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# Short-Term Changes in Surface Velocities on the Becs-de-Bosson Rock Glacier (Western Swiss Alps)

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## Abstract

The observation of the short-term activity of the Becs-de-Bosson active rock glacier (western Swiss Alps) was initiated in 2001. Surface displacements have been surveyed by means of real time kinematics GPS (RTK/GPS). Measurements were carried out in October 2001, October 2003 and intensified since summer 2004 ("monthly" interval). Extension of the measurement network in January 2005 allowed the observation of the year-round rock glacier activity. Preliminary photogrammetry analysis and geodetic survey (1986) allow valuable interpretation of the long term activity of the rock glacier. Significant changes in surface velocities have been recorded over the last two decades (about + 100%), from year to year (10 to 30 %) and also at a seasonal time-scale (50 to 80%).

KEY WORDS: Rock glacier dynamics, GPS survey, surface velocities, Swiss Alps

## 1. Introduction

The active Becs-de-Bosson rock glacier (BBrg) is part of the PERMOS (Permafrost Monitoring Switzerland) program. It is situated in the upper Réchy valley in the western Swiss Alps (46°10'N 7°30.5'E). Several permafrost studies have been carried out in the area, in particular on BBrg, since the mid-1980s. They have provided data on permafrost occurrence and distribution, hydrology of the rock glacier, air and ground temperature, etc. (Tenthorey 1992, 1993, Lugon and Delaloye 2001, Delaloye et al. 2003, Perruchoud in prep.).

In 2001, the survey of the motion of BBrg by means of real-time kinematic GPS (RTK/GPS) was initiated in order to investigate the rock glacier dynamics (Lambiel and Delaloye 2004) and to complete results of ongoing photogrammetry analysis (Kääb 2005). Since summer 2004, the survey has been intensified in order to provide data on the seasonal rhythm of the rock glacier activity. This paper presents some results obtained since 2001 about the dynamics of BBrg with a focus on the short-term variations recorded during the period 2004-2006.

## 2. Site description

The active rock glacier developing north-west of the Becs-de-Bosson summit (3241 m a.s.l.) is a complex periglacial feature extended between about 2810 and 2610 m a.s.l. BBrg is obviously a rock glacier exporting frozen sediments from an area favorable to permafrost toward a non permafrost zone. Indeed, most of the surroundings of the rock glacier main tongue are not underlain by permafrost (Tenthorey 1993, Perruchoud in prep.). However, a small glacier occupied the rooting zone of the rock glacier during the Little Ice Age (LIA) and strongly disturbed the permafrost distribution in the upper section of the rock glacier. Thus, permafrost is still currently lacking in most of the rock glacier rooting zone (Tenthorey 1993, Delaloye et al. 2003, Delaloye 2004). There is no clear evidence of the maximal extent that the LIA glacier reached over the periglacial formation but it appears that the glacier did not exceed the limits of the rock glacier and that 2700 m a.s.l. is the lowest altitude that the glacier could have reached in the central part of the rock glacier.

Downstream of its rooting zone (2810 – 2760 m a.s.l.), the rock glacier becomes steeper (slope angle about 25-30°). By about 2680 m a.s.l., BBrg divides in two adjacent lobes extending on a gentle inclined surface (less than 15°). The main lobe (L1) ends at 2612 m a.s.l. with a steep front scarcely covered with isolated alpine vegetation. The front is steeper and locally unstable on the orographic right side of L1. The secondary lobe (L2) is less extended but characterised by the presence of well developed arched furrows. A small ridge (L2b), 2-5 m high, is growing in loose sediments lying in front of L2.

## 3. Available data on BBrg dynamics

Preliminary works for the study of BBrg dynamics were carried out in 1986 by students of the Basel engineer school (Berweger and Lack 1986). For photogrammetry analysis, thirteen boulders were painted and measured (theodolite) on the rock glacier and 13 others boulders outside the rock glacier. This former study was launched in view of starting a monitoring program for the long-term observation of the permafrost dynamics in the Swiss Alps (Haeberli et al. 1993) – currently PERMOS. High resolution aerial photographs were taken in 1986, 1991, 1995 and 1999.

The photogrammetry analysis of the BBrg surface motion between 1986 and 1999 was carried out in collaboration with Kääb (2005). The 1995 images were not exploitable because large portions of the area were still covered by snow. The 1986-1999 flow field can be succinctly described as following: (1) the area without permafrost in the rooting zone did not moved; (2) maximal horizontal velocity of L1 reached 1.3 m $a^{-1}$ in its steeper section whereas the frontal section was not moving significantly; (3) on L2, horizontal velocities decreased from about 1 m $a^{-1}$ in the upward section to about 0.6 m $a^{-1}$ on the front. Moreover, a significant increase in surface velocities was detected between 1986-1991 and 1991-1999 (Kääb 2005).

