The Climatic and Palaeoclimatic Significance of Rock Glaciers

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Background

Rock glaciers are characteristic and widespread large-scale flow features of frozen material in cold-climate high-relief regions. They are located at the foot of rock free-faces with a high supply of talus and, when active, typically take the form of 20-100 m thick tongue- or lobe-shaped bodies with cascading frontal slopes standing at the angle of repose. Their length may be as much as several kilometers, but the typical length is 200-800 m measured parallel to the flow direction. The longest rock glacier described from Earth is about 5.5 km in length (W Greenland). The surface of rock glaciers is typically covered by coarse (0.2-5 m) and angular rock fragments (talus), and displays a 1-5 m high curving transverse furrow-and-ridge topography. Active rock glaciers typically flow downslope 0.1-1 m per year, that is, they are more sluggish than normal glaciers, but are nevertheless presumably highly efficient as coarse debris transport agents due to their sheer size.

Active rock glaciers are present in many cold-climate mountain regions and are often seen as characteristic of continental environments. A significant number of rock glaciers have, however, been described from more maritime regions, and the topographic and meteorological controls on rock glacier initiation and growth are still far from known in detail. This is not completely surprising, considering the relatively short period during which intensive rock glacier research has been carried out on these generally inaccessible landforms, and only few meteorological data exist from sites occupied by active rock glaciers (Humlum, 1998a, 1999a, 1999b).

Based on field evidence, some authors claim a general non-glacial (periglacial) origin for rock glaciers, while others authors find that certain rock glaciers contain a significant core of glacier ice. A specific landslide origin has been suggested for some other rock glaciers, which, however, may be considered as a special case of the non-glacial (periglacial) rock glacier type. Quite a number of discussions on rock glacier origin, internal structure, rheology and nomenclature have originated from this diversity and have been reviewed by Whalley and Martin (1992), Barsch (1996) and Humlum (1982, 1988a, 1996, 2000).
Climate and Rock Glaciers

With few exceptions (Kerschner, 1978, 1980 and 1985; Buchenauer, 1990 and Humlum, 1998a, 1998b, 1999a, 1999b), the palaeoclimatic potential of rock glaciers has only been exploited in a very general way, even though the association of rock glaciers with permafrost and limited snowfall, however, implies that they have a considerable potential in this respect. The poor knowledge on the typical rock glacier climate is responsible for the limited use of rock glaciers in palaeoclimatic studies, but the importance of this aspect of rock glacier research will presumably increase as meteorological data from sites with active rock glaciers become available.

It is the aim of the present project to contribute towards the knowledge on the typical, regional rock glacier climate by way of collecting geomorphological and meteorological observations from sites with active rock glaciers in various geographical regions, but with emphasis on Svalbard. A few field examples are presented below, in order to outline the line of thought.

Terminology

The terminology of Humlum (1982, 1984, 1988a, 1988b, 1996, 1998a, 1998b, 1999a, 1999b, 2000) is used below. By this, rock glaciers are be divided into talus-derived and glacier-derived rock glaciers, implying non-glacial (periglacial) and glacial types, respectively. As is seen in the idealized diagram below, the abbreviation RILA will be adopted to signify the rock glacier initiation line altitude, the altitude at which rock glaciers creep out from the slope above, in the sense suggested by Humlum (1988a). The initiation line on talus-derived rock glaciers is usually clearly marked by a break in slope, and is easily mapped in the field as well as from aerial photographs. On glacier-derived rock glaciers the initiation line is identical to the upper limit of the debris covered rock glacier. RAL is short for the rock glacier appearance level, while ELA is short for equilibrium line altitude on normal glaciers. In nature, only little difference between RILA and ELA is to be expected.

Figure 1. Definition diagram showing two mountain massifs with rock glaciers and a normal glacier.

A case study from Disko Island, W Greenland

Disko Island (8575 km²) is situated outside the coast of central W Greenland. The island is a part of the Tertiary volcanic province of West Greenland and is mainly made up by lavas. The landscape is a plateau basalt landscape with cirque carved lava plateaus and U-shaped valleys and fjords, with a typical relief of 800-1200 m. There are almost 1000 individual glaciers on the island, covering about 20% (1610 km²) of the total land surface (Humlum, 1988a).

