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Rock-glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps

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ABSTRACT

A widespread risk in high mountains is related to the accumulation of loose sediments on steep slopes, which represent potential sources of different types of geomorphic processes including debris flows. This paper combines data on 50 yr of permafrost creep at the Ritigraben rock glacier (Valais, Swiss Alps) with magnitude–frequency (M–F) relationships of debris flows recorded in the Ritigraben torrent originating at the rock-glacier front. Debris production and volumetric changes at the rock-glacier front are compared with debris-flow activity recorded on the cone and potential couplings and feedbacks between debris sources, channel processes and debris sinks. The dataset existing for the Ritigraben rock glacier and its debris-flow system is unique and allows prime insights into controls and dynamics of permafrost processes and related debris-flow activity in a constantly changing and warming high-altitude environment. Acceleration in rock-glacier movement rates is observed in the (1950s and) 1960s, followed by a decrease in flow rates by the 1970s, before movements increase again after the early 1990s. At a decadal scale, measured changes in rock-glacier movements at Ritigraben are in concert with changes in atmospheric temperatures in the Alps. Geodetic data indicates displacement rates in the frontal part of the rock glacier of up to 0.6–0.9 m yr^{-1} since the beginning of systematic measurements in 1995. While the Ritigraben rock glacier has always formed a sediment reservoir for the associated debris-flow system, annual horizontal displacement rates of the rock-glacier body have remained quite small and are in the order of decimeters under current climatic conditions. Sediment delivery from the rock-glacier front alone could not therefore be sufficient to support the 16 debris flows reconstructed on the cone since 1958. On the contrary, debris accumulated at the foot of the rock glacier, landslide and rockfall activity as well as the partial collapse of oversteepened channel walls have to be seen as important sediment sources of debris flows at Ritigraben and would represent 65–90% of the material arriving on the Ritigraben cone. There does not seem to exist a direct coupling between displacement rates of and sediment delivery by the rock-glacier body and the frequency of small- and medium-magnitude debris flows. In contrast, a direct link between source and sink processes clearly exists in the case of active-layer failures. In this case, failure processes at the rock-glacier snout and debris-flow events in the channel occur simultaneously and are both triggered by the rainfall event.

1. Introduction

A widespread risk in high mountains is related to the accumulation of loose sediments on steep slopes, which represent potential sources of different types of geomorphic processes. Active rock glaciers and other features of creeping mountain permafrost are widely recognized to act as major long-term debris transport systems and a major source for gravitational processes including rockfall or debris flows (Harris et al., 2009; Kääb et al., 2007).

The release of periglacial debris flows depends on the availability of sediment and on the presence of triggers. In high-mountain environments, sediment availability as well as the stability and hydrology of debris slopes are essentially driven by periglacial processes and the respective hazard potential seems to be connected to the presence of permafrost and its change (Kääb et al., 2005a,b). Ground ice may cement loose sediments and thus prevent retrogressive erosion (Zimmermann and Haeberli, 1992). In the case of thaw, however, slope stability is decreased (Harris et al., 2001) and enhanced runoff from permafrost and ground water concentrations above the permafrost table may result in active-layer failures (Kääb et al., 2005a, b) and subsequent debris flows (Stoffel, 2010).

Observational data on surface movements in rock glaciers indicate that displacement rates are usually slow, typically in the range of

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several decimeters per year (Haeberli et al., 2006). Based on recent observations in the Swiss Alps, there is, however, evidence that movement rates of rock glaciers do not only show great inter-annual variations in surface velocity (Delaloye et al., 2008), but that there are also strong indications for a synchronous acceleration of movement rates at many sites across the Alps since the 1990s as well as a partial or even complete destabilization of some rock-glacier tongues (Kääb et al., 2007; Krysiecki et al., 2008). This destabilization is supposed to be induced by changing rheological properties of warming ice (Roer et al., 2008), resulting in annual horizontal velocities and annual front advances in the order of several meters or the development of large crevasse-like cracks (Delaloye et al., 2008). As these destabilizing zones are normally located in the steepest sections of the rock-glacier body and just below significant longitudinal increases of the surface slope, they produce considerable channel recharge rates and may locally lead to increased risks of gravitational processes.

Besides the availability of erodible debris, the release of debris flows also depends on the existence of triggering events. Triggers can either be meteorological events such as high-intensity thunderstorms, persistent rainfall, rain-on-snow events (Rebetez et al., 1997; Guzzetti et al., 2008; Stoffel et al., in review) or hydrological incidences in the form of sudden water release stored on or underneath a glacier or the breaching of natural dams (Chiarle et al., 2007; Huggel et al., 2003, 2004; Kääb et al., 2005a).

Although the frequency and magnitude of periglacial debris-flow activity clearly depend on sediment availability and channel recharge rates (Jakob et al., 2005), there is virtually no quantitative data available on the potential control of debris volumes available in the periglacial headwaters of torrents and the actual occurrence or size of debris flows (Stoffel, 2010). This lack of data is partly due to missing long-term observational data on rock-glacier movement on one hand and on fragmentary information on the frequency and magnitude of debris flows on the other hand.

