PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **15**: 229–241 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/ppp.496

Contribution of Real-time Kinematic GPS in the Study of Creeping Mountain Permafrost: Examples from the Western Swiss Alps

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ABSTRACT

The use of real-time kinematic (RTK) GPS for studying the dynamics of creeping mountain permafrost is evaluated on the basis of measurements carried out on three test sites in the Western Swiss Alps. The high precision of the method and its ease of use make the RTK GPS appropriate for this kind of study. A wide range of information can be obtained by comparing the position of a set of surveyed points after two campaigns of measurement: determination of both horizontal and vertical components of surface movements, identification of compression and extension zones, estimation of thickness variation and, finally, determination of three-dimensional (3D) rotational movements of individual boulders. Temporal variations of all these parameters can then be identified after more than two repetitions of the measurement series. The results obtained on the test sites are presented and discussed from a geomorphological point of view. They were sometimes surprising, for instance the strong difference in surface velocities of two morphologically similar rock glaciers situated in the same area or the small 3D rotation of blocks located on the front of a rapidly moving rock glacier. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: GPS; rock glaciers; dynamics; surface movements

INTRODUCTION

The understanding of creeping mountain permafrost (especially rock glaciers) dynamics and its evolution with time still represents a major interest in periglacial geomorphology (see, e.g., Ødegård *et al.*, 2003), particularly in view of potential responses to ongoing climate warming trends. As the direct observation of internal movement of rock glaciers by deformation surveys within deep boreholes can only rarely be attempted (see, e.g., Arenson *et al.*, 2002) due to the expense of this type of study, an approach based only on surface measurements has been more common. Borehole deformation surveys in rock glaciers showed that most of the horizontal movements are concentrated in ‘shear zones’, situated more than ten metres below the surface, and that sharing restricted only to the superficial layers is rather low (see, e.g., Haeberli *et al.*, 1998; Hoelzle *et al.*, 1998; Arenson *et al.*, 2002). This means that studying the dynamics of rock glaciers and other deep creeping permafrost terrains by means of surface displacement measurements gives a good approximation of the deep movement of the formation and, therefore, is fully justified.

Kääb *et al.* (2003) offer a complete overview of information on rock glacier dynamics provided by surface velocity measurements. In a remote sensing approach, photogrammetry represents, up to now, the best technology for monitoring the superficial deformation of rock glaciers. Kääb *et al.* (1997, 1998) and

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Received 19 January 2004
Revised 21 May 2004
Accepted 17 June 2004

Kääb and Vollmer (2000) have proven its efficiency. D-InSAR (Differential Synthetic Aperture Radar Interferometry) is a promising tool permitting very high precision to be obtained (Kenyi and Kaufmann, 2003). Triangulation using a theodolite was hitherto the most frequent technique applied in a ground-based approach (see, e.g., Francou and Reynaud, 1992; Sloan and Dyke, 1998; Koning and Smith, 1999; Isaksen *et al.*, 2000; Ikeda *et al.*, 2003). Recent development permits the successful use of a high precision Global Positioning System (GPS) for monitoring rock glacier deformation (Berthling *et al.*, 1998), in particular the real-time kinematic (RTK) technique (Roer, 2003; Lambiel *et al.*, 2003). The advantages of the latter appear to be numerous: high precision, ease of use, rapidity of data acquisition etc.

The objectives of this paper are to relate our experience gained on three test sites (Yettes Condjà, Réchy and Aget) in the Western Swiss Alps (about 46°05 N/7°20 E, Figure 1) with the use of RTK GPS and to explore the results that can be expected. The geomorphological significance of the results obtained is discussed in the last section.

THREE STUDY SITES

The small Yettes Condjà valley (Verbier area) contains three rock glaciers (rgB, rgC and rgD, Figure 2). RgB and rgC morphologically correspond to active rock glaciers, whereas rgD seems to be mainly inactive. DC resistivity soundings and mapping lines carried out in 1998 (Reynard *et al.*, 1999) evidence low resistivity ice in rgB and rgD (20–90 kΩ m). These values may be related to a low ice content as well as to a permafrost temperature close to the thawing point. Higher resistivities were measured on rgC (350 kΩ m up to more than 1 MΩ m). Such values could indicate the presence of massive and possibly colder ice within the formation. The burial of an ice patch (basal freezing of a long laying snow bank, Haeberli and Vonder Mühll, 1996) is clearly visible in the rooting zone of this rock glacier. The position of 100 points was measured by RTK GPS on the three rock glaciers and on an adjacent talus slope at the end of August 2000. Four control points were added. One year later, the positions were surveyed again (Lambiel *et al.*, 2003). A third campaign was finally performed in early September 2003.

Situated in the upper Réchy valley, the Becs-de-Bosson rock glacier (2610–2820 m a.s.l., Figure 3) was partially covered by a Little Ice Age glacieret. As a consequence, permafrost is lacking in a large part of the rooting zone of the formation despite favourable north-west orientation and high elevation (Tenthorey, 1992; Métrailler *et al.*, 2003; Delaloye, 2004; Delaloye *et al.*, 2003). The median and lowermost parts of the rock glacier are still frozen

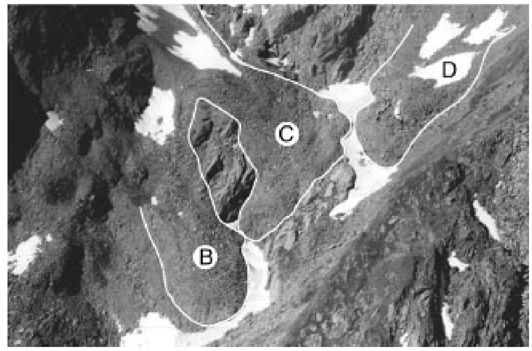

Figure 2 View of the rock glaciers of the Yettes Condjà valley.

