Observations and Considerations on Destabilizing Active Rock Glaciers in the European Alps

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Abstract

In many high mountain regions, warming of perennially frozen ground in both coarse debris and rock walls has a major influence on slope stability. In this context, indications of destabilizing active rock glaciers, such as high horizontal velocities (up to 4 ma^{-1}), front advance rates of up to 4 ma^{-1}, and development of crevasse-like cracks (up to 14 m deep), have been documented and monitored in the Alps for a few years. Beside the limited knowledge of rock glacier dynamics, our principle hypothesis is that the primary factors controlling the development of cracks and the destabilization of rock glacier tongues are the rheological properties of warming ice. In addition, we postulate that hydrological effects of unfrozen water within the active layer, the permafrost body, or at its base may contribute to the initiation of the slide-like mass wasting.

Keywords: European Alps; kinematics; rock glacier; slope destabilization.

Introduction

In the context of recent climatic changes and their impact on the cryosphere, high-mountain environments play a key role due to their sensitivity to thermal changes. The indicative role of rock glaciers in these geosystems was emphasized only recently (e.g., Harris & Haeberli 2003, Haeberli et al. 2006), but was up to now mainly restricted to temperature variations within the permafrost body and variations in active layer thickness. Within the last decade, an increasing number of studies monitored and quantified the creep behavior of rock glaciers in the European Alps and observed increasing surface displacements since the 1990s (Schneider & Schneider 2001, Ikeda et al. 2003, Lambiel & Delaloye 2004, Kääb et al. 2007, Roer 2007). In this context it is described that the Alpine rock glaciers show a rather synchronous behavior and respond sensitively to recent temperature increase (Roer et al. 2005a, Roer et al. 2005b, Kääb et al. 2007, Delaloye et al. 2008). In 2003, Kääb et al. stated that the correlation between the velocity field (e.g., speed, creep direction, strain rates) and the present day three-dimensional geometry indicates that most active rock glaciers have not undergone significant dynamic changes in the past. But recently, distinct changes in surface topography are described for a number of active rock glaciers in the Alps, indicating the landslide-like behavior and destabilization of these landforms.

Based on these observations, the study aims at identifying primary factors controlling the development of cracks and causing the landslide-like behavior of the landforms. Furthermore, possible natural hazards due to rock glacier instabilities are discussed.

Observations

The destabilization of active rock glaciers is indicated by distinct changes in their kinematics, geometry and strongly modified topography. These phenomena are investigated qualitatively by field inspection and by interpretation of terrestrial and aerial photographs. In addition, horizontal velocities, advance rates of the rock glacier front, as well as the growth and depth of cracks, are measured and quantified by the use of digital othophotos and by differential GPS measurements in the field. Also, recently the remote sensing technique InSAR (Interferometric Synthetic Aperture Radar) has been applied to detect landform changes (Delaloye et al. in prep., Lambiel et al. 2008). Once indications for destabilizations are detected, the rock glaciers have been surveyed regularly and monitored in detail. Examples are provided from different regions of the European Alps:

(1) rock glacier Hinteres Langtalkar, Carinthia, Austria
(2) rock glacier Grueo1, Valais, Switzerland
(3) rock glacier Furggwanghorn, Valais, Switzerland
(4) rock glacier Petit-Vélan, Valais, Switzerland
(5) rock glacier Tsaté-Moiry, Valais, Switzerland

First, observations on variations in velocity fields accompanied by the development of transverse cracks were described for the rock glaciers Äusseres Hochebenkar and Hinteres Langtalkar, both situated in Austria (Kaufmann &

