Ann. Rep., Inst. Geosci., Univ. Tsukuba, no. 27, pp. 11-16, Dec. 25, 2001.

Geological control on the distribution and characteristics of talus-derived rock glaciers

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Introduction

Talus-derived rock glaciers, which characterize the alpine landscape, originate from thick debris accumulation under a permafrost climate. Further growth of the rock glacier requires continuous debris input from rockwalls (*e.g.* Olyphant, 1983; Haeberli *et al.*, 1999; Humlum, 2000), which exceeds the possible removal of debris from the rock glacier. Modelling of the rock glacier dynamics should incorporate debris budget in the rockwall-talus-rock glacier system.

Debris input mainly results from physical weathering on rockwalls, which periodically provides coarse materials on talus slopes and rock glaciers. Since the rate of weathering depends on both environmental and geological factors (*e.g.* Matsuoka, 1990), the rock glacier dynamics depends also on these two factors. This paper focuses on the geological constraints on rock glaciers, based on the literature review and field investigations in the Swiss Alps.

Bedrock geology favorable for rock glaciers

Table 1 lists bedrock geology feeding rock glaciers, compiled from the literature. Some references cite a number of rock types associated with rock glaciers, but only major rocks are listed. Table 1 also displays the activity status (active, inactive or fossil) and surface composition (boulders or pebbles) of the rock glaciers.

The major four rock types, granite (including granodiorite), gneiss, sandstone and limestone (including dolomite), tend to produce boulders or blocky debris up to 5 m in diameter, in response to wide joint spacing (*e.g.* Wahrhaftig and Cox, 1959). This situation agrees with the visual impression that the majority of rock glaciers display blocky upper surface. These block-producing rocks, also including basalt and quartzite, are generally considered to resist rock weathering and sustain a high rockwall (*e.g.* Whalley, 1984). Annual freeze-thaw action reaching several meters depth in the bedrock may play a vital role in producing such blocks (Matsuoka and Sakai, 1999).

In contrast, rock types mainly producing finer or platy debris, including schist, shale and rhyolite, are less common in rock glaciers. These rocks are densely jointed and susceptible to rock weathering (*e.g.* Matsuoka, 1990). In fact, protalus accumulations below rockwalls composed of these rocks consist mainly of finer clasts of the order of centimeters to a few decimeters in diameter. Such small clasts can originate from shallow diurnal freeze-thaw action (Matsuoka, 1990, 2001).

The contrast in rock glacier distribution between the two rock groups can be seen within a mountain region like the Alaska Range, where the geological boundary between granodiorite and schist (or sedimentary rocks) coincides with the boundary between abundant and fewer rock glaciers (Wahrhaftig and Cox, 1959). Rock glaciers having a source area consisting of multiple rock types often display horizontal variations in surface topography and composition reflecting the lithological variation (*e.g.* Elconin and La Chapelle, 1997).

Geological constraints on rock glacier morphology and composition

The literature survey shows that bedrock geology also affects the morphology of rock glaciers. The boulder-producing rocks feed both tongue-shaped (length larger than width) and lobate (length smaller than width) rock glaciers, while rocks producing finer materials are associated with small (and mostly lobate) rock glaciers with a longitudinal length less than 300 m (Table 1).

Field observations in the Swiss Alps have also contrasted rock glacier morphology derived from the two rock groups. For instance, rockwalls made of crystalline and hard carbonate rocks tend to result in large rock glaciers made of coarse blocks (Fig. 1). This type of landform is defined as '*the bouldery rock glacier*'. In contrast, shale rockwalls produce much smaller and steeper forms made of finer debris (Fig. 2). This type is referred to as '*the pebbly rock glacier*', which is probably comparable to the earthy rock glacier defined by Evin (1987). Other contrasting features in morphology involve that the pebbly rock glaciers have

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Table 1. Bedrock geology associated with rock glacier distribution.

