

Advance Mechanisms of Rock Glaciers

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ABSTRACT

Rock glacier advance is believed to be the result of the advection of frozen debris to and over the front, (partial) melt-out of ice, and incorporation and subsequent overriding of the mass at the base of the rock glacier. In this contribution, an approach to measure mass balance and transport within rock glacier fronts is presented. The technique is applied to Gruben and Suvretta rock glaciers, Swiss Alps. The results confirm a 'conveyor belt'-like advance mechanism for both features. At the Gruben rock glacier front, an average excess ice content of approximately 65% was detected, 15% more than at Suvretta rock glacier. The frontal part of Suvretta rock glacier turned out to have a linear velocity profile over the entire thickness. At Gruben rock glacier, the horizontal mass transport is, for the most part, concentrated in a 5–10 m thick surface layer. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: rock glacier; creep; ice content; Swiss Alps

INTRODUCTION

The advance mechanisms of rock glaciers are some of the important characteristics of these creeping mountain permafrost features. In sharp contrast to glaciers, active rock glaciers have to grow continuously in length due to their thermal condition, which limits ice melt and, due to their solids content, is usually not removed from the frontal zone.

Theoretical concepts of rock glacier advance have been developed by Wahrhaftig and Cox (1959) and Haeberli (1985). In their descriptions, they considered different vertical profiles of the horizontal velocities, ranging from pure sliding conditions, to a parabolic velocity profile, to restriction of movement to a surface layer only (Figure 1). From considerations about mass conservation and from velocity profiles found from borehole experiments, Haeberli *et al.* (1998) derived a conceptual model of rock glacier advance: material of the upper layers overrides the lower layers, is subse-

quently deposited in front of the rock glacier, and is finally overridden again by new material from the upper layers ('conveyor belt', or 'caterpillar' effect).

The effective mean advance rate of a rock glacier is a function of several factors: (1) The vertical variation of horizontal velocity, (2) the volume, altered by melting and refreezing of ice and water respectively, within the advancing material where this term refers only to the ice volume which exceeds the pore volume (excess ice), (3) the air content of the rock glacier, material at the front might change during the advance, (4) erosion and removal of solid material is usually limited and restricted to fine fractions of the material or to cases where the rock glacier terminates over steep terrain; accumulation of solids from outside the front system might be only found in rare cases.

The few quantitative field investigations on the advance of rock glacier fronts conducted so far focus mainly on the remote sensing of advance rates (Kääb *et al.*, 1997; Bauer *et al.*, 2003). Koning and Smith (1999) surveyed the movement of blocks above a rock glacier front. These studies reveal a range of ratios between surface speed above the front, on the one hand, and mean advance rate, on the other hand. This

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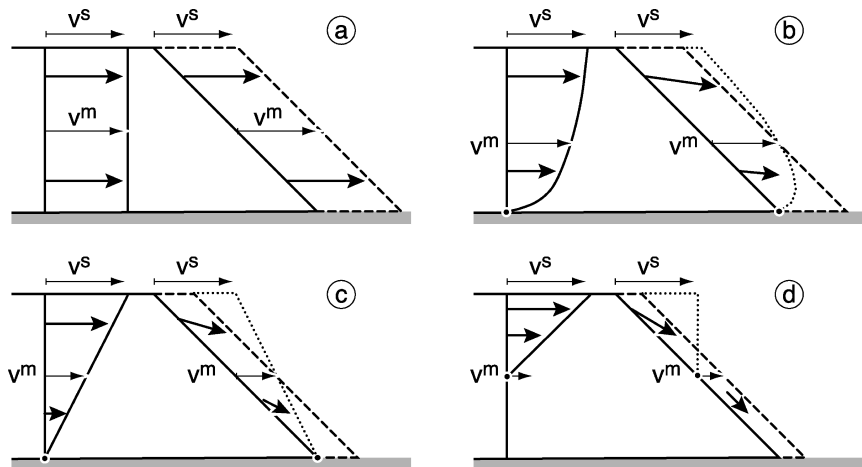