GPS survey was initiated in 2001-2003 on the rock glacier front (Lambiel and Delaloye 2004). Sixty-one blocks were initially surveyed. Since July 2004, GPS survey has been performed at "monthly" interval (in fact, every 30 to

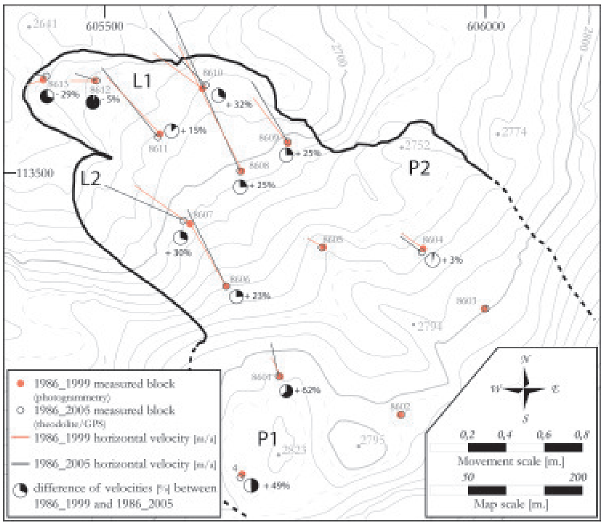


**Figure 1:** Mean annual horizontal movement [m $a^{-1}$] on BBrg for the time period 1986-1999 (photogrammetry) and 1986-2005 (theodolite-GPS). Dots show the initial position of "photogrammetric" and "geodetic" boulders used for comparison (they may be different).

| Boulders n° | 4 | 8613 | 8601 | 8612 | 8604 | 8609 | 8610 | 8607 | 8606 | 8611 | 8608 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| movement 1986-1999 [m] | 0,26 | 1,3 | 1,43 | 1,69 | 1,82 | 3,9 | 4,16 | 4,55 | 4,81 | 5,33 | 9,62 |
| velocities 1986-1999 [m/a] | 0,02 | 0,10 | 0,11 | 0,13 | 0,14 | 0,30 | 0,32 | 0,35 | 0,37 | 0,41 | 0,74 |
| direction (azimuth) | 60 | 253 | 335 | 270 | 305 | 323 | 306 | 305 | 330 | 317 | 333 |
| movement 1986-2005 [m] | 0,57 | 1,37 | 3,41 | 2,37 | 2,77 | 7,16 | 8,10 | 8,70 | 8,69 | 8,99 | 17,69 |
| velocities 1986-2005 [m/a] | 0,03 | 0,07 | 0,18 | 0,12 | 0,14 | 0,37 | 0,42 | 0,45 | 0,45 | 0,47 | 0,92 |
| direction (azimuth) | 67 | 275 | 348 | 288 | 307 | 329 | 316 | 294 | 333 | 321 | 336 |
| difference of velocities 86-99/86-05 [%] | 49 | -29 | 62 | -5 | 3 | 25 | 32 | 30 | 23 | 15 | 25 |

**Table 1:** Comparison of horizontal movement between 1986-1999 (photogrammetry) and 1986-2005 (theodolite-GPS).

| Boulders n° | 8609 | 8611 | 8606 | 8610 | 8607 | 8608 |
|---|---|---|---|---|---|---|
| movement 1999-2005 [m] | 3,26 | 3,66 | 3,88 | 3,94 | 4,15 | 8,07 |
| velocities 1999-2005 [m/a] | 0,54 | 0,61 | 0,65 | 0,66 | 0,69 | 1,34 |
| difference of velocities 99-05/86-99 [%] | 81 | 49 | 75 | 105 | 98 | 82 |

**Table 2:** Mean annual horizontal movement [m $a^{-1}$] between 1999 and 2005. Values derived from difference between 1986-2005 geodetic survey and 1986-1999 aerial photogrammetry analysis. Last row indicates acceleration [%] during the time period 1999-2005 compared to 1986-1999 velocities.

60 days) on L2 front. The measurement network was then extended in January 2005 (85 new points) to the whole moving area of the BBrg. Boulders as large as possible were chosen as marks in order to facilitate the survey during the whole winter season.