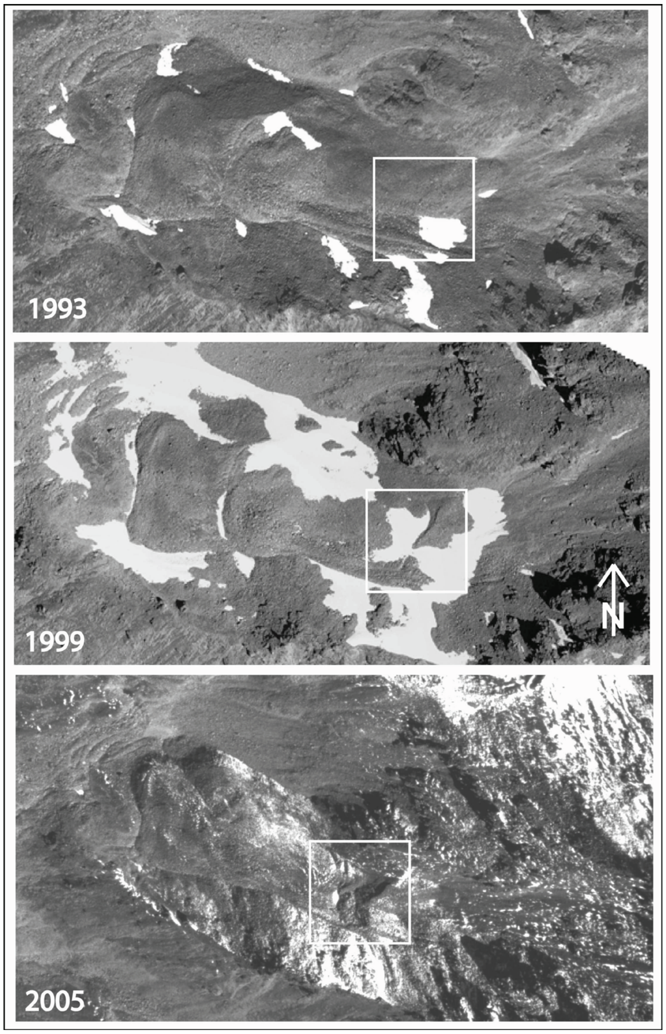

Figure 1. Development of cracks cracks phenologically similar to crevasses occurring on glaciers, in the rooting zone of rock glacier Furggwanghorn (Valais, Switzerland). A small crack started to grow between 1993 and 1999 and evolved into two 14 m deep cracks until 2005. In parallel, the former stable front of the rock glacier advanced about 1.55 ma^{-1} during this time. Orthoimages of 1993, 1999, and 2005 © Swiss Federal Office of Topography (Swisstopo).

Ladstädter 2003, Avian et al. 2005). The strong deformation of the lowest part of the rock glacier Hinteres Langtalkar was interpreted as expression of enhanced strain due to movement of the landform over a terrain ridge into steeper terrain. Thus, the sudden change in slope inclination seemed to cause this specific dynamic response. Later, further rock glaciers showing similar creep instabilities accompanied by the formation of surface ruptures were detected in the Valais, Switzerland.

Rock glacier topography

At the scale of an entire rock glacier, its typical topography is characterized by a relatively smooth and unstructured surface in the upper part (with sometimes longitudinal ridges) and a distinct pattern of ridges and furrows in the lower part, indicating compressive flow. Thus, the surface structure of a rock glacier depicts the complex strain history of the landform (Haeberli 1985, Kääb & Weber 2004). Normally, even if the horizontal velocities are high, the geometric change of the creeping permafrost body is very small (Kääb & Vollmer 2000, Roer 2007).

