Research article

Geomorphic evidence of extreme events in the High Arctic (Wedel Jarlsberg Land, Svalbard)

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Abstract

Among the geomorphological processes determined by meteorological conditions, topography and geological factors, floods and various mass movements have an extreme origin. In the High Arctic, which is the domain of cryogenic processes, extreme events can reach a scale and intensity never before observed, considering the exceptionally rapid environmental changes caused by global warming. It is widely believed that the frequency of extreme events will increase. However, knowledge about their past activity is limited due to the low population density in high-latitude areas and the deficit of adequate observations before the digital era. They are recorded in sediments and landforms, which require comparative analysis. This paper gives two examples of landforms resulting from extreme geomorphological events occurring in Wedel-Jarlsberg Land on the western coast of Svalbard (approx. 77°N). A basic description of an alluvial fan with an area of 0.067 km^2 was provided, resulting from mud-debris flows from the Steinvik Valley, likely due to water being pushed out of a shallow lake with an area of 0.022 km^2. The possibility of a landslide occurring in the postglacial period on the slopes of the Jens Erikfjellet massif was also indicated. The timing of the events is discussed based on the existing dating of raised marine terraces. The presented data come from preliminary studies, such as field observations, simple measurements, and GIS analysis of available digital materials. The outcomes can introduce a better understanding of the scale of extreme processes and the search for similar landforms. Such inventory has not yet been comprehensively conducted on Svalbard, even though extreme events commonly occur during the Holocene climate fluctuations in this area. Their frequency and scale remain unknown.

Keywords: *extreme events, alluvial fan, landslide, Wedel Jarlsberg Land, Svalbard*

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Introduction

Svalbard is an area where climate change-driven landscape transformations are particularly noticeable. The increase in air temperatures, which is progressing 2–4 times faster than in other parts of the globe (Rantanen *et al.* 2022), affects the hydrosphere and cryosphere, causing a decrease in the extent and frequency of sea ice surrounding the archipelago (Urbański & Litwicka 2022), and on land, an apparent regression of glaciers (Farnsworth *et al.* 2020; Noël *et al.* 2020, Schuler *et al.* 2020) and thawing of permafrost (Biskaborn *et al.* 2019; Karjalainen *et al.* 2019). Changes in the hydrological regime include reducing snowfall in favour of rain and releasing loose sediment no longer bound by ice, intensifying geomorphological processes (Owczarek *et al.* 2014). Mass movements, including rockfalls, landslides, and debris flows, are noteworthy. In Arctic conditions, they can occur even on surfaces with a slight slope, using the slip surface, which is often the permafrost table (Kokejl *et al.* 2009; Lewkowicz & Way 2019). A particular category is also created by rapid glacial lake outburst floods (GLOFs) in the paraglacial zone (Taylor *et al.* 2023).

It can be argued that activating hydrological and geomorphological processes, which reflect climate change, is a normal reaction of the natural environment, striving to achieve equilibrium in new conditions. Nevertheless, their scale and dynamics often place them in the category of extreme events (Overland 2021; 2022). Among the many definitions of extreme events (Thywissen 2006), it is worth pointing out that their size, intensity or time of occurrence are usually surprising to humans.

The study of geomorphological effects of extreme events has entered a new phase with the digital revolution of recent decades, including the availability of data and the popularisation of remote sensing and GIS tools. In Svalbard, the turning point was undoubtedly the development of a high-resolution orthophotomap and other digital data of the entire archipelago by the Norwegian Polar Institute (geodata.npolar.no). Detailed studies began to appear, looking for landforms associated with GLOF events (Wieczorek *et al.* 2023) and the formation of gullies or landslides (Nicu *et al.* 2022; 2023; 2024), similar to other polar and mountain areas. Studies conducted on the scale of the entire Arctic are noteworthy (e.g. Lützow *et al.* 2023; Makopoulou *et al.* 2024). A feature of this type of work is the relatively easy creation of large-area databases using specific, uniform criteria, usually based on detailed field mapping instructions (e.g. Fell *et al.* 2008).

However, there is no appropriate material to which contemporary statistics could be related, primarily when the recognised landforms are not assigned an age. There are also visible differences resulting from the method of collecting information on the landforms, which in the traditional approach was not separated from geological observations and measurements, and their authors knew the research area perfectly well. However, the effects of conventional geomorphological mapping were often limited to certain areas or were performed by geologists/geomorphologists guided by different principles. As a result, there is a gap in knowledge about past extreme events before aerial photography, especially when considering uninhabited areas.

