Rock glacier dynamics: implications from high-resolution measurements of surface velocity fields

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ABSTRACT: Recent high-resolution measurements of surface velocity fields using terrestrial, air- and spaceborne methods have deepened insight into the dynamics of rock glaciers. Here, we compare selected studies on surface velocity fields in order to identify basic processes involved in the development of rock glacier surfaces. The evolution of rock glacier geometry is shown to be a function of mass advection, 3-dimensional straining, and thaw settlement or frost heave, respectively. All of these processes can reach the same order of magnitude. Available studies revealed creep fields to be highly coherent in space, clearly pointing to the presence of stresstransferring ice in the ground. The magnitude and type of dynamic processes reflect a high thermally-induced inertia of the creeping mountain permafrost. Systematic globally distributed monitoring series are identified as a major requirement for future research.

1 INTRODUCTION

Creeping mountain permafrost, best represented by so-called rock glaciers, is basically defined by its material properties and thermal conditions, and by its deformation. Knowledge about 3-dimensional surface velocities contributes towards detecting and understanding the dynamic processes involved in permafrost creep, and, generally, in landscape evolution in cold high mountains (e.g. Kääb et al., 1997; Berthling et al., 1998; Haeberli et al., 1998; Konrad et al., 1999; Frauenfelder & Kääb, 2000; Isaksen et al., 2000; Kaufmann & Ladstädter, 2000; Kääb et al., 2002).

Optimal investigation of permafrost creep requires: (1) area-wide information on kinetics to account for 3-dimensional effects, (2) the application of precise high-resolution techniques in view of the low deformation rates, and (3) long-term monitoring for documenting slow temporal changes at a sufficient level of accuracy.

Recent advances, especially in image processing, allow for measuring surface deformation of rock glaciers with a resolution and accuracy which were not known until present. As a consequence, better process understanding and a number of new insights into rock glacier development arise from such measurements. The IPA/ICSI task force on rock glacier dynamics recently addressed these advances. Here, we present a short review on methods used so far for monitoring of rock glacier surface deformation with high resolution and precision. From selected examples in the European Alps and on Svalbard, as well as from a number of already published studies we identify the dynamic processes involved in rock glacier development and summarise general findings about these processes. Thereby, conclusions made by earlier studies and confirmed by our inter-comparison are also included. Open questions in the field of rock glacier dynamics terminate our contribution.

2 MONITORING TECHNIQUES

Both ground-based approaches, and air- and spaceborne ones have been applied hitherto for monitoring rock glacier dynamics with high resolution. Groundbased surveys use triangulation and laser ranging (e.g. Haeberli, 1985; Zick, 1996; Sloan & Dyke, 1998; Koning & Smith, 1999; Konrad et al., 1999; Krainer & Mostler, 2000) or satellite geodesy (e.g. GPS; Berthling et al., 1998). Other methods for deformation measurements, such as steel tapes or strain wires are seldom used (e.g. White, 1987). Terrestrial laser scanning provides local digital terrain models (DTM) with very high resolution and accuracy (Paar et al., 2001).

Photogrammetry represents the best established remote sensing technology for rock glacier monitoring. From repeated stereo-imagery the surface geometry (DTM), rock glacier thickness changes, and surface displacements can be measured (e.g. Haeberli & Schmid, 1988; Kääb et al., 1997; Kääb et al., 1998; Kaufmann, 1998a; Kaufmann, 1998b). In particular, recent digital image processing techniques have provided measurements of rock glacier dynamics with an accuracy and spatial resolution which had not been attained before (Kääb & Vollmer, 2000; Kaufmann & Ladstädter, 2003). Space-borne differential synthetic aperture radar interferometry (DInSAR) is also able to register rock glacier surface deformation with an accuracy of few mm to cm (Rott & Siegel, 1999; Kenyi & Kaufmann, 2003; Nagel et al., 2001). Space-borne optical remote sensing was not applicable to date for rock glacier monitoring due to its limited resolution. However, recent and upcoming highest resolution sensors will allow to derive surface deformation from optical space-imagery with an accuracy of ± 0.5 –1 m (Kääb, 2002). Airborne laser scanning will be a tool to monitor rock glacier thickness changes with high resolution (Baltsavias et al., 2001).

