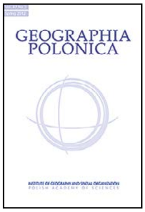

Geographia Polonica
2024, Volume 97, Issue 2, pp. 189-204
https://doi.org/10.7163/GPol.0275

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POLISH ACADEMY OF SCIENCES
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POTENTIAL ROCKFALLS IN THE PERIGLACIAL ZONE OF THE POLISH HIGH TATRAS: EXTENT AND KINEMATICS

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Abstract

The study offers the first attempt to combine the identification of rock cliffs particularly prone to rockfall with estimates of the potential trajectories and kinetic energies of the material released in this way in the Tatra Mountains. The results obtained suggest that the potential energy of the relief and the initial size and shape of the rock fragments released have not fundamentally changed since the complete disappearance of the glaciers. It was also found that the degree to which glacial and periglacial landforms are buried by such material depends not just on the location, number and size of the release areas or rockfall frequency but also on the kinetic energy of the rock material released. The rockfalls observed in recent years and those perceived as potential ones are linked not so much to permafrost degradation as to the relief, geology and weather conditions.

Key words

rockfalls • granitoid slopes • natural hazards cartography • RAMMS::Rockfall software • Tatra Mts.

Introduction

Rocky cliffs and talus covers are integral parts of any high-mountain denudation system. Their morphodynamics depends on the geology, topography, climate, glacial extent, the thickness of the active layer and seismic activity (Fischer et al., 2012; Romeo et al., 2017; Mair et al., 2020; Knoflach et al., 2021). Within the periglacial zone, mechanical weathering is the primary process responsible for degrading rock slopes (e.g. Eppes & Keanini, 2017). This process, often with the assistance of chemical weathering (Dixon & Thorn, 2005), leads to the propagation of cracking (Draebing & Krautblatter, 2019) and the consequent release of rocky fragments that fall, bounce, roll and slide downhill (Luckman, 2013). Deposited at the foot of rocky cliffs, the talus material forms colluvium that is subject to further shaping by paraglacial, periglacial and alluvial processes (Senderak et al., 2019, 2020).

Climate warming and especially deglaciation and permafrost degradation have been leading to an increasing magnitude and frequency of rockfall in high-mountain areas (Gruber & Haeberli, 2007; Fisher et al., 2012; Knoflach et al., 2021). Also, climate change has led to higher rates of rock and fracture kinematics (Draebing, 2021) at lower altitudes, which is controlled by the properties of the slope geology (André, 1996; Matsuoka, 2008; Lubera, 2016). The cracking and release processes display significant variability in time and space. The results of cosmogenous isotope dating of talus material in the Tatras suggest that the largest rockfalls in the area occurred approximately 20 ka BP as a result of the deglaciation processes and during the warmer and more humid periods at the transition between the Pleistocene and the Holocene (Pánek et al., 2016). Lichenometric dating covering the last several hundred years, on the other hand, points to the low magnitude and continuous nature of these processes (Kotarba et al., 1987; Gądek et al., 2016), even if medium-scale rockfalls have occurred (Rączkowska & Cebulski, 2022; Kajdas et al., 2024). A considerable intensity of rockfall events was observed in the 19th and at the beginning of the 20th century (Kotarba & Pech, 2002). Dendrochronological data revealed increased rockfalls over the last five decades (Zielonka & Wrońska-Wałach, 2019). At present, rockfalls are predominantly activated by rainfall, snow melting and frost weathering (Kajdas et al., 2024), but in addition, it is impossible to exclude delivery of talus material from the degradation of permafrost (Šilhán & Tichavský, 2016), mainly since the biggest rockfalls of the last decade occurred in an area within which permafrost could potentially occur (Gądek et al., 2023).

Due to the growing hazard of rockfalls (Zielonka & Wrońska-Wałach, 2019), cliffs in areas in the Polish High Tatras where there is very intensive tourist and climbing activity (https://tpn.pl/zwiedzaj/turystyka/statystyka) are now being monitored using terrestrial laser scanning (TLS) (Gądek et al., 2023; Kajdas et al., 2024). However, comprehensive research into the rockfall hazard at the scale of the entire region is still lacking. This study offers the first such attempt. The idea is to identify areas particularly prone to rockfall and to estimate the trajectories and kinetic energy of the material potentially released from these areas. In this way, it has been possible to i) find the extent of potential rockfalls vis-à-vis the extent of the current talus slopes, ii) determine the relationships between potential rock material release zones and the current occurrence of permafrost, and iii) identify areas dangerous to tourist and climbing activity. The study employs the results of direct field observation, large-scale geological maps, high-resolution digital elevation models (DEMs), aerial orthophotomaps, numerical rockfall simulation methods (Bartelt et al., 2022) and geographical information systems (GIS).

Study area

The Polish part of the High Tatra Mountains (Fig. 1) covers an area of approximately 63 km^2, bounded by the WGS84 coordinates: N49.17956°/E20.088° and N49.28503°/E20.03425°. The area reaches an altitude of 2499 m a.s.l. (Mt. Rysy).

The local geology is dominated by Carboniferous granitoids marked by joint planes along the NW-SE and NE-SW axes, with cataclasites, tectonic breccias and mylonites being found in fault zones (Piotrowska, 1997; Piotrowska et al., 2015). The high-mountain relief is a result of Pleistocene glaciation (Klimaszewski, 1988; Zasadni & Kłapyta, 2014) and during the post-glacial period, vast talus cones exceeding 30 m in thickness formed at rocky gully mouths (Gądek et al., 2016; Senderak et al., 2019). The rate of rock wall retreat ranged from nearly 0 to 0.004 ma^{-1} (Kotarba et al., 1987; Lubera, 2016; Gądek et al., 2023).

The moderate climate of the Tatras is mainly determined by polar maritime and polar continental air masses (Niedźwiedź, 1992). The average air temperature ranges from approx. 6°C at the mountain foot to approx. -2°C in its highest zones (Łupikasza & Szypuła, 2019). Permafrost may sporadically occur above 1900 m a.s.l. (Dobiński, 2005; Gądek et al., 2009; Gądek & Szypuła, 2015). The

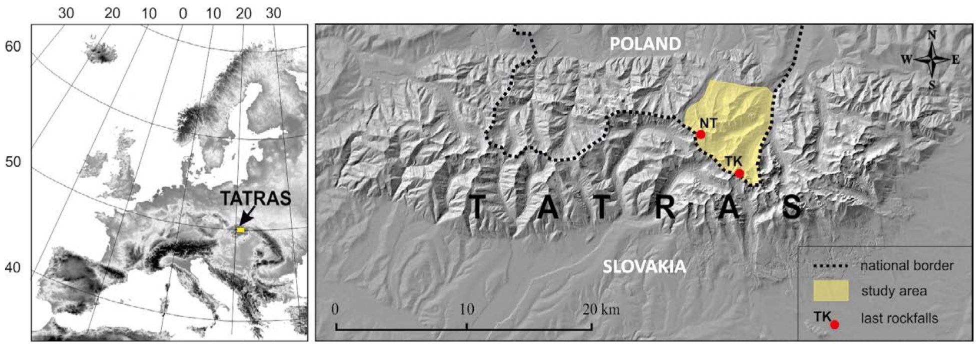

Figure 1. Study area. Yellow polygon: the Polish part of the High Tatra Mountains. Red dots: release areas of the Turnia Kurczaba (TK) and Niebieska Turnia (NT) rockfalls

most significant frequency of the freeze-thaw cycle is observed within the zone of 1700-2050 m a.s.l. (Rączkowska, 2007). Annual precipitation increases with altitude from approx. 1400 mm to approx. 2000 mm (Ustrnul et al., 2015), while the number of days with seasonal snow cover varies from approx. 150 to above 210 (Gądek & Szypuła, 2015).