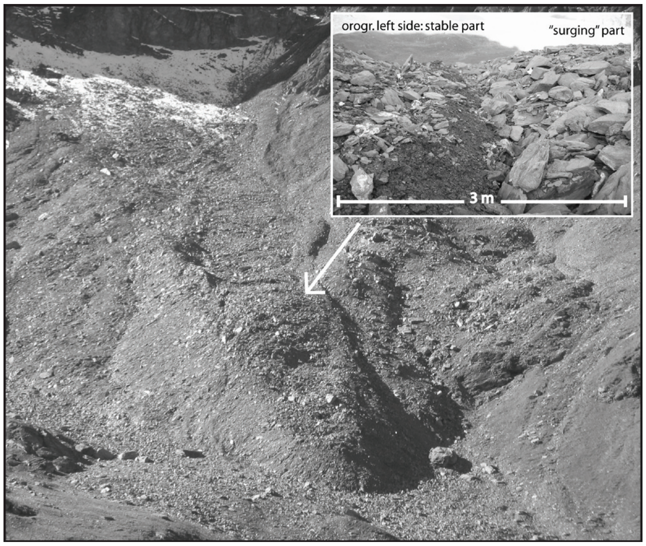

Figure 2. Rock glacier Tsaté-Moiry, Valais, Switzerland. Several scars, developing since the 1980s, are found all over the landform. Velocities at the front were about 7 ma^{-1} between 2006 and 2007. In the field, stable and surging parts can easily be differentiated due to stability (wedged or loose blocks) as well as sorting of the material at the rock glacier surface (Photos: C. Lambiel, 2007).

Most of the rock glaciers investigated here show a smooth morphology prior to the sliding behavior (e.g., rock glacier Furggwanghorn 1993, Fig. 1). In addition, those landforms featuring failures at the front in parallel, indicate smooth surfaces with continuous horizontal displacements in their rooting zones (Kaufmann & Ladstädter 2003, Roer 2007). In the case of rock glacier Tsaté-Moiry, indications for destabilization are not restricted to one part, but affect the whole landform (Fig. 2). Most of the rock glaciers show a collapse behavior in the lowermost part of their tongue. Such failures are indicated by the rugged topography due to the crack formation and by the strong advance of the tongue which is accompanied by a lowering of the surface.

Horizontal velocities and advance rates

As mentioned before, the morphological change of the rock glaciers studied here is caused by distinct high horizontal velocities over the entire landforms, between 1.00–3.76 ma^{-1} (Table 1). These velocities indicate strong spatial variations. In general, deformation rates of the investigated rock glaciers are very small in the rooting zone and at the margins of the landform; the highest movement rates are found in the central flow field. On most of the destabilizing rock glaciers, highest velocities are measured at the front, where most of the morphological changes occur (e.g., Fig. 3). For some of these rock glaciers, measurements of velocities were even inhibited on the destabilized parts of the tongue, due to a loss in corresponding features in the repeated orthophotos. In such cases, the surface is not slowly changing anymore,

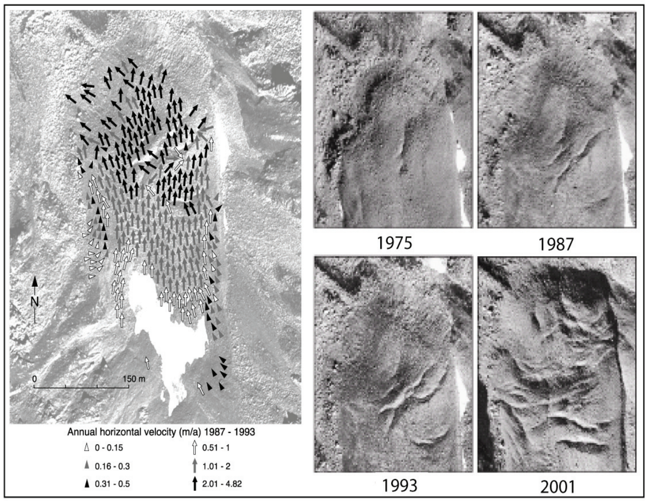

Figure 3. Collapsing tongue and development of deep cracks of rock glacier Grueo1 (Valais, Switzerland) between 1975 and 2001. The cracks started to develop on the orographic right side, while later (between 1993 and 2001) the landslide-like failure extended over the entire tongue. Between 1975 and 2001 the rock glacier advanced about 60 m (~ 2.3 ma^{-1}). (See also Roer 2007, Kääb et al. 2007). Orthoimages of 1975, 1987, and 1993 © Swiss Federal Office of Topography (Swisstopo). Orthoimage of 2001 © RTG 437, Department of Geography, University of Bonn.

