leading to the formation of an extensive area of colluvium. The most frequented tourist trail in the Tatra Mountains (Choiński & Pociask-Karteczka 2014), used by as many as several thousand people a day in the summer season, runs to the Morskie Oko lake (Tatrzański Park Narodowy 2023). In addition, there are many popular climbing routes on the adjacent rockwalls, one of which used to run across the Turnia Kurczaba peak (Sobiecki 2015).

The moderate climate of this area is mainly shaped by Polar maritime and Polar continental air masses (Niedźwiedź 1992). The mean annual air temperature varies from approx. 3°C at the Morskie Oko lake (1,395 m a.s.l.) to approx. –2°C on the highest peaks (Żmudzka et al. 2015, Łupikasza & Szypuła 2019). Permafrost may occur sporadically above 1,900 m a.s.l. (Dobiński 1998, Gądek et al. 2009, Gądek & Szypuła 2015). The annual mean rainfall totals increase with altitude from 1,400 mm to 2,000 mm (Ustrnul et al. 2015), and the number of days with seasonal snow cover ranges from about 150 to over 210 (Gądek & Szypuła 2015).

METHODS

Terrestrial laser scanning and complementary measurements

The terrestrial laser scanning (TLS) of the rockfall release, transit, and deposit zones was performed using a Riegl VZ-2000 laser scanner fitted with a Nikon D810 camera and a GPS receiver. The measurements were carried out on 28 September and 28 October 2021 (i.e. 24 days before and 6 days after the rockfall, respectively) from the same two spots. The first spot was located on the shore of the Czarny Staw pod Rysami lake (49°11'24"N; 20°04'25"E), at an altitude of 1,600 m a.s.l., 970 m NE of the rockfall release area (RRA), while the second was on the shore of the Morskie Oko lake (49°12'02"N; 20°04'19"E), at an altitude of 1,395 m a.s.l., 1,000 m NNE from the lower boundary of the run-out zone (Fig. 1). The frequency and range of the laser light were 50 Hz and approx. 2,000 m, respectively.

The so-called ‘false points’ were removed from the point cloud using the ‘reflectance gate,’ ‘deviation gate’ and ‘octree’ filters, which are available in the RiSCAN PRO v. 2.12.1 software. The point clouds were given natural colours and were mutually oriented and fitted with an accuracy of ±2 cm. The planes of adjustment were differently oriented and evenly distributed over the surface of the area studied. Their number was 670, and their sizes ranged from 0.25 m to 65 m. The density of both point clouds varied from 5 to 25 points·m^{-2}. The resulting spatial dataset was used for delimiting three polygons that marked (i) the release area, (ii) the run-out area within the Bandzioch Męguszowiecki cirque, and (iii) the run-out area within the Szeroki Piarg talus cone at the Morskie Oko lake. The blind spots within these polygons represented from about 5% to about 10%. The digital elevation models (DEM) of the individual areas, produced through triangulation, had a resolution of 0.1 m × 0.1 m. On their basis, differential digital models of the changes in relief (in planes parallel to the slope surface) caused by the Turnia Kurczaba rockfall were generated. The heights, lengths, gradient, and exposures of the solid and talus components of the slope system within which the rockfall occurred were measured, along with the surface areas and volumes of the rock loss and rock deposits.

In addition, photographic documentation was made of the entire slope system, especially of the areas invisible from the TLS spots. The pictures were then used to map the spots with freshly deposited debris material on a high-resolution digital orthophotomap. Based on this, in turn, their approximate surface areas were measured using GIS tools. In addition, in the lowest part of the slope system, on the Szeroki Piarg talus cone, in situ mapping of fresh deposits was carried out and the maximum diameters of the boulders and rock blocks comprising it were measured.

Video footage analysis

The moment of the Turnia Kurczaba fall and the subsequent descent of the debris was filmed by two accidental witnesses using cameras on their mobile phones. Both videos were made from locations near the TLS sites on the shores of the Czarny Staw pod Rysami and Morskie Oko lakes. The video footage posted by the authors on YouTube was helpful in assessing the duration, dynamics, and trajectory of motion of the rock fragments. Their approximate velocity was estimated on the basis of readings from the video-recording time counter and the approximate length of the trajectory measured in the ArcGIS software on the basis of the identification of the filmed spot locations on a high-resolution orthophotomap integrated with a digital elevation model. The first video was shared with us by its author Agnieszka Brożyna, while the second video is available at: https://www.youtube.com/watch?v=xhL-XL2oIjU (accessed 30 March 2023).

