SURFACE DEFORMATION OF CREEPING MOUNTAIN PERMAFROST. PHOTOGRAMMETRIC INVESTIGATIONS ON MURTÈL ROCK GLACIER, SWISS ALPS

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Abstract

Computer-aided aerial photogrammetry is applied to analyse surface topography and surface kinematics, i.e., changes in elevation and horizontal surface velocities, on Murtèl rock glacier (Swiss Alps) over the period of 1987 to 1996. Together with measurements of three-dimensional borehole deformation, the area-wide information about surface kinematics is used to estimate the magnitude of different components of the kinematic boundary condition at the surface. Analysis of surface kinematics along a longitudinal profile, which was measured with high spatial resolution, shows that transverse ridges on Murtèl rock glacier propagate down stream with a velocity which approximately equals that of the surface rocks. The first appearance of the transverse ridges coincides with a point of a marked decrease in average slope. The subsequent increase in ridge amplitude seems to be related to general longitudinal compression. The formation and growth of transverse ridges towards their maximum amplitude takes several millennia.

Introduction

Beside their thermal and mechanical material properties, active rock glaciers are essentially defined by their kinematics. Surface topography and surface kinematics can be analysed in detail with photogrammetric methods. In conjunction with other studies, knowledge of surface kinematics substantially helps the understanding of the dynamic processes of creeping permafrost. To reach this goal, investigations using a combination of techniques, concentrated on selected rock glaciers, seem to be very promising.

Murtèl rock glacier in the Upper Engadin, Grisons, Swiss Alps (Figure 1) is a good candidate for such investigations, because various information is available for it. Measurements in a borehole drilled through the permafrost of the rock glacier in 1987 have given valuable information about its internal structure and deformation(for summary cf. Haeberli et al., 1998a). Geophysical investigations have provided findings about the stratification of the creeping permafrost (Vonder Mühll, 1993). Murtèl rock glacier is part of the Swiss permafrost monitoring network (Haeberli et al., 1993). The first photogrammetric investigations on it were carried out by Barsch and Hell (1976). Recent high-resolution measurements of surface kinematics over the period of 1987 to 1996 by means of computer-aided photogrammetry represent a further step towards understanding of the creep of Murtèl rock glacier.

Kinematic boundary condition at the surface

Surface kinematics of creeping permafrost can be understood and analysed by using the kinematic boundary condition at the surface. This condition describes all components influencing surface kinematics. For the three-dimensional case the kinematic boundary condition at any surface point is

$$b = \frac{\partial h}{\partial t} + v_x^{\ s} \frac{\partial h}{\partial x} + v_y^{\ s} \frac{\partial h}{\partial y} - v_z^{\ s} \qquad [1]$$