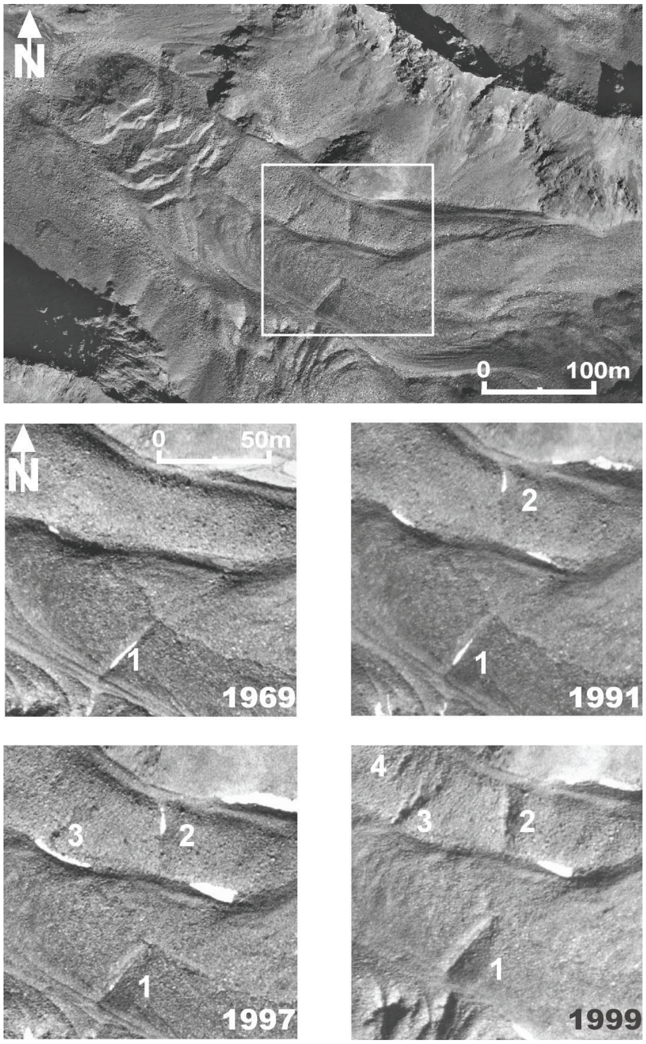

Figure 4. Rock glacier Hinteres Langtalkar (Carinthia, Austria): formation of cracks (1–4) between 1969 and 1999 in the middle part of the landform (square in uppermost image). Aerial photographs of rock glacier Hinteres Langtalkar for 1969, 1991, 1997, and 1999 © Austrian Federal Office of Metrology and Survey (BEV), Vienna, 2001.

but is rather characterized by tilting and toppling of blocks into the forming cracks.

In addition to the high displacement rates, all rock glaciers considered here indicate extraordinary changes at their fronts. Regarding typical rock glaciers, even if different advance mechanisms occur (Kääb & Reichmuth 2005), the annual rates are very small (0.1- 0.4 ma^{-1} in the Alps (Roer 2007)). In contrast, rock glaciers showing a landslide-like behavior, feature extraordinary advances of several meters per year (see Table 1, Fig. 5). Due to that fact, the shape of the terminal fronts changed significantly. Hence, they are not stable anymore, and often show a high rockfall frequency.

