Research Article

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Postglacial talus slope development imaged by the ERT method: comparison of slopes from SW Spitsbergen, Norway and Tatra Mountains, Poland

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Abstract: Talus slopes are a common sedimentary formation both in polar and high-mountain areas, but their development is still not sufficiently understood. This article discusses the environmental factors that have been influencing development of talus slopes since the deglaciation and their impact on the internal structure of slopes. Case studies of the slopes from SW Spitsbergen and the Tatra Mountains in Poland were compared in order to explore different evolution stages. Slopes' structure was analysed using geophysical surveys based on two-dimensional electrical resistivity tomography (ERT) with a Wenner-Schlumberger array and an electrode spacing of 5 m, combined with geomorphological observations. The investigated talus slopes represent the paraglacial, periglacial and talus-alluvial environments. New data on the internal structure of talus slopes developing in the present or past glaciated areas adds to understanding talus slope evolution. There are many different views concerning the development of slopes during the paraglacial period, whose analysis seems to be crucial in the background of climate change and their record in slope structures. In addition, the study provided valuable information on the development and degradation of permafrost in slope materials.

Keywords: climate change, debris flow activity, deglaciation, development, internal structure, paraglacial, periglacial, permafrost, talus slope evolution, electrical resistivity tomography (ERT)

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1 Introduction

Talus slopes are an integral part of high-mountain landscape in all latitudes [1]. According to a commonly cited definition, talus slopes are "accumulations of loose, coarse, usually angular rock debris at the foot of steep bare rock slopes" [2]. The first research on talus slopes was already at the turn of the 19th and 20th century [3]. Those pioneer studies of talus slopes created the starting point for other research such as cross-sectional geomorphological studies of talus slopes conducted at the Tempelfjorden on Spitsbergen by Rapp [4], and also at the entire archipelago by Jahn [5]. Also Luckman [6] investigated the snow avalanches on slopes in the Canadian Arctic. In the 1980s, Åkerman [7] and André [8] focused on a more detailed understanding of the mechanisms responsible fora mass movement on Spitsbergen slopes. There were attempts to estimate slope retreat on the basis of direct morphometric measurements of slopes, *e.g.* using lichenometric methods [9, 10]. Additionally, extensive investigations were carried in the Tatra Mountains, Poland related to the morphodynamics of talus slopes in the background of glaciations in the Late Pleistocene [11, 12].

Knowledge on talus slopes is extensive, but many studies are narrowly specialized and limited to few research problems. Not many authors have focused their work on talus slope evolution. Ballantyne's concept of the paraglacial sediment adjustment [13] assumes a two-stage evolution: (I) period under the influence of glacier recession that causes the relaxation of exposed area, and (II) period linked with 'normal' conditions set by specific climate and environmental features (topography and geology) of place in a postglacial climate. His concept and also earlier attempts to explain evolution are based on geomorphological observations. However, Blikra and Nemec [14], Van Steijn *et al.* [15] and Itturizaga [16] have shown that the internal structure of a slope, as well as the properties of its surface layer contain information about the mechanisms that control the supply of debris to talus slopes. This implies a close relationship between climate and talus slope development. Therefore, in order to better understand the talus slope environment, selected geophysical methods were used in high-mountain and polar areas [17]. In slope studies they were first used in the Alps with the focus on determining the talus thickness and developing the methods themselves [18, 19]. Further, Sass [20] evaluated a rockwall retreat rates based on the ERT measurements in the Alps. Siewert *et al.* [21] used it to evaluate Arctic rockwall retreat rates and their results ranged from 0.33 to 1.96 m ka^{-1}, which served as a partial confirmation of rockwall recession exceeding 1-2 m ka^{-1} during the Holocene for Spitsbergen, as estimated by André [22], and 0.30-0.62 m ka^{-1}, as indicated Berthling and Etzelmüller [23]. From the point of view of talus slope evolution, more data was generated in the course of a complex investigation in the Tatra Mountains, where the GPR method was used [24]. In this work, the authors analysed climate changes over the last 200 years, as reflected in the structure and morphodynamics of talus slopes. This step allowed determining time periods characterized by either higher or lower rates of development. Finally, Senderak *et al.* [25] applied the ERT and GPR methods to the study of talus slopes on Spitsbergen. They selected hill slopes in a marginal zone of the glacier and slopes without contact with the glacier in order to compare the effect of the glacier on the internal structure of talus slopes. The study showed that early evolution of talus slopes depends on interaction with the glacier – and the level of activity of paraglacial processes conditioned by the glacier is the highest by the time glacial ice is completely melted from the internal structure of slopes.

In this paper we continue the discussion on talus slope evolution, but we focus on a broader time scale than the paraglacial period. The aim of the research is to explore in detail the internal structure of talus slopes that differ in terms of age and climatic conditions, and to identify mechanisms responsible for permanent activity during their geological history. ERT measurements and geomorphological observations were conducted on two talus slopes on SW Spitsbergen (Norway), and also on one slope in the Tatra Mountains (Poland). Observations were carried out in 2012, 2015-2017. Studied slopes are characterized by: (1) the initial structure of the talus slope; (2) relatively mature landforms, but shaped by conditions typical for the periglacial environment; and (3) mature landforms that have existed from the beginning of the Holocene, but which are still characterized by continued and highly active morphogenetic processes. In this study, we compare the slopes on the different development stages, and we make an attempt to interpret the talus slope evolution on northern hemisphere after deglaciation.

2 Study areas

2.1 Hornsund Fjord, SW Spitsbergen, Norway

The investigation in SW Spitsbergen was based on two talus slopes located in the Hornsund Fjord region (Figure 1). The first slope (profile 1) is part of the Fugleberget massif (569 m a.s.l.) above the surface of the Hansbreen (*breen* means *glacier*). The second slope (profile 2) is part of the Gullichsenfjellet massif (583 m a.s.l.) and is located in the Bratteggdalen (*dalen* means *valley*) about 4 km below the snout of the Bratteggbreen.

Both slopes are located near the Polish Polar Station in Hornsund, where the average air temperature for the period 1979-2009 was −4.3°C. The warmest month was July, while the coldest was January. The average air temperature in these months was +4.4°C and −10.9°C [26]. The average precipitation was 434.4 mm, with the highest rainfall during the summer [27]. The location of the study sites on the coast of the Greenland Sea and the area's level of precipitation lead to a high level of humidity – the average for the studied period was 79% [28]. Changes in air temperature and precipitation in the study area are also linked to sea ice conditions [29]. The study area is affected by permafrost conditions, which is treated as a state of a ground with temperature at or below 0°C occurring in a period of 2 years [30]. The depth of the active layer is 2-5 m [31–33].

