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Conceptual model for talus slope development in Brattegg Valley (SW Spitsbergen) based on sedimentology of debris deposits in periglacial zone

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Abstract: The talus slopes occur in all climatic zones on the Earth. These forms are sensitive to climate fluctuations, therefore they may be indicators of changes in the environment and contain the record of the geomorphological events after the deglaciation period. Both in the past and nowadays, slopes in area of the High Arctic have been developing in the specific conditions of periglacial zone. This is caused by simultaneously occurring different processes of weathering and deposition. The article presents the methodological approach and the results of the sedimentological measurements and geomorphological studies of the eight talus cones located in SW Spitsbergen. The study was conducted in the non-glaciated valley near the Stanislaw Baranowski Polar Station in Spitsbergen. The aim of the investigation was to determine the modern mechanisms of material transport on talus slopes and their impact on relief of slope surface in the polar environment. The obtained results and literature data allowed to indicate four separate zones of talus slope environment and develop a conceptual model for talus slope development in the Brattegg Valley, SW Spitsbergen.

Keywords: Arctic, Svalbard, slope processes, deglaciation, sedimentology.

Introduction

Talus slopes, otherwise referred to as talus cones, colluvial fans, debris cones or scree, develop commonly in different climatic zones (Rapp and Fairbridge 1968; Albjär *et al.* 1979; Luckman 2013). The greatest dynamics of morphogenetic processes is characteristic of the forms occurring in the periglacial environment, due to intense frost weathering, which constitute the second stage in the post-glacial history. In the first stage of slope system evolution, decompression and disintegration of the rock slopes without glacial support are dominant (Ballantyne 2002). The snow avalanche-dominated talus slopes in Spitsbergen are among the most common depositional environments (de Haas *et al.* 2015). These are also the places of high sensitivity to changes in climatic conditions, therefore they have been utilized in paleoclimatic research in the High Arctic and the areas of high mountains (Blikra and Nemec 1998; Sanders 2010; Owczarek *et al.* 2013; Latocha-Wites and Parzóch 2023). Most of the modern observed forms began to develop during the last deglaciation (Ballantyne 2002). Thus, the oldest internal structures of these forms are post-Last Glacial Maximum or may date back to the beginning of the Holocene (Farnsworth *et al.* 2020; Senderak *et al.* 2021; Dolnicki and Grabiec 2022).

The research on geomorphological evolution in the periglacial area of Spitsbergen, usually did not addressed talus slopes. Researchers confined greater attention to the dynamics of glaciers, material transport in the glacial system and the ocean-glacier interactions (Zwoliński *et al.* 2013). The research in non-glaciated areas was focused on permafrost, solifluction and the activity of patterned grounds (Czeppe 1960; Humlum *et al.* 2003; Kasprzak 2015). A series of the important papers on the morphodynamics of the talus slopes in the periglacial zone was initiated by Rapp (1960a, 1960b). The slope processes and depositional forms typical of the periglacial zone in Spitsbergen were described by Jahn (1960, 1967). A comparison of the talus slopes occurring in cool and warm climates was drawn by Albjär *et al.* (1979). Pękala (1980) presented the intra-annual variability of slope processes while explaining the mechanisms of the material transport. Åkerman (1984) pointed out to the differences in the functioning of the slopes of different exposures. Nitychoruk and Dzierżek (1988) distinguished three microclimatic zones of Spitsbergen's talus slopes defined by altitude and the range of the glaciers.

Until now, little attention has been paid to the role of the deposition in shaping the talus slopes. The differences in the character of the deposition may be observed on the entire surface of the slope. The delivery of the eroded material and the relief of slope surface usually depend from weathering and rockfall. Their morphology is reshaped mainly by snow avalanche and debris flows (Blikra and Nemec 1998; Gądek *et al.* 2009, 2016; de Haas *et al.* 2015; Tomczyk 2021), which topographic features may act as geoindicators of environmental changes (Latocha-Wites and Parzóch 2023). Dolnicki and Kroh (2022) made an attempt to describe the grain-size composition on talus slopes developing in the periglacial mountain zones in Spitsbergen and Central Asia, which conclusions agree with this study.

This paper presents a specific methodological approach to study the mechanisms of material transport on the talus slopes in SW Spitsbergen. The first step was to determine the main slope processes and associated morphology, *i.e.* channels after the debris flows. In the next step, the geomorphological observations were validated by the detailed sedimentological measurements. This study aims to document the grain-size signature of the geomorphologically effective processes in different slope zones and develop the generalized, zonal model of talus slope, highlighting typically dominant mass-wasting processes.

Study area

The study area is located in Wedel Jarlsberg Land, on the SW Spitsbergen, *ca.* 10 km to the NW of the Polish Polar Station in Hornsund. The study was conducted in the Brattegg Valley (Bratteggdalen) in the foreland of the retreating Brattegg Glacier (Bratteggbreen) (Fig. 1A).

In the valley, there are three proglacial lakes: upper, middle and lower. The last one is Myrkt Lake (Myrktjørna). They are located at the altitude of 235, 138 and 75 m a.s.l., respectively (Migoń 2004; Senderak and Wąsowski 2016). The eastern slopes of the valley are gentle, whereas the western ones are steep. On the western slopes, at the mouth of the deep gullies, the rock-walls of the Gullichsen Massif (Gullichsenfjellet), a system of eight talus cones has been developing (Fig. 1B). The slope surface is mainly modeled by the debris flows and snow or snow-debris avalanches (Senderak *et al.* 2019). The debris flows are regular, frequent and seasonal, leaving the gullies with a depth of 1–2 m, which were observed on all studied cones. The lengths of flows are different, but usually exceed half the length of the slope, especially in the case of the largest cones, *i.e.* S-2, S-4 and S-6. The overall relief is concave, and only in the lower parts the cones are convex, related to the rock-deposits accumulation of numerous avalanches (Rapp 1959).

