Global and Planetary Change 73 (2010) 202–210

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

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

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ARTICLE INFO

Article history:
Received 13 January 2010
Accepted 29 June 2010
Available online 6 July 2010

Keywords:
Permafrost
Debris flows
Geodesy
Photogrammetry
Dendrogeomorphology
Tree rings
Climate change
Swiss Alps

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).

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doi:10.1016/j.gloplacha.2010.06.004

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 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-

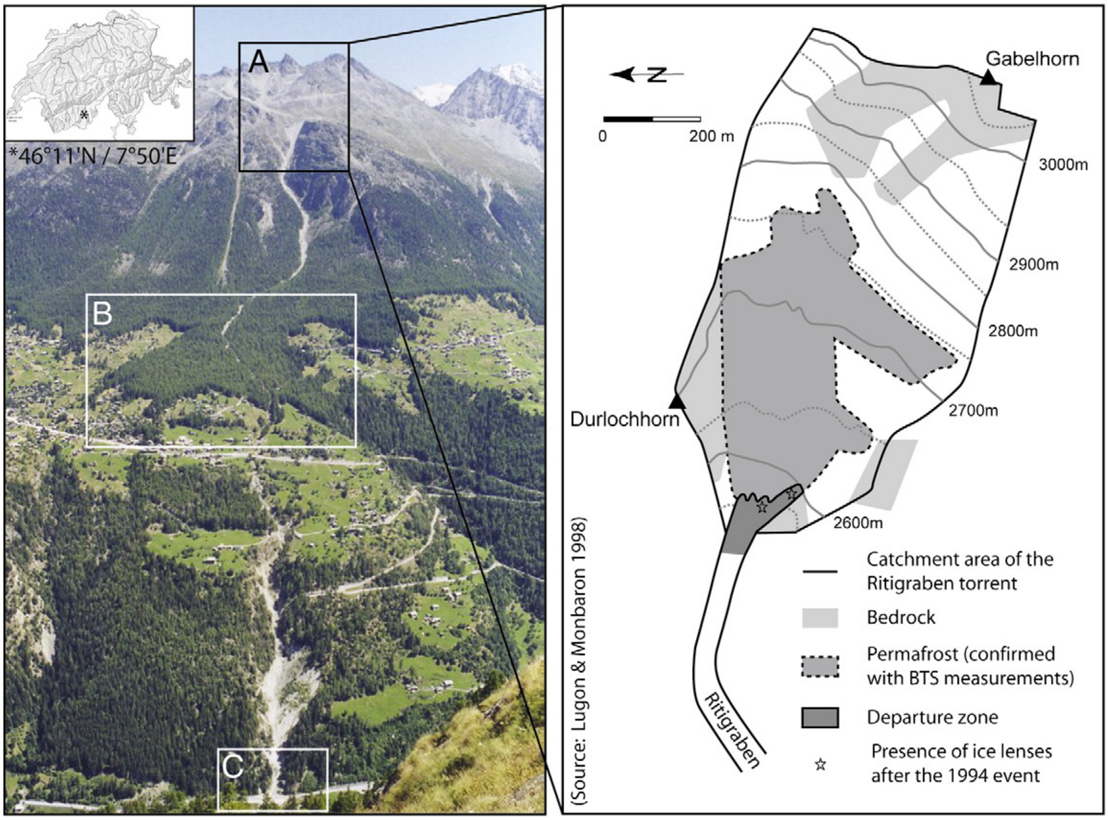

Fig. 1. Overview picture of the Ritigraben torrent (Valais, Swiss Alps; left) with the initiation zone (A), the intermediate debris-flow cone (B), the confluence of the torrent with the Mattervispa River (C), as well as the active rock-glacier body (right) in the initiation zone of debris flows.

resolution photogrammetric analysis (Fig. 3). Highly resolved displacement measurements with measurement accuracy in the range of a few millimeters were performed with annual geodetic surveys of 15 blocks located in the terminal part of the rock glacier since 1995. In 2003, the number of surveyed blocks was augmented to 21 (Arn and Rovina, 2003).

In addition, a low-resolution photogrammetric analysis was performed to assess mean movement rates for three periods of the last 50 yr, namely 1958–1975, 1975–1993 and 1993–2005. In this approach, the position of boulders (see Fig. 3) was assessed on stereo pairs of analogue black-and-white aerial photographs (Swisstopo) using an analytical DSR 14 Leica plotter. Ideally, precisions of ± 0.5 m can be obtained, but errors may double in difficult conditions. A total of 25 blocks were surveyed on the undisturbed part of the rock glacier. Boulders located in the proximity of the ski run were excluded from analysis due to the possible presence of anthropogenic interventions.

Fig. 2. (A) Overview of the Ritigraben rock glacier as seen from its central part looking to the frontal part. (B) Debris-flow channel on the intermediate cone with oversteepened walls as a result of very large debris flows (60,000 m^3) on 24 September 1993 (Picture taken on 1 November 1993 at ca. 1540 m asl).