with mass balance at the surface b, surface altitude h, change in surface elevation with time $\partial h/\partial t$, the hori-
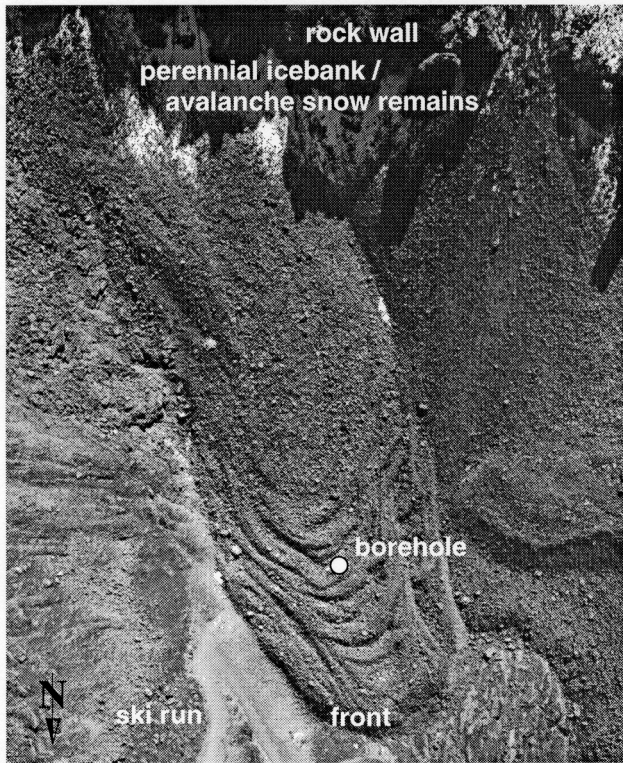
Figure 1 Aerial photograph of Murtèl rock glacier, taken by the Federal Office of Cadastral Surveys in 1996.
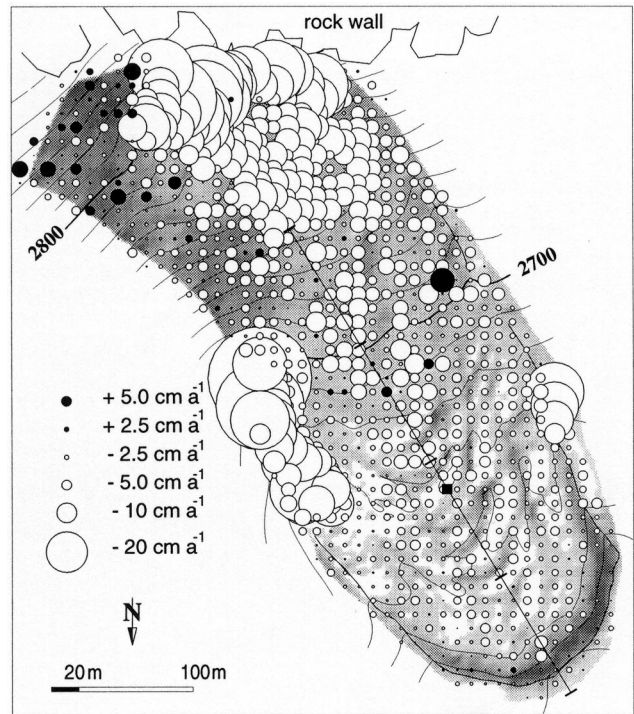

Figure 2 Changes in surface elevation over the period of 1987 - 1996. Results smoothed from a 5 m-grid and resampled to 10 m-grid. Borehole marked as rectangle. Location of the longitudinal profile Figure 6.

zontal velocity components v_x and v_y of the three-dimensional velocity vector $\mathbf{v} = (v_x, v_y, v_z)^T$ the surface slope components $\partial h/\partial x$ and $\partial h/\partial y$ and the vertical velocity at the surface v_z^s (cf. Hutter, 1983; Paterson, 1994).

The vertical velocity at the surface is

$$v_z^{\,s} = \int_{z^b}^{h} \frac{\partial v_z}{\partial z}\,dz + v_z^{\,b} \qquad [2]$$

with the vertical velocity at the basal layer V_z^b where $v = 0$ for $z < z_b$. Thus, with the vertical strain rate

$$\dot{\varepsilon}_{zz} = \frac{\partial v_z}{\partial z}$$

, Equation (2) can be written as

$$v_z^{\,s} = v_x^{\,b} \frac{\partial z^b}{\partial x} + v_y^{\,b} \frac{\partial z^b}{\partial y} + \int_{z^b}^{h} \dot{\varepsilon}_{zz}\,dz \qquad [3]$$

Assuming incompressibility of permafrost

$$\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy} + \dot{\varepsilon}_{zz} = 0 \qquad [4]$$

the vertical velocity at surface v_z^s can be written as

$$v_z^{\,s} = v_x^{\,b} \frac{\partial z^b}{\partial x} + v_y^{\,b} \frac{\partial z^b}{\partial y} - \int_{z^b}^{h} \dot{\varepsilon}_{xx}\,dz - \int_{z^b}^{h} \dot{\varepsilon}_{yy}\,dz \qquad [5]$$

All terms of Equation (1) are related to the surface only. Therefore, surface mass balance b represents the sum of all thawing and freezing processes of ground ice as well as other mass changes like sediment loss or accumulation which result in a corresponding change in surface elevation. The kinematic boundary condition at the surface does not comprise internal mass variations having no influence on surface elevation or flow regime. Furthermore, structured permafrost - in contrast to massive ice or supersaturated permafrost - mignt not be incompressible, in which case Equations (4) and (5) may not be exactly fulfilled. All terms on the right hand side of Equation (1), except the vertical velocity at surface v_z^s, can be determined by means of aerial photogrammetry.