The bedrock in the study area consists of Caledonian metamorphic rocks, which belong to the Hecla Hoek Succession. Three formations (Fms) have been allocated: the Bratteggdalen Fm, the Gullichsenfjellet Fm and the Skälfjellet Fm (Birkenmajer 1990; Czerny *et al.* 1993). The Bratteggdalen Fm is represented by a series of metavulcanites covered partly by an older metabasit of the Skälfjellet Fm. It includes amphibolites, metariolites and mica schists. Thick insertions of quartzites of the Gullichsenfjellet Fm are present in metavulcanites in the form of blocks and lenses of metagranitoids. The Gullichsenfjellet Fm is formed by a complex of quartzites, partially covered with metavulcanites of the Bratteggdalen and Skälfjellet Fms (Czerny *et al.* 1993).

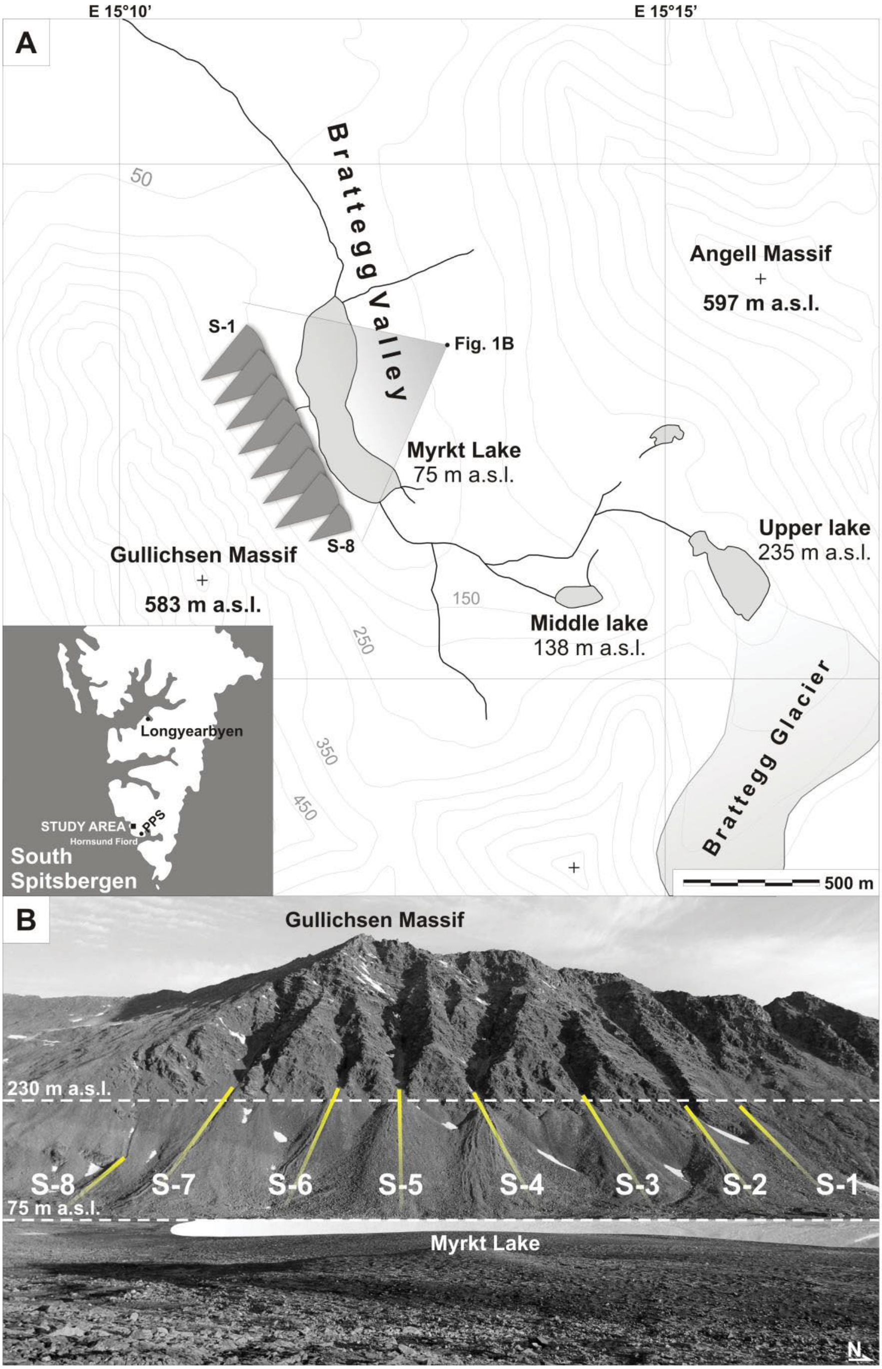


Fig. 1. The map of the Brattegg Valley with the marked system of eight cones (**A**) and image of the eastern slopes of the Gullichsen Massif (**B**) with marked yellow lines of profiles investigated for grain size. S-1 through S-8 mark different talus cones. PPS on the map of South Spitsbergen indicates location of the Polish Polar Station in Hornsund.

The mean annual air temperature for the period of 1979–2018 was −3.7°C. The coldest month was March (−10.2°C), while the warmest was July (+4.6°C). The annual average humidity for the study period was 79.7%. The average precipitation was 478 mm, with the highest precipitation during the summer (Wawrzyniak and Osuch 2020).