The Polish High Tatras are part of the Tatra National Park (TPN) and a UNESCO Biosphere Reserve. The outstanding quality of the area's natural environment attracts tourist traffic that sometimes exceeds what is referred to as the tourism carrying capacity (TCC) (https://tpn.pl/zwiedzaj/turystyka/statystyka), while it also constitutes the most important climbing area in Poland (https://wspinanie.pl/topo/polska/tatry/).

Data and methods

The potential rockfall extent and kinematics were determined by numerically simulating their development using archival rockfall data and cartographic and remote sensing data.

Archival rockfall data

The historical data used to calibrate the numerical simulations of potential rockfalls came from the latest two rockfalls recorded in the study area: Niebieska Turnia (21 May 2018) and Turnia Kurczaba (22 October 2021). Specifically, the data included (a) terrestrial photos of the release and deposition zones taken immediately after each of the events, (b) video footage, (c) terrestrial laser scanning (TLS) data (Kajdas et al., 2024) and (d) drone image dataset of Turnia Kurczaba (made available by the TPN).

Cartographic and remote sensing data

The study employed a 1:10,000 digital geological map of the Tatra Mountains (Piotrowska et al., 2015) from the website – https://geolog.pgi.gov.pl/. Additionally, 0.25 m resolution rectified aerial orthophotomaps with a 1 m resolution LiDAR-based digital elevation model (DEM) were obtained from the Head Office of Geodesy and Cartography.

Digitalisation and cartometric measurements

The QGIS package was used to identify slopes located in fault zones on the geological map, including those with tectonic breccia, cataclasites and mylonites. Their location and extent (shape and size) were extracted as a separate vector layer, as were the rocky slopes and their talus foot areas. DEM and orthophotomap analyses were used to define (i) rocky slopes with an inclination greater or equal to 70° (cliffs), (ii) terrain surface types divided into extra hard, hard, medium hard, medium, medium soft, soft, extra soft, and snow (Bartelt et al., 2022), and (iii) lake and forest (dense, medium, open) (Bartelt et al., 2022).

Rockfall modelling and map composition

The RAMMS::Rockfall (WSL-SLF) software was used to simulate potential rockfalls. It follows a rigid-body approach to simulate rockfall trajectories in 3D terrain, taking into account the influence of rock shape on rock-terrain interaction (Caviezel et al., 2019). The software provided the runout distance, jump height, velocity and kinetic energy of the released rocks and their deposition locations/reach probabilities (Leine et al., 2014; Zhang, 2022). The inputs included: (i) the DEM, (ii) the release area, (iii) ground hardness, (iv) forest density, (v) environmental barriers (lake, dense forest), and (vi) rock form, volume and density. The density of granitoid rocks was assumed to be 2700 kg m^{-3} (Columbu et al., 2015).

The 3D rockfall model calibration involved the back-analysis of the rockfalls at Turnia Kurczaba and Niebieska Turnia. This required tuning simulation results to the observational data by applying the earlier derived input data, defining the shape and size of the boulders and an optimum DEM resolution. In both cases, the best simulation results were obtained at 5m DEM resolution after considering the real shape and size of the lowermost of the deposited boulders (rock form: Real_flat_1.8 and 3.04 m^3). The random orientation and total simulation numbers were, respectively, 10 and 1000.

The thus-derived parameters of the model were then used to simulate potential rockfalls released from the most-fractured and steepest rocky cliffs above the timberline in the Polish High Tatras. A simple assumption was made that the cliffs most prone to releasing a rockfall under the influence of frost weathering or the degradation of permafrost are those that combined an inclination equal to or greater than 70° with a location in the periglacial zone (above the timberline) and in the fault/mylonite zone (Kajdas et al., 2024). Fifty-two such potential release areas were identified, and the total number of rockfall simulations, ranging from 400 to 1000, depended on their size. The simulated rockfall locations, reaches and kinematic parameters were presented together with the surrounding rocky and talus slopes, the vegetation zones (orthophotomap integrated with DEM) and the tourist infrastructure in the area (layers downloaded from OpenStreetMap) using the World Geodetic System 1984 (WGS84/EPSG: 4326).

Results

Turnia Kurczaba rockfall scenario

Figures 2 and 3a illustrate the back-calculations of the Turnia Kurczaba (TK) rockfall. It originated on a >70° cataclasite-mylonite cliff. The release area of around 2500 m^2 produced 7200 m^3 of rock material (Kajdas et al., 2024). The overall top-view surface area of the rockfall zone (including release, transit and deposition zones) was just over 17 ha. The rock material was displaced along a distance of approx. 1120 m within a stepped slope system spanning a vertical range of 815 m. After its free-fall phase, the released material continued along the rocky chute towards E and then down the talus cover at the bottom of a hanging post-glacial cirque known as Bandzioch Mięguszowiecki. Downslope from there, within a high rocky threshold dissected by a deep rocky gully, the relief deflected the travelling material towards the NE and N into the Szeroki Piarg talus cone above the Morskie Oko lake (Figs. 2 and 3).

The average calibrated velocity of the largest boulders, which also travelled the farthest, was 20 ms^{-1}, their jump height was 5.5 m, and their kinetic energy reached 2.4 MJ. The maximum values of the three parameters were achieved in the transition zone between the rocky threshold of the hanging cirque and the lowest talus cone. The threshold height is close to 200 m, and its inclination ranges from 50° to 90°. The results of the simulations and the observed trajectories closely matched each other. This would suggest that the largest boulders (8 t) were

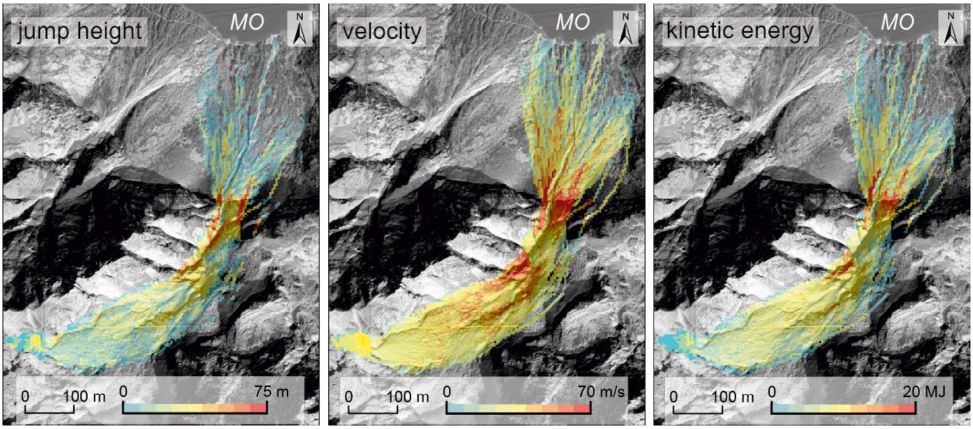

Figure 2. Numerical simulation of the motion trajectory, jump height, velocity and kinetic energy of the Turnia Kurczaba rockfall. MO: Morskie Oko lake