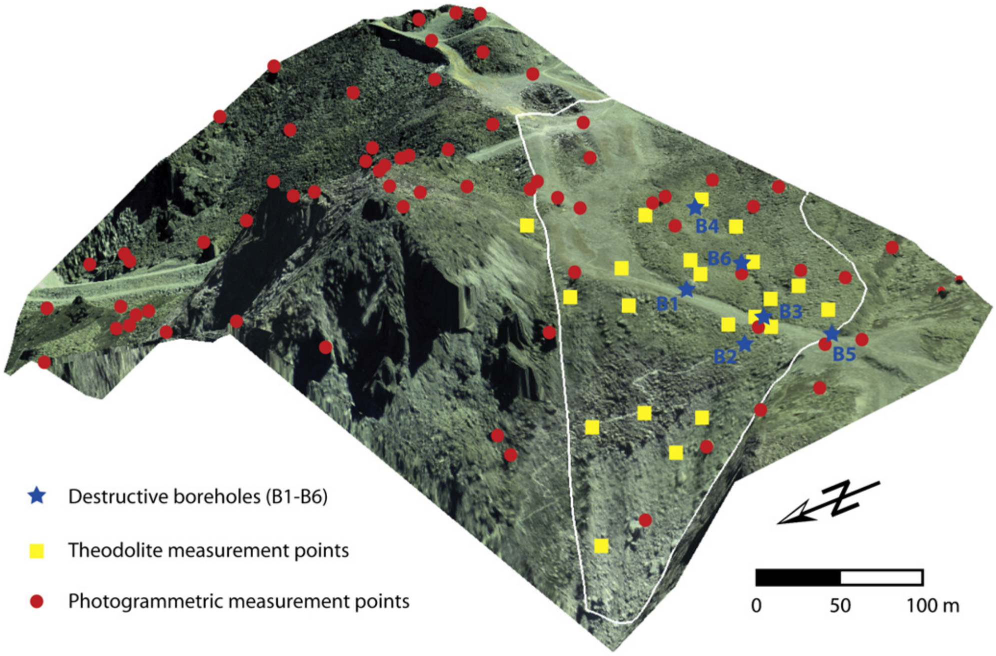

Fig. 3. Three-dimensional view of the wider rock-glacier area with positions of boreholes (B1–B6), geodetic points (theodolite measurements) and photogrammetric data.

The calculation of horizontal velocities (cm yr^{-1}) was derived from the total movement measured per period. Boulders with a total displacement ≤ 1 m per period were disregarded.

3.3. Mass transfer from the rock glacier into the debris-flow channel and erosion of the rock-glacier snout

The rate of sediment delivery to the foot of the rock-glacier snout depends on (i) mass-transfer rates produced by rock-glacier creeping, (ii) the volume of ice and voids in the moving rock-glacier section estimated to represent ~50% in the present case (*Rovina, verbatim*), (iii) the rate of non-consolidated material accumulations due to active-layer failures that are triggered by debris flows, and on the (iv) amount of material produced occasionally by the degradation of permafrost ice lenses exposed at the surface of the rock-glacier snout. Based on the data of shear zone depths and horizontal movement velocities, the rate of mass transfer through the creeping process is estimated with Eq. (1).

$$V = {}^{1}\!/_{2}\,(v \times W \times D) \tag{1}$$

where V is the volume [m^3], v the creep velocity [cm yr^{-1}], W the rock-glacier width [m], and D the depth of the shear zone [m]. We take account of the presence of voids and ice in the rock-glacier body by dividing the yearly sediment production rate by a factor of 2.

In addition to the sediment yield, we analyzed changes in the position of the upper limit of the rock-glacier snout (advance or retreat) so as (i) to identify visible signs of retrogressive erosion and (ii) to derive volumes eroded at the rock-glacier front. We therefore mapped the lower limit of the rock-glacier snout on the aerial photos of 28 August 1958, 5 August 1975, 1 September 1993 and 17 August 2005 as was on an oblique picture taken after the very large debris flow recorded in September 1993 on 5 October 1994.

3.4. Dendrogeomorphic reconstruction of debris-flow frequency and magnitude

The reconstruction of debris flows on the intermediate cone of the Ritigraben torrent was performed with dendrogeomorphic investigations (Stoffel and Bollschweiler, 2008, 2009) including a detailed mapping of features associated with past events (i.e. lobes, levees, abandoned flow paths) and a sampling of trees that have been disturbed by past debris-flow activity. We used data from 1204 trees (2450 increment cores) used to date the age and determine the size of lobate deposits (Stoffel 2010; Stoffel et al., 2005, 2008). Magnitudes are given semi-quantitatively and described as small ($S = 5 \times 10^2$–10^3 m^3), medium ($M = 10^3$–5×10^3 m^3) large ($L = 5 \times 10^3$–10^4 m^3) and extra large ($XL = 10^4$–5×10^4 m^3) events.

In a last analytical step, tree-ring data on the frequency and magnitude of debris flows recorded on the intermediate cone were compared with the volumes transported to the channel through the rock-glacier creep and with the changes in the position of the upper limit of the rock-glacier snout.

4. Results

4.1. Internal structure and deformations of the rock glacier

The internal structure of the rock-glacier body was assessed with data from five destructive boreholes (B1 to B5) and based on pictures taken with borehole cameras (Table 1). Camera interpretation allows distinction of three different layers inside the rock-glacier body. The first 5–6 m below the rock-glacier surface are formed by a seasonally unfrozen horizon (i.e. active layer) containing plurimetric gneiss boulders with voids filled with air and water. Underneath, the permafrost body is characterized by an alternation of water-rich ice layers and a heterometric granulometry composed of a mixture of fine- and coarse-grained rocks and boulders.

