PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. (2016)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/ppp.1910

Estimating the Effect of Different Influencing Factors on Rock Glacier Development in Two Regions in the Swiss Alps

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ABSTRACT

To elucidate the factors that influence rock glacier distribution, we created a rock glacier inventory for two regions in the Swiss Alps (the Albula Alps and the Glarner Alps) and identified their spatial characteristics by adding topographical and meteorological data to a GIS. We evaluated the influence of mean annual precipitation (MAP), mean annual air temperature, head wall erosion, glacier coverage, lithology, slope, aspect, elevation and snow cover on rock glacier occurrence and characteristics, taking into account the interactions between these factors. MAP, lithology and head wall erosion significantly influenced rock glacier distribution, and the interaction of precipitation and lithology seemed to play a key role. Wind-driven snow redistribution influenced rock glacier frequency on hillslopes with different aspects. Rock glaciers interact with all of the factors analysed and exhibit complex relations with their regional environments. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: rock glaciers; mountain permafrost; GIS; influencing factors; spatial distribution

INTRODUCTION

The origin and development of excess ice in rock glaciers are important issues of mountain permafrost research. Explanations range from ice segregation in fine material to burial of surface snow and ice by rock fall material and integration of glacier ice (Berthling, 2011; Clark *et al*., 1998; Haeberli and Vonder, 1996). Although all of these processes may contribute to rock glacier genesis (Haeberli *et al*., 2006), rock glacier development and the influence of external factors are still poorly understood. For example, the maximum values of mean annual air temperature (MAAT) that preserve permafrost in rock glaciers and talus slopes vary, depending on the study site and landform (Chueca, 1992; Marchenko, 2001; Payne, 1998). Consequently, additional factors may influence rock glacier genesis and spatial distribution, such as topography, lithology or aspect (Johnson *et al*., 2007). Elevation changes in rock glacier distribution through time have been commonly attributed to changes in MAAT (Chueca, 1992; Frauenfelder *et al*., 2001; Frauenfelder and Kääb, 2000; Haeberli, 1983; Payne, 1998; Sailer and Kerschner, 1999). These studies have deduced a long-term MAAT signal from the elevation distribution of active and relict rock glacier fronts, which raises the question as to whether the elevation pattern of rock glacier fronts over time is in fact controlled by air temperature only. Because rock glaciers may develop over thousands of years (Haeberli *et al*., 1998), their response periods are probably much longer than existing observation records of influencing factors, which themselves show large temporal variations. This is why the long-term effects of temporally variable influencing factors on rock glacier development remain insufficiently understood.

The aim of this study is to identify the influence of different environmental factors on the characteristics, frequency and spatial distribution of rock glaciers in two regions of the Swiss Alps. We hypothesised that the heterogeneous development of rock glaciers in different regions represents the long-term effect of spatially variable influencing factors. We used a GIS-based approach that seeks spatial correlation between rock glacier occurrence, size, state and morphology with environmental parameters identified in the literature. The Swiss Alps are an optimal study site for this approach as they provide heterogeneous external conditions over small areas. First, we present the GIS and make some theoretical pre-considerations, before we analyse the effect of the individual factors on rock glaciers.

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Received 3 June 2014
Revised 4 December 2015
Accepted 24 May 2016

COMPOSITION AND CHARACTERISTICS OF THE GIS

Influencing Factors

We initially defined the factors that may influence the development of rock glaciers, based on the literature (Frauenfelder *et al*., 2008; Ikeda and Matsuoka, 2006; Johnson *et al*., 2007; Morris, 1981). Then we grouped them into temporally variable factors (head wall erosion rate, glacier coverage, MAAT, mean annual precipitation (MAP), snow cover) and temporally stable factors (elevation, aspect, slope and lithology (sedimentary rock vs metamorphic/crystalline rock)). The timescale considered here for the attribute stability is the Holocene Epoch.

Influencing Factor Proxies

Two indirect indicators (proxies) of influencing factors are noted: aspect and elevation. This means that the distribution of rock glaciers depends on another factor that is highly correlated with the obvious one. The dependency on aspect results mainly from the variable duration and intensity of solar radiation upon different aspects. Aspect is therefore used as a proxy for insolation because: (1) the distribution of rock glaciers according to aspect has been analysed in several studies of Swiss rock glaciers (Gruber and Hoelzle, 2001; Noetzli *et al*., 2007; Nyenhuis *et al*., 2005); (2) aspect is easier to interpret and to categorise than solar radiation values; and (3) potential insolation energy specifications as provided by GIS analysis tools give a false accuracy. They depend, for example, on unknown variables like cloud coverage, which often differs between morning and afternoon (Stubenrauch *et al*., 2012), which in turn disturbs the spatial solar radiation balance and the absolute insolation values. Factors like slope and shadow effects that are not considered by aspect are randomly distributed and neglected due to the high number of rock glacier records.

The dependency of rock glacier distribution on elevation results mainly from its dependency on air temperature. We used elevation data as a temperature proxy since they have a much higher resolution than the MeteoSwiss MAAT grid data (Table S1 in the Supporting Information).

Study Regions

Two study regions were chosen in the Swiss Alps: the Glarner Alps and the Albula Alps (Figure 1). The Glarner Alps are part of the Alpine North Slope and are characterised by a high precipitation regime. The central and eastern parts of this mountain range consist of sedimentary rock, whereas metamorphic/crystalline rock occurs in the western parts. The Albula Alps represent an inner alpine region with a relatively continental climate. The majority of the Albula Alps consists of metamorphic or crystalline rock, and the southern and western parts of sedimentary rock (see Figure 2).

GIS Data Input

The sources of topographical, meteorological and land cover data used for the GIS analysis are given in the Supporting Information. Additional data were derived manually from the Swissimage orthophotographs provided by Swisstopo (Table