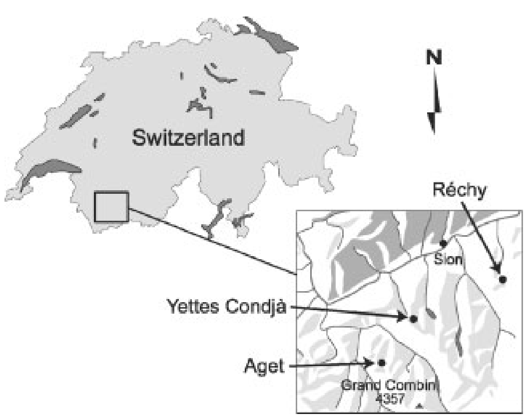

Figure 1 Location of the three study sites.

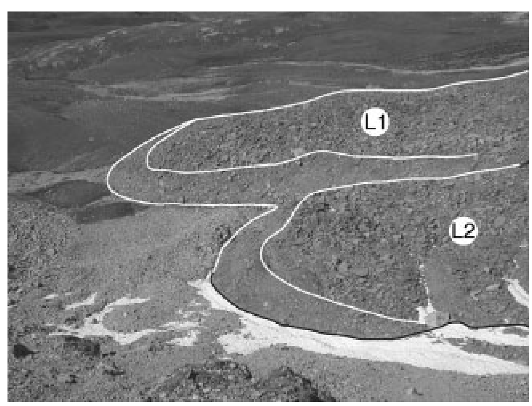

Figure 3 The two main lobes L1 and L2 of the Becs-de-Bosson rock glacier (Réchy valley).

Figure 4 Re-equilibrating mass movement in the deglaciated historical forefield of the Aget glacier. Melting pattern of an early snowfall permits both front and starting scar (upper right) of the deforming sediments to be distinguished. The black arrow indicates the flowing direction of the former glacier. The dashed line indicates the upper limit (lateral moraine) reached by the glacier during the Little Ice Age.

(Tenthorey, 1993). The latter divides into a main tongue (L1) and a secondary, less extended lobe (L2). Fifty blocks were painted at the top of the front of L1 and L2 in 1986, as well as seven blocks located on a small ridge (L2b) developing in loose sediments about 30 m downwards from L2. In October 2001, most of the blocks were still lying at the top of both L1 and L2 steep margins. At that time, three points were marked and measured on each block (Métrailler and Turatti, unpublished data). They were surveyed again in October 2003.

On the Aget site (Bagnes valley), morphological indices (steep front 5–20 m high, starting scar) evidence recent re-equilibrating mass movement in the orographic left southeast-oriented side of the currently deglaciated historical forefield of the Aget glacier (Figure 4). DC resistivity soundings and mapping revealed the continuous frozen state of the sediments (50 to more than 200 kΩ m, about 20 m thick) involved in the moving terrain under an active layer reaching an unusual thickness, estimated to be more than 5 m (Delaloye and Devaud, 2000; Delaloye, 2004; Reynard *et al.*, 2003). Detection of surface movement was initiated in late October 2001 with the localization of 101 points. A second campaign was performed in mid-July 2003.

METHOD

A complete presentation of GPS is given, for example, by Hofmann-Wallenhof *et al.* (1994). Eiken *et al.* (1997), who used GPS on Svalbard glaciers, present a summary of the basic concepts of the system. More recently, Little *et al.* (2003) have published a description of the differential GPS technique.

Real-Time Kinematic GPS

The working principle of GPS is based on the distance measurement between several satellites and a receiver. Because of perturbations in the satellite signals provoked by the high atmosphere, a single receiver only permits an accuracy of a few metres. The accuracy is strongly improved with the use of a second receiver (the *differential GPS* technique). The first receiver, called the *reference*, is set up at a fixed point that must be the same for each repetition of the measurement. This point is assumed not to be subject to any kind of movement. The reference GPS receives in permanence the satellite signals, calculates its ‘GPS’ position and determines the difference with the coordinates attributed to its own position. The process is repeated each second. The second receiver, called the *rover* (Figure 5), is mobile and placed successively on the points that need to be positioned. Different modes of measurement exist. The *real-time kinematic (RTK)* one signifies that the two receivers—reference and rover—are in a permanent state of observation. The correction values are directly sent by radio from the reference to the rover. In this way, the latter continuously ‘knows’ its relative position to the reference point with a precision often better than 3 cm. This technique allows a rapid acquisition of data.

The main advantage of the RTK GPS over the triangulation technique is that visibility between the stations is not necessary. Once the reference station is installed, it is no longer necessary to move it. However,

Figure 5 The 'rover' GPS receiver.

the topographic horizon can drastically limit the number of available satellites and can therefore prevent any data acquisition. This problem is especially encountered in the roots of rock glaciers as they are often lying directly at the foot of high headwalls.

Field Work

Two people are sufficient for the success of a measurement campaign. Whereas marking is time consuming during the first campaign, the following measurements are more rapid and 100–200 points can be surveyed in one day. Crucial steps of the field survey are briefly outlined in the following lines. The equipment used in this study is the SR 530 of Leica Geosystems.

The reference station has to be installed for each campaign at precisely the same position on bedrock that is not susceptible to instability. An anomaly in the position of the reference station can then be detected by measuring a few control points (ideally three to five) also located on stationary bedrock (in Yettes Condjà, a vertical subsidence of 11 cm was however recorded between 2000 and 2003 for a control point unfortunately situated on a highly fissured wall). On the Aget study site, a displacement of 4 cm towards the north-west relative to the reference station was measured between 2001 and 2003 for the three control points. The cause is still unknown, but it could suggest a slight movement of the reference station emplacement towards the south-east. The coordinates of all measured points was corrected to take account of the anomaly in the position of the control points.

