# Observations And Considerations On Destabilizing Active Rockglaciers In The European Alps

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## Abstract

In many high mountain regions, warming of perennially frozen ground in both coarse debris and rockwalls has a major influence on the slope stability. In this context, indications of destabilizing active rockglaciers, such as high horizontal velocities (up to $4ma^{-1}$), front advance rates of up to $4ma^{-1}$, and development of crevasse-like cracks (up to 14 m deep), are documented and monitored in the Alps since a few years. Beside the limited knowledge of rockglacier dynamics, our principle hypothesis is that the primary factors controlling the development of cracks and the destabilization of rockglacier 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; rockglacier; slope destabilization

## Introduction

In the context of the recent climatic changes and their impact on the cryosphere, high-mountain environments play a key role due to their sensitivity towards thermal changes. The indicative role of rockglaciers 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 as well as variations in active layer thickness. Within the last decade, an increasing number of studies monitored and quantified the creep behavior of rockglaciers 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 rockglaciers 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 rockglaciers have not undergone significant dynamic changes in the past. But recently, distinct changes in surface topography are described for a number of active rockglaciers 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 rockglacier instabilities are discussed.

## Observations

The destabilization of active rockglaciers 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 rockglacier 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. Recently, also the remote sensing technique InSAR (Interferometric Synthetic Aperture Radar) is applied to detect landform changes (Delaloye et al. in prep., Lambiel et al. 2008). Once indications for destabilizations were detected, the rockglaciers have been surveyed regularly and monitored in detail. Examples are provided from different regions of the European Alps:

1 -> rockglacier Hinteres Langtalkar, Carinthia, Austria
2 -> rockglacier Grueo1, Valais, Switzerland
3 -> rockglacier Furggwanghorn, Valais, Switzerland
4 -> rockglacier Petit-Vélan, Valais, Switzerland
5 -> rockglacier Tsaté-Moiry, Valais, Switzerland

First observations on variations in velocity fields accompanied by the development of transverse cracks were described for the rockglaciers Äusseres Hochebenkar and Hinteres Langtalkar, both situated in Austria (Kaufmann & Ladstädter 2003, Avian et al. 2005). The strong deformation of the lowest part of the rockglacier 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 rockglaciers showing similar creep instabilities accompanied by the formation of surface ruptures were detected in the Valais, Switzerland.

*Rockglacier topography*

At the scale of an entire rockglacier 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. This, the surface structure of a rockglacier 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).

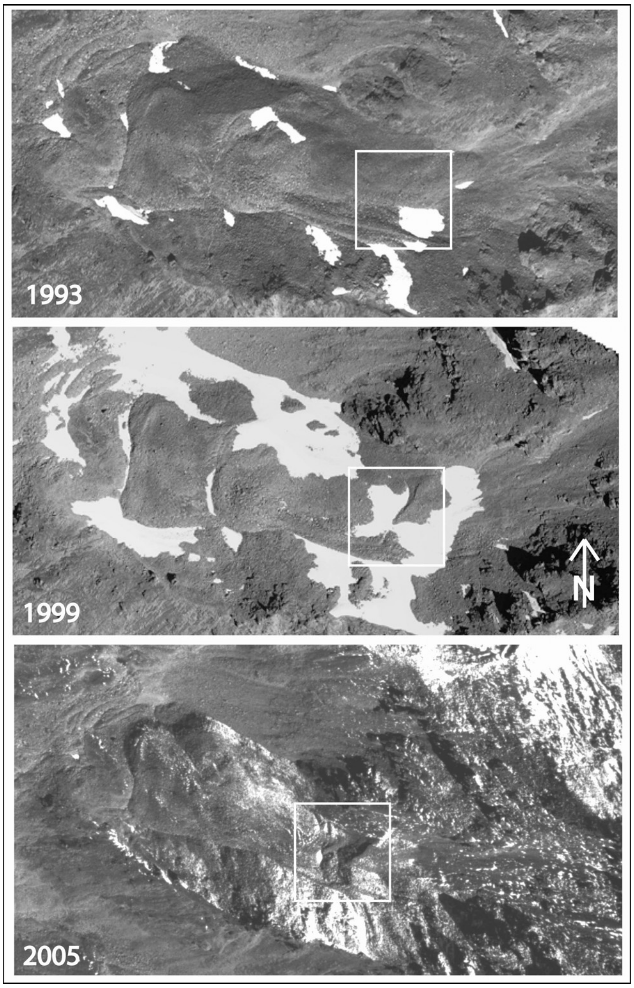


Figure 1: Development of cracks – phenological similar to crevasses occurring on glaciers - in the rooting zone of rockglacier Furggwanghorn (Valais, Switzerland). A small crack started to grow between 1993 and 1999 and evolved into two 14 m deep cracks until 2005. In parallel, the former stable front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

Most of the rockglaciers investigated here show a smooth morphology prior to the sliding behavior (e.g., rockglacier 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 case of rockglacier Tsaté-Moiry, indications for destabilization are not restricted to one part, but affect the whole landform (Fig. 2). Most of the rockglaciers 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.

