

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

Andreas Käab¹, G. Hilmar Gudmundsson², Martin Hoelzle³

1. Department of Geography, University of Zurich – Irchel, Winterthurerstrasse 190
CH-8057 Zurich, Switzerland
kaeab@geo.unizh.zh

2. 3. Laboratory for Hydraulics, Hydrology and Glaciology (VAW), ETH Zentrum
CH-8092 Zurich, Switzerland
2. hilmar@vaw.baum.ethz.ch
3. hoelzle@vaw.baum.ethz.ch

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.

KEY WORDS: rock glacier, creep, deformation, ridges, photogrammetry

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 some selected rock glaciers, seem to be most 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 rock glacier Murtèl in 1987 have given valuable information about the internal structure and deformation within the rock glacier (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). First photogrammetric investigations on Murtèl rock glacier 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 rock glacier Murtèl.

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

$$b = \frac{\partial h}{\partial t} + v_x^s \frac{\partial h}{\partial x} + v_y^s \frac{\partial h}{\partial y} - v_z^s \quad (1)$$

with mass balance at the surface b , surface altitude h , change in surface elevation with time $\partial h / \partial t$, the horizontal 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

$$v_z^s = \int_{z^b}^h \frac{\partial v_z}{\partial z} dz + v_z^b \quad (2)$$

with the vertical velocity at the basal layer v_z^b where $\mathbf{v} = 0$ for $z < z^b$. Thus, with the vertical strain rate $\dot{\epsilon}_{zz} = \frac{\partial v_z}{\partial z}$, Equation (2) can be written as

$$v_z^s = v_x^b \frac{\partial z^b}{\partial x} + v_y^b \frac{\partial z^b}{\partial y} + \int_{z^b}^h \dot{\epsilon}_{zz} dz \quad (3)$$

Assuming incompressibility of permafrost

$$\dot{\epsilon}_{xx} + \dot{\epsilon}_{yy} + \dot{\epsilon}_{zz} = 0 \quad (4)$$

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

$$v_z^s = v_x^b \frac{\partial z^b}{\partial x} + v_y^b \frac{\partial z^b}{\partial y} - \int_{z^b}^h \dot{\epsilon}_{xx} dz - \int_{z^b}^h \dot{\epsilon}_{yy} dz \quad (5)$$

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 evacuation 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 might - in contrast to massive ice or supersaturated permafrost - 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 rock glacier Murtèl, 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

DTM's give the 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 rock glacier Murtèl lowered by around 4 cm a^{-1} on average, on perennial ice banks in the upper and right part of the rock glacier, however, considerably more (Figure 2). Surface lifting 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 ($\mathbf{v}_{\text{hz}}^s = (v_x^s, v_y^s)^T$) on rock glacier Murtèl over the period 1987-1996 were determined by simultaneously comparing two aerial photographs taken at different times and from different 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^{-1} 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 point to lower activity in the left and right margin parts (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 ($h - z^b = 30\text{m}$). The remaining one third of the total horizontal movement occurs in the upper layer (3-28m depth), which consists of nearly massive ice (cf. Figure 8; Vonder Mühll, 1993). At the lower margin of the shear zone ($z=30\text{m}$) no significant horizontal deformation can be observed ($v_{\text{hz}}^b = 0$). The shear horizon is roughly parallel to the average surface slope ($\frac{\partial z^b}{\partial x} \approx \frac{\partial h}{\partial x}$ etc.; Vonder Mühll, 1993).

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 ($\dot{\epsilon}_{xx}^s = \frac{\partial v_x^s}{\partial x}$ etc.) were derived from the surface velocity field. Assuming incompressibility of the permafrost the vertical surface strain rates can be obtained from the 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 for Murtèl rock glacier 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 can not 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 ($\int_{z^b}^h \dot{\epsilon}_{zz} dz$), requested 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 $\partial h/\partial t = -5 \text{ cm a}^{-1}$, $v_{hz}^s = 6 \text{ cm a}^{-1}$, surface slope in flow direction 10° and $v_z^s = -0.5 \text{ cm a}^{-1}$, 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 (v_z^s , $v_x^s \frac{\partial h}{\partial x}$).