The points to be measured on the 'moving' terrain are usually set on boulders (one per block) and simply marked with a chisel. To avoid measuring individual movements of blocks instead of the general displacement of the creeping body, large boulders deeply buried into the ground are preferably chosen. Another solution (however requiring more time) to prevent misinterpretation of detected displacement is to measure three points on the same boulder in order to determine its 3D rotational movement.

The mobile receiver is fixed on top of a 2 m high stake (Figure 5). Despite the fact that an air bubble level permits the device to be placed in a perfectly vertical position, an error in the horizontal coordinates up to 1 cm is possible due to the positioning of the GPS receiver. The relative coordinates of the emplacement are stored after a few seconds. In practice, to gain control of the measurement accuracy, the receiver is left calculating its position for about ten seconds. The average value of five to ten measurements is retained. The standard deviation of positioning during this time lapse is usually less than 1 cm in the horizontal components and less than 2 cm in the vertical one. The range is comparable to the measurement accuracy given by the receiver when performing the measurement. By adding the potential errors of positioning, a total error up to 3 cm can easily be reached when comparing two sets of data. Experience, however, shows that the error is usually lower than 1 cm in horizontal coordinates and 2 cm in elevation for control points. Moreover, in Réchy, the error in the change of the relative position of the three points measured on individual boulders appears to be often less than 1 cm in 3D (*see below*).

CONTRIBUTION OF RTK GPS

Surface Movements

The basic contribution of the RTK GPS is the determination of surface movements by comparing the position of the measurement points between two campaigns of measurements. Surface displacement of less than 3 cm is considered as non-significant, being in the same order as the position error. The total movement can be separated into horizontal and vertical components. The horizontal component corresponds to both horizontal velocity and direction of a moving point. The vertical component is the change in elevation. The latter can be due to at least four distinct sources, whose combination makes the interpretation of observed vertical changes rather difficult.

(a) *Loss in elevation consecutive to the downslope movement*. It is obvious that a change in elevation is primarily linked to the horizontal displacement of the creeping mass and to the slope angle. The greater the slope angle, the stronger the decrease in elevation relative to the horizontal displacement.
(b) *Change in elevation due to extending or compressing flow*. In a rough estimation, the volume of the moving mass remaining unchanged, a 1% extension of a reference surface induces a decrease of 10 cm in surface elevation if the deforming material is 10 m thick. The vertical change becomes twice as large if the sediments affected by movement are 20 m thick.
(c) *Change in elevation in response to melting or aggradation of ice lenses* (or massive ice layers) in the ground.
(d) Finally, to a lesser extent, *loss of volume provoked by creeping* when it occurs in massive ice layers (Arenson *et al.*, 2002).

More than two campaigns of measurements allow the temporal evolution of surface movements to be observed. Since absolute changes depend on the magnitude of the movements, it appears to be appropriate to express these variations in terms of rate of increase (or decrease) of the surface movements. However, low horizontal surface velocities are likely to be problematic because a great exaggeration (and uncertainty) in the variations can be displayed (a velocity passing from 1 cm a^{-1} to 20 cm a^{-1} gives an increase of 1900%!). It is indeed advised to represent values lower than a given threshold, for example in our study 5 cm a^{-1}, only with the absolute values of variation in cm a^{-1}.

Compressing/Extending Flow

Compression and extension zones can be determined from a set of points more or less regularly distributed over a given area. A net of triangles can be established, each apex corresponding to the 3D coordinates of a measured point. A respective decrease or increase, in the area of a triangle after the second measurement campaign allows the identification and quantification of either compressing or extending flow. For a triangle of 100 m^2, an error up to about 0.25% in the area has to be taken into account due to the possible error in the position of the points. Compression/extension rates higher than 1% per year were observed at Yettes Condjà and Aget (*see below*). A way to represent this information on a map is to determine the central coordinates of the triangles, to assign them the variation of area calculated as a percentage and finally to interpolate this information (we used the ordinary kriging method).

Individual Movements of Blocks

The determination of 3D rotational movements of individual blocks can be estimated by the measurement of several points marked on the same boulder. A test was carried out on the blocks located at the front of the Becs-de-Bosson rock glacier (Réchy). Three points about 20 cm apart were systematically positioned on the upper face of the block looking downstream. Some examples of results are proposed in Figure 6. Block 06 was subject between 2001 and 2003 to a backward tilting: the point located in the general direction of the block displacement (determined by the average absolute displacements of the three points) moved back and up by 2–3 cm towards the other two points. This movement is opposite to the general displacement of the block (horizontal component 6 cm, subsidence 4 cm). The three points on block 11 show another type of movement, namely a 1–1.5 cm anticlockwise horizontal rotation without vertical movement. Block 39 had a simple clockwise horizontal rotation less than 1 cm. Block 42 had a slight tilting on its left-hand side.

The test carried out in Réchy not only allows the characteristics of the individual movement of blocks to be determined, but also allowed an assesment of the reliability of RTK GPS. Indeed, for the great majority of the blocks (this is the case for the examples presented), the relative movements of each point of a triangle are consistent and do not show a contradictory behaviour. The 3D precision of the relative position of the three points (in relation to each other) appears to be often less than 1 cm when comparing two data series.