This paper aims to provide basic geomorphological information on the effects of two past extreme events in Wedel Jarlsberg Land, on the western coast of Spitsbergen – the outflow of mud-debris-flows from the neotectonically uplifted Steinvik Valley and a potential landslide that delivered rock material to the foot of the Jens Erikfjellet massif. Specific landforms have been identified, which have not been precisely characterised in the literature. The situation in the Steinvik Valley was observed by Jahn (1967), and his report was repeated by André (2017), although the given information was not precise in light of current knowledge. The connection of the debris from Jens Erikfjellet with extreme events has not been associated so far. Despite their considerable size, both landforms were not taken into account by the authors of detailed geological maps made in the study area (Birkenmajer 1990; Czerny *et al.* 1993), who were interested in the diversity of the occurrence of solid rocks, not the origin of Quaternary sediments. Also, the authors of the geomorphological map of this area (Karczewski *et al.* 1984) did not see the effect of extreme processes in them. The premise for taking up the subject is the fact that although an intensification of geomorphological processes is currently observed in the study area (Owczarek *et al.* 2014), none of them is comparable in scale to the documented events that took place before the period of contemporary, intensive climate change in Svalbard.

Methods

The presented material is based on field mapping conducted in the summer (July–August) of 2011 and 2012. The observations were supplemented by analysis of currently available digital data, including an orthophotomap generated in the Metashape program (Agisoft LLC) based on aerial photos purchased from the Norwegian Polar Institute and ArcticDEM v.4.1 (Porter *et al.* 2022) with a resolution of 2×2 m. The DEM was corrected based on elevation data from a topographic map to equalise the sea level to the zero height value and other elevations in proportion to the average height difference found for the highest peaks.

In the field, additional oblique photos of the studied area were taken from the surrounding peaks. They allowed for the transformation of some images into orthophotomaps to illustrate the shape of selected landforms better. To register images in the UTM33N coordinate system, photo points were used – 5 bright sheets placed in the field, the position of which was measured by a GPS receiver (Trimble GeoXT) with a differential correction, giving a measurement accuracy of 10–30 cm. This work was carried out when aerial mapping techniques using UAVs were not widely available.

A Schmidt hammer type N (Proceq) was also used to check the relative age of the rock debris deposited below the Steinvik Valley mouth. Rock blocks with diameters greater than 1 m were selected for measurements, distinguishing their lithology. This activity aimed to check whether separate levels of the alluvial fan have the same or different ages. The values of the rebound of a metal pin from the rock surface, converted into force units, can be related to the resistance of the rock surface to damage (Goudie 2006; Niedzielski *et al.* 2009). The rock weathering level is assumed to increase with time, and the rebound values should decrease. Due to the geological settings, three lithologically different types of blocks were tested, 50–70 of each type at two levels of the alluvial fan.

Study area

The study area is located on the western coast of Spitsbergen, north of Horn Fjord and south of the eastern part of Torellbreen, the largest glacier of Wedel Jarslberg

Land (Figure 1). This is an area intensively explored since 1956 by Polish researchers (Zwoliński *et al.* 2013), who later established polar stations on Isbjørn Bay in Hornsund and at the moraine of the Werenskiold glacier – Baranowski Polar Station.

The Greenland Sea coast of this part of Spitsbergen is formed by the Hecla Hoek Succession rocks, predominantly greenstones, mica schists, amphibolites, and quartzites, assigned by the authors of the geological map (Czerny *et al.*, 1993) to four separate groups depending on age (middle and upper Proterozoic) and location. A complex of raised beaches (Birkenmajer 1960; Jahn 1968; Karczewski *et al.* 1981a) was formed along the coast, composed of marine gravels on a rocky base (Strzelecki *et al.* 2017). Inland, a mountain range rises to heights averaging 500–950 m a.s.l. It is cut by wide valleys, some of which remain glaciated (Błaszczyk *et al.* 2013). Smaller valleys with limited snow accumulation are not glaciated or consist of glaciers in the final recession phase (Wołoszyn & Kasprzak 2023). The terrain surface is covered with moraine deposits and weathering products in periglacial conditions: blockfields, debris, and finer -grain material, commonly subject to solifluction and frost sorting. Outside the zones of water impact in the taliks, the ground is perennially frozen (Kasprzak *et al.* 2017; Glazer *et al.* 2020; Kasprzak & Szymanowski 2023).

Local climate conditions are determined by measurements conducted continuously since 1979 at the Hornsund Polar Station (10 m a.s.l.). Since the beginning of measurements, mean annual air temperature (MAAT) has increased by more than 4 °C at an average rate of 1.14 °C per decade (Wawrzyniak and Osuch, 2020). Although in the measured multi-year period, MAAT has a value of −3.7 °C, in 2016, MAAT was recorded at a level of +0.3 °C (*Meteorological bulletins…* 2009–2023). The highest air temperature, 16.5 °C, was noticed on July 25, 2020. An increase in rainfall efficiency is also observed. On September 18, 2017, the highest daily rainfall was recorded, with an amount of 73.5 mm, higher than the previous record from September 2, 2012 by 13.7 mm. The average annual rainfall is 477 mm. In 1979–2023, it ranged from 230 mm in 1987 to 805.5 mm in 2016.

