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COMBINING TREE-RING DATING AND GEOMORPHOLOGICAL ANALYSES IN THE RECONSTRUCTION OF SPATIAL PATTERNS OF THE RUNOUT ZONE OF SNOW AVALANCHES, RYBI POTOK VALLEY, TATRA MOUNTAINS

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Abstract

The snow avalanche is one of the major processes that shapes the landscape of high mountains. A significant manifestation of its activity is changing the course of the timberline, whose course and growth disturbances constitute a good source of information about the history of avalanche activity. The aim of this study was to: i) detail the temporal and spatial reconstruction of snow avalanche events within the three surveyed couloirs in the Rybi Potok Valley, in the High Tatras, ii) analyse of the relationship between the relief of the runout zone and the course of the avalanches. Dendrogeomorphological, geomorphological and cartographic methods were employed here. Detailed geomorphological maps comprising the runout zone were prepared and use to divide the runout zone into subzones of similar relief. The dendrogeomorphological reconstructions of avalanche events were carried out on two scales, i.e. for the entire runout zone and for the determined subzones. The courses of major avalanche events in the studied couloirs over the past 100 years were reconstructed. A detailed dendrogeomorphological analysis in the subzones allowed the identification of additional local avalanche events whose extent had not covered the entire avalanche path.

Key words

snow avalanche • relief • dendrogeomorphology • tree-rings • Tatra Mountains

Introduction

Snow avalanches belong to the group of nival processes, which have the strongest impact on the mountain landscape. One of the most noticeable changes attributed to snow avalanche activity is a local, but nonetheless significant, lowering of the timberline (Bebi et al. 2009). Moreover, they may endanger people's lives and health, and destroy infrastructure (Keylock 1997). However, only some types of avalanches affect the relief (Rapp 1960; Klimaszewski 1981; McClung & Schaerer 1994; Kotarba 2002; Rączkowska 2006).

The process of snow avalanche formation depends on many climatic and geomorphological factors (Keylock 1997; Rączkowska et al. 2016a; Rączkowska et al. 2016b). Adequate precipitation and temperature provide suitable conditions for the accumulation of snow and relevant changes in its structure (Kłapa 1959). However, this is only possible on slopes whose inclination is conducive to snow accumulation (Schweizer et al. 2003). According to various authors, it should range from 10-60° (Klimaszewski 1981), 22-65° (Luckman 2010), or 35-45° (Sekiguchi et al. 2005). Nevertheless, not only triggering of snow avalanches, but also their course is related to the relief (McClung & Schaerer 1994; Keylock 1997; Ancey 2001). This relationship is complex and has a different character in each of the zones of snow avalanche paths: the starting zone, transportation zone and runout zone (Mădălina 2011). In the runout zone, the role of the relief increases along with the decrease of the kinetic energy of snow avalanches. It may be assumed that, together with landforms at the macro-scale, landforms at the meso- and micro-scale are becoming equally significant for a particular area. The course of the timberline (Walsh et al. 1994; Czajka et al. 2012; Kaczka et al. 2015) and growth disturbances of the trees in the neighbourhood of the avalanche path constitute good tools for reconstructing the activity of snow avalanches in the past and determining their spatial variability (Corona 2010, Lempa et al. 2014).

Starting from these assumptions, an attempt was made to reconstruct spatial and temporal patterns of the runout zone of snow avalanches at a detailed scale. The basis for this was provided by studies aimed at:

- determination of the relief features in the runout zone of three adjacent snow avalanche paths in the High Tatras;
- temporal and spatial reconstruction of snow avalanche events on the basis of dendrochronological data within the studied avalanche paths;
- determination of the relation between relief and the course of the snow avalanche in the runout zone.

Research area

The study area is situated in the upper part of the Rybi Potok Valley in the High Tatras (Poland and Slovakia), which are the highest mountain range in the Carpathians (Fig. 1). The High Tatras are built from Carboniferous-aged granites and granodiorites (Nemčok et al. 1994) and have alpine relief, which was formed during the Pleistocene glaciation (Klimaszewski 1988; Rączkowski et al. 2015). The mean annual precipitation ranges from approx. 1100 mm in the northern foothills to over 2000 mm in the highest parts (Niedźwiedź 1992; Ustrnul et al. 2015). A large percentage of the total precipitation is represented by snow. The average annual number of days with snowfall ranges from about 80 in the foothills of the Tatra Mountains to up to more than 137 in the higher parts of the mountains (Żmudzka 2013). From an altitude of 1500 m a.s.l., snowfall occurs in each month of the year (Orlicz 1962).