Thickness Variation

The vertical component of surface movement results from the effects of slope angle, compression/extension strain rate and ice aggradation or thaw settlement. The first two parameters are related to the horizontal velocity, whereas the latter mainly depends on permafrost thermal regime. The role of each of these parameters in the vertical movement is difficult to determine accurately. However, the variation of thickness of the creeping body can be roughly estimated after two series of measurements by calculating and comparing the average rock glacier slope and the average slope angle of the block movement (cf. Table 1). If the latter is higher than the topographical

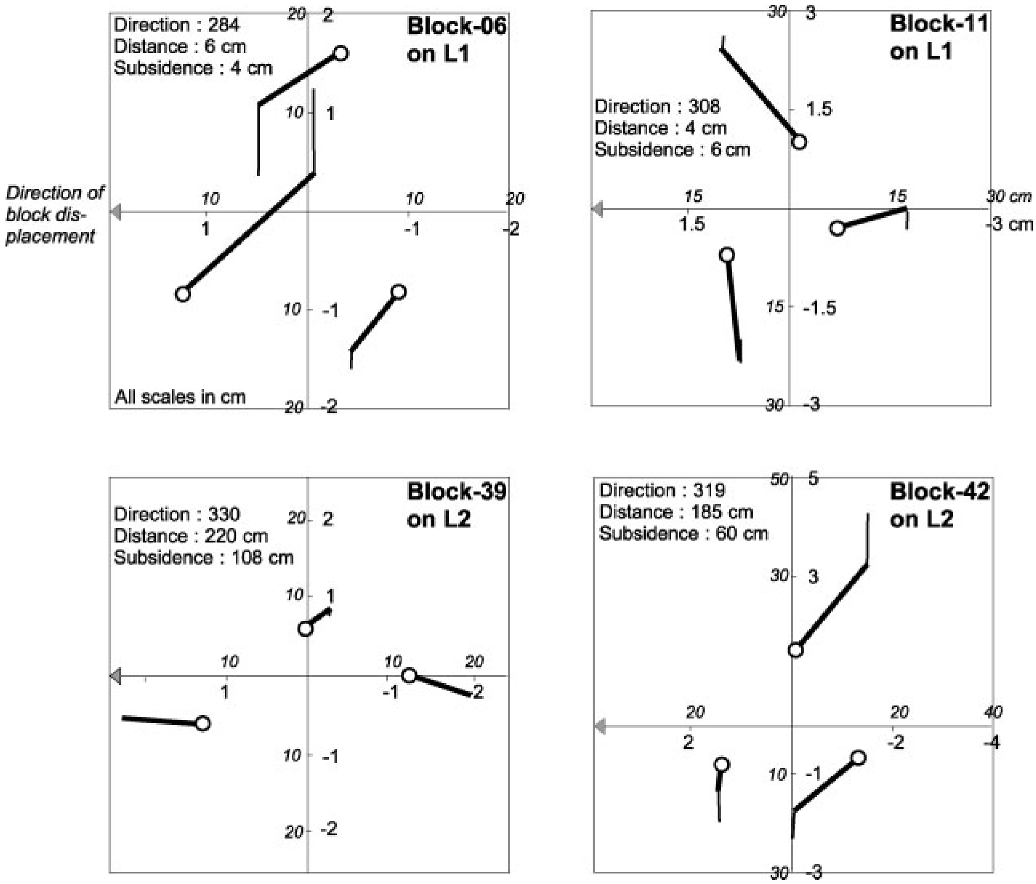

Figure 6 Three-dimensional rotation of single blocks on the Becs-de-Bosson rock glacier. The direction of the block displacement is given by the arrow at the extremity of the x-axis and its 3D characteristics are indicated at the upper left edge of the graph. White dots correspond to the horizontal position (italic scales) of the three points measured on a block relative to the centre of the triangle that they form. Broad lines indicate the horizontal relative displacement (normal scales) of each point between the two campaigns. Fine vertical lines indicate the change in relative elevation (normal vertical scale). All scales are in cm.

Table 1 Comparison of the average slope angle of the block movement between 2000 and 2001 with the average rock glacier slope in the Yettes Condjà valley. dH = mean horizontal surface velocities, dV = mean changes in vertical elevation.

	Points			Rock glaciers		
	dH 00–01 [cm a^{-1}]	dV 00–01 [cm a^{-1}]	Slope [%]	Length [m]	Height [m]	Slope [%]
Rock glacier B	53.0	27.9	53	300	150	50
Rock glacier C	7.0	5.8	84	325	145	45

slope, it means that a loss in thickness of the moving mass has probably occurred. Conversely, a gain in thickness is detected when the surface movement is less inclined than the surface slope angle. After having estimated the effect of the compression/extension flow pattern, the residual change in thickness may be interpreted as representing melting or aggradation of massive ice in the ground. The same approach can be applied for individual points along longitudinal profiles by comparing the slope angle of the observed movement and the topographical slope angle (cf. Figure 7).

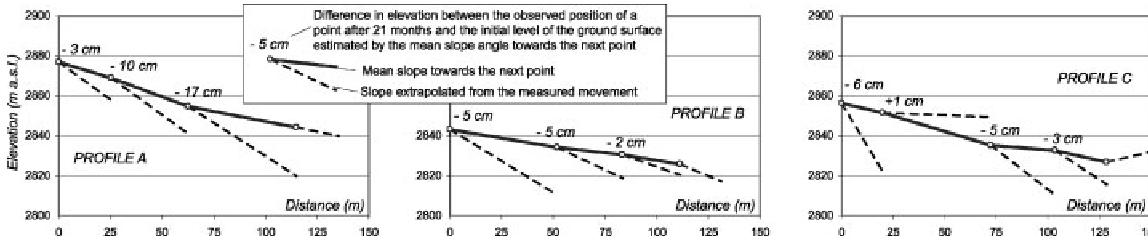

Figure 7 Comparison between estimated topographical slope and movement of single blocks along longitudinal profiles on the Aget site (location of the profiles in Figure 14).

RESULTS AND DISCUSSION

Yettes Condjà

Measurements of surface movements carried out on the Yettes Condjà valley display spectacular differences between all three rock glaciers (Figure 8). The strongest movements are encountered on rgB, where annual horizontal surface velocities are up to 135 cm a^{-1} in the central part of the formation. RgC is also affected by movements, but to a much lesser extent. The orographic right-hand side, toward the frontal part, displays the greatest velocities (35 cm a^{-1}), whereas the left-hand side and the upper flat area appear to be more stable. Finally, no horizontal movement seems to affect rgD.