In the village Qeqertarsuag (Godhavn), at the southern coast of Disko Island, meteorological observations have been carried out since 1923. The present (1961-1990) mean annual air temperature (MAAT) is -3.9°C; the coldest month is March (-15.1°C), while July is the
warmest month (7.1°C). The mean annual precipitation at Qeqertarsuaq is about 400 mm water equivalent. Meteorological measurements 1993-97 in Mellemfjord, central western Disko Island, indicate a MAAT of about -7.5°C (35 m asl.), which is about 3°C lower than the contemporary 1993-96 mean air temperature in Qeqertarsuaq (20 m asl.). Measurements by myself in the Qeqertarsuaq area 1983-1986 and 1995-2000 suggest a mean annual vertical lapse rate of about 0.006-0.007°C m⁻¹.

No systematic mapping of permafrost or permafrost related terrain features have been carried out in this part of West Greenland. Weidick (1968), however, places Disko Island within the zone of continuous permafrost. This is supported by the occurrence of open system pingos (Christiansen, 1995) and numerous rock glaciers (Humlum, 1982, 1984, 1988a, 1988b, 1996; Humlum et al., 1995), which are geomorphic indications of widespread permafrost. Adopting a standard continental geothermal gradient of about 0.033°C m⁻¹, the MAAT of -7.5°C (1991-96) indicates a potential permafrost thickness of about 175-225 m. This estimate is presumably somewhat conservative, as the Little Ice Age MAAT presumably was at least 2°C below modern values (Humlum, 1996), which would provide conditions for a somewhat thicker permafrost layer than is suggested by modern meteorological values. The high number of rock glaciers (nearly 1700) on Disko Island may reflect extraordinary high rock weathering rates (Frich and Brandt, 1985; Humlum, 1992). Ignoring glacier-covered areas, the mean frequency of rock glaciers is quite high; about 24 per 100 km².

The high frequency of active rock glaciers in Disko Island makes it possible to identify quite a number of sites where active rock glaciers are located in proximity to other geomorphological features with special climatic significance, such as glaciers. An example of this is shown below.

![Figure 2. Valley head in western Disko Island with a small glacier located close to a group of active, talus-derived rock glaciers. The mountain in the central part of the picture reaches 1070 m asl. and the valley bottom is at about 500 m asl. Seen towards NE.](image-url)

The figure above shows a valley with a small glacier located close to a group of active, talus-derived rock glaciers. The glacier is situated only slightly higher than the rock glaciers, only about 50-100 m, and the major difference as to the topographic setting is the height of the rock free face (basalts) above, which is 30-80 m higher above the rock glacier site than above the glacier.

Vegetation, lichen cover and thickness of weathering rind thickness indicate the moraine ridge in front of the glacier to have been deposited during the Little Ice Age, most likely during the last major glacier advance, which culminated AD 1895-1900 on Disko Island (Humlum, 1987 and 1999). The moraine is dominated by supra- and englacially transported debris (talus-like), and subglacially derived material (abraded...
is subordinate. The unstable character of the rock glacier terminus indicates ongoing activity, but it may reasonably be assumed that the activity was somewhat greater during cold periods of the Little Ice Age, in time corresponding to the deposition of the moraine ridge. From this, it is relevant to compare the altitude of the reconstructed Little Ice Age equilibrium line altitude (ELA LIA) and the rock glacier initiation line altitude (RILA) as defined in the definition diagram above (Fig. 1).

The ELA LIA can be estimated directly from the upper end of LIA-moraines, rather than using an indirect mathematical-geometrical approach. The reconstructed ELA LIA and the RILA are at about 720-670 m asl. and 650-580 m asl., respectively, in the case shown in Figure 2. The geomorphological association between glacier and rock glaciers thus indicate a small difference only concerning the critical altitude for glacier and rock glacier initiation. The MAAT is presumably only slightly higher, if at all, at the rock glacier site, compared to the glacier site. More likely, the main control on the evolution of the two different geomorphological units is topoclimatic differences such as a higher net accumulation of snow at the glacier site, due to snow drifting across the saddle at the valley head. At both sites the weathering rate of the headwall is considerable, as is visually shown by abundant fresh debris lying on the glacier and on the talus sheets above the rock glaciers.