Formation of cracks

Caused by the high horizontal velocities and the pronounced advance of the fronts, cracks that are –phenologically similar to crevasses which occur on glaciers –developed on all rock glaciers in this study. These cracks are mostly found in the lower part of the tongues; rock glacier Furggwanghorn is the only one with cracks in the rooting zone after 1993 (Fig. 1). They are up to 14 m deep and feature lengths of 150 meters and more. An interesting fact is that, on most of the rock glaciers investigated, first indications of the existence and growth of cracks go back for over 20 years (Table 1). The formation of cracks on the rock glaciers Grueo1 (Fig. 3) and Hinteres Langtalkar (Fig. 4), expanded and accelerated in the 1990s. This is in accordance with observations on rock glacier Furggwanghorn, which show a more recent crack formation (between 1993 and 1999, Fig. 1). In the case of rock glacier Tsaté-Moiry, the phenomena is instead described by the occurrence of scars (which are less deep than cracks, and therefore seem to affect the active layer only) occurring all over the landform.

Inspections and investigations of these cracks in the field offered more questions than answers. In most of the cracks, neither ice nor evidence of water was found during the summer months, hinting at a well-developed drainage through and/or underneath the creeping permafrost bodies. However, on rock glacier Hinteres Langtalkar (Fig. 4), two of the cracks were filled with water during summer.

Destabilization of rock glacier tongues

A destabilization of the rock glacier tongues happens in those cases where deep cracks form in the lower part of the landforms (i.e., rock glaciers Hinteres Langtalkar, Grueo1, and Tsaté-Moiry). The cracks indicate deep shear-zones similar to those known for rotational landslides (Dikau et al. 1996). Also, the movement of the tongue, which is characterized by a massive downslope displacement of the mass accompanied by a distinct lowering of the surface (see Fig. 5), is analagous to sliding processes. Hence, a change

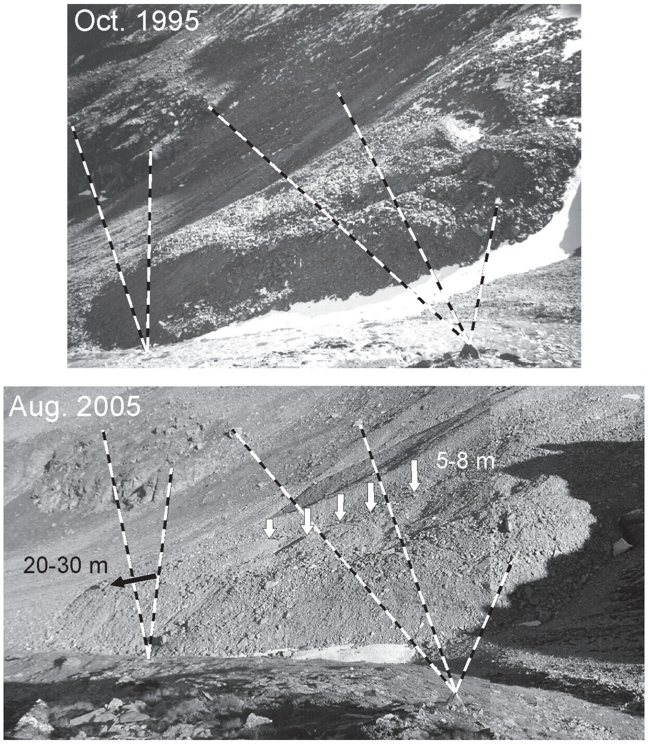

Figure 5. Instability of the tongue of rock glacier Petit-Vélan (Valais, Switzerland). The dashed lines connect the fixed points in stable terrain outside the rock glacier and provide the basis for the photo analysis. Between October 1995 and August 2005, this landform advanced about 20–30 m (approx. 2.5 m per year). Due to that shift of mass, vertical lowering of 5–8 m occurred (Photos: R. Delaloye)

in process regime is indicated. Related to the landslide-like mass wasting, the lowermost part of the tongues changed from a formerly convex to a more concave morphology.