Geological surveys

The geology of the RRA was derived from the digital geological map 1:10,000 (Piotrowska et al. 2015b) using ArcGIS software and a shapefile with the contour of the RRA. Moreover, the rock cracks were identified, and their length was measured on the RRA photograph provided by the Tatra National Park. This photograph was taken from a distance of approx. 100 m from the rockwall by means of an unmanned aerial vehicle (UAV), with the picture framed in such a way as to position the RRA in the centre of the photo, where the distortions linked to the central projection are the smallest. The average scale of the photograph used was calculated based on the RRA area as measured on the digital model of the terrain surface changes. The spatial resolution of this photograph (pixel size) was 0.04 m. However, by influencing the colour and brightness of pixels, homogeneous linear features are visible in the images even when their width is smaller than the pixel size. The surface density of the cracks (D_s) identified in the photograph was determined with Equation (1) (Liszkowski & Stochlak 1976):

$$D_s = \frac{\Sigma l}{P} \qquad (1)$$

where:
Σl – the sum of the crack lengths,
P – the RRA area.

Meteorological monitoring

In order to identify the meteorological conditions of the rockfall, air temperature monitoring data from the University of Silesia and rainfall and snowfall data from the Institute of Meteorology and Water Management (IM&WM) were used, spanning the period from 15 September to 22 October 2022.

Air temperature monitoring was carried out in the Bandzioch Mięguszowiecki cirque at an altitude of 1,975 m a.s.l., at a distance of 300 m ESE from the RRA. The temperature was sampled and recorded every hour using a HOBO U23 Pro v2 data logger by ONSET. The temperature sensor was placed in a radiation shield at a height of 2 m above the ground. The factory-set resolution and accuracy of the measurements were 0.02°C and 0.2°C (at and above 0°C), respectively.

Daily data on the amounts and type of precipitation were collected at the IM&WM precipitation station adjacent to the tourist shelter on the shore of the Morskie Oko lake, which is situated at an altitude of 1,408 m a.s.l. at a distance of 1.7 km NNE from the RRA. The daily data on the depth of snow cover were taken from the synoptic station on Kasprowy Wierch, which lies at 1,991 m a.s.l. at a distance of 7.5 km NW from the RRA.

RESULTS

Morphometry of the slope system

The slope system within which the study rockfall occurred consists of several elements with different morphogenesis and morphometry, which determined both the way in which the released rock material moved, and how it was deposited (Fig. 2). The upper reach of the system is formed by the rockwall of the Wielki Szczyt Mięguszowiecki peak (2,439 m a.s.l.) with a height of 389 m and a gradient exceeding 70°. Its lower NE boundary is marked by a rocky chute that transports the products of weathering to a hanging glacial cirque known as Bandzioch Mięguszowiecki. The length and gradient of this talus area are 245 m and 33°, respectively. The threshold of the cirque has two steps. The upper step has a height of 120 m and a maximum gradient of 74°, whereas the lower step has a height of 205 m and its maximum gradient is 90°.

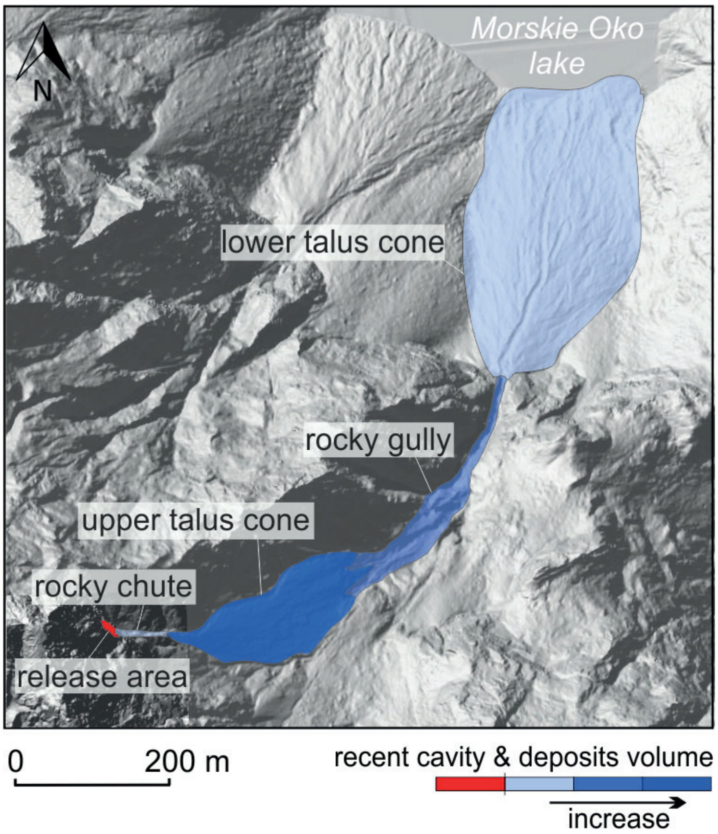

***Fig. 2.** Components of the studied slope system: Turnia Kurczaba peak (release area) – Morskie Oko lake (see also Fig. 7)*

