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Factors Controlling Velocity Variations at Short-Term, Seasonal and Multiyear Time Scales, Ritigraben Rock Glacier, Western Swiss Alps

Robert Kenner,[1*] *Marcia Phillips,*[1] *Jan Beutel,*[2] *Martin Hiller,*[1] *Philippe Limpach,*[3] *Eric Pointner*[4] *and Martin Volken*[5]

[1] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[2] Computer Engineering and Networks Laboratory, ETH Zürich, Switzerland
[3] Institute of Geodesy and Photogrammetry, ETH Zürich, Switzerland
[4] Rovina & Partner AG, Varen/Visp, Switzerland
[5] Aufdenblatten GEOMATIK AG, Zermatt, Switzerland

ABSTRACT

This study analyses the factors controlling variations in short-term, seasonal and multiyear deformation velocity of an alpine rock glacier from data obtained over periods of 1–20 years. The Ritigraben rock glacier, in the western Swiss Alps, was monitored using tacheometry, terrestrial laser scanning, an *in situ* global positioning system and borehole deformation measurements. Rock glacier stratigraphy and ground temperature data were obtained from boreholes, and long-term meteorological data (temperature, precipitation, snow water equivalent) from nearby weather stations. Shearing within a distinct water-bearing layer represents the major component of the displacement. Short-term accelerations and seasonal velocity patterns of the rock glacier deformation appear to have been triggered by water supply to this layer. A long-term acceleration of the rock glacier was probably also caused by increased water supply. Permafrost temperature in the rock glacier has increased slightly since 2002, yet no direct causality could be established between this limited warming and rock glacier acceleration. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: Rock glacier velocity; shearing; plastic deformation; rock glacier hydrology; water-bearing talik; permafrost

INTRODUCTION

Alpine rock glaciers have generally accelerated in recent decades (Kaufmann and Ladstädter, 2007; PERMOS, 2016). Such accelerations have often been directly attributed to the increasing temperature of permafrost ice induced by climate warming (Kääb *et al.,* 2007; Ikeda *et al.,* 2008). Hydrological factors have also been proposed as driving mechanisms (Krainer and He, 2006) and exceptionally strong velocity variations have been attributed to topographic conditions or to overloading by major rock fall events (Delaloye *et al.,* 2013). Despite such explanations, clear evidence about the processes leading to rock glacier accelerations is still rare. In particular, little is known about short-term velocity fluctuations of rock glaciers.

Here we analyse the variations in rock glacier velocity at three different time scales and discuss the influence of spring snow melt, summer rainfall, subsurface water fluxes and permafrost temperatures on these variations. Our study is based on geodetic measurements, meteorological and subsurface data measured at and near the Ritigraben rock glacier, Switzerland.

STUDY SITE

The active, ice-rich Ritigraben rock glacier has an area of 0.25 km^2 and is located approximately 2 km south of Grächen, Canton Valais, in the western Swiss Alps. The rock glacier originates at the western base of the Gabelhorn and flows into the upper end of the Ritigraben gully, its front around 2600 m a.s.l. (Figure 1). Here the topography steepens and the rock glacier forms a detachment zone. The central part of the rock glacier has slope angles below 20°, whereas the front and root zones slope between 30° and 35°. Boulders with a maximum size of a few cubic metres cover the rock glacier surface (Figure 2). As our datasets are mostly limited to the rock glacier front, we focus on this part of the landform (Figure 1). In the 1990s large debris flows originated from the detachment zone at

* Correspondence to: R. Kenner, WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland. E-mail: kenner@slf.ch

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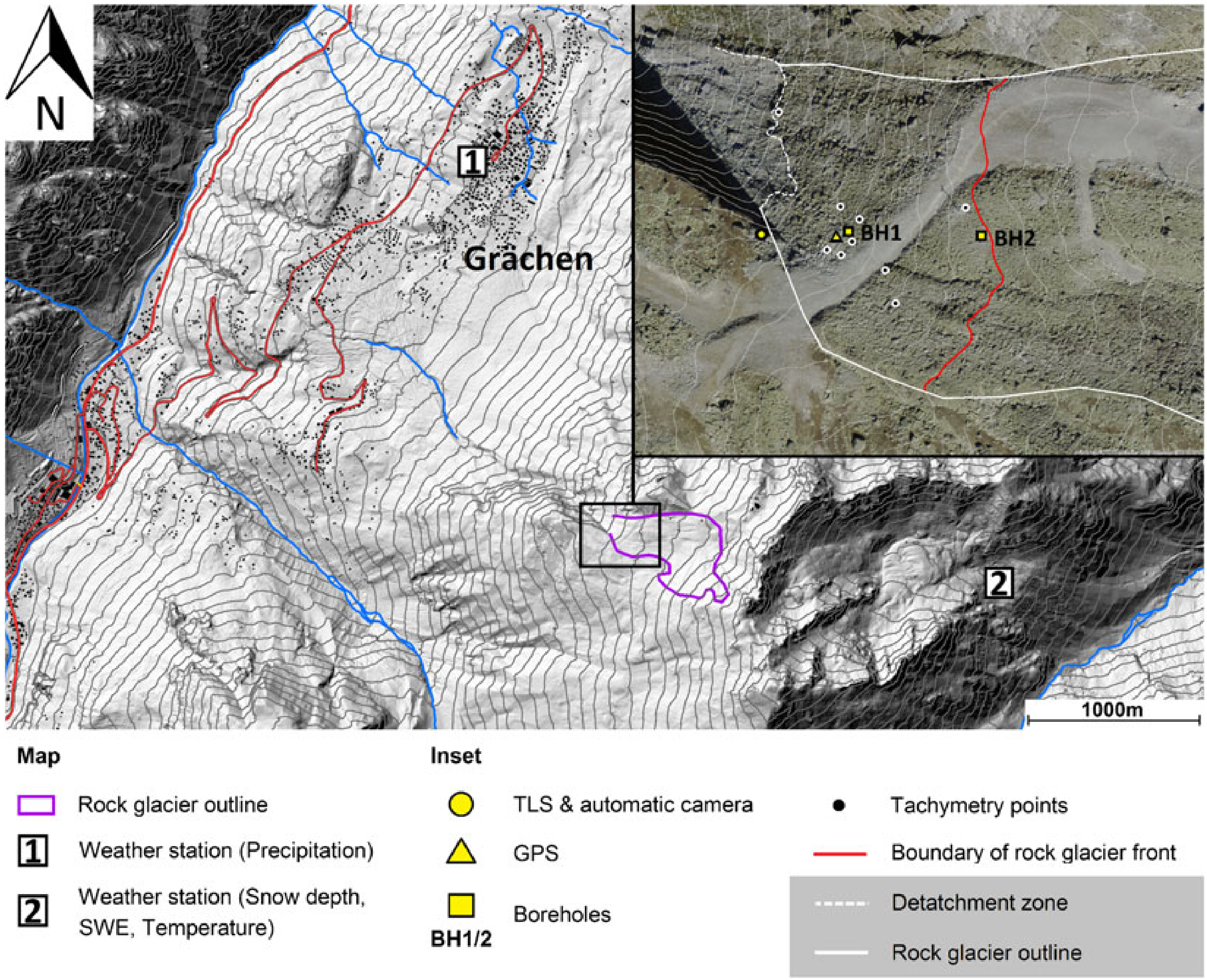

