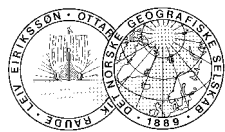


Geometry and dynamics of two lobe-shaped rock glaciers in the permafrost of Svalbard

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Photogrammetric measurements of geometry, thickness changes and horizontal movements over time periods of more than 20 years were performed for two rock glaciers in western Svalbard. The results for Brøggerbreen rock glacier revealed no significant thickness changes (i.e. $<1 \text{ cm a}^{-1}$) and horizontal velocities in the range of a few cm a^{-1} . No significant horizontal or vertical changes over the observation period were detected for a rock glacier at Nordenskiöldkysten. A number of observations, however, indicate slow deformation and advance of the body. Under this assumption, the age of the rock glacier can be estimated in the order of 50 ka, which implies potential impact on the rock glacier by (de-)glaciations and sea level changes. While rock glaciers on Svalbard represent creep of cold and continuous polar permafrost, those in the European Alps are an expression of warm and discontinuous mountain permafrost creep. From inter-comparison of the above results with two rock glaciers in the Swiss Alps, we conclude that the observed differences in creep speed and surface micro-topography could, to a large extent, be explained by the substantial differences in ground thermal regime.

Keywords: *Creep, geometry, rock glacier, Svalbard*

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Preface

This contribution is dedicated to Johan Ludvig Sollid, for a number of reasons: (1) J. L. Sollid was one of the first to recognize the significance and distribution patterns of rock glaciers on Svalbard. He might know more about them than anyone else, having seen most of them himself. He has mapped rock glaciers over the entire Svalbard archipelago (Kristiansen & Sollid 1986, Tolgensbakk & Sollid 1987, Sollid & Sørbel 1992). (2) J. L. Sollid is a propulsive and tireless power behind the strong cooperation between the University of Oslo and the Universities in Zurich in the field of permafrost – cooperation that has led to a number of scientific fruits in Svalbard (Hoelzle 1993, Vonder Mühll 1996, Wagner 1996a, Isaksen 1998, Berthling et al. 1998, Wåle 1999, Isaksen et al. 2000, Berthling et al. 2000, Hauck et al. 2001, Berthling 2001, Eiken et al. 2001, Isaksen 2001) and to stimulating personal experiences. (3) J. L. Sollid initiated the study presented here and led the related field expedition to Svalbard in the summer of 2000.

The reason J. L. Sollid's name does not appear among the authors of this paper is because it is dedicated to him. With this contribution we thank him for his unique introduction to rock glaciers on Svalbard, phenomena which are so typical for this polar archipelago.

Introduction

Creeping mountain permafrost, so-called rock glaciers, is one of the most striking and visible expressions of the earth's cryosphere. An understanding of the processes involved in rock glacier distribution and evolution significantly con-

tributes to our understanding of landscape evolution in mountainous permafrost regions, in both space and time. Present efforts to improve our knowledge of creeping permafrost focus mainly on spatial approaches, such as inventory analysis, or on process-oriented detailed investigation. Precise integrative studies covering geophysics, velocity measurements, topography, etc., exist for a limited number of individual rock glaciers, e.g. in Svalbard (e.g. Berthling et al. 1998, 2000, Isaksen et al. 2000), in the Alps (e.g. Kääb et al. 1997, Haeberli et al. 1998, Kaufmann 1998), in the Rocky Mountains (e.g. Konrad et al. 1999) and in the Andes (Francou et al. 1999). The identification of local effects versus general behaviour can be improved by such studies, and, thus, extraction of the basic controls involved in rock glacier creep. In addition, such knowledge helps us to design a set of uniform tools for future rock glacier investigations and to identify parameters suitable for permafrost monitoring.

In this study, we analyse the geometry and dynamics of two rock glaciers in Svalbard. Inter-comparing these two bodies is aimed at a better understanding of the morphological expressions and evolution of permafrost creep in Svalbard. We relate these studies to studies outside Svalbard, especially in the European Alps, in order to identify common controls and differences. For our two detailed studies in Svalbard, rock glacier geometry is derived from large-scale aerial stereo-photography taken by the Norwegian Polar Institute. Digital photogrammetric techniques are applied to acquire high-resolution digital terrain models (DTMs; cf. Kääb et al. 1997, Kääb & Vollmer 2000). Surface geometry profiles were measured directly or interpolated from high-resolution DTMs. Ortho-images were computed digitally using the scanned images and the respective DTMs. Surface

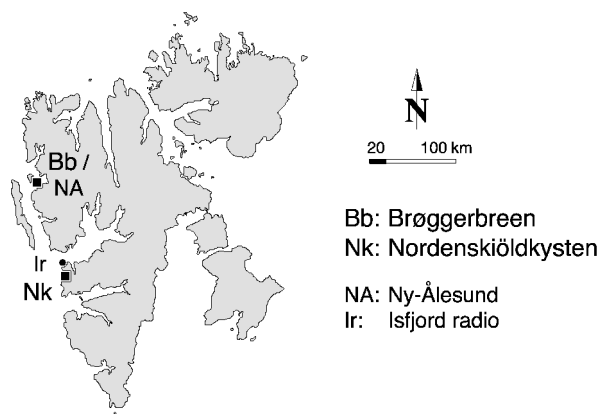


Fig. 1. Location of the study sites in Svalbard.

displacements were determined automatically using correlation techniques applied on repeated digital ortho-images (Kääb & Vollmer 2000).