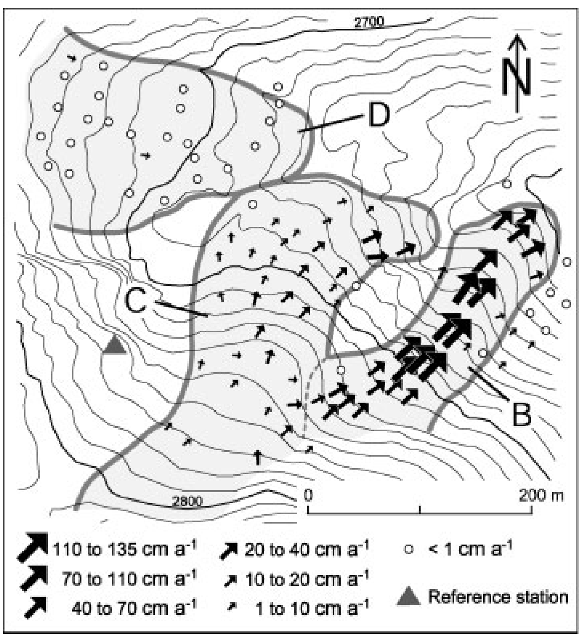

Figure 8 Mean annual horizontal surface velocities between 2000 and 2003 on the Yettes Condjà rock glaciers.

The comparison of these results with those obtained through geoelectrical prospecting shows that rgB has the lowest electrical resistivity and presents at the same time the strongest surface velocities (Lambiel *et al.*, 2003). On the other hand, rgC shows higher resistivities, but moves much more slowly than its neighbour does. Although the topographic conditions of rgB are certainly favourable to rapid displacements (the formation creeps on a steep (27°) and regular slope), this is certainly not sufficient to explain the marked differences in movement affecting the two rock glaciers.

As reported by many authors (e.g. Haeberli and Vonder Mühll, 1996; Arenson *et al.*, 2002; Ikeda *et al.*, 2003; Kääb *et al.*, 2003), rock glaciers with temperatures close to the thawing point creep faster than colder rock glaciers. The low resistivities, i.e. the low ice content and/or the relatively warm temperatures of the permafrost, could therefore explain the high velocities recorded on rgB. Moreover, considering the length of the formation (about 300 m), these high velocities (about 100 cm a^{-1} in the central part) would indicate, if the speed was constant, that the rock glacier could have developed in only 300 years. This is not reasonable if we consider that alpine active rock glaciers usually have an age of some thousands of years (see, e.g., Haeberli *et al.*, 1999). We can, on the other hand, imagine an acceleration of the formation consecutive to the atmospheric warming of the last decades. A thinning of the sedimentary body observable at the roots supports this assumption: the debris supply does not compensate the probable acceleration of the rock glacier. The lower velocities recorded on rgC are probably related to lower temperatures. It is possible that with increasing air temperature a large amount of latent heat is consumed at the permafrost table (where massive ice was identified), which could maintain relatively low temperatures in the rock glacier.

The strain rate pattern on rgB displays a succession of extension and compression zones from the roots towards the front of the rock glacier (Figure 9).

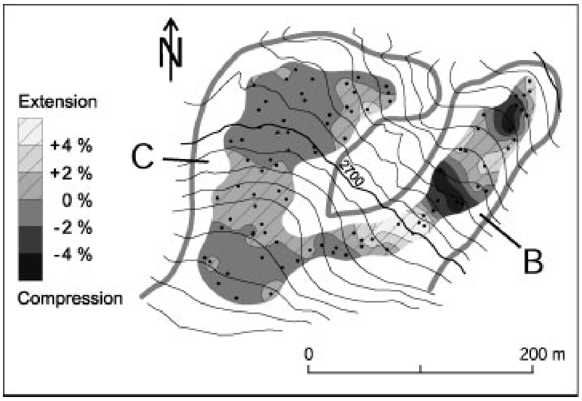

Figure 9 Compression and extension zones identified on Yettes Condjà rock glaciers B and C. Variation in percentage of the area of triangles between 2000 and 2003.

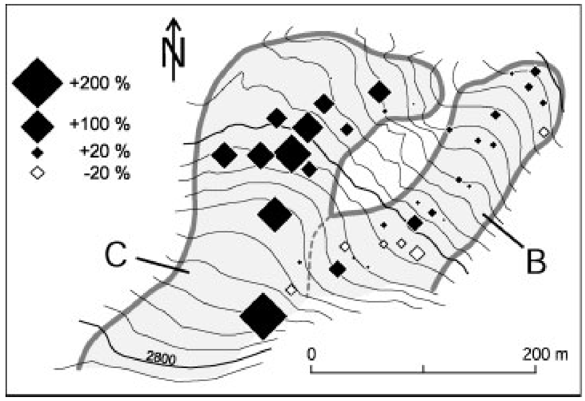

Figure 10 Changes in horizontal surface velocities between 2000–2001 and 2001–2003 on rock glaciers B and C in the Yettes Condjà valley.

Extensive flow evidenced at the roots can clearly be identified in the field as thinning of the sedimentary body. This corresponds to what was measured on other rock glaciers, namely that the roots display generally longitudinal extension and vertical thinning (see, e.g., Haeberli and Vonder Mühll, 1996). Downstream, a steeper and progressively concave slope coincides with compressive flow. The measurements carried out further down display a complex distribution of compressive and extensive zones, which is difficult to explain at the moment. A denser distribution of measurement points would give a better image of compression/extension zones on this part of the rock glacier.