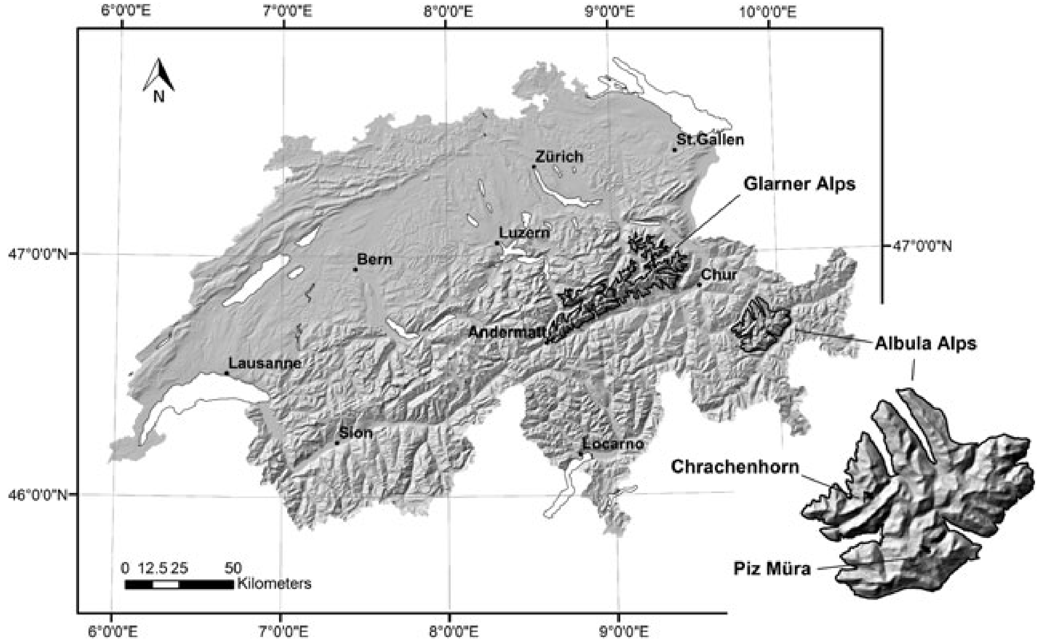

Figure 1 Location map of the study sites: the Glarner Alps and the Albula Alps in Switzerland. Inset shows the location of two wind measurement stations (Chrachenhorn and Piz Müra) in the Albula Alps.

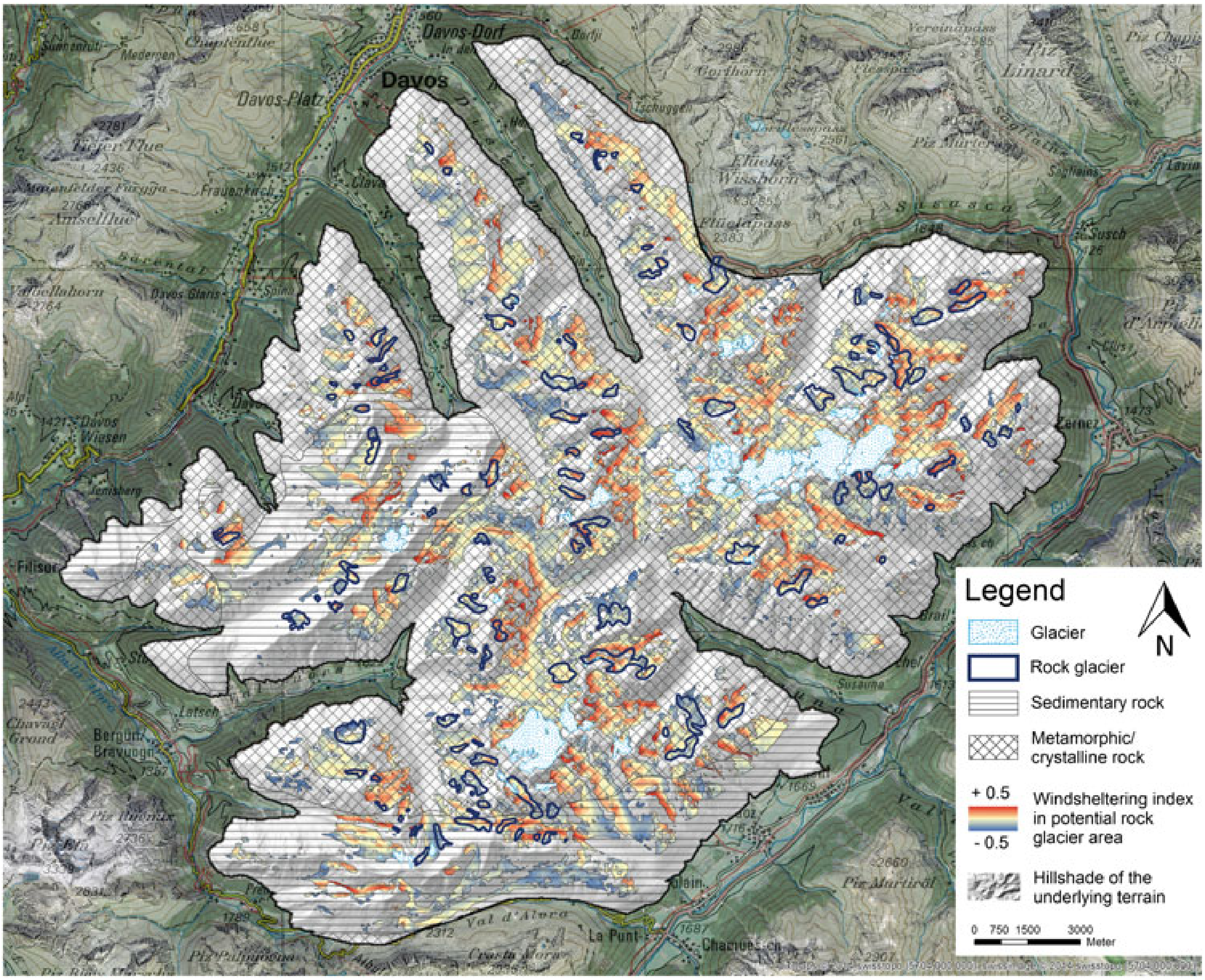

Figure 2 Rock glacier distribution in the Albula Alps. The areas currently occupied by glaciers in the Albula Alps and the distribution of the lithology classes are indicated. For the potential rock glacier area (slope < 30°, elevation > 2300 m asl, curvature below the convexity threshold and no glaciers), the wind sheltering indices are shown in the background. In areas unfavourable for rock glaciers, the background is mapped as grey hillshade. Swissimage© 2014 swisstopo (DV 033594), DTM-AV DOM-AV © 2015 Eidg. Vermessungsdirektion (DV033531).

S1 in the Supporting Information). Study areas were first delimited by the surrounding valley bottoms. Regions below 2000 m asl were excluded to obtain a similar distribution of elevation between the study regions.

Rock glaciers were defined with polygons identifying clearly visible creeping features on the orthophotographs (e.g. transverse or longitudinal ridges and furrows, and steep front or side walls). Rock glaciers were divided into 'relict' and 'active' categories by analysing the rock glacier morphology and vegetation cover. Relict ones were identified where vegetation cover was evident, in particular at their fronts and at the front of creeping lobes superimposed on the rock glacier body. Analysis of infrared aerial images aided identification of vegetation. Relict rock glaciers also showed rounded, eroded creep forms with signs of subsidence. The transition from active to relict rock glacier state is not sharply defined and a long period of inactivity probably separates them (Barsch, 1996). However, remote sensing methods cannot distinguish between relict and inactive rock glaciers still containing ice. Hence, we include inactive rock glaciers in the category of relict rock glaciers. In the case of relict rock glaciers with superimposed active rock glaciers in the upper parts, the extent of the active rock glacier was included in the area of the relict one.