Figure 1 Location map showing the study site and the measurement setup. Inset: Orthophotograph from 20 August 2013, showing a close up of the rock glacier area. The red line indicates the upper limit of the lower part of the rock glacier that is referred to in the text as the 'rock glacier front' (Orthofoto: Swissimage (2016) swisstopo 5704000000).

the front of the rock glacier in the uppermost part of the Ritigraben gully, damaging roads and infrastructure below (Lugon and Stoffel, 2010; Stoffel, 2010). Further debris flows are likely after intense rainfall within the next few years, due to debris accumulating in the gully below the rock glacier.

METHODS AND INFORMATION PROVIDED

We used terrestrial laser scanning (TLS), an *in situ* global positioning system (GPS) and georeferenced time-lapse photography to acquire data on the surface movement of the Ritigraben rock glacier. Tachymetric monitoring of surface points, carried out between 1995 and 2014, was incorporated in the analysis. Swissimage orthophotographs were analysed to obtain information on the rock glacier deformation between 2005 and 2014. The dates of the measurement campaigns are summarised in Table 1.

Terrestrial Laser Scanning

TLS of the rock glacier surface was carried out once a year between 2012 and 2016 using a Riegl (Horn, Austria) VZ6000 long-range scanner (Figure 1). The laser scanning point clouds were transformed into digital elevation models (DEMs) with 20 cm resolution. Vertical changes between the measurements were defined by calculating differences between DEMs. Horizontal changes (i.e. the expression of displacement at the rock glacier surface) were tracked by correlating surface structure patterns of the rock glacier between two measurements. The surface structure was extracted from the DEMs using a high-pass filter. The

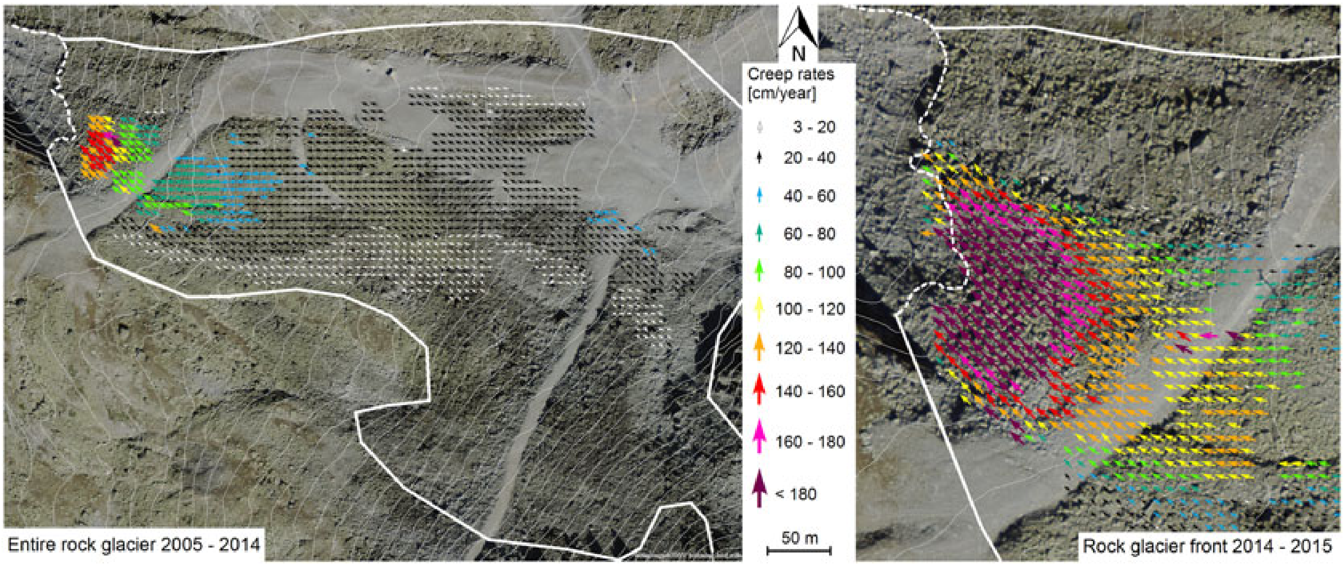

Figure 2 Deformation rates calculated from the Swissimage orthophotographs from 2005 and 2014 (left) and the TLS measurements from 2014 and 2015 (right). The solid white line marks the extent of the rock glacier, and the dashed white line shows the detachment zone (Orthofoto: Swissimage (2016) swisstopo 5704000000).

Table 1 Acquisition time of the data sets.

Dataset	Time of acquisition
Meteorological data	Daily mean values
Swissimage orthophotographs	1999; 2005; 2008; 2011; 2014
Borehole temperature	Since 27.03.2002, daily mean values
TLS	12.07.2012; 13.09.2013; 20.08.2014; 11.08.2015
GPS position data	Since 20.07.2012, daily mean values
Time-lapse photography	Since 03.07.2015; every 3 h
Total station	13.10.1995; 09.10.1996; 01.09.1998; 07.09.1999; 26.09.2000; 03.09.2003; 06.09.2006; 07.10.2010; 21.10.2014

resulting displacement vectors were filtered to remove single mismatches or zones in which the whole vector field was chaotic (Kenner *et al.,* 2014). The smallest remaining vectors after this filter process approximate well with the accuracy obtained for calculating displacement rates (Kenner *et al.,* 2014). For Ritigraben this was 3 cm.