Location	Igneous / metamorphic rocks						Sedimentary rocks					Activity	Shape	Surface material	Reference
	Gr/Gd	Rh	Ba/An	Gn	Po	St	Qz	Cg	Ss	Sh	Ls/Do				
Svalbard									O			A	T	B/P	Isaksen et al. (2000)
Svalbard									O	O		A	L	B	Swett et al. (1980)
Svalbard				O		O	O				O	A	L		André (1994)
W Greenland			O									A, I	L	B	Firch & Brandt (1985)
W Greenland			O									A	L	B	Humlum (2000)
Brooks Range, Alaska								O	O			A, I, F	T, L	B	Ellis & Calkin (1979)
Brooks Range, Alaska						O				O		A, I, F	T, L	P	Ellis & Calkin (1979)
Iceland			O									A	T		Martin & Whalley (1987)
Alaska Range	O			O								A, I, F	T, L	B	Wahrhaftig & Cox (1959)
Alaska Range						O						A, I, F	T, L	P	Wahrhaftig & Cox (1959)
Alaska Range					O							A	T	B	Capps Jr. (1910)
Faroe Island			O									F	T, L	B	Humlum (1998)
Rondane, Norway									O			A, I, F	L	B	Shakesby et al. (1987)
SW Yukon	O											A	T	B	Johnson (1987)
SW Yukon									O	O		A, I	T	B/P	Johnson & Lacasse (1988)
SE Yukon & NWT				O								A	T, L	B	Sloan & Dyke (1998)
SE Yukon & NWT						O			O		O	A	T, L	P	Sloan & Dyke (1998)
Cairngorms, Scotland	O						O		O			F	L	B	Sandeman & Ballantyne (1996)
NW Ireland							O					F	L	B	Wilson (1990)
Canadian Rockies											O	A	T	B	Konig & Smith (1999)
Canadian Rockies							O					A, I, F	T, L	B	Luckman & Crockett (1977)
Carpatians	O											A, I, F	T, L	B	Urdea (1998)
Tirolian Alps (Stubai)				O		O						A	T	B	Krainer & Moster (2000)
Tirolian Alps											O	F	T, L	B	De Jong & Kwadijk (1988)
Swiss Alps				O								A	L	B	Fisch et al. (1977)
Swiss Alps (Bernese)	O			O							O	A, I, F	T, L		Imhof (1996)
Swiss Alps (Schilthorn)									O		O	I, F	T	B	Imhof et al. (2000)
Swiss Alps (Schilthorn)										O		I, F	L	P	Imhof et al. (2000)
Swiss Alps (Gruben)				O								A	T	B	Barsch et al. (1979)
Swiss Alps (Macun)				O								A	T, L	B	Barsch (1969)
Swiss Alps (Murtèl)	O			O		O						A	T	B	Haeberli et al. (1999)

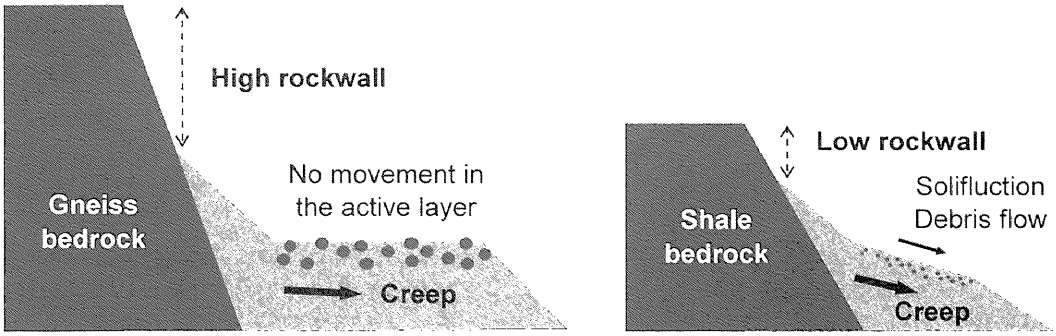
Swiss Alps (Corviglia)										O		A, I, F	L	P	This study
Swiss Alps (Corviglia)	O							O			O	A, I, F	T, L	B	This study
French Alps	O											A	T	B	Francou & Reynaud (1992)
French Alps						O			O		O	A, I	T, L		Evin & Fabre (1990)
Italian Alps (Aosta)				O								A, I	T, L	B	Smiraglia (1992)
Italian Alps (Livigno)				O								A, I	T, L		Guglielmin et al. (1994)
Italian Alps				O								A, I	T, L		Guglielmin & Smiraglia (1998)
SW Alps	O								O	O	O	A, I, F	T, L	B	Evin (1987)
SW Alps						O					O	A, I	T, L	P	Evin (1987)
N New Hampshire						O	O					F	T	B	Thompson (1999)
Absaroka, Wyoming			O									A	T	B	Potter, Jr. (1972)
N Tien Tian	O											A	T, L	B	Gorbunov (1992)
Apennies, Italy											O	F	L		Dramis & Kotarba (1992)
Pyrenees	O					O				O		A	T, L	B	Serrano et al. (1999)
Albanian Alps											O	F	T		Palmentola et al. (1995)
Colorado Plateau			O									A, I, F	T, L	B	Shroder Jr. (1987)
Colorado Rockies	O			O								A	T	B	White (1971)
Mestas, Colorado								O		O		F	T	B	Giardino & Vitek (1988)
La Sal, Utah	O				O							A, F	T, L	B	Nicholas & Butler (1996)
Sierra Nevada	O											A	T	B	Konrad & Clark (1998)
San Mateo, New Mexico		O										F	T, L	B/P	Blagbrough & Farkes (1968)
Japanese Alps	O								O			I, F	T, L	B	Ishikawa et al. (2001)
Japanese Alps		O										I	L	P	Ishikawa et al. (2001)
Nepal Himalaya	O			O								A	T, L	B	Barsch & Jacob (1988)
Bolivian Andes			O									A	T	B/P	Francou et al. (1999)
Central Andes (Mendoza)							O					A	T, L	B	Wayne (1981)
Central Andes (Mendoza)		O										A	T, L	P	Wayne (1981)
S Alps, New Zealand									O			A, I, F	L	B	Kirkbride & Brazier (1995)
S Alps, New Zealand									O			A, I	T		Jeanneret (1975)
James Ross, Antarctica			O									A	T, L		Strelin & Sone (1998)
Total occurences	16	3	8	14	2	10	6	3	13	8	12				