The Rybi Potok Valley is characterised by glacial relief (Lukniš 1973; Klimaszewski 1988), which comprises deep glacial troughs with glacial cirques hanging from rocky steps of a total height of up to 300 m in its uppermost part. The steep or vertical rocky slopes of the valley sides are dissected by numerous chutes and couloirs with debris cones and

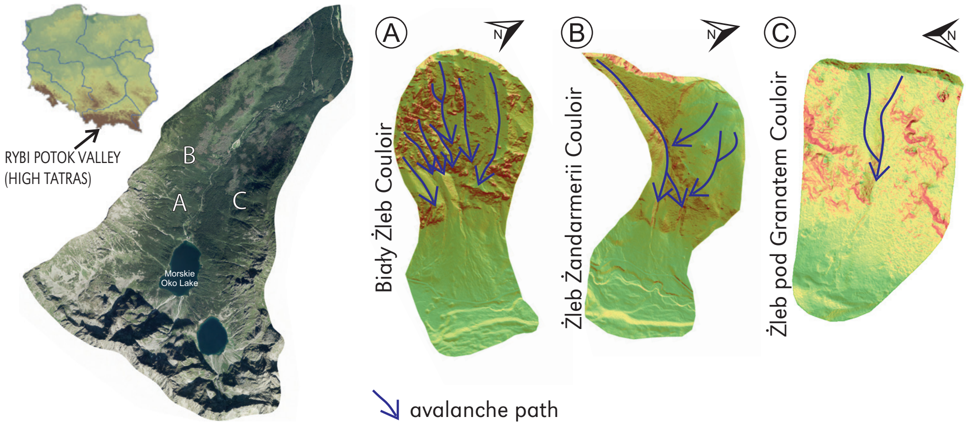

Figure 1. Location of the study area in Southern Poland, High Tatras, upper part of Rybi Potok Valley

slopes developed below. The valley bottom filled with glacial, fluvioglacial and fluvial sediments exhibits hummocky topography with distinct lateral, medial and frontal moraine ridges (Klimaszewski 1988). In the valley, all the climatic and vegetation altitudinal belts typical of the Tatras are present. Above the subalpine forest, reaching an altitude of about 1550 m a.s.l., there are belts of dwarf pine (up to about 1800 m a.s.l.), alpine meadows (up to about 2300 m a.s.l.) and bare rock (up to 2499 m a.s.l.: Hess 1965; Pawłowski 1972). The snow avalanche paths stretch from the alpine meadow belt (the starting zone) over the dwarf pine belt to the subalpine forest belt (the track and the runout zone). What snow avalanches affect most is the subalpine forest – inducing lowering of the climatically controlled course of its upper boundary by at least 215 m (Kaczka et al. 2015). Although snow avalanches occur fairly often in the Tatra Mountains, records of both historical and recent events are discontinuous (Kłapowa 1969; Chrustek 2008; Laska & Kaczka 2010; Czajka 2011; Lempa et al. 2014).

Two out of the three snow avalanche paths selected for this study are located on the southwestern slope of the valley (couloirs: Żleb Żandarmerii and Biały Żleb); the other one on the northeastern slope of the valley (Żleb pod Granatem). The basic morphometric parameters of the studied couloirs are presented in Table 1. The longest and simultaneously the narrowest of the couloirs is Żleb Żandarmerii. The broadest and with the largest difference in the altitude is Biały Żleb. The smallest of the couloirs, Żleb pod Granatem, is short and has the smallest difference of the altitude. The range of the avalanche paths descending from the southwestern slopes of the valley encroaches on the most frequented tourist trail in Poland (over 600,000 tourists per year: TPN 2015) – the road to Morskie Oko lake, thereby presenting

Table 1. Basic morphometric parameters of the studied avalanche paths

	Biały Żleb	Żleb Żandarmerii	Żleb pod Granatem
Length [m]	710	1,002	370
Width [m]	272	107	120
Maximum lowering of GGL [m]	325	561	248
Minimum altitude [m a.s.l.]	1,384	1,332	1,382
Maximum altitude [m a.s.l.]	2,082	2,000	1,772
Difference in altitude [m]	698	668	390

a potential threat to those visiting this place at the time when the long-lying snowpack is present on the slopes.

Methodology

The study was conducted using dendrogeomorphological, geomorphological and cartographic methods.

The dendrogeomorphological method utilises, as a proxy, tree growth disturbances that occurred as a consequence of slope processes, such as debris flows, landslides, rock falls and also other extreme events, such as snow avalanches, floods, forest fires, storms and volcanic eruptions (Alestalo 1971; Stoffel et al. 2010). For the purpose of this study, trees of both coniferous (*Picea abies* (L.) *H. Karst*, *Pinus cembra* L.) and deciduous species (*Sorbus aucuparia L., Betula pubescens Ehrh. subsp. carpatica*) were sampled using an increment borer. The cores were taken from trees bearing signs of damage, scars or decapitations (Fig. 2), and growing on the boundary of the avalanche paths and the dense forest. In the case of trees whose part of the trunk was damaged, the sample was taken directly from the wound (X) and from the side diametrically opposite the wound (Z). In the case of coniferous trees, the cores were also collected directly from above the wound, in order to obtain the sample wherein traumatic resin ducts may have developed (Y: Fig. 2). Information about the difference between the number of annual rings from the undamaged and from the damaged part of the trunk and the year when the most recent ring was developed allows the moment of the avalanche event to be determined. The damage was associated with a snow avalanche only if the complete latewood was present in the last annual ring developed before the injury.These requirements prevent the inclusion of scars generated by debris flows and rock falls that occur in the studied area only during spring and summer. As for trees where the crown is damaged, the sample was collected below the damage recorded in the shape of the trunk or crown. Identification of avalanche events in decapitated trees consists of finding out the growth suppression resulting from damage (Fig. 2; Butler & Malanson 1985; Chiroiu 2013). Each tree was mapped with the use of precise GPS. The obtained cores were appropriately prepared and analysed: measurements of the ring width and identification of growth disturbances (Stoffel & Corona 2014) were performed. Detailed information on the amount of the collected samples and the mapped trees is presented in Table 2. All the spruce samples were cross-dated against the local chronology. The investigated periods were trunked according to repetition of minimum five trees per year.

