POLISH POLAR RESEARCH
vol. 44 no. 3, pp. 291–312, 2023 DOI: 10.24425/ppr.2023.144539

Can topographic features of debris cones (SW Spitsbergen) be geoindicators of environmental changes?

Agnieszka Latocha-Wites* and Krzysztof Parzóch

Institute of Geography and Regional Development, University of Wroclaw, Pl. Uniwersytecki 1, 50-137 Wroclaw, Poland

** corresponding author <agnieszka.latocha@uwr.edu.pl>*

Abstract: Evidence of recent geomorphic processes within debris cones, their spatial distribution and diversification on cones surface are interpreted in the context of contemporary slope morphogenesis. The detailed inventory of relief features on debris cones in the SW Spitsbergen revealed their great spatial diversity. It is linked with a dominance of different morphological processes in adjacent areas. Spatial and temporal diversity of process-relief assemblages on cones is strongly related with local factors, like bedrock lithology, slope aspect and inclination, local circulation and climatic conditions. However, the potential role of debris cones and their topographic features as geoindicators archiving information about the environmental impact of global changes, cannot be explicitly estimated. Local constraints obscure the regional expression of any global trends, which could be detected on the basis of process-relief assemblages on debris cones in polar regions.

Keywords: Arctic, Svalbard, slope morphology, geomorphic processes, debris flow.

Introduction

Many recent scientific studies in the Arctic are focused on recognition and interpretation of various environmental indicators of global change (Van Steijn *et al.* 2002; Lønne 2017; Senderak *et al.* 2021; Dolnicki and Grabiec 2022).

Landform features of different scales, regarded as reflection of diverse morphological processes, might be also used as geoindicators of environmental changes (Daanen *et al.* 2012). Geoindicators are defined by Berger (1997) as high-resolution measures of geomorphic and geologic short-term (<100 years) processes, which occur at or near the Earth's surface. They can be used for assessment of the magnitudes, frequencies, rates, and trends in long-term or rapid landscape transformations (Berger 1997), as well as be of practical importance for environmental impact assessment (Rivas *et al.* 1997). Thus, the assemblages of landform features may allow for assessment of variable phases of relief development and diversification of morphological processes resulting from a global change (Church *et al.* 1979; Strzelecki *et al.* 2020).

Debris cones, being one of the most characteristic features of slope relief, are often used as valuable sources of information for palaeogeographical analyses, based on interpretation of cones inner and superficial structure, their morphometric characteristics, type of material and its distribution within the cone, *etc.* (Jahn 1961; Piasecki 1968; Hinchliffe *et al.* 1998; Curry and Morris 2004). Debris cones are especially well developed and exposed in high mountain and polar regions, where scarce or no vegetation cover does not obscure their morphological expression. These features are often relict forms of former phases of slope development and, as such, they become important indicators of past morphological processes, their intensity, effectiveness and relief expression (Pérez 1989; Curry and Morris 2004). However, debris cones might constitute valuable resources also for assessing current trends of relief development, as their older surfaces are remodelled by recently active processes (Åkerman 2005; De Haas *et al.* 2015). Detailed analyses of recent processes within debris cones, their spatial distribution and diversification on cones surface may be interpreted in the context of contemporary slope morphogenesis and intensity of various morphological processes (Owczarek *et al.* 2013; Dzierżek *et al.* 2019). This issue is especially important regarding world-wide debates on the environmental change. In this aspect, debris cones may be regarded as 'mirrors' of currently dominating morphological processes, reflecting the environmental impact of global changes.

The slope processes have been studied for a long time in Svalbard with diverse methodologies, starting with a detailed geomorphic mapping of slope topography and landforms (Jahn 1967; Åkerman 1984; André 1990), and up to the use of electrical resistivity tomography, ground-penetrating radar, or unmanned aerial vehicle (Siewert *et al.* 2012; Senderak *et al.* 2019; Tomczyk *et al.* 2019). A comprehensive overview of the latest research on the dynamics of slope processes in Svalbard has been presented in Senderak *et al.* (2021) and Senderak (2023). However, the complexity of drivers and factors responsible for development of slope processes and associated landforms due to their high spatial diversity and impact of the local environmental constraints is still no fully understood (Dzierżek *et al.* 2019; Dolnicki and Grabiec 2022). Our study attempts to add more information on the diversity of the debris cones in the

Arctic and link these landforms with adequate processes, which is in accordance with Van Steijn *et al.* (1988), who concluded that each site should be analysed and interpreted individually due to a high complexity and diversity of site-specific processes.

In this study, several dozen debris cones in the SW part of Spitsbergen are analysed for their topographic features as indicators of current relief development. The aim of this research is threefold: (*i*) inventory of diverse relief features on debris cones, their classification and linkage with genetic morphological process; (*ii*) explanation of spatial and temporal diversity of process-relief assemblages, including recognition of factors favouring or limiting current morphological processes on cones surfaces and their diverse morphological expression; (*iii*) the assessment of the potential role of process-relief assemblages on debris cones as geoindicators of environmental change in polar regions.

Study area

The study area is located in the SW part of Spitsbergen, on NW shores of the Hornsund fiord, which is called the Wedel Jarlsberg Land. It comprises the foreland of the Werenskiold glacier (Werenskioldbreen), stretching from the mountain range of Jens Erikfjellet (NW limit of Werenskiold valley) to the valley of Revdalen, including its NW facing slopes of the Skoddefjellet range (Fig. 1). The bedrock is composed mainly of the metamorphic rocks of the Hecla Hoek succession, which include pre-Devonian quartzites, schists, amphibolites and greenstones (Birkenmajer 1990; Czerny *et al.* 1993). The relief is dominated by mountain massifs with elevation from *ca.* 450 to >700 m a.s.l. and coastline with several dozen or so raised marine beaches (Karczewski *et al.* 1981). The mountain slopes in the study area are intensively shaped by mass movements and the debris cones are among the most common landscape features.

The periglacial climate of the Wedel Jarlsberg Land is typical for the High Arctic. It is characterised by very weak diurnal and strong seasonal patterns (Przybylak 2003). The mean annual air temperature for the period 1979–2018 was −3.7°C, the average precipitation was 478 mm, with a peak in the summer season and a high level of humidity (79.7%) (Wawrzyniak and Osuch 2020). The vegetative period is very short, lasting 40–70 days in June to August (Owczarek *et al*. 2013).

