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Active Rock Glaciers in a Changing Environment

Geomorphometric Quantification and Cartographic Presentation of Rock Glacier Surface Change with Examples from the Hohe Tauern Range, Austria

Contents

Summary

This paper gives a comprehensive overview on the geomorphometric mapping of active rock glaciers, which are creep phenomena of mountain permafrost. Various methods of detection and quantification of rock glacier surface change are outlined, focusing especially on mapping flow velocity and surface elevation change. We briefly outline how this kind of geometric information can support process understanding of rock glaciers and climate change studies. Furthermore, the importance of good cartographic visualization of rock glacier surface change is addressed. Examples taken from on-going rock glacier monitoring projects carried out in the Hohe Tauern Range (Eastern Alps, Austria) not only illustrate the different cartographic possibilities, from static maps to computer animations, but also highlight quantitative information describing the kinematics of each selected rock glacier in more detail. Our preliminary findings are that change rates of flow velocities of the different rock glaciers are highly correlated and largely depend on climatic conditions, such as air temperature and ground thermal conditions.

Keywords: permafrost, rock glacier, monitoring, surface deformation, surface flow velocity, change detection, climate change, visualization, Hohe Tauern Range

1 Introduction

Rock glaciers are creep phenomena of mountain permafrost (Barsch 1996) and are relatively common in high-mountain areas around the world (Barsch 1996; Haeberli et al. 2006; Berthling 2011). Active rock glaciers flow downslope by force of gravity due to internal deformation of the ice-rock mixture, creating typical flow patterns reminiscent of lava flows. The flow patterns (wrinkles, longitudinal and transversal ridges) are the cumulative result of sustained surface flow/deformation under the influence of permafrost. Flow velocities are generally low (up to max. several meters/year) and vary over time depending on permafrost as well as topoclimatic conditions. In case of unfavorable topographic conditions at the rock glacier bed, the rock glacier body may start to disintegrate (e.g. Avian et al. 2009) or even completely tear apart and collapse (Krysiecki et al. 2008).

In general, rock glaciers under widespread permafrost conditions may be active (moving) or inactive (not moving). Climate change might lead to permafrost degradation and hence an inactive rock glacier might turn first to a pseudo-relict (containing patches of permafrost) and finally to a relict (no permafrost) rock

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glacier. The latter two types are rather stable and are commonly vegetated on the surface despite the rugged topography of ridges and furrows developed during the active phase (Barsch 1996; Kellerer-Pirklbauer 2008). Changes in meteorological conditions from one year to the next have a strong impact on the kinematics of active rock glaciers underlining the importance of climate effects (Kääb et al. 2007; Delaloye et al. 2008; Kellerer-Pirklbauer & Kaufmann 2012).

The present paper intends to answer the following research questions: (a) Where are active rock glaciers located and how fast are they moving? (b) How is the movement pattern changing over time and space? (c) What is the relationship between rock glacier movement and climatic factors? (d) What are the effects of climate change on rock glaciers? Practical investigations have been carried out at selected test sites in the Hohe Tauern Range, Austria, to answer these questions.

2 Detection and quantification of rock glacier surface change

The determination of rock glacier flow velocity has a long tradition that dates back to the early beginning of rock glacier research (Chaix 1923). In general, the knowledge about the geometrical change of a rock glacier in space and time is crucial to answer rock glacier related research questions. Reliable information about the geometric state of an object can be retrieved by means of a deformation analysis which is a classic geodetic task. Its typical steps are measurement, evaluation, analysis and interpretation. In present rock glacier research the classical deformation analysis concept (congruence model) is mostly based on purely geometrical comparison of the state of the permafrost body at two different points of time. Other advanced concepts, such as kinematic or dynamic deformation models, are currently under investigation, however publications are rare.

The majority of the rock glaciers deform rather slowly and smoothly over time. However, in some rare cases the movement of rock glaciers can accelerate greatly causing partial or even complete disintegration of the rock glacier body (Krysiecki et al. 2008; Avian et al. 2009; Schoeneich et al. 2014). Various measurement methods exist to observe deformation of a rock glacier at its surface but also in its interior (e.g. Haeberli et al. 2006). In this paper we will only focus on surficial measurements. Inclinometer measurements in boreholes within rock glaciers are intentionally not considered since such measurements are not available for our study area.

From a practical and also sensorial point of view, each individual rock glacier (which is a continuum) will be approximated by discrete points at which displacement, consisting of movement and distortion, is observed. In the optimal case the measurement technique provides direct three-dimensional (3D) displacement vectors forming a 3D vector field at the surface. Furthermore, geometrical subsets may be also two-dimensional (2D), mostly planar, or one-dimensional (1D), mostly vertical, depending on the measurement and/or analysis technique. The existing measurement techniques in rock glacier monitoring can be classified into three groups, i.e., geodetic methods (total station, GNSS-based), image-based methods, and laser scanning (Kääb 2005; Haeberli et al. 2006). The respective sensors of the latter two may be ground-based, airborne and spaceborne.