In September 2005, the position of 24 of the 26 boulders used for the photogrammetry analysis in 1986 was measured again by RTK/GPS. It revealed the 19-year motion of the rock glacier surface for 12 boulders (fig.1). Tab. 1 compares the data obtained in 1986-1999 (photogrammetry) and 1986-2005 (thedolite-GPS). It evidences homogeneous changes in mean velocities and direction of movement only for the six boulders that have experienced a displacement larger than 0.2 to 0.3 m $a^{-1}$ (right part of table). Therefore, the comparison between photogrammetry and field data appears to be not significant for lower mean velocities.

On the basis of the RTK/GPS results and by comparison with photogrammetry data, three types of variations of BBrg activity can be highlighted with three distinct time scale.

## 4. Decadal scale of variations ("long term" trend)

Tab. 2 compares the movement observed for the 6 rapidly moving boulders (evidenced here above, Tab. 1) between 1986-1999 and 1999-2005. It shows a very strong increase of the mean annual horizontal velocity that reached 82% in average (+49 to +105%). The mean annual velocity of the surface deformation of BBrg over the period 1999-2005 is probably more than two times greater than observed by photogrammetry between 1986 and 1991. This acceleration however started before 1999 as stated by Kääb (2005).

## 5. Inter-annual variations

Mean horizontal velocities recorded on L2 front are reported on Fig. 2. The value of 0.88 m $a^{-1}$ observed in 2001-2003 was already about 50% greater than those determined between 1986 and 1999. The velocity still increased of 10-15% in 2003-2004 for culminating at 0.97 m $a^{-1}$ before to drastically drop in 2004-2005 (5-13% slower than in 2001-2003). The decrease has continued in 2006 (0.68 m $a^{-1}$ between July 2005 and July 2006), the motion of L2 front remaining still slightly faster than between 1986 and 1999.

Fig. 2 also illustrates the behavior of the mean annual ground surface temperature (MAGST) recorded at 2700 m a.s.l. on BBrg as well as those of the mean annual air temperature (MAAT) on the site over the last years. The changes in L2 annual velocities appear to be connected with variations of MAGST with a delay of about one year. The fastest movement rate in 2003-2004 followed the exceptionally warm MAGST value in 2003. The decrease in rock glacier activity since that time appears to be related to the strong cooling of the ground surface that occurred since 2004.

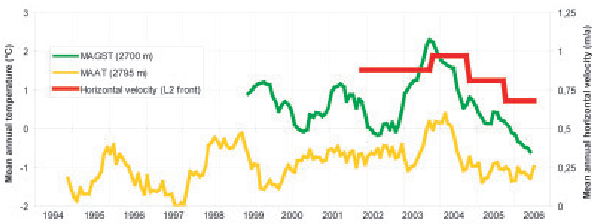


**Figure 2:** Comparison between MAGST [°C] MAAT [°C] and mean annual velocities [m $a^{-1}$] on front of L2.

## 6. Seasonal variations ("short term" scale)

Measurements carried out since July 2004 on the front of L2 and since January 2005 on the whole rock glacier allow a detailed analysis of short-term variations of velocities on BBrg. Two main observations must be noticed:

(1) Strong seasonal fluctuations (fig. 3 and 4): In 2004, maximal velocities occurred during late summer and stayed high until January 2005 before suffering a strong decrease until April-May (50 to 80% of reduction). The horizontal movement increased then again rapidly in late May to reach values that remained high until December 2005 before a new decrease until May 2006. Summer/autumn velocities were most often 10 to 40 % slower in 2005 than in 2004 corresponding to the decrease observed at the inter-annual time scale. Late winter velocities in 2006 were also significantly lower than in 2005.

The winter-spring decrease is gradual, conversely to the later reacceleration that is much more abrupt. Comparing with the ground surface thermal regime, the decrease in BBrg velocities occurs 1 to 3 months after the cooling of the surface temperature. The reacceleration is conversely quite simultaneous to the snowmelt period. It occurred slightly later in 2006 than in 2005. The snowmelt period began also quite two weeks later in 2006.

