

Rockglacier occurrence and related terrain parameters in a study area of the Eastern Swiss Alps

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ABSTRACT: Rockglaciers act as a transport mechanism of frozen debris in the periglacial alpine environment, and represent a link in a process chain, combining frost weathering, rock fall, and debris transport by permafrost creep. In this study, the relationship of terrain parameters (rock wall extent, geology, etc.) and rockglacier parameters (rockglacier size, slope, velocity, etc.) are statistically analysed. Two empirical data sets containing information on 84 and 44 rockglaciers, respectively, were used. The results show that a relation between rock-wall extent and rockglacier size indeed exists but is complex and involves factors such as cliff recession rates (as a function of geology, temperature, water content, etc.) and subsequent talus input variations. Concerning flow velocities, the findings indicate that non-linear thermal influences on strain rates probably predominate over effects from stress-related geometry (slope-dependent thickness).

1 INTRODUCTION

Rockglaciers are transport systems of frozen rock debris in the periglacial alpine environment. They are part of a process chain linking frost weathering, rock fall, and debris displacement by permafrost creep. Their development is dependent upon the supply of debris from the source headwall(s) and the long-term preservation of an ice matrix or ice core inducing flow (Morris 1981). According to Barsch (1996) there exists a close relationship between the size of a rockglacier, the size of the source area for its material, and the intensity of talus production in the source area. Olyphant (1983) modelled the rockglacier debris transport system by mathematically linking it to its bedrock-cliff source area and by combining expressions for debris input and rockglacier flow with a continuity approach.

It is often assumed that the transport of debris, i.e. the movement of the rockglacier, follows a viscous deformation law similar to the one of glacier ice (e.g. Wahrhaftig & Cox 1959, Haeberli 1985, Barsch 1996, Konrad et al. 1999). The deformation or creep of rockglaciers can then be described by Glen's flow law (Paterson 1994).

The purpose of this study is to investigate if any topographical and/or rheological relationships can be identified from statistical analyses of regional inventory data. Two main questions are addressed: (a) is there a dependence between rockglacier size and the extent of the debris-supplying source headwall (also known as "rock free face above a rockglacier", e.g. Humlum 2000), and (b) can topographic or climatic controls on transport rates of rockglaciers be identified?

In the presented study, first results from statistical analysis of terrain parameters (rock wall extents, geology, etc.) and their relationship to rockglacier

parameters (rockglacier size, slope, velocity, etc.) are discussed.

2 DATA BASE AND METHODS

Two main data sources are used: *Data set no. 1 (DS#1)* comprises a rockglacier inventory of the Engadin and its adjacent regions as compiled by Hoelzle (1998). The inventory contains spatial data on 84 active rockglaciers. *Data set no. 2 (DS#2)* contains selected measurements on 44 rockglaciers in eleven different regions of the European Alps and the Rocky Mountains sensu lato as compiled from publications of various authors.

In *DS#1*, information on length (l_{RG}) and width (b_{RG}) for each rockglacier was extracted from the inventory. Additional data such as height (l_F) and width (b_F) of the source headwall, average slope of the rockglacier body (α_{RG}), and dominant rock types were compiled using a digital elevation model, and both digital and analogue maps of the region (Fig. 1). This data was then used to explore the relation between parameters of the debris source area, i.e. the source headwall, and the spatial extents of the rockglacier bodies.

In *DS#2*, information relating to rockglacier rheology was compiled from published literature and map evaluation. The following parameters were derived (cf. also Fig. 1): rockglacier length (l_{RG}), elevation of rockglacier front (H_{min}), average slope of the creeping body (α_{RG}), mean and maximum surface velocity (v_{mean} , v_{max}), altitude of regional 0°C-isotherm and regional temperature lapse rate. Using regional temperature lapse rates and altitude of the 0°C-isotherm, the mean annual air temperature at the front of each presently active rockglacier was estimated ($MAAT_{RGF}$). For several rockglaciers in the Swiss Alps, where digital