Modern meteorological observations in Mellemfjord (6 km from the site) indicate a MAAT at 600-700 m asl. of -11±1°C, adopting a the vertical lapse rate reported above. During cold periods of the Little Ice Age the MAAT is likely to have been at least 2°C below modern values (Humlum, 1996, 1999). The regional precipitation is presumably about 400 mm w.e. at sea level, increasing to at least 500±50 mm w.e. at 700 m asl. The local effective precipitation along the foot of the rock free face in Figure 2 is in all likelihood greater than this regional value suggests, owing to effects of winter snow blow. Calculations on the net summer radiation suggest typically annual accumulation values of 800-900 mm w.e. at cirque glacier equilibrium lines at about 700 m a.s.l. in this region of Disko Island, and 1500-1800 mm w.e. at exposed ice cap equilibrium lines at about 900-1000 m a.s.l. (Humlum et al., 1995).

A case study from Spitsbergen, Svalbard

Svalbard (63000 km²) is situated between 76°N and 81°N, between the Norwegian-Greenlandic Seas and the Polar Ocean. The study locality is situated in central Spitsbergen, at 78°N, near Longyearbyen. The local bedrock is mainly sandstones and shales of Tertiary age. The landscape is a plateau landscape intersected by U-shaped valleys and fjords, typically displaying a local relief of 400-1000 m. Along both the western and eastern coasts of Spitsbergen, alpine topography dominate.

Near Longyearbyen, in upper Longyearvalley, a series of active, talus-derived rock glaciers are found, shortly beyond the terminus of Larsbreen. Some of these rock glaciers have even been pushed somewhat by Larsbreen during the final Little Ice Age advance, presumably ending around 1915.
Figure 3. Talus-derived rock glaciers in upper Longyearvalley, as seen from Næssfjellet towards ESE, late June 2000. To the right is seen the outermost position reached by Larsbreen (blue outline) in the early 20th century. The rock glaciers form three parallel ridges, extending from the snow-covered foot of the headwall toward the lower central part of the picture. RILA indicated by orange line. Red and yellow dots indicate position measurement of for air- and ground temperatures, respectively. Note the snow avalanches lining the foot of the headwall. The rock glaciers have been slightly pushed by the LIA advance of Larsbreen. The mountain plateau is at about 500 m asl, while the valley bottom is at about 150 m asl.

At the head of the rock glaciers at Larsbreen, the air temperature near the terrain surface have been measured since August 1999, in order to obtain information on modern temperatures at the starting point of the rock glaciers. Shortly below, ground temperatures have been measured to gain insight in the thermal properties of the active layer on the rock glaciers. The sediment is unmodified talus material, angular and 5-20 cm i diameter. Typically, the rock glacier active layer consists of coarse sediment at the surface and finer sediments in the lower part (Fig.4).
The coarse surface layer on the rock glaciers operates as an insulating layer between the rock glacier surface climate and the permanently frozen core below. During periods with low wind speed and no or thin snow cover, comparatively cold air masses penetrate into the active layer due to density differences, displacing warmer air masses. In contrast to this, comparatively warm air masses tend to stay at the rock glacier surface, without tendency toward penetrating into the active layer. In this situation, warming of the lower part of the active layer is sluggish, as heat transfer is only by conductive means, while cooling may take place much more rapidly, using conductive as well as non-conductive means. Consequently, when wind speed is low and snow cover thin or absent, the coarse surface layer on rock glaciers apparently acts as a thermal filter, insulating against the effect of surface warming but readily transmitting the effect of surface cooling (Fig.5).
Figure 5. Temperature measurements at the Larsbreen rock glaciers August 1999 - September 2000. The coarse active layer is seen to operate as a highly efficient thermal filter, providing background to have the permafrost table at shallow depth, little more than 90 cm. The fluctuating temperature at the rock glacier surface (red) indicate the absence of a thick snow cover throughout the winter.