Methods

We conducted detailed geomorphic mapping of all 81 debris cones located in the study area. Their surface and their surroundings, including minor forms and structures within cones, were mapped and measured in the field. Cartographic,

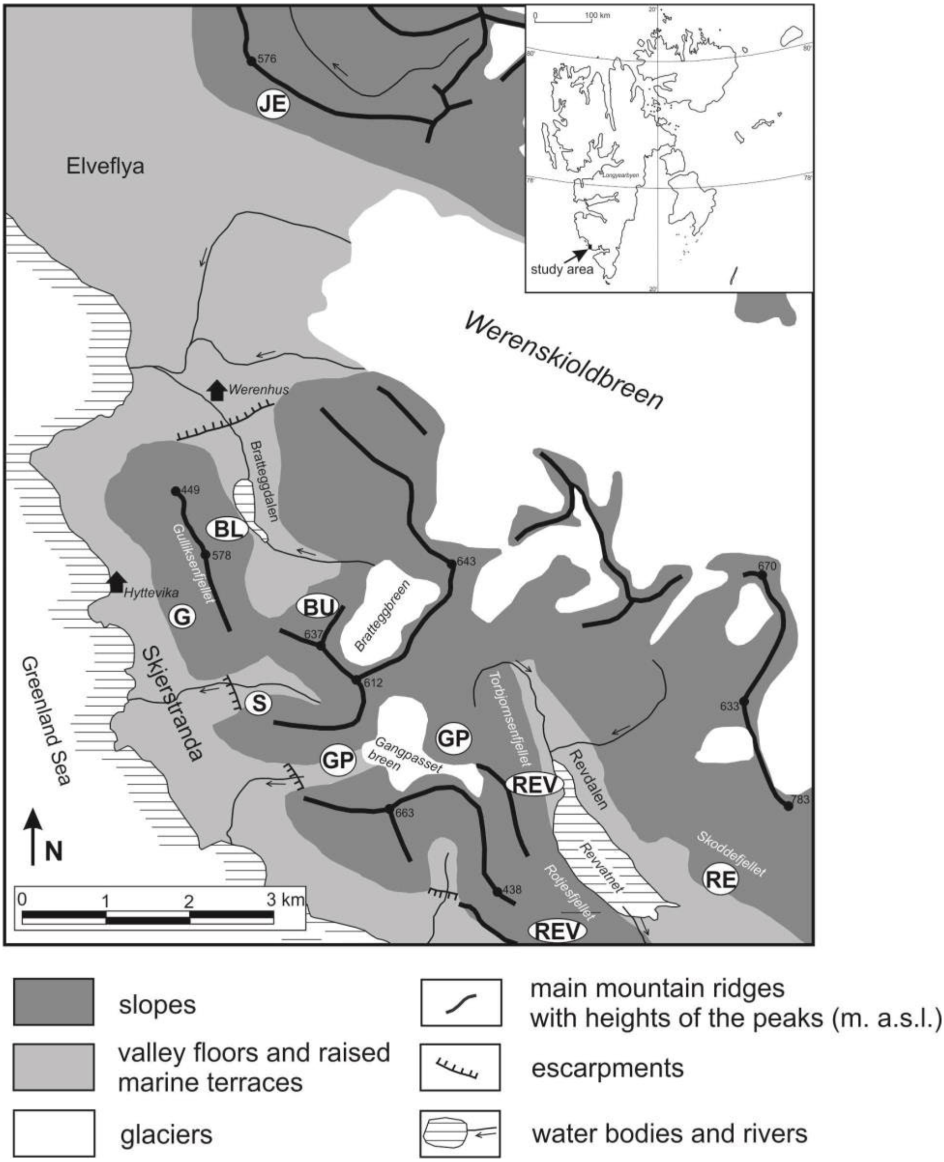

Fig. 1. The study area was divided into eight sub-areas. Abbreviations: G – Gulliksenfjellet, BL – Bratteggdalen Lower, BU – Bratteggdalen Upper, JE – Jens Erikfjellet, REV – Revdalen-Rotjesfjellet and Torbjörnsenfjellet, RE – Revdalen-Skoddefjellet, S – Steinvikdalen, GP – Gangpasset.

cartometric, GPS and aerial photographs data were additional sources of information. The field surveys were performed in 2005 and 2007.

The study area was divided into eight sub-areas, clearly separated by major topographic lines, showing similar features like bedrock, aspect or inclination within their boundaries, however, varying from adjacent regions. They include broad valleys with steep, rocky slopes: SW and S slopes of Jens Erikfjellet, Brattegdalen Lower and Upper, WSW slopes of Gulliksenfjellet, Steinvikdalen, Gangpasset, Revdalen-Rotjesfjellet, Revdalen-Torbjörnsenfjellet and Revdalen-Skoddefjellet (Fig. 1).

Results and interpretation

The spatial distribution of debris cones within the study area is diverse, although they are of generally similar size. Cones length ranges from 100 to 340 m and their width varies from 50 to 170 m. Their basic characteristics are presented in Table 1.

Table 1.

General characteristics of debris cones features in the study area.

Total number of debris cones	Debris cones with rockfall evidence	Debris cones with active debris flows*	Debris cones with inactive debris flows*	Debris cones with features related to episodic runoff	Debris cones with solifluc-tional features	Debris cones with vegetation > 50% of cones surface
Jens Erikfjellet						
10	3	3	1	4	2	7
Bratteggdalen Lower						
7	4	1	2	5	4	5
Bratteggdalen Upper						
9	9	-	-	7	-	-
Gulliksenfjellet						
7	4	3	5	2	4	7
Steinvikdalen						
1	-	1	-	-	1	1
Gangpasset						
12	12	2	-	1		-
Revdalen (Rotjesfjellet and Torbjörnsenfjellet)						
31	27	2	5	9	2	7
Revdalen-Skoddefjellet						
4	3	1	2	3	2	3

* including debris cones with both active and inactive debris flows

Surface features on debris cones as process indicators. — The surfaces of debris cone in the Hornsund region show diverse mezo- and microrelief forms. They could be interpreted as expression of diverse morphological processes, which are currently modelling former debris cone surfaces.

Scattered boulders. — The surfaces of debris cones are covered with various amount of boulders, rock fragments with size >25 cm (Neuendorf *et al.* 2005). The boulders in the study area range mainly from 0.5 to 1.5 m in diameter. They are mostly covered with vegetation, mainly lichens, but also with mosses and shrubs (polar willow); for the latest mainly in the Revdalen-Rotjesfjellet and western parts of Jens Erikfjellet. In contrast, some boulders on the debris cones located in the upper parts of the investigated valleys are mostly devoid of any vegetation cover.

The spatial distribution of boulders is diverse within the entire study area and within single cones. Some slopes are entirely debris-covered and separate forms of debris cones cannot be distinguished, *e.g.*, in inner parts of Gangpasset, Steinvikdallen, Brattegdalen and Revdalen. On some debris cones in outer parts of Revdalen and the Jens Erikfjellet range, no scattered boulders occur at all. Within most cones, the presence of fresh boulders is limited either to their upper parts, in the direct vicinity of gully outlet, or to the furrows. The latter case is typical for debris cones on Gulliksenfjellet, Brattegdalen Lower and Revdalen-Rotjesfjellet. The presence of scattered boulders at various locations within the debris cones, both in upper and lower parts, as well as at sides and in furrows, without any zonation, is characteristic for debris cones in Gangpasset, Steinvikdalen, Brattegdalen Upper and Revdalen-Torbjörnsenfjellet.