The sediment supply area of the first slope consists of amphibolites [34]. The rocky slope that forms the Fugleberget massif and produces slope material in the study area covers about 0.33 km^2 (Table 1). The slope is located next to the western marginal zone of the Hansbreen, which descends to the water of the fjord, with a length of around 15 km and an area of around 50 km^2 [35, 36]. In the period 1936-2010 the length of this glacier decreased by nearly 1.8 km [37, 38]. The trimline extends through the Fugleberget's slopes. Sites above the trimline produce texturally immature debris and block material from rockfalls. Below this line, slope material is mixed with moraine material. The surface of this slope is levelled and moulded by snow avalanches. The upper part of the slope features debris flow gullies with depths of 0.5-1.0 m.

The Bratteggdalen, where the second study slope is located, features three elevation levels connected by a network of streams and proglacial lakes. The highest lake is located at 234 m a.s.l. in front of the Bratteggbreen, which filled the entire valley a few thousand years ago. The "middle" lake is found at 139 m a.s.l. and the lowest lake, named Myrktjörn (*jörn* means *lake*), is at 72 m a.s.l.

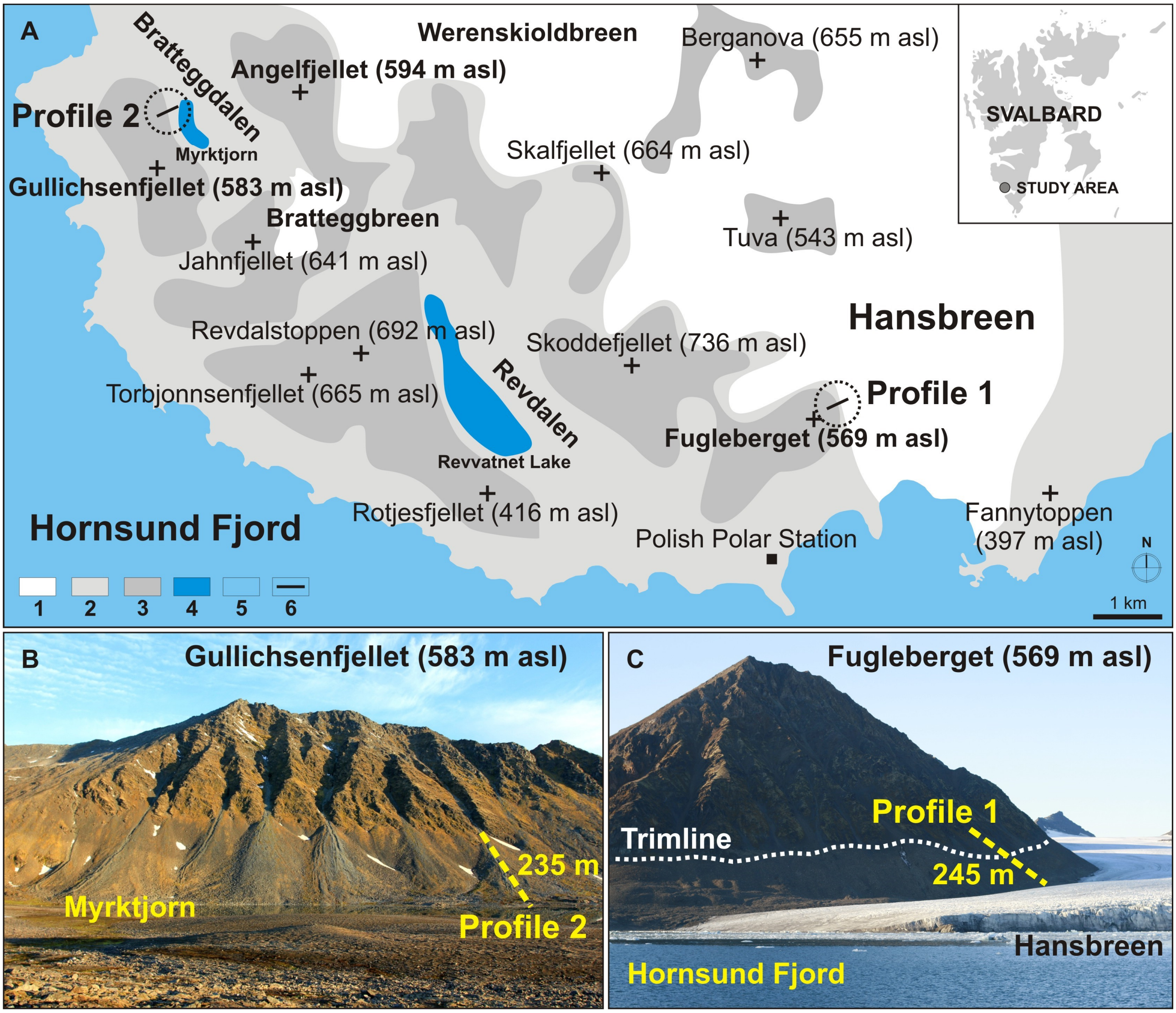

Figure 1: Study area on SW Spitsbergen: A – simplified geomorphological map of the Hornsund Fjord region; B – Gullichsenfjellet's slopes in the Bratteggdalen with location of profile 2; C – Fugleberget's slopes near the Hansbreen with location of profile 1. Symbols: 1 – glaciers, 2 – debris-mantled slopes, 3 – rock slopes, 4 – lakes, 5 – Hornsund Fjord, 6 – geophysical profiles.

[39]. The valley has an asymmetrical shape. The smooth slopes of the Angelfjellet massif (597 m a.s.l.) limit the valley to the northeast. In this part there is debris cover, which, on the lower slopes, appears in the form of polygons of patterned ground flooded partly by the waters of Myrktjörn. The other side of the valley is steeper and limited to the southwest by the quartz Gullichsenfjellet massif (583 m a.s.l.). At the foot of this massif, a complex of 8 talus cones developed and one of its slopes was chosen for study purposes. The shape of the slope is straight in the proximal part and concave in the distal part. Morphogenetic processes typical of slopes in Spitsbergen such as snow avalanches transporting slope material from rockfalls and debris flows moulding upper slopes are common here [40]. On the studied cone, debris flow gullies are deep (up to 1.5-2.0 m) and characterized by high levées.