Lithology: Gr/Gd Granite or Granodiorite, Gb Gabbro, Rh Rhyolite, Ba/An Basalt or Andesite, Ph Porphyry, St Schist, Qz Quarzite, Cg Conglomerate, Ss Sandstone, Sh/Ms Shale or Mudstone, Ls/Do Limestone or Dolomite.

Activity: A Active, I Inactive, F Fossil. Surface material: B Bouldery or Blocky, P Pebbly or Platy.

Fig. 1. A bouldery rock glacier below gneiss rockwall, Muragl, Swiss Alps.

Fig. 2. Pebbly rock glaciers below shale rockwall, Corviglia, Swiss Alps.



Bouldery rock glaciers ***Pebbly rock glaciers***

Fig. 3. Constraints on bouldery and pebbly rock glaciers. The left and right illustrations correspond to Figs. 1 and 2, respectively.

a subdued frontal slope and lack multiple ridges on the upper surface, while the bouldery rock glaciers have a sharp frontal edge and multiple ridges.

In addition to the size of surface clasts, the composition of the active layer differs between the two rock glaciers. Bouldery rock glaciers shows the open-work active layer lacking interstitial fine materials, commonly 1-3 m thick, although the frozen core underlying the active layer is composed of coarse clasts embedded in ice and fine materials (*e.g.* Barsch, 1996). The active layer of pebbly rock glaciers usually contains interstitial fine materials composed of sand and finer grains, apart from the uppermost 10-20 cm.

Discussion

The predominance of rock glaciers in bedrock geology producing blocky materials contradicts the conventional understanding on the susceptibility to rock weathering. Rock types unfavorable for large rock glaciers (*e.g.* shale and schist) have been thought to experience more rapid weathering, reducing the clast size to pebbles or finer materials, than the favorable rocks (*e.g.* Potts, 1970; Whalley, 1984). This implies that debris input to rock glaciers may also be more rapid in the former rocks, but in fact only a small lobate form is produced below shale rockwalls.

At least two conditions should be taken into account to solve this problem. Firstly, weak rocks can only support low rockwalls, so that the source area and total debris input may be much smaller than hard and high rockwalls (Fig. 3). Secondly, bouldery rock glaciers lack fine materials in the active layer, while pebbly rock glaciers are usually supported by interstitial fine materials. The fine debris may activate solifluction or debris flow, which tends to remove the surficial debris of pebbly rock glaciers. In the Swiss Alps, in fact, solifluction lobes and sorted patterned ground, which indicate high freeze-thaw activity of the surficial layer, dominate debris slopes in shale and porous carbonate rock regions (Matsuoka *et al.*, 1997). Such debris removal may prevent thick debris accumulation which permits continuous permafrost creep (Fig. 3). As a result, permafrost creep in talus slopes derived from shale rockwalls can only develop small lobate rock glaciers.

Acknowledgements

This study was supported by a grant-in-aid (12680086) for Scientific Research from the Ministry of Education, Science and Culture, Japan.

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Key words: rock glacier, permafrost, bedrock geology, debris composition