Because it was impracticable to estimate the volumes of every rock glacier record in this study, we used the two-dimensional (2D) rock glacier area (projected on the Swiss coordinate grid) as a proxy for the relative size of rock glaciers. The total number of rock glaciers in the study areas is 239, including 75 relict rock glaciers in the Albula Alps (see Table 2).

The head wall (i.e. the rock wall which supplies rock material to the rock glacier) was defined as the area lying in the slope line directly above the rock glacier and having a slope angle of at least 40°. Talus slopes reach maximum angles of around 40° and rock movements above this threshold result in rock fall or rock avalanches (Carson, 1977) which can cover snow patches. The area of the head walls was defined in three dimensions (3D).

Correlations between Influencing Factors

Correlations between the influencing factors (e.g. MAP and elevation) can lead to ambiguities in their analysis. The very different spatial resolution of the input data-sets (Table S1 in the Supporting Information) hinders the interpretation of correlation coefficients. We therefore focus on citing established relations between influencing factors and discuss their relevance for the study:

- The dependency of MAAT on elevation is described by the lapse rate. We used elevation as a proxy for MAAT.
- MAP also depends on elevation. At elevations between 2000 and 3000 m asl, MAP increases with elevation (Brutsaert, 2005). This relation is not relevant for the analysis because (1) rock glaciers tend to occur in continental environments in the Alps, and (2) high MAP values are unfavourable for rock glacier development (Barsch, 1996; Dramis *et al*., 2003). MAP increases with elevation and can therefore control the upper elevational border for rock glaciers (e.g. by glaciation). MAAT, however, decreases with increasing elevation and will therefore influence the lower elevational border for rock glaciers.
- Snow cover distribution is only analysed at local scales in this study. An unproven but possible dependency of snow cover and aspect is considered as critical. All other combinations are treated as having no relevant dependencies for this study.

Distribution and Frequency of Influencing Factor Characteristics

The characteristics of influencing factors are defined as specifications or specification intervals of an influencing factor (e.g. W-N sector for aspect/2000–2100 m asl for elevation). The spatial distribution and frequency of these characteristics can be influenced by many complex sources. They can therefore differ between two regions (e.g. the frequency of occurrence of W-N slopes differs between the Albula Alps and the Glarner Alps) and between two specifications of another factor (e.g. the distribution of snow differs for individual aspect sectors).

Unequal distributions of influencing factor characteristics can falsify the analysis of the influence of individual factors on rock glaciers. Hence, unequally distributed influencing factors must be detected and normalised before analysis. This problem mainly concerns the distribution of factors of high spatial variability (i.e. MAAT, elevation, aspect, slope, glacier coverage) within one specification of factors of low spatial variability (i.e. regions with different precipitation regimes and lithologies). Therefore, these distributions were calculated for all factors that were spatially highly variable. For example, the frequency of occurrence of W-N, N-E, E-S and S-W slopes was calculated for both the Glarner and the Albula Alps. The frequencies were compared between both regions and categorised as being equally or unequally distributed. The frequencies of specifications of an equally distributed factor differ by less than 5 per cent of the basic population (e.g. all aspects). Head wall erosion was omitted in this test, as its effect on rock glacier distribution was analysed in a special way.

As specified in Table 1, the characteristics of all factors are equally distributed between the lithology classes of one region, and therefore do not influence the effect of lithology. However, all factor characteristics except MAAT and slopes below 30° are unequally distributed between the regions and must be treated carefully.

ANALYSIS OF INFLUENCING FACTORS

Two basic concepts are used to analyse the influence of individual factors on rock glaciers. First, we analysed rock glacier characteristics in two environments that differ by only one influencing factor. However, there are cases where at least one other influencing factor also varies. Second, we defined a potential rock glacier area that is reduced in a stepwise manner by factors adverse to rock glacier occurrence, such as glaciation. Using this area as a basic unit for defining rock glacier frequency, the effect (e.g. of glacier coverage or steep slopes) can be excluded from the following analysis of other influencing factors.

The results of the GIS analysis are summarised in Table 2 and schematically illustrated in Figure 3, to facilitate understanding of the workflow.

Slope Angle

Methods

To define a maximum slope angle of the underlying terrain for rock glaciers, rock glacier shapes were again defined, excluding the steep front and side walls and steep scree slopes between the head wall and creeping form. Slope angles for these areas were determined using the digital elevation model DEM25 (Table S1 in the Supporting Information).

Table 1 Distributions of influencing factor characteristics (ED – equal distribution, UD – unequal distribution).

	Mean annual precipitation	Mean annual air temperature	Elevation	Aspect	Slope $<30°$	Snow cover	Glacier coverage
Lithology	ED	ED	ED	ED	ED	ED	ED
Region	UD (Table 2, line 9)	ED	UD (Table 2, line 12)	UD (Table 2, lines 24–27)	ED (Table 2, line 31)	UD	UD (Table 2, line 28–29)

Table 2 Results of the GIS analysis. PRGA = Potential rock glacier area; MAAT = mean annual air temperature.

Line	Garner Alps	Glarner Alps metamorphic/ crystalline rock	Glarner Alps sedimentary rock	Albula Alps	Albula Alps metamorphic/ crystalline rock	Albula Alps sedimentary rock	Albula Alps relict rock glaciers
1 Total area [km^2] Albula Alps > 2000 m asl/Glarner Alps > 2000 m asl	715.8	189.4	526.5	361.0	275.9	85.1	361.0
2 PRGA: Slope < 30°, no glaciers, Albula Alps > 2300 m asl/Glarner Alps > 2100 m asl and 'no convexity' [% total area]	16.7	20.1	15.7	31.9	33.5	26.6	—
3 Number of rock glaciers	40	29	11	124	101	23	75
4 Rock glacier surface (absolute) [km^2]	2.1	1.7	0.3	13.6	11.8	1.8	14.1
5 Rock glacier surface (relative to PRGA) [%]	1.7	4.5	0.4	11.7	12.8	8.0	3.9
6 Mean size of rock glaciers [m^2]	53 500	64 400	24 900	109 300	116 700	76 600	188 100
7 Largest rock glacier [m^2]	185 701	185 701	53 912	658 859	658 859	216 212	975 709
8 Rock glacier surface relative to head wall [%]				130			175
9 Mean annual precipitation [mm]	1764	1677	1783	950	961	904	—
10 Mean annual precipitation rock glacier [mm]	1720	—	—	971	—	—	—
11 Spatial average of MAAT (normalised by elevation) [°C]	1.9	—	—	0.7 (1.4)	—	—	—
12 Mean elevation of the region [m asl]	2380	2409	2370	2482	2490	2456	2482
13 Elevational belt of rock glaciers (mean) [m asl]	2030–2780 (2500)	2180–2780 (2540)	2030–2720 (2260)	2260–3110 (2650)	2260–3110 (2650)	2350–2920 (2640)	2070–2910 (2456)
14 Elevational belt of rock glaciers S-aspect (mean) [m asl]	2030–2780 (2560)	—	—	2319–3110 (2747)	—	—	—
15 Elevational belt of rock glaciers N-aspect (mean) [m asl]	2050–2760 (2465)	—	—	2260–3030 (2620)	—	—	—
16 Rock glacier area in aspect W-N [% of total rock glacier area]	29	—	-	46	-	-	-
17 Rock glacier area in aspect N-E [% of total rock glacier area]	14	-	-	29	-	-	-
18 Rock glacier area in aspect E-S [% of total rock glacier area]	36	-	-	10	-	-	-
19 Rock glacier area in aspect S-W [% of total rock glacier area]	21	-	-	14	-	-	-
20 Rock glacier area in aspect W-N [% of PRGA in W-N]	1.3	-	-	15.6	-	-	-
21 Rock glacier area in aspect N-E [% of PRGA in N-E]	0.5	-	-	9.6	-	-	-
22 Rock glacier area in aspect E-S [% of PRGA in E-S]	0.6	-	-	3.5	-	-	-