Figure 1 Schemes of rock glacier advance mechanisms as a function of velocity variation with depth (modified according to the present study on the basis of Wahrhaftig and Cox, 1959). The initial vertical velocity profile within the rock glacier is displayed to the left of each individual panel. The dotted line indicates the hypothetical form of the front after the advected mass is horizontally added to the declined front. The dashed line indicates the form of the front after the advected mass has been distributed evenly over the entire front. The degree of the latter mass redistribution influences the particle vectors (bold arrows) within the front. The thin horizontal arrows indicate the surface velocity (v^s) and the mean velocity (v^m) of the deforming column. Ice melt is neglected in the schemes. Letters (a)–(d) referred to in the text.

finding indicates a significant variation of the processes involved in the advance among different rock glaciers.

Here, we attempt to quantify three-dimensional kinematics in rock glacier fronts using a novel measurement approach. After introducing this measurement method, we discuss corresponding results for two rock glacier fronts in the Swiss Alps.

MEASUREMENT METHOD

For the study presented here, 1–2 m long steel rods were placed at the front of Gruben and Suvretta rock glaciers, Swiss Alps, and their behaviour was monitored over a period of several years until the rods were destroyed. The aim of this approach was to track the position of the rod head *B* and the head *A* of a removable extension (Figure 2) by polar survey using an electronic theodolite, which includes a laser ranger, servo motors and an automatic reflector targeting device (automatic total station TCA 1102 by Leica Geosystems). Terrain surface *C* at the intersection with the rod and the end of the rod *D* can then be computed:

$$\vec{C}(t) = \vec{B}(t) + \frac{\vec{B}(t) - \vec{A}(t)}{e} \cdot o(t) \quad (1)$$

and

$$\vec{D}(t) = \vec{B}(t) + \frac{\vec{B}(t) - \vec{A}(t)}{e} \cdot l \quad (2)$$

where the Cartesian coordinates of points *A* and *B* are directly measured, the extension *e* and the rod length *l* are known, and the offset *o* from the rod head to the front surface is measured. By this approach, the three-dimensional behaviour of the front material can be observed to a depth of 1–2 m.

In this work, the maximum distances from the total station to the rods were about 70 m for Gruben and about 120 m for Suvretta. From this distance, from the

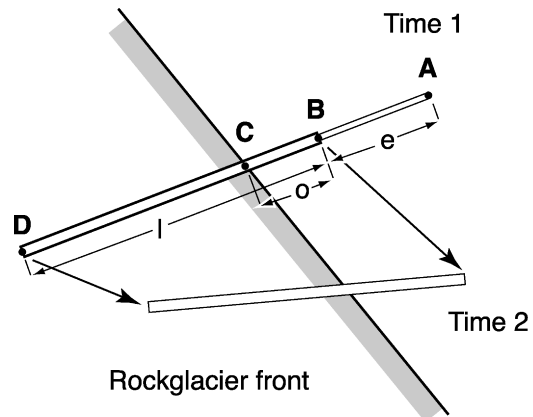


Figure 2 Measurement principle used for determining three-dimensional displacements in a rock glacier front from surveying of steel rods. *e* is the length of an extension fixed only during survey campaigns; *o* is the length of the measurement rod above surface, measured at each survey campaign. The positions of points *A* and *B* can be measured, the positions of points *C* and *D* can be calculated using vector algebra.

precision of the instrument used and from control measurements to stable points the accuracy of the individual coordinates obtained is estimated at the order of ± 1 cm root mean square.

RESULTS

Gruben Rock Glacier

Gruben rock glacier is located near the Fletschhorn in the Saas valley, Canton of Valais, central Swiss Alps. Detailed analyses and discussions of the Gruben rock glacier kinematics can be found in Kääb *et al.* (1997) and Kääb (2004). Shallow core drilling, geophysical soundings and lichen-cover studies have been conducted on the rock glacier (Barsch *et al.*, 1979; Haeberli *et al.*, 1979; Haeberli, 1985; King *et al.*, 1987).

