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 space-borne ones have been applied hitherto for monitoring rock glacier dynamics with high resolution. Ground-based surveys use triangulation and laser ranging (e.g. Haeberli, 1985; Zick, 1996; Sloan & Dyke, 1998; Koning & Smith, 1999; Konrad et al., 1999; Frauenfelder & Kääb, 2000; Isaksen et al., 2000; Kaufmann & Ladstädter, 2000; Kääb et al., 2002).

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accuracy and spatial resolution which had not been
tained 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 accu-
rcy 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 sen-
sors will allow to derive surface deformation from
optical space-imagery with an accuracy of \( \pm 0.5-1 \) m
(Kääb, 2002). Airborne laser scanning will be a tool to
monitor rock glacier thickness changes with high res-
olution (Baltsavias et al., 2001).

The approaches used to analyse high-resolution
data of rock glacier surface dynamics range from
interpretation to numerical modelling. The deforma-
tion 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, vari-
abilities 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
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 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

Figure 2. Thickness changes of Muragl rock glacier meas-

Figure 3. Negative total of horizontal strain rates on
medium the given values would be equivalent to the verti-
cal 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 high-precision 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 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
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 & Ladstätter, 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.](image-url)
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 m a\(^{-1}\) – 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. High-resolution 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 systematically distributed monitoring series could substantially help to extract the basic processes of rock glacier creep from the large dynamic variability of individual examples.

ACKNOWLEDGEMENTS

We would like to thank the Swiss Federal Office of Topography/Federal Office of Cadastral Surveys, the Norwegian Polar Institute and the Austrian Federal Office of Metrology and Surveying for acquisition of the invaluable aerial photography. The comments of two reviewers and the editor are appreciated.

REFERENCES