(*Continues*)

Table 2 (Continued)

Line		Garner Alps	Glarner Alps metamorphic/ crystalline rock	Glarner Alps sedimentary rock	Albula Alps	Albula Alps metamorphic/ crystalline rock	Albula Alps sedimentary rock	Albula Alps relict rock glaciers
23	Rock glacier area in aspect S-W [% of PRGA in S-W]	0.6	-	-	5.1	-	-	-
24	PRGA in aspect W-N [% of line 2]	15	-	-	25	-	-	-
25	PRGA in aspect N-E [% of line 2]	20	-	-	26	-	-	-
26	PRGA in aspect E-S [% of line 2]	40	-	-	25	-	-	-
27	PRGA in aspect S-W [% of line 2]	25	-	-	24	-	-	-
28	Glacier surface [km^2] (% total area)	62.8 (17.4)	—	—	8.6 (1.2)	—	—	—
29	Glacier surface [% (km^2) of PRGA incl. glacier]	13 (30.8)	—	—	5 (7.4)	—	—	—
30	Slope of 95% of rock glacier surface without front/side walls and without scree slope below the head wall (mean) [°]	0–27 (18)	0–27 (18)	0–27 (18)	0–28 (18)	0–28 (18)	0–28 (18)	—
31	Slopes <30°/30°–40°/>40° [% of total area line 1]		53/25/22			55/32/13		

Results

Ninety-five per cent of the analysed rock glacier creep forms are on slopes gentler than 30°. This value is therefore considered as being the threshold slope angle for rock glacier formation. Although some parts of rock glaciers are steeper than 30° (e.g. the upper talus), the erosion of such steep slopes is probably too strong to allow the development of characteristic creep forms.

Glacier Coverage

Methods

First, we defined an area of potential rock glacier occurrence. An elevation limit was defined by the condition that 95 per cent of the area occupied by active rock glaciers is situated above this limit. Subsequently, all slopes steeper than the maximal slope angle of 30° were excluded. Rock glaciers mainly occur in concave or smooth terrain where avalanche snow and rocks are deposited. The potential rock glacier area was thus confined to the condition 'no convex curvature'. A threshold of convexity was defined by the condition that 95 per cent of the true rock glacier area is either below the threshold, or is concave or smooth (see Figure 2).

We assume that increased glacier cover affects the true rock glacier area to the same extent as this potential rock glacier area. We therefore calculated the percentage of the potential rock glacier area that is currently occupied by glaciers to interpret the effect of the factor 'glacier coverage'.

The potential rock glacier area was now supplemented by the condition 'no glaciers' and was used as the basic unit area when analysing the remaining factors. In this way the influence of glaciation on rock glacier frequency was excluded from the following analysis.

Results

The lowest limit of rock glacier occurrence was approximately 2300 m asl in the Albula Alps and 2100 m asl in the Glarner Alps. Comparing the study regions, 8 per cent (23.4 km^2) more of the potential rock glacier terrain is glaciated in the high-precipitation Glarner Alps than in the dry Albula Alps (Table 2, line 29). Hence, 8 per cent less potential rock glacier area is available for the Glarner Alps due to glaciation and so 8 per cent fewer rock glaciers are estimated.

Aspect

Methods

We computed the aspect of the observed rock glacier surfaces divided into four aspect sectors (N-E, E-S, S-W and W-N). Subsequently, the fraction of each direction of the true rock glacier surface was calculated to define the influence of aspect on rock glaciers. However, the four aspect sectors can themselves have different frequencies within the study areas, influencing the total area of rock glaciers in each sector. To rule out the influence of varying aspect frequency and the influence of the factors elevation, slope