The approaches used to analyse high-resolution data of rock glacier surface dynamics range from interpretation to numerical modelling. The deformation data itself provide creep velocity (Fig. 1) and thickness changes (Fig. 2), and, thus, the degree of activity. The general surface velocity field and its local pattern show spatio-temporal coherence, variabilities and interactions.

Spatial gradients can be calculated from the velocity field and zones of compressive, or extending flow, respectively, can be derived (Kääb et al., 1997; Fig. 3). Stream line interpolation allows for assessing the particle paths on a rock glacier and their age (Kääb et al., 1997; Kääb et al., 1998). The kinematic boundary



Figure 1. Horizontal surface velocities on Muragl rock glacier, Swiss Alps, measured for 1981–1994 from repeated aerial photography. The bold dots indicate the location of the surveying markers of Fig. 6. No. 202 is the rightmost, No. 208 the leftmost marker. Orthoimage based on photo 23.08.1994 – 0726 ©Swiss Federal Office of Cadastral Survey.

condition at the surface is used to analyze the local relation between permafrost creep, geometry change and mass balance (Kääb et al., 1998; Kaufmann, 1998a). Spatial modeling of permafrost creep is mostly based on the assumption of glacier-ice like behaviour (Konrad et al., 1999). High-resolution velocity data can thereby be used for estimation of creep-parameters or model validation.



Figure 2. Thickness changes of Muragl rock glacier measured for 1981–1994 from repeated aerial stereo-photography.



Figure 3. Negative total of horizontal strain rates on Muragl rock glacier for 1981–1994. For an incompressible medium the given values would be equivalent to the vertical surface strain rates.

3 DYNAMIC PROCESSES

The kinematic boundary condition on the surface predicts that the processes involved in geometric rock glacier development are general mass advection, advection of topography by creep, 3-dimensional straining and local mass changes from, for instance, ice melt or refreezing (Kääb et al., 1998). The following processes can be identified from high resolution measurements of 3-dimensional surface velocity fields:

(1) The fundamental process is permafrost creep. Nearly all high-resolution studies on the deformation of (visually) active rock glaciers were able to detect creep. Whereas maximum speeds were found to be in the order of several m a^{-1} (Figs 1 and 4), the detection of minimum speeds seems mostly restricted by the available measurement accuracy (Fig. 5). Recent highprecision studies using GPS (Berthling et al., 1998) or DInSAR (Kenyi & Kaufmann, 2003) detected movement rates of a few cm a^{-1} to mm a^{-1} , suggesting a continuous transition from stable slopes to mountain permafrost creep. Inter-comparison of available studies suggests that differences in slope, thickness, temperature, or internal composition are not sufficient to explain individual differences in speed. On the other hand, there are clear indications that all these factors play a major role for the deformation rate: within a single rock-glacier speed seems often related to the slope pattern (Figs 1 and 4; Konrad et al., 1999). 'Cold' polar rock glaciers seem in general to creep more slowly than 'warm' Alpine ones (Fig. 5; Kääb et al., 2002). Smaller thickness of the deforming layer might explain



Figure 4. Horizontal surface displacements on a section of the lowermost part of Outer Hochebenkar rock glacier, Austrian Alps, for 1971–1977. The terminus of the rock glacier showed a creep instability indicated by missing targets for displacement measurements, and by crevasse-like transverse ruptures. After Kaufmann & Ladstädter (2003).

the generally lower speed at the rock-glacier root zones and margins (Fig. 1; Kaufmann, 1998a; Kaufmann & Ladstädter, 2003). The resulting surface speed is considered to be a combination of factors. Separation of individual influences is difficult, especially due to the lack of knowledge on the internal structure (thickness, composition).

