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Overview of rock glacier kinematics research in the Swiss Alps

Seasonal rhythm, interannual variations and trends over several decades

Reynald Delaloye, Fribourg, Christophe Lambiel, Lausanne, Isabelle Gärtner-Roer, Zurich

1 Introduction

Rock glaciers are key geomorphological landforms for furthering understanding of permafrost creep on periglacial mountain slopes. There is to-date no comprehensive inventory of rock glaciers in the Alps. However, it is estimated that more than 2000 active landforms may be found in the Swiss Alps alone. Active rock glaciers act as sediment conveyors which transfer large quantities of rock debris originating from headwalls or moraines slowly – typically at velocities in the order of 0.1 – 2.0 m/y – over centuries and millenia (BARSCH 1996; HAEBERLI 1985; HAEBERLI et al. 2006; KÄÄB et al. 2003).

During the last decade, an increasing number of studies have quantified and/or monitored the creep behaviour of rock glaciers in the Alps (e.g. BODIN et al. 2009; IKEDA et al. 2003; LAMBIEL & DELALOYE 2004; ROER 2007; SCHNEIDER & SCHNEIDER 2001). Observations show that most Alpine rock glaciers surveyed, irrespective of size and velocity, respond sensitively and almost synchronously to interannual and decennial ground temperature changes (DELALOYE et al. 2008a; KÄÄB et al. 2007; ROER et al. 2005a). Many Alpine rock glaciers are located near the lower limit of discontinuous permafrost and have temperatures close to 0°C (between -2 and 0°C). Such «warm» rock glaciers are expected to react far more sensitively to even small changes in temperature than «colder» rock glaciers (FRAUENFELDER et al. 2003; KÄÄB et al. 2007). Besides thermal conditions, the amount of snowmelt water may also play a significant role on rock glacier kinematics (IKEDA et al. 2008).

Rock glaciers located on steep slopes may be the source for gravitative mass movements such as rock falls, landslides and debris flows. On those landforms, any change in the permafrost creep rate modifies the delivery of loose material at the rock glacier snout and may affect the frequency, the magnitude, and/or even change the type of related geomorphological processes (e.g. ARENSON 2002; ROER et al. 2005b, 2008). In the context of climate change and in view of the management of natural hazard risk, concern is growing in mountain areas, particularly in densely inhabited Alpine regions. There is, thus, a great need to further

understanding on current and future changes of the high-altitude permafrost environment, of which rock glaciers are a part. This article summarizes findings on the temporal behaviour of rock glaciers in the Swiss Alps and the changes that have occurred during the last years and decades. Emphasis is put on ongoing efforts to systematically document interannual variations of rock glacier kinematics in the framework of the monitoring strategy of PERMOS (Permafrost Monitoring Switzerland) and includes independent activities of several research institutions.

2 Permafrost creep and measurement methods

Permafrost creep is defined as the steady-state deformation of a mass of debris supersaturated with ice (e.g. BARSCH 1996; HAEBERLI 1985). Creep is notably dependant on permafrost temperature, which affects ice viscosity. Water pore pressure is a further factor that may influence creep rate. Borehole deformation measurements have shown that the deformation of a rock glacier mainly occurs at a shear horizon situated at depth within the rock glacier, but above the bedrock (e.g. ARENSON et al. 2002). Additional deformation also occurs above the shear horizon. For the most rapid rock glaciers, a sliding phase at the base or within the rock glacier is assumed to occur (ROER et al. 2008). The creep characteristics (e.g. occurrence and depth of shear horizon, deformation above shear horizon, influence of liquid water) may differ distinctly between rock glaciers and depend to a great deal on topographical factors (e.g. slope angle).

Kinematics is defined as the quantification of movement (velocity, acceleration). Changes of rock glacier surface geometry (horizontal as well as vertical changes) are considered to give insight into all ongoing processes, such as aggradation or ice melt at the permafrost table or basis, deformation of the permafrost body, sliding. Monitoring of the kinematics of a rock glacier provides a basic understanding of the ongoing processes and their behaviour over time. The comparison to complementary time series data such as – if existing – permafrost temperature at depth, ground surface temperature and snow depth would allow a more detailed interpretation of some of the processes involved.

In order to quantify rock glacier kinematics, various spaceborne, airborne and terrestrial methods are used

(KÄÄB 2005). The analysis of satellite InSAR (synthetic aperture radar interferometry) data has proven to be a useful technique for assessing the order of magnitude of rock glacier activity (DELALOYE et al. 2007; LAMBIEL et al. 2008). Because of high creep velocities, monitoring of the kinematics of active rock glaciers by means of InSAR is nevertheless still a difficult – if not almost impossible – task.

Thanks to photogrammetric methods, kinematics can be quantified for a specific period, depending on the frequency of flight campaigns (6 or 7 years for swisstopo). Information on average displacements can be obtained for the whole time interval with an accuracy of 0.25–1 m, depending on the flight altitude (KÄÄB 2005; ROER et al. 2005b). Analysis of aerial photographs is possible for the Swiss Alps reaching back about 50 years. However, significant fluctuations in rock glacier kinematics can occur at shorter time scales.

Terrestrial methods like geodetic survey (total station) or differential GPS (Global Positioning System) measurements can be applied to quantify annual and seasonal changes in rock glacier kinematics. Both methods allow high accuracy measurements (about 1 cm in horizontal coordinates and 2 cm in elevation). A geodetic network is established by setting up reference points in non-moving terrain and observation points on the rock glacier (e.g. LAMBIEL & DELALOYE 2004). The observation points should be distributed regularly at the surface, on blocks embedded in the matrix of the active layer, and possibly reaching down to the permafrost (ROER 2005). Each monitoring campaign requires a few hours and should be carried out at approximately the same time each year – ideally by late summer – in order to avoid potentially strong seasonal variations affecting the reliability of the data. In order to get seasonal information, several surveys per year are necessary. The use of stationary GPS can provide year-round high temporal resolution of rock glacier motion.