The rocky slopes of the Gullichsenfjellet massif are steep and cut by a system of deep chutes and gullies formed on bedrock fractures [41]. Both of them transport not only debris and block material, but also water from the snow patches' melting occurring throughout the year. Water found at the apex of the cones infiltrates into the internal structures. Some water flows through dissolving slope material, and some is stored in the slope material in the form of pore ice. Local conditions predisposed to the retention of precipitation and snowmelt water are affected by topography, irradiation, and relatively high precipitation associated with the short distance to the coast [42].

Table 1: Characteristics of the studied talus slopes.

Profile Name	Profile 1 Fugleberget	Profile 2 Gullichsenfjellet	Profile 3 Szeroki Piarg
Location	Near Hansbreen, Hornsund Fjord region, SW Spitsbergen, Norway	Bratteggdalen, Hornsund Fjord region, SW Spitsbergen, Norway	Rybi Potok Valley, Tatra Mountains, Poland
Scale of age/time	hundreds	thousands	tens of thousands
Length of slope/profile	245 m	235 m	460 m
Elevation range	90-190 m a.s.l.	85-150 m a.s.l.	1,395-1,550 m a.s.l.
Dominant lithology	amphibolite	quartzite	granitoids
Slope angle	35°	30°	25°
Aspect	NE	NE	N
Sediment supply area	0.33 km^2	0.66 km^2	0.50 km^2
Height of sediment supply area	379 m	433 m	888 m

2.2 Rybi Potok Valley, Tatra Mountains, Poland

Studies in the Tatra Mountains were carried out on the Szeroki Piarg cone, which is the largest and oldest talus landform among all study sites. It is estimated that this structure developed about 10 ka and is related to the end of the last glaciation in this region [24, 43]. The studied slope is found in the upper part of the Rybi Potok Valley and constitutes the lowest part of the Mięguszowieckie Szczyty slope system (Figure 2). This system includes the northern walls of the valley, which culminate in the Mięguszowiecki Szczyt Wielki peak (2,438 m a.s.l.); Mięguszowiecki Kocioł glacial cirque, partially occupied by a firn-ice patch (glacieret); and the Szeroki Piarg cone that descends to Morskie Oko Lake, the largest lake in the Tatra Mountains located at 1,395 m a.s.l. with a surface area 0.35 km^2. The system consists of the sediment supply area of the Szeroki Piarg cone, which is formed of granitoids and occupies 0.5 km^2 (Table 1). The gully above the studied slope is a few to several tens of meters wide and deep. It also serves as the channel of the stream that collects water from the sediment supply area. This stream flows in a chute on the cone's surface in the proximal part to about 150 m, then the water infiltrates into the slope material. The surface of the Szeroki Piarg cone is covered by debris flow gullies a few meters deep [44]. The slope material is characterized by poor fall sorting and a large amount of blocky material causing numerous air-filled spaces in its surface layer.

The climatic conditions in the Tatra Mountains are milder than in SW Spitsbergen, but are characterized by low average air temperatures, high precipitation, long-lasting snow cover and intense thunderstorms [45]. The coldest month is February and the warmest July; the mean annual air temperature is in the range of 2-3°C at elevations of 1,400-1,550 m a.s.l. [46]. The elevation zones dividing rocky masses in terms of temperature variation, level of precipitation, and permafrost occurrence in the alpine zone are typical for this area [47, 48].

3 Method

3.1 Electrical resistivity tomography (ERT)

The ERT method has become increasingly popular in studying both the polar and alpine environments, especially in the context of permafrost occurrence [49]. However, in the context of talus slopes this method has certain limitations. Primarily, they include obstacles deriving from extremely difficult terrain conditions, such as inaccessible and steep slopes, logistical constraints, and in effect higher costs. Secondly, the material of talus slopes usually consists of blocky debris [14, 50, 51]. Air-filled spaces in the internal structure and lack of sufficient moisture in the surface layer make it difficult to perform measurements and may cause electrical contact failure in the case of many electrodes [52].

Despite those obstacles, numerous studies of slopes confirmed the usefulness of generating ERT measurements in different latitudes that allow to identify the most important elements of internal structure and determine the current stage of development for selected slopes. Based on ERT results, we cannot identify traces of earlier stages, because the stratification of talus slope material is difficult to examine in detail. Thus, the use of a second geophysical method, ground-penetrating radar (GPR), is rec-