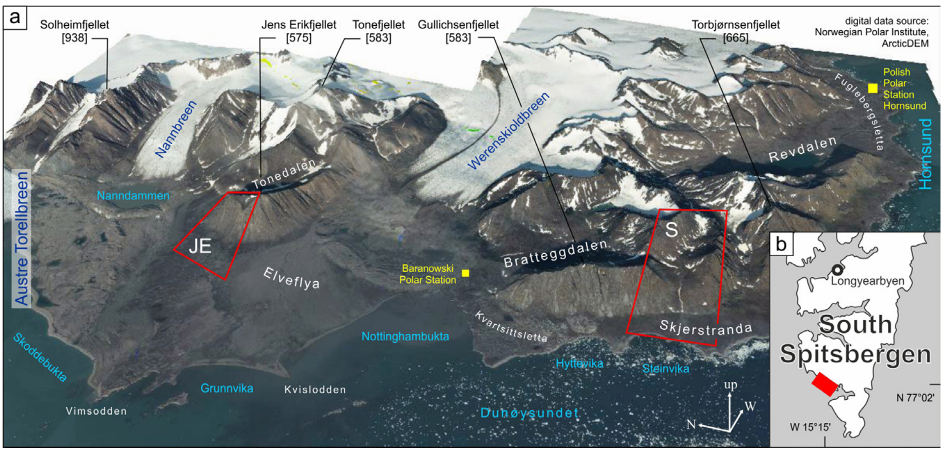

Figure 1. Study area (a) on the coast of South Spitsbergen (b): JE – Jens Erikfjellet area, S – Steinvikdalen (valley).

Results

Steinvik Valley

The Steinvik Valley has not been the subject of detailed geomorphological mapping, although it is included on the geomorphological map of the Horn Fjord area at a scale of 1:75,000 (Karczewski *et al.* 1984). It attracted the attention of geomorphologists after discovering marine gravels at its mount hang at a height of over 200 m a.s.l. (Jahn 1959). An alluvial fan was also identified below (Jahn 1967), but no more detailed research was conducted into the valley. In the summers of 2009–2011, hydrological and hydrogeological measurements were carried out here to identify the water's chemical and isotopic composition in the active layer above the permafrost table (Rysiukiewicz *et al.* 2023).

The Steinvik Valley is 2 km long, with a floor width of up to 250 m and a distance of up to 400 m between opposite mountain ridges. The valley bottom runs E–W and opens towards the sea coast (Figs 2 and 3). The bedrock is formed by Proterozoic metamorphic rocks classified by Czerny *et al.* (1993) as the Eimfjellet Group. The course of the upper part of the valley closely follows the lithological boundaries. The northern slopes of the valley are formed mainly by mica schists, its axis by varieties of amphibolites, and the southern slopes by quartzites.