Both steps are incised by a steep and deep rocky gully. The Szeroki Piarg talus cone located at its mouth enters the Morskie Oko lake (1,395 m a.s.l.). Its length and average gradient are 420 m and 22°, respectively. The surface of this complex slope system is exposed in the E, NE and N directions (Fig. 1), the total length is 955 m, and the average gradient is 41° (Table 1).

Internal structure of the release area

The rockfall originated within a strongly fractured fault zone built of cataclysites and mylonites (Fig. 3). This zone runs among granitoids from SW to NE. The discontinuity areas identified in the photograph, which probably vary in age, have different orientations, i.e. both vertical and near-horizontal or oblique. The main vertical cracks run SW-NE and SE-NW. The vertical and horizontal cracks account for 22% and 19% of all discontinuities, respectively, and their maximum lengths exceed 20 m. The surface density of the cracks in the rockfall release area is 0.42 m^{-1}. On the day of the observations made in situ, this zone was not stable, with large fragments separated from the rest of the slope by vertical crevices.

Meteorological triggers

The meteorological data show that the rockfall was preceded by considerable fluctuations in air temperature above and below 0°C, rainfall and snowfall (Fig. 4). Since mid-September, more than 100 mm of rain had fallen in the study area. On the cool days of 20–23 September and 12–14 October, snow layers from several centimetres to more than ten centimetres thick covered flat surfaces at altitudes above 1900 m a.s.l. The air temperature over that period fluctuated between 10.2°C and –6.2°C. The rapid increase in air temperature in the days preceding the fall resulted in the rapid and complete melting of the snowpack, leading to the saturation of the ground with meltwater. One day before the Turnia Kurczaba rockfall, the air temperature dropped from 9°C to 1°C, oscillated around 0°C the next day and dropped to –1°C at the time of the rockfall.

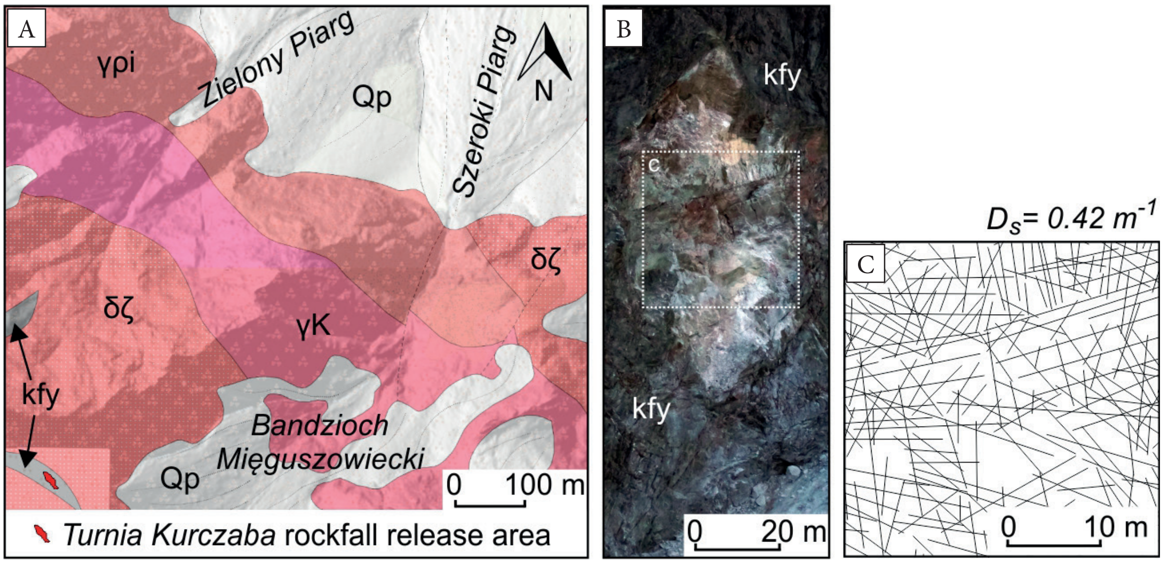

Fig. 3. *Lithology of the study area (A) with the location of the rockfall release area (B) and its crack density (C). The modified fragment of the geological map (Piotrowska et al. 2015b): δζ – granitoids and tonalites, γK – granitoids with pink feldspar crystals, γpi – granites with pegmatites and aplites, kfy – cataclysites, tectonic breaches, phyllonites and mylonites, Qp – talus material; D_s – surface density of the cracks*