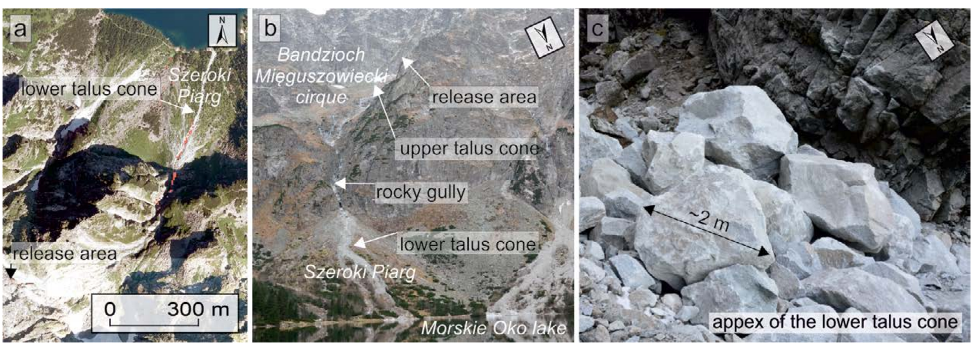

Figure 3. Simulated and observed deposition locations of 8-tonne boulders released from the cliff on Turnia Kurczaba on 22 October 2021; a) red dots: probable deposition locations of the boulders (2009 orthophotomap: Head Office of Geodesy and Cartography); b) Turnia Kurczaba slope system: fresh talus material stands out within the rocky gully and in the debris flow channel in the central part of the lower talus cone (photo taken on 28 October 2021: Z. Rączkowska); c) shape and size of the boulders deposited at the transition between the rocky gully and the lower talus cone (photo taken on 28 October 2021: Z. Rączkowska)

mainly deposited within the lower rocky gully, at its mouth and on the top of the Szeroki Piarg talus cone, along the debris flow channel (Fig. 3). Only isolated boulders made it all the way to the lower edge of that talus cone.

Niebieska Turnia rockfall scenario

The Niebieska Turnia (NT) back-calculation results are illustrated in Figs. 4 and 5a. The rockfall originated in a fault zone on a >70° granitoid cliff. Its release area covered approximately 1000 m^2. Roughly 90% of the rocky material fell on the southern side of the ridge into the Dolinka pod Kołem postglacial cirque. The rocky deposits came to their resting points along the entire length of a talus cone that encroaches onto a fossil rock glacier stretching all the way to the Zadni Staw lake (Zasadni et al., 2023a). This slope system spans about 400 m vertically and 450 m horizontally. The remaining 10% of the rock mass fell into the Zadnie Koło cirque on the northern side of the ridge and was deposited

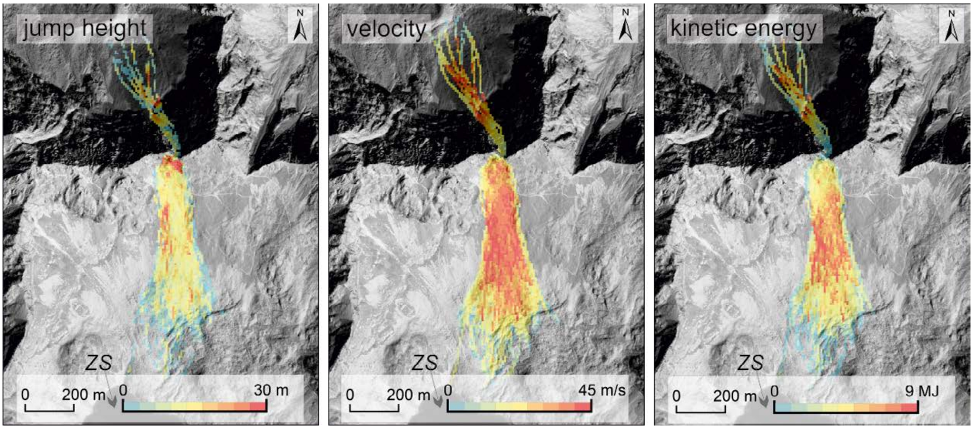

Figure 4. Numerical simulation of the motion trajectory, jump height, velocity and kinetic energy of the Niebieska Turnia rockfall. ZS: Zadni Staw lake

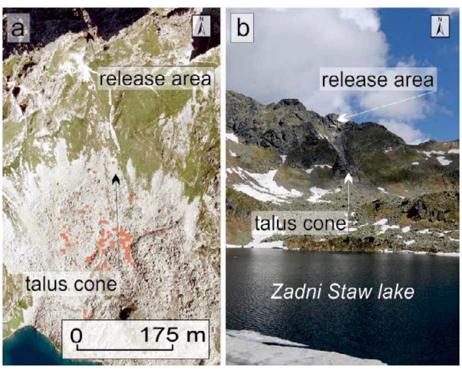

Figure 5. Simulated and observed deposition locations of 8-tonne boulders released from the cliff on Niebieska Turnia on 21 May 2018; a) red dots: probable deposition locations of the boulders (2009 orthophotomap: Head Office of Geodesy and Cartography); b) Niebieska Turnia slope system: fresh talus material stands out in the top section of the talus cone with some isolated large blocks also visible in the middle section and lower down (photo taken on 22 May 2018: M. Szumny)

on a talus slope closed by a moraine ridge from the period of the last glaciation (Zasadni et al., 2023b). This slope system extends 300 m vertically and 340 m horizontally, and the surface area onto which the falling rock spread was approximately 2 ha (Fig. 4).

The average velocity of the 8-tonne rock boulders, its jump height and kinetic energy were 21 ms^{-1}, 4.0 m and 2.48 MJ, respectively. These three parameters reached their highest values on the top sections of the steep rocky-debris slope and midway down the talus slope (Fig. 4). There were no significant differences between the observed and the simulated trajectories and deposition positions of the boulders (Fig. 5).

Potential rockfalls

Rocky and talus slopes represent approx. 28% and 19%, respectively, of the surface area of the of the Polish High Tatras. In the light of the numerical simulations, the rocky material released from the 52 rockfall-prone cliffs, inclined at 70° or more and located in fault-mylonite zones, should come to rest within the existing colluvia (Fig. 6).

The simulations placed the potential release areas between 1690 m a.s.l. and 2361 m a.s.l. (on average: 2140 m a.s.l.). The relevant slope systems span between 184 m and 967 m vertically and 200 m to 1274 m horizontally. The average velocities of the material released may vary from 12 m s^{-1} to 37 m s^{-1}. The travelling boulders are expected to jump between 2 m and 21 m and to carry from 0.95 MJ to 8.1 MJ of kinetic energy (Fig. 7). These maximum values can be reached on slope systems with the most significant vertical drops where rocky cliffs exceed 400 m in