Methods

Morphometric measurements. — The length, width and surface area of the studied talus slopes from Table 1 have been determined based on a digital version of a contour orthophotomap 1:25000 of the region of the Werenskiold Glacier (Werenskioldbreen) (Kolondra 2002) with the ArcGIS software. The location of the study sites was determined using GPS receivers. Slope inclination was measured by inclinometer.

Table 1.

Morphometric characteristics of the talus cones in the Brattegg Valley. The length, width and surface area were calculated on a digital version of a contour orthophotomap, and the inclination was measured on the cones.

Talus cones	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
Length (m)	369	476	442	373	436	319	413	170
Width (m)	122	221	186	182	185	104	179	75
Surface (m^2)	22.544	52.663	41.180	33.919	40.429	16.679	36.901	6.400
Avg. incl. (°)	25	23	27	28	32	31	26	26
Max. incl.(°)	36	34	40	34	36	39	37	34
Min. incl. (°)	5	1	1	8	26	26	2	5

Analysis of the debris for talus slopes. — For granulometric measurements of the material of coarse fraction (>2 mm), a 1x1 m measurement window with the sections located every 20 cm was used (Fig. 2). The measurements were performed at 99 locations distributed along profiles in the axes of the eight talus cones (Fig. 1B). A three-digit numbering of the stations was adopted. The first digit is the number of the cone, whereas the other two indicate the number of the measuring site, *e.g.* site 5 on the S-2 cone has been attributed number 205. At every point, a photographic documentation of the measurement window directed downwards the slope was completed. In addition, the information on the lithology and microrelief of the slope surface, outflows of water, vegetation and presence of snow patches was recorded. The photographs of the measurement windows were digitally analyzed with ImageJ programme. After having scaled the photographs, the largest diameters of all the photographed rock fragments

Fig. 2. Measurement window in Site 211 showing only 20 clasts (**A**) and Site 806 with 999 measurements (**B**).

were semi-automatically measured. Rock fragments >1 m were not measured. The total of 27 139 measurements were carried out. The average number of the measurements within the cone was 3392 and 274 within a single site. The division of fractions (Table 2) was employed after Blair and McPherson (1999) as well as Blott and Pye (2001).

Table 2.

Size scale adopted in granulometric analysis, modified after Blair and McPherson (1999) and Blott and Pye (2001).

Grain size		Main fraction	Sub-fraction
(phi)	(mm)		
< −10	>1024	boulders	very large
−9 to −10	512–1024		large
−8 to −9	256–512		medium
−7 to −8	128–256		small
−6 to −7	64–128		very small
−5 to −6	32–64	debris	very coarse
−4 to −5	16–32		coarse
−3 to −4	8–16		medium
−2 to −3	4–8		fine
−1 to −2	2 – 4		very fine
4 to −1	0.063–2	sand	
8 to 4	0.004–0.063	silt	
9 to 8	0.002–0.004	clay	

Analysis of the fine sediments for talus slopes, patterned grounds and solifluction lobes. — Twenty samples of fine sediments, deposited near the shoreline of the Myrkt Lake, were collected. Three samples were excluded from the research because of a high content of organic material and the <0.063 mm fraction, which is usually not dominant for described depositional environment of talus slopes. The remaining seventeen samples (G-1 to G-17) were subject to the granulometric analysis. Ten samples came from the depositional environment of the talus slopes, the other seven were obtained on the other side of the lake, in the area of patterned grounds and solifluction lobes (Fig. 3), and constituted

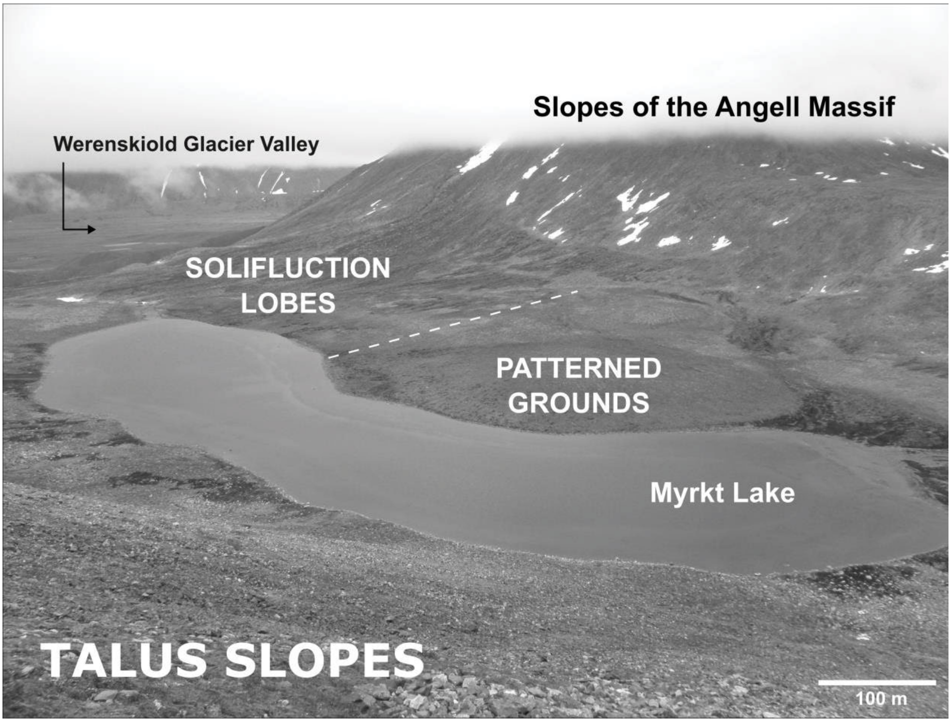


Fig. 3. The Myrkt Lake in the Brattegg Valley with geomorphological features, where the ground samples were collected. Solifluction lobes (samples G-1 to G-4), talus slopes (G-5 to G-14) and patterned grounds (G-15 to G-17) are marked.