(2) Non homogenous spatial behavior: Fig. 5 depicts the relative variations of BBrg motion for 8 consecutive phases between January 2005 and February 2006 compared to the average annual velocity during this whole period. Phase velocities lower than 0.02 m $a^{-1}$ are not taken into account in the analysis (too high variability in changes rate). This explains the lack of data represented on the front and on the rooting zone of L1. Similar amplitude of fluctuations is observed on the whole rock glacier than on L2. However, the fluctuations are not perfectly synchronous and show a complicated spatial pattern:

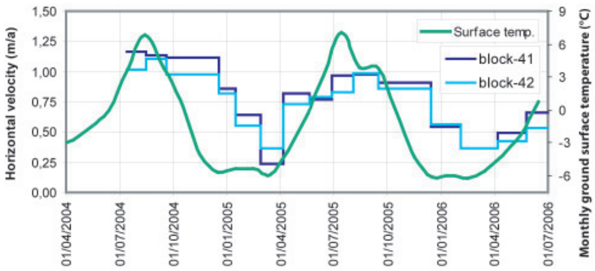


**Figure 3:** Seasonal variations of horizontal velocities [m $a^{-1}$] (Jun04-Jul06) of boulders 41 and 42 placed on the front of L2 and ground surface temperature (°C).

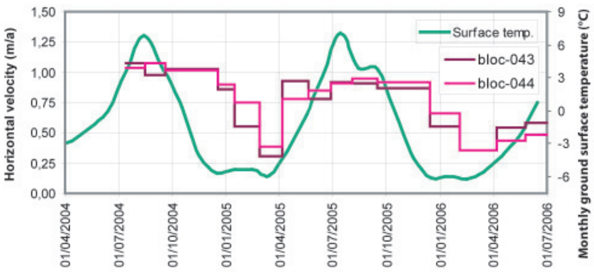


**Figure 4:** Seasonal variations of horizontal velocities [m $a^{-1}$] (Jun04-Jul06) of boulders 43 and 44 placed on the front of L2 and ground surface temperature (°C).

A) Jan-Feb: Pronounced deceleration on L2 while other parts of the BBrg continue to move with velocities higher than the annual average.

B) Feb-Apr: General deceleration of velocities on the whole rock glacier, stronger on L2.

C) Apr-May: Deceleration continues on L1 while acceleration begins on the terminal part of L2, even if speed remains generally lower than the average.

D) May-Jun: General acceleration, more pronounced in the lower parts of BBrg.

E) Jun-Aug: Horizontal velocities generally higher than in D except for the fastest part of L1.

F) Aug-Sep: Stabilization of velocities, remaining high on the whole rock glacier except for boulders 319 and 320 in the north-eastern part of BBrg that were affected by a severe deceleration.

G) Sep-Dec: Opposite situation to D. Significant deceleration of the "frontal" section of the two lobes while the upper parts continue to move fast and even to accelerate.

H) Dec-Feb: General "braking" of the whole rock glacier.

## 7. Preliminary conclusions and open questions

Complex spatio-temporal variations of surface velocities (decadal, annual, seasonal) have been detected on the BBrg. On the basis of the data available at present and according to the delay and attenuation of surface-induced heat transfer with depth, a preliminary conceptual model of the BBrg dynamics can be inferred. Three gradual levels can be distinguished reacting with different time lag to changes in ground surface temperature. This model partly corresponds to those proposed by Kääb(2005).

There are significant variations (50 to 80%) in seasonal rock glacier activity on BBrg. According to Kääb (2005), large seasonal fluctuations seem to be characteristic for rock glacier with temperature close to 0°C, what appears to be the case for BBrg (Tenthorey 1993, Delaloye 2004). The seasonal variations, that occurred with a lag maximally restricted to a few months in winter, may be related