On rgC, the amplitude of the compressive/extensive flow is not very pronounced, but its pattern is simple and corresponds to topographic and geomorphologic evidence. A compression zone is followed by an extension zone and a new compression zone from the upper part of the rock glacier up to the altitude of about 2680 m a.s.l. (Figure 9). The observation of the topography shows that the extension area corresponds more or less to a convex slope and that the compression zones correspond to concave slopes. Compressive flow is generally favourable to the development of ridges and furrows (see, e.g., Haeberli *et al.*, 1998; Kääb *et al.*, 1998). On this rock glacier, even if they are not extremely well developed, ridges and furrows are visible on the orographic left-hand part of the rock glacier where compressive flow occurs.

An estimation of the variation in thickness was carried out for rgB and rgC (cf. Table 1). For rgB the rock glacier slope (50%) and the inclination of the block movement between 2000 and 2001 (53%) are roughly the same. The rock glacier thickness has

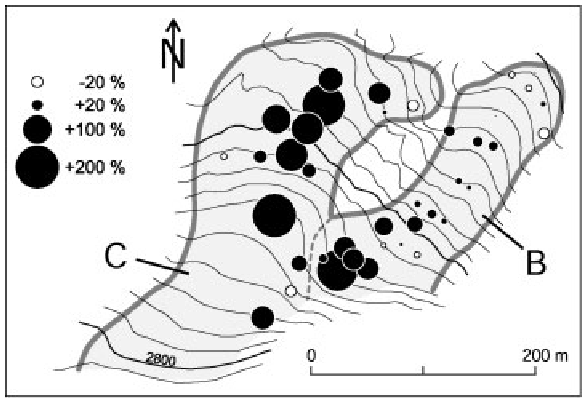

Figure 11 Variations of the changes in elevation between 2000–2001 and 2001–2003 on rock glaciers B and C in the Yettes Condjà valley.

certainly been more or less constant over those two years. This is not the case with rgC, where the measured blocks have lost more elevation than could be explained by the rock glacier slope. Indeed, the average block movement slope is 84% whereas the rock glacier gradient is only 45%. On the basis of this observation a loss of thickness seems to have occurred between 2000 and 2001, probably resulting from ice melting in the permafrost table.

The third measurement campaign permitted the variations in surface velocity (horizontal component, Figure 10) and in changes in elevation (vertical component, Figure 11) between 2000–2001 and 2001–2003 to be calculated. Thus, rgB displays a slight acceleration, both in the horizontal component (+10%) and in the vertical one (+20%, Table 2). The values are quite homogeneous over the formation,

Table 2 Mean changes between 2000–2001 and 2001–2003 in both horizontal and vertical components on rock glaciers B and C in the Yettes Condjà valley (only the points where horizontal surface velocities were higher than 5 cm a^{-1} were taken into consideration).

	dH 00–01 [cm a^{-1}]	Mean change in the horizontal component		dV 00–01 [cm a^{-1}]	Mean change in the vertical component	
		[cm a^{-1}]	[%]		[cm a^{-1}]	[%]
Rock glacier B	61.5	+4.7	+10	−32.4	−4.6	+20
Rock glacier C	12.1	+4.6	+50	−9.7	−4.3	+60

except at the roots where a slight deceleration seems to occur. Conversely, the loss of elevation here has increased very clearly (up to 180%). This may be interpreted as the result of thaw settlement. The lower rate of subsidence between 2001 and 2003 near the front of the rock glacier is difficult to interpret, but it may be partially related to the high velocity and the slight acceleration of the rock glacier that leads to a rapid and effective transportation of debris towards the front.

On rgC, the increase in surface movements between 2000–2001 and 2001–2003 is much more important than on rgB, both in the horizontal dimension (+50%) and the vertical (+60%) (cf. Table 2 and Figures 10 and 11). The stronger increase in the vertical component than in the horizontal one is evident (Figure 12), especially on the upper part, where massive ice is present directly under a few tens of centimetres of block cover.

The results obtained on the Yettes Condjà rock glaciers probably point to the large influence of climate variations on rock glacier dynamics and would be in accordance with Hoelzle *et al.* (1998), who observed that 'the velocity fluctuations are probably mainly caused by variations in permafrost temperatures'. Due probably to warm permafrost, rgB creeps with relatively high velocities, whereas changes in dynamics on rgC are probably delayed because of the large amount of latent heat that is consumed during the warming of massive ice present at the permafrost table. Finally, the changes in behaviour of rgB and rgC observed between 2001 and 2003 may be connected to the mild winter of 2002–2003 (Delaloye and Monbaron, 2003), which would have contributed to warming permafrost and to increase deformation velocity (a similar case is described by Ikeda *et al.* (2003) in the eastern Swiss Alps), and also the heat wave of summer 2003, which would have induced melting of ice at the permafrost table.

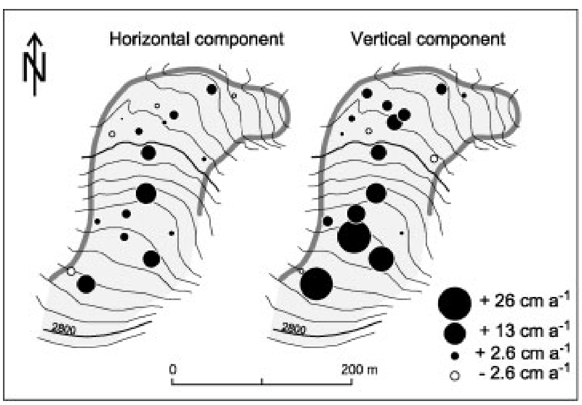

Figure 12 Changes in the horizontal (left) and the vertical (right) component between 2000–2001 and 2001–2003 at points where horizontal surface velocities were lower than 5 cm a^{-1} (rock glacier C, Yettes Condjà). For the vertical component, positive values have to be interpreted as an increasing loss of elevation.