3 Temporal variability in rock glacier kinematics

Three types of superimposed temporal variability in rock glacier surface motion can be considered on a secular time scale (e.g. KÄÄB et al. 2007; PERRUCHOU & DELALOYE 2007): a decennial to multidecennial trend, interannual variations and a seasonal rhythm. Non-thermally induced changes in rock glacier dynamics (e.g. sediment supply, glacier occurrence in the rooting zone, topography effect) or long-term climatic effects (e.g. ice aggradation or melting) are expected to influence the creep rate of rock glaciers more in the long-term.

3.1 Decennial trend

Studies carried out in various parts of the Alps have shown that the kinematics of rock glaciers have significantly accelerated since the 1980s, probably in response to increased permafrost temperature resulting from warmer air temperatures (e.g. DELALOYE et al. 2008a; KÄÄB et al. 2007; KAUFMANN & LADSTÄDTER 2007; ROER et al. 2005a; VONDER MUEHLL et al. 2007). The long-term series of surface kinematics on the Doesen rock glacier (Austria) shows a high mean velocity between 1950 and 1970, then a decrease until the early 1990s, followed by a strong acceleration once again (KAUFMANN & LADSTÄDTER 2007). This behaviour, which corresponds well with the decennial variations of the mean annual air temperature (Fig. 1), is also reported for the Ritigraben (LUGON et al. 2008) and Becs-de-Bosson (PERRUCHOU & DELALOYE, unpublished data) rock glaciers in the western Swiss Alps. Decennial variation may be related to shifts in the temperature of the entire rock glacier (down to 20 m depth or more). Over the last 20 years, no warming trend has been observed in the borehole of the Murtèl rock glacier, the longest permafrost temperature time series existing in the Alps (Fig. 1).

Over the last years or decades, some rock glaciers have experienced severe changes in their kinematics, geometry and/or topography. At present, 15 Alpine rock glaciers have so far been identified as destabilized features (DELALOYE et al. 2008b; LAMBIEL et al. 2008; ROER et al. 2008); among them are 11 rock glaciers located in Switzerland, all in the Valais Alps. They display velocities of up to 10 m/y. An exceptionally high value of about 100 m/y was even observed on the Graben Gufer rock glacier in 2009/2010. Beside high horizontal velocities and advance rates, many rock glaciers considered in this category show distinct cracks (located either in the rooting zone or closer to the front), indicating deep shear-zones similar to those known for rotational landslides, as well as significant changes at their front (Fig. 2). Despite the limited knowledge on rock glacier dynamics, the principle hypothesis is that the rheological properties of warming ice and the resulting changes in the stress-strain relation control the development of cracks and destabilization of rock glacier tongues. In addition, hydrological effects (unfrozen water) within the permafrost body or at its base may contribute to the initiation of rapid flow acceleration in tertiary creep (ROER et al. 2008).

3.2 Interannual variations

Annual terrestrial survey has been carried out on an increasing number of Alpine rock glaciers over the last few years. A review of existing data until 2007 (DELALOYE et al. 2008a) showed that strong interannual variations of rock glacier kinematics occur throughout the whole Alpine range. Considering their similarity and

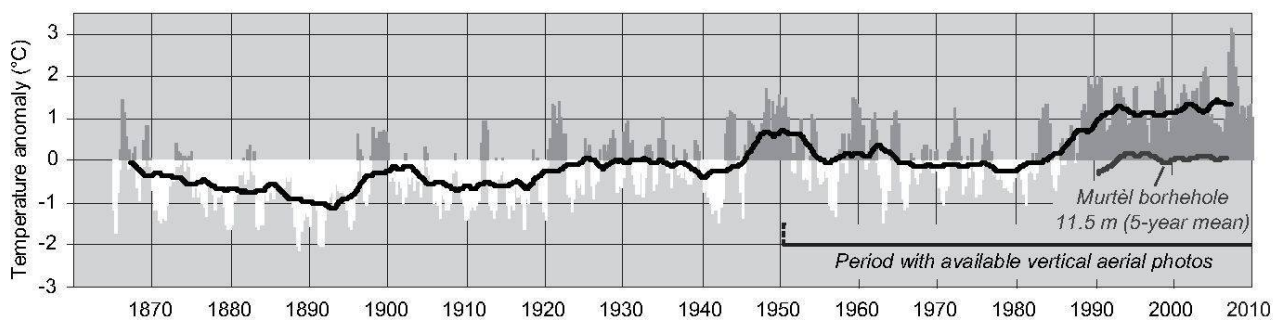


Fig. 1: Anomaly of the mean annual air temperature (12-month running mean) at the Säntis summit, 2472 m a.s.l., in comparison to the mean for 1864–2008 (homogenized data, © Meteoswiss), including 5-year running mean (black line) and 5-year running mean of the permafrost temperature anomaly (compared to the 1987–2007 mean) at 11.5 m depth in the Murtèl rock glacier (© PERMOS). The Säntis and Murtèl time series are the longest high-quality temperature series available for analysis of permafrost in the Swiss Alps and conditions close to free atmosphere at high elevation.

Ecart de la température moyenne annuelle de l'air (moyenne mobile sur 12 mois) par rapport à la moyenne 1864–2008 au Säntis, 2472 m (données homogénéisées, © Météosuisse), avec moyenne mobile sur 5 ans (ligne noire), et écart de la moyenne mobile sur 5 ans de la température du pergélisol à 11,5 m de profondeur dans le glacier rocheux de Murtèl comparée à la moyenne 1987–2007 (© PERMOS). Les séries de température du Säntis et de Murtèl sont les plus longues disponibles respectivement pour des conditions proches de l'atmosphère libre à haute altitude et pour le pergélisol dans les Alpes suisses.