Boulders scattered on debris cones surfaces are indicators of rockfall. Their distribution patterns suggest that even though rockfall is still active on most rock cliffs above the cones, its intensity is variable in different regions. The most efficient rockfalls occur on slopes, which are located further from the shore line, in inner parts of the valleys, especially in closer vicinity of glaciers, moraines with ice-cores or long-lasting snow patches, where the rate of weathering seems accelerated. Distribution of boulders may be also influenced by the lithological constraints. Areas, which are built of metamorphic schists, like outer parts of Revdalen and Jens Erikfjellet, do not support formation of large and resistant blocks and debris.

Furrows and levées. — Debris flow is a type of sediment-gravity flow, defined as a gravitational movement of a shearing, highly concentrated, yet relatively mobile, mixture of debris and water (Rapp 1960; Blikra and Nemec 1998), which form a sequence of typical landforms: furrow (transport and erosion), levées (accumulation along the furrow) and depositional zone in form of a fan or block piles at the furrow outlet. The exact number of hillslope debris flow events is often not possible to detect, as older forms can be either destroyed by subsequent geomorphic processes or their material can be redistributed within the cone surfaces, for example by snow avalanches, obscuring their morphological expression. Debris flows often use existing furrows of former events and their effects are superimposed (Piasecki 1968), therefore only the minimal number of debris flows can be estimated (Owczarek *et al*. 2013).

The surfaces of some debris cones in the study area are dissected by a single or multiple systems of furrow-levées assemblages. Such landforms were distinguished on 18 debris cones which constitute *ca.* 22% of all debris cones within the study area (Table 2). However, most of these are old, inactive forms,

Table 2.

Characteristics of the debris flows most pronounced in the relief within the study area. Symbols of debris flows are in accordance with Fig. 1 and Table 1; G – Gulliksenfjellet, BL – Bratteggdalen Lower, JE – Jens Erikfjellet, REV – Revdalen–Rotjesfjellet and Torbjörnsenfjellet, RE – Revdalen–Skoddefjellet, S – Steinvikdalen, GP – Gangpasset. Lithology according to a geological map by Czerny *et al*. 1993.

Debris flows	Lithology	Exposition	Debris flow furrow incision (m)	Debris flow furrow average width (m)	Levées height (m)	Debris size (within the debris flow zone) (m)
G1	quartzite	W	0.5–1.0	2	0.5–1.0	<0.5
G3	quartzite	W	<0.5	3	<2	0.5–1.0
G4	quartzite	W	<0.2	2	<0.3	<0.5
G5	quartzite	W	<0.5 (in upper part)	0.5	0.3–0.5	<1.5
G6	quartzite	W	0.5	2	0.6–0.7	<0.5 (sporadically max>1)
G7	quartzite	W	0.3–0.5	2–3	0.6–1.0	<0.5
BL2	quartzite	E	–	0.5	0.3–0.4	<1.0
BL4	quartzite, schist, amphibolite	E	0.5–1.5	2	0.5–1.0	0.5–1.5
JE3	greenstone, schist	SW	0.5 (in upper and middle part)	2.7	0.4–0.8	<0.2 (sporadically 0.5–2)
JE4	greenstone, schist	SW	<0.3	2	0.2–0.4	<0.5 (sporadically 0.5–1.0)
JE10	quartzite, schist	S	1.0	4	1.0	<0.5 (sporadically up to 1.0)
REV3	schist, gneiss	NE	0.1–0.15	1.5	0.15–0.2	<0.5
REV19	feldspar quartzite	E	0.4–0.9 (in upper part)	4	0.4–0.6	0.2–0.3 (sporadically up to 0.5)
RE1	gneiss, schist	SW	<1.2	5	0.5	0.2–0.3 (max. 0.5)

Table 2 - *continued.*

Debris flows	Lithology	Expo-sition	Debris flow furrow incision (m)	Debris flow furrow average width (m)	Levées height (m)	Debris size (within the debris flow zone) (m)
RE3	gneiss, schist	SW	<0.15 or lack	3	0.5–2.5	<0.1 (sporadically <0.5)
S	amphibolite	NW	0.2–0.3 (only in upper part)	0.5	0.6–0.7	0.5 (max.1.0)
GP7	feldspar quartzite	NW	<0.3 (in upper part) or lack	0.5	0.2–0.3	<0.5 (sporadically <1.0)
GP12	amphibolite, gabbro	NW	<0.1 or lack	<2–2.5 (in lower part)	0.4–0.7	<0.3 (sporadically 0.5–1.5)

often overgrown with vegetation or filled with finer material (Fig. 2). Their levées and depositional zones are poorly visible in the ground, as they have been either overgrown (on Revdalen-Skoddefjellet, Revdalen-Rotjesfjellet and Jens Erikfjellet), or eroded, which results in their irregular shapes, boulders accumulated within the furrows and accumulation of debris material within the adjacent slope surfaces, obscuring their former sharp boundaries.

Fig. 2. Old debris flow furrow and levées overgrown by vegetation on Jens Erikfjellet.

The inactive furrows-levées landforms could be recognised on 15 debris cones, whereas more recent assemblages of such landforms were noted within 13 debris cones. On several debris cones, both active and inactive landforms could be distinguished, while the others show either only active or exclusively inactive forms (Table 1). On some cones, a few generations of furrows-levées assemblages can be recognised. There are seven cones with several furrows and levées within inactive cones, three cones with active ones and five cones with active and inactive forms. Debris cones with only a single visible furrow with levées and depositional zone are present in only a few cones. These are two debris cones on SW slopes of Jens Erikfjellet, one on W slopes of Gulliksenfjellet and one in Steinvikdalen. Regarding the spatial distribution of debris cones with recent and fresh, *i.e.*, with no vegetation, furrow-levées landforms, there are three cones on W slopes of Gulliksenfjellet, one on E slopes of Gulliksenfjellet (in Bratteggdalen), three on Jens Erikfjellet, one in Steinvikdalen, two in Gangpasset and three in inner part of Revdalen-Torbjörnsenfjellet.

The incision of the furrows within the debris cone surface is rather small and ranges from 0.1 to at most 1.5 m (Table 2). In most cases, the incision occurs only in the upper part of furrows. In lower parts of the furrows, the incision usually does not exist, even though the levées benches are well preserved. Additionally, the imbrication of smaller debris, which forms a compact structure, as well as presence of rounded gravels have been observed within the lower parts of several furrows in contrast to their upper parts where similar features and structures were not observed. It is likely due to a different mode of deposition, taking place during torrential runoff within an old furrow.

Furrows and levées were detected in various types of rocks, *i.e.*, quartzites, metamorphic schists of diverse components, gneisses, greenstones and amphibolites. Moreover, debris cones both with and without these landform assemblages occur within the same lithology, often in adjacent position. Thus, the slope aspect seems to have an important impact on debris flow occurrence. The most pronounced landforms typical for debris flows were observed on slopes with a predominant western component (Table 2), which can be related to the westerly winds and precipitation. The role of topography in differentiating the distribution and morphology of debris flows is discussed in one of the next sections.