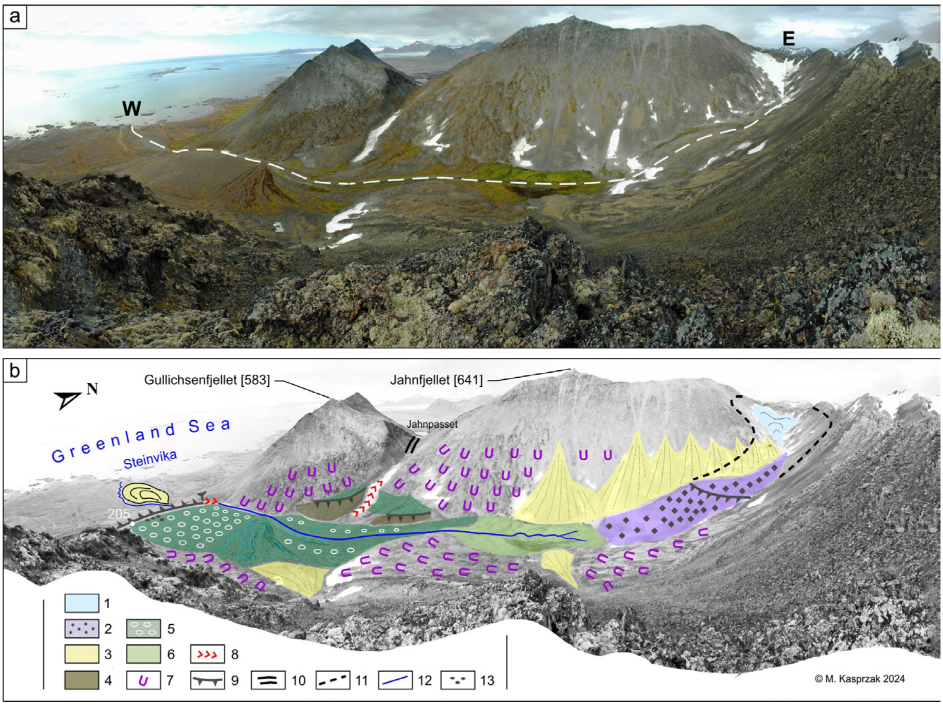

Figure 2. Steinvikdalen: (a) panoramic view based on a series of photos derived by M. Rysiukiewicz, section W–E in figure 3f; (b) geomorphological simplified sketch; 1 – glacier in deep recession phase or firn, 2 –coarse-grain glacial deposits (till and boulders) over bedrock, 3 – taluses and alluvial fans, 4 – bedrock, 5 – uplifted marine terraces, partially with pattern ground, 6 – wetland, 7 –solifluction-modelled slopes, 8 – ravines, 9 – main morphological edges, 10 – pass, 11 – LIA trimline, 12 – river channel, 13 – exposed marine cobbles.

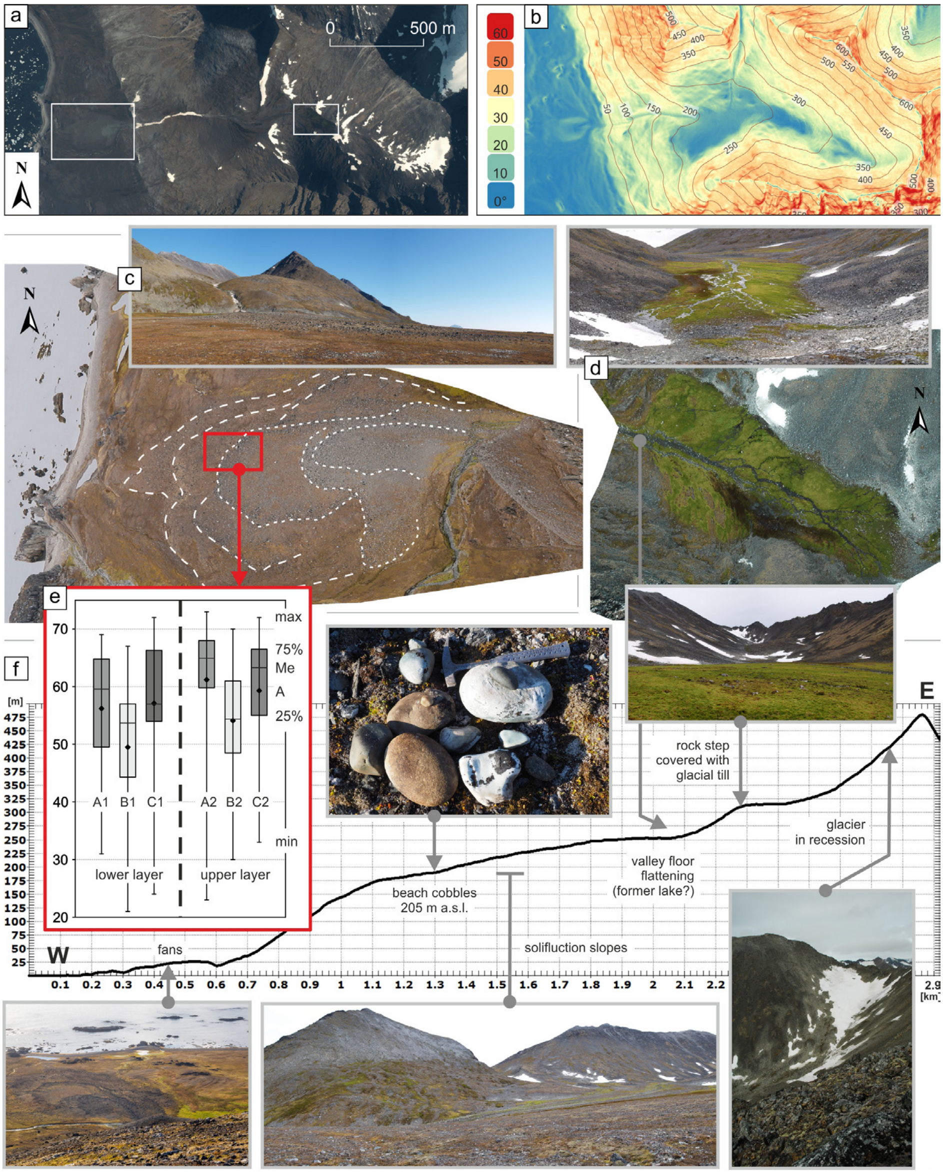

Figure 3. Landforms and sediments of Steinvikdalen: a – orthophotomap with framed areas shown in sections c and d; b – slope map; c – alluvial fan with marked two different generations of debris on which Schmidt hammer measurements were carried out (e); d – flattening of the valley bottom; e – results of measurements with the Schmidt hammer of blocks (quartzites, mica schists, amphibolites); f – longitudinal profile of the valley and its geomorphological features.