Figure 3 shows the measurement setting in the Gruben rock glacier front. At point nos. 1–6, rods as described above were installed; at point nos. 7–9, small metal bolts were drilled into big blocks and only their velocity but not their rotation, was monitored. Figure 4 depicts the position of the rods over time. The main results for the individual rods are:

- No. 6: strong surface-parallel displacement and horizontal emergence; advance of front; downward tilting; rod destroyed after third measurement.
- No. 5: mainly surface-parallel displacement; little front advance; downward tilt; some emergence; rod presumably bent after second measurement.

Elevation (m ASL)

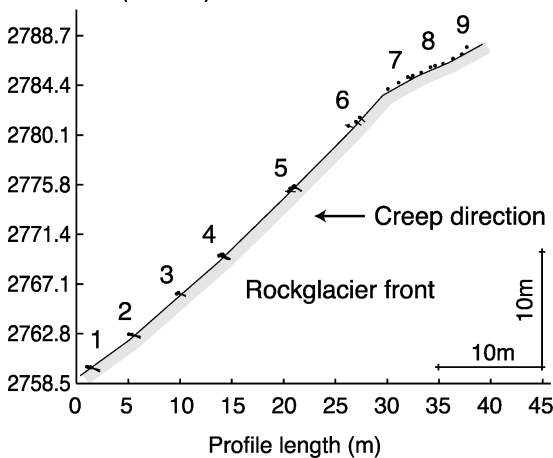


Figure 3 Cross-section of the front of Gruben rock glacier with steel rods for deformation measurement.

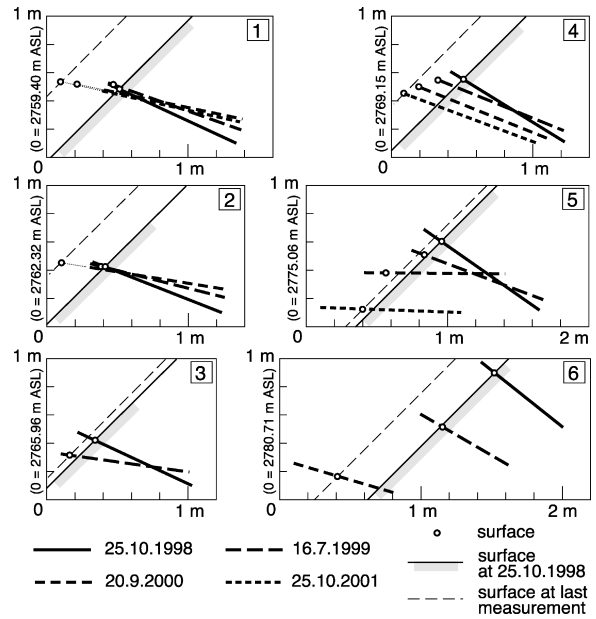


Figure 4 Gruben rock glacier front: detailed displacement of the individual rods in Figure 3. Rod nos. 1 and 2 were buried by debris during the observation period. The rod heads are thus located below the surface (small circles).

- No. 4: only slight surface-parallel displacement; horizontal front advance; downward tilting, some submergence.
- No. 3: surface-parallel displacement; downward tilting; some submergence; rod destroyed after second measurement and possible already damaged after first period.
- Nos. 2 and 1: little to no displacement, tilting; significant advance of the front combined with submergence of the rods; rod no. 2 was lost after the third measurement.

At the last measurement date, most rods were damaged or covered by debris.

The horizontal velocity components of the rods and bolts (Figure 5) reveal a slow, nearly block-wise movement for the lower 15 m of the front. For the uppermost 5 m a sharp increase in velocity magnitude to an amount nearly as high as the surface speed can be observed. The horizontal speeds at bolts 7–9 are similar or slightly higher as compared to the speed measured on the basis of multi-temporal photogrammetry (cf. Kääb *et al.*, 1997). The average advance rate of approximately 0.12 m a^{-1} obtained from the rod measurements is identical to the one obtained from photogrammetry between 1970–1995 (Kääb *et al.*, 1997).