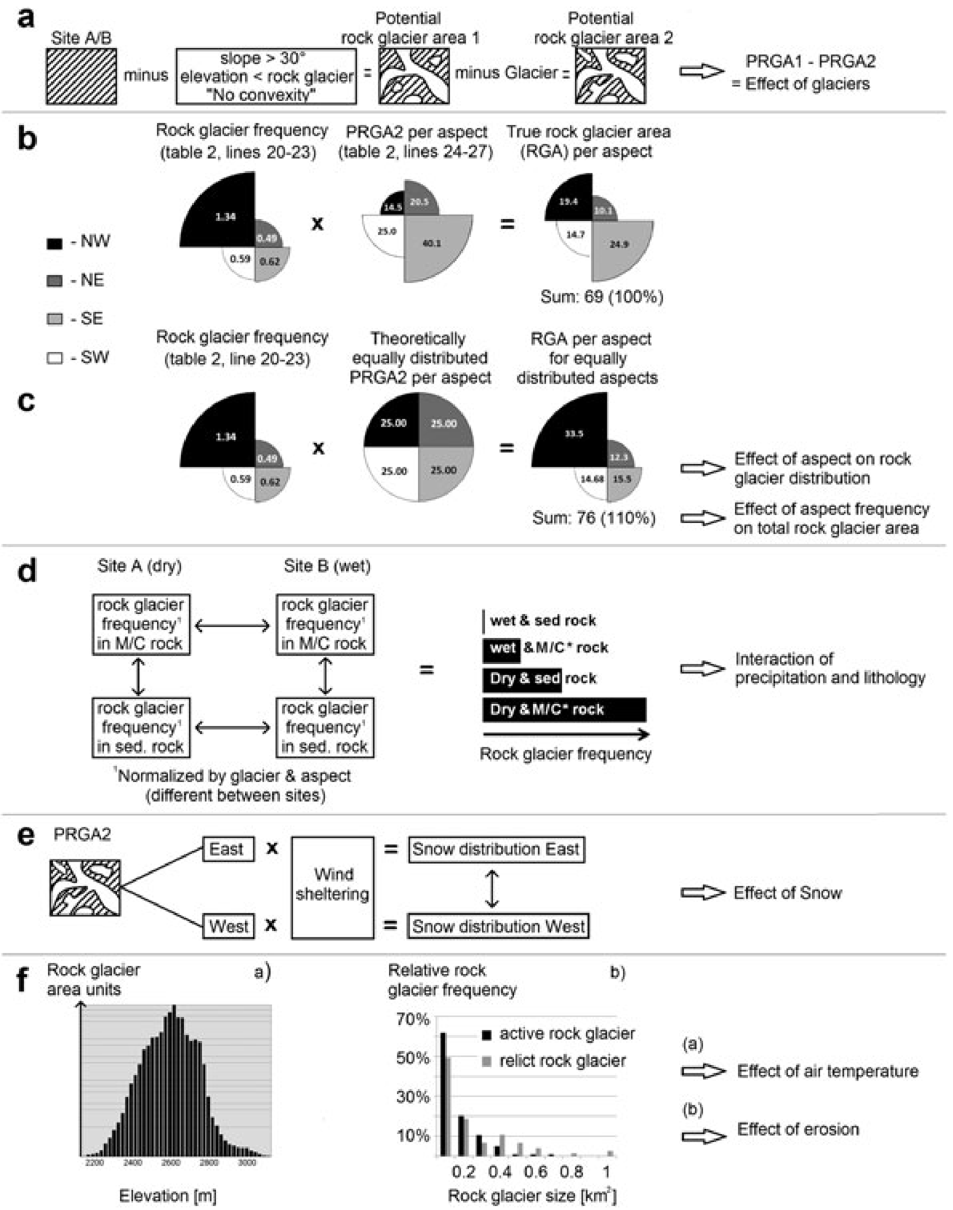

Figure 3 Rock glacier surface distribution and aspect in the Glarner Alps. (a) Definition of the potential rock glacier area (PRGA) and the effect of glacier coverage. (b) Relation between rock glacier frequency, PRGA and true rock glacier area (RGA) (measured). (c) True RGA for an equally distributed PRGA according to aspect. (d) Definition of the effect of mean annual precipitation in metamorphic/crystalline (M/C) rock and sedimentary (sed.) rock. (e) Definition of the effect of snow in different aspects. (f) Histograms showing the effect of temperature and head wall erosion.

and glaciers, the percentage of the true rock glacier area on the potential rock glacier area of an aspect sector was calculated. This value is called the rock glacier frequency (Figure 3).

Results

Aspect is another factor clearly influencing rock glacier distribution. All aspect sectors have the same frequency within the potential rock glacier area of the Albula Alps (Table 2, lines 24–27). This region is thus appropriate for the analysis of the aspect effect. Three times more rock glaciers exist in the northern aspects than in the southern ones here. However, western and eastern aspects also show differences with a rock glacier ratio of 2:3 (Table 2, lines 16–19 and 20–23), which corresponds to the permafrost distribution described by Keller *et al*. (1998) and Gruber and Hoelzle (2001). Haeberli (1975) considered diurnal variations in solar radiation as an explanation for this E-W ratio. Referring to data from five MeteoSwiss mountain weather stations (Table S1 in the Supporting Information), there is 5 per cent less incoming global radiation in the afternoon after the solar zenith than before. On the other hand, the difference between GIS-derived potential solar radiation values in the Albula Alps in north-facing and south-facing slopes in summer is more than 20 per cent. If a 20 per cent difference in solar radiation leads to a rock glacier ratio of 3:1, it is questionable whether a 5 per cent difference in solar radiation on eastern and western aspects alone can cause a rock glacier ratio of 2:3.

Aspect sectors in the Glarner Alps have different frequencies (Table 2, lines 24–27). Accordingly, the distribution of rock glaciers with relation to aspect is distorted here, as shown in Table 2, lines 16–19. Instead, the rock glacier frequency shown in Table 2 (lines 20–23) must be analysed. This value shows a cumulation of rock glaciers in the sector W-N, similar to the Albula Alps. The different frequency of aspect sectors in the potential rock glacier area of the Garner Alps also affects the total amount of rock glacier surface here. The sector W-N is clearly under-represented but has the highest rock glacier frequency. The total amount of rock glacier surface in the Glarner Alps would be 10 per cent higher if all aspect sectors had the same frequency. This issue is shown in Figure 3.

MAP

Methods

To analyse the effect of MAP, we focus on the differences in rock glacier frequency between the wetter Glarner Alps and the drier Albula Alps (Table 2, lines 9 and 10).

However, three other factors differ between the Albula Alps and Glarner Alps: frequency of the lithology classes, glacier coverage and aspect (Table 2, line 1; 24–29). To exclude the influence of lithology when analysing MAP, both lithology classes were compared separately for both regions. The regionally different effect of glaciation was eliminated using the potential rock glacier area as the basis of computation. The effect of unequal aspect distribution remained an uncertainty in this calculation.

Results

The rock glacier frequency in the potential rock glacier area of the wetter Glarner Alps in comparison to the Albula Alps was 65 per cent lower for metamorphic/crystalline rock and 96 per cent lower for sedimentary rock (Table 2, line 5). The overall effect of MAP is therefore very strong and the intensity of the effect seems to be related to the lithology. This will be analysed in the Discussion section.

Lithology

Methods

To determine the effect of lithology, the frequency of rock glacier surface occurrence was compared for the potential rock glacier area in sedimentary rock and metamorphic/crystalline rock separately in both regions.

Results

In the Albula Alps, the frequency of rock glaciers in sedimentary rock areas was 38 per cent lower than in metamorphic/crystalline rock areas, whereas in the Glarner Alps it was 91 per cent lower compared to the metamorphic/crystalline rock areas (Table 2, line 5). Again, the mutual reinforcement of the two rock glacier adverse factors is evident (high MAP and sedimentary rock). In sedimentary areas, rock glaciers were not only less frequent, but they were also considerably smaller (Table 2, line 6) and their morphology less clearly defined. Furthermore, they show that rock type has a strong influence on rock glacier development, comparable to that of MAP.