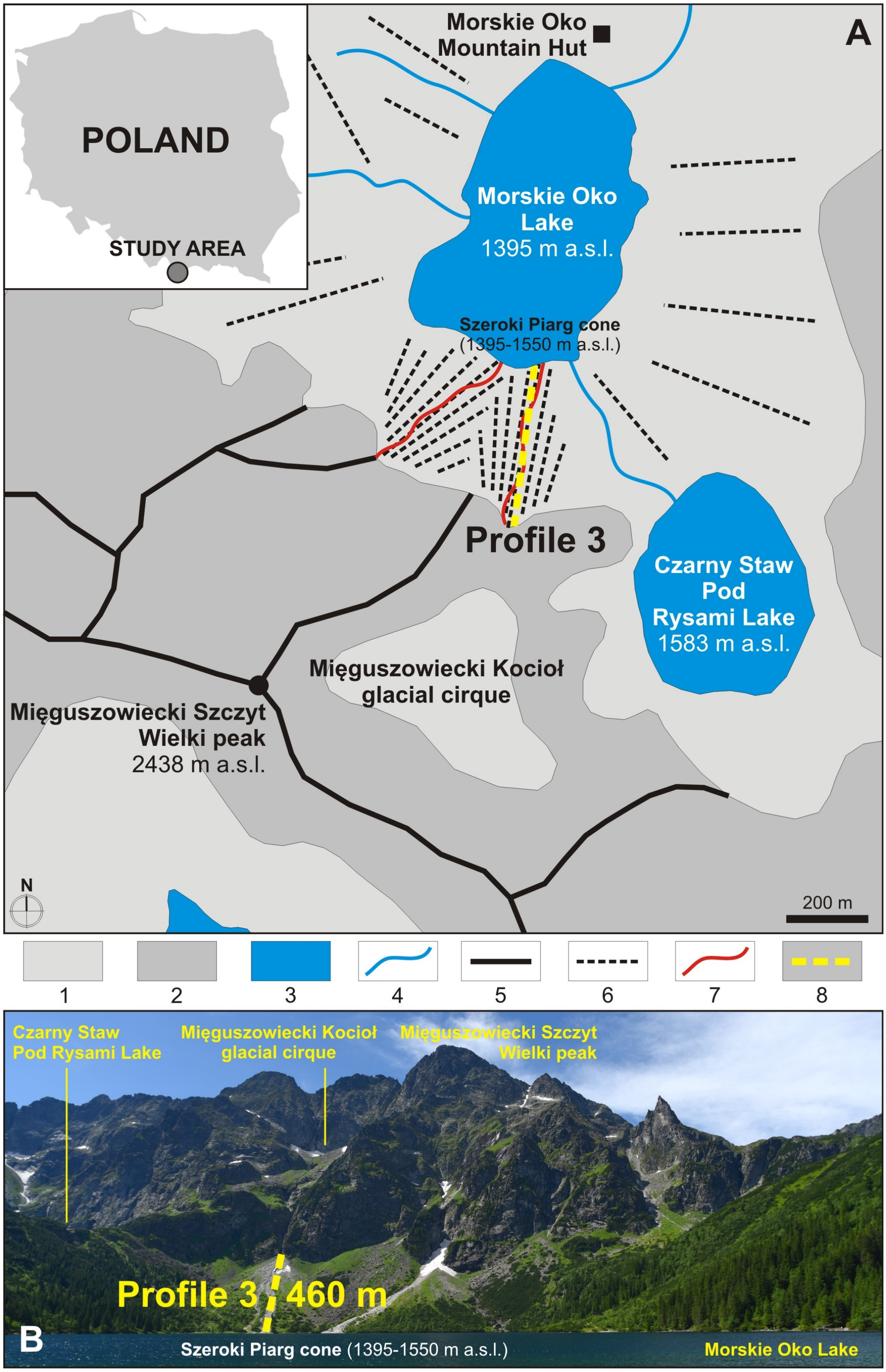

Figure 2: Study area in the Tatra Mountains: A – Simplified geomorphological map of the highest part of the Rybi Potok Valley; B – A view of the Szeroki Piarg cone with marked location of profile 3 from the Morskie Oko Mountain Hut (photo by B. Gądek). Symbols: 1 – debris-mantled slopes, 2 – rock slopes, 3 – lakes, 4 – rivers and streams, 5 – sharp rocky ridges, 6 – talus slopes or cones, 7 – debris flows, 8 – geophysical profile.

ommended to confirm ERT measurements and minimize the ambiguity of the individual geophysical solutions.

Studies performed on Spitsbergen and in the Tatra Mountains were based on two sets of measurements: (1) LUND automatic electric imaging system with SAS (Signal Averaging System) 4000 Terrameter manufactured by ABEM (Sweden) (profiles 1 and 3), (2) ARES made by the Czech company GF Instruments (profile 2). All study profiles were examined using a Wenner-Schlumberger array, which is recommended for horizontal structures [53, 54], but can be also successfully used in analysing vertical structures [55]. All profiles were established using 5-m spacing between electrodes. The length of the profiles was depending on the length of the slope and for profiles 1 to 3 was respectively 245 m, 235 m and 460 m what effected on the depth recognition – respectively 30 m for profiles 1 and 2 and 70 m for profile 3.

The resulting measurements were analysed via RES2DINV software (Geotomo Software, Malaysia). The root-mean-squared (RMS) error, which indicate the differences between calculated and measured values of apparent resistivity, for the 5^{th} iteration equalled 4.9% (profile 1), while for the 4^{th} iteration it equalled 4.1% (profile 2) and 5.3% (profile 3). The resulting model was based on 298 points, 476, and 1,129 points, respectively. A distorted finite-element grid with damped distortion was used in topographical modelling (damping factor = 0.75).

3.2 Geomorphological observations and measurements

Cartographic data including topographic maps, orthophotomaps and aerial photos of the study areas were used for basic morphometric measurements and observations [34, 38, 56–58]. The detailed measurements of the talus slopes were made using ArcGIS tools (Table 1). The results of morphometric measurements and geomorphological observations supported the interpretation of the ERT measurements. Additional data, such as photos of study area and descriptive material, were the supplement for collected material. The positions of the ERT profiles were recorded by a precise GPS receiver. Slope inclination was measured using a manual inclinometer, and then, the measurement was tested in ArcGIS.

3.3 Selection of study sites

The research concept assumes a comparison of talus slopes on the different stage of development. Therefore, the main selection criterion was the age of studied slopes, which for these kind of depositional forms can be determined since the beginning of deglaciation. Furthermore, the talus slopes were the subject of earlier study on broadly understood geomorphology [24, 25, 59]. Additionally, it should be noted that the studied sites are respectively representative for SW Spitsbergen and Tatra Mountains, because these forms occur commonly in both regions.

4 Results and interpretation

4.1 Profile 1 – Fugleberget, Spitsbergen

The results of ERT measurements conducted on the talus slope of Fugleberget indicate the presence of two different zones in its internal structure: an upper zone in the upper 0-100 m of the profile and a lower zone in the lower 100-245 m (Figure 3). On the surface, the boundary between them corresponds to the well-preserved trimline of the Hansbreen.

The upper zone is characterized by a three-layer structure. The surface layer of the slope to a depth of 2-3 m exhibits the lowest values of electrical resistivity (ER) for the entire profile (excluding the bedrock) in the range of 4-20 kΩm, which may indicate the presence of an active layer that includes loose slope material. Below, at a depth of 3-25 m, there is a layer characterized by significantly higher values of ER in the range of 20-60 kΩm, which is typical for debris affected by permafrost, *i.e.* pore ice [21]. The deepest layer in this zone found at a depth of 25 m indicates the presence of materials with values of ER in the range of 4-20 kΩm, which indicates weathered amphibolite bedrock of the Fugleberget massif.