Study sites

Brøggerbreen rock glacier (Figs. 1 and 2) creeps down the west slope of Zeppelinfjellet mountain, at the right margin of the tongue of Austre Brøggerbreen, south of Ny-Ålesund (approximately $11^{\circ}52.3'E$, $78^{\circ}54.5'N$). Mean annual air temperature in Ny-Ålesund totals approximately $-6.4^{\circ}C$ and mean annual precipitation approximately 385 mm. The blocks of the rock glacier surface consist of dolomitic limestone and show average diameters of some decimetres, rarely more. Active layer thickness on the rock glacier is between 0.5 m and 1 m in the lower part, and between 1 m and 3 m in the upper part (Hoelzle 1993). Seismic refraction and DC resistivity soundings by Wagner (1996a) gave a rock glacier thickness of up to 50 m at the front. Permafrost thickness is estimated to be 150 m or more in the region, i.e. the permafrost base is significantly deeper than the rock

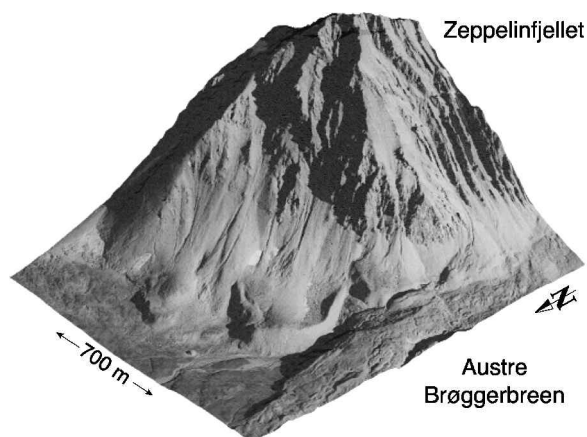


Fig. 2. Brøggerbreen rock glacier (middle) at the tongue of Austre Brøggerbreen near Ny-Ålesund, Svalbard, 1995. Synthetic oblique view based on aerial photograph S95-1086 © Norsk Polarinstitutt.

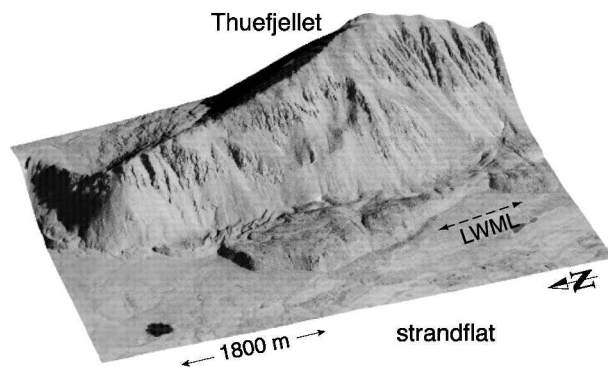


Fig. 3. Rock glacier at Nordenskiöldkysten near Isfjord Radio, 1990. Note the smaller lobate type rock glacier to the very left. The dashed arrow indicates the approximate position of the Late Weichselian Marine Limit (LWML). Synthetic oblique view based on aerial photograph S90-6295 © Norsk Polarinstitutt.

glacier base. Seismic velocities between approximately 3.5 km s^{-1} (front) and 4.5 km s^{-1} (upper part) were interpreted as signs of a generally high ice content, possibly increasing towards the front. Gravimetry suggested an ice content of roughly 50%, partly up to 80% or more in the upper part (Vonder Mühl 1996). Both studies seem to disagree on the spatial variability of the ice content, but also clearly state the uncertainties involved, for instance from snow remains on the upper part. In general, however, a high ice content of the body is clearly indicated by both studies. Geodetic surveying of surface velocities was started by Sollid & Sørbel (1992; see section on dynamics). Morphologically, Brøggerbreen represents the most common type of rock glacier on Svalbard, a lobate type (Liestøl 1962, Barsch 1996), ending on a strandflat area or a flat valley bottom. Lobate-type rock glaciers on Prins Karls Forland, Svalbard have been investigated in detail by Berthling et al. (1998, 2000) and by Berthling (2001) including terrestrial surveying and geophysical soundings.

The second body under study is, basically, also of lobate shape. On a first view, it appears to be situated in a topographic situation similar to Brøggerbreen rock glacier, but shows striking differences in terms of size and surface micro-topography. A number of similar looking phenomena are situated in the Nordenskiöldkysten area. Here, we present results on a rock glacier situated on the strandflat south of Isfjord Radio (approximately $13^{\circ}54'E$ $77^{\circ}53'N$; Figs. 1 and 3). Mean annual air temperature at Isfjord Radio is approximately $-5.1^{\circ}C$, and mean annual precipitation approximately 480 mm. The blocks on the rock glacier surface are of metamorphic origin. First visual inspection indicates that occurrence of the rock glaciers in the vicinity of the one investigated here might be related to variations in headwall geology, i.e. weathering rates and resulting block sizes. The block size on the Nordenskiöldkysten rock glacier varies markedly from a few centimetres to several metres in diameter, showing some spatial systematic zones covered mainly with small blocks and others with predominantly coarse material. Preliminary geophysical results (H. Farbrøt unpubl. data) suggest an ice-rich body with a layered