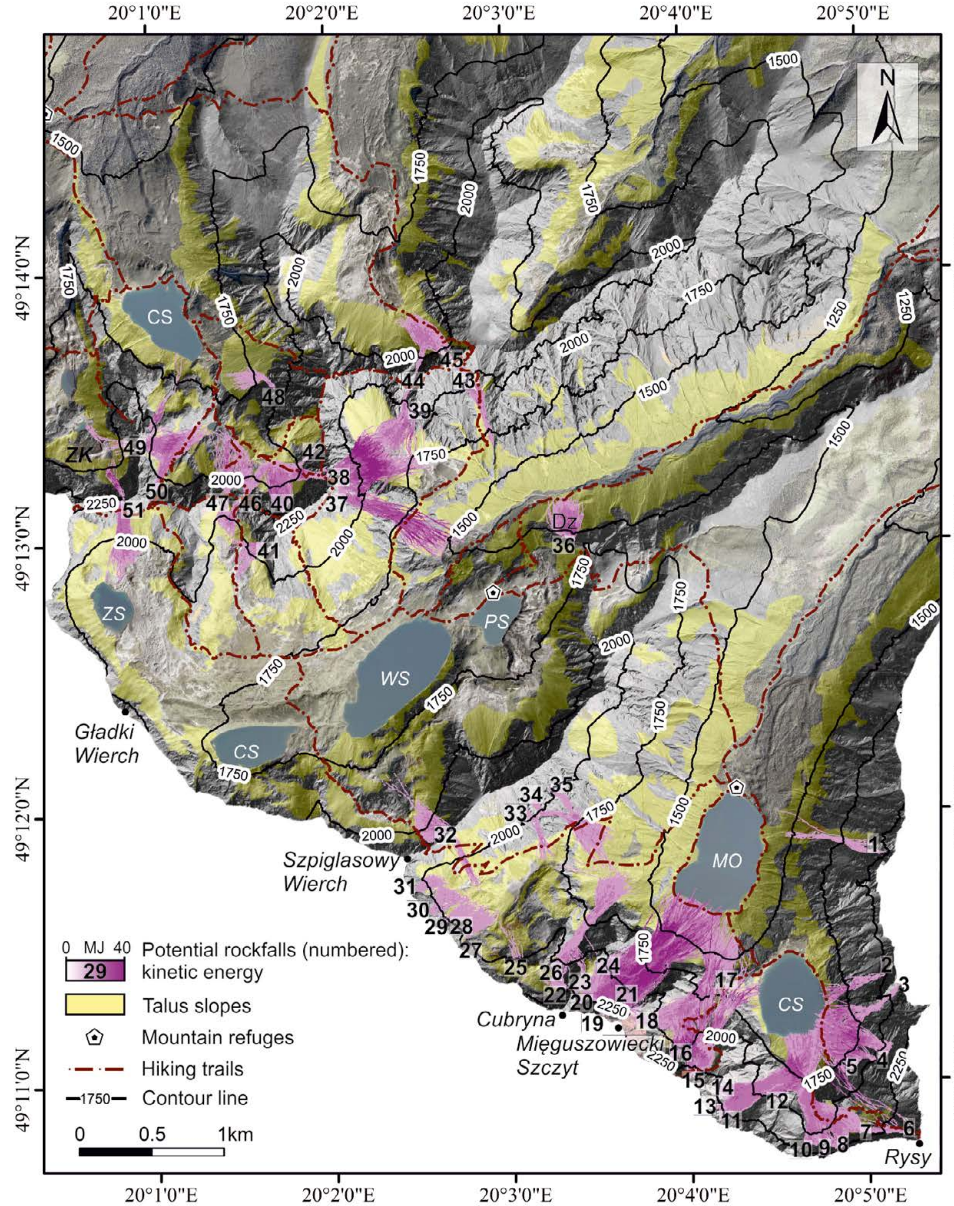

Figure 6. Potential rockfalls in the Polish High Tatra Mountains, their distribution, extent and kinetic energy. Outlines of talus slopes based on the 1:10,000 geological map of the Tatra Mountains (Piotrowska et al., 2015). Abbreviations of topographical names: DZ – Dziadula, ZK – Zadnie Koło, MO – Morskie Oko, CS – Czarny Staw, ZS – Zadni Staw, WS – Wielki Staw, PS – Przedni Staw. Base map: digital elevation model integrated with an orthophotomap (Head Office of Geodesy and Cartography). Geographic coordinates: World Geodetic System 1984

height and are footed by postglacial cirques that are also hanging high above the valley bottoms. For these reasons, exceptionally high levels of kinetic energy, reaching up to 40 MJ, may be expected in rockfalls released from the slopes of the cirques of Morskie Oko and Czarny Staw pod Rysami (Fig. 6).

Depending on the slope relief and coverage, the areas exposed to simulated rockfalls ranged from 1.1 ha to 25 ha (on average: 7.6 ha). The total of these areas accounted for approx. 6% of the study area, but also covered approx. 10 km of tourist trails, or 15% of the overall length of all tourist trails in this part of the Tatras. Approximately 35 km of the tourist trails run on top of talus and rock slopes. The trails most exposed to rockfalls are those leading to Mt. Rysy, Zawrat pass,

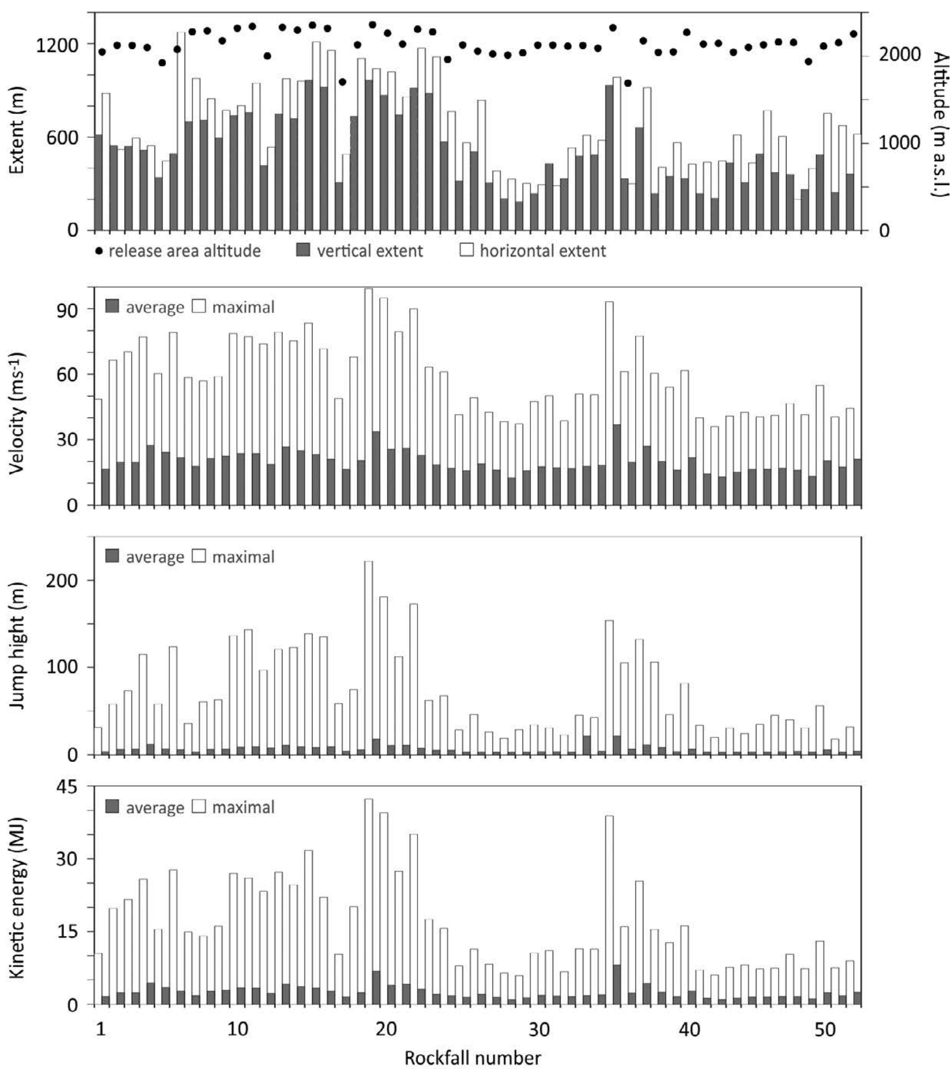

Figure 7. Extent and kinematics of potential rockfalls in the Polish High Tatra Mountains. The numbering of rockfalls as in Fig. 6

Przełęcz pod Chłopkiem pass, Szpiglasowa Przełęcz pass, Krzyżne pass, Pusta Dolinka valley, Kozia Dolinka valley and also the trail along the southern shore of the Morskie Oko lake. All mountain refuges have been found to be located in a 'rockfall-safe' area, but the path up the Dolina Roztoki valley to the refuge in the Dolina Pięciu Stawów Polskich valley traverses a forested zone, known as Dziadula, that is exposed to a potential rockfall (Fig. 6).