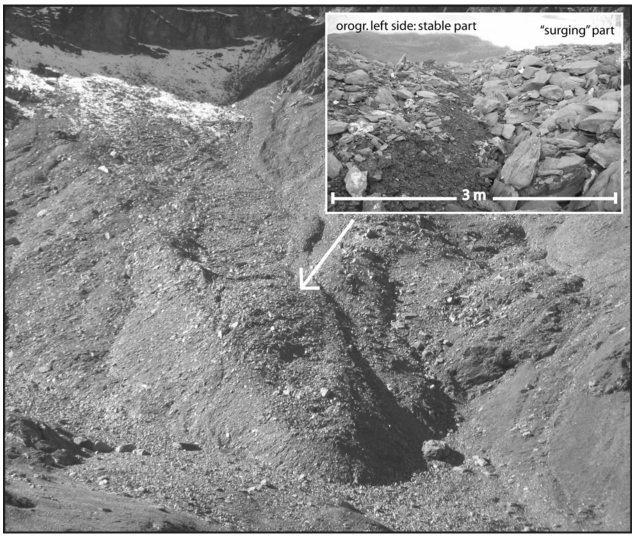


Figure 2: Rockglacier Tsaté-Moiry, Valais, Switzerland. Several scars, developing since the 1980s, are found all over the landform. Velocities at the front were about 7 $ma^{-1}$ between 2006 and 2007. In the field, stable and surging parts can easily be differentiated due to stability (wedged or loose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

*Horizontal velocities and advance rates*

As mentioned before, the morphological change of the rockglaciers studied here is caused by distinct high horizontal velocities over the entire landforms, between 1.00 – 3.76 $ma^{-1}$ (Tab. 1). These velocities indicate strong spatial variations. In general, deformation rates of the investigated rockglaciers are very small in the rooting zone and at the margins of the landform; the highest movement rates are found in the central flowfield. On most of the destabilizing rockglaciers, highest velocities are measured at the front, where most of the morphological changes occur (e.g., Fig. 3). For some of these rockglaciers, 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, but is rather characterized by tilting and toppling of blocks into the forming cracks.

In addition to the high displacement rates, all rockglaciers considered here indicate extraordinary changes at their fronts. Regarding typical rockglaciers, 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, rockglaciers showing a landslide-like behavior feature extraordinary advances of several meters per year (see Tab. 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.

Table 1: Summary of characteristics of the investigated rockglaciers. The numbers refer to the rockglaciers listed on page 1.

| rockgl. | mean annual velocity ($ma^{-1}$) | front advance ($ma^{-1}$) | crevasses in lower part | crevasses in rooting zone | beginning of crevasse formation |
|---|---|---|---|---|---|
| 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 |

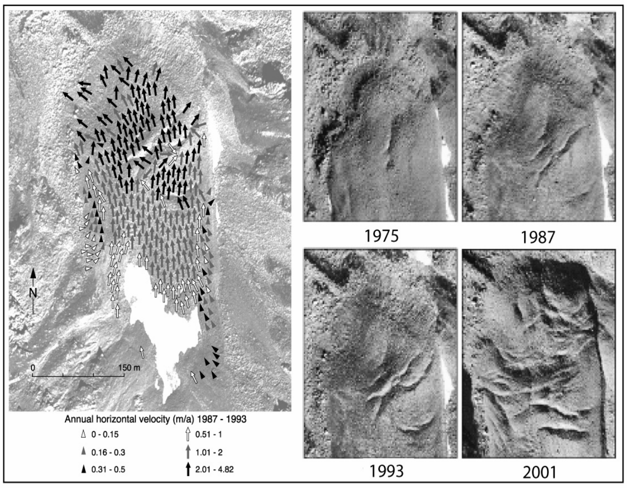


Figure 3: Collapsing tongue and development of deep cracks of rockglacier Grueo1 (Valais, Switzerland) between 1975 and 2001. The cracks started to develop on the orographic right side, while later (between 1993 and 2001) the landslide-like failure extended over the entire tongue. Between 1975 and 2001 the rockglacier 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.