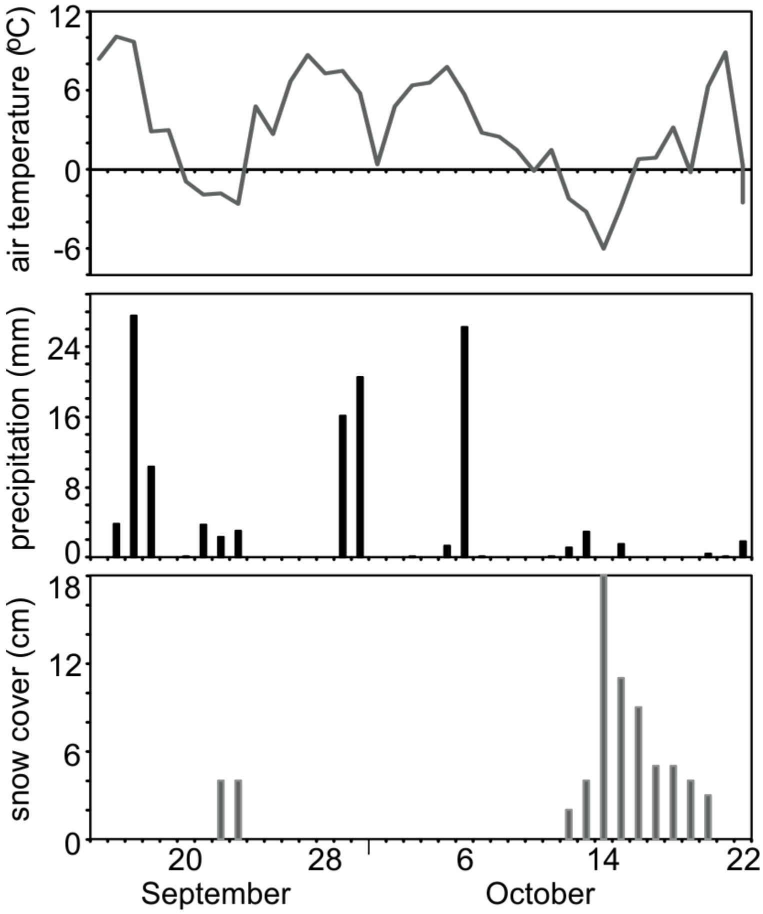

Fig. 4. *Weather conditions during the days preceding the Turnia Kurczaba rockfall (15.09.2021–22.10.2021)*

Geometry, size and velocity of the rockfall

The rockfall release area

The Turnia Kurczaba peak was part of the E rockwall of the Wielki Mięguszowiecki Szczyt peak. The rock niche formed as a result of the Turnia Kurczaba rockfall traverses the altitude zone 2,130–2,210 m a.s.l., i.e. 80 m above the bottom of the Bandzioch Mięguszowiecki cirque. The height and maximum width of this niche are 80 m and 40 m, respectively. As shown by the results of the TLS measurements, the rockwall retreated by 1–10 m within the RRA (Fig. 5), and by 3.1 m on average. The TLS also demonstrates that 7,200 m^3 of rock material was lost (Table 1).