It is therefore the goal of this paper to combine data on permafrost creep with magnitude–frequency (M–F) relationships of debris flows recorded in a small catchment in the Swiss Alps originating from periglacial environments. The study spans almost fifty years (1958–2005) and presents results on (i) the nature and long-term changes of permafrost in the departure zone of debris flows obtained with borehole observations, photogrammetric analyses and geodetic measurements at the rock-glacier front as well as (ii) on M–F relationships of debris-flow activity on the cone reconstructed from tree-ring records of living conifers disturbed by past events. In a last analytical step, (iii) debris production and volumetric changes at the rock-glacier front will be compared with debris-flow magnitudes recorded on the cone and (iv) potential couplings and feedbacks between debris sources, channel processes and debris sinks will be discussed.

2. Study site

The Ritigraben torrent is located on the west-facing slope of the Mattertal valley (Valais, 46° 11′ N., 7° 49′ E.). The torrent system spans a vertical range of over 2000 m from its confluence with the Vispa River at 1080 m asl and the summit of the Seetalhorn at 3100 m asl. A rock glacier occupies a large part of the headwater basin (1.4 km^2) between 2500 and 2800 m asl (Fig. 1) representing the principal source of loose material in the upper part of the Ritigraben catchment area and constituting the main starting zone of debris flows. The construction of a ski run in 1984 has partially destroyed the original coarse blocky surface of the rock glacier (Fig. 2A).

DC resistivity soundings detect a low-resistivity permafrost inside the rock glacier (10 to 110 kΩm, Lugon and Monbaron, 1998), being characteristic of a temperate permafrost with temperatures close to the melting point. A 30-m deep borehole located close to the front of the rock glacier confirms this interpretation (i.e. borehole B6 in Fig. 3; Herz et al., 2003; Herz, 2006). Temperature profiles indicate a mean annual temperature varying between −0.3 and −0.6 °C in the permafrost body for the period 2002–2005 and a depth of the zero annual amplitude (*ZAA*) at −13 m with a mean annual temperature of −0.3 °C.

Based on tree-ring analyses realized on the intermediate cone of the Ritigraben torrent (1500–1800 m asl), 124 debris-flow events were reconstructed with monthly precision since AD 1570 (Stoffel and Beniston, 2006; Stoffel et al., 2008). The mean decadal frequency of debris flows for the period 1706–2005 is 3.26 events 10 yr^{-1} (Stoffel and Beniston, 2006). The largest event on record occurred on September 24, 1993, when persistent rainfall (115 mm in 72 h; Rebetez et al., 1997; Stoffel et al., in review) resulted in an active-layer detachment triggering eleven debris-flow surges that eroded 6000 m^3 at the front of the rock glacier (Zimmermann et al., 1997). On the intermediate cone, the surges led to a deep incision of the channel with erosion rates of up to 4 m at certain locations (Fig. 2B). At the confluence with the Mattervispa River, an estimated 60,000 m^3 were deposited, disrupting the main transportation axes and destroying infrastructure (Zimmermann et al., 1997).

Following an active-layer detachment in 1993, massive ice lenses were exposed at the front of the rock glacier. During summer 1994, degradation of the exposed ice lenses led to intense retrogressive erosion at a rate of roughly 1 m per month at the upper height of the rock-glacier front (Lugon and Monbaron, 1998). The accumulated material was partly released during a rain-on-snow event on September 24, 1994, resulting in a debris flow with an estimated volume of 5000 m^3 deposited at the confluence with the Mattervispa (Zimmermann et al., 1997). Retrogressive erosion continued in summer 1995, leading to the formation of subsidence on the ski run close to the front of the rock glacier.

The principal trigger mechanisms of debris flows at Ritigraben are advective or convective rainfall as well as – to a minor extent – rain-on-snow events (Stoffel et al., 2005, in review). Debris-flow activity in the torrent was most pronounced during a period of wet summers toward the end of the LIA (1864–1895) as well as during the early decades of the 20th century (1916–1935), when warm-wet summers favored the release of 14 debris flows in 20 yr (Stoffel et al., 2008). In contrast, comparably low activity is observed for the recent past with only three debris-flow events recorded since 1994 (Stoffel, 2010). This temporal absence of debris flows does not, however, reflect limited sediment availability, but results from an absence of triggering precipitation events (Stoffel and Beniston 2006, Stoffel et al., subm.).

3. Material and methods

3.1. Internal structure and deformations of the rock glacier: Borehole observations

The internal structure of the rock glacier and deformations of the rock-glacier body were analyzed with data from five destructive boreholes (B1–B5; Stump Sondages AG; ∅143 mm and 116 mm) drilled in the terminal and central parts of the rock-glacier body with a cold-air flushing system in fall 2002 (Arn and Rovina, 2003; Fig. 3). Borehole depths vary between 30 and 50 m and the internal structure of the permafrost body was investigated with borehole cameras (Stump Foratec AG). Manual inclinometers (Tilt Sensor, Model 6300-1, Geokon) were used to identify shear surfaces and for a quantification of deformations in borehole B1 shortly after the borehole drilling in November 2002, March 2003 and July 2003. In addition, we used published data from borehole B6 (Herz, 2006; Herz et al., 2003) to complete our records.

3.2. Variations in superficial rock-glacier movement rates

Variations in superficial horizontal rock-glacier movement rates were assessed with high-resolution geodetic surveys and low-