Continuous Differential L1-GPS

In 2012, an *in situ* L1-GPS device was installed on a boulder of the southern side of the rock glacier front (Figure 1). The GPS data were processed with the Bernese GNSS Software (Dach *et al.,* 2007) using reference data from a local base station with a baseline distance of 5.845 km and an elevation difference of 102 m (WGS84: N46.12350°N, 7.82129°E). The daily GPS coordinates are estimated with an error (standard deviation) of approximately 1–2 mm horizontally and 2–3 mm vertically. Velocities were calculated from the daily coordinate series between the first and last values of an 11 day window. For analysing individual short-term accelerations this window was reduced to 3 days, taking into consideration that GPS measurement errors can distort the velocity signal during such a short time period. GPS velocity time series are used to identify accelerations in the order of a couple of days to a few weeks. These short-term accelerations were checked for obvious error influences such as coordinate shifts in varying directions. The GPS data also display a seasonal pattern of the deformation velocity. Interannual differences can be captured but long-term trends have to be interpreted carefully, as the GPS device moves with the rock glacier (5.5 m displacement between 2012 and 2016).

Time-Lapse Photography

A time-lapse camera (Panasonic, Wiesbaden, Germany) was installed 10 m south of the Ritigraben rock glacier front in July 2015 (Figure 1) to photograph the front and parts of the detachment zone at 3 h intervals. The photogrammetric matching algorithm introduced by Roesgen and Totaro (1995) was used to calculate translation vectors between the time-lapse images, which represent the displacements of the rock glacier surface. The translation vectors were automatically georeferenced, scaled and orientated in global coordinates, and velocities were calculated from them using a monoplotting algorithm developed using the MathWorks (Natick, MA, USA) MATLAB® software package. Faulty correlations were eliminated from the results using the same filter algorithm as for the TLS data (Kenner *et al.,* 2014). When processing an image time series (temporal resolution of 3 days) for summer 2015, the relative velocity of each displacement vector relative to its initial velocity between the first two images was calculated. These relative velocities were averaged for each image step to obtain a relative rock glacier velocity for the entire image section.

The velocity data obtained from time-lapse photography have a higher temporal resolution than the GPS data and are, in addition, spatially resolved. Relative velocity time series obtained from two image time series showed a root mean square error of 5.6 per cent between them, which indicates a high precision of the method. However, these time series can be interrupted by thick snow cover or long periods of poor visibility. We used these data to analyse spatial and temporal short-term variations of the deformation process, and provide information on the weather conditions and the snow cover.

Total Station and Orthophotograph Monitoring

A network of 22 points on the rock glacier surface and nearby was monitored between 1995 and 2014 using a TCA 2003 (Leica, Wetzlar, Germany) total station. Data were acquired in annual or multi-annual resolution (Table 1). Nine of these points are located on the rock glacier front (Figure 1) and were used to define multi-annual velocity variations of the rock glacier.

Swisstopo (Wabern, Switzerland) provides Swissimage orthophotographs for all of Switzerland, with a spatial resolution of 50 cm in alpine terrain. For smooth terrain, the position accuracy of the orthophotographs is specified to be 50 cm from 2005 onwards. Based on these orthophotographs (Table 1) we calculated multi-annual deformation velocities of the rock glacier between 2005 and 2014, using the same correlation method as applied for the time-lapse images.

Borehole Measurements

Two vertical boreholes, B1 (48 m deep) and B2 (30 m deep), were drilled in 2002 on the Ritigraben rock glacier to provide information on the rock glacier stratigraphy, internal deformation and subsurface temperatures (Figure 1). Inclinometer measurements were carried out in borehole B1 using a Slope Indicator Digitilt inclinometer (DGSI, Mukilteo, USA) between 2002 and 2006, revealing the internal deformation patterns. Borehole B2 was equipped with 30 YSI 44006 thermistors (Yellow Springs, Ohio, USA) with a calibrated precision of ±0.02°C. Borehole temperatures were measured daily and registered using a Campbell Scientific (Loughborough, UK) CR1000 data logger. The borehole is gradually being sheared off from the base upwards and all thermistors below 13 m depth have been cut off. The borehole temperature data provide point information on the active-layer thickness and temperature, permafrost temperature and the size, position, temperature and occurrence of a talik located between 10 and 13 m depth, described by Zenklusen Mutter and Phillips (2012).

Meteorological Data

Meteorological data were obtained from two automatic weather stations. A Meteoswiss station in Grächen is located at 1600 m a.s.l., 2.5 km northwest of Ritigraben, and an IMIS (Intercantonal Measurement and Information System) station (Russi *et al.,* 2003) is located at 2500 m a.s.l. in the Seetal valley 2 km east of the Ritigraben catchment, on the eastern side of the Seetal ridge (Figure 1). Liquid summer precipitation is measured only at the Grächen station and the absolute values are probably lower here than at Ritigraben, due to the elevation difference. Snow depth and air temperature are measured at the Seetal weather station, which we consider to represent the Ritigraben site. Using temperature, wind and radiation data from the Seetal station, the simulation model Snowpack continuously calculates the snow water equivalent (SWE) at this station (Lehning *et al.,* 1999). We removed all decreases of the SWE time series during winter, which can occur due to melt or wind erosion, and thus obtained the total SWE for winter. This corresponds to the maximum amount of water that can potentially infiltrate the rock glacier during snow melt.

RESULTS

Rock Glacier Velocity and Velocity Variations

The surface displacements derived from the Swissimage data and from the TLS measurements provide a good overview of the deformation velocities at the Ritigraben rock glacier (Figure 2). The moving part of the upper rock glacier was up to 150 m wide and moved up to 40 cm/year. The rock glacier accelerated strongly towards the front, reaching velocities of over 200 cm/year close to the detachment zone.

Rock glacier velocity varied over short-term, seasonal and multi-year time scales. Short-term accelerations usually lasted about 1 day. Such surges are evident in both the GPS time series and the time-lapse images (Figures 3 and 4). It is difficult to specify the exact duration of most of these events, as the GPS time series is temporally smoothed. However, some surges are perfectly documented by the time-lapse image data (Figure 4), such as the one on 9 August 2015. During the course of 1 day only, the rock glacier front moved 16 times faster compared to its previous velocity (Figure 4, inset). With two exceptions (30 November 2013 and 13 February 2014), these short-term accelerations occurred during the snow-free summer period or during the snow melt season.