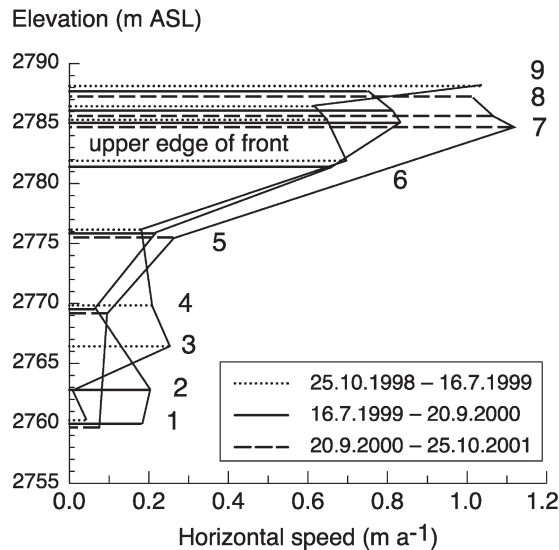


Figure 5 Vertical profile of the horizontal component of rod displacements over the front of Gruben rock glacier.

Suvretta Rock Glacier

Suvretta rock glacier is situated in the Upper Engadine, Canton of Grisons, eastern Swiss Alps. The surface velocity field, thickness changes and the age of the rock glacier have been discussed by Kääb (2000), Frauenfelder *et al.* (2004), and Kääb (2004). Geophysical soundings on Suvretta rock glacier have been presented by Vonder Mühll (1993).

At point nos. 1–4 in the Suvretta rock glacier front, rods were installed, and at point nos. 5–7 bolts were affixed to large rocks (Figure 6). A significantly

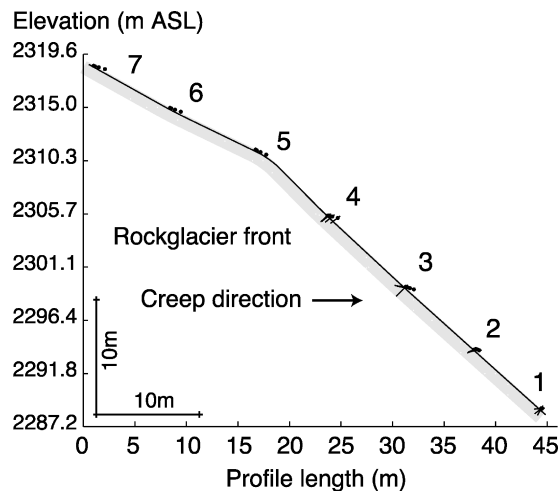


Figure 6 Cross-section of the front of Suvretta rock glacier with steel rods for deformation measurements.

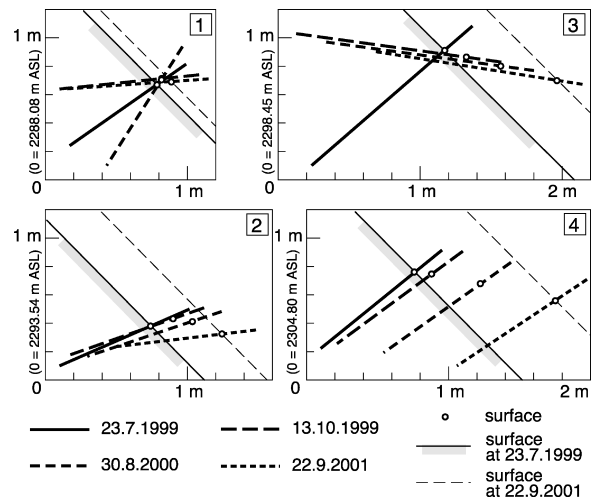


Figure 7 Suvretta rock glacier front: detailed displacement of the individual rods in Figure 6.