Head Wall Erosion

Methods

Frauenfelder *et al.* (2003) established correlations between the length of rock glaciers and debris supply. Degenhardt (2009) showed the relation between individual rock glacier lobes and catastrophic rock fall events. This underlines the dependency of active rock glaciers on an ongoing debris supply, the intensity of which is a limiting factor for the size of a rock glacier. In addition to the size of the rock glacier head wall, head wall erosion is crucial for the intensity of the debris supply. However, there are no GIS data on the spatial differences of long-term head wall erosion processes. We therefore analysed two groups of rock glaciers that represent different periods of head wall erosion: relict and active rock glaciers of the Albula Alps. Differences in size between these groups include three effects: The effect of different head wall erosion intensity, the effect of different durations of the active phase and differences in head wall size. To exclude the effect of the head wall size, the ratio between the 2D rock glacier area and the 3D head wall area was compared between relict and active rock glaciers.

Results

The entire relict rock glacier surface is just slightly larger than the active rock glacier surface in the Albula Alps (Table 2, line 4). However, the individual relict rock glaciers are much larger than the active ones. The mean size of the relict Albula rock glaciers is over 70 per cent greater than the mean size of their active counterparts (Table 2, lines 6 and 7). The rock glacier/head wall ratio is 35 per cent higher for relict Albula rock glaciers (Table 2, line 8). The lower elevation boundary for relict Albula rock glaciers is approximately 200 m lower than that for the active ones.

Snow Cover

Methods

The different frequencies of rock glacier occurrence in western and eastern aspects were mentioned above. Different amounts of incoming solar radiation (5%) were found for western and eastern slopes but their influence on a rock glacier ratio of 2:3 between E and W was questioned. Snow cover was considered as another factor contributing to this distortion. To validate the influence of snow on different aspects, possible snow deposition/erosion zones within the

Albula Alps were analysed. Schirmer *et al.* (2011) showed that the snow distribution in alpine terrain at the end of the accumulation period is mainly influenced by the effect of a few major winter storms. Erickson *et al.* (2005) verified the terrain parameters introduced by Winstral *et al.* (2002) as being most influential for snow distribution, with the wind sheltering index being the most significant parameter. For the following analysis, the sheltering index proposed by Winstral *et al.* (2002) was used for identifying deposition/erosion zones of snow.

We analysed the predominant wind directions in the Albula Alps based on the two wind measurement stations on the summits of Chrachenhorn and Piz Müra (Figure 1), differentiating between half-hourly mean wind speed and half-hourly mean wind exceeding 5 m/s. The wind sheltering index was computed for these predominant wind directions. This index provides a value of wind exposure for each grid cell of the DEM24. Positive values represent wind-sheltered areas and negative values indicate wind-exposed regions. We computed the wind sheltering index using the input parameters given by Plattner *et al.* (2006) (wind directional tolerance 10°, maximum range 250 m). We defined terrain that is wind sheltered for all main wind directions as being a necessary condition for a regular deep snow cover. Areas that are exposed to at least one main wind direction were treated as being prone to snow redistribution and having an irregular small-scale snow cover distribution. Translating this into the GIS data, we calculated a grid representing the minimum wind sheltering index of all main wind directions for each grid cell. The spatial averages of the minimum wind sheltering indices in the aspects W-N, N-E, E-S and S-W were compared for the potential and the true rock glacier areas.

Results

The analysis of the wind fields showed two predominant wind directions, SSW and NNW (Figure 4). The wind speed ranges were identical for both wind directions. Both wind directions occurred with similar frequency and should therefore have a similar influence on snow redistribution.

For both the potential rock glacier area and the true rock glacier area, the spatial average of the resulting wind sheltering indices was negative in the western sectors (wind exposed, low snow accumulation) eltered, high snow accumulation) (Table 3; Figure 2).

MAAT

Methods

The MAAT (MeteoSwiss 1961–90) (Begert *et al.*, 2003) was compared between the study regions. The MeteoSwiss MAAT grid uses a nonlinear parametric function to model the vertical temperature profiles (Frei, 2014). Systematic large-scale nonlinearities in alpine regions are mainly limited to lower elevations close to the valley bottoms. Apart from random small-scale effects, temperature lapse rates

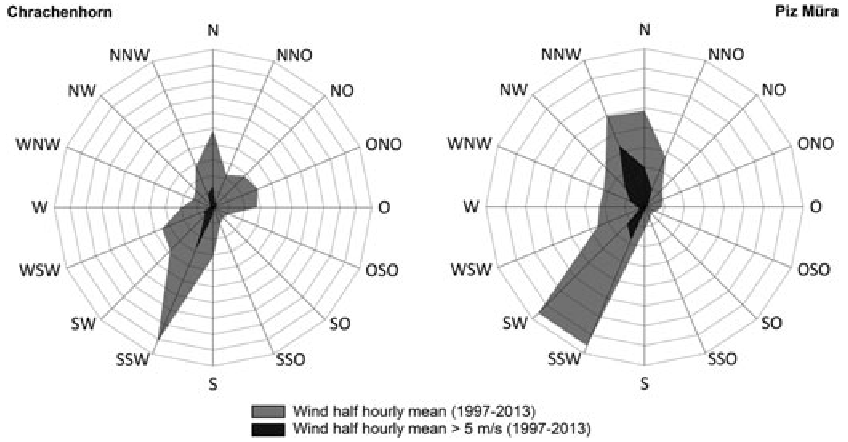

Figure 4 Wind rose diagrams showing dominant wind directions in the Albula Alps.

Table 3 Spatial average of the minimum wind sheltering indices for different aspects in the Albula Alps.

	Wind sheltering index			Wind sheltering index		
	W-N	N-E	Difference	E-S	S-W	Difference
Potential rock glacier area	−0.11	0.08	0.19	0.04	−0.13	0.17
True rock glacier area	−0.14	0.06	0.20	0.13	−0.03	0.16

Note: In 90 per cent of the study site, this wind sheltering index varies between−0.56 and 0.3.

are approximately linear between 2000 and 3000 m asl (Frei, 2014). We therefore extracted linear lapse rates for each region from the grid data: temperature-elevation pairs of values were ordered by elevation and a linear trend was calculated through the temperature values. In addition, the lapse rates were used to calculate a MAAT normalised by elevation for each entire region. The mean elevation of the MAAT grid of the Glarner Alps was used as a reference elevation. After verifying the comparability of the regions regarding MAAT, we analysed the distribution of rock glacier surface against elevation for both regions.

Results

The air temperature lapse rates calculated from the grid data are 0.52 °C/100 m for the Albula Alps and 0.62 °C/100 m for the Glarner Alps, and they intersect at around 2700 m asl. The regionally specific MAAT normalised by elevation differs by 0.5 °C (Table 2, line 11). The distribution of MAAT with regard to elevation is shown in Figure 5 for both regions. Although there is a considerable variance in the elevation signal, which is the expression of local small-scale temperature anomalies (Begert *et al*., 2003), the large-scale temperature distribution is quite similar for both regions. Thus, the effect of MAAT on rock glaciers mainly becomes apparent with regard to their elevation distribution within the regions.

