

Detecting and quantifying mountain permafrost creep from *in situ* inventory, space-borne radar interferometry and airborne digital photogrammetry

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Abstract. In this paper three different techniques for detecting and quantifying mountain permafrost creep are compared: (1) rock glacier inventory and characterization from *in situ* indicators, (2) space-borne radar interferometry, and (3) digital processing of repeated airborne imagery. The specific characteristics of the three methods and their complementarity are investigated for the Fletschhorn mountain range in the Simplon/Saas valley region, Swiss Alps. We found that radar interferometry is suitable to quantify the degree of activity and the order of surface velocity of rock glaciers over large areas in one process, with the possibility to also detect very small movements of inactive and relict rock glaciers. On the other hand, aero-photogrammetry represents a valuable base for additional interpretation of the three-dimensional surface flow field (including speed, direction and change in thickness) of the most active rock glaciers. Results from radar interferometry can also form the basis for further detailed *in situ* investigations.

1. Introduction

Permafrost, i.e. underground with temperatures below 0°C all year round, may contain a significant percentage of ice. Under mountainous conditions, such frozen debris is able to creep due to gravity and to form debris lobes similar-looking to lava streams. These slope instabilities, so-called rock glaciers, are typical for dry and cold mountain regions (Barsch 1996). Besides their thermal condition and material composition, rock glaciers are basically defined by their deformation. The ice/rock-mixtures creep with characteristic surface velocities of centimetres, decimetres and sometimes up to a few metres per year (Kääb *et al.* 2003).

Rock glaciers are characterized by a vertical structure of three principal layers (Haeberli *et al.* 1998, Arenson *et al.* 2002):

1. The upper few metres, where ground temperatures reach positive values during summer time, consist of ice-free debris with typical diameters of decimetres to metres (active layer).

2. Between the active layer and the permafrost base, temperatures are below 0°C throughout the year. This permafrost body consists of debris–ice mixtures of various compositions, and of some metres to many tens of metres thickness. Rock glacier deformation primarily takes place within the permafrost body. The active layer is passively riding on this layer, however, affected by the underlying deformation in various forms.
3. Below, at the permafrost base, geothermal heat flux over-compensates for the atmospheric energy loss, which cools the permafrost body above.

Depending on their thermodynamic state and ice content, three types of rock glaciers can be defined (Barsch 1996, Frauenfelder and Kääb 2000):

1. Active rock glaciers show both a significant degree of deformation and amount of ice content. They reflect current permafrost conditions underground.
2. Inactive rock glaciers might still contain some ice remains but show no more movement. Such inactivation might result either from change in thermal conditions (climate warming) and subsequent loss of an ice content high enough for viscous deformation, or from dynamic influences such as topographic barriers or loss of debris support. In the case of thermally induced deactivation, inactive rock glaciers might be considered as a transitional form between active and relict rock glaciers.
3. Relict rock glaciers lack both ice content and movement. They reflect former permafrost conditions. The time needed to melt out the entire ice content from an active rock glacier by a natural increase in air temperature is estimated at several hundreds of years.

Due to their coupling with atmospheric temperatures and related shifts from climate variability, active rock glaciers usually form the uppermost elevation zone of rock glaciers, inactive rock glaciers an intermediate zone, and relict rock glaciers the lowermost zone.

Investigating rock glacier dynamics has become an important scientific and applied task in high-mountain research for two main reasons:

- Rock glaciers represent a system of continuous mass transport in high mountains, thus, forming an integral part of this landscape. Furthermore, due to their ice content rock glaciers are highly sensitive to climate impacts. Investigating rock glacier dynamics contributes decisively, therefore, to understanding the evolution of cold mountain terrain in space and time, and under varying climate conditions (Frauenfelder and Kääb 2000, Frauenfelder *et al.* 2001).
- Rock glaciers may also be involved in natural hazard formation:
 1. The continuous debris transport by rock glacier creep causes rockfall activity at the rock glacier front. Such rockfall is often limited to the direct vicinity of the front, but is sometimes able to produce more far-reaching rockfall hazards.
 2. Steady mass transport by mountain permafrost creep may also feed into steep channels, which then represent a potential source of debris flows (Hoelzle *et al.* 1998, Kääb 2000).
 3. The cementation of debris by ice increases the angle of repose of the material significantly. Ice-rich permafrost, therefore, enhances the stability of debris slopes in general. On the other hand, climate warming, as

presently observed, influences the thermal and mechanical conditions of the frozen material and might reduce its stability (Davies *et al.* 2001, Arenson *et al.* 2002). In fact, a significant number of recent debris flows in the European Alps seem to have started from the lower boundary of permafrost distribution which is potentially most affected by climate change (Zimmermann and Haeberli 1992, Haeberli *et al.* 1997).