a reference material. In total, >9.15 kg of the sediment was analyzed, in average >0.5 kg per sample. In order to separate the silt and clay fraction, the mineral detritus was rinsed on the 0.063 mm sieve. In the process, 1/2 to 1/3 of the sample volume remained to further analysis. After drying for 24 hours at the temperature of 105°C, the sediment was re-weighed for determining the content of the <0.063 mm fraction. The further granulometric analysis were performed with an application of standard sieves with the compartments of one phi to specify the content of the sand (0.063–2 mm) and debris fraction (2–32 mm). The central value of the intervals (median) and the arithmetic mean were calculated for all measurements taken within each cone.

Sedimentological parameters calculation. — The results of the both granulometric analysis in debris and fine sediments were used to determine mean

(M_Z) or average diameter for grain size, standard deviation (σ_I) meaning degree of sorting, skewness (Sk_I) describing the distribution asymmetry, and kurtosis of the distribution (K_G), which indicates the number of results close to the average and the amount of extreme results. The formulas by Folk and Ward (1957), which were employed for the calculations, allow determination of the sediment provenance, transport history and contemporary transport of material, as well as depositional conditions (Blott and Pye 2001).

Results and interpretation

Talus slope morphology. — The Gullichsen Massif, on which eastern slopes, the system of cones is developing, is predominantly built of quartzite. The talus cones are quite steep, especially in their upper parts. The average slope inclination is 23–32° and usually depends on the fraction of deposits, whereas the length ranges from 170 m to 460 m (Table 1). Several of the cones, often those further away from the shoreline of the lake, are subject to dichotomy and transition into an accumulative form of fans, *i.e.* formed by alluvial processes, of an inclination of 2° to 10°. The transition is constituted by a clear change from a steep to flat slope, and the presence of numerous solifluction lobes. Right now the solifluction or gelifluction processes are the main processes transforming this part of cones. The cones are characterized by the location of the apexes at an average altitude of 230 m a.s.l. The distal part of the cones in almost all cases reaches the lake at elevation 75 m a.s.l.

The system of eight talus cones is heterogeneous, with the S-2 and S-5 cones standing out. Cone S-2 has the longest measured axis, width, and slope surface. It shows a dichotomy demonstrated in a division into a gravitational slope and fluvial-flow-dominated slope (Senderak *et al.* 2019). The S-5 cone is similar in morphometry and it is characterized by the greatest inclination in the entire system. Moreover, it is the only cone, which entire distal part forms the shoreline of the lower lake. At the same time, the slope is not dichotomous.

Surface structure of talus slopes (debris and boulders). — The measuring sites on the talus slope profiles are characterized by the median in the range of 32–66 mm and exhibit similar values within the range of the whole system (Table 3). This corresponds with the range of fraction from very coarse debris to very small boulders. The highest values of median are characteristic for the S-6 cone (Table 3) and reflected in a high degree of the activity of the morphogenetic processes on the selected slope, which results in an increased content of large fractions (Bertran *et al.* 1997). The largest diameters of debris and boulders of rock in the investigated system range from 0.5 to >1 m. In many places, however, the occurrence of very large rocky blocks, often of a size of 2–3 m, and sometimes even 6 meters, was observed. The largest blocks were most frequently found at the sites of the formation of colluvium belts forming in the distal zones of the slopes,

Table 3.

Granulometric characteristics of the material of coarse fractions on the surface of the eight talus cones (in mm).

Talus cones	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
Median	40	47	37	42	53	66	43	32
Average	60	75	64	63	76	90	62	54
Max.	544	1.093	1.055	776	759	910	812	830
Min.	5	6	5	6	9	12	7	3

which indicates gravitational transport (rockfalls and sorting). The smallest measured fragments do not exceed 1 cm. Within the extent of the entire slope, even in the proximal parts, the presence of very fine debris (2–4 mm) up to coarse sand (>2 mm), which is transported in the debris and fluvial flows, was observed.

On graphs showing the relationship between the mean grain size and the other parameters (Fig. 4), the most significant relationship is observed between the mean grain size and the standard deviation (the degree of sorting) for $f(x)=\sigma_I(M_z)$. The diagram points out to the diverse dynamics of the environment and a high variability of the forces transporting the material. A linear increase of the mean grain size with a simultaneous decrease in the degree of sorting illustrates this type of situation (Fig. 4A). This is a natural relationship in the environment of the talus cone. The values of the mean grain size determine the dominant fraction, from very coarse debris to small boulders of rock (phi range from −5 to −8 or 32–256 mm). The parameter of the degree of sorting indicates the extremely poor sorting of the material.

The other two correlations are determined by the relationships between the mean and the skewness $f(x)=Sk_I(M_Z)$ as well as the mean and kurtosis $f(x)=K_G(M_Z)$. The first relationship shows that the size of the material does not affect the skewness of the distribution, which incites its asymmetry. The measurements from all of the sites are strongly positively skewed and within the range of +0.3 to +1.0. Such is the case when a fine fraction has a greater share in the material than a fraction of the maximum grain size (Blott and Pye 2001). This parameter also points to the dominant fractions in the deposit. In the studied system, the volume of the debris-fraction material is far greater than the volume of the boulder-fraction.