In order to detect the avalanche events, the avalanche activity index (AAI) was employed (Schroder 1978; Corona et al. 2010; Germain et al. 2010), which represents the ratio of the number of trees with dated growth disturbances in a given year, to the number of trees growing in that year. The index is expressed as a percentage. In order to filter out the noise related to non-avalanche influences (e.g. animals, human impact) from the avalanche signal, a threshold of 5% was established. This is rather low compared to the values used by other researchers (e.g. Butler et al. 2010; Corona et al. 2010; Decaulne et al. 2012); however it ensures detection of the main events. For reconstruction of the avalanches affecting trees growing in the particular determined zones, the threshold value was raised to 10%.

Table 2. Number of sampled trees and collected cores in the studied couloirs

Couloir name	Number of sampled trees	Number of collected samples
Biały Żleb	521	1,200
Żleb Żandarmerii	439	1,040
Żleb pod Granatem	131	224

The relief of the studied snow avalanche paths was determined on the basis of an analysis of the literature (Klimaszewski 1988),

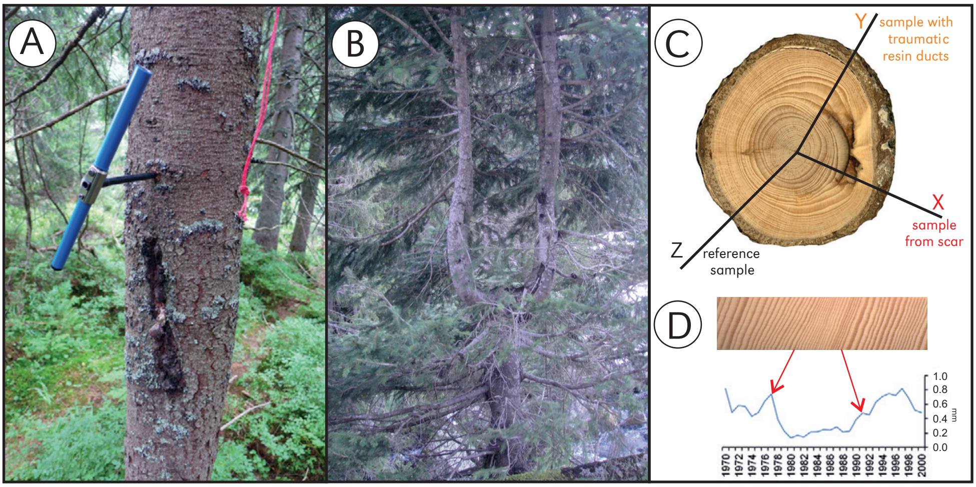

Figure 2. Damage caused by snow avalanches: scar (A) and decapitation (B). Strategy of sampling from the tree whose trunk was damaged (C), reduction of the growth (D) resulting from decapitation

geomorphological maps (Klimaszewski 1981; Kotarba 1992), geological maps (Bac-Moszaszwili et al. 1979) and field inspections. Although the relief of the High Tatras has been well documented, making use of new technologies opens the possibility of obtaining new data broadening the knowledge of the details of the relief. These include LiDAR data, which for the study area reveal the point density from 4 /m^2 to 6 /m^2 (www.isok.gov.pl), allowing the creation of a detailed digital model of the terrain. This model, hillshade relief and slope inclination were generated using Esri ArcGIS. All these data were used for a more detailed interpretation of the relief within the studied snow avalanche paths. On the basis of the LiDAR data and geomorphological mapping (Klimaszewski 1985; Kotarba 1992), geomorphological sketches of the studied area were made. Morphological and morphometric characteristics (Lempa et al. 2016) of the lower part of the snow avalanche path were used to determine the zones of relatively homogenous relief in the runout zone (see Fig. 5A1, 5B1, 5C1) and dendrogeomorphological analyses within the limits of each zone were performed.

The analysis of the impact of the relief on the course of snow avalanches was carried out through comparing the geomorphological data with the results of the spatio-temporal reconstructions.

Results

Morphological characteristics of the runout zone of avalanches

The detailed geomorphological maps of the runout zone of the studied snow avalanche paths enabled precise identification of the forms of relief occurring there. The runout zone of the snow avalanche path in Biały Żleb is located among the outlet of six rock chutes (at an altitude of around 1540 m a.s.l.) and the moraine ridge located in the bottom of the valley, on the opposite bank of the channel of Rybi Potok (Figs. 1 and 3A). The lowest point of the runout zone is the bottom of the channel (1384 m a.s.l.). Its main portion extending between the rocky slopes of the western valley side and the channel is occupied by a talus-alluvial cone 400 m long (Fig. 3D) and an even longitudinal profile, which is inclined towards the south (Fig. 3G). Within the cover of the bottom moraine lying between the erosion edges of the channel of Rybi Potok and the moraine ridge, plains are present; whereas at the southern boundary of the cone within the moraine covers, small and low-altitude isolated hummocks occur (around 2 m), enriching the relief of the valley.