In order to investigate permafrost creep and assess the related hazards, various methods – ranging from field interpretation to ground surveys, from airborne to space-borne remote sensing – have been proposed (Frauenfelder *et al.* 1998, Rott and Siegel 1999, Kääb and Vollmer 2000, Kenyi and Kaufmann 2000, Rignot *et al.* 2002, Kääb *et al.* 2003). In this study we compare three different techniques for detecting and quantifying mountain permafrost creep: (1) rock glacier inventory and characterization from *in situ* indicators, (2) space-borne radar interferometry, and (3) digital processing of repeated airborne imagery. The specific capabilities of the three methods and their complementarity were studied in the Flletschhorn mountain range in the Simplon/Saas valley region, Swiss Alps (approximately 8.0° E, 46.1° N). The area consists of typical high-mountain terrain with an elevation range from approximately 1500 m a.s.l. to over 4000 m a.s.l. Numerous glaciers and rock glaciers can be found in the area, some of which have been intensively studied both for process research and hazard prevention purposes (Frauenfelder 1997, 1998, Kääb *et al.* 1997, Frauenfelder *et al.* 1998, Haeberli *et al.* 2001, Strozzi *et al.* 2002).

2. Methods

2.1. Inventory

Assessing the degree of rock glacier activity is often done qualitatively by visual inspection and supplementary field investigations, such as geomorphological interpretation, source water temperature measurements, mapping of perennial snow patches, estimation of the percentage of vegetation, and inventorying of the composition of vegetation cover. Active rock glaciers show little or no vegetation cover (mainly composed of plants specialized for growth on creeping substrate), small (i.e. young) lichens, and rockfall activity at the front, all signalling ongoing deformation of the underground (Barsch 1978, 1996). The intact ice content gives the bodies a flat or even convex shape. Water temperatures of close to 0°C measured in sources at the rock glacier front hint at buried permafrost or ice (Haeberli 1975).

Inactive rock glaciers show more vegetation and lichen cover, especially at the front where low to absent rockfall activity allows a larger number of plant species to grow. Often, the onset of collapsing structures can be observed originating from the melt-out of the ice. Relict rock glaciers can be densely vegetated – as far as permitted by the coarse surface substrate – and can show a strongly collapsed surface topography with the entire ice melted out and only the solid debris content remaining (Barsch 1996). The locations of burrows of hibernating Alpine marmots (*Marmota marmota*) give an indication of the absence of permafrost in the vicinity of a rock glacier (due to the fact that the Alpine marmot cannot hibernate in soils with temperatures clearly below 0°C) and, thus, additional information about the possible thermal state of the rock glacier.

Together with other indicators such as the base temperature of the snow cover (Haeberli 1973), the above criteria have been used to compile a rock glacier inventory of the study area. For such rock glacier mapping, the surface

displacement rates are not directly measured but inferred from natural indicators. This procedure is efficient for mapping of large areas but an uncertainty may remain for individual rock glaciers. Furthermore, the dynamic activity of rock glaciers presumably represents a temporal continuum rather than a stepwise function with the three states 'active', 'inactive' and 'relict'.

2.2. Satellite radar interferometry

Space-borne synthetic aperture radar (SAR) systems offer the possibility of surveying large areas, even in remote locations. Differential SAR interferometry (DInSAR) is an emerging technique for the mapping of geophysical displacements at mm to cm resolution which makes use of two SAR images acquired from slightly different orbit configurations and at different times to exploit the phase difference of the signals (Bamler and Hartl 1999, Rosen *et al.* 2000). The phase signal derived from an image pair relates both to topography and line-of-sight surface movement between the acquisitions, with atmospheric phase distortions, signal noise and inaccuracy in the orbit determination as main error sources (Werner *et al.* 2000, Strozzi *et al.* 2001). The basic idea of DInSAR is to subtract the topography related phase from the interferogram to derive a displacement map. Recent studies on rock glacier deformation suggest that the technique is promising also for relatively small objects in mountainous terrain (Rott and Siegel 1999, Kenyi and Kaufmann 2000, Kenyi and Kaufmann 2001, Nagler *et al.* 2002, Rignot *et al.* 2002).