Velocity field 1987-1996

In order to investigate the surface kinematics of Murtèl rock glacier, regular-gridded digital terrain models (DTM) of 1987 and 1996 were determined. For this purpose aerial photographs taken by the Federal Office of Cadastral Surveys were used (Figure 1, 11 September 1996, line 066155, photo 2435). The differences between the multitemporal DTMs give the
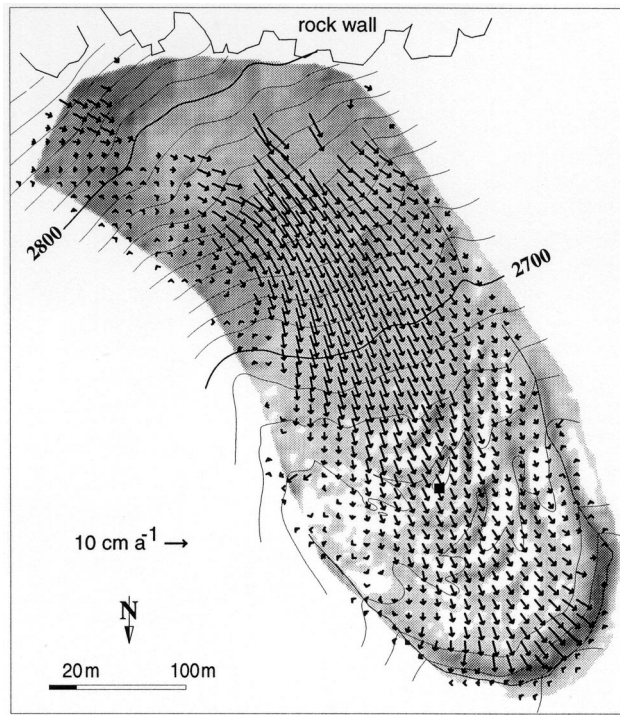
Figure 3 Horizontal surface velocities 1987 - 1996 measured with 10 m regular grid distance.

Figure 5 Horizontal (left) and vertical (right) surface strain rates 1987-1996, derived from the velocity field. Vertical strain rates calculated from the horizontal ones assuming incompressibility of the permafrost.

changes in elevation at every DTM-point ($\partial h/\partial t$). The accuracy of a single vertical surface variation with time is around ± 1-2 centimetres per year (cm a^{-1}). Over the period 1987-1996 the surface of the rock glacier lowered by around 4 cm a^{-1} on average, and much more on perennial ice banks in the upper and right part of the rock glacier, (Figure 2). Surface rise in the upper left part is assumed to be due to debris accumulation from the rock wall. The increase in surface elevation at the rock glacier front indicates an advance rate of approximately 1 cm a^{-1} over 1987-1996 (Kääb, 1998).