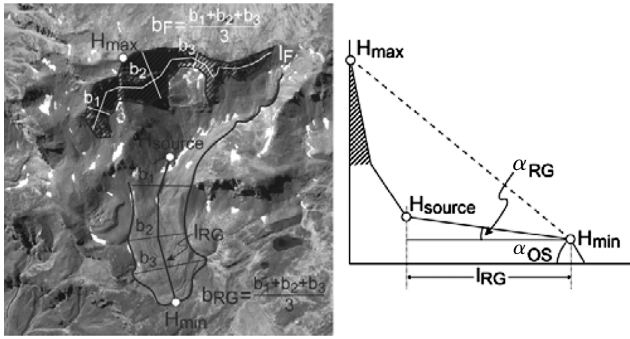


Figure 1. Schematic sketch displaying the parameters measured and discussed in the text. Black-and-white aerial photograph of the Swiss Federal Office of Topography, 1.9.1999, Flight-line 116, Image-No. 2641.

terrain models are available, potential direct solar radiation at the rockglacier front was computed.

3 RESULTS

3.1 Debris supply and rockglacier size

Concerning the source of debris, 64 of the rockglaciers in *DS#1* presumably originated from periglacial talus. The other 20 rockglaciers developed from glacier-transported debris (mostly lateral and terminal moraines); the first group of rockglaciers will be referred to as talus-derived rockglaciers, the latter as moraine-derived rockglaciers. Different interactions of the various parameters analysed might apply for these two groups of rockglaciers, a fact which is accounted for in the interpretations.

Mean length (l_{RG}) of the talus-derived rockglaciers amounts to $410 \text{ m} \pm 209 \text{ m}$ (min = 125, max = 1274), mean width (b_{RG}) to $136 \text{ m} \pm 64 \text{ m}$. The mean source headwall above such a rockglacier is $117 \text{ m} \pm 77 \text{ m}$ high (l_F) and $405 \text{ m} \pm 255 \text{ m}$ wide (b_F). Average values for a moraine-derived rockglacier are slightly higher, with $l_{RG} = 487 \text{ m} \pm 207 \text{ m}$, $b_{RG} = 154 \text{ m} \pm 61 \text{ m}$, $l_F = 110 \text{ m} \pm 88 \text{ m}$, and $b_F = 499 \text{ m} \pm 273 \text{ m}$. In general, the talus-derived rockglaciers in the Engadin are somewhat smaller in size (mean area = ca. $57,700 \text{ m}^2 \pm 45,500 \text{ m}^2$) than moraine-derived rockglaciers (mean area = ca. $79,000 \text{ m}^2 \pm 40,100 \text{ m}^2$). The mean source headwall area, approximated by mean height multiplied by mean width, is similar for both types of rockglaciers with a mean area of $50,000$ to $53,000 \text{ m}^2$.

To investigate the possible dependence of rockglacier size on source headwall area, we performed three analysing steps: Firstly, the relationship between rockglacier length (l_{RG}) and source headwall area (A_F) was analysed. Rockglacier length (l_{RG}) is the simplest parameter describing rockglacier extent. However, it is only one proxy of the three dimensions

Table 1. Correlation values for different parameters of talus-derived rockglaciers and moraine-derived rockglaciers when compared versus source headwall area.

Analysis type	Talus-derived r-value	Moraine-derived r-value	All r-value
l_{RG} vs. A_F	0.56	0.32	0.49
A_{RG} vs. A_F	0.58	0.66	0.55
A_{RG} vs. $A_{F, \text{weighted}}$	0.62	0.33	0.55