Discussion

While the TK and NT rockfalls occurred in very different geological and topographical conditions, their best numerical simulations (extent of the colluvium) were obtained after adopting the assumption that the travelling rock fragments had the Real_flat shape (Bartelt et al., 2022) and were 3 m^3 in volume. The dimensions along the X/Y/Z axis assigned to the rock shape class were 1.94 m, 2.37 m and 1.33 m, respectively (Rock Library of the RAMMS::Rockfall software). These assumptions stand out as particularly closely matching the field observations (Kajdas et al., 2024). It also confirms that it is the heaviest boulders and, consequently, the ones with the highest kinetic energy that tend to travel the furthest from their release area (Evans & Hungr, 1993; Caviezel et al., 2021). Also, the similarity of the size and shape of the rocky boulders found in the TK and NT rockfalls would suggest that the Tatra mylonite rocks have preserved discontinuity planes typical for the granitoids, among which they occur (Piotrowska, 1997). These planes predetermine the initial size and shape of the released rock fragments (Fityus et al., 2013). Considering that the most recent phase of increased tectonic activity in the Tatra Mountains occurred between 29.5 and 10.11 ka ago (Szczygieł et al., 2024), it can be inferred that the patterns of these discontinuities have remained relatively stable since that time. The actual density of these discontinuities, and consequently the size of fragments falling from the rocky cliffs, exhibit spatial variability (Gądek et al., 2023). It does happen, however, that the force of impact is greater than the compressive strength of the falling rock, and it disintegrates against a hard landing surface. A particular case in point in the Tatras was the rockfall of a mylonite cliff on Mt. Cubryna on 23 September 2012, where all of the falling rock packets disintegrated into debris or finer fractions on impact against the granitoid surface (own observations; Rączkowska & Cebulski, 2022). In such cases, a correct numerical rockfall simulation based on the moving rocky fragments' constant size and shape is impossible, and its results would be overestimated.

The calibrated kinematic parameters of potential rockfalls can be extremely high (Fig. 7). Such values reflect the properties of the relief and the substratum in the upper zones of the High Tatras (Klimaszewski, 1988; Buczek & Górnik, 2020) and in particular: (i) the great vertical extent and steepness of rocky slopes, (ii) the stepped long-profile of slope systems which also involve small post-glacial cirques hanging hundreds of meters above the talus slopes, (iii) hard granitoid surfaces beneath, and (iv) the large mass of the rock fragments that travelled the farthest. This is the basis for the calculation of the rock boulder "jump height", i.e. the plumb vertical distance (Bartelt et al., 2022), which exceeded 200 m with a velocity of fall nearing 90 ms^{-1} (Figs. 7 and 8) on several of the simulations presented.

The largest number of potential release areas and the greatest kinetic energy levels are found on the slopes of two post-glacial cirque-holding lakes, Czarny Staw pod Rysami and Morskie Oko. Talus material there forms expansive debris covers reaching and shaping the shorelines of the lakes at the bottom of the cirques (Rączkowska et al., 2017/2018; Choiński & Zieliński, 2023). These landforms are also reflected in the bathymetry of both lakes (Służba Topograficzna Wojska Polskiego, 1992; Choiński & Strzelczak, 2011). The maximum thickness of the talus slopes above Morskie Oko reaches 55 m (Gądek et al., 2016; Senderak et al., 2019). The only depositional

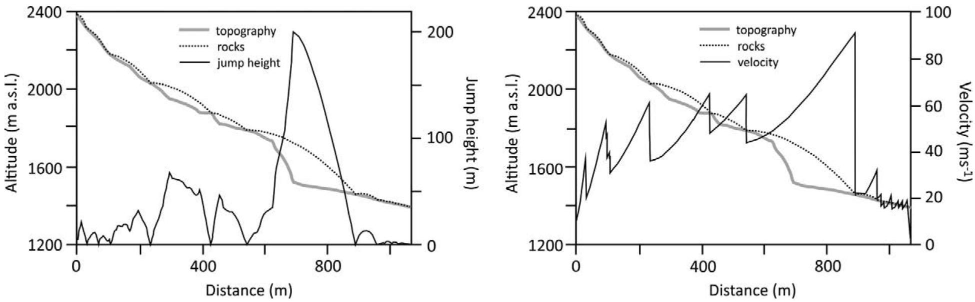

Figure 8. Example of motion trajectory and kinematics of a 8-tonne rocky block between the cliff on Mt. Mięguszowiecki Szczyt (2400 m a.s.l.) and Morskie Oko lake (1395 m a.s.l.) (see text above)

landforms that predate the talus slopes are the deglaciation moraines, which are several thousand years old and are preserved on top of the rocky lips of the two lakes (Zasadni et al., 2023a). Elsewhere within the Polish High Tatras, where rockfall kinetic energy levels are lower, glacial and periglacial formations are common – also above and adjacent to lakes (Rączkowski et al., 2015; Zasadni, 2015). Among the periglacial terrain features are relict rock glaciers (Kłapyta et al., 2024), of which the youngest are dated to the Younger Dryas (Zasadni et al., 2023b). Talus cones do not exceed 35 m in thickness near these landforms (Gądek et al., 2013; Gądek et al., 2016). In the light of the numerical simulations of potential rockfalls, the degree to which Pleistocene-age landforms are buried with colluvium in the periglacial zone of the Polish High Tatras depends not just on the intensity of the slope degradation and the location, number and size of the release zones (Gądek et al., 2016), but also on the boulder dimensions (rockfall kinetic energy).

Considering the distribution and the age of the glacial and periglacial formations (Lukniš, 1973; Klimaszewski, 1988; Rączkowski et al., 2015; Zasadni, 2015), as well as the size of the talus slopes (Lukniš, 1973; Gądek et al., 2016), it could be concluded that the potential energy of the Tatra relief has not fundamentally changed since the complete disappearance of the glaciers (Zasadni et al., 2023b). This would explain the consistency of the extent of the observed and simulated rockfalls with the extent of the talus covers. It could, therefore, be expected that the reach of the rockfalls in this area will likely not exceed the limit of the existing taluses in the coming decades. What could change, just as in the past, are the causes and/or intensity of rockfalls (Kotarba & Pech, 2002; Pánek et al., 2016; Zielonka & Wrońska-Wałach, 2019; Rączkowska & Cebulski, 2022; Gądek et al., 2023).

As climate warming continues, high mountain areas commonly experience permafrost degradation and an increased incidence of rockfall (Gruber & Haeberli, 2007; Fischer et al., 2012; Ravanel et al., 2017; Savi et al., 2020; Knoflach et al., 2021). Also, large-scale rockfalls in the Tatras are typically released in areas where permafrost can occur. However, each rockfall case during the last decade was found to have been caused by frost weathering after the delivery of rain and/or melt water (Kajdas et al., 2024). However, it so happens that 96% of spots exposed to rockfall due to slope steepness and a fault-zone location in the Polish part of the High Tatras are also located within the area of potential permafrost. This coincidence of the two rockfall-favouring conditions with the harsh climatic conditions means that climate warming and the resulting increase in the thickness of the active ground layer cannot be entirely ruled out as a cause of rockfall in the Tatras (Gądek & Leszkiewicz, 2012). This factor would be mitigated by the only sporadic occurrence of permafrost, which is limited to very favourable conditions in this area

(Mościcki & Kędzia, 2001; Gądek & Kędzia, 2008; Gruber, 2012).