The lower zone of profile 1 also consists of three layers. The first part of the slope is a continuation of the active layer visible in the upper zone, but is built of mixed moraine and slope material. Material to a depth of 2-3 m has values of ER in the range of 4-20 kΩm. Below, at a depth of 3-10 m, there is a section of the profile in which the ER of the medium is in the range of 20-60 kΩm, indicating the presence of material affected by permafrost. The depth was analysed in detail on the cross-sectional profile made by the ERT method for this site [25]. The deepest level of the lower zone yields the highest values of ER for the entire profile, in the range of 60-750 kΩm. These values indicate the presence of glacial ice in the internal structure of the slope to a depth of at least 10 m [49]. The thickness of the ice was not determined, but it is at least 30 m. The existence of buried glacial ice was also found several meters

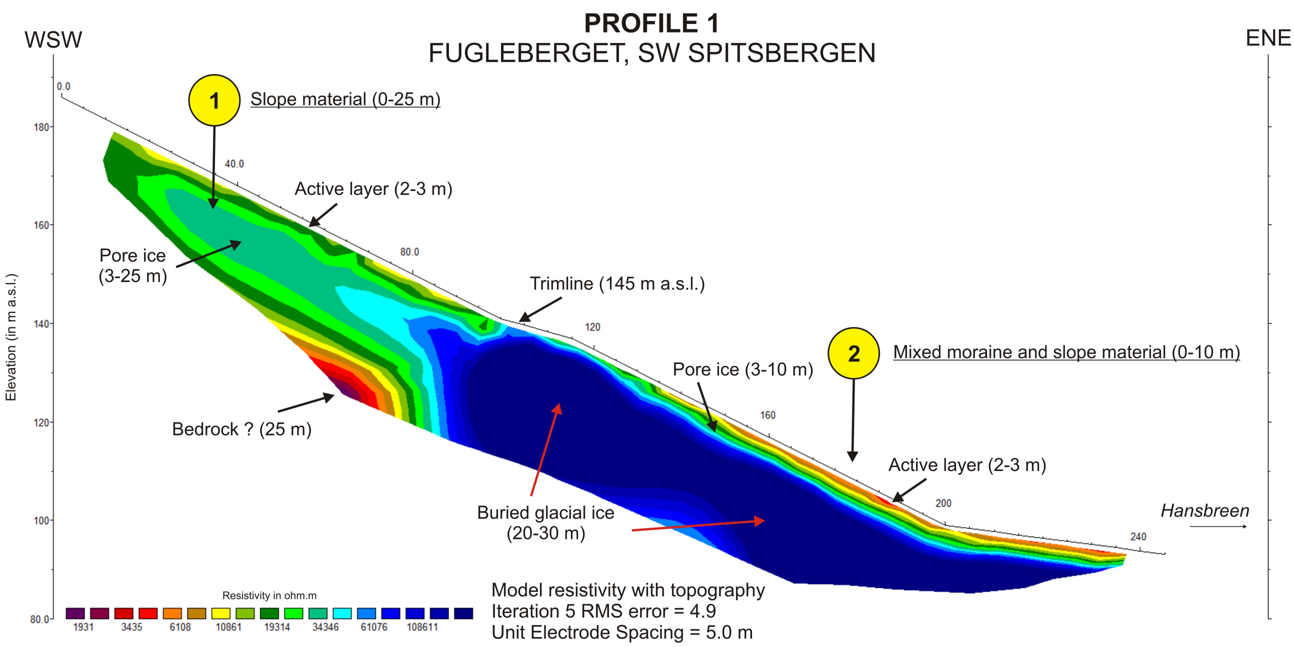

Figure 3: Profile 1: ERT longitudinal section of Fugleberget's eastern slopes; the length is 245 m (modified from Senderak *et al.* [25]).

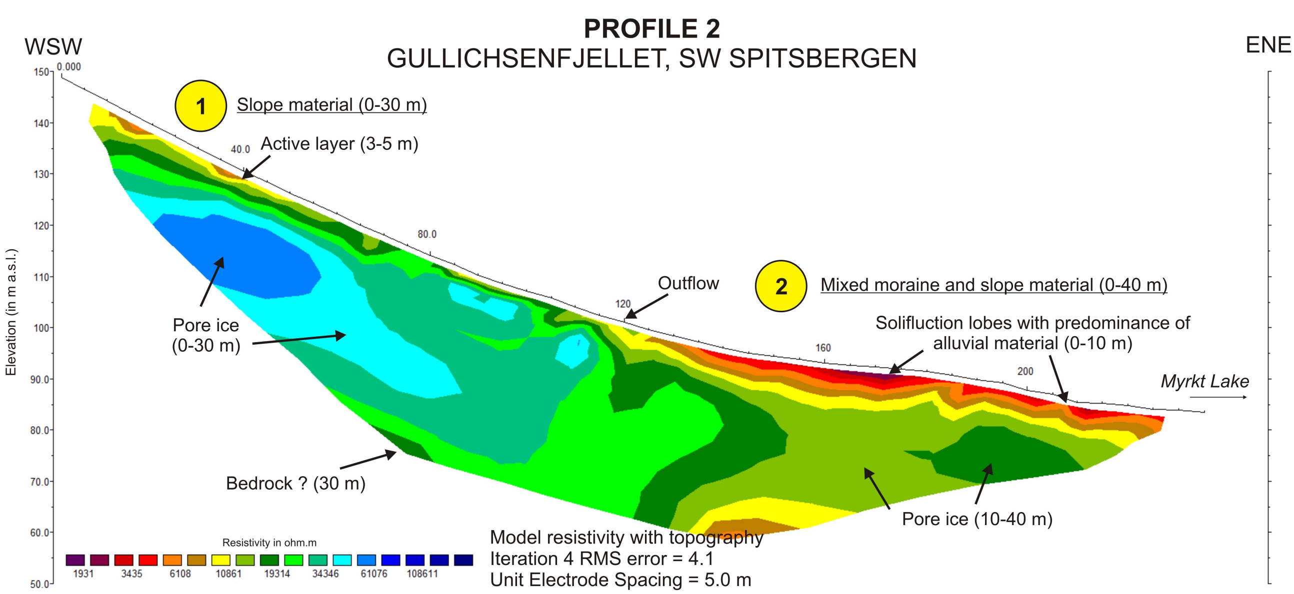

Figure 4: Profile 2: ERT method, longitudinal section of Gullichsenfjellet's northern slopes; the length is 235 m.

above trimline. It was located at a depth of a few meters (ca. 10 m). The height of its roof was therefore very similar to the height of the ice surface diagnosed near trimline. This kind of structure is connected with the glacier surface in ablation zone [36]. In profile 1, the glacial ice detected in the contact zone with the trimline is very close to the slope surface and may incorrectly indicate an absence or small thickness of the slope material that forms the active layer or is affected by permafrost. It is due to the relatively low resolution of the surface layer observations caused by the spacing of the electrodes (5 m) and the topography of the terrain affecting the distortion of ERT measurements.