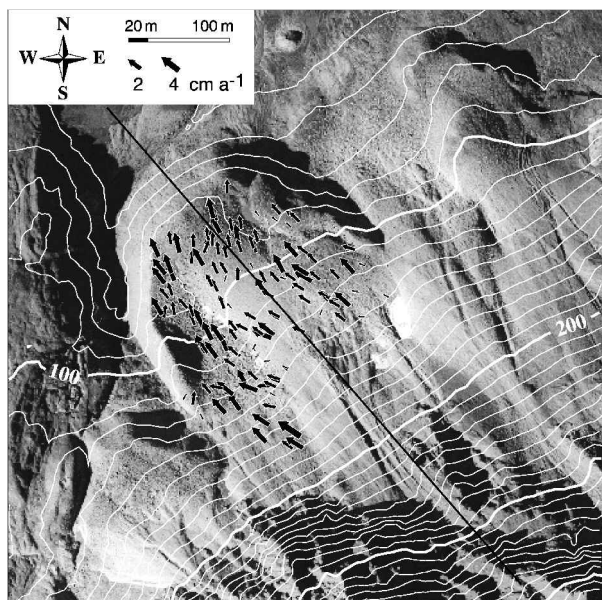


Fig. 4. Orthophoto 1995 of Brøggerbreen rock glacier with overlaid unfiltered surface velocities as measured photogrammetrically from 1971 and 1995 imagery. The straight line indicates the location of the profile in Fig. 6. Base photo same as Fig. 2.

structure and resistivity values typical of Svalbard rock glaciers (cf. Wagner 1996a, Berthling *et al.* 1998, Isaksen *et al.* 2000). Measurements of ground thermal conditions within the rock glacier are not available. As for Brøggerbreen rock glacier, the depth of the permafrost base far exceeds the depth of the rock glacier.

In the vicinity of the investigated Nordenskiöldkysten rock glacier showing complex morphology, smaller lobate-type rock glaciers with simpler morphology similar to the Brøggerbreen rock glacier can be found (Figs. 3 and 5). While the large and complex body faces west towards the strandflat and the sea, the smaller rock glaciers are mainly situated at bottoms of valleys entering the strandflat. For the Nordenskiöldkysten area, visual inspection of aerial photographs and views from a helicopter indicate that there are little or no intermediate forms between both types, suggesting that there are marked differences involved in their evolution.

Geometry and surface characteristics

As in the case of numerous other lobate-type rock glaciers in Svalbard, the most striking geometric characteristics of Brøggerbreen rock glacier are: the smooth micro-topography with no transverse ridge-and-furrow structure visible, and the longitudinal and lateral surface depressions. Longitudinal surface slope decreases from about 35° in the talus to the longitudinal depression, and further up to -7° . The profile section with the latter counter-slope is approximately 25 m long and about 2 m high (Figs. 4 and 6). These numbers lie within the range found for similar rock glaciers on Prins Karls Forland, but indicate a relatively well-developed

depression for Brøggerbreen rock glacier (cf. Berthling *et al.* 1998). The rock glacier front is about 45 m high and up to 40° steep. The lateral depressions on Brøggerbreen rock glacier are perhaps not as typical for this rock glacier type as the longitudinal depression, but can nevertheless be found on numerous other rock glaciers on Svalbard. A sharp and steep ridge marks the left side of the rock glacier. The lateral smooth furrow between the ridge top and the rock glacier centre is up to 10 m or more deep. The coherent and smooth outline of the rock glacier (Fig. 4) and the velocity field (see below section) clearly suggests that the lateral ridges and depressions are part of the rock glacier. The central talus cone on the rock glacier is covered by fine material of several centimetres to a few decimetres in diameter. In contrast, the lateral furrows are covered by significantly coarser blocks, as is the frontal depression (several decimetres in diameter).

A rather different geometry can be observed for the rock glacier at Nordenskiöldkysten (Figs. 3 and 5). A complex system of horizontally bent ridges and furrows covers the body. Depressions amount to approximately 15 m with the