In the Polish part of the High Tatras, nearly all the tourist paths traverse areas exposed to the hazard of rockfalls (section 4.3). Considering that each year, millions of people walk along these paths (https://tpn.pl/zwiedzaj/turystyka/statystyka) and that the frequency of rockfall has increased over the last 50 years (Zielonka & Wrońska-Wałach, 2019), it might be useful to start work on a preventive system. Currently, rockfall risk management within the Tatra National Park is reduced to the temporary closing-off of paths in areas of active release, transport and deposition of rocky material, which is communicated on the TPN website (https://tpn.pl/zwiedzaj). Measures that could be added would include: (i) detailed identification and monitoring of unstable/instability-prone locations using comprehensive field monitoring, including with a UAV and motion photogrammetry, airborne/terrestrial laser scanning systems, interferometric synthetic aperture radar in addition to the currently used geological map and DEM analysis (Fanos & Pradhan, 2018; Carlà et al., 2019; Sun et al., 2023), (ii) maps of the degree of rockfall hazard (Blahůt et al., 2013), and (iii) weather warnings during high-risk periods (D'Amato et al., 2016). Numerical simulation of potential rockfall would also greatly benefit from measurements of the shape and size of talus material considering each slope system's geology (Fityus et al., 2013; Glover, 2015; Bartelt et al., 2022).

Conclusions

Areas currently exposed to rockfall released in the Polish High Tatras' periglacial zone coincide with the extent of rocky slopes and existing talus covers – including those below the timberline.

The potential energy of the relief of the Polish High Tatras and the initial size and shape of the rocky fragments released have not fundamentally changed since the complete disappearance of glaciers. The degree to which the glacial and periglacial landforms are buried depends not just on the location of these forms, the intensity of rock slope degradation and the location, number and size of the release areas but also on the rockfall kinetic energy. Therefore, the spatial variability of the potential energy of the relief may be reflected in the extent of the talus slopes and in the degree to which the Pleistocene-age substratum is buried.

Above the timberline, the steepest and most fractured cliffs are in a sporadic permafrost zone. On the other hand, both the rockfalls observed in recent years and simulated potential rockfalls are caused by the geology and weather conditions (rainfall/snow melting and frost weathering) rather than by permafrost degradation.

Due to the extreme intensity of the tourist traffic within potential rockfall hazard areas, initiating work on an integrated rock-and-weather monitoring and rockfall early warning system for the Polish High Tatras would be useful. The most dangerous area is around the Morskie Oko and Czarny Staw pod Rysami lakes, where the number of visitors sometimes exceeds the tourism carrying capacity. At the same time, the particularly numerous potential rockfall release areas identified there are also characterised by the greatest values of kinetic energy and extent.

Acknowledgments

We express our gratitude to Maria Król (TPN) for providing us with photographic material and valuable consultation focused on recent rockfalls in the Tatra Mountains. We also appreciate Marc Christen's (SLF) support in evaluating the results of rockfall simulations using RAMMS::Rockfall software. Additionally, we acknowledge Krzysztof Gaidzik (University of Silesia) for his consultation regarding the tectonics of the Tatra Mountains.

This study was funded by the Institute of Earth Sciences at the University of Silesia in Katowice. Fieldwork was conducted using equipment from the Polar Laboratory at the University of Silesia in Katowice.

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

References

André, M. F. (1996). Rock weathering rates in arctic and subarctic environments (Abisko Mts., Swedish Lappland). *Zeitschrift fur Geomorphologie*, *40*(4), 499-517. https://doi.org/10.1127/zfg/40/1996/499

Bartelt, P., Buehler, Y., Christen, M., Dreier, L., Gerber, W., Glover, J., … & Schweizer, A. (2022). *A numerical model for rockfall in research and practice User Manual v. 1.7 –Rockfall*. Zurich: Swiss Federal Institute of Technology.

Blahůt, J., Klimeš, J., & Vařilová, Z. (2013). Quantitative rockfall hazard and risk analysis in selected municipalities of the České Švýcarsko National Park, Northwestern Czechia. *Geografie-Sbornik CGS*, *118*(3), 205-220. https://doi.org/10.37040/geografie2013118030205

Buczek, K., & Górnik, M. (2020). Evaluation of tectonic activity using morphometric indices: case study of the Tatra Mts. (Western Carpathians, Poland). *Environmental Earth Sciences, 79*(8), 176. https://doi.org/10.1007/s12665-020-08912-9

Carlà, T., Nolesini, T., Solari, L., Rivolta, C., Dei Cas, L., & Casagli, N. (2019). Rockfall forecasting and risk management along a major transportation corridor in the Alps through ground-based radar interferometry. *Landslides, 16*(8), 1425-1435. https://doi.org/10.1007/s10346-019-01190-y

Caviezel, A., Lu, G., Demmel, S. E., Ringenbach, A., Bühler, Y., Christen, M., & Bartelt, P. (2019). RAMMS::ROCKFALL-a modern 3-dimensional simulation tool calibrated on real world data. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-2019). ARMA.

Caviezel, A., Ringenbach, A., Demmel, S. E., Dinneen, C. E., Krebs, N., Bühler, Y., … & Bartelt, P. (2021). The relevance of rock shape over mass – implications for rockfall hazard assessments. *Nature Communications, 12*(1). https://doi.org/10.1038/s41467-021-25794-y

Choiński, A., & Strzelczak, A. (2011). Bathymetric measurements of Morskie Oko Lake. *Limnological Review*, *11*(2), 89-93. https://doi.org/10.2478/v10194-011-0030-4

Choiński, A., & Zieliński, A. (2023). Changes of the surface area of Morskie Oko and Wielki Staw in the Tatra Mountains. *Quaestiones Geographicae*, *42*(1), 15-24. https://doi.org/10.14746/quageo-2023-0002

Columbu, S., Cruciani, G., Fancello, D., Franceschelli, M., Musumeci, G. (2015). Petrophysical properties of a granite-protomylonite-ultramylonite sequence: Insight from the Monte Grighini shear zone, central Sardinia, Italy. *European Journal of Mineralogy*, *27*(4), 471-486. https://doi.org/10.1127/ejm/2015/0027-2447

D'Amato, J., Hantz, D., Guerin, A., Jaboyedoff, M., Baillet, L., & Mariscal, A. (2016). Influence of meteorological factors on rockfall occurrence in a middle mountain limestone cliff. *Natural Hazards and Earth System Sciences*, *16*(3), 719-735. https://doi.org/10.5194/nhess-16-719-2016

Dixon, J. C., & Thorn, C. E. (2005). Chemical weathering and landscape development in mid-latitude alpine environments. *Geomorphology*, *67*(1-2), 127-145. https://doi.org/10.1016/j.geomorph.2004.07.009

Dobiński, W. (2005). Permafrost of the Carpathian and Balkan Mountains, eastern and southeastern Europe. *Permafrost and Periglacial Processes*, *16*(4), 395-398. https://doi.org/10.1002/ppp.524

Draebing, D. (2021). Identification of rock and fracture kinematics in high Alpine rockwalls under the influence of altitude. *Earth Surface Dynamics*, *9*(4), 977-994. https://doi.org/10.5194/esurf-9-977-2021

Draebing, D., & Krautblatter, M. (2019). The efficacy of frost weathering processes in alpine rockwalls. *Geophysical Research Letters*, *46*(12), 6516-6524. https://doi.org/10.1029/2019gl081981