4.2 Profile 2 – Gullichsenfjellet, Spitsbergen

As with profile 1, the subsurface image of profile 2 is characterized by a bipartite nature of its horizontal profile (Figure 4). There is no geomorphological feature on the slope

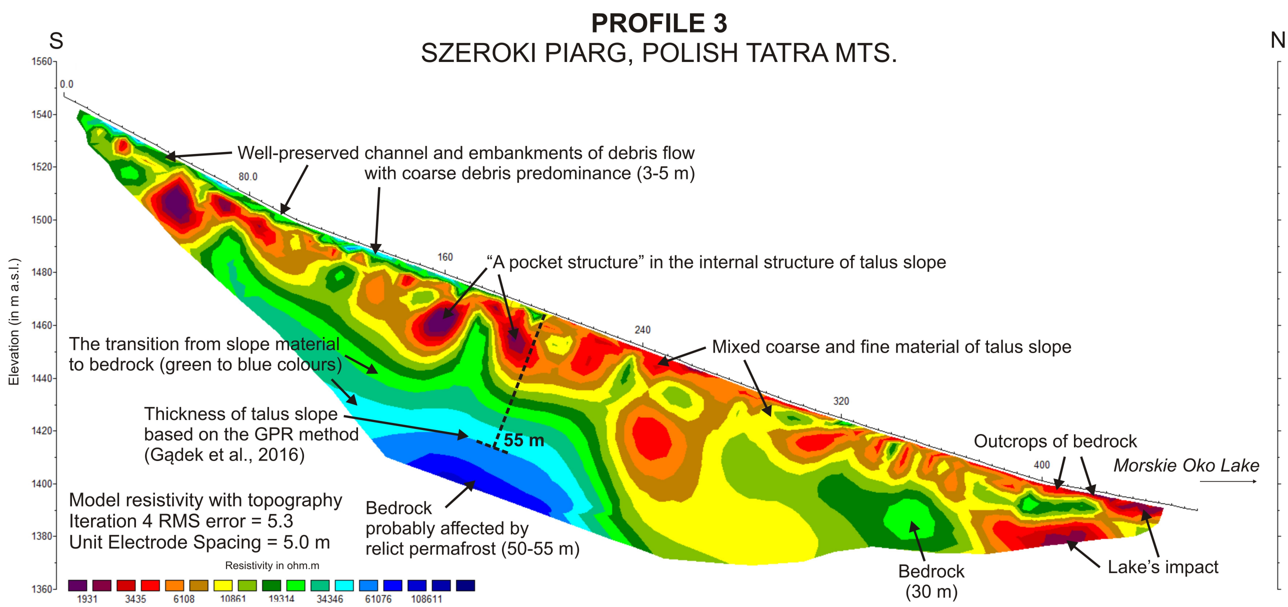

Figure 5: Profile 3: ERT method, longitudinal section of the Szeroki Piarg cone located on the northern slopes of the Mięguszowieckie Szczyty massif; the length is 460 m.

surface that can determine the boundary of two zones (*e.g.* trimline). At 120 m down the profile, however, there is a periodic outflow of water dividing the slope surface into a straight upper zone (section 0-120 m) and a slightly concave lower zone (section 120-235 m).

The upper zone has a 2-layer structure. The upper 0-80 m of the profile yield a surface layer with a depth of 3-5 m that has values of ERin the range of 7-20 kΩm, which may correspond to an active layer with a large amount of empty space in the slope material [49]. This layer wedges out about 80 m down the slope, probably because the large supply of fresh slope material in the apex of the cone gradually thins with transport on the slope surface. The second layer in the upper zone is found at a depth of 0 (at 80-120 m of the profile) to 30 m and has the highest values of ER for the entire profile in the range of 20-60 kΩm. The maximum thickness of this zone is beyond the maximum penetration depth of this ERT survey.

The lower zone also consists of two layers, where contemporary development is dominated by alluvial processes. The surface layer has the lowest absolute values of ER for the entire profile, in the range of 2-10 kΩm, occurring at a depth of 0-10 m. This part of the slope is covered by fine-fraction material (less than 2 mm), which is carried by water emerging at 120 m down the profile. Fine material and surface runoff cause an intensification of solifluction processes (*e.g.* gelifluction and frost creep). The deeper layer is characterized by higher values of ER in the range of 10-20 kΩm, and affects the slope structure at a depth of 10-40 m. Based on these results, mixed moraine and slope material affected by permafrost may be inferred. Unusual values of ER for permafrost on Spitsbergen are discussed in the following section.

4.3 Profile 3 – Szeroki Piarg, Tatra Mountains

The results of ERT measurements on the Szeroki Piarg cone indicate the existence of a one-layer structure and no clear division into zones was revealed in the slope profile. It suggests that existing layer consists of the irregular slope material directly overlying a layer that includes granite bedrock. The internal structure of the slope is characterized by two parts (Figure 5).

The first part of layer is found at the slope surface with a depth range of 0-25 m and has the lowest values of ER in the range 2-8 kΩm. The slope material in the upper part of the profile, at 0-280 m, characterises "a pocket structure", which contains many spaces filled with fine material. This part of the slope is formed primarily from large rockfalls whose products were blocks deposited at the end of the studied gully and below it. In this part of the profile (0-280 m), the slope surface to a depth of 3-5 m has higher values of ER in the range of 8-25 kΩm. As show an observations at site, this correlates with a well-consolidated channel and embankments of debris flow. The surface layer found over the remainder of the profile, at 280-460 m, has values of ER

Table 2: Summary and comparison of results obtained using the ERT method for all profiles.

Profile Name	Profile 1 Fugleberget, SW Spitsbergen, Norway	Profile 2 Gullichsenfjellet, SW Spitsbergen, Norway	Profile 3 Szeroki Piarg, Tatra Mts, Poland
Thickness (m)	25	40	55
Active layer (m)	2-3	3-5	No
Permafrost (pore ice) (m)	3-30	5-40	No
Buried glacial ice	Yes, 10-30 m	No	No
Zone of minimum electrical resistivity	Bedrock and thin layer of sediments at the slope surface	Slope surface below outflow at the 120 m point of the profile	Zone affected by Morskie Oko Lake
Zone of maximum electrical resistivity	Buried glacial ice in lower zone of slope	Pore ice in upper zone of slope	Bedrock of talus slope
Layer structure	3	2	1

in a narrower range of 6-8 kΩm, which may correspond to coarse debris, fewer empty spaces in the internal structure, and greater stability of this part of the cone associated with less activity of moulding processes of its surface. Very low values of ER in the range of 2-4 kΩm noted in the lowest parts of the studied slope at 400-460 m are related to its proximity to Morskie Oko Lake, the waters of which affect the distal part of the Szeroki Piarg cone.