The horizontal surface velocities ($\mathbf{v_{hz}}^s = (v_x{}^s, v_y{}^s)^T$) on Murtèl rock glacier over the period 1987-1996 were determined by simultaneously comparing two aerial photographs taken at different times and from different
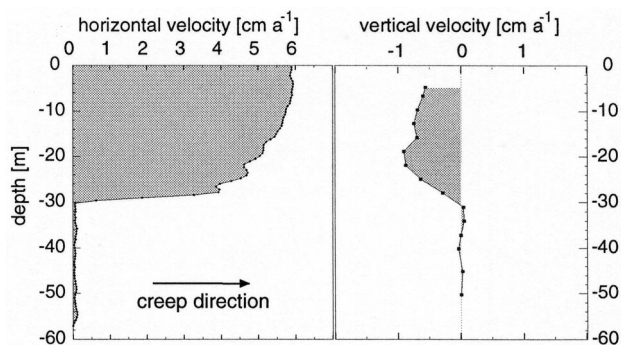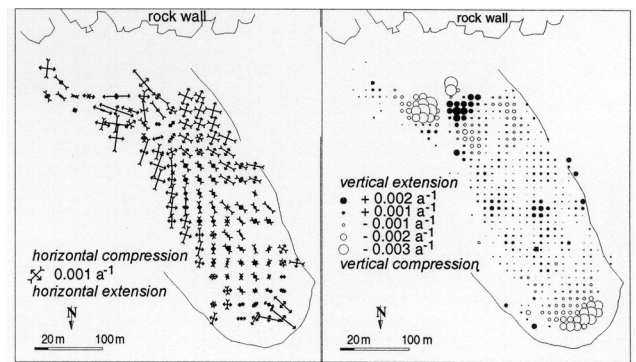

Figure 4 Borehole measurements: Vertical profile of average horizontal creep velocities 1987-1994 from inclinometer measurements (left). Vertical velocity profile from magnetic-ring measurements 1987-1996 (right).

positions (Kääb, 1996; Kääb et al., 1998). The accuracy of a single horizontal surface velocity is about ± 1-2 cm a^{-1}. Over the investigated period, the horizontal creep rates at the surface amount up to 15 cm a^{-1} in the steep upper part and decrease to about 5 cm/a in the flat lower part (Figure 3). The observed velocity increase towards the rock glacier front may be related to the increase in slope. However, the measurements seem to be affected to some extent by debris sliding along the surface down the front. The velocity field points to the existence of two dynamically different parts of the creeping permafrost: (1) high velocities and transverse surface buckling indicate high activity in the inner part; (2) low velocities and lack of significant surface structures suggest lower activity in the left and right marginal (cf. Figure 1).

Borehole inclinometer measurements by Wagner (1996) together with more recent measurements (Figure 4 left) show that about 2/3 of the observed horizontal surface velocity at the borehole site are due to deformation in a shear zone of frozen sand at a depth of 28-30m ($h - z^b = 30$ m). The remaining one third of the total horizontal movement occurs in the upper layer (3-28 m depth), which consists of nearly massive ice (cf. Figure 8; Vonder Mühll, 1993). At the lower margin of the shear zone ($z = 30$ m) no significant horizontal deformation can be observed ($v_{hz}{}^b = 0$). The shear horizon is roughly parallel to the average surface slope

$$\left(\frac{\partial z^b}{\partial x} \approx \frac{\partial h}{\partial x} \quad \text{etc.; Vonder Mühll, 1993} \right).$$

Surface deformations of creeping permafrost can be best understood by analysing the strain rates. Using a method developed by Gudmundsson (Kääb et al., 1998) the horizontal surface strain rates ($\dot{\varepsilon}_{xx}{}^s = \frac{\partial v_x{}^s}{\partial x}$ etc.) were derived from the surface velocity field. Assuming incompressibility of the permafrost the vertical surface strain rates can be obtained from the
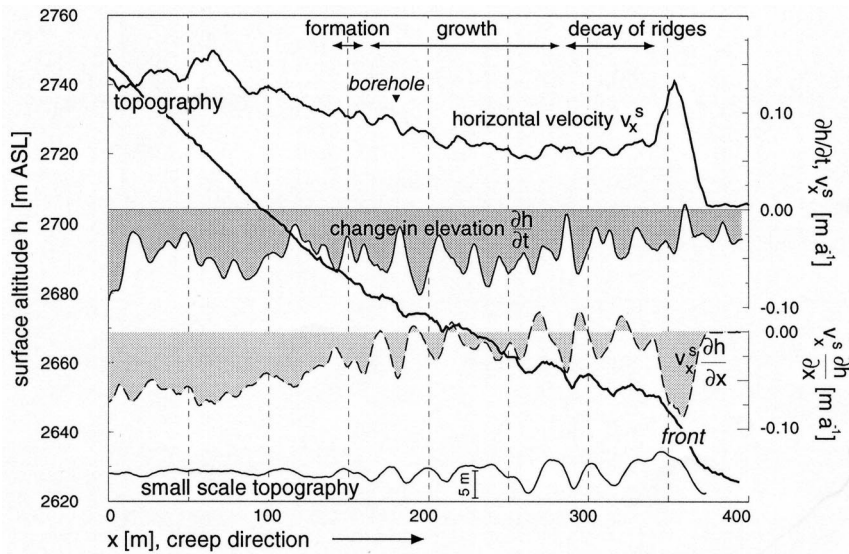
Figure 6 Longitudinal profile of rock glacier surface, surface velocities and derived kinematic quantities 1987-1996. The photogrammetric profile measurements have a spatial resolution of 1 m. Surface topography depicted with two times exaggeration. Small scale topography defined as difference between surface topography at each point and a running average over 200 m (four times exaggeration).