A pronounced seasonal pattern in the deformation velocity of the rock glacier is recorded by the GPS time series (Figure 3). Maximum velocity was reached between August and November. During winter the rock glacier decelerated slowly and smoothly until a fast and strong acceleration coincided with the onset of snow melt in spring. This acceleration decreased after the snow melt ended but continued until the maximum velocity recurred.

Multi-year acceleration of the rock glacier, relative to the period 1999–2000, is evident in the results of all three

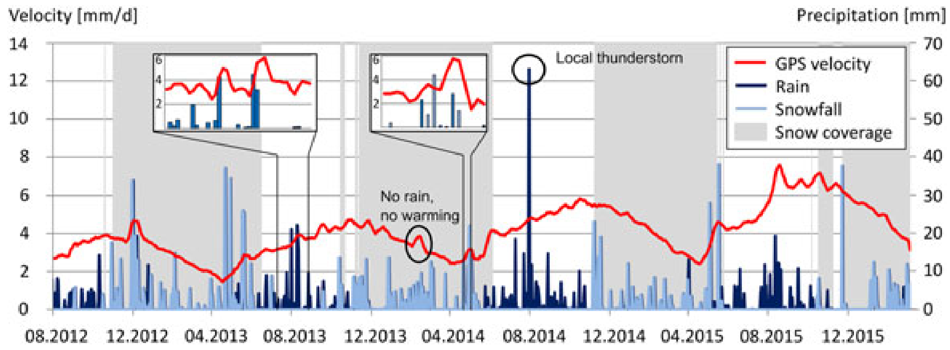

Figure 3 Time series showing the GPS-based deformation velocity and precipitation events. Periods with snow cover are highlighted in grey. The velocity values in the main plot are based on an 11-day window, and the values in the insets on a 3-day window.

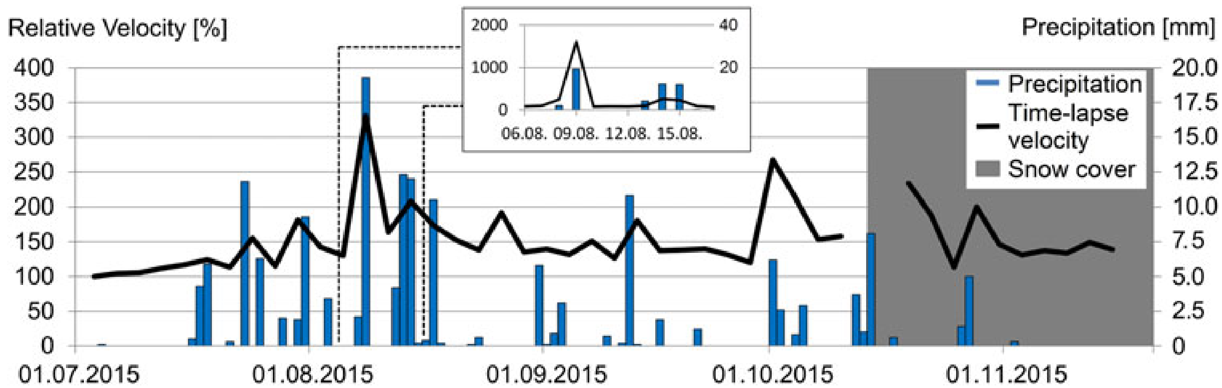

Figure 4 Time series showing relative deformation velocity (derived from time-lapse photography) and precipitation. A strong deformation surge coincided with a heavy precipitation event between 9 and 10 August 2015. The velocity values in the main plot are based on a 3-day window, and the values in the inset on a 1-day window.

geodetic measurement systems (total station, TLS and GPS) (Figure 5). As the TLS and GPS data series began in summer 2012, their initial relative velocity was compared with the relative velocity in 2012 defined by the total station. The rock glacier has accelerated by 400 per cent since 1999–2000 (Figure 5). The acceleration is also confirmed by the mean annual deformation rates obtained from the Swissimage dataset between 2005 and 2014 when compared with the TLS values from 2014 to 2015 (Figure 2).

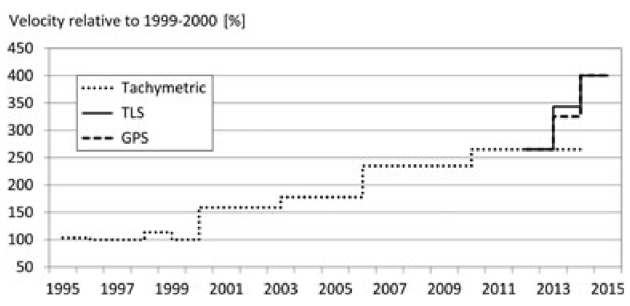

Figure 5 Multiyear velocity variations of the Ritigraben rock glacier front, relative to the period 1999–2000. The initial relative GPS- and TLS-derived velocities have been fitted to the relative tachymetric velocity at the relevant date.

Borehole Stratigraphy and Deformation

The active layer in borehole B1 was approximately 5 m thick and consisted of a blocky layer with large pore spaces, overlying a permafrost body that contained a mixture of fine material to large blocks (Figure 6). Ice and frozen sand were evident to 21 m depth. Below this was a 16-m-thick, ice-free layer, consisting of blocks and fine material. The zone between 20.8 and 30.2 m was very wet, with water encountered at depths of 22, 24, 25.9, 27.2 and 28 m. Between 37 and 41 m depth the ground was frozen again. Massive gneiss bedrock occurred below 41 m.