The longitudinal profile of the valley contains two distinct terrain steps (Figures 3b and 3f), probably of neotectonic origin. However, geologists did not interpret this as such when mapping this area (Czerny *et al.* 1993). The shape of the valley floor and the finds of marine cobbles prove that it contains two levels of marine terraces, raised to heights of 200–210 and 220–230 m a.s.l. Marine gravels were not found in the highest level of the valley bottom 300–310 m a.s.l., possibly due to their weathering. Above the valley head is a patch of firn and a debris cover, hiding the remains of glacial ice. The trace of the small glacier, which evolved in the past, is a coarse-grained till covering the bottom of the highest section of the valley and a weakly outlined trimline on the slopes. The trimline descends, reaching the valley bottom in the area of the rock step (Figure 2b). It marks the maximum extent of the glacier during the LIA, the scale of which does not differ from the small glaciers of the neighbouring valleys (Wołoszyn & Kasprzak 2023).

Based on the terrain features and surface moisture differences, it can be assumed that in the past, a shallow proglacial lake with a surface area of approx. 0.022 km^2 (Figures 2 and 3d) existed in the Steinvik valley, the bottom of which was at a height of approx. 250 m a.s.l. The lake could have been emptied rapidly under the episodes of glacier degradation, a type of slush flow resulting from melting snow and ice or snow avalanches descending the steep slope of the valley. Evidence of the rapid nature of the water outflow is the alluvial fan formed below the valley mount (Figures 2b and 3c), continuing towards the sea. It was not recognised on the geomorphological map of the Hornsund area (Karczewski *et al.* 1984), on the geological map of Birkenmajer (1990), it was incorrectly marked as an outcrop of crystalline rocks, and on the map of Czerny *et al.* (1993), it was ignored. It is a sediment of debris cones lying on an older accumulation landform, covering an area of 0.067 km^2 (Figure 3c). The described complex of fans rises to 8–10 m above the terrain surface. Based on the orthophotomap made, at least six separate cones can be distinguished here. Differences in the degree of weathering of the rock material forming them are noticeable.

The Schmidt hammer was used to check the age separation of the block-boulder-debris material between two levels of the fan, where the weathering contrast of rock elements is evident (Figure 3e). This demonstrated significant differences in the mechanical resistance of blocks within three lithological groups A–C (quartzites, greenstones, and mica schists), as presented in the box plot (Figure 3e). The interpretation of this result suggests that the flood episodes occurred over a significant time interval, likely thousands of years.

Jens Erikfjellet massif

The Jens Erikfjellet massif (575 m a.s.l.) mainly comprises greenstones and greenschist (Czerny *et al.* 1993). At its foot are accumulative landforms composed of debris with a coarse fraction. Over 40 years ago, they were the subject of consideration by a team of geomorphologists (Karczewski *et al.* 1981b). At that time, they classified all footslope accumulation landforms as nival moraines, unaware of the formation process of rock glaciers, including most of the sites they described (Hartvich *et al.* 2017). The best example is the rock glaciers at Hytte Bay (Figure 1). They also did not see the effects of extreme mass movements.

At the foot of the Jens Erikfjellet massif, in addition to the usual taluses, the proximal parts of which have turned into rock glaciers, there is also a convex terrain of a different origin (Figures 4 and 5). On the strongly weathered surface of the marine terrace remnant, rock material is deposited, rising to 30 m above the terrain surface (Figure 5a). The height of the terrace remnant reaches 16–18 m a.s.l. and more, rising above the surrounding level of the terrace 8–12 m a.s.l., which was not indicated in the study of Karczewski *et al.* (1981a). Due to the small tonal diversity of the orthophotomap (Figure 4a), it is difficult to determine the extent of the debris. The debris is arranged in fans directed from the slope towards the west. The sediment consists of blocks and boulders exceeding 5 m in size, sometimes resembling a tors (Figure 4d). Observations of random foliation directions prove that boulders are not a stable bedrock element but haphazardly scattered. The debris is partially separated from the slope and contemporary scree deposits by distinct depressions.