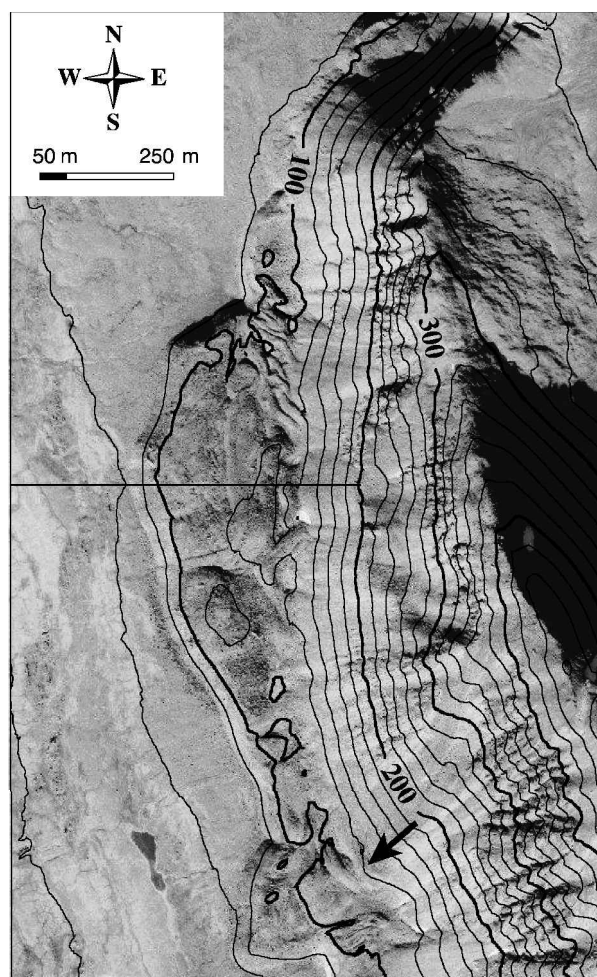


Fig. 5. Orthophoto 1990 of the rock glacier at Nordenskiöldkysten. The arrow to the lower right marks a zone of surface displacements of some centimetres per year over 1969–1990. Elsewhere, no significant movements were detected. The solid line indicates the location of the profile in Fig. 6. Base photo same as Fig. 3.

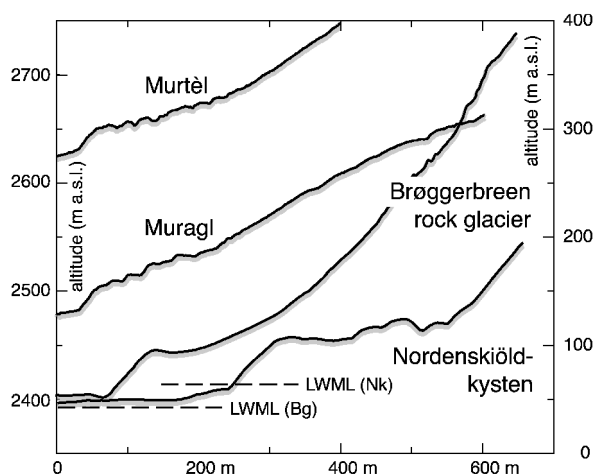


Fig. 6. Longitudinal profiles along the investigated Svalbard rock glaciers, and, for comparison, Murtèl and Muragl rock glaciers, Swiss Alps. The left elevation-axis refers to the Alpine rock glaciers Murtèl and Muragl, the right axis to the Svalbard rock glaciers at Brøggerbreen and Nordenskiöldkysten. The horizontal dashed lines indicate the Late Weichselian marine limit (LWML) for the Brøggerbreen (Bg) and the Nordenskiöldkysten (Nk) area.

largest values close to the talus slope. The front is up to 40 m high and up to 40° steep. A number of individual debris cones enter the rock glacier. Most individual ridges (or furrows) are complexly bent in their horizontal extent, but are coherent over distances of up to several hundred metres (Fig. 5). From the talus foot towards the rock glacier front, the ridges coherently change from being predominantly covered by coarse blocks (up to several metres in diameter) to ridges with fine material on top and on their individual fronts (Fig. 7). Assuming a slow temporal evolution for this sequence rather than a sudden event, several ramps in the lower part of the talus with coarse-block cover might be interpreted as initial stage for the above sequence.

Dynamics and age

Horizontal surface displacements and thickness changes of the investigated rock glaciers were determined from repeated aerial stereo-photography. Imagery of approximately 1:15,000 scale and time intervals of 21 or 24 years, respectively, was available. We estimate the accuracy of the applied change detection to approximately $\pm 1 \text{ cm a}^{-1}$.

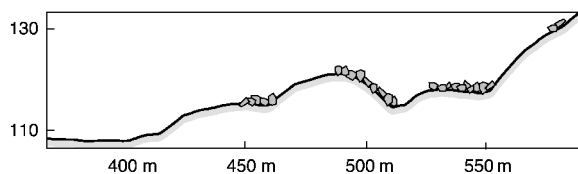


Fig. 7. Schematic detail of the surface profile over the Nordenskiöldkysten rock glacier (Fig. 6). The zones with coarse blocks of 1–2 m in average diameter were mapped from ortho-images of 20 cm ground resolution. Small blocks of some decimetres in diameter or smaller prevail at other places of the surface profile with no specific signature.

RMS for the Brøggerbreen and Nordenskiöldkysten rock glaciers (cf. Kääb & Vollmer 2000).

The photogrammetrically measured surface displacements 1971–1995 for Brøggerbreen rock glacier amount to 4 cm a^{-1} maximum (Fig. 4). Since these velocities are close to the significance level of the method applied, the measured flow field appears noisy (Fig. 4 shows the raw results with no filters applied). In addition, owing to the small block size on the rock glacier, the applied correlation techniques did not work at all places of the surface. Theoretically, erratic movement of individual blocks may therefore add to the overall creep of the frozen body in some places. From digital overlay of the multi-temporal ortho-images, however, it is clear that there is a prevailing coherent deformation of the body with little or no blocks individually displacing or turning over. The displacement rates obtained by Sollid & Sørbel (1992) for Brøggerbreen rock glacier coincide with results by Berthling (2001) for two rock glaciers on Prins Karls Forland, and with results obtained from age/velocity calculations using lichenometry for rock glaciers (André 1994).