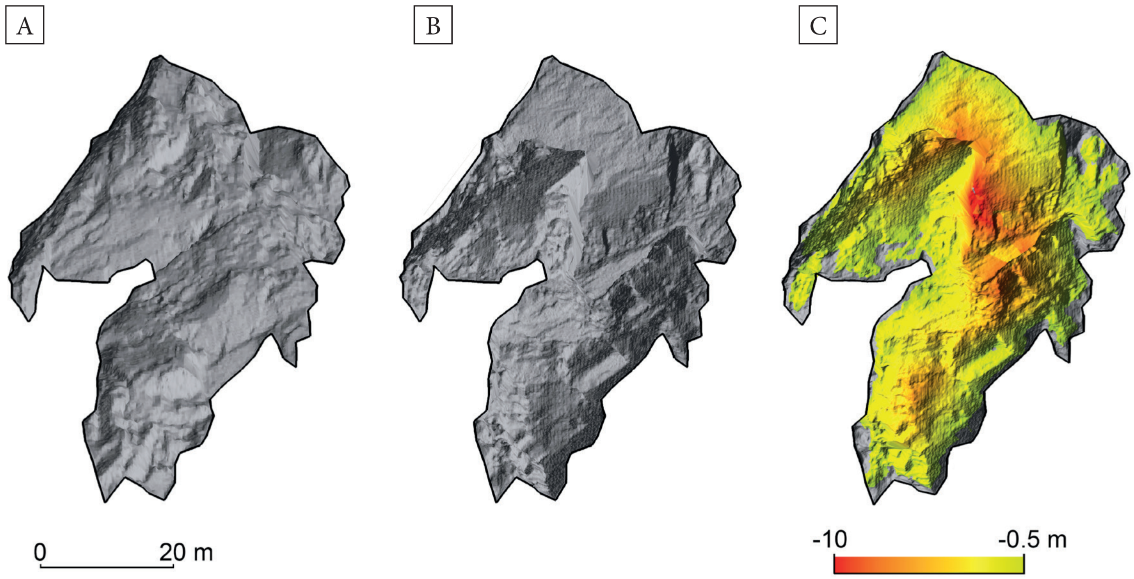

Fig. 5. *The release area: A) DEM before the rockfall; B) DEM after the rockfall; C) DEM of Difference (rock wall retreat)*

Table 1
Morphometry of the Turnia Kurczaba slope system (release area) – Morskie Oko lake (see Fig. 2)

Slope component	Length [m]	Gradient [°]	Altitude [m a.s.l.]		Vertical extent [m]	Volume of cavity and deposits [m^3]
			max.	min.		
Release area	80	75–90	2,210	2,130	80	7,200
Rocky chute	75	40–80	2,105	2,050	55	ca. 150
Talus cone (upper)	245	33	2,050	1,860	160	4,200
Rocky gully (upper part)	161	36–74	1,890	1,770	120	≤2,590
Rocky gully (lower part)	219	43–90	1,770	1,565	205	
Talus cone (lower)	420	22	1,565	1,395	170	260

Mode, trajectories and velocity of movement of rock material

As the video footage shows, the disintegration of the Turnia Kurczaba lasted about 10 min and was propagated in several stages from its lower reaches. The detached fragments of the rock wall separated along the surface of the discontinuities, falling freely, usually for about 3 s, at a velocity of up to 30 $m \cdot s^{-1}$. After impact, the rocks travelled on, bouncing, rolling, and sliding, or stopped on rough surfaces. This went hand in hand with the displacement of older talus material, the formation of impact craters, the disintegration of colliding rock fragments and the uplift of dust, which formed a dense cloud that initially moved down the cirque and then rose across its width to a height of well over 100 m. The zones of transit and deposition overlapped each other as early as from the base of the upper talus cone. The largest volume of the material was deposited within the Bandzioch Męguszowiecki cirque (Fig. 6A). The velocity of the coarse rock fragments that were mainly rolling in this zone often exceeded 10 $m \cdot s^{-1}$. Only dust suspended in the air and individual rock blocks reached the talus cone on the shore of the Morskie Oko lake, mainly rolling and bouncing over the surface of the threshold, often at a velocity of >20 $m \cdot s^{-1}$ or pouring out of the gully that incised it.

Distribution of rock deposits

The quantitative and spatial changes related to the displacement and deposition of the material from the Turnia Kurczaba rockfall are shown in Figure 6. However, the illustrations do not show the rocky chute at the base of the rockfall slope or the threshold of the Bandzioch Męguszowiecki cirque, which the rocky chute leads into, because these zones were not visible from the TLS sites. Nevertheless, field surveys indicated that the narrow rocky chute that first received the falling fragments of the rock wall was a transit zone (Fig. 2). Most probably, the volume of material that stopped there (only in its lower parts), which mainly consisted of fine debris, did not exceed 150 m^3 (Fig. 7). The largest deposit was in the talus cone below the chute at the bottom of the cirque. The fresh colluvium covered 62% of the slope area. First of all, the debris flow channels along the northern (marginal) and central parts of the talus cone were filled and locally overlain. The depth of the material deposited on this slope was up to 5 m, but typically was in the range of 1–2 m. The overall volume of all fresh deposits was 4,200 m^3. It was also noted that a certain amount of the talus material was missing from the central part of this zone. The losses covered 5% of the slope area. The largest ones were point-like and reached 4 m (Fig. 6A). They originated in the spots where large rock blocks were knocked out. The SE part of the talus cone changed the least.