Photographs from B2 and B5 also indicate the presence of plurimetric layers without ice in the permafrost body. These features, known as talik, are characterized by humid, probably saturated layers and are observed in borehole B2 over a vertical distance of 16 m between −21 and −37 m. In boreholes B1 and B4, in contrast, the permafrost body is entirely frozen and there are no signs of water circulation. Bedrock is reached at 46 m in borehole B1, 41.2 m in B2 and 23 m in B5. The lower boundary of the permafrost body was not reached in boreholes B3 and B4.

Excessive deformation of borehole B1 occurred between the initial zero reading in November 2002 and the first determination of deformation rates in March 2003, this is why there is no data

Table 1
Overview of the five boreholes drilled in the Ritigraben rock glacier and summary of the main observations.

Borehole data	B1	B2	B3	B4	B5
Elevation [m asl]					
Depth of borehole [m]	50	48.5	39.8	37.2	33.5
Depth of bedrock [m]	46	41.2	Not reached	Not reached	23
Active-layer thickness [m]	5	5	6		5
Depth of shear stress zone [m]	Unknown	18–23	Unknown	Unknown	Unknown
Permafrost characteristics	A	C	B	A	C

A: Frozen in the whole profile, without water infiltration.
B: Frozen to humid, with some water infiltrations.
C: Very humid, unfrozen layers with important water infiltrations, i.e. presence of taliks.

available on horizontal displacement rates or shear surfaces. Borehole B2, in contrast, yielded good data and indicates the presence of two shear zones: A first zone of limited deformation is located at −4 m in the active layer and a second zone at −18 to −23 m. It is worthwhile to note that this shear horizon is located in the middle of the permafrost body and that a large frozen layer with some intermittent water infiltrations located between −5 and −20 m depth apparently moves on the humid 16 m talik located between −21 to −37 m.

The annual shear velocity at B2 averages 52 cm yr^{-1} and is based on a measurement of 65 cm yr^{-1} obtained for the winter 2002/03 (November 19, 2002–March 03, 2003) and of 43 cm yr^{-1} for the following spring and part of the summer (March 3, 2003–July 16, 2003), indicating seasonal changes in permafrost creep and increased velocities during the winter half year. Movements are, in contrast, absent under the shear horizon.

4.2. Variations in superficial rock-glacier movement rates

The low-resolution movement rates based on the three periods covered with aerial photographs (1958–1975, 1975–1993, and 1993–2005) exhibit an identical spatial distribution of displacement amplitudes. Higher velocities in the order of some decimeters per year are located in the central and terminal part of the rock glacier, where photogrammetric data indicates mean movement rates of 15 cm yr^{-1} (1958–1975), 12 cm yr^{-1} (1975–1993) and 21 cm yr^{-1} (1993–2005). Calculation of displacement rates was not possible at the rooting zone of the rock glacier, as values measured were within the error range of the method. Extreme values of 50 to 90 cm yr^{-1} are observed on the ski run and in the southern part of the rock-glacier snout. Table 2 presents the average, maximum and minimum surface movement rates for the central part of the rock glacier (cm yr^{-1}) and for the three periods analyzed with photogrammetry between 1958 and 2005.

Geodetic measurements performed with a theodolite on a yearly basis show mean rock-glacier displacement rates of 37 cm yr^{-1} for the period 1995–2006. This value is considerably higher than those obtained with photogrammetric methods (21 cm yr^{-1}) for almost the same period (1993–2005). In this sense, it seems that the imprecision of measurement inherent to low-resolution photogrammetry leads to an underestimation of displacement rates of rocks and boulders in the present case. Theodolite measurements also allowed for a determination of creep velocities in the lateral northern part of the rock glacier, where displacement rates are as low as 2–8 cm yr^{-1}.

A comparison of borehole with theodolite data also shows that deformation and horizontal movements are in the same order of magnitude at the level of the shear zone (at −18 to 23 m) and at the surface of the rock-glacier body in its central and terminal parts, with displacement rates measured by theodolite of 70–80 cm yr^{-1} (mean values for 1995–2006: 60–90 cm yr^{-1}) in the frontal part of the rock-glacier body and 43–65 cm yr^{-1} in the shear zone of borehole B2 (Fig. 4).

Table 2
Comparison of mean annual movement rates (in cm yr^{-1}) in the central part of the rock glacier for the periods 1958–2005 (photogrammetry) and 1995–2006 (theodolite).

Annual velocities	1958–1975	1975–1993	1993–2005	1995–2006
Mean [cm yr^{-1}]	15	12	21	37
Max. [cm yr^{-1}]	27	23	44	88
Min. [cm yr^{-1}]	3	4	7	16
Boulders [*n*]	14	14	12	7

4.2.1. Decadal scale of speed variations

Table 2 indicates that the central part of the rock glacier exhibits the largest movement rates. Analysis of variations in "decadal" displacement rates between 1958 and 2005 focuses on this area and neglects the almost inactive lateral rock glacier sections. As can be seen from Table 2, a drop of movement rates by about 30% can be observed between 1975 and 1993 as compared to the period 1958–1975. In contrast, an increase by about 70% is discernible for the most recent period 1993–2005 as compared to 1975–1993. The increase in movement rates is reduced to about 20% when comparing the period 1993–2005 to 1958–1975. Measurements also show evidence that changes in mean velocities (cm yr^{-1}) for each boulder are in general homogenous and that they follow comparable trends.