Eppes, M. C., & Keanini, R. (2017). Mechanical weathering and rock erosion by climate-dependent subcritical cracking. *Reviews of Geophysics, 55*(2), 470-508. https://doi.org/10.1002/2017RG000557

Evans, S. G., & Hungr, O. (1993). The assessment of rockfall hazard at the base of talus slopes. *Canadian Geotechnical Journal, 30*(4), 620-636. https://doi.org/10.1139/t93-054

Fanos, A. M., & Pradhan, B. (2018). Laser scanning systems and techniques in rockfall source identification and risk assessment: A critical review. *Earth Systems and Environment*, *2*(2), 163-182. https://doi.org/10.1007/s41748-018-0046-x

Fischer, L., Purves, R. S., Huggel, C., Noetzli, J., & Haeberli, W. (2012). On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas. *Natural Hazards and Earth System Science*, *12*(1), 241-254. https://doi.org/10.5194/nhess-12-241-2012

Fityus, S. G., Giacomini, A., & Buzzi, O. (2013). The significance of geology for the morphology of potentially unstable rocks. *Engineering Geology, 162*, 43-52. https://doi.org/10.1016/j.enggeo.2013.05.007

Gądek, B., Grabiec, M., & Kędzia, S. (2013). Rzeźba i wybrane elementy klimatu najwyżej położonych cyrków polodowcowych na przykładzie Koziej Dolinki. In Z., Rączkowska, A., & Kotarba (Eds.), Dolina Suchej Wody w Tatrach. Środowisko i jego współczesne przemiany, *Prace Geograficzne,* 239, 49-66. Warszawa: Instytut Geografii i Przestrzennego Zagospodarowania PAN.

Gądek, B., Grabiec, M., Kędzia, S., & Rączkowska, Z. (2016). Reflection of climate changes in the structure and morphodynamics of talus slopes (the Tatra Mountains, Poland). *Geomorphology, 263*, 39-49. https://doi.org/10.1016/j.geomorph.2016.03.024

Gądek, B., Kajdas, J., Krawiec, K. (2023). Contemporary degradation of steep rock slopes in the periglacial zone of the Tatra Mts., Poland. *Geographia Polonica*, *96*(1), 53-68. https://doi.org/10.7163/GPol.0245

Gądek, B., & Kędzia, S. (2008). Winter ground surface temperature regimes in the zone of sporadic discontinuous permafrost, Tatra Mountains (Poland and Slovakia), *Permafrost and Periglacial Process*, *19*(3), 315-321. https://doi.org/10.1002/ppp.623

Gądek, B., & Leszkiewicz, J. (2012). Impact of climate warming on the ground surface temperature in the sporadic permafrost zone of the Tatra Mountains, Poland and Slovakia. *Cold Regions Science and Technology*, *79-80*, 75-83. https://doi.org/10.1016/j.coldregions.2012.03.006

Gądek, B., Rączkowska, Z., & Żogała, B. (2009). Debris slope morphodynamics as a permafrost indicator in zone of sporadic permafrost, High Tatras, Slovakia. *Zeitschrift für Geomorphologie, Supplementary Issues*, *53*(2), 79-100. https://doi.org/10.1127/0372-8854/2009/0053S3-0079

Gądek, B., & Szypuła, B. (2015). Contemporary cryosphere. Sheet V.1, Map 3, 1: 250,000. In K., Dąbrowska, & M., Guzik (Eds.), *Atlas of the Tatra Mountains: Abiotic Nature*, Zakopane: Wydawnictwa Tatrzańskiego Parku Narodowego.

Glover, J. (2015). *Rock-shape and its role in rockfall dynamics*. Doctoral thesis, Durham University.

Gruber, S. (2012). Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere, 6*(1), 221-233. https://doi.org/10.5194/tc-6-221-2012

Gruber, S., & Haeberli, W. (2007). Permafrost in steep bedrock and its temperature-related destabilization following climate change. *Journal of Geophysical Research: Earth Surface*, *112*(2). https://doi.org/10.1029/2006JF000547

Kajdas, J., Gądek, B., Rączkowska, Z., & Cebulski, J. (2024). 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). *Geology, Geophysics and Environment*, 50(1), 23-38. https://doi.org/10.7494/geol.2024.50.1.23

Klimaszewski, M. (1988). *Rzeźba Tatr Polskich*. Warszawa: Państwowe Wydawnictwo Naukowe.

Kłapyta, P., Zasadni, J., & Gądek, B. (2024). Glacial landscape evolution during the Holocene in the Tatra Mountains. In D., Palacios, P. D., Hughes, V., Jomelli, & L. M., Tanarro (Eds.), *European Glacial Landscapes: The Holocene* (pp. 315-330), Elsevier. https://doi.org/10.1016/B978-0-323-99712-6.00013-1

Knoflach, B., Tussetschläger, H., Sailer, R., Meißl, G., & Stötter, J. (2021). High mountain rockfall dynamics: rockfall activity and runout assessment under the aspect of a changing cryosphere. *Geografiska Annaler, Series A: Physical Geography*, *103*(1), 83-102. https://doi.org/10.1080/04353676.2020.1864947

Kotarba, A., Kaszowski, L., & Krzemień, K. (1987). High-mountain denudational system of the Polish Tatra Mountains. *Geographical Studies*, *3* (Special Issue), Wrocław: Polish Academy of Sciences, Institute of Geography and Spatial Organization.

Kotarba, A., & Pech, P. (2002). The recent evolution of talus slopes in the High Tatra Mountains (with the Pańszczyca Valley as example). *Studia Geomorphologica Carpatho–Balcanica*, *36*, 69-76.

Leine, R. I., Schweizer, A., Christen, M., Glover, J., Bartelt, P., & Gerber, W. (2014). Simulation of rockfall trajectories with consideration of rock shape. *Multibody System Dynamics*, *32*(2), 241-271. https://doi.org/10.1007/s11044-013-9393-4

Lubera, E. (2016). *Wietrzenie mrozowe i odpadanie ze ścian skalnych w obszarze wysokogórskim, na przykładzie Tatr Zachodnich*. Manuscript of the PhD thesis, Archive of IGiGP UJ, Cracow.

Luckman, B. H. (2013). Processes, Transport, Deposition, and Landforms: Rockfall. In F. J. Shroder (Ed.), *Treatise on Geomorphology* (pp. 174-182). San Diego: Academic Press. https://doi.org/10.1016/B978-0-12-374739-6.00162-7

Lukniš, M. (1973). *Reliéf Vysokých Tatier a ich predpolia*. Bratislava: Vydavatelstvo Slovenskej Akadémie vied.