In Żleb Żandarmerii, the runout zone of the avalanche path is situated between the narrow outlet of the couloir (at an altitude of around 1400 m a.s.l.) and the belt of the lateral moraine ridge on the opposite bank of the channel of Rybi Potok (Figs. 1 and 3A). Just like in Biały Żleb, the lowest point of the runout zone of Żleb Żandarmerii is the bottom of the channel of Rybi Potok. The relatively wide (around 230 m) bottom of the valley comprises plains of glacial, fluvioglacial and alluvial accumulation, wherein moraine hummocks are located, which were built up in the moraine cover of the bottom of the valley. The talus-alluvial cone is 250 m long and is inclined mainly towards the southwest (Fig. 3E). An aligned longitudinal section of the cone (Fig. 3H) at its lower part is disturbed by the indentation of the road.

The runout zone in Żleb pod Granatem has different relief (Figs. 1 and 3C). Its range is not limited by any landform. It comprises a small talus-alluvial cone (200 m long), which

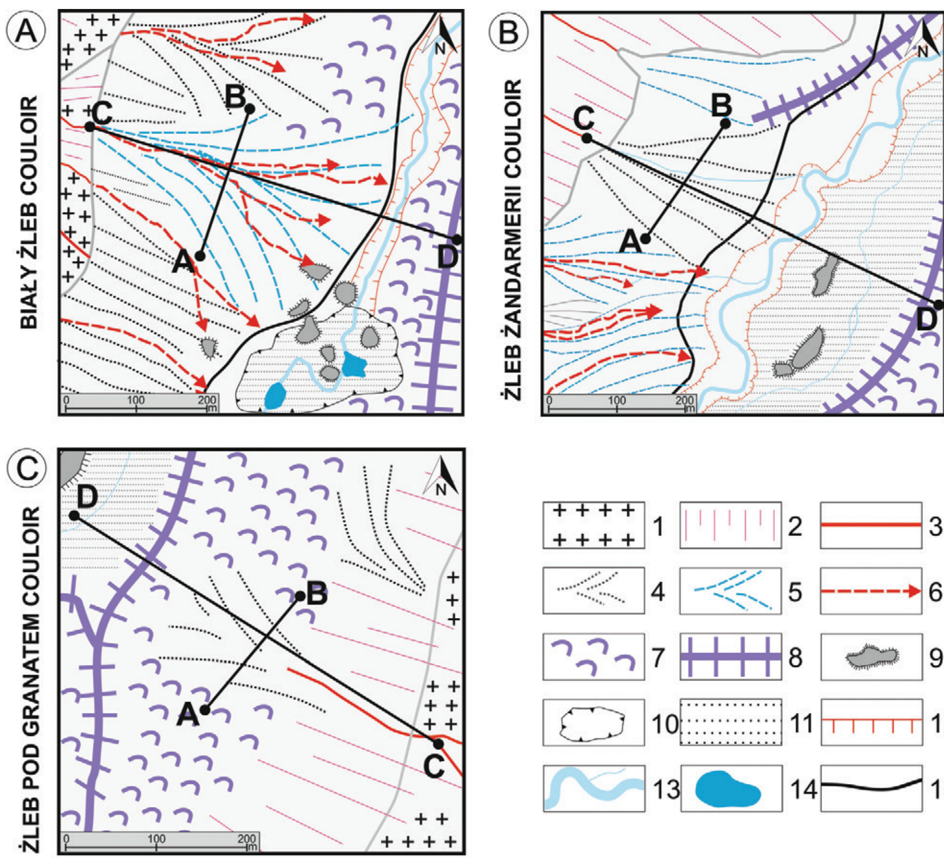

Figure 3A-C. Geomorphological sketches of the runout zone of the studied couloirs, and lateral and longitudinal sections through the talus cones of the studied couloirs

Key: 1 – rocky slopes; 2 – rocky slopes with debris cover; 3 – couloir; 4 – talus cone; 5 – talus-alluvial cone; 6 – debris flow gully and levée; 7 – slopes covered with moraine; 8 – moraine ridge; 9 – hummock within the moraine cover; 10 – no outflow depression in the moraine cover; 11 – plain of fluvioglacial accumulation; 12 – erosion edge; 13 – river channel; 14 – lake; 15 – road