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 noticeable influenced by spatial variations of the flow regime (Kääb, 1998).

TRANSVERSE RIDGES

For detailed studies of surface kinematics and micro-topography on Murtèl rock glacier surface topography, horizontal velocities and changes in surface elevation 1987-1996 were measured with a resolution of 1m 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 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 200m (Figure 6). The wavelength of the transverse ridges is about 20 m, their amplitude up to 3.5m (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 $x=70\text{m}$ to $x=270\text{m}$. From the point $x=270\text{m}$ down to the steep front no marked changes in horizontal surface velocities can be observed. (Cf. the above section 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 $v_x^s \frac{\partial h}{\partial x}$ (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, therefore, 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 ($x=150\text{m}$). 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 ($x=150\text{m}$ to $x=280\text{m}$) could be made responsible for the growth of the ridges (Figure 8), as their height continues to grow up to about 7m 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 2m thickness (cf. following paragraph) over the time of 3000 years, gives a total vertical growth of 6m. 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 5m within the ridges down to about 0.5m in the furrows, 2m on average and 3m 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 to about -5 cm a^{-1} , horizontal velocities range from 15 down to 5 m a^{-1} . With respect to the error estimate of $\pm 1\text{-}2\text{ cm a}^{-1}$ 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 drill 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 ($10^1\text{-}10^1\text{ m}$) 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.

ACKNOWLEDGEMENTS

Special thanks are due to Wilfried Haeblerli and Urs Fischer for critical discussions on the presented work and the manuscript. The photogrammetric investigations are based on photographs taken by the Federal Office of Cadastral Surveys. The analysis of the photographs was carried out at the Laboratory for Hydraulics, Hydrology and Glaciology, ETH Zurich.

REFERENCES

- Barsch, D.** (1973): Refraktionsseismische Bestimmungen der Obergrenze des gefrorenen Schuttkörpers in verschiedenen Blockgletschern Graubündens. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **4**(1-2), 143-167.
- Barsch, D. and Hell, G.** (1976): Photogrammetrische Bewegungsmessung am Blockgletscher Murtel I, Oberengadin, Schweizer Alpen. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **11**(2), 111-142.
- Haerberli, W.** (1985): Creep of mountain permafrost. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich*, **77**, 142pp.
- Haerberli, W. and Schmid, W.** (1988): Aerophotogrammetrical monitoring of rock glaciers. In *Proceedings, Fifth Internat. Conference on Permafrost*, Trondheim, Norway, Vol 1, 764-769.
- Haerberli, W., Hoelzle, M., Keller, F., Schmid, W., Vonder Mühll, D. and Wagner, S.** (1993): Monitoring the long-term evolution of mountain permafrost in the Swiss Alps. In *Proceedings, Sixth Internat. Conference on Permafrost*, Beijing, China, Vol 1, 214-219.
- Haerberli, W., Hoelzle, M., Kääb, A., Keller, F., Vonder Mühll, D. and Wagner, S.** (1998a, submitted): Ten years after drilling through the permafrost of the active rock glacier Murtèl, Eastern Swiss Alps: answered questions and new perspectives. *7th International Conference on Permafrost*.
- Haerberli, W., Kääb, A., Wagner, S., Geissler, P., Haas, J.N., Glatzel-Mattheier, H., Wagenbach, D. and Vonder Mühll, D.** (1998b, in press): Pollen analysis and ¹⁴C-age of moss remains recovered from a permafrost core of the active rock glacier Murtèl/Corvatsch (Swiss Alps): geomorphological and glaciological implications. *Journal of Glaciology*.
- Hoelzle, M., Wagner, S., Kääb, A. and Vonder Mühll, D.** (1998, submitted): Surface movement and internal deformation of ice-rock mixtures within rock glaciers in the Upper Engadin, Switzerland. *7th International Conference on Permafrost*.
- Hutter, K.** (1983): Theoretical Glaciology. *D. Reidel Publishing Company*.
- Kääb, A.** (1996): Photogrammetrische Analyse zur Früherkennung gletscher- und permafrostbedingter Naturgefahren im Hochgebirge. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich*, **145**, 182pp.
- Kääb, A.** (1998, in press): Oberflächenkinematik ausgewählter Blockgletscher des Oberengadins. *Jahrestagung 1997 der Schweizerischen Geomorphologischen Gesellschaft*.
- Kääb, A., Haerberli, W. and Gudmundsson, G.H.** (1998, in press): Analyzing the creep of mountain permafrost using high precision aerial photogrammetry: 25 years of monitoring Gruben rock glacier, Swiss Alps. *Permafrost and Periglacial Processes*.
- Loewenherz, D.S., Lawrence, C.J. and Weaver, R.L.** (1989): On the development of transverse ridges on rock glaciers. *Journal of Glaciology*, **35**(121), 383-391.
- Paterson, W.S.B.** (1994): *The physics of glaciers*. Pergamon Press, Oxford.
- Vonder Mühll, D.** (1993): Geophysikalische Untersuchungen im Permafrost des Oberengadins. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich*, **122**, 222pp.
- Wagner, S.** (1996): Dreidimensionale Modellierung zweier Gletscher und Deformationsanalyse von eisreichem Permafrost. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich*, **146**, 135pp.
- White, S.E.** (1987): Differential movement across ridges on Arapaho rock glaciers, Colorado Front Range, USA. In Giardino J.R., Shroder F. and Vitek J.D. (eds.), *Rock glaciers*. Allen & Unwin, London, pp 145-149.