(2) The advance of an entire rock glacier or overriding of individual flow lobes causes zonal thickening (Kääb et al., 1997; Kääb et al., 1998; Kääb, 2000). From elevation-change data for Muragl rock glacier (Fig. 2) it can be seen that surface heaving of several $cm a^{-1}$ occurs at the front of individual creep lobes. Similar rates of heaving can be observed at the front of the main rock glacier (2500 m a.s.l), but also at the front of the adjacent rock glacier to the East (2640 m a.s.l).

(3) Analogously, the advection of surface microtopography by creep may result in a pattern of local positive and negative thickness changes. Heaving patterns in front of individual transverse ridges and corresponding lowering patterns at their rear were observed from high-resolution studies (Kääb et al., 1998; Kääb & Vollmer, 2000). Comparing the observed vertical rates with the ones calculated from creep speed and surface slope clearly confirms that this advection process is taking place.

(4) 3-dimensional straining (compression, or extension, respectively) by spatial gradients of the creep field may lead to local heaving or thinning. Horizontal compression is expected to cause vertical extension, i.e. by surface heaving, and vice-versa. For an incompressible medium like pure ice both amounts would strictly equal. For ice-rock mixtures the assumption of



Figure 5. Horizontal surface displacements on Brøggerbreen rock glacier, Svalbard, measured from 1971 and 1995 aerial imagery. Orthoimage of photo S90–6295 ©Norsk Polarinstitutt. After Kääb et al. (2002).

incompressibility might certainly be questionable, especially for short time scales. Considering (super-) saturation with ice, the above relation between horizontal and vertical strain rates will, however, qualitatively apply also for rock glaciers over long time scales. Figure 3 shows the negative total of horizontal strain rates derived from the velocity field (Fig. 1). Comparing the pattern of the computed strain rates (Fig. 3) with the pattern of observed thickness changes (Fig. 2) clearly suggests the described relation. The same process could be also detected in other studies (Kääb et al., 1998; Kääb & Vollmer, 2000).

(5) General thaw settlement and frost heave as an expression of climate forcing affects large parts of a rock glacier in a similar way. The degree of such heaving or settlement may also reflect the internal composition. Thickness loss due to ice melt may be significant for zones in the vicinity of perennial ice patches (e.g. Fig. 2, top) or for dead ice remains (Kääb et al., 1997). Such pronounced mass losses might, therefore, rather be an expression of missing thermal equilibrium (active layer depth < debris cover thickness) than a climate signal. In fact, for most monitoring series of rock-glacier mass-changes no clear signal of overall mass gain or loss could be observed. Only two studies showed clearly an overall mass loss by few cm a⁻¹ (Kääb et al., 1998; Kaufmann & Ladstädter, 2003).

Whilst the first group of processes above considers the fundamental dynamic processes involved in steady-state permafrost creep, the following group of processes covers spatial and temporal variations:

(6) Transverse gradients in the horizontal velocities result in a rotational component of the strain rates and to horizontal shearing. For high rates such shearing may have its expression in a disturbed surface topography (Fig. 4 middle; Kääb et al., 1997).

(7) Little is known about temporal changes of rock glacier creep. In this paragraph, we do not consider velocity variations in the scale of millennia or centuries, although some velocity fields clearly indicate rock glaciers or parts of them which must have shown a degree of activity other than today (e.g. inactive layer at the northern margin of Muragl rock glacier (Fig. 1) overridden by an active lobe; Frauenfelder & Kääb, 2000). Monitoring series of rock glacier speed indicate both cyclic and non-cyclic temporal speed variations. Cyclic variations have been observed for seasonal velocity variations (e.g. Fig. 6; Haeberli, 1985). Continuous pluriannual changes in speed might be a result of external (climate?) forcing (Zick, 1996; Kääb et al., 1997; Kääb & Frauenfelder, 2001; Schneider, 2001). So far, monitoring of rock-glacier speed-variations revealed several possible causes mostly connected to thermal impacts.