The inclinometer measurements in B1 showed a distinct shear layer at 18–24 m depth, which corresponds to the top of the ice-free layer and the water encountered. In 2003, about 80 per cent of the total deformation occurred in this shear layer, increasing constantly to 93 per cent in 2006 (Figure 6). Below, the deformation was minimal, whereas above a slight deformation between 18 and 4 m was evident,

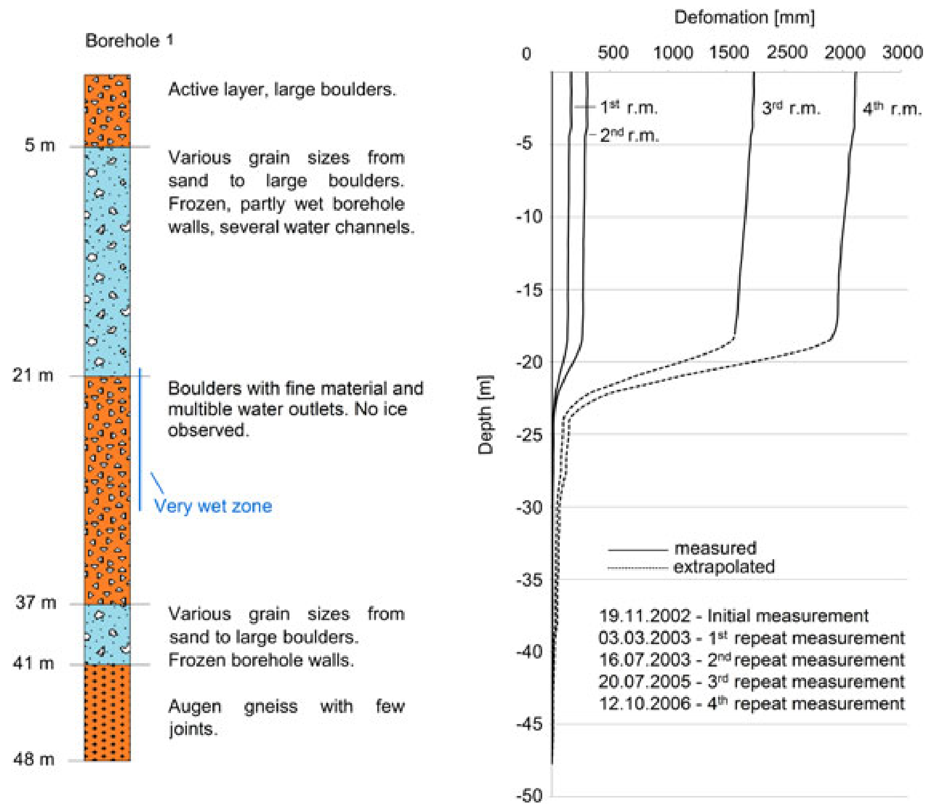

Figure 6 Left: Stratigraphy in borehole B1. Blue colours indicate the presence of ice, and orange ones ice-free rock debris. Right: Inclinometer data from borehole B1 between 2002 and 2006. Data could not be acquired below 19 m during the third and fourth repeat measurements as the shearing process had destroyed the borehole tubing. The surface displacement of the borehole is known from tachymetric measurements. The dashed lines below 19 m in 2005 and 2006 are extrapolated, assuming a fixed ratio relative to the values of the second repeat measurement.

contributing about 20 per cent to the total deformation in 2003 and 7 per cent in 2006. The ratio between the deformation in the shear layer and above was measured directly by the first two repeat measurements in 2003. Afterwards, the borehole was destroyed at about 19 m depth and the deformation within the shear horizon was defined by the difference of the surface displacement of the borehole and the deformation in the upper 18 m.

Borehole Temperatures

The borehole temperature data (Figure 7) show that the active-layer thickness has remained constant at around 4 m, indicating the presence of ice-rich permafrost below. The lowest thermistor at 30 m depth measured temperatures indicating permafrost before being sheared off. At 11–12 m depth, a seasonal talik has developed since 2007 (Figure 7). Associated with this, an abrupt warming occurred in the permafrost above the talik and a persistent warming trend started below the talik. The occurrence of positive temperatures at 12 m depth were originally attributed to the infiltration of snow melt water and precipitation in summer (Zenklusen Mutter and Phillips, 2012). However, since 2012 talik temperatures at 12 m depth have increased and remained more or less constantly positive in summer and sporadically positive in winter. Individual snow melt or precipitation events can no longer be discerned thermally. Simultaneously, talik temperatures at 11 m depth have decreased since 2012, whereas permafrost temperatures at the first thermistor below the talik at 13 m depth continued to increase. This indicates downward growth of the talik.

DISCUSSION

Seasonal Acceleration

The seasonal pattern of the rock glacier velocity at Ritigraben appears to be controlled by water, either from snow melt or from rainfall. Conductive energy input at the rock glacier surface reaches the shear layer at approximately 20 m depth with a considerable delay. However, the sudden and sharp acceleration of the rock glacier every spring coincides with the start of snow melt and an increase of temperature in the talik (Figure 8). The laterally induced warming in the talik starts earlier than the conductive warming at the first thermistor above the talik, which indicates that the seasonal acceleration is not controlled by conductive heat transfer. Rock glacier acceleration declines

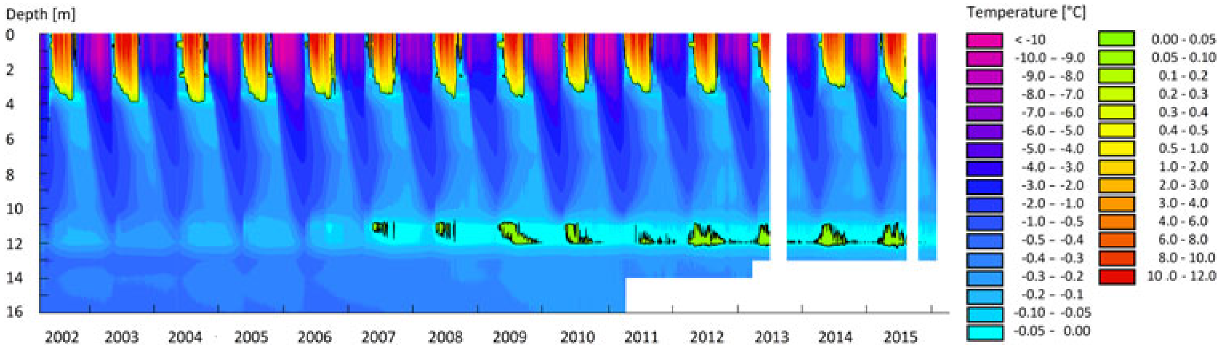

Figure 7 Contoured time series showing ground temperature in borehole B2 between 2002 and 2016.