The western part of the Jens Erikfjellet slope also has certain features that distinguish it from its surroundings. In the described section, its relative height reaches 440 m. The shape of the slope is convergent (Figure 4b). Directly above the accumulation landforms, up to 300–350 m a.s.l., the slope morphology is not diverse, in contrast to its neighbouring parts (Figure 4d). It resembles a slip surface for sliding rock masses before the scree development. It can be assumed that this is a scarp of the old landslide, and the debris below is partly colluvium formed due to a sudden movement. It cannot be

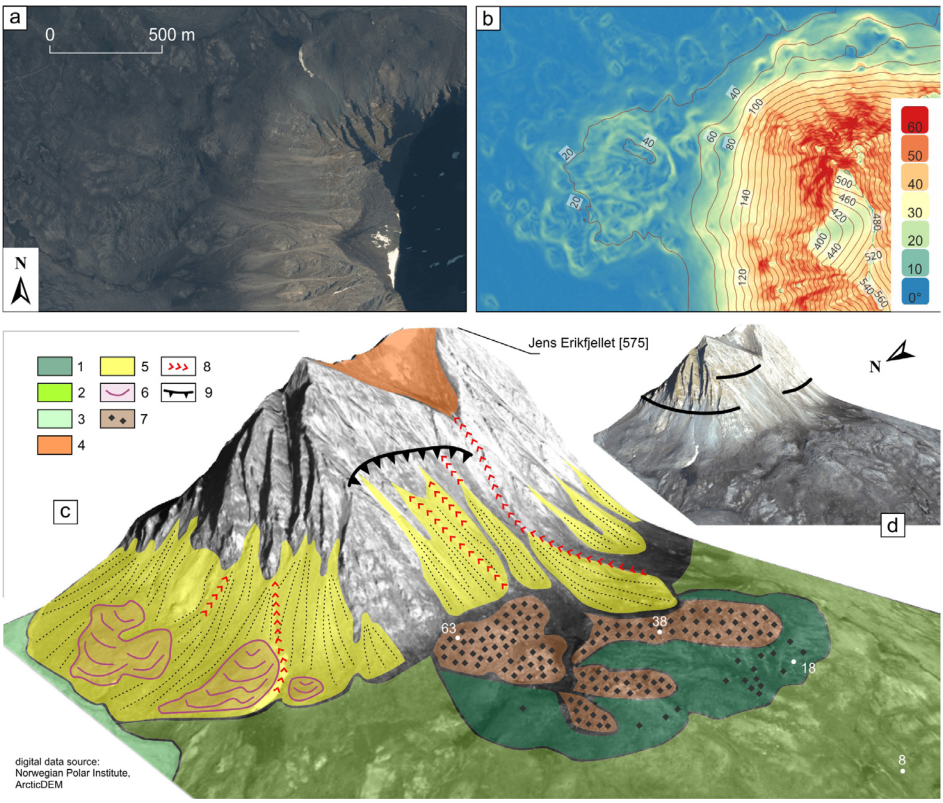

Figure 4. Landforms in the Jens Erikfjellet area: a – orthophotomap; b – slope map; c – simplified geomorphological sketch; 1 – terrace 16–18 m a.s.l., 2 – terrace 8–12 m a.s.l., 3 – Vimsa River bed, 4 – denudation surface, 5 – taluses, 6 – rock glaciers, 7 – colluvium, 8 – debris flow channels with lateral levees, 9 – probable landslide scarp; d – schematically marked differences in the height of the slope with diverse morphology.