4.2.2. Inter-annual speed variations

Inter-annual variations of velocities (1995–2006) follow more or less the same trend, i.e. acceleration or deceleration of boulder displacement is synchronous. It is worthwhile to note, however, that

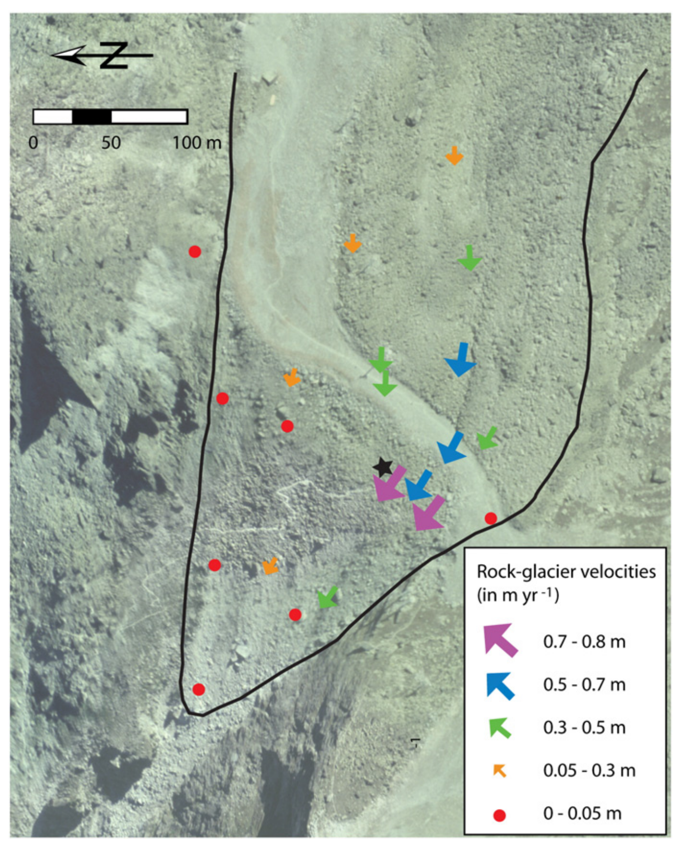

Fig. 4. Yearly displacement rate of boulders located in the frontal part of the rock glacier for the period 2003–2006. Note the huge debris accumulation in the channel of the Ritigraben torrent, at the foot of the rock glacier front slope (bottom part of illustration). The star indicates the position of the boulder described in greater detail in the results section (Orthophoto 1999 © swisstopo).

homogenate changes in displacement rates can only be observed for boulders with horizontal speeds larger than 10 cm yr^{-1}, i.e. in the central and terminal part of the rock-glacier body. Largest values have been measured for the period 2000–2003, when displacement rates increased by ca 20% as compared to the mean values of the period 1995–2000. This acceleration is followed by a slight decrease in displacement rates between 2003 and 2006. For instance, the block indicated with a star in Fig. 3 moved at a rate of 61 cm yr^{-1} between 1995 and 2000, 50 cm yr^{-1} in 1999–2000, 88 cm yr^{-1} in 2000–2003 and 79 cm yr^{-1} between 2003 and 2006.

4.3. Rock-glacier mass transfer and channel recharge rates

The net mass-transfer rates and debris production have been determined with Eq. (1) and indicate the amount of annual sediment delivery from the rock-glacier body into the uppermost segment of the debris-flow channel. Based on the data from the boreholes (B1–B6), the mean depth of the shear zone of the rock glacier is estimated to be 20 m. To take account of the differences in movement velocities between the northern, central and southern segments of the rock-glacier body, the following displacement rates were used: 10 cm yr^{-1} for the northern part (W ≈ 50 m), resulting in a mass flux of ~100 m^3 yr^{-1}. For the central and southern parts (W ≈ 90 m), we use mean displacement rates of 30–40 cm yr^{-1}, suggesting a mass flux of 500–700 m^3 yr^{-1} out of the rock-glacier complex into the debris-flow system. As a result of the considerable amount of voids and ice contained in the rock-glacier body (~50% at Ritigraben), the rate of sedimentary delivery is much smaller and estimated at maximum 300 to 400 m^3 yr^{-1}.

4.4. Comparing rock-glacier sediment yield with debris-flow frequency and magnitude

In a last analytical step, morphological changes in the rock-glacier front (i.e. advances and erosion of the terminal part) and associated sediment production are compared with the frequency and magnitude of debris flows as reconstructed with tree-ring records on the cone of the Ritigraben torrent (1800 m asl).

During the oldest period analyzed (1958–1975), we observe a general advance of the rock-glacier front (width 7 m) with a mean displacement rate of ~0.4 m yr^{-1}. As signs of erosion are completely missing (Fig. 5), sediment delivery was apparently rather limited and consisted of probably less than 100 m^3 of material falling from the snout of the rock-glacier body into the debris-flow system. At the same time, as shown in Table 3, tree-ring records indicate the presence of at least six debris-flow events during this period, namely four *S* and two *L* events, which would have transported at least 22,500 m^3 (i.e. ~1325 m^3 yr^{-1}) onto the cone (Fig. 6).