horizontal ones using Equation (4). The decrease of surface velocities towards the margins of Murtèl rock glacier (Figure 3) causes typical horizontal strain rates with 45°-rotation of the strain-rate tensor with respect to the flow direction (Figure 5 left). Increasing velocity at the front leads to horizontal extension and vertical compression, respectively (Figure 5). Horizontal extension prevails in the upper part and horizontal compression in the lower part. The surface strain rates determined are of the same order of magnitude as on other Alpine rock glaciers (Kääb et al., 1998; Kääb, 1998). The related strain rate pattern shows general similarity to that on Arapaho rock glacier (White, 1987).

From magnetic ring measurements of vertical velocities by Wagner (1996), together with more recent measurements in the Murtèl borehole (Figure 4, right), the vertical velocity v_z^s at the borehole site is known. Over the period 1987-1996 a vertical velocity at the surface of about 0.5 cm a^{-1} on average could be observed. The variation of vertical velocities and strain rates is not a simple function of depth (cf. Wagner, 1996; Hoelzle et al., 1998). Therefore, the total vertical strain at surface cannot be calculated from the strain rates at the surface. However, the surface strain rates are useful to estimate the order of magnitude and spatial variations of the total vertical strain at surface $\int_{zb}^{h} \varepsilon_{zz}\ dz$, needed in Equation (3) and Equation (5), respectively.

For the borehole site, all right hand side components of the kinematic surface boundary condition Equation (1) are known at Murtèl rock glacier. Thus, the mass balance b can be calculated. With $\partial h/\partial t$ = -5 cm a^{-1},

v_{hz}^s = 6 cm a^{-1}, surface slope in flow direction 10° and v_z^s = -0.5 cm a^{-1}, an average mass balance over the period 1987-1996 of about -5 cm a^{-1} can be calculated. It turns out that the numerical values for b and $\partial h/\partial t$ are the same within the measurement accuracy. Of course, this is not a general rule because changes in surface elevation are not only affected by b but also by properties of the flow regime $\left(v_z^{\ s}, v_x^{\ s}\ \dfrac{\partial h}{\partial x} \right)$. In fact, all components of the kinematic boundary condition at the surface are of the same order of magnitude at the borehole site. Elevation change cannot be equated to mass balance (cf. Haeberli and Schmid, 1988). Owing to the kinematic inertia of creeping mountain permafrost reducing short-term variations of vertical velocity (Haeberli, 1985), short-term variations of surface elevation may mostly be caused by mass balance changes (climate impact) and advecting surface topography (see next section). In contrast, spatial variations of $\partial h/\partial t$ may be noticeably influenced by spatial variations of the flow regime (Kääb, 1998).

Transverse ridges

For detailed studies of surface kinematics and microtopography on Murtèl rock glacier surface topography, horizontal velocities and changes in surface elevation 1987-1996 were measured with a resolution of 1 m along a profile approximately following the central flow line through the borehole position (Figures 2 and 6).