(8) Temporal discontinuities in rock glacier creep can seldom be observed. The slide of the lowermost part of



Figure 6. Seasonal velocity variations on Muragl rock glacier, Swiss Alps, measured from repeated terrestrial surveying. For location of the markers see Figure 1. The thin line indicates the temperature measured by a miniature logger at approximately 0.5 m depth. The rock glacier speed varied from close to zero to up to 1 m a⁻¹ within a few months and with some delay to surface temperature variations.

Outer Hochebenkar rock glacier, Austria, (Fig. 4) represents a rare example for such creep instability accompanied by transverse surface ruptures (Kaufmann & Ladstädter, 2003).

(9) Locally varying permafrost conditions might lead to differential thaw settlement or frost heave as, for instance, thermokarst processes (Kääb & Haeberli, 2001). According to the available monitoring series such small-scale differential melting or frost heave is an exception compared to (5) and represents rather a disturbance of the general thermal equilibrium (cf. (6)) The only situation of common differential melt on rock glaciers might be at the front where the ice content melts out (Kääb et al., 1997).

All the above dynamic processes overlay each other so that a clear identification from individual monitoring series is difficult. Inter-comparison of a number of series, however, clearly confirms their (variable) existence in nature.

4 GENERAL CHARACTERISTICS

Analysing and inter-comparing high-resolution surface velocity fields allows for identifying some general characteristics of creeping mountain permafrost:

The typical smooth and continuous morphology of rock glaciers points to the absence of high-frequency spatial and temporal speed variations, and to the absence of pronounced differential frost heave and melting. Thus, the smooth topography compared to debris-covered glaciers or dead-ice remains is an expression of the thermally-induced inertia of rock glaciers. This high inertia against thermal forcing is also manifested in low vertical change rates, and even lower changes in overall mass.

The evolution of the rock glacier geometry is due to cumulative deformation and 3-dimensional straining,



Figure 7. Horizontal surface velocities on Murtèl rock glacier for 1987–1996. The dotted lines represent selected stream lines interpolated from the velocity field 1987–1996. The time step between two adjacent dots is 100 a. The dashed transverse lines indicate 1000 a – isochrones interpolated from the streamlines. A white rectangle indicates the location where moss remains were found in the permafrost, later dated to c. 2300 a BP. Orthoimage of photo 07.09.1988 – 4768 ©Swiss Federal Office of Cadastral Survey.

as well as frost heave and thaw settlement. A climate signal can not be deduced from monitoring surface geometry without considering 3-dimensional dynamics. The rates from such straining or mass advection may exceed the rates expected from mass balance and their changes. Whereas the evolution of transverse ridges and furrows on rock glaciers is not clear, some spatial correlation between zones of compressive creep and zones of ridge-topography can be observed (cf. Figs 3, 4 and 7) suggesting some influence from 3-dimensional straining (Kääb et al., 1998).

The surface flow fields with magnitudes of up to several ma^{-1} – better known than for many other slope movements – indicate clearly a both spatially and temporally continuous deformation pointing to the presence of stress transferring ground ice. Highresolution velocity fields (Fig. 4; Kääb & Vollmer, 2000) show that the surface deformation of rock glaciers is highly coherent even at the scale of individual rocks, and that it is not only the sum of individually displacing or sliding particles.

The range of seasonal to pluriannual speed variations can reach up to several tens of percents (Fig. 6; Zick, 1996; Schneider, 2001).

Stream line interpolations (e.g. Fig. 7) or rougher age assessments from velocity-length ratios indicate that the age of rock glaciers has to be counted in millennia rather than in shorter time scales (Kääb et al., 1997; Kääb et al., 1998; Frauenfelder & Kääb, 2000; Berthling, 2001; Kääb et al., 2002). Such age estimates are clearly confirmed by other dating methods (e.g. Sloan & Dyke, 1998; Haeberli et al., 1999; cf. also this issue) and by comparing rock glacier masses with headwall weathering rates (Haeberli et al., 1999; Berthling, 2001; Kääb et al., 2002). The correlation between the actual velocity field (e.g. speed, creep direction, strain rates, stream lines, isochrones), and the actual 3-dimensional geometry indicates that most active rock glaciers observed have not undergone drastic dynamic changes in the past.