Anomalie der mittleren jährlichen Lufttemperatur (12-monatiges laufendes Mittel) im Vergleich zum langjährigen Mittel 1864–2008 am Säntis-Gipfel, 2472 m NN (homogenisierte Daten, © Meteoswiss), mit 5-jährigem laufendem Mittel (schwarze Linie) und 5-jähriger laufender mittlerer Anomalie der Permafrosttemperatur, gemessen im Blockgletscher Murtèl in 11.5 m Tiefe zwischen 1987 und 2007 (© PERMOS). Die Säntis- und die Murtèl-Messreihen sind die längsten zuverlässigen Messreihen für Bedingungen der freien Atmosphäre in hohen Lagen sowie für Permafrostbedingungen in den Schweizer Alpen.

simultaneous character, these variations are likely to be related to external climatic factors rather than to internal characteristics of the rock glaciers. If most interannual changes appear to be follow temperature changes at depth, seasonal percolation of snowmelt water could also be a relevant factor.

In the Swiss Alps, the first systematic annual survey series was initiated in 1994 on the Furggentälti/Gemmi rock glacier (KRUMMENACHER et al. 2008). Monitoring was also carried out on the Mont-Gelé and Becs-de-Bosson/Réchy rock glaciers since 2001 and 2002, and more recently on the Aget push-moraine (LAMBIEL & DELALOYE 2004) and on two landforms in the Turtmann Valley (ROER 2005). On the Muragl rock glacier, interannual as well as seasonal surveys were carried out between 1998 and 2003 (KÄÄB 2005). Other non-continuous or interrupted series also exist, as for example on the Gruben (HAEBERLI 1985; KÄÄB 2005), Ritigraben (LUGON et al. 2008), Schaffberg (HOELZLE et al. 1998) and Trais Fluors/Büz North (IKEDA et al. 2008) rock glaciers. Currently, several rock glaciers are being monitored in Switzerland, predominantly in the Valais Alps. In a survey of research focusing on inter-

annual monitoring (DELALOYE et al. 2008a), a lack of data for several major climatic regions in the Alps was observed, as for example in the central and southern Swiss Alps, where snow conditions can be significantly different to those prevailing in the Valais Alps or in the Grisons. In order to fill this gap and to explore the role of snow conditions and, more generally, of precipitation, new research sites were established in 2009 in these regions. The current set of observation sites (Tab. 1, Fig. 3), partly integrated into PERMOS (PERMAFROST MONITORING SWITZERLAND - PERMOS 2010), covers the whole range from low active (a few cm per year) to destabilized rock glaciers (up to 10 m/y) and permits specification of regional characteristics. It is envisaged that the new monitoring sites will contribute towards a better understanding of underlying processes and provide long-term data series for specific rock glaciers in view of supporting environmental monitoring and natural hazards management.

Figure 4 presents the data of most existing series in the Valais Alps. The reference value is the mean horizontal velocity for a set of moving blocks with uninterrupted measurement series. The value is considered to be a