The surface topography profile (Figure 6) clearly shows the transverse ridges on the lower part of Murtèl
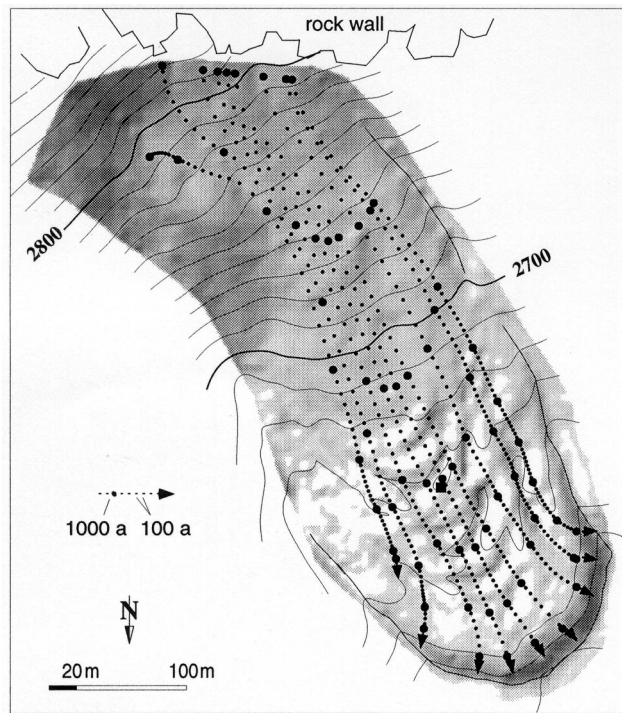
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Figure 7 Selected stream lines at the surface, interpolated from the velocity field 1987-1996.
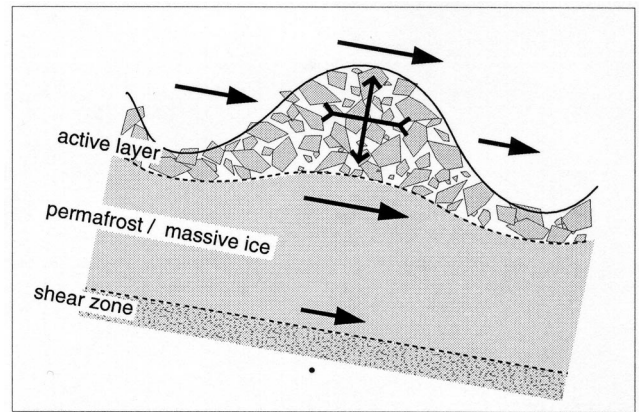

Figure 8 Schematic longitudinal cross section of a transverse ridge and the upper permafrost zone. Longitudinal compression causes vertical extension, over-compensating diffusion and erosion, and, therefore, may lead to the growth of transverse ridges.

rock glacier. In contrast, the surface of the upper part shows no such features. The longitudinal surface slope in general decreases along flow direction towards the steep front from about 20° in the upper part to about 10° in the lower part. The small- scale topography was defined as the difference between the measured altitude at each point and the running average over 200 m (Figure 6). The wavelength of the transverse ridges is about 20 m, their amplitude up to 3.5 m (total height from furrow bottom to ridge top up to 7 m, respectively). The longitudinal horizontal velocities (v_x^s), in general, show a velocity increase in the upper part of the profile and a decrease from x = 70 m to x = 270 m. From the point x = 270 m down to the steep front, no marked changes in horizontal surface velocities can be observed. (Cf. the section above for the velocity increase at the front). Spatial variations in horizontal velocity seem to be roughly correlated with the small-scale topography.

The close correlation of $\partial h/\partial t$ and $v_x^s \dfrac{\partial h}{\partial x}$ (Figure 6) indicates that the transverse ridges on Murtèl rock glacier propagate down stream with a velocity which approximately equals that of the creeping permafrost. The other terms in Equation (1) are small or have a lower spatial variation frequency and, thus, seem not to have clear influence on the above mentioned correlation. Moreover, the vertical borehole profile of horizontal velocities (Figure 4 left) shows no significant horizontal deformation in the uppermost zone, and there-

fore confirms the determined propagation process of the transverse ridges.