In the case of the relationship between the mean grain size and the kurtosis, the situation is different. The graph shows the trend of the kurtosis decreasing along with an increase of the mean (Fig. 4B). The majority of the points are characterized by a mezokurtical and leptokurtical distribution of the values of 0.9–1.5, which indicates that most of the results is close to the mean, whereas the extreme results are relatively scarce, indicating similarity between different sites. This observation, however, does not rule out a low degree of sorting, as the coarser fraction, the more heterogeneous the material is (Mycielska-Dowgiałło 1995).

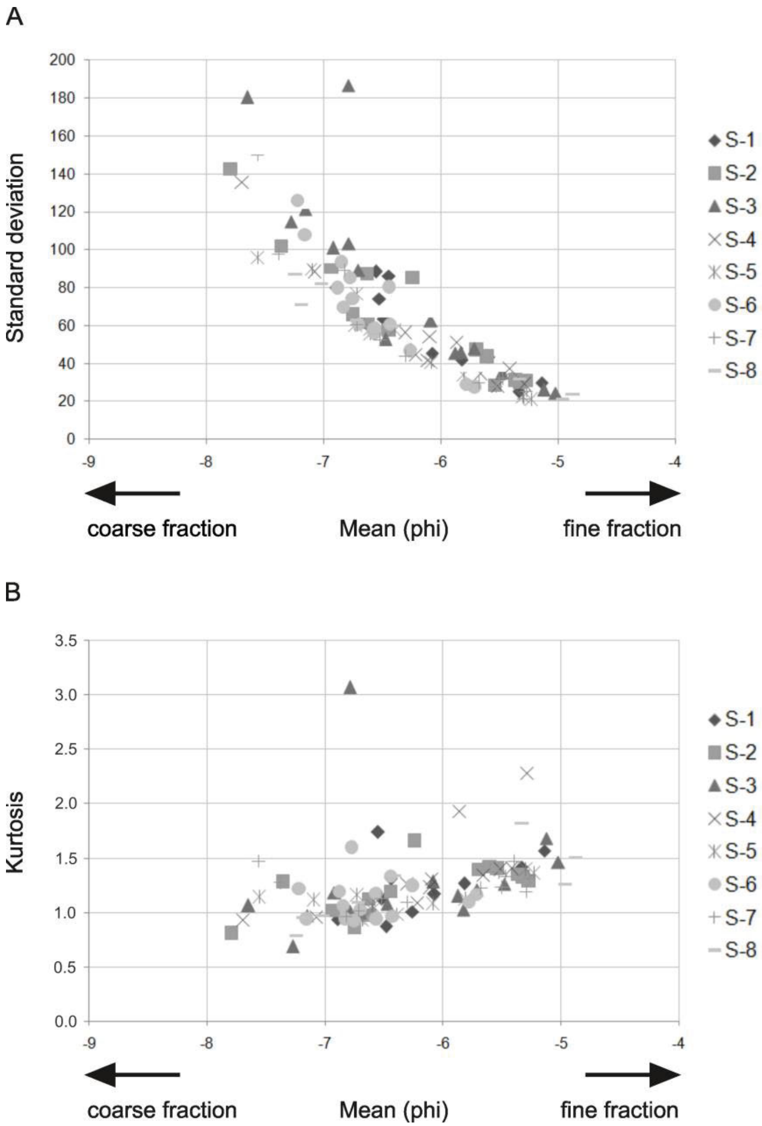


Fig. 4. The relationships between mean grain size and: **A** – standard deviation (the degree of sorting) and **B** – kurtosis (dimensionless). S-1 trough S-8 mark data from different talus cones.

The basic model of the talus slope structure assumes natural gradation of the material, *i.e.*, coarsening down the slope (Blikra and Nemec 1998; Bertran and Texier 1999). The research in the Brattegg Valley demonstrates that the talus slopes developing in the polar environment are characterized by variable fraction of the surface material along the axis of the cone (Bertran *et al.* 1997). The presence of coarse fractions in the proximal and distal parts of the slopes could confirm an extremely high morphodynamics of this environment. It should be noted that flat and large fragments of rock may be found on the upper parts of the slope, against the natural gradation, while more rounded fragments will be seen more frequently at the base of the slope, because their transport on the slope surface is much easier. The shape of the quartzite fragments observed on the slopes of the Brattegg Valley is regular and sharp-edged, but more similar to a rounded than a flat rock fragments, as in the case of quartzite shales. It is hard to provide a comprehensive interpretation of the data obtained by the method of the measurement window. The varied slope surface reflects the coexistence of different geomorphic processes such as mass movements (*e.g.* rockfall), debris flows and snow avalanches. The conducted study shows that debris and boulders dominate on the slopes, but simultaneously it does not exclude the presence of the finer fractions on the entire slope surface.

Fine sediments of talus slopes in the background of patterned grounds and solifluction lobes. — The material collected on the talus slopes may be distinguished from sediment from around the lower lake, including patterned grounds and solifluction lobes (Fig. 3), based on the higher values of the mean and a smaller degree of sorting (Table 4). For comparison, the talus cones are characterized by the sorting of 30–40, whereas in the other environments this parameter is in the range of 20–30. The high activity of the morphogenetic processes on the slopes result in texturally immature fine sediments.