Two characteristics of the displacement pattern seem to be significant considering the measurement accuracy: firstly, along the central flow line the velocities decrease slightly towards the surface depression. Secondly, velocities seem slightly higher in the lateral parts, where measurement points are also denser owing to the larger block size. Over long time periods, higher lateral mass flux would lead to a different shape of the rock glacier, with the lateral parts being longer than the centre. Thus, the presently higher lateral surface velocities have to be either a temporary phenomenon or are compensated by a different vertical velocity profile resulting in a lower overall mass flux at the sides than in the centre. The direct digital overlay of the ortho-images suggests that the movement observed for the lateral depressions is mainly due to coherent deformation; it does not give any information on the velocity variation with depth. No significant changes in thickness during 1971–1995 were detected, i.e. possible changes are less than 1 cm a^{-1} .

Estimating the age of Brøggerbreen rock glacier from its surface velocities leads to a surface age of up to 7 ka and a total age of 10–20 ka, i.e. a late glacial age (cf. Isaksen 2001). This age assessment agrees well with analogous calculations by Berthling (2001). Estimating the evolution time of the rock glacier from cliff erosion (cf. Berthling 2001) gives roughly 50 ka per 0.1 mm a^{-1} cliff retreat rate for a body of 40 m average thickness, 150 m length, 50% ice content and 400 m cliff height. For a reasonable 0.3 mm a^{-1} cliff retreat rate, for instance (cf. André 1997, Berthling 2001), the corresponding age estimate totals 20 ka. The difference between our estimate and the one obtained from lichenometry by André (1994; 3–4 ka) can be reduced significantly by correcting the latter value for the conveyor-belt effect which makes the oldest, i.e. frontal, surface material falling over the front and be buried by the advancing rock glacier (Haerberli et al. 1998).

A crucial assumption necessary when calculating rock glacier ages from present-day velocities consists in neglecting differences between the actual velocities and the average velocities over the entire rock glacier evolution. We consider

this assumption to apply for the following reasons: (1) similar age estimates for a rock glacier in the European Alps gave good agreement between the calculated surface isochrones and the surface topography, which reflects the cumulative deformation of the frozen body (Kääb et al. 1998). (2) For Brøggerbreen rock glacier and rock glaciers on Prins Karls Forland (Berthling 2001), age estimates from surface velocities agree with respective ages assessed from the mass accumulation by headwall retreat. (3) The sensitivity of ice deformation to temperature changes decreases with decreasing temperatures (see below section on the comparison to other rock glaciers). Thus, rock glaciers under cold permafrost conditions might be comparably insensitive to temperature-induced velocity variations (Irving 2000).

For the rock glacier at Nordenskiöldkysten (Fig. 5), no significant horizontal or vertical displacements were detected between 1969 and 1990. Only in a small section in the talus south of the main terrace coherent displacements of a few cm a^{-1} were found, indicating that permafrost creep is, in general, possible in the area (arrow to the lower right in Fig. 5). The results for the main body show that its movement lies in the range $0\text{--}1 \text{ cm a}^{-1}$. Several observations suggest that its deformation rate, however, is greater than zero: (1) the front has a sharp upper edge and is at the natural slope angle. The blocks on the front show, in contrast to the rock glacier surface, no or sparse vegetation and lichen cover. The clear signs of movement in the active front are interpreted as an expression of deforming ice-rich sediments. (2) The horizontally coherent geometry of individual ridge-and-furrow structures (Fig. 5) points to a slow deformation rather than to a sudden deposition event (e.g. by a rock fall). (3) Similarly, the sequential changes of the longitudinal cross-sections of the ridges from the talus towards the front indicate a continuous evolution (Fig. 7). (4) The outermost part of the front exceeds the Late Weichselian Marine Limit (LWML) indicating some advance of the body over the last 10 ka (Fig. 6, see below section on comparisons for details). (5) With the high ice content indicated by the preliminary geophysical results, a necessary condition for continuous deformation is fulfilled. Thus, the body under study shows clear signs of permafrost creep, i.e. of cumulative deformation of a thermally controlled ice/rock mixture, leading to large-scale stress transmission and steady flow over long time intervals (Haeberli 2000).

Following the above argumentation for a slow evolution of the Nordenskiöldkysten rock glacier, and assuming a maximum average surface speed of 1 cm a^{-1} for it, gives a surface age of $>25 \text{ ka}$, or a total age of at least 50 ka (cf. Isaksen 2001). Assuming the rock glacier is slowly deforming and being fed by headwall erosion allows for an independent age estimate. Building up a body of 200 m length and 40 m thickness from a 200 m high cliff would require approximately 250 ka per 0.1 mm a^{-1} cliff retreat rate and for 0% ice content. Increasing retreat rates and ice content reduce the age estimate proportionally. For a retreat rate of 0.3 mm a^{-1} , for instance (cf. André 1997, Berthling 2001) and an ice content of 40% (cf. Vonder Mühll 1996, Berthling 2001) gives an age estimate of approximately 50 ka . The order of magnitude of this number is in agreement with the age obtained from the surface velocity assessment.