Features related to episodic runoff. — A very common feature for most of the debris cone surfaces are shallow channels, up to 1 m deep. In extreme cases, they may be of braided-type with multiple cross-cutting channels over large parts of cones surfaces, as on SW slopes of Skoddefjellet in Revdalen (three cones), E slopes of Gulliksenfjellet (Brattegdalen Lower, two cones), on Jens Erikfjellet (one cone) and on W slopes of Gulliksenfjellet (one cone); see Fig. 3. In many cases, there are no erosional landforms or incisions, but lines and stretches of fine rock material, which is often imbricated (compacted), can be distinguished instead. Patches of sand and fine rounded gravel occur within local depressions.

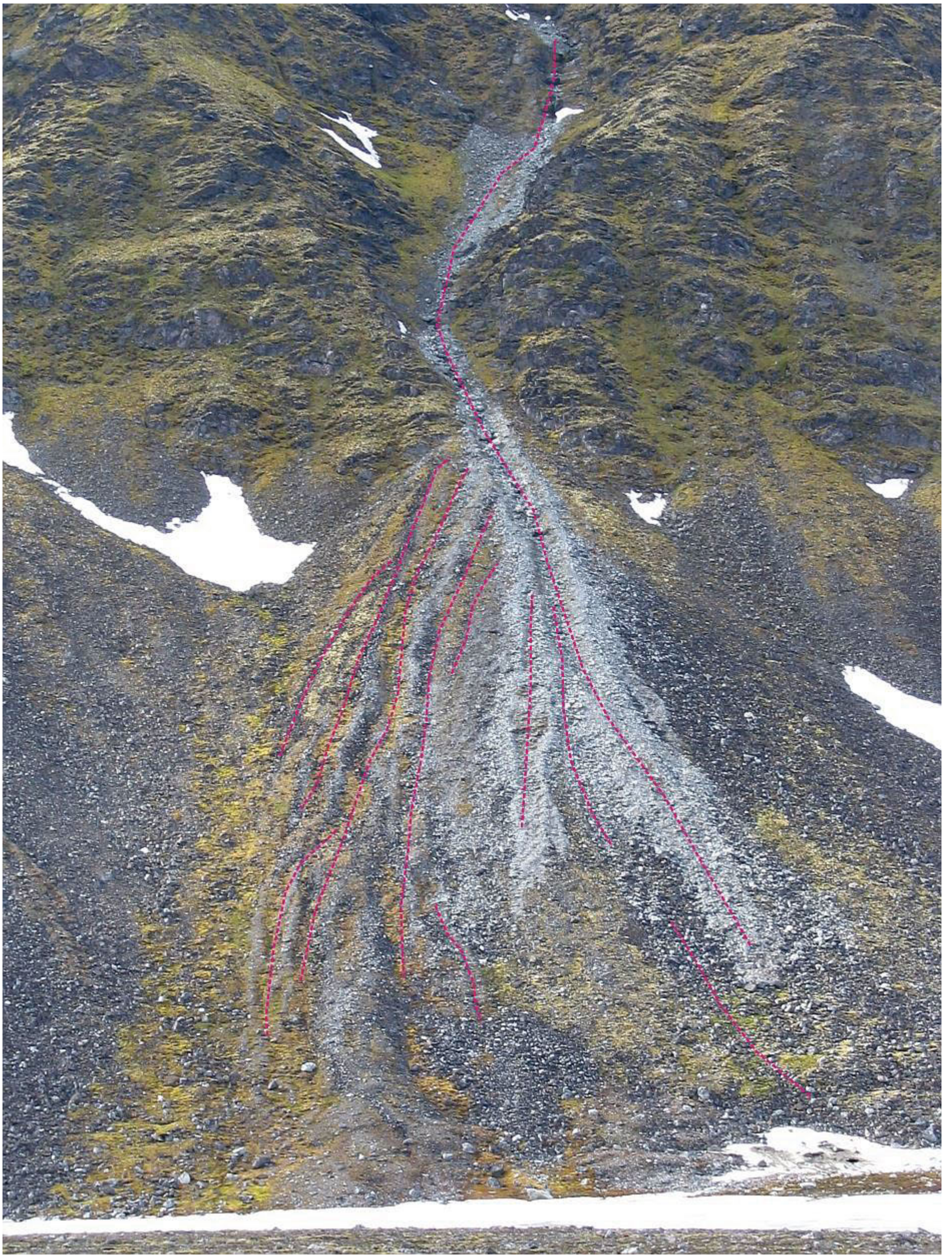

Fig. 3. Channels of episodic runoff indicated by dotted red lines; Bratteggdalen Lower.

These forms and sediments occur both within the furrows and directly on the debris cone surfaces. Such well preserved and distinct landforms and sediments were recognised on 23 debris cones, while on further eight cones they could be only vaguely noted. All these landforms and sediments can be connected with episodic torrential activity within the debris cones surfaces, especially with selective surface wash and accumulation. Such traces are usually much better developed and preserved in upper parts of the cones, while imbrication is preserved mainly in their lower parts.

The structure of debris cones. — The observations of the structure of debris cones refer to the surface layer of the slope deposits. With only a few exceptions, most cones have open-work structure, with vast spaces between the blocks. Even on cones with vegetation and initial soil cover, their inner parts are composed of loose large blocks with open space between, *e.g.*, on Jens Erikfjellet and Gulliksenfjellet. In contrary, in cone foothills, a substantial quantities of fine-grain material are found. The sandy-silty material accumulation zones are especially well developed at the foothills of Gulliksenfjellet (W and E slopes) and Skoddefjellet. There are also numerous springs at the base of many debris cones. These zones of water outflow have especially rich vegetation, *e.g.*, along the foothill of W slopes of Gulliksenfjellet in Skjerstranda.

The open-work structure of debris cones, along with the accumulation zones of fine-grain material at cone foothills indicate inter-debris water flow, which is a common and efficient process. Surface water flows occur often above the cones, in gullies with firm rocky bedrock. At the transitional zone between gully outlet and upper part of a cone, the change of surface material from firm bedrock to loose debris favours inter-debris flows and surface water occurs on cones only episodically after heavy rainfall or snowmelt. The open-work structure allows storing large quantities of water and thus retards its outflow from slopes. Additionally, the regime of water flow is influenced by the colmatation of pores with fine material in the lower part of the cones, which results from selective wash from upper slopes. The spring lines and wetter grounds developed as a result.

Microrelief. — Microrelief on debris cones, which may have form of step-like terraces and girlandes, stripes, benches, tongues or other concave-convex surfaces, has been recognised only on 15 debris cones. The occurrence of these landforms is concentrated mainly on W and E slopes of Gulliksenfjellet, SW slopes of Jens Erikfjellet and on SW slopes of Skoddefjellet with isolated presence also in Steinvikdalen. All these minor landform features result from solifluction processes. Their uneven distribution within the study area can be linked with the lithology of the bedrock, as in other areas of Spitsbergen (Pękala 1980; Jania 1982). The microrelief landforms have been detected on cones formed within bedrock composed of schists or with schists intercalations. The only addition are quartzitic slopes of Gulliksenfjellet with well-developed solifluctional structure within the debris cones. Moreover, most solifluction-shaped cones are exposed to the west (SW, W and NW) and thus they have sufficient meltwater supply from snow, which plays an important role in solifluction processes.