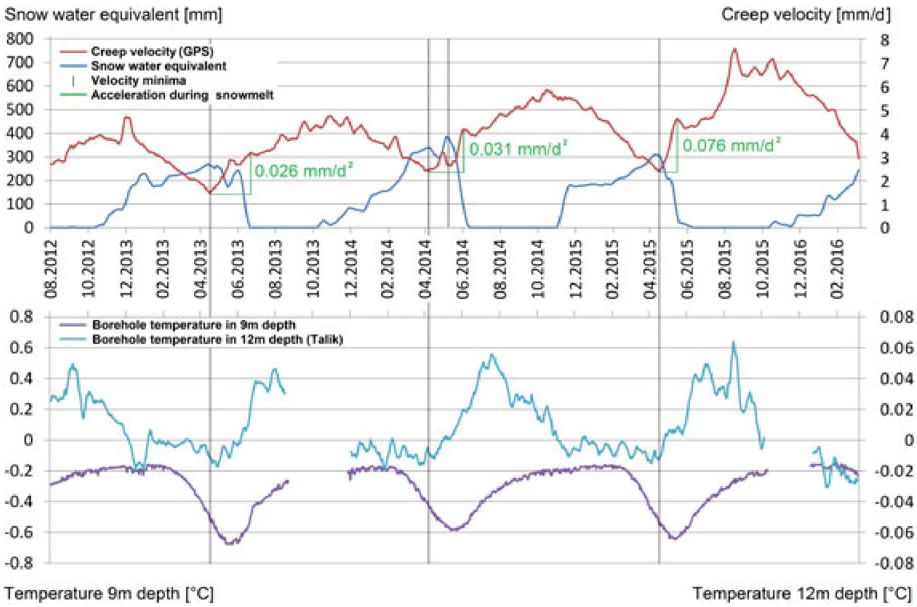

Figure 8 Time series showing the simultaneous onset of snow melt, talik warming and rock glacier acceleration between 2012 and 2016. These accelerations increased during this period despite similar SWE maxima.

after the end of snow melt and ceases with the onset of the autumn snow cover. During winter, the rock glacier velocity decreases. This seasonal velocity pattern corresponds to observations made on other rock glaciers by Delaloye *et al.* (2010, 2013).

Short-Term Acceleration

In most cases, heavy rainfall triggered short-term acceleration of the rock glacier, although in a few cases the triggering mechanism is unknown. On 9 August 2015, the weather station in Grächen recorded 20 mm of rainfall, an exceptional amount in this dry inner-alpine region, with a return period of 100 days between 2012 and 2016. Simultaneously, the rock glacier moved 16 times faster for just 1 day before slowing to its former velocity (Figure 4). Other short-term accelerations linked to precipitation are shown in Figure 4 and the two insets in Figure 3. Two distinct velocity peaks immediately followed heavy rainfall on 29 July and 8 August 2013, and a velocity peak resulting from warming by intense rainfall at high elevations occurred in the last days of April 2014 (Figure 3). However, some rock glacier accelerations are not linked to precipitation, and one surge occurred in winter, on 13 February 2014 (marked with a black ellipse in Figure 3). Abrupt surges such as that on 9 August 2015 suggest that states of internal stress may develop in the rock glacier during the deformation process and are compensated for by these surges.

Multiyear Acceleration

The displacement data reveal a strong multiyear acceleration of the Ritigraben rock glacier front since 2000. Two triggering factors may explain such acceleration:

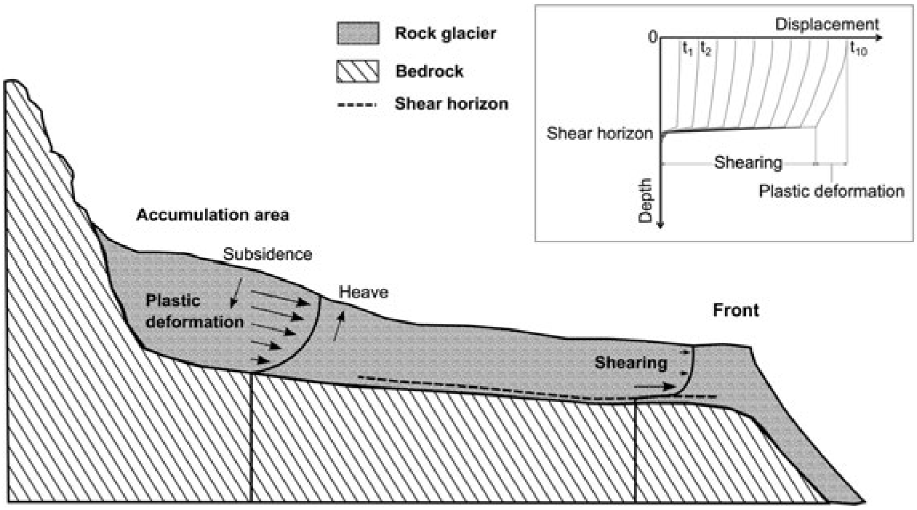

Figure 9 Schematic diagram showing a deformation profile of an idealised rock glacier. Close to the root zone, plastic deformation dominates due to the local overloading by rock fall deposits. The internal deformation of the viscous material corresponds to a gravitationally influenced power law fluid. The deformation rates increase towards the surface, causing surface subsidence in the area of overloading and surface heave at the front of the downslope propagating mass. Due to the thinning of the moving layer, plastic deformation decreases further downslope and basal shearing becomes the dominant deformation process.

an increase in permafrost temperature (Ikeda *et al.,* 2003; Kääb *et al.,* 2003) and an increase in water supply from precipitation, or melt of snow or ground ice (Krainer and He, 2006; Roer *et al.,* 2008; Delaloye *et al.,* 2010). Both factors relate to two processes that are known to deform rock glaciers: shearing within a distinct layer, and internal plastic deformation of the rock glacier body due to the viscosity of the permafrost ice (Hausmann *et al.,* 2007; Roer *et al.,* 2008; Delaloye *et al.,* 2010). Shearing is influenced by water supply and water pressure controlling the frictional resistance in the shearing zone (Harbor *et al.,* 1997). Plastic deformation depends on the mechanical characteristics of the permafrost ice: warming can cause significant changes in the viscosity, hardness, shear- and crushing strength of polycrystalline ice (Barnes *et al.,* 1971; Hobbs, 1974; Arenson and Springman, 2005) and, theoretically, can therefore trigger rock glacier acceleration. Both shearing and plastic deformation are indicated by inclinometer measurements in rock glacier boreholes (Arenson *et al.* (2002).