The mean elevation of rock glaciers is generally around 2600 m asl (Table 2, line 13). Referring to the calculated linear temperature lapse rate, this is the exact level of the 0 °C MAAT isotherm approximation. Hence, approximately half of the rock glacier surfaces lie above the 0 °C isotherm and the other half below it. Rock glaciers in the Glarner Alps do not occur above 2800 m asl, which can be explained by the higher degree of glaciation. Three very small rock glaciers in the Glarner Alps are clearly lower than any Albula rock glacier and decrease the lower limit of rock glacier occurrence. In both regions, the elevation of rock glaciers is highly variable: rock glaciers occur within an elevation belt of 850 m in the Albula Alps and 750 m in the Glarner Alps. Individual rock glaciers exist below the current 0 °C isotherm (Table 2, line 13). Marchenko (2001) showed that permafrost can occur at sites with a positive MAAT. The large elevational distribution of rock glaciers suggests that within a certain interval they are not highly sensitive to MAAT. In addition, many other factors influence the elevation distribution of rock glaciers, such as aspect (Table 2, lines 14 and 15), MAP or head wall erosion (Table 2, line 13).

DISCUSSION

The study shows that all the factors analysed influence rock glacier development. Nevertheless, only the slope factor has a sharp delimiting value (30°) for rock glacier occurrence. The delimiting values for all other factors vary according to the local characteristics of their counterparts. For example, the lower elevational border for rock glacier occurrence depends on aspect, lithology and erosion.

The combination of MAP and lithology was found to have the strongest impact on rock glacier development. Dry areas with metamorphic/crystalline lithology favour rock glacier development, whereas wet sedimentary mountain ranges virtually exclude it.

Precipitation, Rock Debris Grain Size and their Interaction

Rainfall directly transports energy through the insulating coarse surface boulder layer to the ice. Rist and Phillips (2005) described how refreezing of a water-saturated zone above the permafrost layer can rapidly transfer latent heat into the permafrost body. In addition, thick snow reduces ground cooling in winter (Keller and Gubler, 1993) and counteracts permafrost conservation (Zhang, 2005). In flat ice-rich terrain, meltwater runoff is slow and ponding can rapidly degrade permafrost bodies (Haeberli *et al*., 2001).

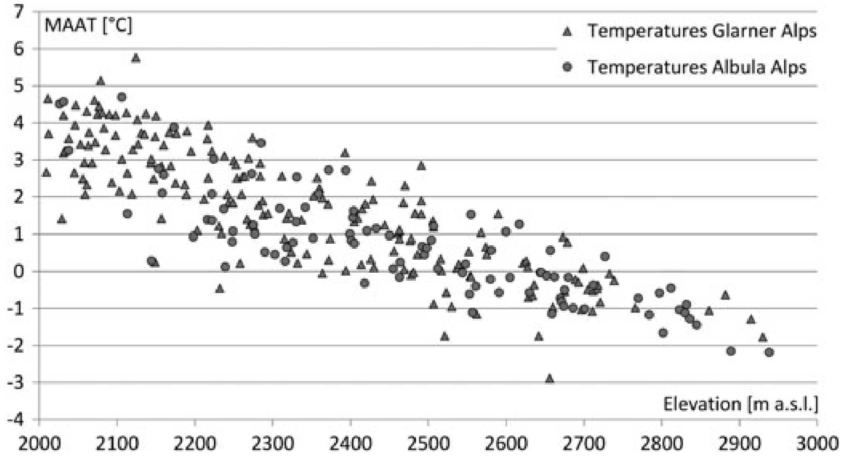

Figure 5 Relationship between mean annual air temperature (MAAT) and elevation for both study regions.

Ikeda and Matsuoka (2006) distinguished between pebbly and bouldery rock glaciers. Pebbly rock glaciers have smaller dominant grain sizes (<20 cm), rounder and more strongly eroded features and are shorter (length <200 m) than bouldery rock glaciers. Ikeda and Matsuoka (2006) showed that pebbly rock glaciers occur mostly in areas of sedimentary rock, indicating the strong influence of lithology on scree grain size. The smaller the grain size, the less air is contained and the greater the conductive heat transfer within the ground (Putkonen, 1998). Pebbly rock glaciers also contain more water, thus delaying winter freezing of the ground (Boike *et al*., 1998). In contrast, a coarse layer of boulders is a good insulator in summer (Gruber and Hoelzle, 2008) and delays the formation of a closed snow cover in winter (Keller and Gubler, 1993).

The strong interaction between high MAP and sedimentary rock is notable. Both reduce rock glacier frequency, but their combined effect clearly exceeds the sum of both factors. The smaller grain sizes in sedimentary rock debris compared to metamorphic/crystalline debris are more prone to water erosion and so are the steep front or side walls of pebbly rock glaciers. This makes them sensitive to strong precipitation. Furthermore, throughflow within the active layer is slower in smaller grain sizes (Bodman and Harradine, 1939), which can increase the energy exchange between the water and the permafrost.

Head Wall Erosion Rates Control Rock Glacier Size, Velocity and Front Elevations

To quantify the effect of head wall erosion on rock glacier size, we analysed the rock glacier-head wall ratio. This ratio is controlled by head wall erosion rates (specific to individual rock walls) and the duration of the active phase of the rock glacier. Comparing active and relict Albula rock glaciers, we found that the rock glacier-head wall ratio for relict rock glaciers was distinctly higher than that for active ones. Following Böhlert *et al.* (2011), this is not a result of a longer active phase of relict rock glaciers. Böhlert *et al.* (2011) dated rock glaciers in the Albula Alps and attributed the main phase of activity of the relict rock glaciers to between the end of the Younger Dryas and the early Holocene. In contrast, today’s active features developed during the entire Holocene. The active phase of the relict Albula rock glaciers investigated was therefore much shorter than those of currently active rock glaciers. Accordingly, Böhlert *et al.* (2011) estimated a mean creep velocity of 30 ka for the active phase of the relict rock glaciers. If this value were applied to currently active rock glaciers, which started creeping in the beginning of the Holocene (Böhlert *et al.*, 2011), they would now be 3 km long. In our data-set, very few, exceptionally long rock glaciers currently have a maximum length of 1 km. Consequently, relict rock glaciers reached larger sizes in a shorter time span, which can only be explained by very high head wall erosion rates.