Vegetation cover. — The vegetation cover on debris cones, including lichens, mosses and shrubs, can be very diverse both in its form, density, occurrence pattern and range (Fig. 4). In general, most cones are covered with vegetation to

Fig. 4. Densely vegetated debris cones on Revdalen-Rotjesfjellet (upper image) and cones with no vegetation in Gangpasset (lower image).

a certain degree. The exceptions are debris cones in Brattegdalen Upper, where no vegetation has developed and in Gangpasset and Revdalen-Torbjörnsenfjellet, where vegetation is scarce, covering 0–50% of cones surface. Cones with vegetation covering >50% include cones completely covered by dense mosses and shrubs, where the organic layer is especially thick (up to 20 cm) and abundant, *e.g.*, several cones on Jens Erikfjellet, Gulliksenfjellet and in Revdalen-Rotjesfjellet. There are also cones with vegetation limited only to either upper or lower parts, or along the furrows, which is the case on Jens Erifjellet, Revdalen-Skodefjellet and Gulliksenfjellet. In some cases, also the gullies above the cones apex are densely vegetated, *e.g.*, on Jens Erikfjellet and in Revdalen-Rotjesfjellet. However, the most striking feature of vegetation cover within the entire study area is its very diverse occurrence pattern. A cone which is densely overgrown is often adjacent to a cone with very scarce vegetation pattern. Such situation is common for debris cones in Revdalen, Brattegdalen Lower and on Gulliksenfjellet. The vegetation density and distribution may vary even within a single cone. The same diversity refers to the vegetation cover on boulders scattered on the debris cones.

To some extent, vegetation is influenced by local climatic conditions, especially proximity of the sea and exposition to humid winds (Jania 1977). The rate of debris cones becoming overgrown by vegetation cover seems to be influenced by the bedrock lithology. Cones, which have developed within schists, covered by fine-grained weathering mantles, *i.e.*, on Jens Erikfjellet, in Revdalen-Skoddefjellet and Revdalen-Rotjesfjellet, have a dense and abundant vegetation cover. The only exception are again W slopes of Gulliksenfjellet, where cones developed in quartzites are densely overgrown. The reason for that may be bird colonies located on these slopes supplying high amount of organic matter, which enhances chemical decomposition of rocks and fertilises initial soil. Another key factor differentiating the vegetation cover might be the size-fraction of the surface material. Where large grain size dominates, the accumulation of the fine-grained material deep between the boulders may delay the formation of an ecological niche adequate for the vegetation to growth.

Dominant geomorphic processes in slope transformation. — The mezo- and microforms within the debris cones surfaces are very diverse within the study area. Thus, they are indirect indicators of varied morphological processes, which take place on certain slopes. In general, the main modelling agent is water activity, which can be in form of either surface flow, wash, erosion or debris flow. The dominance of water-related processes, especially runoff, over frost-related processes has been also noted in other regions in Spitsbergen (Mercier 2002), although the role of snow avalanches is also important in some parts of the Arctic (André 1990; De Hass *et al.* 2015). The increasing impact of water in shaping slope and cone surfaces has been highlighted by many authors especially in the context of the global climate change, including increase in rainfall in the Arctic and accelerated thawing of permafrost (Daanen *et al.* 2012; Repelewska-Pękalowa *et al.* 2013; Dolnicki and Grabiec 2022).

Traces of water flows were recognised on 38% of all the investigated cones, while 22% of the cones have landforms, which resulted from debris flows.

A single cone could be quantified in both groups, as both processes often occur on the same location. The presence and intensity of water-related processes is strongly influenced by climatic and morphological constraints (Åkerman 1984; Owczarek *et al.* 2013; Dolnicki and Grabiec 2022). Most of the debris cones, which are or have been recently modelled by water and debris flows, are located in outer parts of mountain ranges, on slopes bordering broad valleys and on slopes with western aspect (SW, W and NW). In opposite, slopes which are further away from the shore line, in inner parts of mountain ranges are rarely reshaped by water flows. In turn, they show the highest intensity of rockfalls, which result in covering entire slopes with fresh debris. It is due to climatic differences between these two areas. Areas in close vicinity of the shore, *i.e.*, W slopes of Gulliksenfjellet, SW slopes of Jens Erikfjellet, Steinvikdalen or Revdalen-Skoddefjellet, experience more intense precipitation and snowfall and thus greater water supply. In turn, the inner parts of the mountain ranges that are behind this orographic barrier are drier, which do not favour debris flows. Only 1/5 of debris cones with traces of debris flows are located there.

The meltwater from snow patches, which are accumulated in gullies and niches above the cones, is considered to be the main driving force of debris flow (Piasecki 1968; Pérez 1988; André *et al.* 2001). The size and characteristics of the alimentation zones are thus crucial for the local differentiation of the slope processes (Senderak *et al.* 2021). The dominating western wind favours accumulation of snow within the topographic depressions on the leeward slopes, while potential snow accumulation within the windward slopes is much limited due to deflation (Jahn 1967). Therefore, the availability of snowmelt water is very limited. As a result, debris flow occurrence on such slopes is rare in the study area.

The intense process of rockfall, which is vital for development of debris cones (Jahn 1967; Church *et al.* 1979) in the inner part of the island is associated with more extreme climatic variations (Pereyma 1988). Mountain ranges are also higher towards the inner parts of the region and thus temperature oscillations around 0ºC occur more often, favouring more intense mechanical weathering and constant supply of abundant debris. Therefore, the entire slopes are debris-covered and shaped mainly by gravitational processes. Also the vegetation cover is very scarce on these slopes due to high activity of slope processes and dryer climate in comparison to more seaward areas densely overgrown by tundra, *e.g.*, NE slopes of Rotjesfjellet, W slopes of Gulliksenfjellet or SW and S slopes of Jens Erikfjellet. Moreover, the lithological constraints are responsible for even more complicated spatial pattern of geomorphic processes and landforms. The slopes formed within the bedrock of the metamorphic schists do not support the rockfalls.