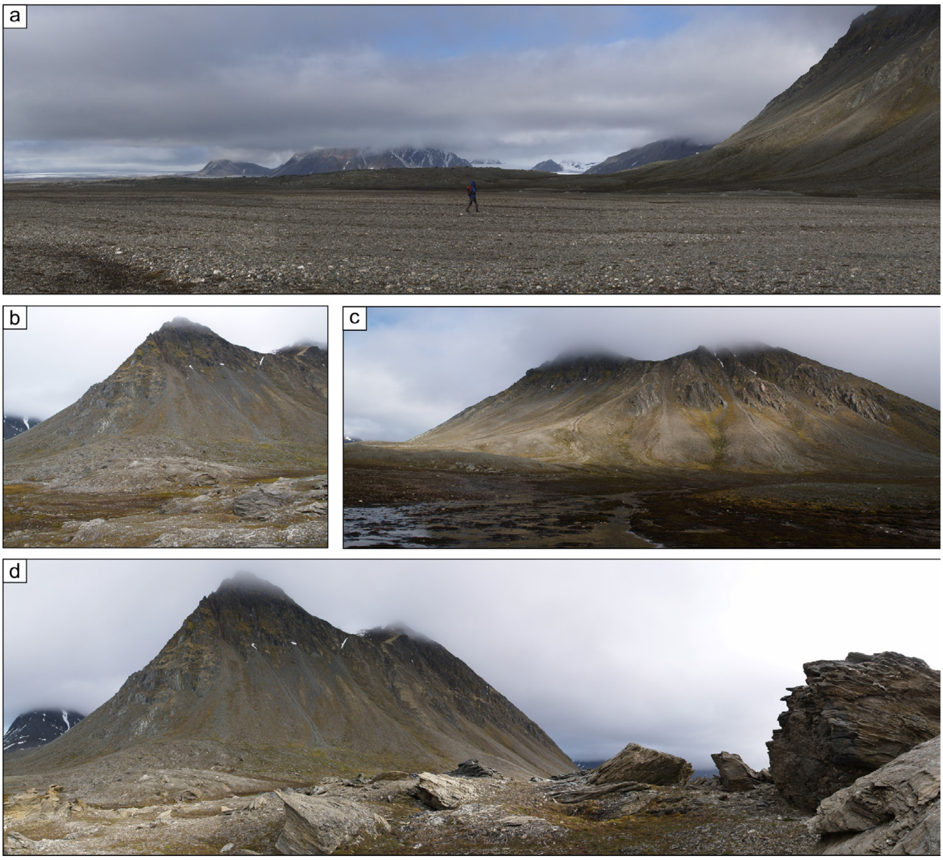

Figure 5. The debris accumulation under the Jens Erikfjellet slope: a – general view from Elveflya towards the north, b – generations of rock debris, c – differences in slope morphology, d – scattered, strongly weathered blocks and boulders.

ruled out that a large-scale rock avalanche also occurred on the slope in addition to the landslide. The indicated area requires a deeper analysis and verification of the proposed scenario.

Discussion

The landforms described in the previous chapter witness extreme events on a scale not observed in recent decades on Wedel Jarlsberg Land, between Horn Fjord and Austre Torell Glacier. In light of the collected materials,reconstructing their course and timing is challenging without more detailed studies, which is not the direct purpose of this study. Nevertheless, a few facts can be presented for discussion.

The alluvial fan, first described by Jahn (1967) as a slushflow effect from the Steinvik Valley, was formed by several outflows containing a large amount of debris. In the Steinvikdalen, apart from the ravine developed by the draining stream, no significant traces of erosion or a moraine barrier could have been breached, as is usually the case in GLOFs. The source of the debris could have been the eroded till and solifluction covers, as well as the sediments of a shallow lake filling the depression of the raised marine terrace. This scenario is supported by an unnaturally flat and saturated part of the valley in front of the rock step and the local glacier at its maximum LIA stage. The lack of contemporary growth of the alluvial fan and the cessation of rapid outflows are potentially related to the filling of the lake. There is not enough water here to be pushed out as a mudflow. In an alternative scenario, glacier deglaciation reduces runoff, which could have episodically formed debris-mud flows in the past.

The alluvial fan rests on a system of 5 marine terraces rising 30–40 m a.s.l. (Karczewski *et al.* 1981). Their dating remains an open issue. Attempts were made to determine the age of the terraces using ^{14}C determinations of shells, whale bones, plant remains in fossil soils and driftwood, and the thermoluminescence method. The material found in the sediments of the most extensive terraces 7–9 and 8–12 m a.s.l. was determined to be 7,690 ± 90 – 7,230 ± 50 B.P. (Chmal 1987) and 16,000 ± 2,500 – 12,000 ± 1,800 BP (Lindner *et al.* 1991), respectively. Radiocarbon dating of whale remains and driftwood on the surface of the lower beach level 4.5–6 m a.s.l. suggests that it was formed 1,000–800 years ago (Lindner *et al.* 1991). The alluvial fan developed after the formation of the terrace system and is younger than it. Unfortunately, the authors of the cited papers determined the ranges and heights of the marine terraces in the study area in different ways. This problem should be solved in the future by objectively distinguishing the terrace levels using high-resolution DEM and geomorphometric tools. Determining the absolute age of the marine terrace levels is difficult because the rate of neotectonic uplift is very diverse on Svalbard. Perhaps better data in this respect will be provided by dating rocks using cosmogenic nuclide methods. It should also be added that the analysed alluvial fan was formed before 1936. On oblique aerial photos taken at that time (toposvalbard.npolar.no), one can see a stream flowing around this landform, i.e. a situation similar to the present one.

More recent reconstruction of landscape evolution close to the study area focused on the Horn Glacier (Osika *et al.* 2022). It indicates significant environmental changes that occurred in the Early and Middle Holocene. Local glaciers retreated at that time, 10.9 and probably around 1.3 ka cal. BP, respectively. This means that Svalbard experienced many changes during the Holocene that affected the activity of hydrological and geomorphological processes. Due to the significant variation in the degree of weathering of debris, it is difficult to reject the conclusion that the fan below Steinvik Valley was formed at different times of substantial environmental changes. It is also possible that its genesis is more complex and results from the action of other processes (e.g. older moraine degraded by sea waves?).