Indeed, Böhlert *et al*. (2011) postulated a rapid glacier retreat at the end of the Younger Dryas, which resulted in smaller glacier extents than during the Little Ice Age maximum. This implies that huge amounts of debris were available due to deglaciation, debuttressing and head wall warming, leading to permafrost thaw; it also indicates climate conditions comparable with the current situation. Other investigations on climate history in central Europe and the Alps also suggest a rapid and strong warming at the end of the Younger Dryas (Dansgaard *et al*., 1989; Lemdahl, 2000). High head wall erosion rates in permafrost rock walls during phases of atmospheric warming are mentioned by Fischer *et al.* (2006); Gruber and Haeberli (2007) and Noetzli *et al*. (2003). Hales and Roering (2005) showed for timescales of 10–15 ka that erosion rates are lower in permafrost rock walls than in neighbouring permafrost-free rock walls. It is therefore likely that warming-induced high head wall erosion rates favour larger and faster rock glaciers.

Moreover, as the lower elevation limit of rock glaciers is also a function of creep length and velocity, strong warming with high head wall erosion rates rather than colder climate conditions could have forced the presence of rock glacier fronts at lower elevations. The absolute size difference between relict and active features is much greater than the difference in the rock glacier-head wall ratio (Table 2, lines 6–8). This implies a high frequency of relict rock glaciers under very large rock walls. It is conceivable that the combined effect of large rock walls and high head wall erosion rates led to rock glacier advances in elevation ranges that were otherwise unsuitable for long-term rock glacier existence. This is supported by Figure 6 in Frauenfelder and Kääb (2000) which shows that the elevational differences between active/relict rock glaciers vary substantially in neighbouring regions, despite a similar MAAT history.

Wind-Driven Snow Redistribution Affects Rock Glacier Frequency

At scales of a few hundred metres, the wind sheltering index has proved to be the most significant factor describing snow distribution close to crests (Plattner *et al*., 2006). This scale is also relevant for rock glaciers. Our study showed that the wind sheltering index differed between eastern and western aspects but was similar for southern and northern aspects (Table 3). The comparison of northern and southern aspects therefore reflects the undistorted influence of insolation (rock glacier ratio 3:1). The influence of snow cover becomes evident in the rock glacier ratio between eastern and western slopes (rock glacier ratio 2:3). In other studies (Gruber and Hoelzle, 2001; Nyenhuis *et al*., 2005), a significant accumulation of rock glaciers and permafrost in the northwestern aspect is evident too. This corresponds to the higher wind sheltering on eastern slopes (Table 3). A deeper snow cover there reduces the effect of atmospheric cooling of the ground during winter and large amounts of meltwater transport energy in taliks on and within the permafrost body (Zenklusen Mutter and Phillips, 2012). The contrasting snow accumulation on western and eastern slopes can thus explain the differences in permafrost and rock glacier occurrence between these aspects.

MAAT: An Indistinct Threshold for Rock Glacier Development

Overall, we suggest that MAAT defines an elevational range for rock glacier occurrence that depends on the influencing factors mentioned previously. However, we found no sharp MAAT threshold value for rock glacier occurrence, which implies that MAAT is not the only limiting factor for the lower boundary of rock glaciers. In addition, MAAT did not prove to be a clearly definable reference value. In alpine terrain, MAAT is highly influenced by local conditions such as long- and shortwave radiation and wind exposure. Accordingly, the location of air temperature measurements has a considerable influence on the MAAT data and might lead to inconsistencies between specifications for individual rock glaciers or between different studies. Although the MAAT range of over 5 °C determined for the occurrence of active rock glaciers in the Albula Alps is an approximation, it indicates a relatively high tolerance of rock glaciers to air temperature variations. Borehole temperatures in alpine rock glaciers have increased to just below 0 °C during the last two decades without displaying widespread permafrost thaw (Haeberli *et al*., 2006; PERMOS, 2013). This might be a response to the current atmospheric warming, the end of the Little Ice Age or another influence; the time series are still too short for definitive conclusions. It is not clear how stable the current isothermal state of ice-rich rock glacier permafrost is in the Alps. An interruption of response has probably been reached here for the moment, which explains how rock glacier ice outlasted former warming periods during the Holocene and reached ages of several millennia (Böhlert *et al*., 2011; Haeberli *et al*., 1999).

Rock Glacier Development and its Controlling Factors

What do the results for the individual influencing factors imply about rock glacier genesis? Konrad *et al*. (1999) showed that the sensitivity of rock glaciers to climate forcing is strongest in the root zone (where accumulation takes place) and that effective insulation by rock debris reduces this sensitivity to almost zero towards the terminus. On the one hand, this supports our results showing a nonlinear sensitivity of rock glaciers to air temperature. On the other, it highlights the fact that the root zone of rock glaciers is both the zone of accumulation and potentially the zone of highest mass loss. This observation mainly favours the accumulation of talus and avalanche snow under steep alpine rock walls as dominant processes of ice formation in rock glaciers. The snow is either conserved and transformed into ice under a layer of insulating rock debris or slowly melted if the debris cover is not thick enough to insulate against atmospheric warming and solar radiation. This process is certainly not the only source of ice in rock glaciers but probably the most relevant one. It explains that rock glacier development can differ considerably under equal temperature conditions, depending on other factors, the significance of which was shown in our study:

1. The intensity of head wall erosion processes and grain size control (a) the formation time of an insulating debris layer superimposed on avalanche snow in the accumulation area, and (b) the accumulation mass that determines rock glacier length and long-term creep velocity; and
2. The amount of precipitation that can infiltrate the debris layer and supply a constant energy input, independent of the thickness of the insulating debris layer.

CONCLUSIONS

Rock glacier distribution and characteristics in two regions of the Swiss Alps are influenced by MAP, lithology, MAAT, head wall erosion rates, glacier coverage, slope, aspect and snow cover. Some of these factors interact in a nonlinear way, precluding simple explanations for rock glacier development. High values of MAP (both in terms of summer rainfall and winter snow accumulation) disfavour rock glaciers. Differences in snow distribution on small and medium scales due to wind sheltering lead to lower frequencies of rock glaciers on snow-rich slopes. At regional scales, winter precipitation is the dominant factor controlling snow depth on rock glaciers and therefore influences rock glacier frequency. Head wall erosion and lithology also strongly influence rock glaciers. The influence of the lithology on rock glaciers clearly increases with increasing MAP. In contrast, the response of permafrost in rock glaciers to MAAT is less linear than in other landforms and is sometimes overemphasised in the literature. Rock glacier growth probably increases during warming periods due to higher head wall erosion rates. Next to MAAT, head wall erosion and MAP are temporally variable factors that influenced rock glacier development during the Holocene. The reaction of rock glaciers to atmospheric warming must therefore be interpreted carefully due to multiple uncertainties and the fact that the effects of temporally variable influencing factors are hard to distinguish.

ACKNOWLEDGEMENTS

We acknowledge Marcia Phillips, Christian Frei and Rebecca Mott, the Editor, Julian Murton, and the reviewers, Sébastien Monnier and Wilfried Haeberli, for their constructive input to the paper.

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