The major limiting factors in mountainous terrain arise from decorrelation and the SAR image geometry, both leading to incomplete spatial coverage. Over rock glaciers, where dense vegetation is no longer present, high coherence is regularly observed during the snow free period between early summer and mid-autumn, but large displacements may also cause decorrelation. The very rugged topography of alpine regions causes incomplete coverage due to layover and shadowing. In addition, there is a privileged slope direction, namely that facing away from the SAR look vector, where the technique is better suited for detection and monitoring of displacements.

In this study, a series of 18 SAR images from the European Remote Sensing Satellites ERS-1 and ERS-2 from 1995 to 1999 and of seven SAR images from the Japanese Earth Resources Satellite JERS-1 from 1993 to 1996 have been analysed. From the large number of the possible interferometric pairs, we considered a total of nine interferograms with short baselines for further analysis. The topographic reference determined from two winter ERS-1/2 tandem pairs was subtracted from interferograms with acquisition time intervals between 1 and 736 days. The differential interferograms were orthorectified to the Swiss cartographic system with a pixel spacing of 10 m by use of a Digital Elevation Model (DEM) derived from aerial photogrammetry, superimposed to a topographic map and used for the survey of rock glaciers in the Fletschhorn region.

For the most convincing interferometric pairs the analysis continued with phase unwrapping permitting the quantitative measurement of the displacement field of identified rock glaciers. Phase unwrapping of interferograms in rugged terrain and for complicated displacement fields is a critical task that was successful only for small areas. The line-of-sight displacement was finally transformed into displacement along the slope gradient using the aerial photogrammetry DEM.

The DInSAR records of creeping measurements are only valuable if errors can be shown to be small in comparison to the signal. From the different error sources

of DInSAR (atmospheric phase distortions, signal noise, inaccuracy in the orbit determination, phase unwrapping mistakes, assumption of creeping along the slope direction), we consider signal noise and assumption of creeping along the slope direction as the main limiting factors for the proposed application. All the analysed rock glaciers have a small dimension, whereas atmospheric artefacts and inaccuracy in the orbit determination mainly cause relatively large-scale distortions. Phase unwrapping was carefully performed with a region-growing algorithm (Rosen *et al.* 1994) and only areas with reliable information were retained. To prevent errors caused by the transformation of the line-of-sight displacement to the displacement along the slope direction, only measurements of slope with an orientation within 80° of the line-of-sight are presented. Assuming an error in phase noise of one-quarter of the wavelength leads to an error in line-of-sight displacement of 0.7 cm for ERS and of 2.9 cm for JERS.

2.3. Digital photogrammetry

Optimal quantitative investigation of permafrost creep requires: (1) area-wide information on kinetics to account for 3-D 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. As demonstrated by earlier studies (Kääb and Vollmer 2000, Kaufmann and Ladstädter 2000, Kääb 2002) digital photogrammetry based on repeated aerial photography represents a suitable remote-sensing tool to measure such slow geometrical changes of alpine permafrost surfaces.

Here we applied a method by Kääb and Vollmer (2000) for deriving surface displacements for selected rock glaciers in the study area. Using the software SOCET SET of LH Systems, multitemporal DEMs and orthoimages were automatically computed from scanned aerial imagery of approximately 1:20 000 scale, taken on 6 October 1975 and 1 September 1999 by the Swiss Federal Office of Topography. Horizontal surface displacements were derived from automatic comparison of the two corresponding orthoimages of 1975 and 1999. The software CIAS used for that purpose (Kääb and Vollmer 2000) calculates the terrain displacement from grey value matching between the multitemporal orthoimages. Verifications of the procedure revealed accuracy for individual displacements of approximately one image pixel, also including uncertainties resulting from the terrain itself such as tilting rocks. In our case, the applied orthoimages have a resolution of 0.5 m in ground scale. This absolute accuracy translates into an accuracy for the velocity of approximately $\pm 2 \text{ cm year}^{-1}$ RMS for the 24 year period investigated.