5 CONCLUSIONS AND PERSPECTIVES

The technology applied for monitoring rock glacier dynamics is relatively far developed. Research deficits rather lie in the availability of the techniques and in systematic monitoring strategies. Current research tendencies point towards an increase in accuracy and tempo-spatial resolution, towards an increase in measurement automation, and towards enhanced application of space-borne techniques in order to cover remote areas too.

The knowledge of geometry and surface kinetics of rock glaciers is comparably detailed, whereas the basic understanding of the underlying processes is by far not adequate compared to the available data. This discrepancy might most likely be due to the fast recent development of monitoring technologies. The current lack of process understanding implies flow laws or creep mechanisms, but also speed variations, sensitivity to external forcing, rock glacier advance mechanisms, and the development of (and implications from) microtopography. A larger number of systematic globally distributed monitoring series could substantially help to extract the basic processes of rock glacier creep from the large dynamic variability of individual examples.

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REFERENCES

Baltsavias, E.P., Favey, E., Bauder, A., Boesch, H. & Pateraki, M. 2001. Digital surface modelling by airborne laser scanning and digital photogrammetry for glacier monitoring. *Photogrammetric Record* 17(98): 243–273.

- Berthling, I. 2001. Slow periglacial mass wasting processes and geomorphological impact. Case studies from Finse, southern Norway and Prins Karls Forland, Svalbard. Dissertation Thesis, University of Oslo.
- Berthling, I., Etzelmüller, B., Eiken, T. & Sollid, J.L. 1998. Rock glaciers on Prins Karls Forland, Svalbard. I: internal structure, flow velocity and morphology. *Permafrost and Periglacial Processes* 9: 135–145.
- Frauenfelder, R. & Kääb, A. 2000. Towards a palaeoclimatic model of rock glacier formation in the Swiss Alps. *Annals of Glaciology* 31: 281–286.
- Haeberli, W. 1985. *Creep of mountain permafrost*. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich 77, 142 pp.
- Haeberli, W., Hoelzle, M., Kääb, A., Keller, F., Vonder Mühll, D. & Wagner, S. 1998. 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. Yellowknife, Canada: 403–410.
- Haeberli, W., Kääb, A., Wagner, S., Geissler, P., Haas, J.N., Glatzel-Mattheier, H., Wagenbach, D. & Vonder Mühll, D. 1999. 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* 45(149): 1–8.
- Haeberli, W. & Schmid, W. 1988. Aerophotogrammetrical monitoring of rock glaciers. *Proceedings of the 5th. International Conference on Permafrost* 1: 764–769.
- Isaksen, K., Ødegard, R.S., Eiken, T. & Sollid, J.L. 2000. Composition, flow and development of two tongueshaped rock glaciers in the permafrost of Svalbard. *Permafrost and Periglacial Processes* 11: 241–257.
- Kääb, A. 2002. Monitoring high-mountain terrain deformation from digital aerial imagery and ASTER data. *ISPRS Journal of Photogrammetry and remote sensing* 57(1–2): 39–52.
- Kääb, A. 2000. Photogrammetry for early recognition of high mountain hazards: new techniques and applications. *Physics and Chemistry of the Earth, Part B*, 25(9): 765–770.
- Kääb, A. & Frauenfelder, R. 2001. Temporal variations of mountain permafrost creep. Abstract. *1st European Permafrost Conference. Rome*: 56.
- Kääb, A., Gudmundsson, G.H. & Hoelzle, M. 1998. Surface deformation of creeping mountain permafrost. Photogrammetric investigations on rock glacier Murtèl, Swiss Alps. 7th International Permafrost Conference. Yellowknife, Canada: 531–537.
- Kääb, A. & Haeberli, W. 2001. Evolution of a high-mountain thermokarst lake in the Swiss Alps. *Arctic, Antarctic, and Alpine Research* 33(4): 385–390.
- Kääb, A., Haeberli, W. & Gudmundsson, G.H. 1997. Analysing the creep of mountain permafrost using high precision aerial photogrammetry: 25 years of monitoring Gruben rock glacier, Swiss Alps. *Permafrost* and Periglacial Processes 8(4): 409–426.
- Kääb, A., Isaksen, K., Eiken, T. & Farbrot, H. 2002. Geometry and dynamics of two lobe-shaped rock

glaciers in the permafrost of Svalbard. *Norwegian Journal of Geography* 56: 152–160.