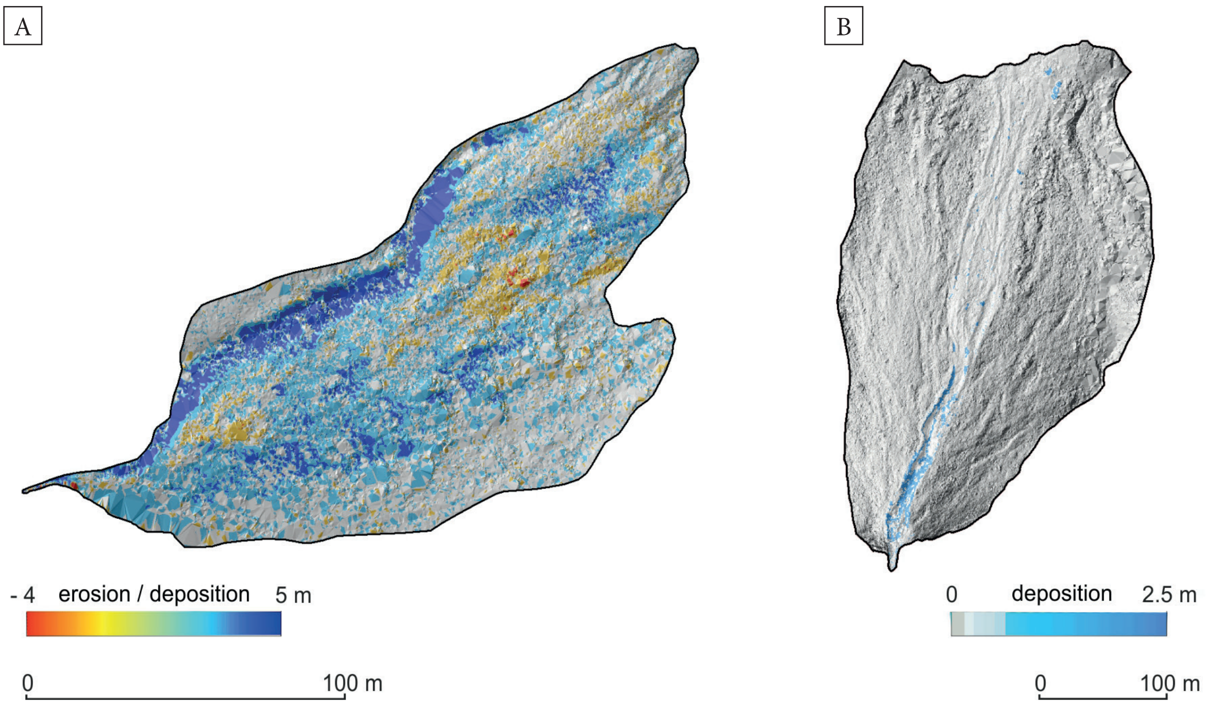

Fig. 6. *The DEM of differences before and after the Turnia Kurczaba rockfall: A) upper talus cone; B) lower talus cone (Szeroki Piarg)*

Fig. 7. *The Turnia Kurczaba rockfall: release and rock deposits area (see also Figs. 2, 5, 6)*

Within the threshold of the Bandzioch Męguszowiecki cirque (not covered by the differential models), the presence of fresh talus material was only found in the rocky niche and the rocky gully forming its extension (Fig. 5). These deposits covered an area of 2,073 m^2. However, it was not possible to measure their total volume. Fresh talus material was also found below the rocky gully – mostly in the upper part of the Szeroki Piarg talus cone (Fig. 5), where it formed loose clusters of debris, boulders, and blocks (Fig. 7) scattered in the debris flow channel and in areas adjacent to it (Fig. 6B). The mean maximum diameter of the 25 largest rock fragments was 1.32 m, with the largest block measuring 2.6 m in diameter (Fig. 7). Sand-silt material adhered to the surface of the coarse rock fragments as a result of them having hit soft ground during the bouncing movement. On the lower part of the cone, there were only single rock blocks with a diameter of 1.6 m to 2.5 m. The total volume of the deposits on the Szeroki Piarg talus cone was 260 m^3.