In contrast to the 1960s and the first half of the 1970s, as illustrated in Fig. 5, we observe an overall tendency towards erosion between 1975 and 2005, when the rock-glacier front retreated with a calculated mean rate of −0.8 m yr^{-1} between 1975 and 1993, −20 m yr^{-1} between 1993 and 1994, and −1.1 m yr^{-1} between 1994 and 2005 (Fig. 5). During the period 1975–1993 (i.e. from August 5, 1975 to September 1, 1993), the front of the rock-glacier retreated by −15 m in its northern part (2600 m^3 of material eroded) and advanced by a maximum of 5 m in its southern part. Seven debris-flow events are recorded on the cone during this period: three *S*, three *M* and one *L* incidence with a cumulated deposited volume of almost 27,000 m^3 (i.e. 1500 m^3 yr^{-1}; see Table 3 and Fig. 6).

Between September 1, 1993 and October 5, 1994, an active-layer failure detachment on September 24, 1993, the melting of ice lenses and yet another debris flow on September 24, 1994, resulted in an overall retreat of the rock-glacier front by −7 m to −20 m. The total volume eroded at the front of the rock glacier was 13,600 m^3. Based on observations and eyewitness reports, the volume of debris-flow material transported beyond the apex of the cone exceeded 18,000 m^3 during the 1993 *XL* and the 1994 *S* events.

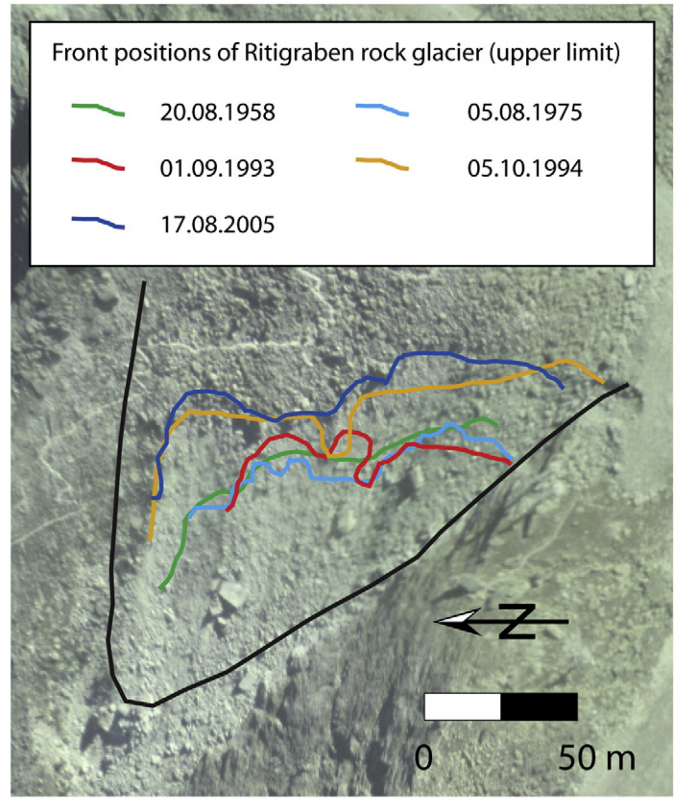

Fig. 5. Snout elevations of the rock-glacier front at Ritigraben in 1958, 1975, 1993, 1994, and 2005 (Orthophoto 1999 © swisstopo).

During the period 1994–2005 (October 5, 1994 to August 17, 2005), a retreat of −12 m is observed, representing at least a volume of 3800 m^3 of material delivered into the channel. During this period, one *S* debris flow occurred in the channel and transported a volume of roughly 1000 m^3 at the cone apex.

5. Discussion

The dataset existing for the Ritigraben rock glacier and its debris-flow system is unique and allows for prime insights into controls and dynamics of permafrost processes and related debris-flow activity in a constantly changing and warming high-altitude environment. One of the only other rock-glacier bodies of the Alps with a comparably long record on horizontal movements is the Hochebenkar (Austria), where measurements started in 1938 (Schneider and Schneider, 2001).

Most interestingly, periods of acceleration and deceleration of the Hochebenkar rock glacier are quasi-synchronous with those of the permafrost body at Ritigraben. At both sites, acceleration in 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 correspond with changes in atmospheric temperatures in the Swiss Alps (Pfister, 1999). As a result, creep velocities were less important during the cooler period of the 1960s and sped up following record breaking temperatures recorded in the 1990s and the early 21st century.

The strong increase in rock-glacier displacement rates measured at Ritigraben since the early 1990s is a phenomenon observed in a large number of rock-glacier bodies throughout the Alps (e.g., Kääb et al., 2007; Roer et al., 2008). These accelerations seem to occur independently of the geographic location of rock glaciers in the Alpine arc, their size or velocity. At an inter-annual scale, acceleration

Table 3
Erosion at the rock glacier front and sediment production compared to the volume deposited on the intermediate debris cone.