The impact of topographic features on slope dynamics. — Climatic factors are important but not exclusively responsible for development of water or debris flows within debris cones. The topographic constraints are of a great importance as well, which was suggested by Mercier (2002) for NW area of Spitsbergen and by Dzierżek *et al*. (2019) for Bellsund. The main role is played by the size and morphology of rock gullies located above the upper parts of debris cones and serving as their alimentation zones (Jania 1982; Senderak *et al.* 2019). They influence the intensity of water flows and thus its potential for transport and erosion (Fig. 5). Debris flows occur on debris cones with long,

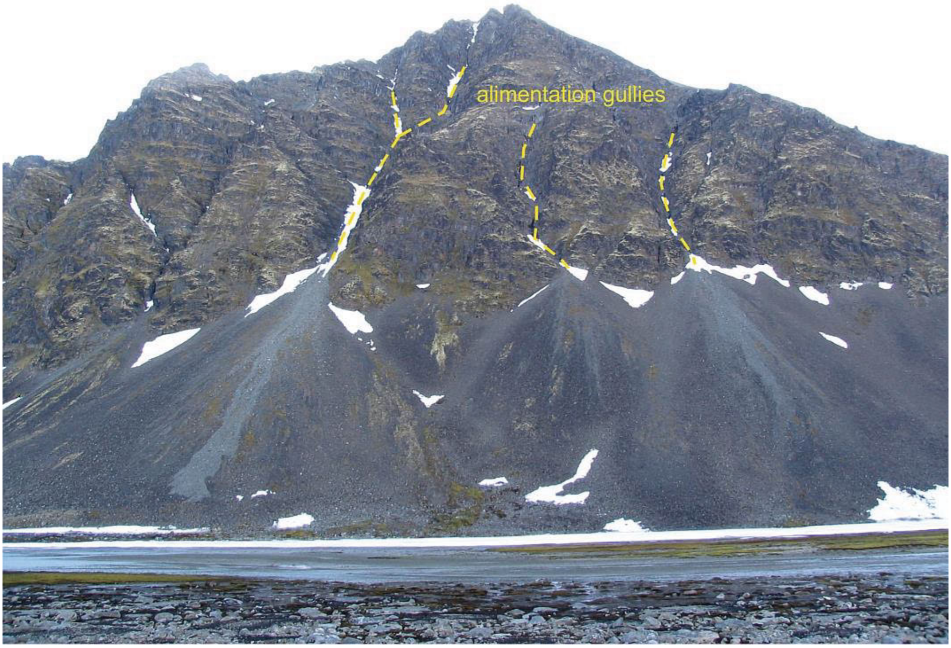

Fig. 5. The morphology and pattern of gullies and alimentation zone influence debris cones development; Revdalen-Torbjörnsenfjellet. More explanations in the text.

narrow, straight and deeply incised gullies. Such topographic features favour strong concentration of water flow, which enhance its transport and erosion potential. Also the landforms and sediments typical for surface wash can occur on such cones. In opposite, broad, shallow, short and curved rock gullies favour water flows over debris flows on cones below. Broad gullies of lower inclination enable debris accumulation, while narrower and steeper gullies are only transitional zones for debris material, which is accumulated either on upper parts of the cones in close vicinity of gully outlet, *e.g.*, in Revdalen-Skoddefjellet and Revdalen-Rotjesfjellet, or transferred towards cone's base, *e.g.*, in Bratteggdalen Upper and Gangpasset.

The intensity of the contemporary slope processes. — The contemporary processes of water and debris flow modelling surfaces of debris cones seem to be of low intensity. The erosional incisions in most cases do not exceed 0.5 m and in places they do not occur at all. The width of erosional furrows is usually limited as well, reaching ~ 2 m on average, with only a few wider ones, up to 3–5 m. Even if there were deeper incisions in the past, they have been filled with material during subsequent episodes of water or debris flows. The accumulation itself, however, is not intensive either. The levées are mostly up to 0.5 m high with only a few more pronounced forms, up to 1 m high. The rather low efficiency of recent water or debris flows in modelling cones surfaces is also indicated by the size of material transported within the flow zones. Rocky debris usually do not exceed 0.5 m in diameter with blocks >1 m in length occurring only locally. Most of the debris flow furrows or water flow channels do not reach the cones foothills, which is a further indicator of their weak efficiency in modelling the slopes. Only on three cones, the debris flow gullies reach the cone's base. Such situation may be explained by the open-work structure of most of the debris cones, which favours inter-debris flows rather than surface flows. This process is also responsible for selective distribution of material within the cones, which results in accumulation of fine-grain sediments in lower parts of the cones or at their base, which, in turn, further modifies hydrological conditions within the cones and at their foothills.

The erosional processes are most active in the upper parts of the debris cones, at the direct vicinity of rocky gully outlets. The erosional impulse is not widespread over the lower parts of the cones or its effects are obscured with further processes of accumulation within the furrows. The distribution and intensity of morphological processes within the debris cones may be additionally complicated and modified by lithology of their alimentation zone bedrock, which was noted for distribution of boulders, solifluctional landforms and development of vegetation cover.

The low intensity of the slope processes or locally even the lack of any changes in the slope morphology over the last 30 years was also observed in other parts of Svalbard (Dzierżek *et al.* 2019). However, in some areas, the acceleration of slope processes was observed in recent decades (Dolnicki and Grabiec 2022). These contradictory findings can be interpreted as evidence for a variety of modes for recent slope development, which highly depend on the local environmental constraints (Church *et al.* 1979).

The diversity of assemblages of landforms and its environmental interpretation. — It should be concluded that the contemporary development of debris cones in the Hornsund region is locally fairly diverse with different morphological processes dominating in various areas, even on neighbouring cones (Fig. 6). The occurrence of process-related mezo- and microrelief features on cones is strongly interlinked with climatic and topographic factors, including most of all morphology of gullies within the rocky alimentation zones and exposition of slopes. The role of local factors influencing the formation of debris slopes has been previously stressed by Jania (1977) for Skoddefjellet range and

Fig. 6. The diversity of adjacent debris cones; Gulliksenfjellet.

recently by Dzierżek *et al.* (2019) for the Bellsund area. These authors point to the presence of permafrost, snow patches, sufficient humidity and diversity in slope inclination as the crucial factors for debris slopes development.

The gravitational slope processes are of greater importance and intensity in inner parts of mountain ranges, while their outer parts, exposed to westerly winds, are modelled mainly by water and debris flows, with some importance of solifluction. The inter-debris flow is an important process active within most slopes, and, even though it cannot be related directly to any landforms, it influences hydrological and sedimentological regime of debris cones (Jania 1977, 1982). The landforms resulting from debris flows are quite common, often with several generations of flows preserved within a single cone. However, their efficiency to shape cone surfaces currently turned out to be minor. At present, depositional landforms are more widespread than erosional ones, which leads to filling and obscuring the landscape expression of former debris flow events. In some situations, former furrows may become convex, as a result of filling up during following torrential events, *e.g.* in Revdalen-Rotjesfjellet. It may affirm, that transport and deposition prevail in these zones while erosional force of debris flow is not efficient enough to dissect cone surfaces. Subsequent events of water flows and alluviation could contribute to filling up the formerly existed incisions (Kotarba *et al.* 1987). This explanation can be proved by the imbrication of smaller debris, as well as by gravels rounded by flowing water, which have been noted within the lower parts of several gullies that resulted from torrential runoff.

The amount of inactive debris flow features prevail over the recently developed landforms. Therefore, it may be concluded that debris flows were of greater importance in the past and that no proof for their intensification in present times has been detected based on their topography. Nevertheless, the landforms related to debris flows are still quite well preserved within many slopes but they should be interpreted as relict features. According to the concept of the magnitude-frequency of geomorphic processes (Wolman and Miller 1960), it can be concluded that the most pronounced landforms within the debris cones, related to debris flows, are not representative of the current slope dynamics. In contrary, the most common processes related to the torrential and inter-debris flows do not form any spectacular landforms. The extreme processes, such as debris flows, are relatively rare in the study area but their impact on slope morphology is more persistent than the impact of the secular processes of lower magnitude but higher frequency, such as water runoff or rockfall.