different behaviour is observed for Suvretta rock glacier, compared to that of the Gruben rock glacier front. The main results for the rod movement are (Figure 7):

- No. 4: strong horizontal displacement; only slight downward component; little to no tilt; no significant emergence or submergence.
- No. 3: strong horizontal displacement; only slight downward component; no significant tilt; no significant emergence or submergence; after the first measurement the rod was obviously hit by rockfall and bent.
- No. 2: almost exclusively horizontal displacement; minimal submergence; slight tilting and an upward component presumably caused by rockfall impact and displacement of large, individual boulders around the rod.
- No. 1: slight horizontal displacement; strong impact and bending caused by rockfall impact and individually displacing large boulders around the rod.

Similar to Gruben rock glacier, most rods were damaged or covered by debris at the last measurement date.

The horizontal velocity components of the rods and bolts (Figure 8) reveal a linear to slightly parabolic increase towards the upper edge of the front. Surface velocities above the front are slightly higher than for the uppermost rod. The horizontal speeds at bolts 5–7 are almost identical to the speed obtained from multi-temporal photogrammetry (0.5 m a^{-1}) (Kääb, 2000).

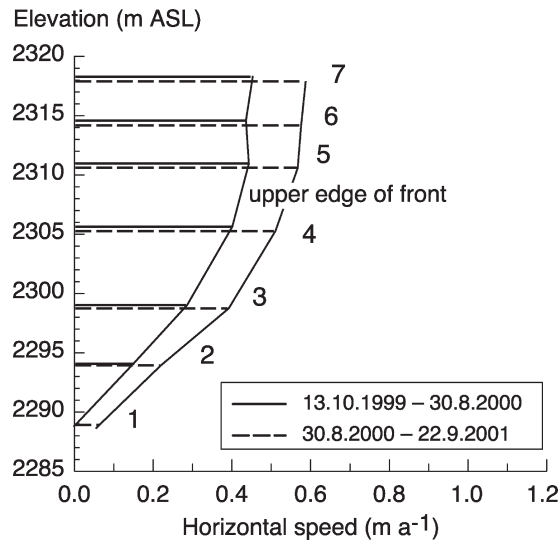


Figure 8 Vertical profile of the horizontal component of rod displacement over the front of Suvretta rock glacier.

The average advance rate from the rod measurements of approximately 0.16 m a^{-1} is identical within the significance level to the 1992–1997 advance rate of 0.18 m a^{-1} from photogrammetry.

DISCUSSION

The findings of this study rely in parts on the measurement rods remaining straight over the observational period. In some cases, either bending was obvious since it took place, for instance, at the airside, or the rod was clearly damaged by rockfall. For the remaining rods possible bending was tested at the observational dates through inserting a smaller rod into the tube-like measurement rods. Finally, a strong discontinuity in the rod deformation over time was treated as sign for rod bending (e.g. Suvretta, rod no. 5).

Gruben and Suvretta rock glacier fronts show significant dynamic differences. The horizontal deformation for Gruben rock glacier front seems to be largely restricted to a 5–10 m thick top layer with at least 0.6 m a^{-1} average horizontal speed. Below this layer a block-wise horizontal speed of about 0.2 m a^{-1} was found. These speed estimates are minimum estimates because thaw settlement originating from greater depths than the rod base reduces the horizontal movement of the rod with respect to the creeping permafrost.

Haeberli (1985) estimated that approximately 30% of the horizontal surface movement could be due to sliding or sediment deformation at the permafrost base. In a 7 m deep borehole on Gruben rock glacier Barsch *et al.* (1979) found a blocky active layer of about 2 m depth (cf. Haeberli, 1985), and layers of frozen gravel, frozen sand and ice from 2 to 7 m depth. These findings neither contradict nor confirm a potential shear horizon of sandy ice within the upper 7 m.

The significant downward component of front material and the observed tilt of the rods complete the picture of a surface layer creeping and eroding over the upper front edge. In sum, Gruben rock glacier front seems to act as a combination of cases (a) and (d) in Figure 1.