Łupikasza, E., & Szypuła, B. (2019). Vertical climatic belts in the Tatra Mountains in the light of current climate change. *Theoretical and Applied Climatology*, *136*(1-2), 249-264. https://doi.org/10.1007/s00704-018-2489-2

Mair, D., Lechmann, A,. Delunel, R., Yeşilyurt, S., Tikhomirov, D., Vockenhuber, Ch., ... & Schlunegger, F. (2020). The role of frost cracking in local denudation of steep Alpine headwalls over millennia (Mt. Eiger, Switzerland). *Earth Surface Dynamics*, *8*(3), 637-659. https://doi.org/10.5194/esurf-2019-56

Matsuoka, N. (2008). Frost weathering and rockwall erosion in the southeastern Swiss Alps: Long-term (1994-2006) observations. *Geomorphology, 99*(1-4), 353-368. https://doi.org/10.1016/j.geomorph.2007.11.013

Mościcki, J. W., & Kedzia, S. (2001). Investigation of mountain permafrost in the Kozia Dolinka valley, Tatra Mountains, Poland. *Norsk Geografisk Tidsskrift*, *55*(4), 235-240. https://doi.org/10.1080/00291950152746586

Niedźwiedź, T. (1992). Climate of the Tatra Mountains. *Mountain Research & Development*, *12*(2), 131-146. https://doi.org/10.2307/3673787

Pánek, T., Engel, Z., Mentlík, P., Braucherd, R., Břežnýa, M., Škarpicha, V., Zonderva, A. (2016). Cosmogenic age constraints on post–LGM catastrophic rock slope failures in the Tatra Mountains (Western Carpathians). *Catena*, *138*, 52-67. https://doi.org/10.1016/j.catena.2015.11.005

Piotrowska, K. (1997). Cios, spękania ciosowe i uskoki w trzonie granitoidowym polskich Tatr Wysokich. *Przegląd Geologiczny*, *45*(9), 904-907.

Piotrowska, K., Danel, W., Michalik, M., Rączkowski, W., & Borecka, A. (2015). Szczegółowa Mapa Geologiczna Tatr w skali 1:10,000, arkusz Mięguszowiecki Szczyt: M-34-101-A-c-3. Warszawa: Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy.

Ravanel, L., Magnin. F. & Deline. P. (2017). Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. *Science of The Total Environment*, *609*, 132-143. https://doi.org/10.1016/j.scitotenv.2017.07.055

Rączkowska, Z. (2007). *Współczesna rzeźba peryglacjalna wysokich gór Europy*. Prace Geograficzne, 212, Warszawa: IGiPZ PAN.

Rączkowska, Z., & Cebulski, J. (2022). Quantitative assessment of the complexity of talus slope morphodynamics using multi-temporal data from terrestrial laser scanning (Tatra Mts., Poland). *Catena, 209*(1), 105792. https://doi.org/10.1016/j.catena.2021.105792

Rączkowska, Z., Cebulski, J., Rączkowski, W., Wojciechowski, T., & Perski, Z. (2017/2018). Using TLS for monitoring talus slope morphodynamics in the Tatra Mts. *Studia Geomorphologica Carpatho-Balcanica*, *51-52*, 179-198.

Rączkowski, W., Boltižiar, M., & Rączkowska, Z. (2015). Relief. Sheet v.1, Map 1, 1:100 000. In K., Dąbrowska, & M., Guzik (Eds.), *Atlas of the Tatra Mountains*: *Abiotic Nature*. Zakopane: Wydawnictwa Tatrzańskiego Parku Narodowego,.

Romeo, S., Di Matteo, L., Melelli, L., Cencetti, C., Dragoni, W., & Fredduzzi, A. (2017). Seismic–induced rockfalls and landslide dam following the October 30, 2016 earthquake in Central Italy. *Landslides, 14*(4), 1457-1465. https://doi.org/10.1007/s10346-017-0841-8

Savi, S., Comiti, F., & Strecker, M. R. (2020). Pronounced increase in slope instability linked to global warming: A case study from the eastern European Alps. *Earth Surface Processes and Landforms*, *46*(7), 1328-1347. https://doi.org/10.1002/esp.5100

Senderak, K., Kondracka, M., & Gądek, B. (2019). Postglacial talus slope development imaged by the ERT method: comparison of slopes from SW Spitsbergen, Norway and Tatra Mountains, Poland. *Open Geosciences*, *11*(1), 1084-1097. https://doi.org/10.1515/geo-2019-0084

Senderak, K., Kondracka, M., & Gądek, B. (2020). Processes controlling the development of talus slopes in SW Spitsbergen: The role of deglaciation and periglacial conditions. *Land Degradation and Development*, *32*(1), 208-223. https://doi.org/10.1002/ldr.3716

Służba Topograficzna Wojska Polskiego. (1992). Tatry Polskie. Mapa topograficzna, 1:10,000, Sheet 14 (Morskie Oko). Warszawa: Wydawnictwo Czasopisma Wojskowe.

Sun, J., Wang, X., Guo, S., Liu, H., Zou, Y., Yao, X., ... & Qi, S. (2023). Potential rockfall source identification and hazard assessment in high mountains (Maoyaba Basin) of the Tibetan Plateau. *Remote Sens*, *15*(13), 3273. https://doi.org/10.3390/rs15133273

Szczygieł, J., Gradziński, M., Grasemann, B., Hercman, H., Wróblewski, W., Bella, P., ... & Sala, P. (2024). Tectonics or rebound: Pleistocene fault reactivation in the highest mountains of the Carpathians. *Tectonophysics*, 871, 230171. https://doi.org/10.1016/j.tecto.2023.230171

Šilhán, K., & Tichavský, R. (2016). Recent increase in debris flow activity in the Tatras Mountains: Results of a regional dendrogeomorphic reconstruction. *Catena*, *143*, 221-231. https://doi.org/10.1016/j.catena.2016.04.015

Ustrnul, Z., Walawender, E., Czekierda, D., Lapin, M., & Mikulova, K. (2015). Precipitation and snow cover. Sheet II.3, Maps 1 and 5, 1:250,000. In K., Dąbrowska, & M., Guzik, (Eds.), *Atlas of the Tatra Mountains: Abiotic Nature*. Zakopane: Wydawnictwa Tatrzańskiego Parku Narodowego.

Zasadni, J. (2015). Dolina Suchej Wody Valley. Sheet V.6, Map 2, 1:20 000. In K., Dąbrowska,. & M., Guzik (Eds.), Atlas of the Tatra Mountains: Abiotic Nature, *Wydawnictwa Tatrzańskiego Parku Narodowego*, Zakopane.

Zasadni, J., & Kłapyta, P. (2014). The Tatra Mountains during the Last Glacial Maximum. *Journal of Maps, 10*(3), 440-456. https://doi.org/10.1080/17445647.2014.885854

Zasadni, J., Kłapyta, P., & Makos, M. (2023a). The evolution of glacial landforms in the Tatra Mountains during the deglaciation. In D., Palacios, P. D., Hughes, M., Jose, J. M., García Ruiz, N., & de Andrés. (Eds), *European Glacial Landscapes: The Last Deglaciation* (pp. 157-164). Chapter 18. Elsevier. https://doi.org/10.1016/B978-0-323-91899-2.00042-5

Zasadni, J., Kłapyta, P., Tołoczko-Pasek, A., & Makos, M. (2023b). The evolution of glacial landforms in the Tatra Mountains during the Younger Dryas. In D. Palacios, P. D. Hughes, M. Jose, J. M. García Ruiz, & N. de Andrés, (Eds.*), European Glacial Landscapes: The Last Deglaciation* (509-515). Chapter 53, Elsevier. https://doi.org/10.1016/B978-0-323-91899-2.00009-7

Zhang, W., Zhao, X., Pan, X., Wei, M., Yan, J., & Chen, J. (2022). Characterization of high and steep slopes and 3D rockfall statistical kinematic analysis for Kangyuqu area, China. *Engineering Geology, 308*. https://doi.org/10.1016/j.enggeo.2022.106807

Zielonka, A., & Wrońska-Wałach, D. (2019). Can we distinguish meteorological conditions associated with rockfall activity using dendrochronological analysis? – An example from the Tatra Mountains (Southern Poland). *Science of Total Environment*, *662*, 422-433. https://doi.org/10.1016/j.scitotenv.2019.01.243

Article first received • 23 January 2024
Article accepted • 17 May 2024