DISCUSSION

In general, the frequency of rockfalls is inversely proportional to their size – the larger they are, the less often they occur (Gądek et al. 2023). Rochet (1987) divided rockfalls into four groups: single block falls (10^{-2}–10^{2} m^3), mass falls (10^{2}–10^{5} m^3), very large mass falls (10^{5}–10^{7} m^3) and mass displacement (>10^{7} m^3). The first two types are characterised by little or no interaction between the descending rock fragments. In the light of the above, the Turnia Kurczaba rockfall represents the mass fall category. While the falling of single rock fragments in the periglacial zone of the Tatra Mountains is common (Kotarba et al. 1987, Kotarba & Pech 2002), larger rockfalls in the area of the Morskie Oko lake have usually been recorded at multiple-year intervals in the last 150 years. Based on the perfunctory information available (Nyka 1956) and approximations (Rączkowska et al. 2018), it can be concluded that most of them belonged to the same category as the Turnia Kurczaba rockfall, and their geological conditions and causes were similar.

The surface density of the cataclysite-mylonite fractures in the RRA that were identified is 50% higher than the mean surface density of the fractures in the granitoid walls towering over the shores of the Morskie Oko lake (Gądek et al. 2023). Although lithology does not necessarily determine the location where a rockfall will occur (Barth 2013), cataclysites and mylonites are characterised by greater amounts of cracks and loosening than the granitoids in which they occur in the High Tatras. This means that rockwalls made of them may be particularly susceptible to gravitational mass movements (Korup 2004, Braathen et al. 2004, Cox et al. 2012, Barth 2013). In the Polish High Tatras, all major rockfalls in the last decade occurred within the cataclysites, mylonites, and fault breccias (Rączkowska & Cybulski 2022, Gądek et al. 2023), where numerous climbing routes (Wspinanie.pl. n.d., Sobiecki 2015) and hiking trails (Tatrzański Park Narodowy 2022) used by about one million people a year are to be found (Niezgoda & Nowacki 2020). Therefore, determining the stability of the slopes in these areas should be considered a priority.

In many high mountain areas, rockfalls are most frequently caused by the degradation of permafrost as a result of climate warming (Allen & Huggel 2013, Fischer et al. 2016, Knoflach et al. 2021), with such events typically occurring in summer (Fischer et al. 2012, Sass & Oberlechner 2012) – often at times of extremely high air temperatures (Allen & Huggel 2013). In the Tatra Mountains, in addition to the Turnia Kurczaba rockfall studied here, fragments of the rockwalls of Cubryna (23–25 September 2012), Zadný Gerlach (17–19 September 2018), Niebieska Turnia (21 May and 28 September 2018) and Malý Kežmarský štít (18 June 2022) peaks have also fallen in the last decade. The elevations of the release areas ranged from 1841 to 2,637 m a.s.l. in moderately cold and cold climate belts (Łupikasza & Szypuła 2019), where permafrost may sporadically occur (Dobiński 2005, Mościcki & Kędzia 2001, Gądek & Leszkiewicz 2012, Gądek et al. 2016). Most of these rockfalls occurred in autumn, except for the Niebieska Turnia (first event) and Malý Kežmarský štít rockfalls, which took place under spring conditions. Notably, all of them were preceded by snowfall or rainfall and a sharp change in air temperature which passed through 0°C (Rączkowska et al. 2018, Rączkowska & Cebulski 2022). Thus, present-day rockfalls in the highest parts of the Tatra Mountains are primarily caused by freezing and thawing of heavily cracked and steep rock slopes saturated with rainwater or meltwater, and not the decay of permafrost. In addition, thermal and humidity factors often trigger rockfalls on non-permafrost slopes in other high mountain areas (Gunzburger et al. 2005, Lueth et al. 2015, Paranunzio et al. 2016, 2019, Sala et al. 2020). It is suggested that information on current and forecast weather conditions in the Tatra Mountains, especially in autumn and spring, be communicated to tourists to warn them of an increased risk of rockfalls, with an indication of areas which are particularly vulnerable in terms of morphology and geology.

The spatial distribution of the material from the disintegration of the Turnia Kurczaba and the videos of the rockfall demonstrate that factors like the trajectories, velocity, and modes of motion, as well as the deposition of rock fragments, all depended on their geometry (size/shape) and were controlled by the local gradient and roughness of the slope. Rock free falling was limited to the upper section, which had the form of a rock cliff. On the remaining slopes, the rock material bounced, rolled, and slid, except that rolling predominated on the talus slopes and bouncing prevailed on the two-stepped steep threshold. Fine debris stopped as early as in the chute above the upper talus cone, while rock blocks reached as far as the lower cone. The regularities described above are confirmed by the results of experimental studies (Azzoni et al. 1995) and should be taken into account in research based on mathematical modelling (Giani et al. 2004, Crosta & Agliardi 2004, Dorren et al. 2013).