3. Results

The classification of rock glacier activity from natural indicators is shown in figure 1. The analysis of all inventoried rock glaciers (only a part of the inventory was investigated here) suggests that relict rock glaciers reach down into considerably lower altitudes than active rock glaciers. Only some few active rock glaciers reach down to lower altitudes. The number of rock glaciers classified as inactive is slightly smaller than the number of inventoried active and relict rock glaciers.

Geocoded differential interferograms for five ERS pairs and one JERS pair of the same area covered by the rock glacier inventory are shown in figure 2. The spatial coverage with phase information (i.e. the areas with colour coding) is limited

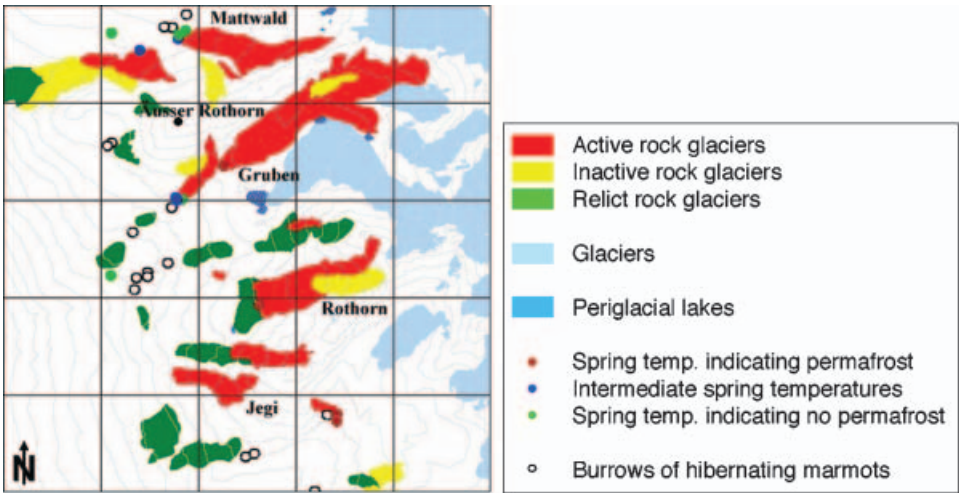
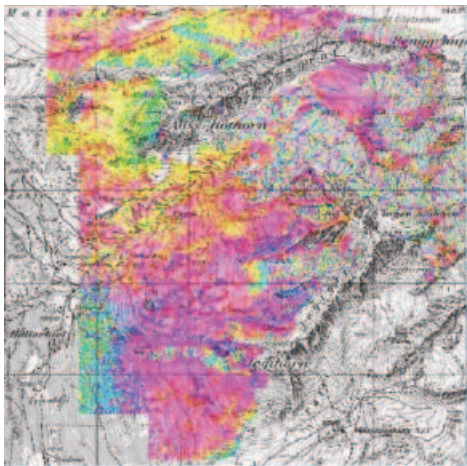


Figure 1. Rock glacier inventory of the Fletschhorn region from *in situ* natural indicators, such as geomorphological interpretation, source water temperatures, existence of perennial snow patches, percentage and composition of vegetation cover, and locations of burrows of hibernating marmots (*Marmota marmota*). In addition, glacier extent as in 1988 is given. The overlaid grid has a mesh of 1 km on the Swiss cartographic system.