The graphs of the grain size distribution (Fig. 5) were drawn for 6 samples from G-5 to G-8, G-12 and G-14, collected on the distal parts of the slopes. The

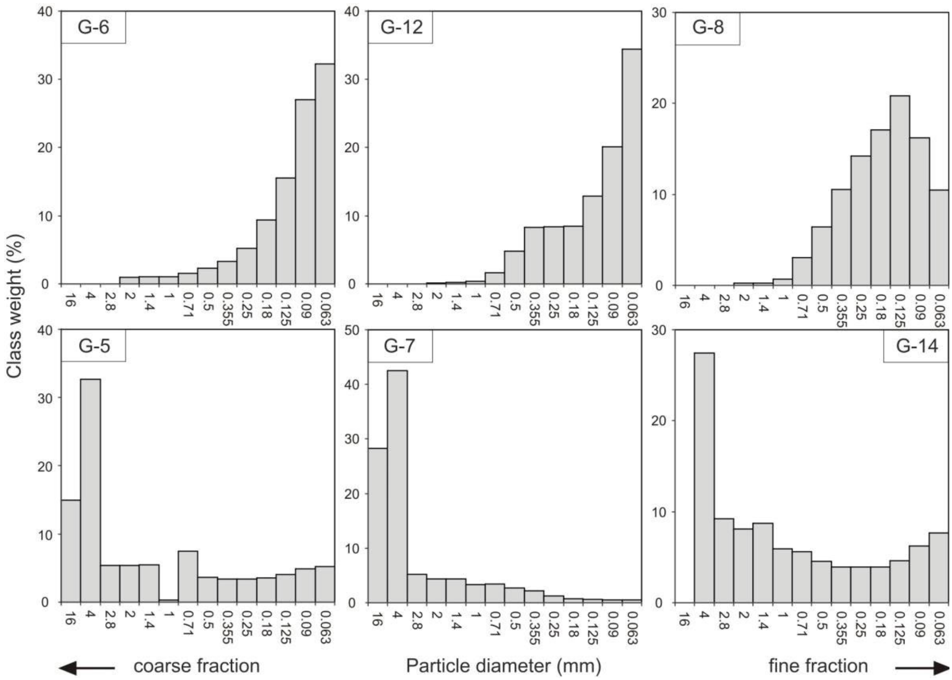


Fig. 5. Histograms for sand (0.063–2 mm) and debris (>2 mm) for different samples of fine sediments.

Table 4.

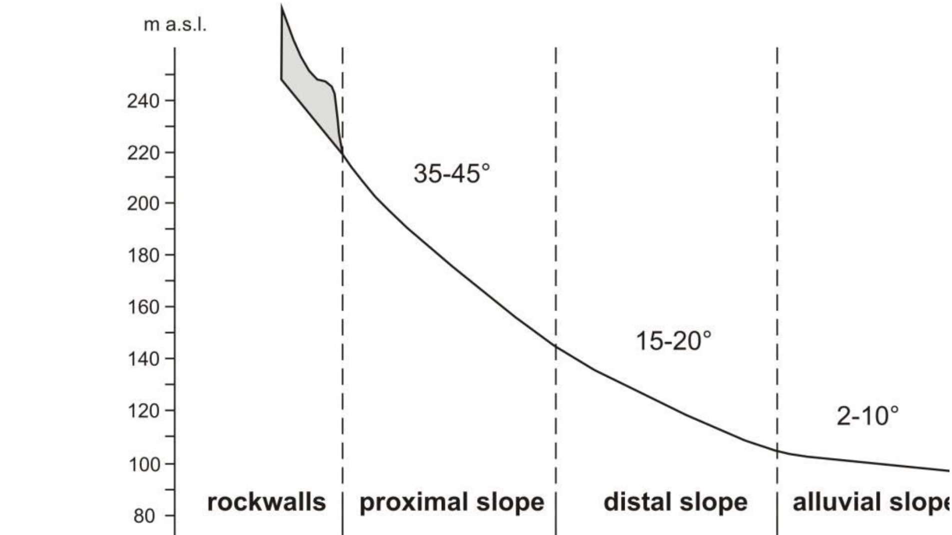
The granulometric characteristics of the material of finer fractions. M_Z – mean grain size, σ_I – standard deviation, Sk_I – skewnees, K_G – kurtosis of the samples of fine sediments.

Sample	Latitude (°N)	Longitude (°E)	Altitude (m a.s.l.)	M_Z	σ_I	Sk_I	K_G	Location, refer also to Fig. 3	Sedimentary environment
G-1	77.062319	15.200656	77	−4.7	23.7	0.6	1.2	N shore of the lake, the left side of the entry	Solifluction lobes
G-2	77.061953	15.198610	82	−3.3	23.5	0.8	8.8		
G-3	77.061666	15.198125	81	−2.9	25.9	0.8	6.4		
G-4	77.061666	15.198125	81	−3.7	23.0	0.7	8.3		
G-5	77.061200	15.198078	83	−4.5	30.5	0.8	6.9	Cone S-1/S-2	Talus cones
G-6	77.060887	15.197914	81	−4.0	27.0	0.9	2.2	Cone S-1/S-2	
G-7	77.060645	15.197550	83	−4.3	41.2	0.4	3.9	Cone S-1/S-2	
G-8	77.059596	15.197974	76	−5.5	42.7	0.3	0.6	Cone S-2/S-3	
G-9	77.058412	15.199997	82	−3.7	27.4	1.0	3.4	Cone S-3	
G-10	77.057641	15.200545	83	−4.2	29.6	0.9	1.6	Cone S-4	
G-11	77.057309	15.201500	90	−4.5	32.9	0.8	1.4	Cone S-4/S-5	
G-12	77.056977	15.202054	84	−4.3	36.7	0.7	2.6	Cone S-5	
G-13	77.056276	15.204443	83	−4.2	32.7	1.0	3.4	Cone S-6	
G-14	77.055843	15.207436	84	−3.9	21.0	0.6	4.8	Cone S-6/S-7	
G-15	77.056485	15.212045	84	−3.8	33.4	0.8	3.3	SE shore of the lake, the right side of the entry	Patterned grounds
G-16	77.056888	15.211852	83	−5.0	47.3	0.9	9.5	E shore of the lake	
G-17	77.061095	15.206358	81	−3.4	27.2	0.9	2.4	NE shore of the lake, right side of the entry	