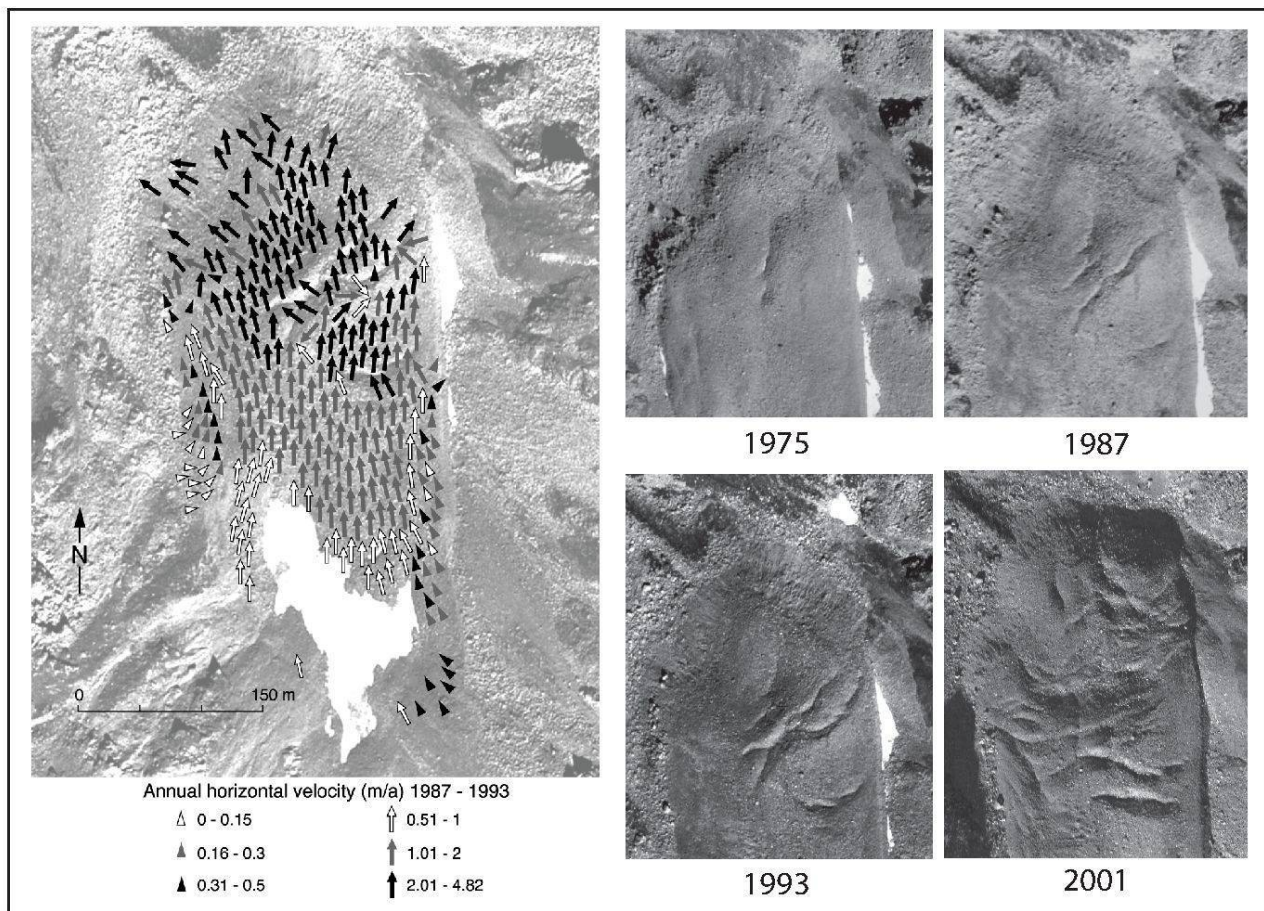


Fig. 2: Collapsing tongue and development of crevasses between 1975 and 2001 of rock glacier Grueo1 (Valais, Switzerland). Crevasses started to build on the orographic right side. Between 1993 and 2001 the surge-like movement spread all over the tongue. Between 1975 and 2001 the rock glacier advanced about 60 m (~2.3 m per year).

Effondrement de la langue et développement de crevasses entre 1975 et 2001 sur le glacier rocheux Grueo1 (Valais, Suisse). Les crevasses ont commencé à se former sur la rive droite. Entre 1993 et 2001, le mouvement de crue s'est étendu à tout le glacier rocheux. Entre 1975 et 2001, le glacier rocheux a avancé d'environ 60 m (~2,3 m par an).

Kollabierende Front sowie Spaltenentwicklung auf dem Blockgletscher Grueo1 (Wallis, Schweiz) zwischen 1975 und 2001. Die Spaltenbildung begann auf der orographisch rechten Seite. Zwischen 1993 und 2001 breitete sich die «surge»-ähnliche Bewegung über die ganze Blockgletscherzunge aus. Zwischen 1975 und 2001 ist die Blockgletscherfront um ca. 60 m vorgestossen (~2.3 m pro Jahr).

Source: KÄÄB et al. 2007; ROER et al. 2008, see also ROER 2007; orthoimages of 1975, 1987 and 1993 © Swiss Federal Office of Topography (swisstopo), orthoimage of 2001 © RTG 437, Department of Geography, University of Bonn

proxy for the activity of a part or the whole landform, keeping local differences in flow rates and intensity of annual changes in mind. From the figure it is apparent that irrespective of rate, the relative changes of velocity since 2001 have been almost similar and have occurred simultaneously throughout the region. The data from the Valais Alps confirms the statements forwarded by DELALOYE et al. (2008a) on homogeneous behaviour after comparison of data from active rock glaciers in

the Swiss, French and Austrian Alps, and extends it to include destabilised rock glaciers.

Indeed, annual variations in horizontal velocities appear to correlate significantly with shifts of the mean annual ground surface temperature (MAGST) – used as a proxy for the temperature of the upper permafrost layers – with a delay of a few months (Fig. 4). Thus, in addition to the influence of seasonal