Hazards

The changes described before can affect all parts of rock glaciers: the active layer, the permafrost body, the rooting zone, or the front. Arenson (2002) stated that instabilities within the active layer seem to be most probable due to the effect of unfrozen water during summer. The accelerated horizontal velocities, as well as the sliding processes, strongly influence the stability of the rock glacier front. Here, enhanced rockfall activity (frequency and magnitude) was recognized on several rock glaciers. In general, the position of the landform (especially the slope angle) is decisive for its hazard potential.

Considerations

Table 1. Summary of characteristics of the investigated rock glaciers. The numbers refer to the rock glaciers listed on page 1.

rockgl.	mean annual velocity (ma^{-1})	front advance (ma^{-1})	crevasses in		beginning of crevasse formation
			lower part	rooting zone	
1	2.80 (mean 1997 - 1998)	-	x	-	before 1954
2	2.79 (mean 1993 - 2001)	2.30 (1975-2001)	x	-	before 1975
3	1.46 (mean 1993 - 2001)	1.55 (1975-2001)	-	x	between 1993 and 1999
4	1.24 (mean 2005 - 2007)	2.50 (1995-2005)	x	-	between 1988 and 1995
5	1.50 (mean 2005 - 2007)	4.00 (1999-2005)	x	x	before 1988

The interpretation of the presented observations is, up to now, strongly limited due to the complexity of the phenomenon and the lack of information on the thermal state and internal structure of the rock glaciers considered here. Borehole data (internal deformation, temperatures) or data delivered by geophysical soundings from adjacent landforms can not be consulted, since the dynamics of individual rock glaciers cannot be readily compared. Therefore, only the given information on rock glacier kinematics can be analysed. Since these data provide a cumulative signal reflecting all components of the creep process (internal deformation, sliding in shear horizons, and deformation at the base), the processes below the surface can be considered to some degree. The key question is which of the creep components increased by certain changes, i.e., whether the internal deformation, the sliding in shear horizons, or the basal sliding increased significantly (Fig. 6).

Under constant temperatures, stresses, and strain rates, rock glaciers show long-term steady-state (secondary) creep behaviour (Haeberli 1985). The flow results from the plastic deformation of the ice inside the supersaturated permafrost body in response to gravity and is controlled mainly by its internal structure (Barsch 1992). Sliding in shear horizons, where reduction in viscosity enables higher deformations, plays an additional role (Wagner 1992, Arenson et al. 2002). Hence, different factors or a combination thereof, may lead to the observed geomorphic changes: changes in ice content or ice characteristics; changes in the shear horizons (e.g., number, position, frictional behaviour, occurrence of unfrozen water); or changes in the internal structure of the permafrost body leading to changes in deformation. Another creep component, which could have led to the observed changes, might be the deformation of subpermafrost sediments (Fig. 6).

All those effects may result from a change in ground temperature regime. The significance of a rise in air temperature for a change in the strength of ice-rock mixtures has been demonstrated by Davies et al. (2001) in laboratory tests. They proved that a rise in air–and consequently ground–temperature leads to a reduction in shear strength of ice-bonded discontinuities and thus may induce slope failures. In addition, Kääb et al. (2007) conclude from modeling and field investigations, that the creep of perennially frozen granular material close to 0°C is significantly more sensitive to climate forcing than the creep of colder material. Their modeling results also stress the importance of a deeper understanding of shear horizons in rock glaciers, since they appear to be the most sensitive parts in the response of the permafrost bodies to atmospheric and ground warming.