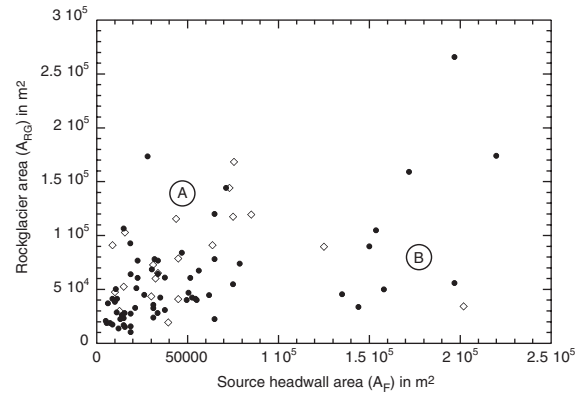


Figure 2. Relation between rockglacier area (A_{RG}) and source headwall area (A_F). Black dots represent talus-derived rockglaciers, outlined rhombi mark moraine-derived rockglaciers. Total sample size $n = 84$.

of a rockglacier, and, as we will see later, it might correlate with other factors such as, for example, the velocity of the rockglacier. Therefore, we compared rockglacier area (A_{RG}) and source headwall area (A_F) in a second step. Rockglacier area (A_{RG}) is that parameter of rockglacier volume (V_{RG}) which can be most easily and directly determined. Thirdly, to account for different rock weathering rates and, thus, for different debris supply rates, a weighting factor for different rock types was introduced.

The analyses yielded the following results:

- The overall statistical relationship between rockglacier length (l_{RG}) and source headwall area (A_F) is moderate, with $r = 0.49$ (no graph shown). A separate treatment of talus- and moraine-derived rockglaciers shows that the correlation is more significant for the talus-derived rockglaciers than for the moraine-derived rockglaciers (Table 1).
- The comparison between rockglacier area (A_{RG}) and source headwall area (A_F) seems, as in the first analysis, to indicate two more or less distinct clusters (Fig. 2).

One cluster of values (A) incorporates rockglaciers with source headwall areas below $100,000 \text{ m}^2$, the area of these rockglaciers varies between 10^4 m^2 and $1.7 \cdot 10^5 \text{ m}^2$. Rockglaciers in the second cluster (B) are characterised by source headwall areas exceeding

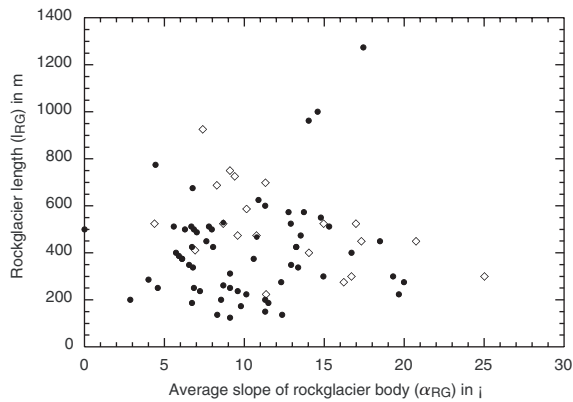


Figure 3. Relation between rockglacier length (l_{RG}) and average slope of the rockglacier body (α_{RG}). Markers as in Figure 2, total sample size $n = 82$.

100,000 m², while the area of these rockglaciers varies between $3.4 \cdot 10^4$ m² and $2.6 \cdot 10^5$ m². Both clusters show a positive relation between rockglacier length and the size of the debris source area, but with only medium statistical significance (cluster A: $r = 0.52$, cluster B: $r = 0.43$, both clusters together $r = 0.49$). Compared to the first analysis, the correlation value is slightly higher for talus-derived rockglaciers and considerably higher for the moraine-derived rockglaciers (Table 1).

The analysis of the source headwall lithology showed that granite, diorite, and gneiss are the predominant rock types, followed by dolomite, limestone, and marble. Approximately two thirds of the source headwalls are composed of two or more different rock types. In the weighting, headwalls mostly composed of granite or diorite got a weighting factor of 1, headwalls composed of faster weathering rock types, such as gneiss, limestone and dolomites, got larger weightings, and headwalls composed of rocks prone to slow weathering, such as gabbros or syenites, got smaller weighting factors. The weathering rates were derived from works by Rapp (1960), Ballantyne & Harris (1994), French (1996), André (1997), and Matsuoka et al. (1997). This procedure resulted in a moderation of the clustering effect, an increase in the correlation for talus-derived rockglaciers, and a considerable decrease in correlation for moraine-derived rockglaciers (Table 1).