Today, we can observe the intensive environmental changes in the slope system. Landslides, debris flows, and erosive cutting of the surface are facilitated by thawing of the ground and climate wetting. On Svalbard, snowfall gives way to rain, which can occur even in winter (Nowak & Hodson 2013). Compared to previous decades, more rapid thaws and increased precipitation with high intensity are being recorded, which have a thermo-erosive effect on the ground (Christensen *et al.* 2021). Precipitation efficiency can reach even half of the annual total, as recorded on August 13–16, 2013, in the Bellsund area (Kociuba 2023). At the same time, the most severe episode of shallow landslide and debris flow activation observed by people occurred near Longyearbyen after heavy rainfall on July 10–11, 1972 (Larsson 1982). It was determined then that the risk of landslides and flows increases significantly with rainfall intensity higher than 2 mm per hour. However, the most spectacular sudden changes in the Svalbard landscape result from GLOFs (Wołoszyn *et al.* 2022) and deep-seated landslides (Kuhn *et al.* 2019).

The issue of rock debris interpreted with some caution as landslide colluvium and potentially accompanying rockfalls in the Jens Erikfjellet massif also requires explanation. The author believes it is sediment after an event or series of events in the distant past. The resulting colluvium could also have been, at least partially, subjected to the action of sea waves. This can explain its fragmentation. The colluvium deposition could have been the direct cause of the preservation of the higher marine terrace. At the same time, in the surrounding area, this level underwent denudation. The older age of the colluvium is evidenced by the high degree of weathering, much more than a weathering effect on taluses at the slopes of Jens Erikfjellet. Significantly, the rock elements of the colluvium also exceed the grain sizes of scree, which is forming contemporarily. No detailed measurements were made in this respect, but this situation is easily noticeable. The largest boulders rest far from the slope. This, in turn, is currently modelled by rock falls and snow avalanches, leading to taluses growth (Senderak, 2023). This rate was determined by Eckerstorfer *et al.* (2013) at 0.2–14 mm per year, examining similar slopes in the central part of Spitsbergen. Active geomorphological processes have not yet led to a varied slope topography on the section interpreted as a potential landslide scarp.

Any determination of the landslide time without specialist dating will remain risky. This event could have occurred after forming the 16–18 m marine terrace and probably earlier than the development of lower terrace levels. In the central part of Spitsbergen, in Billefjorden, attempts were made to date the activity of large, deep-seated landslides based on organic remains in the depressions of fault scarps (Kuhn *et al.* 2022). It was proven that they have a postglacial age of at least 6 ka. A similar age to other large landslides, including those on the slopes of Jens Erikfjellet, cannot be ruled out. In these considerations, not only the climatic factor is essential, but also the tectonic factor, which could have played a triggering role, especially since even today, earthquakes in Svalbard reach M=6.1 (February 21, 2008; earthquake.usgs.gov). The Hornsund area is a moderately active seismic area related to the geotectonic situation in the Barents Sea shelf, isostatic adjustment and stresses induced by glacier movement (Górski & Teisseyre 1991; Mitchell *et al.* 1990; Stemberk *et al.* 2015).

The presented analysis provides only some basic information, provoking more questions. The author declares that further work will be undertaken to clarify the details discussed above. This will be possible by reopening the issue of the age of the elevated sea terraces in the Hornsund area and by using better research methods, including terrain models created photogrammetrically from drone photos (SfM-UAV) and absolute dating of organic and mineral sediments according to the latest standards.

Conclusions

The summary of the presented material will be several basic theses based on field observations, analysis of digital materials and the discussion:

1. On the coast of Wedel Jarlsberg Land, between (the glacier) Austre Torellbreen and Horn Fjord, some landforms indicate extreme geomorphological events on a scale not observed in this area today.
2. In the Steinvik Valley, debris-mud flows were formed, the effect of which is a multi-level alluvial fan on the surface of raised marine terraces below the valley mouth hung 200 m above. The debris-rich flows could have been caused by

the expulsion of water from a shallow proglacial lake due to episodes of rapid thawing of ice and snow or snow avalanches. Other morphogenic factors cannot be ruled out. The age of the fan sediments is difficult to determine without specialist dating, but based on current knowledge, it can be assumed that their oldest generations were formed later than 7 ka BP.

3. A section of the slope in the Jens Erikfjellet massif is morphologically different from the rest. At its foot, there is strongly weathered debris with blocks and boulders larger than in the surrounding scree deposits and debris glaciers. This situation can be considered the effect of a large-scale landslide, possibly combined with rockfalls. The colluvium preserved a higher level of the marine terrace. The potential landslide event took place in the postglacial period.
4. The presented landforms created as a result of extreme events are evidence of environmental changes in the Holocene, at least as significant for the landscape evolution as the currently recorded ones related to the rapid warming of Svalbard.

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