The second part of layer identified in profile 3 is found at a depth of 25-50 m and has values of ER in the range of 8-30 kΩm. The position of this part at the top of the studied slope is parallel to the inclination of the cone surface. High values of ER and their wide range may indicate a gradual transition from slope material to bedrock (green to blue colour on the profile). This part also reaches its maximum thickness on the cone with a depth of 50-55 m in the middle part of the structure (and also the profile). The last part visible in the subsurface image is the zone with the highest values of ER – in the range of 30-60 kΩm – corresponding to the bedrock on which the talus slope is based. The bedrock is found at a depth of 50-55 m.

5 Discussion

Our studies on Spitsbergen and in the Tatra Mountains confirm a number of widely accepted assumptions that the internal structure of talus slopes may reflect the different environmental conditions associated with their development, which have been changing since deglaciation (Table 2). The most relevant factors affecting talus slope evolution are: the rate of deglaciation, type and size of sediment supply area, lithology of the nearest bedrock, and climate [7, 60, 61]. Each factor is characterized by various activity levels and intensities, which depend on the current period in the evolution of the investigated slope. Based on existing literature sources [7, 13, 14] and our new data on internal structure of talus slopes and especially its spatial distribution, we compare the slopes at the different periods of postglacial development, including paraglacial, periglacial, and talus-alluvial periods (Figure 6). Each of the three studied slopes shares common features that allow to trace their evolution from the present time to around 10 ka, which was the beginning of the end of glaciation in the Pleistocene northern hemisphere.

5.1 The paraglacial period

The slope of the Fugleberget massif (Spitsbergen) represents a paraglacial period (Figure 6A). It is understood as a time when non glacial morphogenetic processes are controlled by the glacial environment [62, 63]. As suggested by Ballantyne [13] for the paraglacial period, the relaxation of bedrock during deglaciation plays a major role in the production and deposition of slope material. Senderak *et al.* [25] suggest that the successive stages of early evolution of the same slope, where glacial ice affects the redistribution of slope material and formation of the glacial landscape. The development of the studied slope was affected by active tectonics resulting from the retreat of the Hansbreen [13], but this study indicates a close relationship between slope processes and the glacier [25], which has been in retreat since the end of the Little Ice Age at the turn of the 20th century [36, 64, 65]. In this part of the valley, the glacier was situated at an elevation of around 150 m a.s.l. during the transgression, which is marked by a well-preserved trimline in the form of a shelf shape of approximately 5 m in width. The record of the Hansbreen's for-

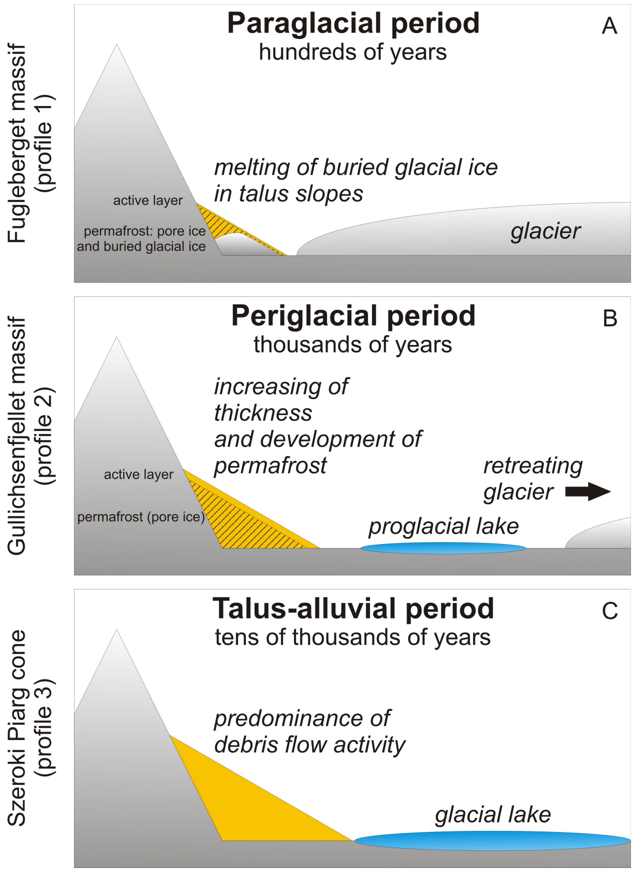

Figure 6: Schematic comparison of three type of studied talus slopes, which were presented from the youngest to the oldest postglacial foms. A – Paraglacial period is dominated by the existence of buried glacial ice in the internal structure of talus slope; B – Periglacial period assumes the activity of frost weathering accelerating the regular supply of debris to talus slopes; C – Talus-alluvial period includes the debris flow activity in the warmer climate conditions with the greater volume of water in the environment of talus slopes.

mer range also consists of glacial ice buried in the internal structure in the lower zone of the slope at a depth of 10 m from the trimline to the profile end (profile section 100-245 m).

During deglaciation and melting of the glacier's marginal part, talus slope was initially covered by lateral moraine deposits. The glacier then began to be covered by a regular supply of slope material transported from the upper part of the slope by debris flows and snow-rock avalanches, which cause gradient of talus accumulation [66]. Similar processes were identified near the Gås Glacier (nor. Gåsbreen) on the other side of Hornsund Fjord using photogrammetric methods [67]. Above the trimline, the slope material contains no glacier ice. A maximum thickness of 25 m confirmed the results of GPR measurements for the same slope [25]. Along the whole slope, the surface layer of 2-3 m thickness corresponds to the active layer. Below, material is affected by permafrost including buried glacial ice of the Hansbreen.