FIGURES

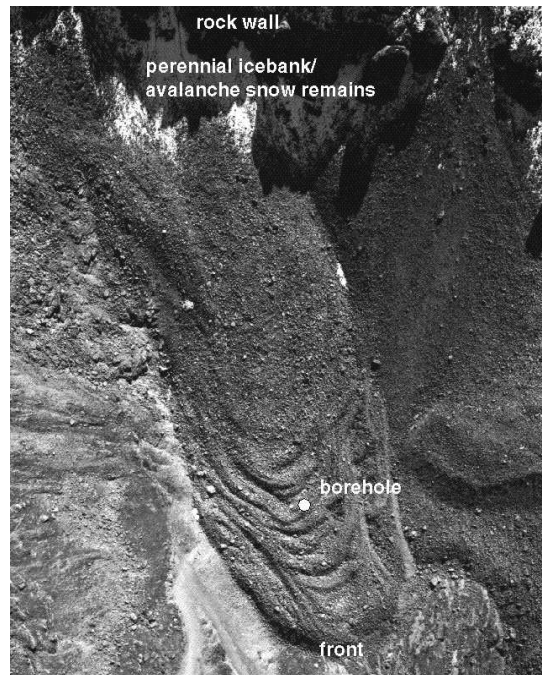


Figure 1 Aerial photograph of rock glacier Murtèl, taken by the Federal Office of Cadastral Surveys in 1996.

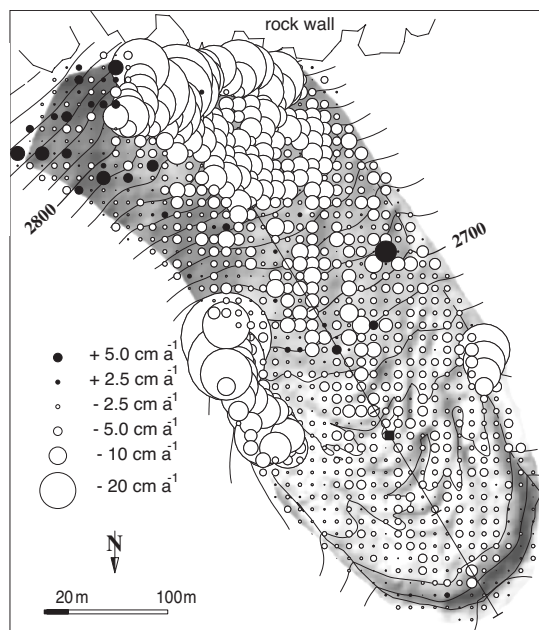


Figure 2 Changes in surface elevation over the period of 1987 - 1996. Results smoothed from a 5m-grid and resampled to 10m-grid. Borehole marked as rectangle. Location of the longitudinal profile Figure 6.