The analysis of the observed development of cracks indicates that strain rates increased significantly. It is not clear whether this formation is a gradual process (as indicated by the slow growth of most of the cracks, Figs. 3, 4) or sudden exceeding of a threshold (as given by the acceleration of crack formation in the 1990s). In addition, this development may differ between rock glaciers. The related changes at the rock glacier surface (e.g., thinning of the protecting debris cover) might enhance the process by positive

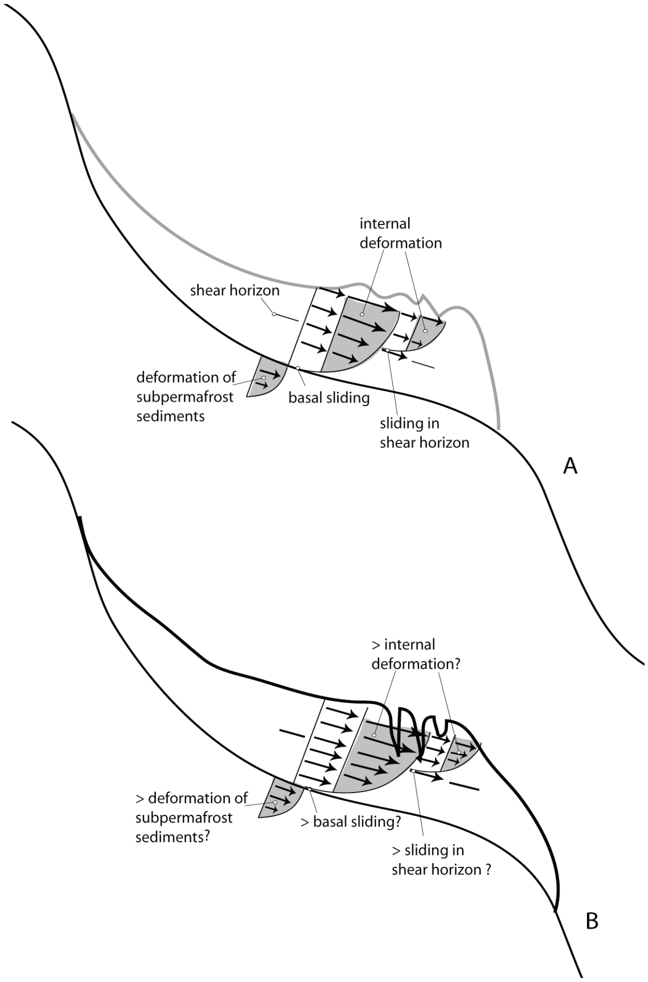

Figure 6. Schematic profile of a typical rock glacier for steady-state conditions (A), and a destabilized rock glacier with crack formation in the lower part of the tongue (B). A deformation profile showing the single creep components is depicted for both cases; it is not clear which component is decisive for the destabilization of the tongue

feedback mechanisms (Kääb et al. 2007). Due to the cracks, latent heat can easily penetrate into the permafrost body, and thus may lead to a warming of the ice (thermokarst phenomena).

The observed changes at the front of the rock glaciers' are probably not exclusively related to permafrost creep processes alone. The analysis of the morphological changes indicates a mass wasting similar to landslides.

Conclusions and Perspectives

Our principle hypotheses are that the primary factors controlling the development of cracks and the destabilization of rock glacier tongues are the rheological properties of warming ice and the resulting changes in the stress-strain relation. In addition, and related to the before mentioned, hydrological effects (unfrozen water) within the permafrost body or at its base may contribute to the initiation of rapid flow acceleration into tertiary creep. Unfrozen water ponding on the permafrost surface could lead to surface instabilities and trigger landslides (Arenson 2002). Another component in this context might be the deformation of subpermafrost sediments. In some cases, topographic influences due to movement onto steep slopes (>25-30°) and/or convex terrain can initiate the destabilization of the landform. Generally, the interpretation of those exceptional rock glaciers is limited, due to the little knowledge of rock glacier dynamics.

The challenge in the investigation of destabilized active rock glaciers lies in the ongoing monitoring of these landforms, for research purpose as well as for hazard assessments. In addition, more data related to internal characteristics are needed in order to develop a process model that couples creep and sliding mechanisms. The coupled analysis will allow for an assessment of how changes in subsurface characteristics will be translated into a rheological response. These goals fit into the key questions of future permafrost research addressing spatio-temporal changes of surface and subsurface processes in response to atmospheric forcing.

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