Testing for a dependence between length (l_{RG}) and average slope of the rockglacier body (α_{RG}) shows a large scatter rather than distinct trends (Fig. 3). Interestingly, the moraine-derived rockglaciers seem to show an inverse relationship. Indeed, if three outliers are excluded from the analysis of the talus-derived rockglaciers (Fig. 3, three points in the upper middle) also this group shows a weak inverse correlation.

A multiple regression with rockglacier length (l_{RG}) as the dependent variable, and, both source headwall

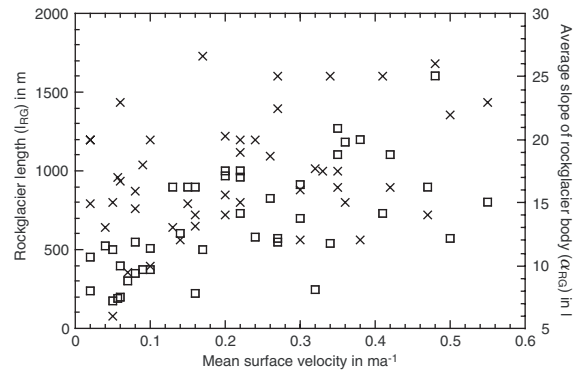


Figure 4. Boxes: relation between mean surface velocity (v_{mean}) and rockglacier length (l_{RG}); crosses: relation between mean surface velocity (v_{mean}) and average slope of the rockglacier body (α_{RG}). Total sample size $n = 45$. Data are from Barsch & Zick (1991), Berthling (2001), Chaix (1942), Von Elverfeldt (2002), Evin & Assier (1983), Evin, Assier & Fabre (1990), Isaksen et al. (2000), Kääb et al. (1997), Kääb (1998), Kääb et al. (2002), Kaufmann (1996), Kaufmann & Ladstädter (2000), Sloan & Dike (1998), and own unpublished data.

height (l_F) and average rockglacier slope (α_{RG}) as independent variables does not substantially change the picture for either of the two groups. The same applies for a multiple regression analysis with rockglacier length (l_{RG}), source headwall area (A_F), and average rockglacier slope (α_{RG}).

3.2 Control on surface velocities

To identify possible topographic or climatic controls on surface velocities of rockglaciers, we investigated data in *DS#2*.

Figure 4 shows that rockglacier length (l_{RG}) is rather correlated to mean surface velocity (v_{mean}) than to average slope of the rockglacier body (α_{RG}): the analysis of rockglacier length against mean surface velocity yields a clearly positive relation with an r -value of 0.63 (marked with boxes), whereas the relation between mean surface velocity and average slope is hardly statistically significant (marked with crosses).

Using mean annual air temperature at the rockglacier front ($MAAT_{RGF}$) as a rough proxy for the temperature of the permafrost allows for comparison between mean surface velocity and ice temperature (Haerberli 1985). Figure 5a shows, as expected from field measurements and laboratory experiments by different authors (e.g. Paterson 1994, Arenson et al. 2002), a positive relationship between v_{mean} and $MAAT_{RGF}$, with an r -value of 0.56 for a linear relationship, and $r = 0.65$ for an exponential relationship.

Maximal surface velocity (v_{max}) versus $MAAT_{RGF}$ seems to indicate an even better exponential relation ($r = 0.82$) between the two parameters (Fig. 5b).