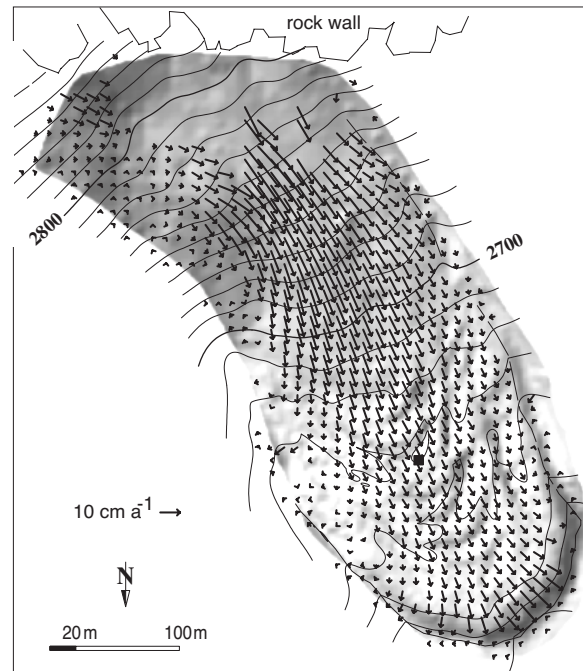


Figure 3 Horizontal surface velocities 1987 - 1996 measured with 10m regular grid distance.

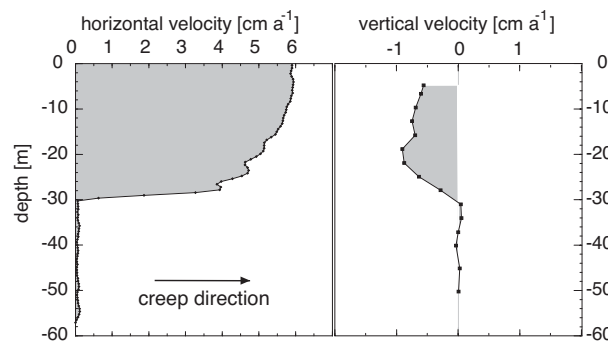


Figure 4 Borehole measurements: Vertical profile of average horizontal creep velocities 1987 - 1994 from inclinometer measurements (left). Vertical velocity profile from magnetic-ring measurements 1987-1996 (right).

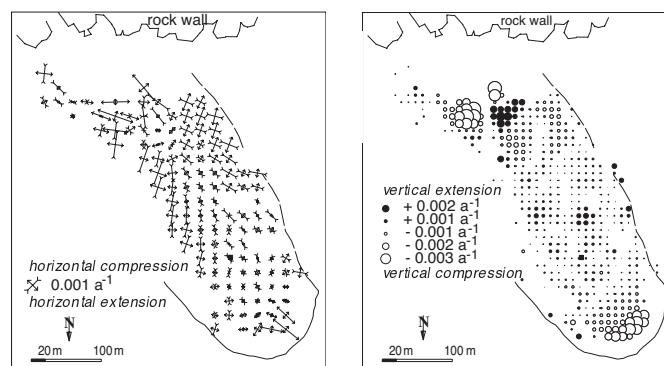


Figure 5 Horizontal (left) and vertical (right) surface strain rates 1987-1996, derived from the velocity field. Vertical strain rates calculated from the horizontal ones assuming incompressibility of the permafrost.