N°	Site	Region	Aspect	Elevation [m a.s.l.]	Velocity rate ¹ [m/year]	Start	Responsible institution ⁴
<i>Valais Alps</i>							
1	Petit-Vélan	Gd-St-Bernard (VS)	NE	2510-2820	3.0 - 10 ²	2005	UniFR
2	Aget	Bagnes Valley (VS)	SE	2810-2890	0.1 - 0.3	2001	UniFR PERMOS
3	Mille	Bagnes Valley (VS)	NE	2350-2440	< 0.1	2003	UniFR
4	Lac des Vaux B	Bagnes Valley (VS)	NW	2710-2780	0.3 - 1.0 ²	2005	UniL
5	Lapires	Nendaz Valley (VS)	NNE	2640-2610	0.3 - 1.0	2007	UniFR PERMOS
6	Mont-Gelé B	Nendaz Valley (VS)	NE	2600-2740	0.3 - 1.0 ²	2000	UniL PERMOS
7	Mont-Gelé C	Nendaz Valley (VS)	NE	2620-2820	0.1 - 0.3	2000	UniL PERMOS
8	Lués Rares	Nendaz Valley (VS)	NE	2340-2420	0.1 - 0.3	2006	UniL
9	Tsarmine	Arolla Valley (VS)	W	2460-2640	1.0 - 3.0	2004	UniFR/L PERMOS
10	Les Closses	Hérens Valley (VS)	W	2460-2600	0.1 - 0.3	2006	UniL
11	Becs-de-Bosson	Réchy Valley (VS)	NW	2610-2850	0.3 - 1.0 ²	2001	UniFR PERMOS
12	Tsaté	Moiry Valley (VS)	NE	2680-2860	3.0 - 10 ²	2005	UniL
13	Bonnard	Anniviers Valley (VS)	WSW	2840-3000	0.3 - 1.0	2006	Canton VS
14	HuHH1	Turtmann Valley (VS)	NNW	2630-2780	0.3 - 1.0	2001	UniZH PERMOS
15	HuHH3	Turtmann Valley (VS)	NW	2515-2650	1.0 - 3.0	2002	UniZH PERMOS
16	Grosse Grabe	Zermatt Valley (VS)	W	2400-2700	3.0 - 10 ²	2007	UniFR
17	Gugla	Zermatt Valley (VS)	W	2600-2800	3.0 - 10 ²	2007	UniFR
18	Dirru	Zermatt Valley (VS)	WNW	2520-2950	3.0 - 10 ²	2007	UniFR
19	Chessi	Zermatt Valley (VS)	WNW	2500-2900	1.0 - 3.0 ³	2009	UniFR
20	Gänder	Zermatt Valley (VS)	NW	2410-2770	3.0 - 10 ^{2,3}	2009	UniFR
21	Jegi	Saas Valley (VS)	W	2460-2730	3.0 - 10 ^{2,3}	2009	UniFR
<i>Bernese Alps</i>							
22	Furggentälti	Gemmi (VS)	N	2450-2650	0.3 - 1.0	1994	UniBE PERMOS
23	Grosses Gufer	Aletsch (VS)	NW	2360-2600	0.3 - 1.0 ²	2007	UniFR PERMOS
<i>Gotthard region</i>							
24	Klein Furkahorn	Furka (UR)	ENE	2630-2740	0.1 - 0.3 ³	2009	UniFR
25	Blaubergsee	Furka (UR)	N	2640-2700	0.1 - 0.3 ³	2009	UniFR
26	Güetsch	Andermatt (UR)	NW	2190-2240	< 0.1 ³	2009	UniFR
27	Monte Prosa A	Gotthard (TI)	N	2430-2600	0.3 - 1.0 ³	2009	UniFR PERMOS
28	Monte Prosa B	Gotthard (TI)	WNW	2450-2520	0.1 - 0.3 ³	2009	UniFR PERMOS
<i>Tessin</i>							
29	Pizzo Nero	Nufenen (TI)	S	2600-2700	0.1 - 0.3 ³	2009	UniFR
30	Cavagnoli	Valle Maggia (TI)	NE	2560-2800	0.3 - 1.0 ³	2009	UniFR
31	Ganoni di Schenadüi	Val Cadlimo (TI)	N	2470-2640	0.1 - 0.3 ³	2009	UniFR
32	Piancabella	Blenio Valley (TI)	NE	2450-2550	0.1 - 0.3 ³	2009	UniL PERMOS
33	Stabbio di Largario	Blenio Valley (TI)	N	2300-2550	0.3 - 1.0 ³	2009	UniL
<i>Grisons</i>							
34	Murtèl	Upper Engadine (GR)	NW	2630-2800	< 0.1	2009	UniZH PERMOS
35	Marmugnun	Upper Engadine (GR)	NW	2650-2700	0.1 - 0.3	2009	UniZH
36	Gupf	Upper Engadine (GR)	NW	2650-2700	0.3 - 1.0	2009	UniZH
37	Chastelets	Upper Engadine (GR)	NW	2650-2700	0.3 - 1.0 ⁵	2009	UniZH
38	Muragl	Upper Engadine (GR)	NW	2490-2750	0.3 - 1.0 ⁵	2009	UniZH PERMOS

¹ Magnitude order of annual horizontal surface velocity as a mean for the whole rock glacier² Magnitude order of annual horizontal surface velocity only in the fastest section(s) of the rock glacier³ Value for summer 2009 only⁴ UniFR, UniL, UniBE, UniZH: University of Fribourg, Lausanne, Berne and Zurich respectively⁵ Value for 08/2009-07/2010 only

Tab. 1: List of current rock glacier monitoring sites with annual terrestrial survey

Liste des glaciers rocheux actuellement surveillés par relevés terrestres annuels

Liste der derzeitigen Blockgletscher-Beobachtungsorte mit jährlicher terrestrischer Vermessung

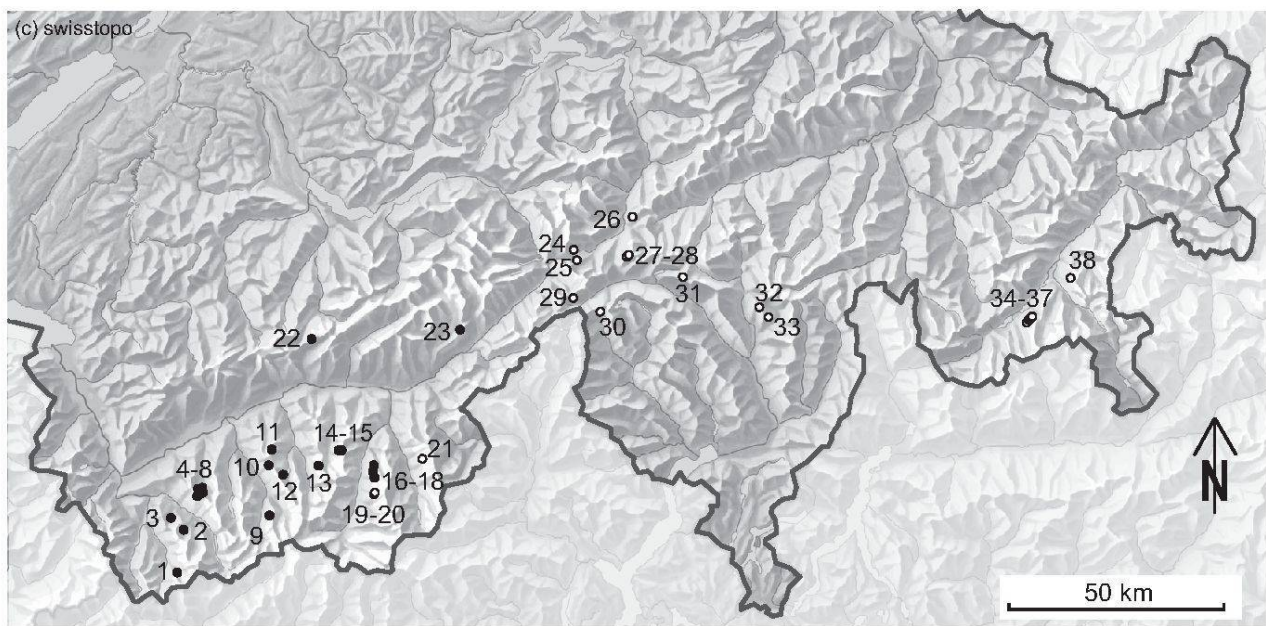


Fig. 3: Location of current rock glacier monitoring sites with annual terrestrial survey. Black dots: series started before 2009. White dots: series started in 2009.