Period	Duration (yr)	Retreat (m)	Advance (m)	Rate (m yr^{-1})	Surface eroded at rock-glacier front (m^2)	Volume eroded at rock-glacier front (m^3)	F-M of debris flows	Debris-flow volume at cone apex (m^3)
1958–1975	17	0	7	+0.4	0	0	4 S, 2 L	<22,500
1975–1993	18	−15	6	−0.8	520	2600	3 S, 3 M, L	<27,000
1993–1994	1	−7 to −20	–	−7 to −20	2710	13,550	S, XL	>15,000
1994–2005	11	−12	–	−1.1	760	3800	S	1000

of Alpine rock glaciers was strongest in 2003, when warm ground surface temperatures during winter (Vonder Mühll et al., 2007) and the hottest European summer on record since AD 1500 (Luterbacher et al., 2004) resulted in large movement rates (Kääb et al., 2007).

Geodetic data indicates displacement rates in the frontal part of the rock glacier of up to 0.6–0.9 m yr^{-1} at the beginning of systematic measurements in 1995. However and while the important velocities observed at the front of the Ritigraben rock glacier are certainly the result of warming atmospheric temperatures, they are also biased by landslide-like movements located at the contact of the rock-glacier snout with the steep debris-flow system.

The Ritigraben rock glacier has always formed a sediment reservoir for the associated debris-flow system, with an estimated volume of $1.2–1.9 \times 10^6$ m^3 in its terminal part. However, as a result of the sensitivity of the permafrost body to changing climatic conditions and the cooler temperatures, one could speculate that rock-glacier movements would have been mostly inexistent during the Little Ice Age (LIA, 1570–1900; Grove, 2004) and the early decades of the 20th century. The dense lichen cover on blocks located on the rock-glacier body suggests that there would have existed a period of reduced movement activity at Ritigraben. However, a close-up look at boulders located next to the rock-glacier snout clearly shows that lichens are largely present on non-exposed faces of the blocks and therefore testify the presence of boulder displacements and toppling of material well before the initiation of systematic surveys at Ritigraben in the 1990s. Tree-ring data from the intermediate debris-flow cone provides further evidence for the existence of debris-flow events from this periglacial environment throughout the LIA (Stoffel and Beniston, 2006; Stoffel et al., 2008), but does not allow assessment of magnitudes prior to AD 1864 (Stoffel, 2010).

Despite the large amplitude of variations in rock-glacier movements, annual horizontal displacement rates of the rock-glacier body have remained quite low at Ritigraben and are in the order of decimeters under current climatic conditions. As a result, it appears that channel recharge rates did not change significantly between the cooler and warmer periods of the last few centuries and probably remained in the same order of magnitude (Stoffel, 2010), i.e. a few hundred cubic meters of annual debris production by the rock glacier altogether. The situation at Ritigraben therefore contrasts with rock glaciers of the wider study region (Valais Alps), where an exponential increase in movement rates without historic parallels has been recorded since the 1990s (e.g., Kääb et al., 2007; Roer et al., 2008).

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.

Sediment delivery from the rock-glacier front into the headwaters of the Ritigraben torrent cannot therefore be sufficient for the supply of the 16 debris flows reconstructed on the cone since 1958. While sediment was available at the snout of the rock-glacier body for the initiation of debris flows, it is also obvious that individual events were substantially alimented by different additional sediment sources along the channel to produce the magnitudes observed at the apex of the cone (Stoffel, 2010). In this sense, debris accumulated in the source area of the torrent at the foot of the rock glacier, as well as landslide and rockfall activity or the partial collapse of oversteepened channel walls have to be seen as important sediment sources for debris flows and would represent 65–90% of the material arriving on the Ritigraben cone (cf. Fig. 6).

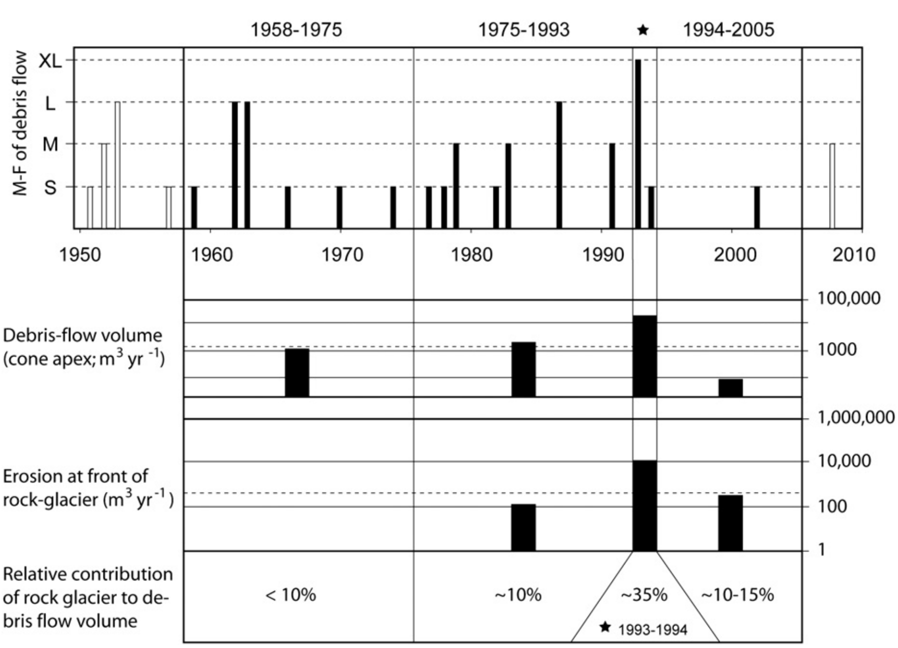

Fig. 6. Sediment delivery of the rock glacier and M–F relationships of debris flows at Ritigraben.