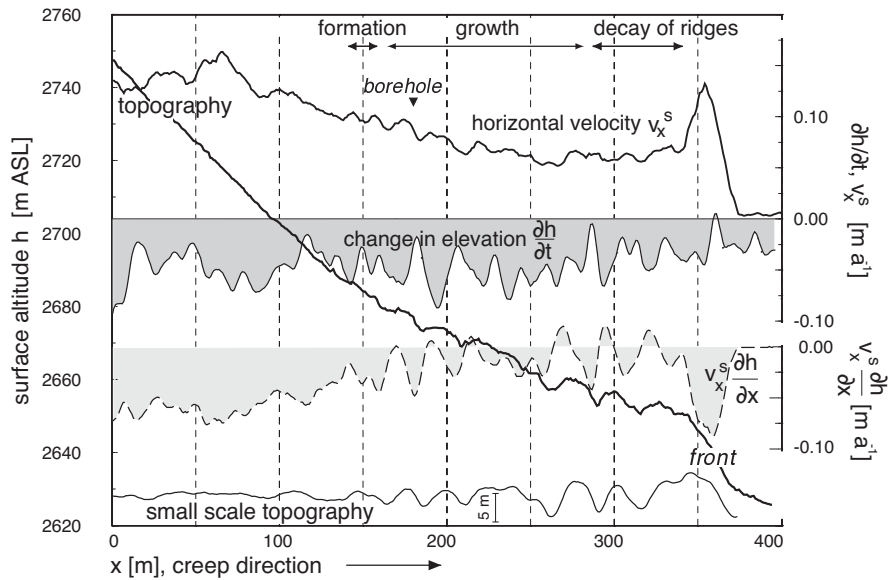


Figure 6 Longitudinal profile of rock glacier surface, surface velocities and derived kinematic quantities 1987-1996. The photogrammetric profile measurements have a spatial resolution of 1m. Surface topography depicted with two times exaggeration. Small scale topography defined as difference between surface topography at each point and a running average over 200m (four times exaggeration).

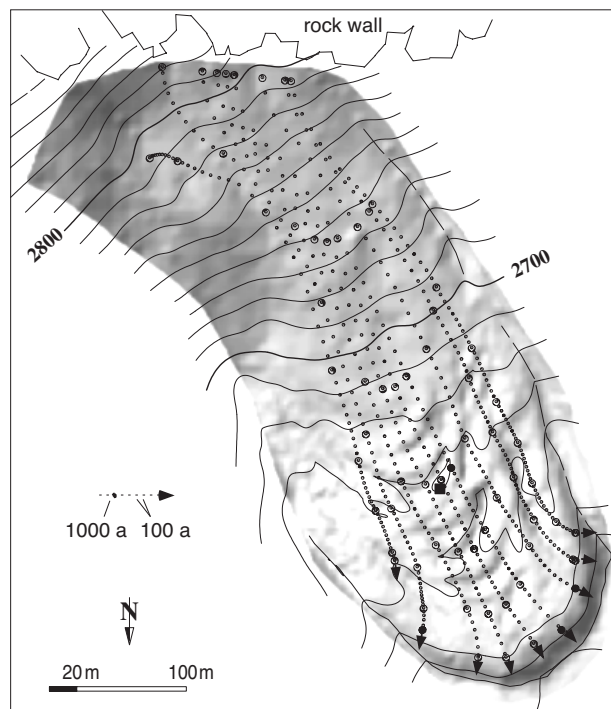


Figure 7 Selected stream lines at the surface, interpolated from the velocity field 1987-1996.

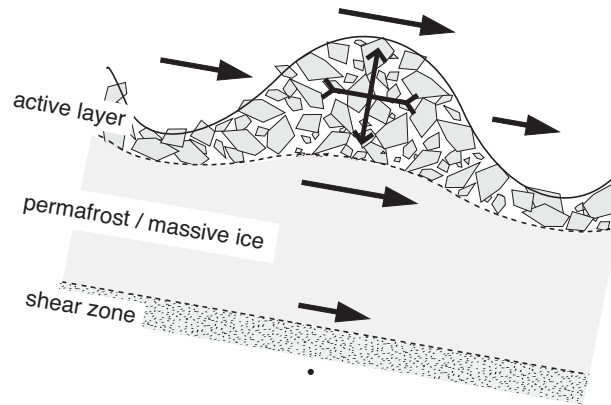


Figure 8 Schematic longitudinal cross section of a transverse ridge and the upper permafrost zone. Longitudinal compression causes vertical extension, over-compensating diffusion and erosion, and, therefore, may lead to the growth of transverse ridges.