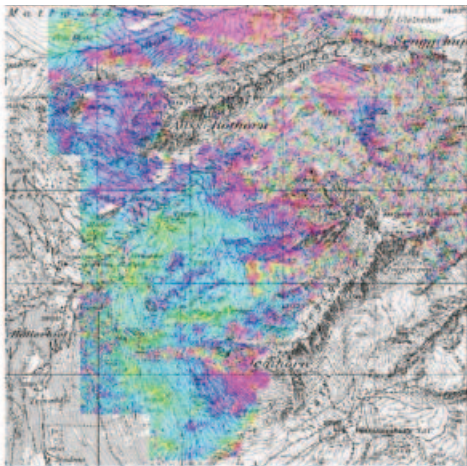
to the region covered by the aerial photogrammetry DEM where the ERS-1/2 tandem pairs used for topographic reference were unwrapped. The phase variations in figure 2 from 0 to 2π are shown as colour coding from blue to blue through yellow and red. A small-scale change of the phase is related to displacement in the satellite line-of-sight direction, with a phase cycle of 2π corresponding to 2.8 cm for ERS and 11.8 cm for JERS. Phase noise is related to decorrelation and large-scale phase changes are principally associated with baseline and atmospheric artefacts.

In all the interferograms of figure 2 glaciated areas are completely decorrelated because of large displacements in the considered time intervals and the presence of wet snow. In the ERS differential interferograms of 35 and 70 days time interval and in the JERS differential interferogram of 88 days time interval two rock glacier systems may be immediately identified, Rothorn and Jegi. The phase signal over the Rothorn rock glacier is particularly clear in the JERS interferogram of figure 2(f). In the ERS interferograms of figure 2(a) and (b) the phase signal is clear only over the front of the rock glacier, where an increase of the fringes can be observed. The Jegi rock glacier is more decorrelated than the Rothorn one, in particular in the ERS interferograms, suggesting a larger creep velocity or a stronger displacement of adjacent scatterers. By far the most decorrelated rock glacier is the Gruben one, which also appears noisy in the ERS interferogram of 35 days time interval and in the JERS interferogram of 88 days time interval.

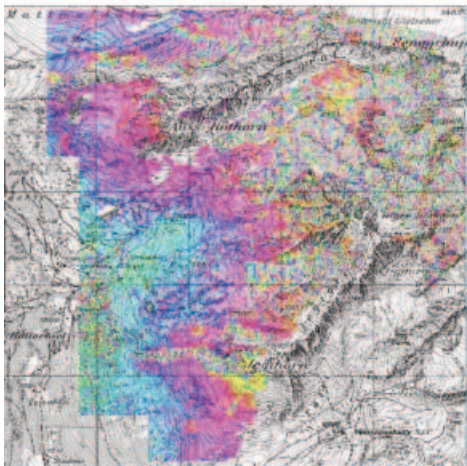
Figure 2. Selected differential interferograms over the Fletschhorn region superimposed to a topographic map. Dates of the SAR acquisitions, sensor, acquisition time interval and perpendicular baseline are: (a) 31 July–4 September 1998, ERS, 35 days, 105.6 m; (b) 16 July–24 September 1999, ERS, 70 days, –108.8 m; (c) 16 July–29 October 1999, ERS, 105 days, 4.7 m; (d) 10 August 1995–26 July 1996, ERS, 351 days, 69.3 m; (e) 10 August 1995–15 August 1997, ERS, 736 days, –18.6 m; (f) 21 June–17 September 1996, JERS, 88 days, –64.5 m.



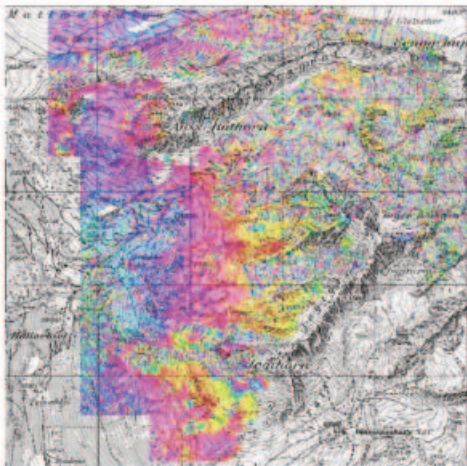
(a)



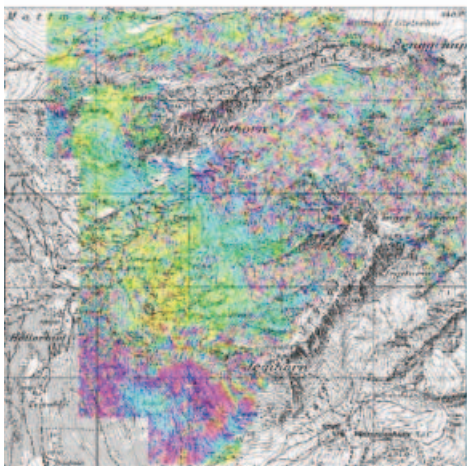
(b)