Réchy

The two measurement campaigns carried out in Réchy revealed strong differences in surface movements between the two lobes of the rock glacier (Figure 13). The front of the largest one (L1) appears to be rather inactive, whereas the terminus of L2 exceeds 100 cm a^{-1} in velocity. Ridge L2b displays velocities of about 40–70 cm a^{-1}.

All surveyed blocks, except one, on L1 show horizontal velocities lower than 4.5 cm a^{-1} (most of the time even lower than 2 cm a^{-1}). Block movements on top of the front, when they occur, are generally directed towards the exterior of the formation, except a few appearing to move in the opposite direction. There is also a trend to a slight subsidence of the material (1–3 cm a^{-1}). These elements suggest both the absence of creep and a very slow settlement in this terminal part of the rock glacier. Most of the blocks located on the L1 front were also subject to 3D rotational movements of up to 2–3 cm (e.g. block 11 and block 06 in Figure 6), which is relatively

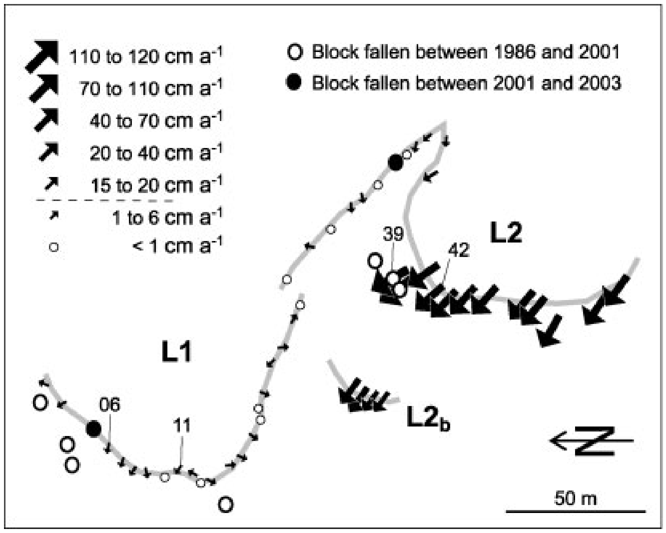

Figure 13 Mean annual horizontal velocities between 2001 and 2003 on top of the fronts of the Becs-de-Bosson rock glacier (Réchy). L1, L2 and L2b are frontal lobes of the rock glacier system.

important with respect to the general displacement of the blocks.

On lobe L2, most of the blocks painted in 1986 are still in place at the top of the front, in spite of a displacement of the rock glacier that may have reached 15–20 m on the basis of the speed observed between 2001 and 2003 (Figure 13). Moreover, the magnitude of the 3D rotational movement of the blocks was small, comparable to those on L1. The examples presented in Figure 6 (block 42 lying on the top of the front and block 39 currently located in the middle of the front, about 10 m below the summit edge) are representative of the movement recorded on the front of L2. The stability of the blocks could mean that the front of L2 moves rather uniformly, and that the top of the front does not move faster than its base. A hypothesis to explain this situation is that the shear zone could be currently located near the base of the rock glacier, even in the subjacent sediments that the rock glacier is progressively covering. This assumption is corroborated by the deformations affecting the sediments (L2b) located about 30 m downstream of L2.

The reason why L2 is active but L1 is not, is still unknown. Planned photogrammetric analyses will give further information on the particular dynamics of this complex rock glacier.

Aget

The two campaigns of RTK GPS measurements demonstrate the current activity of the frozen sediments lying on the left-hand valley side of the Aget glacier forefield (Figure 14). The flow pattern is mainly extending; however, the rate of surface extension remains low and values larger than +0.5% are only found in the uppermost part of the moving terrain, near the starting scar. As a geometric response to the extension flow, a loss of a few centimetres in thickness of the moving mass is thus to be expected in all the concerned area. Compression, leading to a potential thickening of the moving mass, is restricted to the eastern terminus of the deforming terrain.

The slope angle of the surface movements was compared with the topographical slope (assumed to be regular until the next point located downstream on a flow line). Most of the surveyed points showed a decrease in elevation, which was larger than that given by the estimated topographical slope as, for example, illustrated along three longitudinal profiles in Figure 7. For all the points on profile A, the slope angle of the observed movement was steeper than the topographical slope: in the middle part, the loss in elevation is estimated to have been 10–17 cm. These values appear to be clearly larger than those caused by the extension flow. On profile B, the third point (from the top) is located in a compression zone but shows a loss in elevation of 2 cm in comparison to the topographical slope, whereas a slight increase in elevation should have been observed in response to the compressing motion. The same analysis can be carried out for points 1, 3 and 4 (from top to bottom) on profile C. The observations made on the three profiles suggest