*Formation of cracks*

Caused by the high horizontal velocities and the pronounced advance of the fronts, cracks – phenologically similar to crevasses occurring on glaciers - developed on all rockglaciers regarded in this study. These cracks are mostly found in the lower part of the tongues; rockglacier 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 rockglaciers investigated, first indications for the existence and growth of cracks go back for over 20 years (Tab. 1). The formation of cracks on the rockglaciers Grueo1 (Fig. 3) and Hinteres Langtalkar (Fig. 4), expanded and accelerated in the 1990s. This is in accordance with observations on rockglacier Furggwanghorn, which show a more recent crack formation (between 1993 and 1999, Fig. 1). In case of rockglacier Tsaté-Moiry, the phenomena is rather described by the occurrence of scars (which are less deep than the cracks, and therefore seem to affect the active layer only) occurring all over the landform.

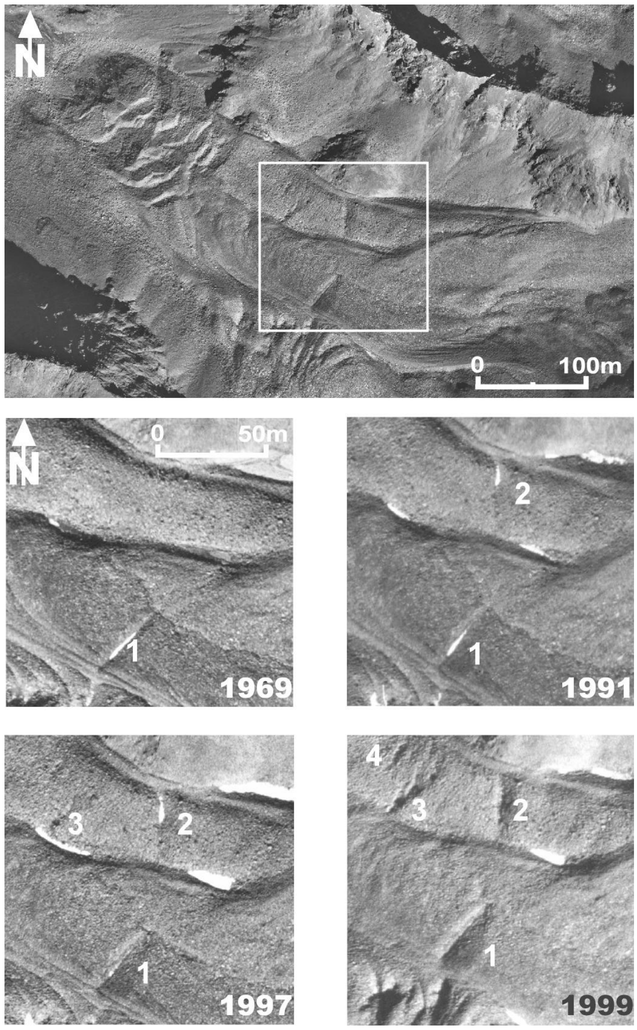


Figure 4: Rockglacier Hinteres Langtalkar (Carinthia, Austria): formation of cracks (1-4) between 1969 and 1999 in the middle part of the landform (square in uppermost image). Aerial photographs of rockglacier Hinteres Langtalkar for 1969, 1991, 1997, and 1999 © Austrian Federal Office of Metrology and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

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 to a well developed drainage through and/or underneath the creeping permafrost bodies. Just on rockglacier Hinteres Langtalkar (Fig. 4), two of the cracks were filled with water during summer.

*Destabilization of rockglacier tongues*

A destabilization of the rockglacier tongues is given in those cases, where deep cracks built in the lower part of the landforms (i.e. rockglaciers 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), depicts the analogy to sliding processes. Hence, a change 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.