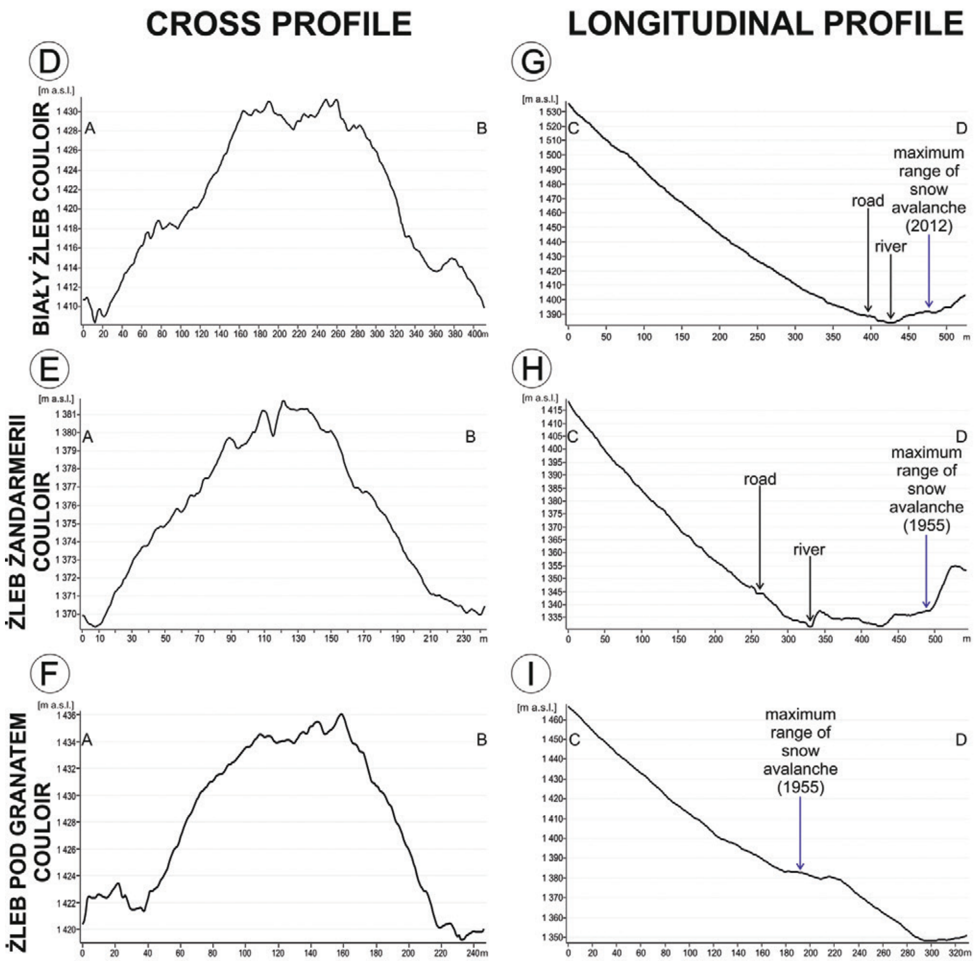

Figure 3D-I. Geomorphological sketches of the runout zone of the studied couloirs, and lateral and longitudinal sections through the talus cones of the studied couloirs

is inclined mainly towards the southwest (Fig. 3F). The moraine ridge, located at the base of the cone, has been buried in it (Fig. 3I) and therefore does not pose an obstacle for avalanches.

Dendrochronological record of avalanches

On the basis of the dendrogeomorphological analyses in Biały Żleb, Żleb Żandarmerii and Żleb pod Granatem, a snow avalanche chronology was created, whose time scope covers at least the last 100 years. In each of the studied snow avalanche paths, major avalanche events extending over the entire couloir and exceeding the threshold of 5% were identified (Fig. 4).

Combining the results of the dendrogeomorphological analyses and precise GPS mapping of damaged trees enabled recreation of the generalised extent of major avalanche events in Biały Żleb and Żleb Żandarmerii (Figs. 4A & B). However, this turned out to be unfeasible in Żleb pod Granatem, owing to its small size and the quantity of dendrochronological data (Fig. 4C). Snow avalanches coming down Biały Żleb and Żleb Żandarmerii,