This situation is clearly favorable for the permafrozen core in active rock glaciers, and is essentially what has been called the Balch ventilation, defined as the insulating effect of air filled voids in a coarse sediment (Thompson, 1962; Barsch, 1996). However, wind pumping generated by high wind speeds may upset this pattern, and drive even comparatively warm surface air masses into the active layer by way of forced ventilation, dynamically displacing colder and denser air masses. When this happens, the thermal effect of surface warming as well as surface cooling may be rapidly transmitted throughout the whole active layer. The above scenario seasonally especially applies to summer and autumn, when the snow cover is thin or absent.

On the other hand, if a rock glacier is covered by a thick snow layer, the above mixture of conductive and non-conductive heat transfer processes is presumably replaced by very sluggish temperature variations and dominance of conductive heat transfer processes. However, depending upon factors such as latitude and topographic shadow, refreezing of percolating surface melt water may again introduce the periodic importance of non-conductive heat transfer processes within the active layer, especially during late winter and spring. This non-conductive heat transfer mechanism efficiently transports surface energy to the lower part of the active layer, while all transmission of surface cooling events is by conductive means only. Thus, with a thick snow cover present on rock glaciers, the coarse surface layer again acts as a thermal filter, insulating against the effect of surface cooling but comparatively readily transmitting the effect of surface warming by release of latent heat. This is clearly not favorable for the rock glacier permafrost core.

In general, it appears that the coarse surface layer on rock glaciers acts as a thermal filter, protecting the permanently frozen rock glacier core when a snow cover is absent or thin, and conversely when a thick snow cover is present. This may explain why rock glaciers tend to be especially frequent in dry, continental areas, and less so in humid areas.

http://www.unis.no/studies/geology/ag_204_more_info/ole/RockGlacierCl... 12/22/2010
Figure 6. Remnants of avalanche snow at the head of Larsbreen rock glaciers, late September 2000. Debris is partially covering the remnants of avalanche snow, which are very compact, 0.2-1.3 m in thickness and extend below the rock glacier surface debris seen to the right.

A significant amount of the ice present within the rock glacier body apparently derives from remnants of snow avalanches as illustrated by Figure 6. Investigations late summer 2000 suggest the actual annual surface mass balance at the rock glacier head to be positive during the year 1999-2000, partly because of high avalanche activity, partly because of the protecting surface cover of debris, released by ablation during the summer season. Refreezing surface meltwater or rain may represent other means of ice input into the rock glacier body, but snow accumulated by avalanche activity clearly remains a highly significant source of internal ice in the rock glacier body. This fact presumably explain why many active rock glaciers on Svalbard as well as in Greenland face downwind in relation to the prevalent winter wind direction.
Fig. 7. Larsbreen and associated talus-derived rock glaciers as seen from Gruvefjellet towards SW, 30. September 2000. The rock glaciers form three flow-parallel ridges in front of the glacier, extending from the talus sheet to the left. The maximum position reached by Larsbreen at the end of the Little Ice Age (LIA) is clearly indicated by a abrupt change in sediment type. The rock glaciers were slightly pushed by the glacier during the advance and can be followed below remnants of glacier ice inside the area affected by the LIA advance. This picture represents a daily scene obtained by an automatic digital camera.

In order to follow the accumulation of avalanche snow at the head of the rock glaciers and the snow cover variations in general, an automatic digital camera (CAM19) has been installed in the mountain slope above the rock glaciers. This camera obtains one daily scene at noon on a year-round basis (Fig. 7). Two additional cameras (CAM22 and CAM23) are installed within the area covered in figure 7, providing more detailed visual information on melting of the debris covered lower part of lower Larsbreen glacier and geomorphic activity at the head of the rock glaciers, respectively.

**Meteorological controls on rock glacier distribution**

Meteorological observations is being measured at several, active rock glaciers in Svalbard and in Greenland. Some other useful meteorological information relating to active rock glaciers may be obtained from published literature, although only at few rock glaciers measurements are being carried out. The diagram below indicate most of the present knowledge on meteorological conditions at the head of active rock glaciers, worldwide.
Figure 8. Precipitation-temperature diagram showing the meteorological position of various ELA's and active rock glaciers, worldwide. It is seen, that most rock glaciers, talus-derived or glacier-derived, apparently are formed at near-glacial climatic conditions.

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