Nevertheless, the role of both types of processes in sediment mobilization and transfer is difficult to assess. On the one hand, the debris flows can potentially contribute to a large sediment flux as evidenced by the landforms formed during these extreme events. On the other hand, the current traces of mobilization and sedimentation of finer-grained material within the cone surfaces, including the furrows, might testify to equally efficient role of more common secular processes, such as runoff, in sediment transport and distribution. A detailed quantitative analysis would be necessary though to verify this assumption. It would be of a great importance especially in the context of the climate change, and the forecasted rise in precipitation and melting in the Arctic, which may increase the impact of water-related processes on slope dynamics.

However, correlation between intensity and frequency of processes modelling cone surfaces, especially water and debris flows, and global climatic changes, based exclusively on the geomorphic characteristics of the cones, is very difficult, as (*i*) debris flows occurrence depends not only on climatic factors, as presented above and by other authors (Åkerman 1984; André 1995), (*ii*) following events may occur within previously existed furrows and they will not have their landscape expression, (*iii*) older forms are reshaped or destroyed by subsequent processes, which is also true for other areas in Spitsbergen (Jania 1982; Mercier 2002). Thus, recognition of the precise number of past debris flow events based on geomorphic features is not possible. Although some interdisciplinary research links geomorphology of debris flows with dendrochronology, many uncertainties in dating different phases of slope processes remain (Owczarek *et al.* 2013).

Conclusions

The spatial diversity of landform features on debris cones in SW Spitsbergen is immense. It implicates that both the type and intensity of morphological processes shaping cones surfaces are highly variable within the entire region and that different processes may be of dominating importance even on adjacent cones. The local differences in bedrock lithology, topography and gully patterns, local climatic conditions and slope aspect seem to be crucial for differentiation of morphological processes shaping the debris cone surfaces and their landform expression. Moreover, the overlapping of the landforms related to both debris flows and water runoff makes it difficult to utilize them as unequivocal geoindicators for the current slope processes, especially that some of the landforms should be interpreted as the relict ones, not reflecting recently dominating processes. The most pronounced topographic features detected within the debris cones, and particularly the debris-flow signatures, appear to be related to processes of high-magnitude but low-frequency. No such significant events appear to have been recorded in the last decades. Nevertheless, the water-related landforms and features, *i.e.*, debris and torrential flows, should be interpreted as better geoindicators of the recent environmental change than the gravitation-related slope features, *e.g.* boulders related to rockfall.

To sum up, the topographic features of debris cones have only limited potential as geoindicators of environmental changes in polar regions. Their analysis should be refined by other methodologies, *i.e.*, dendrochronology, geophysics, laser scanning, unmanned aerial vehicles, *etc*. Moreover, the spatial diversity of the study area does not allow to draw general conclusions for the entire region. There are some parts of slopes with a high activity of morphological processes, *i.e.*, fresh debris flows and new boulders on the slope surface, however, there is no visible trend in development of debris cones. The potential expression of global change is obscured by the local factors, which highly influence the type and intensity of morphological processes within the debris cones. Nevertheless, the reaction of geomorphic system to climate change is often postponed (Starkel 1986) and the contemporary lack of evidence of any global changes does not indicate that they do not occur. At the moment, though, any unambiguous evaluation of the scale of global change cannot be assessed basing solely on the topographic properties of debris cones.

Acknowledgements. — The research was conducted during two Polar Expeditions founded by the University of Wrocław in 2005 and 2007. The authors are grateful to Piotr Migoń for fruitful discussions on the initial version of the manuscript, to Mateusz Strzelecki for his support at the final stage of the preparation of the paper, and to two anonymous referees and the editor for their very constructive comments that helped to improve this manuscript.

References

André M.F. 1990. Geomorphic impact of spring avalanches in Northwest Spitsbergen (79°N). *Permafrost and Periglacial Processes* 1: 97–110. doi: 10.1002/ppp.3430010203

André M.F. 1995. Holocene climate fluctuations and geomorphic impact of extreme events in Svalbard. *Geografiska Annaler. Series A, Physical Geography* 77: 241–250.

André M.F., Peulvast J.-P., Godard A. and Sellier D. 2001. Landscape development in Arctic and circum-Arctic shield environments. *In*: Godard J.-J. Lagasqvie A. and Legeat Y. (eds.) *Basement Regions.* Springer, Berlin, Heidelberg: 210–220.

Åkerman H.J. 1984. Notes on talus morphology and processes in Spitsbergen. *Geografiska Annaler* 66: 267–284. doi: 10.1080/04353676.1984.11880115

Åkerman H.J. 2005. Relations between slow slope processes and active-layer thickness 1972–2002, Kapp Linné, Svalbard. *Norwegian Journal of Geography* 59: 116–128.

Berger A. 1997. Assessing rapid environmental change using geoindicators. *Environmental Geology* 32: 36–44. doi: 10.1007/s002540050191

Birkenmajer K. 1990. *Geology of the Hornsund area, Spitsbergen. Explanations to the map 1:75 000*. University of Silesia, Katowice.

Blikra L.H. and Nemec W. 1998. Postglacial colluvium in western Norway: depositional processes, facies and palaeoclimatic record. *Sedimentology* 45: 909–959.

Church M., Stock R.F. and Ryder J.M. 1979. Contemporary sedimentary environments on Baffin Island, N.W.T., Canada. Debris slope accumulations. *Arctic and Alpine Research* 11: 371–401.

Curry A.M. and Morris C.J. 2004. Lateglacial and Holocene talus slope development and rockwall retreat on Mynydd Du, UK. *Geomorphology* 58: 85–106.

Czerny J., Kieres A., Manecki M. and Rajchel J. 1993. *Geological map of the SW part of Wedel Jarlsberg Land, Spitsbergen, 1:25 000*. Institute of Geology and Minerals Deposits, University of Mining and Metallurgy, Kraków.

Daanen R.P., Grosse G., Darrow M.M., Hamilton T.D. and Jones B.M. 2012. Rapid movement of frozen debris-lobes: implications for permafrost degradation and slope instability in the south-central Brooks Range, Alaska. *Natural Hazards and Earth System Sciences* 12: 1521–1537. doi: 10.5194/nhess-12-1521-2012

De Haas, T., Kleinhans M.G., Carbonneau P.E., Rubensdotterc, L. and Hauber E.G. 2015. Surface morphology of fans in the high-Arctic periglacial environment of Svalbard. Controls and processes. *Earth-science reviews* 146: 163–182. doi: 10.1016/j.earscirev.2015.04.004

Dolnicki P. and Grabiec M. 2022. The thickness of talus deposits in the periglacial area of SW Spitsbergen (Fugleberget mountainside) in the light of slope development theories. *Land* 11: 209. doi: 10.3390/land11020209

Dzierżek J., Szymanek M. and Nitychoruk J. 2019. Slope processes in the High Arctic: a 30-year-long record from Spitsbergen. *Boreas* 48: 856–866. doi: 10.1111/bor.12393.