Since most Svalbard rock glaciers are found close to sea level, the isostatic land uplift since deglaciation (and the related appearance of strandflats) might play an important role in their evolution. In fact, the present maximum front extent of the Nordenskiöldkysten rock glacier exceeds the local LWML by about $20\text{--}50 \text{ m}$ horizontally (Fig. 6, LWML of 11 ka B.P. ; Landvik et al. 1987). The front should, therefore, have advanced by at least 0.2 cm a^{-1} on average for the last 10 ka (Eiken et al. 2001). This number supports our above estimates of slow deformation and high age. The development of Brøggerbreen rock glacier seems not to have been affected by the Weichselian shoreline depression (LWML: $35\text{--}40 \text{ m}$, Lehman & Forman 1992; Fig. 6).

Comparisons

Brøggerbreen and Nordenskiöldkysten rock glaciers

When discussing the above results on geometry and dynamics, two comparisons are interesting: (1) that between Svalbard rock glaciers and (2) that between Svalbard rock glaciers and others.

The major similarity between the Brøggerbreen rock glacier investigated and the Nordenskiöldkysten rock glacier is their topographic situation. It can clearly be seen from rock glaciers in the vicinity of the Nordenskiöldkysten rock glacier that rock glaciers can develop in the area. And, vice-versa, there is no obvious reason why there shouldn't be a rock glacier just at the situation of the one investigated here. The major differences between the two bodies under study consist in their morphology and age. The complex morphology of the Nordenskiöldkysten rock glacier indicates some process taking place or having taken place, respectively, which did not affect the Brøggerbreen rock glacier. The comparable old age of the Nordenskiöldkysten rock glacier and its proximity to the LWML suggest a potential influence by glaciation and corresponding relative sea level changes (cf. Sollid & Sørbel 1992, Humlum 1998, Humlum 2000, Berthling 2001). The differences in both age and morphology might be interconnected in that, for instance, glaciation of the area affected the rock glacier or the related talus slope, or the sea level stopped its advance or eroded the front. Such processes might not have influenced the younger Brøggerbreen rock glacier, as indicated by the Holocene Brøggerbreen lateral moraines to the west of the rock glacier (Figs. 2 and 4). Furthermore, in case of some 50 ka age for the Nordenskiöldkysten rock glacier it was certainly exposed to significantly larger climate variations potentially affecting its geometry and dynamics.

Other rock glaciers

As already explained, the results on geometry and dynamics of Brøggerbreen rock glacier agree with the results found for Prins Karls Forland in all respects indicating similar processes involved (Berthling et al. 1998, Berthling 2001). Extensive information is also available for two tongue-shaped rock glaciers near Longyearbyen, Svalbard, a rock glacier type seldom found on the archipelago (Isaksen et al.

2000). MAAT at Hiorthfjellet and Birkafjellet rock glaciers is estimated to -9°C or -10°C , respectively. Surface slope ranges from 10° to 20° , horizontal velocities from 0.05 m a^{-1} to 0.1 m a^{-1} . Surface age was estimated to approximately 4 ka, with a total rock glacier age correspondingly higher. Results from rock glaciers similar to the Nordenskiöldkysten glacier are not available. Humlum (2000) estimated Holocene headwall retreat rates from rock glacier volumes on Disko Island, Greenland, obtaining rates of an order of magnitude higher than those applied here. The, in general, smaller size of the Svalbard rock glaciers compared to those in Humlum's study suggests (1) lower headwall retreat rates (cf. Wahrhaftig & Cox 1959, Humlum 2000), (2) lower deformation rates, and/or (3) lower ages for the Svalbard rock glaciers.

Rock glaciers in Svalbard are an expression of cold and continuous polar permafrost with temperatures well below zero. Such rock glaciers are usually underlain and surrounded by continuous permafrost with thickness in the order of 10^2 m . Active layer depth ranges from a few decimetres to rarely more than 2 m (cf. above description of the study sites; Sætersdal 1977, Liestøl 1980, Bakkehøi 1982, Bakkehøi & Bandis 1987, Humlum 1997, Åkerman 1998, Isaksen et al. 2000, Isaksen et al. 2001). For comparing Brøggerreen rock glacier to rock glaciers under 'warm' and discontinuous high-mountain permafrost we select two in the Swiss Alps with detailed data available. Such rock glaciers are underlain by no or only thin permafrost in the order of 10^1 m thickness. They usually enter patchy permafrost occurrences or even permafrost-free terrain. Active layer depths exceed depths for the polar rock glaciers by some metres. In contrast to the above polar rock glaciers, their thermal and spatial proximity to melting conditions makes them more sensitive to spatio-temporal changes of boundary conditions (e.g. Haeberli 1975, King & Åkerman 1993, King 2000, Hoelzle et al. 2001, and below site descriptions).