Carte de localisation des glaciers rocheux observés annuellement par relevé de terrain. Points noirs: séries débutées avant 2009. Points blancs: séries débutées en 2009.

Übersichtskarte der Blockgletscher-Beobachtungsorte mit jährlichen terrestrischen Messungen. Schwarze Punkte: Messreihen, die vor 2009 gestartet wurden. Weisse Punkte: Messreihen, die 2009 inziüert wurden.

Base de la carte: Swisstopo

fluctuations, annual velocity reflects in particular the effect of the slow diffusion of annual surface thermal anomalies deeper into the permafrost. Due to early snowfalls in autumn 2002 and the extremely warm summer of 2003, MAGST was highest in the last decade in 2002/03. Maximum velocities were measured in 2003/04. Horizontal velocities decreased significantly during the 2004–2006 period. This drop by about 50% appears to be related to the strong cooling that occurred at ground surface after 2003. The gradual acceleration to be observed after 2006 seems to go hand in hand with the progressive warming of MAGST and consecutive increasing permafrost temperatures since that year. In 2008/09, velocity of all rock glaciers increased in comparison to the year before. However, these values are still definitely slower than those monitored in the record year 2003/04. Seasonal non-thermal factors may also play a significant role on annual velocities. For example, a larger winter snow accumulation, which produces more meltwater in spring time, appears to facilitate a higher rate of rock glacier motion, as was the case in Engadine in 2000/01 (e.g. IKEDA et al. 2008). The general acceleration in 2009 may thus also have been partly caused by the melting of a thick snowcover.

3.3 Seasonal rhythm

Both seasonal variations in rock glaciers (HAEBERLI 1985; HAUSMANN et al. 2007; KÄÄB et al. 2003; PERRUCHOUD & DELALOYE 2007; ROER 2005), and almost constant annual velocities have been observed (KRAINER & HE 2006), particularly where permafrost reaches the bedrock beneath the rock glacier (HAEBERLI et al. 1998). Pioneering measurements on the Gruben rock glacier between 1979 and 1982 indicated already then that strong short-term velocity variations occur where the permafrost base is above bedrock; they also showed that these variations in velocity can be different in the lower and upper parts of the rock glacier (HAEBERLI 1985).

Where existing, seasonal fluctuations can be high, sometimes exceeding 50% of the annual mean. Seasonal fluctuations occur generally every year at around the same time but they do not occur simultaneously for all rock glaciers. Highest velocities appear, in most cases, to be reached between summer and early winter; lowest velocities are generally observed in spring or early summer (e.g. Becs-de-Bosson rock glacier, where seasonal measurements have been carried out since 2004, Fig. 5). The seasonal increase in velocity can be

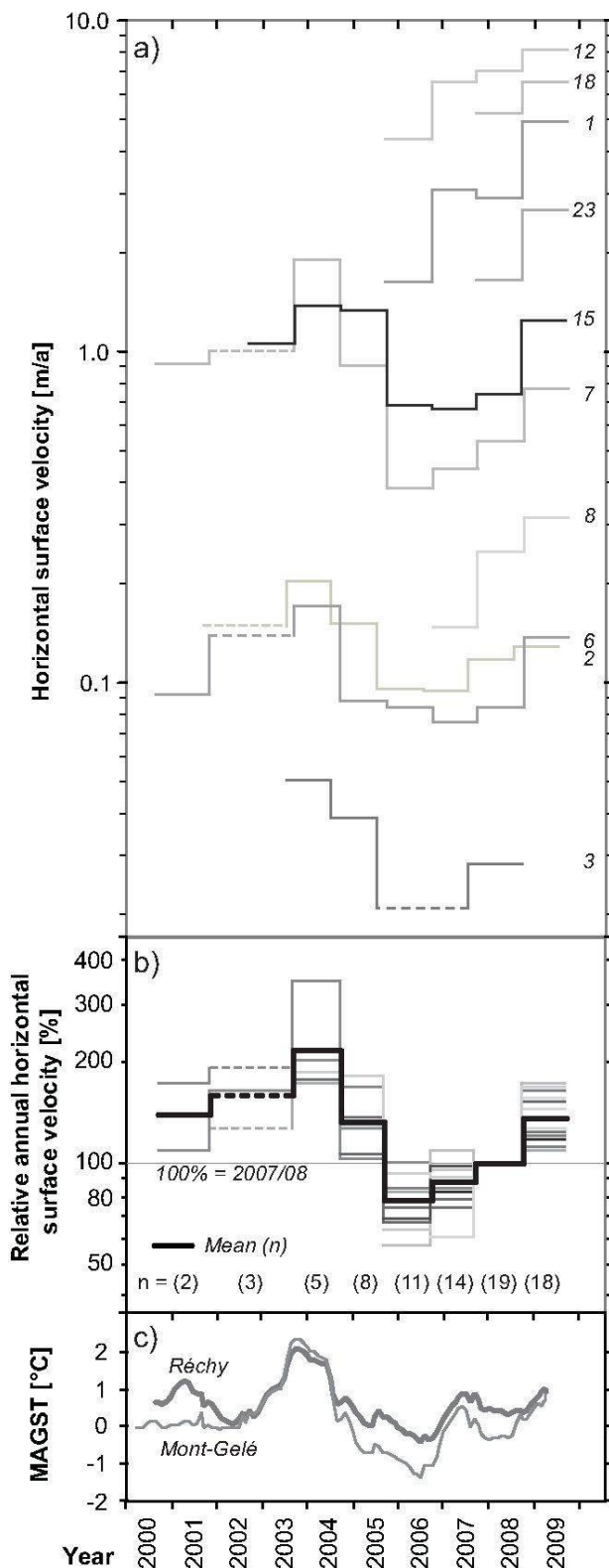


Fig. 4: Rock glaciers in the Valais Alps: a) annual horizontal surface velocities for selected rock glaciers; b) relative changes compared to 2007/08 for all (n) surveyed rock glaciers; c) mean annual ground surface temperature (MAGST).