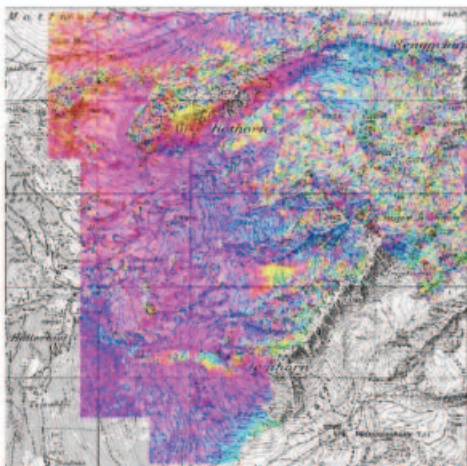
(c)



(d)



(e)



(f)

By moving to the ERS differential interferograms with acquisition time intervals of 105, 351 and 736 days of figure 2(c), (d) and (e), respectively, the rock glacier systems Rothorn and Jegi appear more and more decorrelated. In these interferograms, other minor displacements are evident for rock glaciers that were classified inactive or relict in the *in situ* inventory. Focusing on figure 2(d), this is for instance the case for the regions to the south of the Jegihorn and to the northwest of the Äusser Rothorn. To the west of the Äusser Rothorn there is also a signal where no rock glaciers are present indicating another type of slope instability.

The photogrammetric compilations revealed four rock glacier systems in the study area to be active to a significant degree (i.e. surface speed more than approximately 5 cm year^{-1}): Mattwald, Gruben, Rothorn and Jegi, shown in figure 3(a) to (d).

Gruben rock glacier shows horizontal surface velocities of up to 1 m year^{-1} . The flow direction is mainly directed towards the southwest. Starting at the lake on the rock glacier, velocities continuously increase from a few cm year^{-1} to the maximum velocities of about 1 m year^{-1} which are reached just above the rock glacier front. To the northeast of the rock glacier, remains of glacier ice, de-coupled from the main Gruben glacier (lower right of figure 3(a)) are situated. This so-called dead-ice body is flowing towards the southeast with speeds of more than 2 m year^{-1} . The field classification of activity suggested the Gruben rock glacier to be an active rock glacier. The dead-ice remains to the northeast were partially classified as inactive rock glacier due to the typical concave surface forms from individual patches of dead ice already melted out.

For the central part of Rothorn rock glacier the photogrammetric analyses gave surface velocities of up to 30 cm year^{-1} . The upper stream of the rock glacier showed no significant movement. In a zone further down, velocities between the significance level and 10 cm year^{-1} were found. The lowermost zone below a distinct rock glacier front showed no movement. Main creep direction is to the west, but slightly diverging towards the front. According to the field indicators, the central part of Rothorn rock glacier was classified as active, the upper stream as inactive, and the lowermost zone as relict.

The Jegi rock glacier system consists of two main streams, a northern and a southern one, separated by the ridge of Jegigrat. The southern stream creeps with velocities of up to 50 cm year^{-1} to the west with an increasing speed towards the front. Above the main front and on the lower part of the stream, velocities could not be measured due to missing image coverage. However, image interpretation and recent field inspection partially indicate strong surface destruction since 1975 indicating high deformation and/or strong erosion and rockfall on to the lower part of the system. On the northern stream, slightly significant velocities of some cm year^{-1} were measured. Within the inventory work the upper part of the southern stream was mapped as active, as was the upper part of the northern stream. The lower part of the northern stream was interpreted as relict. The lowest part of the southern stream was not interpreted as a rock glacier in the *in situ* inventory. This area shows structures of slumping and is heavily affected by rockfall activity from the main front of the Jegi rock glacier.