At the front of the Ritigraben rock glacier shearing has dominated movement. Its contribution to the total surface displacement increased between 2002 and 2006: 1st repeat measurement (r.m.) 81 per cent contribution; 2nd r.m. 87 per cent; 3rd r.m. 91 per cent; 4th r.m. 93 per cent (Figure 6). Consequently, the shearing process has accelerated and contributed to the overall acceleration of the rock glacier. Shearing is controlled by water supply, as shown for the short-term and seasonal accelerations, discussed above. This interpretation is supported by the stratigraphic data in borehole B1 (Figure 6), which show that the shear layer is located in a very wet transition zone between the permafrost body and an unfrozen zone below, containing several water-bearing horizons. We assume that this shear layer represents a partly water-saturated continuum between ice-rich permafrost and ice-free rock debris.

Plastic deformation seems to have played no role in the long-term acceleration, although a slight permafrost warming of 0.2°C below 10 m depth has occurred since 2002. Between 2002 and 2006 the absolute borehole displacement values due to plastic deformation did not increase significantly (1st r.m. 107 mm/year; 2nd r.m. 106 mm/year; 3rd r.m. 80 mm/year; 4th r.m. 146 mm/year; see Figure 6). The slight permafrost warming in borehole B2 was at least partly induced by the talik formation and it is unclear whether conductive heat flow resulting from atmospheric warming contributed to it.

Although water seems to control the long-term acceleration of the rock glacier, no obvious increase in water supply to it is evident. Annual precipitation sums in Grächen decreased during the GPS/TLS monitoring period (2013: 630.7 mm; 2014: 588.1 mm; 2015: 531.5 mm), and SWE maxima did not increase significantly (Figure 8). A large input of water from subsurface ice melt can also be excluded because the active-layer thickness in borehole B2 was constant and the TLS data showed no signs of surface subsidence in the small catchment above Ritigraben. We therefore considered an alternative explanation: increasingly long periods with rainfall (instead of snowfall) might lead to longer periods with liquid water in the system and so to longer periods of rock glacier acceleration and shorter periods of deceleration. Surprisingly, the opposite applied at Ritigraben. During the three seasonal cycles with GPS measurements the duration of deceleration per cycle increased, despite the overall acceleration trend.

Although the seasonal duration of rock glacier acceleration did not increase, its magnitude did. The GPS velocity time series shows that the multiyear acceleration is manifested mainly by a strong increase of the maximum velocities in summer and autumn, and less by the winter velocities (Figure 8). Simultaneously, the strong acceleration during snow melt as well as the surges during rainfall events increased in magnitude during the observation period (see acceleration values in Figure 8). Although the water supply did not increase, the efficiency of acceleration triggered by the same amount of water clearly increased. This can be explained by an increasing amount of runoff reaching the shear layer of the rock glacier via flow channels, evident in the Ritigraben borehole data in the form of a water-bearing talik (Zenklusen Mutter and Phillips, 2012). This new drainage system probably explains the higher sensitivity of the rock glacier velocity to water supply and hence the acceleration.

Internal drainage development may help to explain the overall acceleration trend of most rock glaciers in the European Alps. Borehole temperatures show that most Swiss rock glaciers have reached temperatures close to 0°C in the last few decades (PERMOS, 2016). At these temperatures no refreezing can occur and additional energy input contributes to ice melt. These are optimal conditions for the development of taliks in the form of new runoff channels permeating the permafrost body and ensuring a more effective supply of water to the shear layer or the base. Ground-ice melt may also increase the water supply in some cases. Rising temperature of permafrost ice may indirectly influence acceleration but does not directly force it, at least where shearing dominates. Temporal correlations between mean annual air- or permafrost temperatures and rock glacier deformation velocity (Kellerer-Pirklbauer and Kaufmann, 2012; Nickus *et al.,* 2015) are therefore reasonable but do not necessarily occur, as shown by Roer *et al.* (2005) or this study.

Changes in viscosity due to higher ice temperature would cause a more constant and smoother long-term acceleration. Studies which attribute rock glacier acceleration to higher permafrost temperature focus on the internal plastic deformation of the permafrost (Kääb *et al.,* 2007; Ikeda *et al.,* 2008). But this is usually the less dominant process contributing to rock glacier deformation (Arenson *et al.,* 2002; Krainer *et al.,* 2015). Internal plastic deformation is linked to a local overloading of a viscous material (Jiskoot, 2011), and this overloading probably occurs in the root zone of a rock glacier, where snow and rock material accumulate. As a consequence, internal plastic deformation is likely to be most pronounced close to the rock glacier root zone and act as a 'pushing force', initiating the more important process of shearing (Figure 9).

CONCLUSIONS

Water fluxes in the permafrost of the Ritigraben rock glacier appear to influence rock glacier velocity variations at short-term, seasonal and multiyear time scales. The rapid and pronounced acceleration of the rock glacier during rainfall or snow melt suggest a decrease in the frictional resistance in the shear layer by water, which favours shearing. This shear layer is located at the base of an ice-rich permafrost body and several water-bearing horizons were found when drilling through it.

The long-term acceleration of the rock glacier is probably affected not by the amount of water entering it, but by the efficiency of funnelling water towards the shear layer. This funnelling is controlled by the development of run-off channels inside the permafrost body, such as the talik depicted by the borehole B2 temperature data. Changes in permafrost temperature only affect deformation velocity indirectly at this site: the warming of permafrost close to 0°C favours the development of new runoff channels towards the shear horizon and expedites water supply to this zone. This explains the increasingly higher sensitivity of the Ritigraben rock glacier to rainfall or snow melt. This might be similar for other rock glaciers with a dominant shearing component in the deformation movement and may help to explain the widespread rock glacier acceleration during the last few decades in the European Alps.

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REFERENCES

Arenson LU, Springman SM. 2005. Mathematical descriptions for the behaviour of ice-rich frozen soils at temperatures close to 0 °C. *Canadian Geotechnical Journal* **42**: 431–442. https://doi.org/10.1139/t04-109

Arenson L, Hoelzle M, Springman S. 2002. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. *Permafrost and Periglacial Processes* **13**: 117–135. https://doi.org/10.1002/ppp.414

Barnes P, Tabor D, Walker JCF. 1971. The friction and creep of polycrystalline ice. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering*

Sciences **324**: 127–155. https://doi.org/10.1098/rspa.1971.0132

Dach R, Hugentobler U, Fridez P, Meindl M. 2007. Bernese GPS software version 5.0. Astronomical Institute, University of Bern 640: 114.