Borehole measurements and geophysical investigations for the rock glacier Murtél, Upper Engadine, Grisons have given information about the internal structure and deformation (Vonder Mühll 1991, Vonder Mühll 1993, Wagner 1996b, Haeberli et al. 1998, Vonder Mühll et al. 1998, Haeberli et al. 1999, Hauck 2001, Hoelze et al. 2002). Beneath the 3–5 m thick active layer consisting of coarse blocks, two main layers of the rock glacier were found: an upper one with a high ice content of 90–100% by volume, and a lower one of coarse blocks with ice-filled pores but without fine material (around 40% ice content). Two-thirds of the total horizontal deformation takes place in sand-rich ice at the depth of 28–30 m, i.e. in the transition zone between the above-mentioned two main layers. The remaining third of the deformation is distributed within the overlying ice-rich main layer. Mean annual ground temperature at the permafrost table is estimated at approximately -2.5°C . Mean annual air temperature at the borehole is approximately -2.5°C , precipitation about 800–900 mm. The permafrost base under the rock glacier might be at a depth of *c.* 100 m, presumably emerging towards surface in front of the rock glacier, and with a talik at *c.* 55 m depth. Moss remains found at a depth of 6 m were ^{14}C dated to about 2300 years BP calibrated calendar age (Haeberli et al.

1999). Measured surface velocities range from about 0.15 m a^{-1} in the upper part to 0.05 m a^{-1} in the lower part, and revealed a frozen body coherently deforming in space and time (Kääb et al. 1998). No velocity variations could be observed to have taken place since 1987 (Hoelzle et al. 1998). During 1987–1996, Murtél rock glacier thinned by *c.* -4 cm a^{-1} on average (Kääb et al. 1998).

In contrast to the Murtél rock glacier, the average surface block size on Val Muragl rock glacier, Upper Engadine, Grisons, is much smaller by some decimetres in diameter. Borehole measurements and geophysical soundings (Barsch 1973, Vonder Mühll 1993, Arenson & Springman 2000) gave an active layer thickness of about 2–7 m and up to 20 m behind the front. No marked permafrost occurrence is found in front of the Muragl rock glacier, i.e. the creeping permafrost enters a more or less permafrost-free area. During recent geophysical work a low ice content of only a few percent was encountered (Arenson & Springman 2000). A large part of the total horizontal deformation seems to take place in a shear horizon at about 15 m depth. The borehole measurements indicate temperatures of close to 0°C , and the permafrost base in about 20 m depth. Mean annual air temperature is about -1.5°C , precipitation about 800–900 mm. Estimates for the rock glacier age and its dynamic history are given in Frauenfelder & Kääb (2000). Average surface velocities amount to 0.5 m a^{-1} , with large seasonal variations (Kääb & Vollmer 2000, Kääb & Frauenfelder 2001). Muragl rock glacier showed 1981–1994 a pattern of heavings and settlements in the range $\pm 10\text{ cm a}^{-1}$, which seems largely related to the local strain regime of compression and extension (Kääb & Vollmer 2000). As with many high-mountain rock glaciers, both the Murtél and Muragl rock glaciers are characterized by a transverse ridge-and-furrow micro-topography (Fig. 6).

The only other rock glacier with comparable data available is Galena Creek rock glacier, Wyoming. The conditions found for this rock glacier compare well with those for the Murtél and Muragl rock glaciers: 1–2 m surface debris, underlying 25 m of massive ice, ground temperatures -1 to -2°C , surface velocities up to 1 m a^{-1} , surface slopes up to 20° , in places 30° (Konrad et al. 1999).

The most important external differences between the two Alpine and two Svalbard locations might consist in the climate and related ground thermal regime with MAATs around -5°C to -6°C for Svalbard and -1.5°C to -2.5°C for the two Alpine sites. Measured mean annual ground surface temperatures (MAGST) are close to 0°C and -2.5°C for Muragl and Murtél, respectively. Corresponding measurements are not available for the two Svalbard sites. MAGST is estimated to be similar or slightly higher than the respective MAAT (cf. Hoelzle et al. 2001, Isaksen et al. 2001). Assuming that the bodies behave like bodies of pure ice allows for estimating the potential influence of ice temperature variations on the resulting deformation from Glen's flow law and empirical values for the rate factor *A* (Paterson 1994, 97). For massive ice under comparable conditions for surface slope, thickness, etc., a decrease of surface deformation by a factor of 3 between 0°C and -3°C ice temperature, and by 1.5 between -3°C and -6°C (5 between 0°C and -6°C) could be expected (cf. Azizi &

Whalley 1996). Such non-linear effect of ice temperature on the deformation rate factor of massive ice is, in principle, expected also to apply for ice-debris mixtures, as suggested by centrifuge modelling (Irving 2000, Rea et al. 2000, Davis et al. 2001).

Within the accuracy of such rough assumptions, the order of magnitude for the speed differences between both Muragl and Murtél and Murtél and Brøggerbreen rock glaciers are not surprising. Taking into account the low overall slope of the Nordenskiöldkysten rock glacier, also a surface deformation of less than 1 cm a^{-1} for this body is expected.

Analogously varying the ice content instead of the ice temperature by introducing solid rocks within the ice to Glen's flow law affects the ice deformation in two counter-acting ways: (1) the content of un-deformable material reduces the total deformation. (2) Higher density of ice inclusions compared to the ice itself increases the mass of the body and, subsequently, the shear stress. Neglecting any additional boundary effects at the ice-rock contacts, velocity variations from ice-content differences in the order of 100% to 200% can be expected and are, thus, also able to, at least partially, explain the observed differences in speed (cf. Azizi & Whalley 1995, 1996).