The average horizontal velocity over the 25 m vertical column of Gruben rock glacier front amounts to approximately 0.35 m a^{-1} . In contrast, the average actual advance rate of the rock glacier was determined at 0.12 m a^{-1} . Some 60–70% of the frozen mass has, therefore, to be removed by thermal or mechanical erosion. Since the Gruben rock glacier front lies in a vegetated plain, or even depression, with no sign of substantial material transport, erosion of solids can be excluded for the most part. Thus, the measurements revealed a thaw settlement, indicating an average excess ice content of about 60–70% for the frontal part of Gruben rock glacier.

Both the velocity profile and the rod tilt measured for Suvretta rock glacier front gave a linear to parabolic deformation profile with little downward displacement over the front. Speed tends to zero towards the rock glacier base. In contrast to Gruben and other rock glaciers (Arenson *et al.*, 2002), deformation in the frontal part of Suvretta rock glacier seems to be distributed over the entire column but not concentrated in thin shear zones. The average horizontal velocity over the 20 m thick front is approximately 0.3 m a^{-1} , contrasting with the average advance rate of 0.16 m a^{-1} . In sum, Suvretta rock glacier front seems to advance like mechanisms (b) or (c) in Figure 1. The overall excess ice content in the frontal part of Suvretta rock glacier can be estimated at about 50%. Removal of fine solids might play some minor role for the topographic condition found at Suvretta rock glacier. Changes in air content are neglected.

Strictly speaking, the deformation of the measurement rods is only able to reflect the deformation of the upper 1–2 m of the rock glacier fronts. In that way, a significant downslope surface creep was found for the Gruben rock glacier front. The rod measurements alone do not permit us to draw conclusions about the thickness of this surface layer. However, at rods where no strong downward component was observed

this surface effect can largely be ruled out, and the rods reflect the deformation of depths exceeding the rod length. In the case of pure downslope surface creep, no advance would be observed theoretically except some compression from mass accumulation at the front foot. The fact that the upper front sections also advanced significantly further supports the suggestion that the rods reflect more than just a downslope surface creep of the uppermost layer of the front.

CONCLUSIONS

In conclusion, the excess ice content within the frontal part of Suvretta rock glacier (about 50%) may be some 15% lower than for Gruben rock glacier (about 65%). The excess ice content for both rock glaciers lies in the range found from boreholes within Murtèl rock glacier, and above the values for Muragl and Schafberg rock glaciers (Arenson *et al.*, 2002). The measurements confirm that material is transported towards and down the rock glacier fronts, then incorporated at the bottom of the advancing permafrost body, and, finally, overridden by it (see Figure 1). The solid material creeping over the front seems not only to be eroded at the front by individual rockfall or debris flow events, but also to coherently creep down the front as suggested by the continuous deformation of the measurement rods over time (cf. Bauer *et al.*, 2003).

The presented study confirms the findings from previous geophysical and borehole studies that the vertical velocity profile and the ice content between individual rock glaciers can vary significantly. These differences are clearly reflected by different advance mechanisms, and can thus be resolved from according measurements. In turn, the differences in advance rate and mechanism have significant impact on the internal age structure of rock glaciers, and on the relations between, for instance, rock glacier length and age, or rock glacier surface velocity and age.

The method described above for measuring the kinematics of rock glacier fronts proved to be highly efficient. The characteristics of the advance mechanism and the ice content could clearly be detected and differences between the flow regime of the two investigated rock glaciers identified. The approach appears to be a simple and cheap alternative to, or a preliminary evaluation before, drillings in order to assess the vertical velocity profile and overall ice content within rock glaciers. The method can be used to estimate the velocity profile and ice content near the front for a large set of rock glaciers. Knowledge of these properties for a larger sample than just a

few individual rock glaciers with drillings available has the potential to significantly improve the understanding of rock glacier dynamics, composition, development, total age and age structure.

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