majority of the histograms demonstrate typical features of a normal distribution. In the graphs G-6 and G-12, merely the left side of the normal distribution is clearly visible. Laboratory testing of the samples revealed that they contain >50% of the <0.063 mm fraction. This was confirmed by the presence of normal grain size distribution in these samples. The histogram of the sample G-8 shows such a distribution as well, however, it is shifted towards large fractions. The other 3 samples, *i.e.*, G-5, G-7 and G-14, show the highest incidence of a fine debris fraction (4–8 mm), due to a direct impact of the talus cone on shaping the area of the interaction between the lake and the slope. The presence of debris in the sediment of sand fraction (0.063–2 mm) is common. The second important element of the histograms is a fluctuation of grain-size distribution for all ranges of sand fraction, reflecting activity of several parallel processes of sedimentation (Bertran and Texier 1999). It seems that they were dominated by gravitational mass movements and alluvial processes, including washing away and rinsing. A large amount of the material of the <0.063 mm fraction in the sediment is probably due to sand and dust storms, which are typical for the periglacial zone (Bryant 1982; Senderak and Wąsowski 2016).

Mechanisms of transport. — One of the main factors responsible for the developing of talus slopes is a mode of sediment transport (Blikra and Nemec 1998). Fragments of rock from cliff above slope has been relocated in different time periods within all parts of the slope (Dolnicki and Kroh 2022). The slopes are shaped by different dominant mechanisms in four distinct morphogenetic zones: (*i*) rockwalls, (*ii*) proximal slope, (*iii*) distal slope and (*iv*) alluvial slope (Fig. 6). Granulometric analysis may determine simultaneously the type of material, which resulted from increased activity of the specific geomorphic processes. Intensity of the transport processes depends on external conditions and their changes during the year (Pękala 1980; Blair and McPherson 2009). Relocation of some boulder from the cliff to the base of the slope may be very quickly, *e.g.* during the snow avalanche, or they may remain still for tens-hundreds of years on mature inactive slopes (Luckman 2013). The most important geomorphic processes causing transport of the slope material are: (*i*) rockfall, (*ii*) snow avalanches, (*iii*) debris flows and (*iv*) solifluction. Each of these processes can be active in every zone, but importance of particular process varies from one zone to the other (Selby 1993). The proposed model of the slope system, shown on Fig. 6, is strongly generalized and may be considered as typical of SW Spitsbergen. The sketch was based on the present investigations in the Brattegg Valley and two earlier studies of slopes in this region (Åkerman 1984; Nitychoruk and Dzierżek 1988).

Morphodynamics of talus slopes. — The morphogenetic processes within slope system in the Brattegg Valley and their intensity are typical for Holocene periglacial environment in Spitsbergen (André 1995, 2003). The slopes are mainly shaped by rockfall from weathered and steep-up cliffs. Then, a rock material is relocated in the snow avalanches, which is typical for Spitsbergen



zone	1st	2nd	3rd	4th
processes	rockfall	avalanches debris flows	avalanches debris flows solifluction	solifluction fluvial flows avalanches
material	massive rock	boulders debris	debris boulders	debris sand

Fig. 6. Conceptual model of the slope system in the Brattegg Valley.

(de Haas *et al.* 2015). Debris flows are commonly and relatively frequent (Tomczyk 2021). Other processes, like creeping, solifluction or slope wash, are of secondary importance. In the Brattegg Valley, the oldest shrubs of *Salix polaris* in different areas affected by the debris flows were dated to the years of 1973, 1982 and 1991 (Owczarek 2010). A small number of young shrubs gives evidence of frequent supply of fresh rock material in the period of last several decades (Owczarek *et al.* 2013).

The snow or snow-rock avalanches occur quite frequently, resulting in colluvium belts, which emerge in front of the talus slopes (Nitychoruk and Dzierżek 1988; Eckerstorfer and Christiansen 2011). These types of accumulative forms occur in front of all of the observed cones, and are oriented perpendicularly towards the slope. They have slightly curved shapes similar to the fan shape of the cone, and in the scale of the cones, colluvium belts are usually difficult to note. In several locations, the overlapping of the outermost parts of two belts occurs within the fourth zone of slope presented on Fig. 6. Morphologically, they form a bulge of a size of several meters. Between slope and belt, a small niche of a depth reaching up to 1–2 m develops, which confirms the observations by Jahn (1967).

It should be noted that the debris flows and runoff could be dominant in the development of slope surface on Spitsbergen (de Haas *et al.* 2015; Bernhardt *et al.* 2017; Tomczyk 2021). The recent climate change in the High Arctic results in increasing amount of water in environment. Water coming from the fast melting of spring snow and frequent precipitation is the triggering factor of intense mass-wasting processes (de Haas *et al.* 2018; Latocha-Wites and Parzóch 2023). Dolnicki and Kroh (2022) observed that the largest rock fragments are deposited in the upper part of slopes and their size decreases down the slope, therefore the lower part is dominated by sandy and smaller fractions. The gravitational movement of weathered waste, together with the melting processes of permafrost with a large share of runoff from water precipitation and snow-cover melting, shapes the distal and alluvial parts of the slopes (Dolnicki and Kroh 2022).