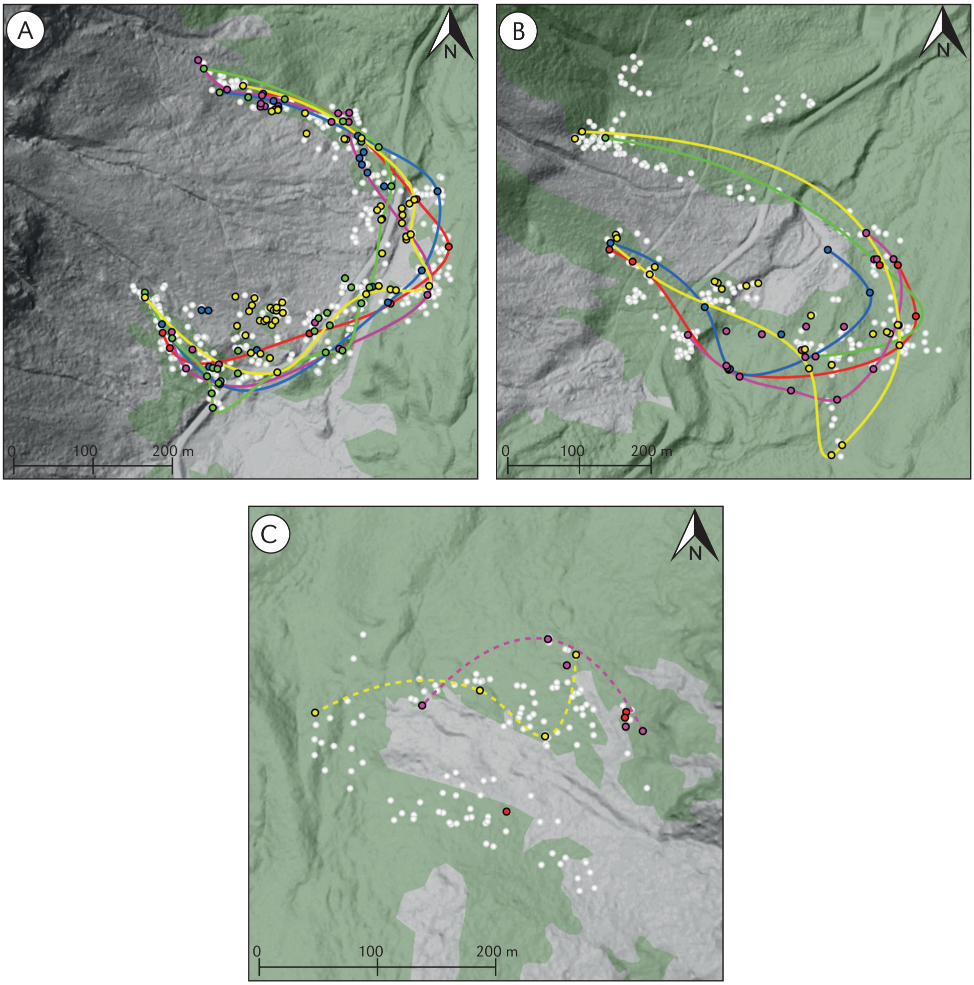

Figure 4. Major snow avalanche events identified in the studied couloirs
A – Biały Żleb couloir: red line – 1913, pink line – 1924, blue line – 1955, green line – 1962, yellow line – 2009, white points – sampled trees; B – Żleb Żandarmerii couloir: red line – 1945, green line – 1946, blue line – 1948, pink line – 1956, yellow line – 1983, white points – sampled trees; C – Żleb pod Granatem couloir: red point – 1913, dotted yellow line – 1939, dotted pink line – 1945, white points – sampled trees

which descend from the northeastern slopes of Opalony Wierch Mt., in most of the cases (90% of the reconstructed avalanches) cross the road leading to Morskie Oko Lake, which creates a major hazard to tourists (Lempa et al. 2014; Kaczka et al. 2015b).

On the basis of the analyses of the particular areas, delimited as a result of geomorphological analyses, an additional six avalanche events were discovered in Biały Żleb, in Żleb Żandarmerii – 13, while in Żleb pod Granatem – as many as 16 (Figs. 5A2, B2 & C2). The application of this method enables the identification of a far greater number of snow avalanches than merely the major avalanche events whose extent covers the entire runout zone. However, the avalanche events identified in particular zones do not always correspond to those events whose record is present in the entire runout zone. This may be illustrated by the avalanche events in Biały Żleb in the winters of 1955 and

2009. These events were identified for the entire runout zone, wherein AAI exceeded the threshold of 5%; however, they did not exceed the threshold of 10% in any of the zones.

The advantage of geomorphological zoning also consists of its enabling detection of the location within the analysed geomorphological zone wherein the avalanche revealed the greatest capacity to injure trees, hence the main direction of the avalanche impact.

In Biały Żleb, none of the snow avalanches occurred with equal intensity throughout the entire runout zone. As a result, none of the reconstructed events left a signal that exceeded a threshold of 10% in all the four zones. The main momentum of 50% of the detected snow avalanche events was directed to zone 1 located in the southern part of the runout zone of Biały Żleb. 33% of the snow avalanche events headed in the opposite direction, to the north. Both of these trends used the movement along the lateral side of the cone. The remainder of the snow avalanches moved straight ahead, to the east, to zones 2 and 3, where the avalanche of greater energy arrived.

Just like in Biały Żleb, in the runout zone of Żleb Żandarmerii, none of the reconstructed events left the signal strong enough to be recorded in each of the eight zones. In Żleb Żandarmerii, the highest number of snow avalanche events that did not cover the whole snow avalanche path was recorded in zone 8 (38%), located on the south side of the runout zone. In zones 2 and 5, 15% of the detected avalanche events were recorded, while in zones 1, 3, 4 and 6, it was only 8%. In zone 7, no avalanche events were recorded.

In Żleb pod Granatem, the highest number of avalanche events not covering the entire avalanche path was observed. Analogous to the other studied couloirs, none of the avalanche events had sufficient energy to register in each of the five zones. The main momentum of the avalanches descending along Żleb pod Granatem headed southwards (zone 5), where the largest number of the events was recorded, i.e. 44%. In zones 1 and 2 located on the northern, steeper part of the talus-alluvial cone, 25% of the avalanche events were detected; in zone 4 it was only 6%; while in zone 3 no avalanche events were recorded. Out of the relatively short (370 m) and less inclined (30-40°) couloir, snow avalanches descend along the cone reaching a relatively flat surface of the moraine. Here, when the kinetic energy has dissipated, the motion of the avalanche dies out. None of the reconstructed avalanches reached the edge of the moraine ridge, behind which the slope inclination is much steeper.