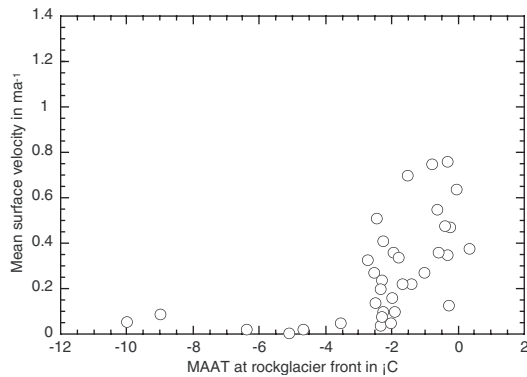


Figure 5a. Relation between *mean* surface velocity (v_{mean}) and MAAT at the present rockglacier front (MAAT_{RGF}). Total sample size $n = 35$. Note: the front of Val Sassa rockglacier in the Eastern Swiss Alps, reaches into non-permafrost areas (MAAT_{RGF} above 0°C). Permafrost modelling results confirm this observation.

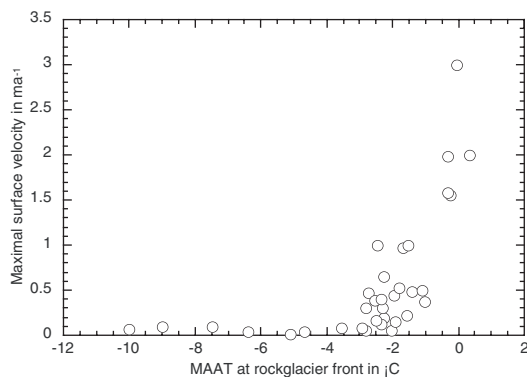


Figure 5b. Relation between *maximal* surface velocity (v_{max}) and MAAT at the present rockglacier front (MAAT_{RGF}). Total sample size $n = 34$.

Data in 5a and 5b: from Barsch & Zick (1991), Berthling (2001), Chaix (1942), Von Elverfeldt (2002), Humlum (1997), Isaksen et al. (2000), Kääb et al. (1997), Kääb (1998), Kääb et al. (2002), Kaufmann (1996), Kaufmann & Ladstädter (2000), Koning & Smith (1999), Krainer & Mostler (2000), Krummenacher (1998), Sloan & Dike (1998), and own unpublished data.

4 DISCUSSION

4.1 Rockglacier size and debris-supply area

The size of the talus-derived rockglaciers in the Engadin is comparable to rockglacier size in other mountain regions (e.g. North America: White 1979, Central Asia: Gorbunov 1983). The moraine-derived rockglaciers, however, are considerably smaller than, for instance, occurrences in Central Asia (Gorbunov 1983) or on Greenland (Humlum 1982).

Sloan & Dike (1998) attribute the aspect of the rockglaciers a high importance, based on a study in the Selwyn Mts. (Yukon) where they found that rockglaciers facing NE were significantly longer and

moved faster than rockglaciers facing other directions. A similar relationship is not apparent in either dataset *DS#1* or *DS#2*. Mean rockglacier length in *DS#1* is greatest with aspects from SW through W to NW. Investigation of fourteen rockglaciers in *DS#2* showed no relation between mean surface velocity and potential direct solar radiation (of which aspect can be viewed as a proxy).

Figure 2 indicates that the relative size of contemporaneous rockglaciers are, to a certain extent, controlled by the area of the source headwall. This confirms that debris supply – together with flow velocity – is an important factor determining rockglacier size. Additionally, although we could not consider this factor in our study, the availability of water/snow is of fundamental importance: in the source headwall, water availability influences the rate of rock weathering, while at the foot of the talus cone, where creeping will be initiated, it is a prerequisites for the build-up of (interstitial) ice and, thus, of a cohesive matrix allowing creep.

The correlation between the size of talus-derived rockglaciers and source headwall area increases when rockglacier length is replaced by rockglacier area, and weathering rates are considered (Table 1). With moraine-derived rockglaciers, in the contrary, a sharp decrease in correlation occurs when weathering rates are introduced (Table 1). This suggests that talus-derived rockglaciers are more closely related to their debris supplying headwalls than moraine-derived rockglaciers. For the latter group, an additional, both spatially and temporally complex transport module (including e.g. the whole glacier history) is involved in the process chain. A moraine-derived rockglacier is not primarily fed by continuous debris input but evolves out of an already (fully) existent debris “reservoir”. There, debris characteristics are significantly different from the original, weathered material accumulated before glacial transport.