Highest surface velocities for Mattwald rock glacier of up to some 20 cm year^{-1} over the period 1975–1999 were found in the southern part from where the speed continuously decreases towards the front. On the northern stream only a few significant velocities of some cm year^{-1} were measured. Creep direction was to the northwest-west. *In situ* the rock glacier was classified as active, with an inactive

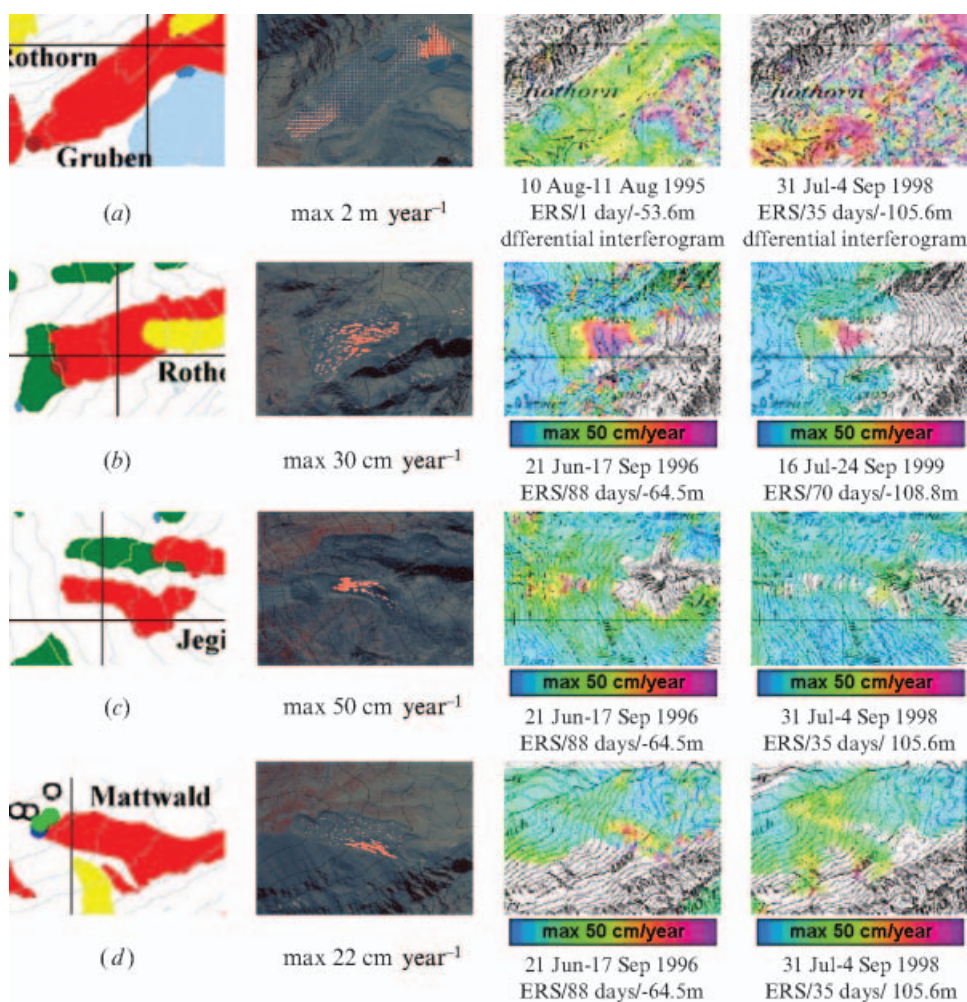


Figure 3. Surface displacement velocity over (a) Gruben, (b) Rothorn, (c) Jegi and (d) Mattwald rock glaciers in the Mischabel region. The first figures to the left are extracts of the rock glacier inventory of figure 1. The second figures to the left show the digital photogrammetry results, with the arrows indicating the direction and magnitude of the displacements. The last two figures to the right are derived from satellite radar interferometry, by assuming creeping in the direction of maximum slope. For Gruben rock glacier differential interferograms are shown because decorrelation did not permit the quantification of the surface displacement.

neighbour to the south. For this latter rock glacier, photogrammetric measurements were difficult due to image quality (shadow, snow) and surface changes. However, at individual points, surface velocities of up to $10\text{--}20\text{ cm year}^{-1}$ to the north seem possible. Similar problems in image analysis apply also for the upper part of the Mattwald rock glacier (classified as active in the *in situ* inventory), but with even larger uncertainties for the velocities.