Stream lines were calculated from the surface velocity field 1987-1996 (Figure 7; Kääb, 1996). Assuming steady state conditions these stream lines represent the trajectories of specific particles on the surface. Thus, they can be used for rock glacier age estimates (Kääb, 1996; Haeberli et al., 1998a; Kääb, 1998). The steady state assumption seems to be justified by the fact that the curvature of the isochrones (represented by dots of same age) is similar to the curvature of the transverse ridges. The development of the ridges on Murtèl rock glacier, as far as they are visible, takes up to several millennia. The wavelength of about 20 m corresponds with an age difference of the ridges of about 300 to 400 years.

As the ridges are advected down stream three regions of formation, growth and decay can be identified (Figure 6). The first clear appearance of transverse ridges is below the point of change in average surface slope (x = 150 m). It should be noted that longitudinal compression is found to prevail well above this point. The exact role of the change in surface slope and the longitudinal compression in the formation of the ridges is not clear. In particular, it can hardly be said that longitudinal compression alone is the sole factor in initiating ridges. However, the compression flow region over the following 130 m (x = 150 m to x = 280 m) could be responsible for the growth of the ridges (Figure 8), as their height continues to grow up to about 7 m over a time period of approximately 3000 years (Figure 7). A horizontal compression of 0.001 a^{-1} - which prevails in the zone of ridge growth - of a block of incompressible material of 2 m thickness (cf. following paragraph) over the time of 3000 years, gives a total vertical growth of 6 m. Although the process of ridge formation and growth is not clear, this estimate shows that the measured longitudinal compression may cause vertical

extension of the same order of magnitude as the observed growth of the ridges. Over the next 80 m, the longitudinal strain decreases and with it the amplitudes of the ridges. Together, this suggests that the growth and the decay of surface ridges coincides with longitudinal compression and extension, respectively (cf. White, 1987). The circumstances of ridge formation at Murtèl rock glacier show some interesting relations to theoretical predictions on surface by Loewenherz et al. (1989). However, one should note that the transient development of the ridges may not only be a result of viscous deformation, but that differential ablation and accumulation related to differences in slope and snow coverage must also be expected to play a role.

Geophysical soundings have shown that the undulations are mostly limited to the active layer, although the underlying massive ice layer is also affected to some extent (Figure 8). The thickness of the active layer ranges from 5 m within the ridges down to about 0.5 m in the furrows, 2 m on average and 3 m at the borehole (Barsch, 1973; Vonder Mühll, 1993).

Conclusions and perspectives

Computer-aided aerial photogrammetry allows for detailed determination and analysis of surface topography, changes in elevation and horizontal surface velocities on Murtèl rock glacier, Swiss Alps, over the period of 1987 to 1996. Temporal changes in surface elevation over the observation period average about -5 cm a^{-1}, horizontal velocities range from 15 down to 5 cm a^{-1}. Given the error estimate of ±1-2 cm a^{-1} for the photogrammetrical measurements, the order of magnitude

of most results appears to be significant. The obtained uniform spatial patterns confirm the significance of the measurements.

At the borehole site, the contributions of the various terms of the kinematic boundary condition to the changes in elevation with time could be estimated. It turns out that all terms are of similar magnitudes (cm a^{-1}) and that height changes are not only related to mass balance, but also to the properties of the flow regime. This becomes particularly evident at small spatial scales (10^{-1}-10^1 m) where temporal elevation changes are primarily due to advection of surface undulations.

A number of transverse ridges is observed on the lower part of the rock glacier. They are advected down stream with a velocity approximately equal to the velocity of the creeping permafrost. Although the detailed mechanism behind the formation of ridges is not clear, changes in mean surface slope seem to play a role. The zone of growth of the surface ridges coincides with a region of longitudinal compression.

Acknowledgments

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