5.2 Periglacial period

The talus cone at the Gullichsenfjellet massif (Spitsbergen) is a more mature landform, but still affected by the conditions of the polar environment. This particular slope represents a more advanced stage of development, which may be termed a periglacial period (Figure 6B). In Ballantyne's conceptualization [13], after the stabilizing of tectonic processes, mechanical weathering, especially frost action, prevails in the exposed bedrock, whereas glaciers do not affect slope evolution. This stage is longer than the preceding paraglacial period [63], and in the case of the studied slope, it may last for a few thousands of years. The overall relief of the studied slope surface is concave, which is typical of similar landforms on Spitsbergen [68]. The only convex landform in slope morphology is the chute found in the lower part of the studied slope, formed of rock debris derived from nival processes. The origin of the chute is vague; on the one hand may be related to the occurrence of snow-rock avalanches transporting material from the upper parts of the massif [6], but on the other hand the avalanches are channelled by the existence of the chute, which may be older than the deglaciation [23, 69]. In the upper part of the slope, the surface is moulded by debris flows, leaving gullies with a depth of 1-2 m. The nival chutes and transport gullies confirm that avalanches and flows of slope material dominate in a periglacial environment [70, 71]. Based on a dating of the youngest glacial and periglacial landforms in the Revdalen located at a similar elevation as the Hornsund Fjord area, the talus slopes in the Bratteggdalen could have started to develop earlier than 3.5 ka [72]. These include the location and shape of zone with the highest values of electrical resistivity in the upper part of the slope, which may suggest the presence of postglacial permafrost (pore ice). The studied slope must have developed in a warmer period, as indicated by the lack of buried glacial ice, or the paraglacial period has never occurred on this slope. If the ice had melted, permafrost could not survive at that time [52]. This part of the slope, however, is reminiscent of the structure of rock glaciers found near the Polish Polar Station in Hornsund, which are a mixture of ice and debris [73, 74]. Examples of similar slopes from Spitsbergen and the Alps show that the permafrost table occurs along the whole slope at the same depth [21, 75]. In the case of profile 2, the thickness of the active layer reaches 3-5 m and is thicker in the lower zone of the slope.

Apart from climatic factors, permafrost can increase or degrade depending on the supply debris to the talus slope [76, 77]. The reason for the relatively large thickness of the active layer of the Gullichsenfjellet's slopes is the regular supply of slope material that overtakes the permafrost accretion process in the slope structure, which confirms the high activity of rock slope destruction processes [78]. In the lower part of profile 2, permafrost has unusually low values of electrical resistivity in the range of 10-20 kΩm, which are about ten times lower than that measured at the other sites on Spitsbergen including the Hornsund Fjord area [21, 32, 79]. This is caused by a large amount of water in the environment coming from higher, orographic precipitation, and also the short distance to Myrktjörn, which may affect the internal structure of distal parts of slopes.

5.3 Talus-alluvial period

The Szeroki Piarg cone in the Tatra Mountains differs from the Spitsbergen examples, especially in the size of the sediment supply area and the length of the profile. The relief of the slope surface is extremely variable, ranging from stable and inactive parts covered with fine material and low alpine vegetation to deep debris flow gullies draining the slope along its whole length. Since the last glaciers retreated from the area around 12.5 ka [80], the Tatra region has developed under conditions typical for high-mountain environments [46, 81, 82], that is exposure to high air temperature fluctuations, frost action, and high activity of surface evolution processes (*e.g.* avalanches, debris flows, rockfalls). Currently, there is much more water in the environment of the Tatra Mountains than in the past, which has an impact on alluvial and fluvial processes [83]. The water involved in the transport of slope material comes from snow melting in the upper parts of the Mięguszowieckie Szczyty massif during spring and also from heavy rains in the summer and autumn [11]. The transformation of the slope caused by short (lasting minutes) and intense rainfall continued for hundreds of years [84]. In the Polish-language research literature, this process is known as "*aluwiacja*", which means debris flow activity, but strictly speaking not alluvial processes [85, 86]. The most suitable genetic type for the Szeroki Piarg cone is the talus-alluvial slope (Figure 6C), which features debris flow landforms as well as fluvial activity, and rockfalls are a predominant process [44]. Another mechanism that transports material is frequent snow avalanches, which tend to smooth the shape of a long slope [87, 88]. The varied slope surface corresponds to a heterogeneous internal structure shown by ERT measurements. In the Tatra Mountains, above 1,900 m of elevation, there may be sporadic permafrost [24]. Geophysical data obtained on the Szeroki Piarg cone, situated below 1,550 m a.s.l., have confirmed the lack of contemporary permafrost in the slope structure. The layer in the form of irregular slope material directly overlying a layer that includes granite bedrock was identified. Examples of similar stratified talus slopes with large boulders coming from high-magnitude rockfalls were studied in the Făgăraș Mountains in Romania using GPR [89]. The thickness of the talus slope exceeds 50 m and is consistent with GPR results produced for the same slope [24]. The deeper increase in the electrical resistivity of the granite bedrock to over 100,000 Ωm indicates a decrease in its temperature. The presence of a relic of permafrost (frozen granite) cannot be excluded. In other places in the Tatra Mountains this possibility was signalled by Dobiński [48]. Deposition of slope material is very intense, although the climatic conditions are more favourable than in the polar environment. However, it should be noted that talus slopes developing in the Tatra Mountains have much larger sediment supply areas than deposition sites on Spitsbergen. This is due to differences in the geological structure of the mountain ranges at both locations, which in each case is a result of the formation of crystalline rocks, which are then subject to displacement associated with the region's orogeny.

6 Conclusions

The study explores various stages of talus slope development, reflected in the ERT profiles. Based on results, three development periods were identified: paraglacial, periglacial, talus-alluvial.

The paraglacial period is the most dynamic stage of talus slopes' development. It is mostly characterized by the melting of buried glacial ice in the internal structure of talus slopes. Interactions between the glacier and slopes play a crucial role at the beginning of the evolution process. In our view, the relaxation of bedrock during deglaciation, as suggested by Ballantyne [13], has secondary importance for the process of development. The earliest period lasts from decades to hundreds of years, when glacial ice becomes completely melted and the glacier does not affect talus slopes directly or indirectly.

Then, the periglacial period begins and causes a stabilization of all slope processes and triggers a regular supply of sediment to slope surfaces, which is consistent with views put forth by Ballantyne. Talus slopes may develop in the periglacial environment for several thousands of years, which was observed and studied mostly on Spitsbergen and in the Alps. The internal structure of talus slopes is usually affected by permafrost (below a depth of 2-5 m) until the end of the period dominated by typical periglacial conditions.

The most mature period, not referred to in previous works on evolution, is the talus-alluvial, which is significantly different and characterized by a greater volume of water in the environment resulting from a warmer climate and higher precipitation. Talus-alluvial slopes are dominated by very high debris flow activity. The oldest landforms developed for at least several tens of thousands of years.

Many elements of the internal and external structure of talus slopes have changed since the beginning of deglaciation and the formation of initial slopes in the northern hemisphere. Research on talus slope evolution has shown that the thickness of slope material increases in the range of 25-55 m, wherein slope angle decreases from 35 to 25°. Based on major changes in structure and detailed interpretation of geophysical and geomorphological data, we have compared three talus slopes involving key elements of glacial landscape (glacier, talus slopes, glacial lake). The proposed typology of development periods need to be expanded using an interdisciplinary approach in further studies and subsequently compared with new case studies of talus slopes.

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