The size and the course of snow avalanches are also influenced by the features of the avalanche starting zone, i.e. the zone of snow accumulation. In the case of Żleb Żandarmerii and Żleb pod Granatem, the relief of the starting zone is not complex: the slopes are almost not dissected. When the balance of the snow cover on the slopes has been disturbed, the snow mass is directed to the transportation zone of the avalanche path; after that, it is the shape of the cone located on the extension of the colouir that determines direction of the avalanche descent. In the case of Żleb Żandarmerii, it is mainly a southeasterly direction, while in the case of Żleb pod Granatem, it is northerly.

Much more complex relief in the starting zone, i.e. of snow accumulation, is typical of Biały Żleb. The catchment of Biały Żleb is dissected by numerous small chutes and corrasion couloirs (Klimaszewski 1985; Digital Terrain Model). The long-lying snow within the snow avalanche starting zone, depending on where the balance between the layers of snow has been disturbed, may affect the momentum of the avalanche by turning it in various directions, regardless of the shape of the talus-alluvial cone. This may be illustrated by the snow avalanches in the winters of: 1962 – when, according to the dendrogeomorphological recording, the avalanche momentum was directed towards the southwest; 1999 – when the avalanche headed a northeasterly direction; and 2009 – when

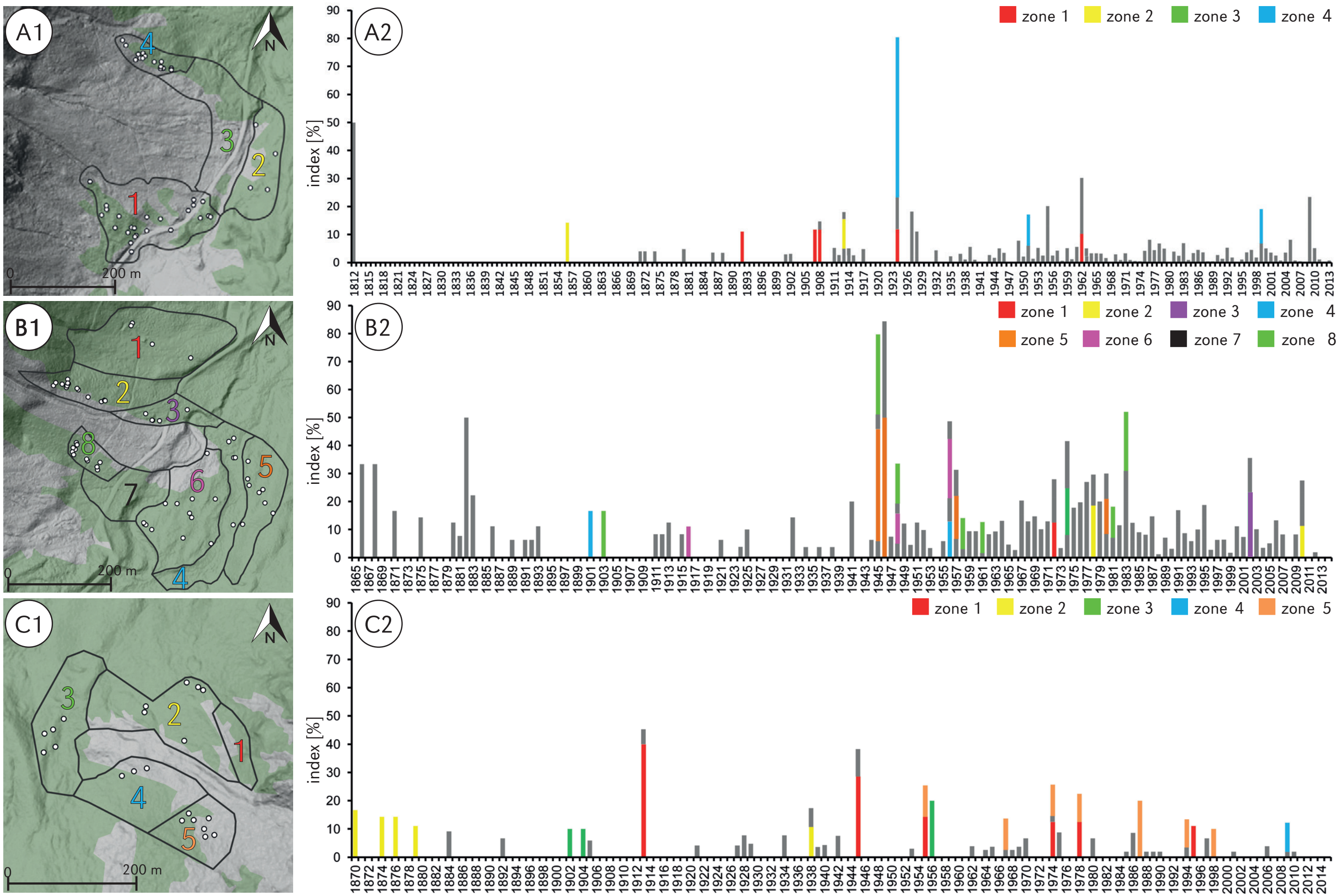

Figure 5. Reconstructed extents of snow avalanches, the zones determined on the basis of DTM (A1, B1, C1), and avalanche chronologies for the studied couloirs (A2, B2, C2)

the avalanche headed mainly towards the southeast leaving still-visible damage to the forest, thus lowering the course of the timberline.