Hinchliffe S., Ballantyne C.K. and Walden J. 1998. The structure and sedimentology of relict talus, Trotternish, Northern Skye, Scotland. *Earth Surface Processes and Landforms* 23: 545–560.

Jahn A. 1961. Quantitative analysis of periglacial processes in Spitsbergen. *Zeszyty Naukowe Uniwersytetu Wrocławskiego* B5: 1–54.

Jahn A. 1967. Some features of mass movement on Spitsbergen slopes. *Geografiska Annaler* 49A: 213–225.

Jania J. 1977. Debris forms on the Skoddefjellet slope. *Acta Universitatis Wratislaviensis* 387: 91–117.

Jania J. 1982. Slope forms and processes in the Gåsdalen region in photogrammetric investigations and repeated terrestrial photograms. *Acta Universitatis Wratislaviensis* 525: 93–114.

Karczewski A., Kostrzewski A. and Marks L. 1981. Raised marine terraces in the Hornsund area (northern part), Spitsbergen. *Polish Polar Research* 2: 39–50.

Kotarba A., Kaszowski L. and Krzemień K. 1987. High mountain denudational system of the Polish Tatra Mountains. *Geographical Studies, Special Issue* 3.

Lønne I. 2017. Terrestrial slopes in northern high latitudes: A paradigm shift regarding sediment origin, composition, and dynamic evolution. *Geomorphology* 276: 180–202. doi: 10.1016/j.geomorph.2016.10.004

Mercier D. 2002. La dynamique paraglaciaire des versant du Svalbard. *Zeitschrift für Geomorphologie* 46: 203–222.

Neuendorf K.K. E., Mehl Jr. J.P. and Jackson J.A. (eds.). 2005. *Glossary of Geology* (5th ed.), American Geological Institute, Alexandria, Virginia.

Owczarek P., Latocha A., Wistuba M. and Malik I. 2013. Reconstruction of modern debris flow activity in the arctic environment with the use of dwarf shrubs (south-western Spitsbergen) – a new dendrochronological approach. *Zeitschrift für Geomorphologie* 57, Suppl. 3: 75–95.

Pereyma J. 1988. Climatology. *In*: Brazdil R. (ed.) *Results of investigations of the geographical research expedition Spitsbergen 1985.* Folia Facultatis Scienatiarum Naturalium Universitatis Purkynianae Brunensis. Přírodovědecká Fakulta Univerzity J.E. Purkyně v Brně. Geografia 24: 55–71.

Pérez L.F. 1988. The movement of debris on a high Andean talus. *Zeitschrift für Geomorphologie* 32: 77–99.

Pérez L.F. 1989. Talus fabric and particle morphology on Lassen Peak, California. *Geografiska Annaler* 71A: 43–57.

Pękala K. 1980. Morphogenetic processes and cover deposits of nunataks in the Hornsund area (SW Spitsbergen). *Polish Polar Research* 1: 9–44.

Piasecki H. 1968. Talus cones in the Hornsund region. Vestspitsbergen. *Polish Spitsbergen Expedition 1957–1960.* Polish Academy of Sciences, III I.G.Y./I.G.C. Committee, Warszawa: 201–209.

Przybylak R. 2003. *The Climate of the Arctic*. Atmospheric and Oceanographic Sciences Library 26, Kluwer Academic Publishers, Dordrecht, Boston, London.

Rapp A. 1960. Recent development of mountains slopes in Karkevagge and surroundings, northern Scandinavia. *Geografiska Annaler* 42: 73–200.

Repelewska-Pękalowa J., Pekala K., Zagórski P. and Superson J. 2013. Permafrost and periglacial processes. *In:* Zagórski P., Harasimiuk M., Rodzik J. (eds.): *Geographical environment of NW part of Wedel Jarlsberg Land (Spitsbergen, Svalbard)*. UMCS, Lublin: 166–191.

Rivas V., Rix K., Frances E., Cendrero A. and Brunsden D. 1997. Geomorphological indicators for environmental impact assessment: consumable and non-consumable geomorphological resources. *Geomorphology* 18: 169–182. doi: 10.1016/S0169-555X(96)00024-4

Senderak K. 2023. Debris deposits of talus slopes as indicator of periglacial processes in Brattegg Valley, SW Spitsbergen. *Polish Polar Research* 44: 271–290. doi: 10.24425/ppr.2023.144543

Senderak K., Kondracka M. and 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: 1084–1097. doi: 10.1515/geo-2019-0084

Senderak K., Kondracka M. and Gądek B. 2021. Processes controlling the development of talus slopes in SW Spitsbergen: The role of deglaciation and periglacial conditions. *Land Degradation and Development* 31: 208–223. doi: 10.1002/ldr.3716

Siewert M.B., Krautblatter M., Christiansen H.V. and Eckerstorfer M. 2012. Arctic rockwall retreat rates estimated using laboratory calibrated ERT measurements of talus cones in Longyeardalen, Svalbard. *Earth Surface Processes and Landforms* 37: 1542–1555. doi: 10.1002/esp.3297

Starkel L. 1986. The role of extreme phenomena and secular processes in the evolution of relief (on the example of the flysch Carpathians). *Czasopismo Geograficzne* LVII: 203–213 (in Polish).

Strzelecki M.C., Szczuciński W., Dominiczak A., Zagórski P., Dudek J. and Knight J. 2020. New fjords, new coasts, new landscapes: The geomorphology of paraglacial coasts formed after recent glacier retreat in Brepollen (Hornsund, southern Svalbard). *Earth Surface Processes and Landforms* 45: 1325–1334. doi: 10.1002/esp.4819

Tomczyk A.M., Ewertowski M.W., Stawska M. and Rachlewicz G. 2019. Detailed alluvial fan geomorphology in a high-arctic periglacial environment, Svalbard: application of unmanned aerial vehicle (UAV) surveys. *Journal of Maps* 15: 460–473. doi: 10.1080/17445647.2019.1611498

Van Steijn H., de Ruig J. and Hoozemans F. 1988. Morphological and mechanical aspects of debris flows in parts of the French Alps. *Zeitschrift für Geomorphologie* 32: 143–161.

Van Steijn H., Boelhouwers J., Harris S.A. and Hétu B. 2002. Recent research on the nature, origin and climatic relations of blocky and stratified slope deposits. *Progress in Physical Geography* 26: 551–575. doi: 10.1191/0309133302pp352ra

Wawrzyniak T. and Osuch M. 2020. A 40-year High Arctic climatological dataset of the Polish Polar Station Hornsund (SW Spitsbergen, Svalbard). *Earth System Science Data Discussions* 12: 805–815. doi: 10.5194/essd-12-805-2020

Wolman M.G. and Miller J. P. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* 68: 54–74.

Received 9 June 2022
Accepted 3 February 2023