The four active rock glacier systems in the study area were also cautiously analysed with DInSAR in figure 3. Displacement maps were computed for three of the rock glaciers, Mattwald, Rothorn and Jegi, whereas for Gruben rock glacier

complete decorrelation was found for interferograms of more than 1 day acquisition time interval so that only the unwrapped phase is shown in this case.

4. Discussion

The DInSAR and the photogrammetric measurements show a good agreement both for the study area in general and for individual rock glaciers in particular. The rock glaciers detected to be active by photogrammetry and field classification were also detected by DInSAR. Similarly, the order of magnitude for the creep speeds compares well, even if DInSAR reveals slightly higher speeds. It is possible to attribute these differences to measurement errors, but it has also to be considered that the photogrammetric measurements deliver an average velocity over 24 years, whereas the DInSAR measurements represent snapshots over some days or weeks in the late 1990s. A change in rock glacier velocity in the observed order of several cm year^{-1} might well be possible. Both seasonal and pluriannual velocity variations of this magnitude have already been observed for other rock glaciers (Haeberli 1985, Kääb *et al.* 1997, Arenson *et al.* 2002, Kääb *et al.* 2003).

For large rock glaciers such as the Rothorn not only were the correct degree of activity and order of surface speeds detected with DInSAR but also the entire displacement field was displayed with a reasonable agreement compared with digital photogrammetry. The interferograms give the typical velocity distribution with highest speeds in the rock glacier centre.

The DInSAR measurements of Gruben rock glacier for acquisition time intervals of more than one month show complete decorrelation and only the unwrapped differential interferograms are shown in figure 3(a). The decorrelation of this rock glacier is not the effect of the SAR imaging geometry or of the presence of wet snow, because the phase signal in summer tandem interferograms is clear. It is probable that the decorrelation over Gruben rock glacier after only 35 days is caused by the large displacement gradients of up to 10 cm in 500 m, similar to that observed with DInSAR for underground coal mining-induced surface deformation (Spreckels *et al.* 2001).

Below the southern Jegi rock glacier, and at the front of the Mattwald rock glacier, the advantage of DInSAR for detecting very small movements becomes apparent. Photogrammetry did not reveal any significant movement (i.e. clearly smaller than 5 cm year^{-1}) for these areas. Field classification gave a transition from active over inactive to relict parts. In some interferograms surface deformation can clearly be seen. It is, however, an open issue whether the deformation observed from DInSAR for the inactive and relict parts of the rock glaciers is due to 'active' ice deformation or due to 'passive' pushing by the upper active rock glaciers. The debris slope below the Jegi rock glacier was not classified as rock glacier, but some interferograms indicate movement. Also here, it is not clear if these small movements are due to deformation of frozen debris.

5. Conclusions

In this study DInSAR proved to be suitable for area-wide detection of rock glaciers. Not only could the degree of activity be retrieved but also the order of surface speed and, for individual cases, characteristics of the displacement field. Until today, such area-wide accurate mapping of rock glacier speed was only possible with repeated photogrammetry. Related photogrammetric measurements require aerial photography over long time periods of tens of years in order to derive

rock glacier surface velocities at a significant level of accuracy. Such mapping of areas larger than some tens of km² is connected with a substantial expenditure in time and finances. On the other hand, aero-photogrammetry is able to provide the three-dimensional surface flow field including speed, direction and also changes in rock glacier thickness (the latter is not discussed in this contribution). The optical imagery used for the photogrammetric analyses represents a valuable base for additional visual interpretations. In contrast to airborne photogrammetry, space-borne DInSAR is capable of covering large areas in one process, and detecting even very small movements or their changes. However, DInSAR provides only the line-of-sight component of the rock glacier speed (transformed into the slope direction in this study).

For rock glacier research and assessment of related slope instability hazards, our study suggests the following priority fields of application for DInSAR:

1. DInSAR is especially useful for area-wide detection of rock glaciers and similar slope instabilities.
2. Such results reveal valuable parameters for further detailed investigations at selected sites by photogrammetric or field-based methods.
3. DInSAR is able to provide rock glacier speed for a large number of such landforms and might, thus, promote the understanding of the coupling between landscape, climate and rock glacier activity.
4. The detection of very small movements by DInSAR will provide new insights into the behaviour of inactive or even relict rock glaciers.

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