It is clear to us that simplifying a rock glacier as a body of massive ice is critical, since permafrost creep is not just a matter of ice temperature, thickness and slope, but also a function of, for instance, ice properties, ice/debris content, debris properties, ice and debris supply, or hydraulic conditions, with no universal creep law known. The above-mentioned observations for the Muragl rock glacier with low ice content and comparable high speed suggest that a high ice content is not a necessary precondition for high deformation as long as there is ice super-saturation (Arenson & Springman 2000, Irving 2000). At least at temperatures close to the melting point, the non-linear increase of deformation with ice temperature might be able to overcompensate for the effect of reduced deformation by reduced ice content. The above estimation points to temperature as a potential control of rock glacier deformation, but does not exclude the importance of factors such as ice content.

The colder ground temperatures for the Svalbard rock glaciers compared to the Alpine ones potentially lead to higher viscosity of the frozen mass, as also indicated by the lower surface velocities. Considering higher viscosity and the flat topography for most Svalbard rock glaciers (strandflat or flat valley, respectively), smaller longitudinal extent and higher rock glacier fronts (indicating larger thickness) can be expected. The deformation of cold ice is less sensitive to temperature variations than the deformation of warm ice (Patterson 1994, 97, Davis et al. 2001, Kääb & Frauenfelder 2001). Therefore, lower rates for spatio-temporal variations in speed can be expected for the Svalbard rock glaciers. In addition, the influence of three-dimensional straining on the geometry of the creeping body is reduced with reduced velocities. Both effects might to some extent explain the observed smoother surface topography of Brøggerbreen rock glacier compared to the two Alpine ones (cf. Fig. 6).

Most studies on area-wide three-dimensional geometric changes of rock glacier surfaces reveal vertical variations to be only some fraction of the horizontal displacement rates

(e.g. Kääb et al. 1997, Kääb et al. 1998, Kaufmann 1998). Thus, the lack of significant thickness changes for the Brøggerbreen and Nordenskiöldkysten rock glaciers is not surprising. Thermokarst processes, an important factor of landscape evolution in arctic environments, seem not to have played a major role in the case of the investigated Svalbard rock glaciers over the observation period. Also the Alpine rock glaciers, although much closer to the melting point, are not much affected by differential melting from thermokarst processes, a further indication of their thermal inertia.

Conclusions and open questions

Our observations and analyses on the geometry and dynamics of the Brøggerbreen rock glacier agree well with previous work on similar rock glaciers on Prins Karls Forland by Berthling et al. (1998, 2000) and Berthling (2001). For the Nordenskiöldkysten rock glacier, a number of independent arguments point to this body as also being a rock glacier. Our study suggests that a major difference between the two types of Svalbard rock glaciers might simply consist in their age (10 ka to 20 ka for Brøggerbreen versus roughly 50 ka for Nordenskiöldkysten). The latter high age, however, implies a number of potential (or even probable) impacts on the body by (de-)glaciations or relative sea level changes (Sollid & Sørbel 1992, Eiken et al. 2001). This, in turn, could make these features important paleo-climatic indicators in a region with rare traces of glaciation.

The differences in ground thermal regime, topographic setting and age between Svalbard and Alpine rock glaciers potentially explain a number of differences found in their geometry and dynamics. Expected different viscosity between Svalbard and Alpine rock glaciers could, in general, be explained by differences in ground temperatures when one assumes all other factors of permafrost creep to be comparable. This, however, does not necessarily mean that permafrost temperatures are the governing control on deformation rates of the bodies. The latter is certainly a function of ice/debris content and stratification, thermo-mechanical properties or supply of the involved ice and debris mixture.

Our study could not clarify the discussion on the longitudinal and lateral depressions typical for lobate-type rock glaciers in Svalbard (cf. Liestøl 1962, Swett et al. 1980, Humlum 1982, Berthling et al. 1998). Frequent monitoring by, for instance, an automatic camera could help our understanding of the influence of the snow-cover pattern from avalanching and snow drift (cf. the UNIS project by Ole Humlum 'Mapping snow cover duration, avalanches and other geomorphic processes by automatic digital cameras, Longyear dalen, Svalbard'). Differential frost-heave or thaw-settlement driven by spatio-temporal variations in energy balance and/or melt-water supply could be powerful processes under the cold temperatures and long time scales considered here.

The origin and development of the Nordenskiöldkysten-type rock glaciers is still an open question. Although a number of indicators point to a coherent and slow evolution, additional investigations on the morphology and inner structure, and on the surrounding geology, are necessary if we are

to understand the bodies (H. Farbrøt, unpublished data). Also a combination of sudden deposition from, for instance, rock falls or rock/snow avalanches (Liestøl 1962) followed by ice super-saturation and subsequent continuous deformation might well be possible.

Our study suggests that monitoring three-dimensional changes on Svalbard rock glaciers from special series of large-scale aerial photography could significantly contribute to the investigation of these phenomena.

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