The data on the distribution of the deposits of the Turnia Kuczaba rockfall material are not complete because the laser scanning did not cover the gullies above and below the upper and lower talus cones, respectively. However, the volumes of released material and rock deposits are in balance, assuming that the volume of the colluvium in the upper chute was close to 150 m^3, and the depth of the colluvium in the lower rocky gully was close to 1 m. However, the volumes of released material and rock deposits are in balance, assuming that the volume of the colluvium in the upper chute was close to 150 m^3, and the depth of the colluvium in the lower rocky gully was close to 1 m. This assumption seems realistic. The greatest amount of rock material was deposited on the talus cone within the hanging cirque, and the greatest change in the morphology consisted of filling the debris flow gullies in the northern and central parts of the cone. By contrast, the Turnia Kurczaba rockfall did not cause any significant changes within the lower talus cone, namely Szeroki Piarg. The presence of a glacial cirque in the supply zone of this talus cone significantly influenced the transfer of sediment. Almost all the rockfall material stopped higher up, within the hanging cirque and the rocky gully that incised its threshold. However, in the future these deposits can be expected to be set into motion by debris flows and are bound to influence the evolution of the Szeroki Piarg cone situated below. Thus, local/regional variations in the morphodynamics of talus slopes are influenced by factors other than differences in the geological setting, size, and shape of the source area (Gądek et al. 2016). An important role is also played by the shape and size of the transit zone, since the latter is usually also a rock deposition zone and may, over time, transform into a supply zone for downhill slopes. Examples of adjacent talus cones that differ in morphodynamics, size, morphology, and functions of the higher-lying part of the slope system are Szeroki Piarg and Zielony Piarg at the Morskie Oko lake, which has already been pointed out (Rączkowska & Cebulski 2022).

Numerical simulations of the rockfall trajectories and run-out zones (Bartelt et al. 2016) may not only be helpful in hazard and risk assessment for rockfall mapping (Jaboyedoff et al. 2005) and protection (Crosta et al. 2015) but also in studies on the evolution of high-mountain slope systems. Rockfall modelling is preceded by the collection of historical inputs that include information on the date, location, and size of rockfalls as well as on the geology, topography, roughness and surface material, although precise and complete data are not usually available (Dorren et al. 2012). The results of comprehensive monitoring of the rockfall in the Tatras and its underlying conditions presented in this paper are unique, since they can be employed in back-analysis/calibration of existing models which, in turn, can improve the results of simulations for other rockfalls, especially within complex slope systems.

CONCLUSIONS

1. The Turnia Kurczaba rockfall was one of the most significant rockfalls recorded in recent decades in the Tatra Mountains. Its height, maximum width, and volume were, respectively, 80 m, 40 m and 7,200 m^3. This rockfall took place in the fault zone of the granitoid massif within densely fractured cataclasites, mylonites, and fault breccias, and at altitude of sporadic permafrost occurrence. Although all of these rockfalls happened during a period of climate warming, their cause was not the degradation of permafrost but freeze-thaw processes with the co-participation of rainwater and meltwater. Thus, information on current and forecast weather conditions in the Tatra

Mountains, especially in autumn and spring, should be communicated to tourists to warn them of an increased risk of rockfall, indicating areas particularly vulnerable in terms of morphology and lithology.

2. The highest-located talus part of the stepped slope system of Turnia Kurczaba is fed directly by rockfalls. In contrast, the development of the lowermost talus cone may be primarily influenced by the redeposition of clastic material from the upper parts of the slope, mainly related to heavy rainfall episodes. Regional and local variations in the morphodynamics of talus slopes thus depend on the geological and morphological features of the supply areas and the shape and size of the transit-deposition zones, which may transform into supply areas for lower slopes over time. So, even adjacent colluviums can differ in their development rate and regime, and different thermal and wetness drivers can control their evolution.
3. The precise projections of the volumes and distribution of rock losses and deposits, the determination of the trajectories, modes, and speeds of movement of rock material, as well as the information on the geological, morphological, and meteorological conditions behind the Turnia Kurczaba rockfall form a unique dataset. The data documents a spectacular episode in the contemporary development of a complex slope system in the Tatras in an all-encompassing way and can be used to validate and calibrate existing models and improve numerical simulations of other rockfalls.

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