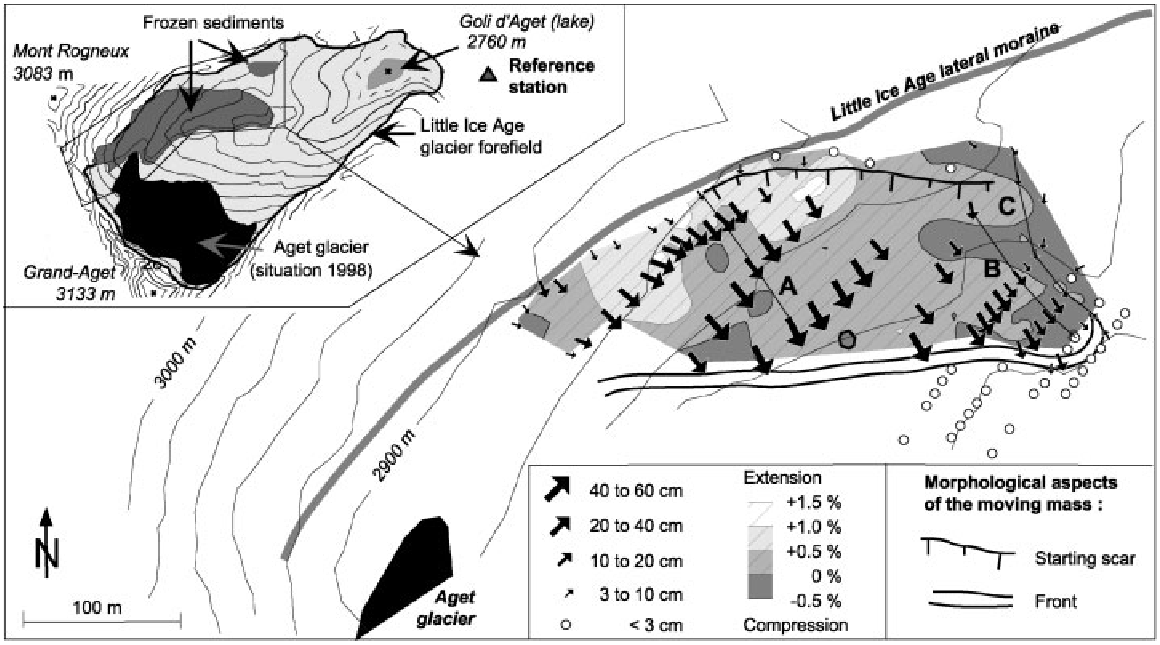

Figure 14 Measured horizontal surface velocities and determined extension/compression zones between October 2001 and July 2003 in the Aget glacier forefield. A–C indicate longitudinal profiles.

the occurrence of a slight settlement (a few centimetres) possibly due to ice melting in the ground.

Besides inducing a geometric thinning of the moving mass, extending flow is usually assumed to cause melting processes in the active layer: a thinning of the covering materials occurs, which leads to a deepening of the permafrost table as a thermal response (Haeberli and Vonder Mühll, 1996). Melting of ice lenses or a massive ice layer at the permafrost table can from then on provoke a subsidence of the ground surface elevation (Lugon *et al.*, 2004). Nevertheless, such a process seems not to act on the Aget site for at least two reasons. High resistivity layers, which can be interpreted as massive ice bodies, were not detected near the surface by means of DC resistivity measurements. Loss in elevation was also determined in areas of compressive flow. The excess subsidence observed at the surface of the moving mass may be caused by melting of relatively deep ice bodies in the ground, possibly associated with disturbance of the frozen sediments by Little Ice Age glacier advance.

CONCLUSIONS

RTK GPS has been shown to be an efficient tool for studying the dynamics of sedimentary bodies like active rock glaciers and moraine deposits. The rapidity and the ease of data acquisition and processing makes the use of this method valuable for monitoring the deformation of such terrains. The different measurements carried out within the framework of this study show that two successive annual campaigns of measurements permit surface movements, compression/extension zones and individual block movements to be determined with an accuracy of 2–3 cm, and even better in certain cases. A rough estimation of the thickness variation can also be obtained. The temporal evolution of surface movements can then be determined after a third measurement campaign. However, a sufficient number of points is absolutely necessary to get a good appreciation of the movements affecting the sedimentary bodies. Finally, the high precision of the RTK GPS revealed by the test carried out in Réchy shows that it is possible to work at scales definitely finer than with photogrammetry. The major weakness of the RTK GPS survey appears to be the lack of accurate information on thickness variation of the moving permafrost.

Among the most interesting geomorphological results obtained is the fact that two rock glaciers situated side by side in the Yettes Condjà valley display not only strong differences in their surface movements, but also strong differences in the temporal movement variation. This behaviour indicates that the reaction of permafrost to climate variations is largely dependant on the amount of ice present in the sediments. The evident acceleration of both rock glaciers in 2003, possibly due to the warm winter of 2002–2003, but also to the extremely warm summer of 2003, confirms what was already demonstrated in other studies (e.g. Ikeda *et al.*, 2003), that warming of permafrost leads to creeping acceleration. In Réchy, marked differences in surface velocities were recorded on two lobes of a same rock glacier. However, the 3D rotational movements of blocks situated at the top of the front were small on the two lobes. On the rapidly moving lobe L2, this could indicate a rather uniform motion of the whole front. Finally, the measurements carried out in Aget permitted the re-equilibrating movement affecting a part of a frozen Little Ice Age glacier forefield to be quantified. They also suggested the thawing of ice in the ground.

PERSPECTIVES

The behaviour of permafrost creeping features observed in this study is probably not unique. In order to better understand the dynamics of frozen sedimentary bodies like rock glaciers and moraine deposits and to follow the impacts of global atmospheric warming on permafrost, a monitoring of the surface movements using the RTK GPS will be continued on the terrains described in this study and undertaken on other study sites. To better discern the influence of the climatic conditions on the dynamics of rock glaciers, measurements carried out seasonally, i.e. at least at the beginning and at the end of the summer season, should be undertaken. Moreover, the lack of points on some parts of the prospected terrains posed some problems for the interpretation of the results obtained. An improvement on the survey strategy, for example a better definition of the point network, would be necessary in some cases. Another contribution would be the systematic survey of longitudinal profiles including a large number of points (one every 10–20 metres). This should provide better information on changes in thickness of the creeping mass with time. The detailed analysis of the variation of horizontal and vertical components would probably also reveal important information on the variation of thickness (e.g. thaw settlement) of creeping permafrost. Finally, combining photogrammetry with GPS seems to be a promising method to analyse and monitor permafrost creep, in the sense that results of the photogrammetry analysis will cover larger areas at a several year interval, whereas GPS survey permits small movements at a seasonal timescale in smaller areas or for a restricted number of points to be determined.

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