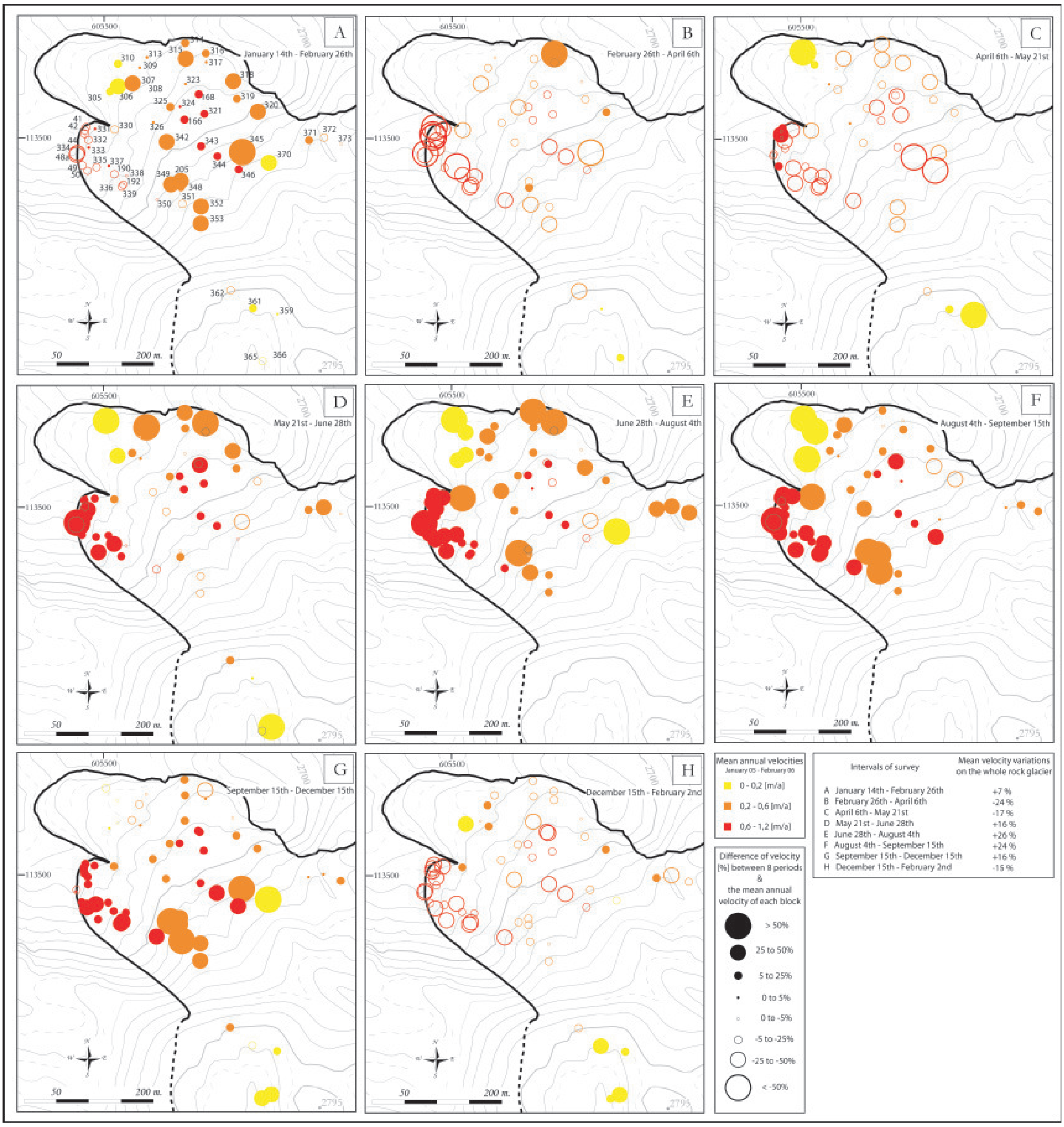


**Figure 5:** Mean annual horizontal velocities (Jan. 05 – Feb. 06) for ~60 boulders on BBrg and "seasonal" velocity variation [in % compared to the annual mean]. For phases A-H, see comments in text.

to changes in deformation rate occurring in layers close to the surface (above 10 m depth ?). The rapid increase in velocities in May-June 2005 appears to be synchronous with the percolation of snowmelt water in the uppermost layers of the ground: it may be due to the rapid warming of the uppermost layers of the rock glacier but also to a strong increase of the water content and water pressure in certain layers or at the base of the rock glacier (Krainer and Mostler in prep). Indeed, the torrent streaming out of BBrg correspondingly suffered a strong increase of discharge at that time of the year and the maximal monthly discharge is occurring in June (Tenthorey 1993). The heterogeneity of BBrg motion over the year cycle is still not understood, but may evidence, at least partially, the complex role of water pressure within the rock glacier.

Inter-annual variations of flow velocity appear to be related to changes in MAGST with a lag of about one year. Ground surface temperature measurements on BBrg thus show that both the maximal rock glacier activity in 2003-

2004 and the decrease in velocities in 2005 and 2006 can be related with a one-year lag to the "MAGST heat wave" observed in 2002-2003 and the severe MAGST cooling since 2004, respectively. Considering the time necessary for the heat transfer to depth, the observed delay between MAGST and velocity changes may indicate that inter-annual variations of the flow rate are due to modifications of the rock glacier deformation rate in its about 10 to 15 uppermost meters. On BBrg, these inter-annual variations of rock glacier activity are much smaller than the seasonal fluctuations.

Finally, decadal variation may be related to shift in the global temperature of the whole rock glacier (down to 20 m depth or more). The strong increase of BBrg velocity (~100%) observed after 1991, and particularly since 1999, seems to be related to a warming of permafrost that occurred by the end of the 1980s and in early 1990s (e.g. SCNAT in prep.). It fits, both in timing and amplitude, with other observations reported for several rock glaciers over the whole European Alps (Roer et al. 2005).

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