- Kääb, A. & Vollmer, M. 2000. Surface geometry, thickness changes and flow fields on permafrost streams: automatic extraction by digital image analysis. *Permafrost* and Periglacial Processes 11(4): 315–326.
- Kaufmann, V. 1998a. Deformation analysis of the Doesen rock glacier (Austria). 7th International Permafrost Conference. Yellowknife, Canada: 551–556.
- Kaufmann, V. 1998b. Geomorphometric Monitoring of active rock glaciers in the Austrian Alp. 4th Int. Symp. on High-Mountain Remote Sensing Cartography. Karlstadt, Sweden: 97–113.
- Kaufmann, V. & Ladstädter, R. 2003. Quantitative analysis of rock glacier creep by means of digital photogrammetry using multi-temporal aerial photographs: Two case studies in the Austrian Alps. 8. Int. Conference on Permafrost, Zurich. This issue.
- Kenyi, L.W. & Kaufmann, V. 2003. Measuring rock glacier surface deformation using SAR interferometry. 8. Int. Conference on Permafrost, Zurich. This issue.
- Koning, D.M. & Smith, D.J. 1999. Movement of King's Throne rock glacier, Mount Rae area, Canadian Rocky Mountains. *Permafrost and Periglacial Processes* 10(2): 151–162.
- Konrad, S.K., Humphrey, N.F., Steig, E.J., Clark, D.H., Potter Jr., N. & Pfeffer, W.T. 1999. Rock glacier dynamics and paleoclimatic implications. *Geology* 27(12): 1131–1134.
- Krainer, K. & Mostler, W. 2000. Reichenkar rock glacier: a glacier derived debris-ice system in the western Stubai Alps, Austria. *Permafrost and Periglacial Processes* 11(3): 267–275.
- Nagel, T., Mayer, C. & Rott, H. 2001. Feasibility of DIN-SAR for mapping complex motion fields of Alpine ice- and rock-glaciers. 3rd International Symposium on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Application. 11–14 Sep 2001. Sheffield, UK.
- Paar, G., Bauer, A. & Kaufmann, V. 2001. Rock glacier monitoring using terrestrial laser scanning. Abstract. *1st European Permafrost Conference. Rome*: 58–59.
- Rott, H. & Siegel, A. 1999. Analysis of Mass Movement in Alpine Terrain by means of SAR Interferometry. *IEEE Geoscience and Remote Sensing Symposium*, *IGARSS'99. Hamburg*: 1933–1936.
- Schneider, B. 2001. Fluctuations of air temperature as a reason for short-term velocity changes at the rock glacier Äusseres Hochebenkar (Ötztal Alps, Tyrol)? Abstract. *1st European Permafrost Conference. Rome*: 62–63.
- Sloan, V.F. & Dyke, L.D. 1998. Decadal and millennial velocities of rock glaciers, Selwyn Mountains, Canada. *Geografiska Annaler* 80A(3–4): 237–249.
- White, S.E. 1987. Differential movement across ridges on Arapaho rock glaciers, Colorado Front Range, US. In: J.R. Giardino, F. Shroder and J.D. Vitek (eds), *Rock glaciers*. Allen &Unwin, London: 145–149.
- Zick, W. 1996. Bewegungsmessungen 1965–1994 am Blockgletscher Macun I (Unterengadin/Schweiz) – neue Ergebnisse. – . Zeitschrift für Geomorphologie N.F., Supplement-Band 104: 59–71.