Delaloye R, Lambiel C, Gärtner-Roer I. 2010. Overview of rock glacier kinematics research in the Swiss Alps: seasonal rhythm, interannual variations and trends over several decades. *Geographica Helvetica* **65**: 135–145. https://doi.org/10.5194/gh-65-135-2010

Delaloye R, Morard S, Barboux C, Abbet D, Gruber V, Riedo M, Gachet S. 2013. In Rapidly moving rock glaciers in Mattertal, Mattertal - ein Tal in Bewegung, St. Niklaus, Graf C (ed). Eidg. Forschungsanstalt WSL; 21–31.

Harbor J, Sharp M, Copland L, Hubbard B, Nienow P, Mair D. 1997. Influence of subglacial drainage conditions on the velocity distribution within a glacier cross section. *Geology* **25**: 739–742. https://doi.org/10.1130/0091-7613(1997)025<0739:IOSDCO>2.3.CO;2

Hausmann H, Krainer K, Brückl E, Mostler W. 2007. Internal structure and ice content of Reichenkar rock glacier (Stubai Alps, Austria) assessed by geophysical investigations. *Permafrost and Periglacial Processes* **18**: 351–367. https://doi.org/10.1002/ppp.601

Hobbs PV. 1974. Ice Physics. Oxford University Press: New York.

Ikeda A, Matsuoka N, Kääb A. 2003. A rapidly moving small rock glacier at the lower limit of the mountain permafrost belt in the Swiss Alps. In Proceedings of the Eighth International Conference on Permafrost, Phillips M, Springman S, Arenson L, Ross N (eds); 455–460.

Ikeda A, Matsuoka N, Kääb A. 2008. Fast deformation of perennially frozen debris in a warm rock glacier in the Swiss Alps: an effect of liquid water. *Journal of Geophysical Research* **113**: F01021. https://doi.org/10.1029/2007JF000859

Jiskoot H. 2011. Dynamics of Glaciers, Encyclopedia of Snow, Ice and Glaciers. Springer Netherlands: Dordrecht.

Kääb A, Kaufmann V, Ladstädter R, Eiken T. 2003. Rock glacier dynamics: implications from high-resolution measurements of surface velocity fields. In *8th International Conference on Permafrost, Zurich, Switzerland*, Phillips, Springman A (ed). A.A. Balkema Publishers: Amsterdam; 501–506.

Kääb A, Frauenfelder R, Roer I. 2007. On the response of rockglacier creep to surface temperature increase. *Global and Planetary Change* **56**: 172–187. https://doi.org/10.1016/j.gloplacha.2006.07.005

Kaufmann V, Ladstädter R. 2007. Mapping of the 3D surface motion field of Doesen rock glacier (Ankogel group, Austria) and its spatio-temporal change (1954–1998) by means of digital photogrammetry. In Proceedings of the 9th International Symposium of High Mountain Remote Sensing Cartography, Kaufmann V, Sulzer W (eds). Graz, Austria; 127–144.

Kellerer-Pirklbauer A, Kaufmann V. 2012. About the relationship between rock glacier velocity and climate parameters in central Austria. *Austrian Journal of Earth Sciences* **105**: 94–112.

Kenner R, Bühler Y, Delaloye R, Ginzler C, Phillips M. 2014. Monitoring of high alpine mass movements combining laser scanning with digital airborne photogrammetry. *Geomorphology* **206**: 492–504. https://doi.org/10.1016/j.geomorph.2013.10.020

Krainer K, He X. 2006. Flow velocities of active rock glaciers in the Austrian Alps. *Geografiska Annaler, Series A: Physical Geography* **88**: 267–280. https://doi.org/10.1111/j.0435-3676.2006.00300.x

Krainer K, Bressan D, Dietre B, Haas JN, Hajdas I, Lang K, Mair V, Nickus U, Reidl D, Thies H, Tonidandel D. 2015. A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). *Quaternary Research* **83**: 324–335. https://doi.org/10.1016/j.yqres.2014.12.005

Lehning M, Bartelt P, Brown B, Russi T, Stöckli U, Zimmerli M. 1999. SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations. *Cold Regions Science and Technology* **30**: 145–157. https://doi.org/10.1016/S0165-232X(99)00022-1

Lugon R, Stoffel M. 2010. Rock-glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. *Global and Planetary Change* **73**: 202–210. https://doi.org/10.1016/j.gloplacha.2010.06.004

Nickus U, Abermann J, Fischer A, Krainer K, Schneider H, Span N, Thies H. 2015. Rock Glacier Äußeres Hochebenkar (Austria) – recent results of a monitoring network. *Zeitschrift für Gletscherkunde und Glazialgeologie* **47**/**48**: 43–62.

PERMOS. 2016. Permafrost in Switzerland 2010/2011 to 2013/2014. Noetzli J, Luethi R, Staub B (eds.), Glaciological Report Permafrost No. 12–15 of the Cryospheric Commission of the Swiss Academy of Sciences, 85 pp.

Roer I, Kääb A, Dikau R. 2005. Rockglacier acceleration in the Turtmann valley (Swiss Alps): probable controls. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography* **59**: 157–163. https://doi.org/10.1080/00291950510020655

Roer I, Haeberli W, Avian M, Kaufmann V, Delaloye R, Lambiel C, Kääb A. 2008. Observations and considerations on destabilizing active rock glaciers in the European Alps. In 9th International Conference on Permafrost, Fairbanks, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks: Fairbanks; 1505–1510.

Roesgen T, Totaro R. 1995. Two-dimensional on-line particle imaging velocimetry. *Experiments in Fluids* **19**: 188–193. https://doi.org/10.1007/BF00189707

Russi T, Ammann W, Brabec B, Lehning M, Meister R. 2003. Avalanche warning Switzerland 2000. In Early Warning Systems for Natural Disaster Reduction, Zschau J, Küppers A (eds). Springer: Berlin; 569–577 DOI:https://doi.org/10.1007/978-3-642-55903-7_77.

Stoffel M. 2010. Magnitude–frequency relationships of debris flows — A case study based on field surveys and tree-ring records. *Geomorphology* **116**: 67–76. https://doi.org/10.1016/j.geomorph.2009.10.009

Zenklusen Mutter E, Phillips M. 2012. Thermal evidence of recent talik formation in Ritigraben rock glacier: Swiss Alps. In 10th International Conference on Permafrost, Salekhard, Russia, Hinkel M (ed). The Northern Publisher: Newcastle, Ontario, Canada; 479–483.