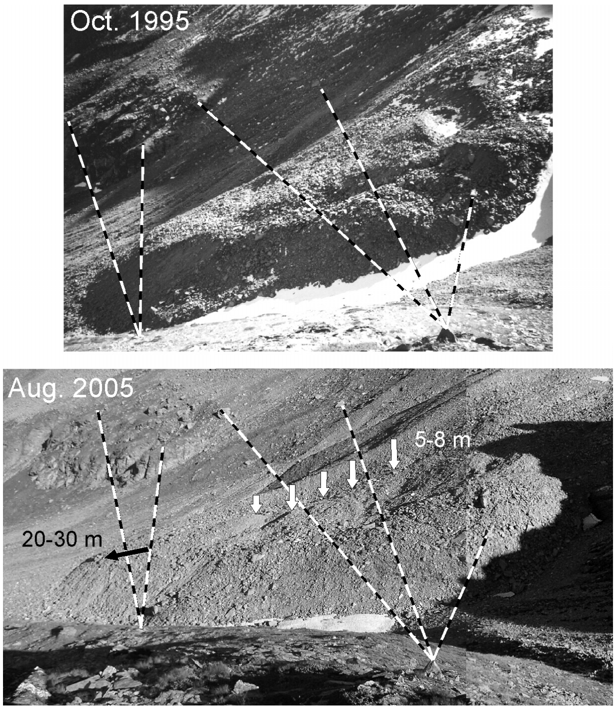


Figure 5: Instability of the tongue of rockglacier Petit-Vélan (Valais, Switzerland). The dashed lines connect the fix points in stable terrain outside the rockglacier and provide the basis for the photo analysis. Between October 1995 and August 2005 this landform advanced about 20-30m (approx. 2.5 m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

*Hazards*

The changes described before can affect all parts of rockglaciers: 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 influence strongly the stability of the rockglacier front. Here, enhanced rockfall activity (frequency and magnitude) was recognized on several rockglaciers. In general, the position of the landform (especially the slope angle) is decisive for its hazard potential.

## Considerations

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 rockglaciers 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 rockglaciers cannot be readily compared. Therefore, only the given information on rockglacier 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, rockglaciers 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 modelling 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 modelling results also stress the importance of a deeper understanding of shear horizons in rockglaciers, since they appear to be the most sensitive parts in the response of the permafrost bodies to atmospheric and ground warming.

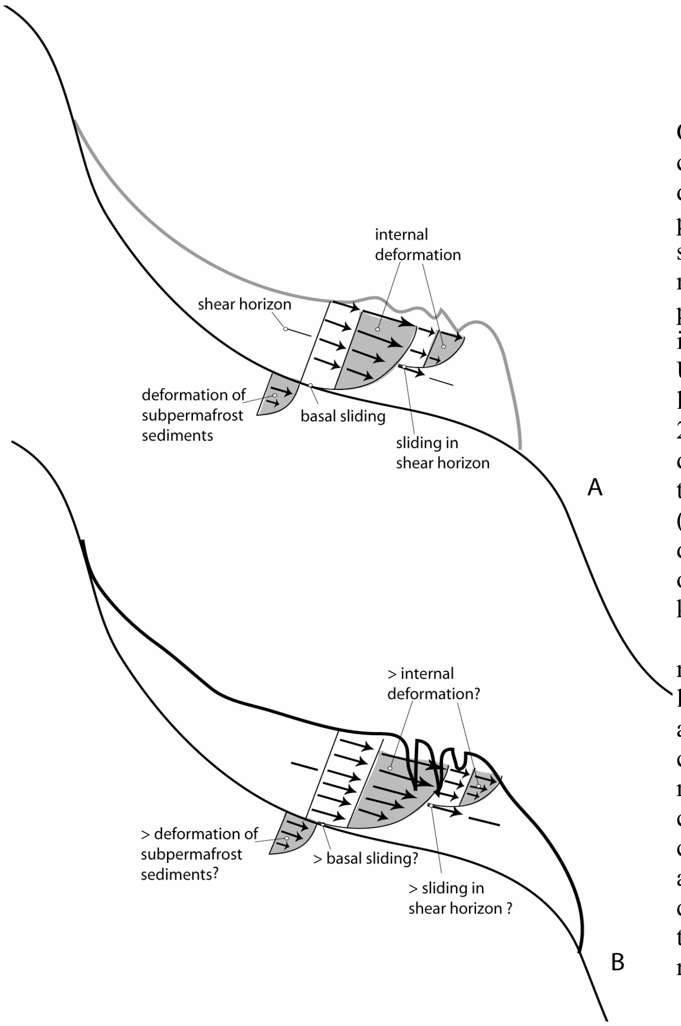


Figure 6: Schematic profile of a typical rockglacier for steady state conditions (A), and a destabilized rockglacier with crack formation in the lower part of the tongue (B). A deformation profile showing the single creep components is depicted for both cases; it is not clear which component is decisive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

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 a sudden exceedance of a threshold (as given by the acceleration of crack formation in the 1990s). In addition, this development may differ between rockglaciers. The related changes at the rockglacier surface (e.g. thinning of the protecting debris cover) might enhance the process by positive 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 rockglaciers fronts 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 rockglacier 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 rockglaciers is limited, due to the little knowledge of rockglacier dynamics.

The challenge in the investigation of destabilized active rockglaciers 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.

## Acknowledgments

The photogrammetric analyses of Furggwanghorn rockglacier were conducted in collaboration with Patrick Thee, Swiss Federal Institute for Forest, Snow and Landscape research. We gratefully acknowledge the valuable comments of two anonymous reviewers.

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