Only two snow avalanche events that occurred in different couloirs (1913 and 1946) recorded growth disturbances intensively enough to exceed the threshold value of AAI = 10%. The other reconstructed snow avalanche events occurred in different time periods. The analysis of the time reconstruction at the level of 5% allowed detection of five snow avalanche events that took place at the same time in two couloirs. The snow avalanches of the winters of 1946, 1956, 1974 and 1978 occurred in Żleb Żandarmerii and Żleb pod Granatem in the same years. The snow avalanche of the winter of 1913 took place in both Żleb pod Granatem and Biały Żleb. The spatial reconstruction of the major snow avalanche events in Biały Żleb has provided information about the extent of avalanches in particular years. The reconstructed ranges of the snow avalanches in Biały Żleb have similar courses (Lempa et al. 2014). In the case of Żleb Żandarmerii, the reconstructed ranges of the snow avalanches are characterised by the variable course and extent.

While analysing the morphometry, cross-sections and longitudinal sections of the studied avalanche paths, it may be concluded that the most significant impact on the strength of avalanches is exerted primarily by the depth, length and width of the couloirs being a snow avalanche path. Żleb Żandarmerii, which is sufficiently deep (Fig. 3E) and long (Table 1), and not excessively broad, creates perfect conditions for the descending snow avalanches to attain sufficient energy to destroy the forest growing in the bottom of the valley. The upper timberline in the runout zone of this avalanche path is the most lowered among the studied couloirs, i.e. by more than 550 m. Existing studies, however, have pointed to the declining avalanche activity in Żleb Żandarmerii, which is manifest in gradual overgrowth of the runout zone (Kaczka et al. 2015).

Conclusions

The direction and extent of a particular snow avalanche is undoubtedly influenced by the following factors: the relief, shape and size of the starting zone (i.e. the zone of snow accumulation), the shape and length of the transportation zone, and the occurrence of natural barriers within the runout zone, which cause dissipation of the avalanche's momentum.

The dendrogeomorphological method combined with relevant GIS techniques allows both temporal and spatial reconstructions of the course and extent of snow avalanches to be undertaken.

The reconstructed snow avalanche extents and the analysis of the relief within the runout zone indicate that, in the case of the analysed couloirs, the direction of the avalanche descent is strongly determined, inter alia, by the shape of the talus-alluvial cone and the direction of its inclination, whereas the extent of snow avalanches is limited by the presence of concave (channels with erosive edges) or convex (moraine ridges) linear forms of the relief, which are located transverse to the avalanche direction. The occurrence of these forms results in dissipating the avalanche's kinetic energy and restraining its capability to injure trees. This may be illustrated by the snow avalanche that descended along the Biały Żleb couloir in the winter of 1962 and stopped at the edge of the Rybi Potok channel.

The geomorphological and dendrogeomorphological analyses have pointed to the fact that the relief in the runout zone is not always the factor conditioning the course and extent of snow avalanche events. In the case of Biały Żleb, the spatial extent of snow avalanches is primarily influenced by natural, transverse barriers. The role of the shape of the talus-aluvial cone is not significant, since it is the relief of the starting zone that determines the course and direction of the snow avalanche. In Żleb Żandarmerii, the direction of the avalanche movement is conditioned by the transportation zone of the snow avalanche path, which is long and narrow. Just like in the case of Biały Żleb, the factor limiting the extent of the snow avalanche is the occurrence of natural barriers arranged perpendicular to the direction of the avalanche descent. The avalanches descending along Żleb pod Granatem are characterised by small transportation and runout zones. The direction of the snow avalanche descent is conditioned by the direction of the inclination of the talus-alluvial cone. The extent of the snow avalanches in Żleb pod Granatem is limited by its short length, which is not conducive to the avalanche attaining sufficient kinetic energy to cross the moraine ridge and descend to the lowest valley bottom point.

The results of the dendrogeomorphological studies allowed the establishment of around 100-year chronologies for the studied couloirs. The combination of the results of the geomorphological and dendrochronological analyses enabled spatial reconstructions of the snow avalanche runout zones of two out of the three studied couloirs, as well as reconstructions of a greater number of avalanche events, and therefore a better recognition of the dynamics of snow avalanches in the past. The dendrogeomorphological investigation leads to detecting previously unknown avalanche events, while also confirming some already-recorded ones e.g. 1955 in Biały Żleb (Kłapa 1959) and 1983 in Żleb Żandarmerii (Jagiełło 2006).

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

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