Solifluction surfaces develop on the distal part of the talus slopes in the Brattegg Valley during periods of intensified precipitation or spring thaw (Ballantyne 2002). The relatively small size of solifluction lobes in the material of debris and boulder fraction causes slow dislocations. In the scale of the slopes, this mechanism provides a backdrop for other processes. However, solifluction affects merely the surface layer of the sediment, up to the maximum depth of 60–80 cm (Dobiński 2011; Senderak *et al.* 2017). In the periglacial environment, the solifluction depth depends on the position of the permafrost table and seasonal frost (Åkerman 1984; Harris *et al.* 2011). The observations in the Brattegg Valley showed that the thickness of the sediment transported by solifluction does not exceed 30 cm.

The shape and size of the talus slopes in the Brattegg Valley are typical of SW Spitsbergen (Åkerman 1984; de Haas *et al.* 2015). The cones have a relatively even surface and a convex-concave shape (Nitychoruk and Dzierżek 1988). The convex shape is associated with the supply of rock material resulting from rockfall. The material falling off from the rockwalls is accumulated primarily in the proximal part of the cones (Fig. 6). The concave shape is generally characteristic of the central part of the cones. In the summer season, their surface is dissected by debris flows, while during winter, the slope is covered by a thick layer of snow (Eckerstorfer and Christiansen 2011). Snow avalanches transport rock material of debris and boulder fraction down the slope to the distal part (Fig. 6), where debris deposits are being built-up (Luckman 1977; Karczewski *et al.* 1981; Sanders *et al.* 2014). Deviations from the presented model of the changes in the cone slopes surface may be related to lithology, tectonics and weather conditions, including air temperature, precipitation and the insolation of rockwalls (Albjär *et al.* 1979; André 1997; McColl 2012).

The conceptual model of studied slope system in the Brattegg Valley is a graphical summary of observations and measurements. It distinguishes four zones represented by different geomorphic processes and heterogenous material of the talus slopes (Fig. 6). Rockwalls (first zone) with massive rock are sediment supply area for talus slope environment. Deposition of rock fragments occurs in the proximal and/or distal part of talus slopes (second and third zone). The talus slope is terminated by alluvial part (fourth zone) with characteristic high volume of fine sediments from washing away and rinsing. It should be noted that this generalized model does not fully represent all studied slopes. One of the problems is the influence of snow avalanches and debris flows on talus slope development. It is clear that these processes occur in proximal and distal parts of slopes in different scale (Fig. 6). This study suggest that these slope processes require a greater distance to transport coarse sediments, in this case probably corresponding more to third zone of the model. However, second zone with coarse material is simply the result of large magnitude rockfalls, thus with greater energy and runout distance. The proximal part is convex, which indicates that it is rather the departure zone of avalanches and debris flows, but this does not exclude the origin of coarse fragments from rockfalls within the apex zone (Fig. 6).

Conclusions

The talus slopes in the Brattegg Valley belong to the most common types of slopes in Spitsbergen, which are shaped by snow avalanches, partly rockfalls and debris flows. Morphometry of these forms is very similar around Spitsbergen. The decisive factor for the size of the slope are geological factors, such as bedrock lithology and tectonics, as well as the size of sediment supply area. In the study area, exposure and altitude has secondary importance. Distance of slopes from the sea coast, however, affects the amount of rainfall and large accumulation of snow within the Gullichsen Massif.

The morphodynamics of the talus slopes of SW Spitsbergen is formed by the mechanical weathering of rockwalls. Due to the spatial variability of these processes, four zones may be distinguished within the slope systems. They are reflected in the morphology and the structure of the slopes, which was suggested by geomorphological observations and subsequent sedimentological measurements. The analysis of debris material for talus slopes as well as the fine sediments for slopes and others environments in the High Arctic valley allowed to divide the slope systems into four zones with characteristic slope processes and material. The conceptual model assumes presence of (*i*) rockwalls, (*ii*) proximal slope, (*iii*) distal slope and (*iv*) alluvial slope (Fig. 6). It should be noted that the borders between proximal and distal parts of slope are not sharp, while rockwalls and alluvial slopes are easy to delimitate.

A part of the talus slopes in the Brattegg Valley are characterized by dichotomy and transition from steep talus slope with dominant mass movement processes into gentle accumulative form of the alluvial fans with the increased role of processes involving water. The surface of studied slopes is built of the large fractions with median in the range of 32–66 mm. The entire system of the talus cones includes rock material varying from very coarse debris to very small boulders (32–256 mm). In this environment, the volume of the debris-fraction material is far greater than the volume of boulders. The measurements of coarse fractions reveal the presence of heterogeneous material. On the other hand, a parameter of the degree of sorting indicates the extremely poor sorting of these sediments, which is typical of mass movement such as snow avalanches and debris flows. The research in the Brattegg Valley confirms that the talus slopes developing in the polar environment are characterized by variable fraction of the material on the surface along the axis of the landform. Natural gradation does not occur, because the remobilization processes on slopes, such as snow avalanches and debris flows, disturb grain size coarsening from the top to the bottom. Sedimentological analysis of sand-dominated material shows that, alongside the patterned grounds and solifluction lobes, the talus slopes are the most dynamic environment in the Brattegg Valley.

This study of talus slopes in the Brattegg Valley indicate that the sedimentological measurements are valuable source of statistical data on slope surface, relief of talus slopes, depositional and erosional structures. It should be noted that the comprehensive interpretation of mass-wasting processes based on the grain size analysis is not possible without the basic geomorphological observations, however, it could be useful for their validating.

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