Based on the above considerations, it also becomes obvious that there does not really exist a direct coupling of displacement rates of and sediment delivery by the rock-glacier body with debris-flow frequency and ensuing magnitude in the torrential system of the Ritigraben torrent. This is due to the temporal gap present between actual sediment production at the front of the rock glacier – a process primarily driven by temperature and gravitation – and the actual entrainment of accumulated material by debris flows – which are, in turn, triggered by rainfall events above certain thresholds. While there is no direct coupling between sediment production at the source of the torrential system and the sink for small events described above, a direct link between source and sink processes clearly exists in the case of active-layer failures. Such active-layer failures have been observed in September 1993, September 1948 and August 1922 after intense and long-lasting precipitation events (Stoffel et al., 2008, subm.), resulting in the largest documented events of the last 150 yr with volumes exceeding 10^4 m^3 (Stoffel, 2010). 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.

In the years following such active-layer failures, exposed ice lenses and destabilized parts of the rock-glaciers snout will produce larger than average amounts of debris and therefore allow for events of several 1000 m^3 at the apex of the debris-flow cone. Considerable recharge rates have been observed at the source area of the torrential system underneath the rock-glacier snout in summer 1994, following the active-layer failure of September 24, 1993 (Lugon and Monbaron, 1998). In contrast to the active-layer failure events of 1993, 1948 or 1922, the triggering of debris-flow events occurs independently of rock-glacier processes but only depends on hydro-meteorological events, as documented by the 1994, 2002 and 2008 events (Stoffel et al., in review).

6. Conclusion

As a result of warming mean temperatures, the movement rates of the rock-glacier body at Ritigraben have increased by more than 70% over the last few decades, resulting in larger sediment production rates at the snout of the permafrost body. The frequency of events has, in contrast, decreased, as above-threshold rainfall events were largely missing over the same period (Stoffel and Beniston 2006). While there does not seem to exist a direct coupling between rock-glacier and debris-flow processes at Ritigraben, it also becomes obvious that immediate feedbacks occur when extensive precipitation events lead to active-layer detachment failures at the snout of the rock glacier. The temporal scarcity of events over the last few years will ultimately result in increased sediment recharge rates and in a higher potential for very large debris flows in the case of future heavy summer rainfall events. In this sense and in spite of the scarcity of very direct coupling effects, it becomes obvious that there exist "delayed" feedbacks of the sediment routing system following perturbations in the climatic driving forces, as stated e.g., by Humphrey and Heller (1995) or Densmore et al. (2007). Results presented in this paper allow first insights into the complex nature of process interactions and feedbacks in high-elevation environments, but they also clearly call for more research in this field.

Acknowledgements

Data from boreholes B1 to B5 and theodolite measurement points were provided by Rovina & Partner AG, and they are used with the permission of the Canton of Valais. This paper benefitted from the support of Photogrammetrie SA, Sion, and has been undertaken in the context of the EU-FP7 *ACQWA* (no. GOCE-20290), Interreg IIIA *HAUT RHONE* and FOEN-SFP-SRCE *RUFINE* (no. 0931030100RA-0000008253) projects.