1: Petit-Vélan (mean of 9 measurement points); 2: Aget (27); 3: Mille (13); 6: Mont-Gelé B (12); 7: Mont-Gelé C (19); 8: Lués Rares (7); 12: Tsaté (6); 15: HuHH3 (22); 18: Dirru (12); 23: Grosses Gufer (15). Dashed segments indicate 2-year surveys. MAGST is computed every month (mean of 4 and 3 measurement points at Réchy and Mont-Gelé, respectively); dates correspond to the median of the 12-month period used for the calculation.

Glaciers rocheux dans les Alpes valaisannes: a) vitesses annuelles horizontales de certains glaciers rocheux; b) changement relatif comparé à 2007/08 pour tous (n) les glaciers rocheux surveillés; c) température moyenne annuelle de la surface du sol (MAGST).

1: Petit-Vélan (moyenne de 9 points de mesure); 2: Aget (27); 3: Mille (13); 6: Mont-Gelé B (12); 7: Mont-Gelé C (19); 8: Lués Rares (7); 12: Tsaté (6); 15: HuHH3 (22); 18: Dirru (12); 23: Grosses Gufer (15). Les segments en lignes discontinues sont des valeurs bi-annuelles. MAGST est calculée chaque mois (moyenne de respectivement 4 et 3 points de mesure à Réchy et Mont-Gelé); les dates correspondent à la médiane de la période de 12 mois utilisée pour le calcul.

Untersuchte Blockgletscher der Walliser Alpen: a) jährliche horizontale Oberflächengeschwindigkeit einiger ausgewählter Blockgletscher; b) relative Veränderungen im Vergleich zum Messzeitraum 2007/08 für alle (n) untersuchten Blockgletscher; c) mittlere jährliche Oberflächentemperatur (MAGST).

1: Petit-Vélan (Mittel aus 9 Messpunkten); 2: Aget (27); 3: Mille (13); 6: Mont-Gelé B (12); 7: Mont-Gelé C (19); 8: Lués Rares (7); 12: Tsaté (6); 15: HuHH3 (22); 18: Dirru (12); 23: Grosses Gufer (15). Gestrichelte Segmente verdeutlichen 2-Jahres-Messungen. Die MAGST wurde für jeden Monat berechnet (Mittel aus 4 bzw. 3 Messpunkten am Réchy bzw. Mont-Gelé Blockgletscher); Daten beziehen sich auf den Median der 12-monatigen Periode, die für die Berechnung genutzt wurde.

rapid and connected to the snowmelt phase, as on the Beccs-de-Bosson and Gemmi/Furggentälti rock glaciers (KRUMMENACHER et al. 2008; PERRUCHOUD & DELALOYE 2007), or progressive and delayed as on the Muragl rock glacier (KÄÄB 2005). The winter/spring velocity

decrease is more gradual and occurs a few months after initiation of seasonal cooling of the ground surface temperature. The annual amplitude of the seasonal rhythm may vary significantly, the winter/spring decrease being reduced by warmer winter ground surface temperature

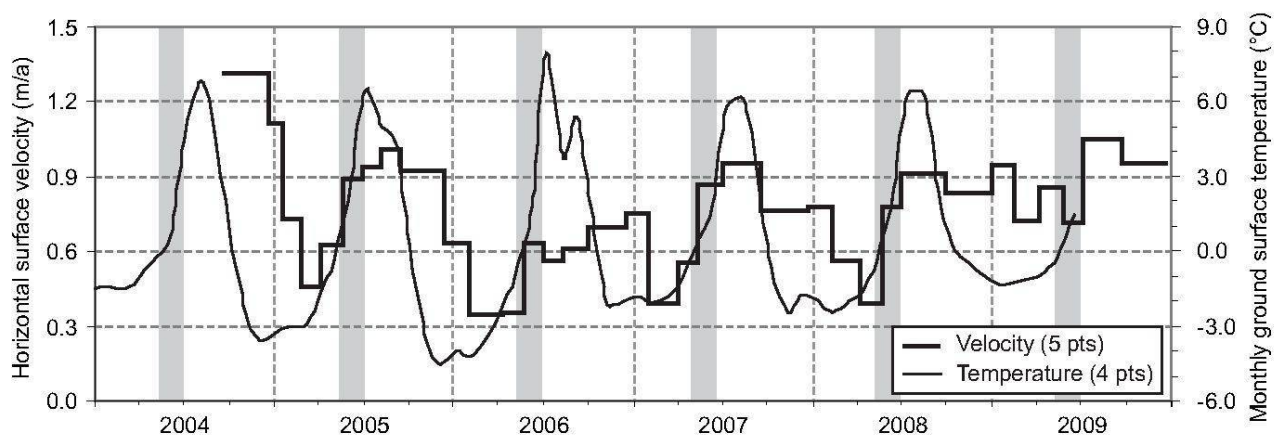


Fig. 5: Seasonal horizontal surface velocity and monthly ground surface temperature on the Becs-de-Bosson/Réchy rock glacier (mean values of 5, respectively 4 measurement points). Grey bars represent snowmelt periods. Strong seasonal fluctuations occur every year with approximately the same rhythm.