The source headwall area is only a proxy for debris supply rates and, in itself, a function of geology, temperature, water content, jointing, etc.). Morris (1981) investigated nineteen rockglaciers in the Sangre de Cristo Mts. (Colorado) concerning their relation with altitude, radiation and rock wall jointing and found that interaction among these factors, rather than additive independent effects, determines the development of rockglaciers in different locations. The same is certainly true for the factors investigated in our study. Other authors, e.g. André (1996), Humlum (2000), Matsuoka et al. (1997), and Matsuoka & Ikeda (2001) found indications for a geological control (rock jointing, headwall retreat rates) on the distribution and characteristics of rockglaciers.

The insignificant influence of slope on rockglacier length points to the fact that the thickness of the

accumulating and deforming ice/rock-mixture is rather independent of stress controls: with a constant basal shear stress and a given volume of frozen debris, thickness would decrease and length correspondingly increase with increasing slope – a relation which is obviously not found in the analysed data.

4.2 Velocities

The good correlation between rockglacier length and both, mean and maximal surface velocity (Figs 5) seems to confirm that all rockglaciers had a similar time span for their development (e.g. time since the onset of the Holocene, i.e. approximately 10,000 years) and a similar initial thickness (possibly zero – no pre-deposited debris): rockglaciers that crept far would therefore have had to move faster than short rockglaciers. Obviously, this assumption would be a black-box approach and does neither enlighten the processes involved nor account for special topographic features such as obstacles, etc. However, it seems that such an idea works just well for the given sample of rockglaciers.

The rather weak relation between average surface slope and mean surface velocity (Fig. 4) again indicates that stress control on geometry and flow are less important than other influences. Such an other influence may be the temperature effect on strain rates in ice-supersaturated frozen materials.

In fact, Figure 5 confirms that flow velocity is a function of ice temperature with warmer ice deforming faster than cold one. As found for glacier ice, the rate factor A increases significantly and in a non-linear way for temperatures approaching the melting point of ice (Paterson 1994). Similar findings are confirmed for rockglacier deformation from borehole measurements and laboratory experiments e.g. by Arenson et al. (2002), and Azizi & Whalley (1996). Furthermore, it can be observed that rockglaciers at high latitudes (i.e. in colder environments) tend to deform significantly slower than rockglaciers in mid-latitude environments such as they were considered here (e.g. Humlum 1997, Bertling 2001, Kääh et al. 2002). Our results support this influence of temperature. The effect of warmer and faster deforming ice, however, could be compensated for by greater thickness and, thus, higher stresses at the base of cold permafrost. The formation of a coarse blocky layer with damped creep at a depth controlled by the original talus geometry (Haerberli et al. 1998) could explain the predominance of effects from the rate factor.

5 CONCLUSIONS

The results of our study on a selected sample of parameters document that a relation between source headwall area, surface velocity and rockglacier size

exists but is complex. The analyses show that obviously neither individual parameters nor their combinations are able to fully explain rockglacier evolution.

Flow velocities appear to exert an important influence on rockglacier length and appear to depend on temperature conditions. Even though MAAT is certainly a very rough proxy for permafrost temperature, the latter is indeed likely to act as an important boundary condition for creep in the frontal part of rockglaciers, especially near local permafrost limits. In contrast to that stress conditions might be critical for triggering creep in the talus cone but seem to have limited effects on further rockglacier evolution.

Other variables must significantly influence rockglacier transport rates. Examples are (a) the vertical velocity profile including deformation rates, thickness, internal structure with stiff layers or sliding processes at depth, shearing within the permafrost, etc., and (b) variable ice content.

A better understanding of the involved parameters and processes may be reached by further analyses of the collected inventory data. The main progress, however, will come from more complete borehole and geophysical data collected on active rockglaciers.

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