References

Arn, K., Rovina, H., 2003. Sondierbohrkampagne Blockgletscher Ritigraben, Gemeinde Grächen. Geologisch-geotechnischer Zwischenbericht. Rovina & Partner AG: Unpublished expert opinion.
Chiarle, M., Iannotti, S., Mortara, G., Deline, P., 2007. Recent debris flow occurrences associated with glaciers in the Alps. Glob. Planet. Change 56, 123–136.
Delaloye, R., Perruchoud, E., Avian, M., Kaufmann, V., Bodin, X., Hausmann, H., 2008. Recent interannual variations of rockglaciers creep in the European Alps. Proceedings 9th International Conference on Permafrost, July 2008. Fairbanks, Alaska, pp. 343–348.
Densmore, A.L., Allen, P.A., Simpson, G., 2007. Development and response of a coupled catchment fan system under changing tectonic and climatic forcing. J. Geophys. Res. 112, F01002.
Grove, J.M., 2004. Little Ice Ages: ancient and modern. Routledge, London.
Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5, 3–17.
Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., Vonder Mühll, D., 2006. Permafrost creep and rock glacier dynamics. Permafrost Periglac. Process. 17, 189–214.
Harris, C., Davies, M., Etzelmüller, B., 2001. The assessment of potential geotechnical hazards associated with mountain permafrost in a warming global climate. Permafrost Periglac. Process. 12, 145–146.
Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M.A., Lehning, M., Matsuoka, N., Murton, J.B., Nötzli, J., Phillips, M., Ross, N., Seppälä, M., 2009. Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. Earth Sci. Rev. 92, 117–171.
Herz, T., 2006. Das Mikroklima grobblockiger Schutthalden der alpinen Periglazialstufe und seine Auswirkungen auf Energieaustauschprozesse zwischen Atmosphäre und Lithosphäre. Ph.D. thesis, University of Giessen.
Herz, T., King, L., Gubler, H., Herz, T., King, L., Gubler, H., 2003. Microclimate within coarse debris of talus slopes in the alpine periglacial belt and its effect on permafrost. Proceedings 8th International Conference on Permafrost, Zürich, pp. 383–387.
Huggel, C., Kääb, A., Haeberli, W., Krummenacher, B., 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. Nat. Hazard. Earth Syst. Sci. 3, 647–662.
Huggel, C., Haeberli, W., Kääb, A., Bieri, D., Richardson, S., 2004. Assessment procedures for glacial hazards in the Swiss Alps. Can. Geotech. J. 41, 1068–1083.
Humphrey, N., Heller, P.L., 1995. Natural oscillations in coupled geomorphic systems: an alternative for cyclic sedimentation. Geology 23, 499–502.
Jakob, M., Bovis, M., Oden, M., 2005. The significance of channel recharge rates for estimating debris-flow magnitude and frequency. Earth Surf. Process. Land. 30, 755–766.
Kääb, A., Reynolds, J.M., Haeberli, W., 2005a. Glacier and permafrost hazards in high mountains. In: Huber, U.M., Bugmann, H.K.H., Reasoner, M.A. (Eds.), Global change and mountain regions — a state of knowledge overview. Springer, Dordrecht, pp. 225–234.
Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., Salzmann, N., Schlaefli, S., Schmutz, K., Schneider, S., Strozzi, T., Weidmann, Y., 2005b. Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview. Nat. Hazard. Earth Syst. Sci. 5, 527–554.
Kääb, A., Frauenfelder, R., Roer, I., 2007. On the response of rock glacier creep to surface temperature increase. Glob. Planet. Change 56, 172–187.
Krysiecki, J.M., Bodin, X., Schoeneich, P., 2008. Collapse of the Bérard Rock Glacier (Southern French Alps). Proceedings 9th International Conference on Permafrost, Fairbanks, Alaska, July 2008, pp. 153–154.
Lugon, R., Monbaron, M., 1998. Stabilité des terrains meubles en zone de permafrost et changements climatiques. Deux études de cas en Valais: le Ritigraben (Mattertal) et la moraine du Dolent (Val Ferret). Rapport scientifique final PNR 31, vdf Horschulverlag, ETH Zürich.
Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., Wanner, H., 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303, 1499–1503.
Pfister, C., 1999. Wetternachhersage — 500 Jahre Klimavariationen und Naturkatastrophen. Paul Haupt, Bern, Stuttgart, Wien.
Rebetez, M., Lugon, R., Baeriswyl, P.-A., 1997. Climatic change and debris flows in high mountain regions: the case study of the Ritigraben torrent (Swiss Alps). Clim. Change 36, 371–389.
Roer, I., Avian, M., Delaloye, R., Lambiel, C., Haeberli, W., Kääb, A., et al., 2008. Observations and considerations on collapsing active rockglaciers in the Alps. Proceedings 9th International Conference on Permafrost, Fairbanks, Alaska, June 2008, pp. 1505–1510.
Schneider, B., Schneider, H., 2001. Zur 60 jährigen Messreihe der kurzfristigen Geschwindigkeitsschwankungen am Blockgletscher in Äusseren Hochebenkar, Ötztaler Alpen, Tirol. Z. Gletscherk. Glazialgeol. 37, 1–33.
Stoffel, M., 2010. Magnitude-frequency relationships of debris flows — a case study based on field surveys and tree-ring records. Geomorphology 116, 67–76.
Stoffel, M., Bollschweiler, M., Beniston, M., in review. Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences — future evolutions. Climatic Change.
Stoffel, M., Beniston, M., 2006. On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophys. Res. Lett. 33, L16404.

Stoffel, M., Bollschweiler, M., 2008. Tree-ring analysis in natural hazards research — an overview. Nat. Hazard. Earth Syst. Sci. 8, 187–202.
Stoffel, M., Bollschweiler, M., 2009. What tree rings can tell about earth-surface processes. Teaching the principles of dendrogeomorphology. Geogr. Compass 3, 1013–1037.
Stoffel, M., Lièvre, I., Conus, D., Grichting, M.A., Raetzo, H., Gärtner, H.W., Monbaron, M., 2005. 400 years of debris flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Arctic, Antarct. Alp. Res. 37, 387–395.
Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I., Maître, G., 2008. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. Glob. Planet. Change 60, 222–234.
Vonder Müehll, D., Noetzli, J., Roer, I., Makowski, K., Delaloye, R., 2007. Permafrost in Switzerland 2002/2003 and 2003/2004, Glaciological Report (Permafrost) of the Cryospheric Commission of the Swiss Academy of Sciences (SCNAT). http://www.permos.ch/publications.html.
Zimmermann, M., Haeberli, W., 1992. Climatic change and debris flow activity in high-mountain areas — a case study in the Swiss Alps. Catena 22, 59–72.
Zimmermann, M., Mani, P., Romang, H., 1997. Magnitude-frequency aspects of alpine debris flows. Eclogae Geol. Helv. 90, 415–420.