Vitesse horizontale saisonnière et température mensuelle de la surface du sol sur le glacier rocheux des Becs-de-Bosson/Réchy (moyenne de respectivement 5 et 4 points de mesure). Les barres grises représentent les périodes de fonte de neige. De fortes fluctuations saisonnières se produisent chaque année avec approximativement le même rythme.

Saisonale horizontale Oberflächengeschwindigkeit und monatliche Oberflächentemperaturen des Becs-de-Bosson/Réchy Blockgletschers (Mittelwert aus 5 bzw. 4 Messpunkten). Graue Balken repräsentieren den Zeitraum der Schneeschmelze. Die deutlichen saisonalen Fluktuationen verlaufen jedes Jahr im ähnlichen Rhythmus.

(KÄÄB et al. 2007), as on the Becs-de-Bosson rock glacier in 2008/09 (Fig. 5). Seasonal variations appear to be almost consecutive to temperature fluctuation above the shear horizon and, at least in some cases, linked to changing pore pressure by snowmelt.

4 Conclusion

Strong fluctuations of rock glacier kinematics occur at various time scales. Considering the diversity of rock glacier characteristics (such as size, shape, slope, material properties), the similarity and synchronism of inter-annual and decennial changes is somewhat unexpected. Even if the factors controlling these changes are still not precisely known, their similarity suggests the predominance of common external climatic factors (e.g. summer air temperature, development of the seasonal snow-cover) governing variations in the movement of almost all rock glaciers throughout the Alps. Indeed, decennial, inter-annual and, to some degree, seasonal changes in rock glacier kinematics appear to primarily reflect permafrost temperature variations. These fluctuations may thus be considered thermally-induced processes.

On the whole, the acceleration of rock glacier surface velocities for the last two decades and the destabilization of several landforms – without knowing if the

latter is linked to any climatic influence – show that permafrost creep conditions are changing in the Alps. Looking at a time scale of several decades, the transfer of loose sediment on Alpine periglacial slopes is increasing (GÄRTNER-ROER & NYENHUIS 2010). As a consequence, the activity rate of rock falls, debris flows and landslides originating from rock glaciers may be locally enhanced. This has to be taken into consideration in some of the densely inhabited valleys of the Alps. Monitoring programmes, such as PERMOS, are thus faced with the challenge of careful observation and documentation of changes in rock glacier kinematics in the coming years and decades.

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Abstract: Overview of rock glacier kinematics research in the Swiss Alps. Seasonal rhythm, interannual variations and trends over several decades

The acceleration of rock glacier surface velocities over the two last decades and the destabilization of several landforms show that permafrost creep conditions are changing in the Alps. This article summarizes and presents current understanding of creep behaviour of rock glaciers in the Swiss Alps and emphasises changes that have occurred over the last years and decades. The almost homogeneous interannual behaviour of rock glaciers despite different geometry and activity rates indicates a common dependence on external climatic factors (summer air temperature, seasonal snowcover development) which govern changes observed in rock glacier creep rate. The article highlights ongoing efforts to document interannual variations of rock glacier kinematics for the whole area of the Swiss Alps.

Keywords: rock glaciers, permafrost, creep, temporal changes, Swiss Alps

Résumé: Aperçu de la cinématique des glaciers rocheux dans les Alpes suisses. Rythme saisonnier, variations interannuelles et tendance pluri-décennale

L'accélération des vitesses de surface des glaciers rocheux au cours des deux dernières décennies et la déstabilisation de plusieurs d'entre eux montrent que les conditions de reptation (*creep*) du permafrost sont en train de se modifier dans les Alpes. L'article décrit le comportement des glaciers rocheux dans les Alpes suisses et les changements qui ont été mesurés durant les dernières années et décennies. Le comportement interannuel plutôt homogène des glaciers rocheux, quels que soient la géométrie et le degré d'activité de ces derniers, indique que les changements observés ont été causés de manière prédominante par des facteurs climatiques externes communs (température de l'air en été, évolution du manteau neigeux). L'article informe aussi sur les efforts désormais entrepris pour documenter les variations interannuelles des mouvements des glaciers rocheux à l'échelle des Alpes suisses.

Mots-clés: glaciers rocheux, pergélisol, reptation, changements temporels, Alpes suisses

Zusammenfassung: Überblick über die Blockgletscherkinematik in den Schweizer Alpen. Saisonalen Rhythmus, interannuelle Variationen und mehrdekadige Tendenz

Die Zunahme der Oberflächengeschwindigkeiten von Blockgletschern während der letzten beiden Dekaden sowie die Destabilisierung einiger Landformen verdeutlichen die Veränderungen im Permafrost in den Schweizer Alpen. Der vorliegende Artikel fasst die Untersuchungen und Erkenntnisse zur Kinematik der

Alpenblockgletscher zusammen und zeigt die Veränderungen auf, die in den letzten Jahren und Dekaden gemessen wurden. Auch wenn die Blockgletscher ganz unterschiedliche Geometrien und Aktivitätsraten aufweisen, so zeigen die beobachteten Variationen der Kinematik ein sehr homogenes interannuelles Verhalten und deuten damit auf die Steuerung durch externe klimatische Faktoren (sommerliche Lufttemperatur, Entwicklung der Schneedecke) hin. Darüber hinaus informiert der Artikel über das Vorhaben, die Variationen der Blockgletscherkinematik im gesamten Raum der Schweizer Alpen systematisch zu dokumentieren.

Schlüsselwörter: Blockgletscher, Permafrost, Bodenkriechen, zeitliche Variationen, Schweizer Alpen

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