Many rock glacier monitoring programs rely on an existing geodetic network consisting of a few stable reference points located outside of the rock glacier and a set of well-distributed observation points on the rock glacier itself. These observation points are measured on a regular basis, preferably annually, within a predefined geodetic reference frame. Measurements using a total station are highly accurate, i.e. in the subcentimeter range. In any case, stable reference points are a prerequisite and their stability must be checked each epoch. Due to the technical complexity of the method and its requirement for a skilled operator and additional assistants, it has been replaced by GNSS (Global Navigation Satellite System)-based positioning in recent years. Modern GNSS equipment is affordable and allows point determination in real time in the 1–3 centimeter range (Hofmann-Wellenhof et al. 2008). RTK (real-time kinematic) GNSS positioning is possible using either a local base station in close vicinity of the rock glacier (a second GNSS receiver is needed) or a virtual reference station (VRS) provided by a dedicated service. In contrast to the optical measurements of the total station, GNSS-based measurements can also be made under bad weather conditions. However, GNSS positioning is sometimes poor in mountainous regions due to shadowing effects of surrounding mountains and also multipathing of signals.

A total station or a GNSS-based method allow only a limited number of points to be observed within a day's work. Current research work focuses on continuous rock glacier monitoring using low-cost receivers (Wirz et al. 2011). In-situ wireless sensor networks (WSN) will make it possible to receive and process GNSS data of several nodes in near real time (Singer et al. 2009; Buchli et al. 2012). GNSS data will also be augmented by simultaneous measurements of other sensors, e.g. inclinometers or temperature loggers. The results obtained from both measurement techniques are often used to validate results obtained by other, often newly developed observation techniques.

Dense and area-wide information on rock glacier surface deformation can only be provided by image-based techniques or laser scanning. Digital photogrammetry is one of the most powerful techniques for obtaining 3D (2D) displacement vectors based on multi-temporal photographs (Kaufmann & Ladstädter 2002; Debella-Gilo & Kääb 2011; Debella-Gilo & Kääb 2012a; Debella-Gilo & Kääb 2012b). Various processing schemes have been developed to handle terrestrial, airborne and spaceborne image data. Highly automated software systems support democratization of this technique (Klug et al. 2012). Digital photogrammetry has benefited considerably from new digital sensors, e.g. aerial cameras, and from developments in computer vision. The use of highly overlapping photographs and dense image matching technology makes it possible to compute dense point clouds on a pixel-per-pixel basis surpassing current high point densities of modern airborne laser scanning (ALS) systems. Thus, digital elevation models (DEMs) can be derived with high spatial resolution and accuracy, and made comparable to ALS-derived DEMs. DEM differencing provides information on both surface elevation change and volume change. High-resolution multi-temporal DEMs can also be used to retrieve 3D displacement vectors through matching of surface structures (e.g. Avian et al. 2008 using laser scanning data). The evaluation of repeat terrestrial photography to detect and quantify rock glacier changes has been described, for example, by Ladstädter & Kaufmann (2004) and Kaufmann (2012).

Differential SAR interferometry is a powerful remote sensing technique to monitor geometric changes of the Earth's surface with high precision. Rott & Siegel (1999), Kenyi & Kaufmann (2003) and Barboux et al. (2014) describe various examples of successful application of this technique using image data from various spaceborne SAR sensors, such as ERS-1/2 or JERS. The surface deformation information obtained is restricted, however, to the line-of-sight of the SAR sensor used. Challenges include the temporal decorrelation of the SAR signal, the simultaneous detection of both slow and fast moving rock glaciers, and the mapping of 3D deformation vectors. Monserrat et al. (2014) describe the application of ground-based SAR (GBSAR) interferometry for deformation measurement of mountain slopes using both the interferometric principle and image matching of radar intensity data. A practical application of this technique to rock glacier monitoring, however, is not known to the authors.

Laser scanning is an active remote sensing technique which provides dense point clouds for computing high-resolution DEMs. ALS has recently become a standard method for obtaining DEMs of large areas, such as whole countries. Surface elevation change, and thus volumetric change, and even 3D displacement vectors can be derived from multi-temporal DEMs as outlined by Bollmann et al. (2012), Daehne & Corsini (2013) and Kenner et al. (2014). Several examples demonstrate the combined evaluation of ALS data and digital aerial photographs for mapping mass movements in mountainous terrain. Terrestrial laser scanning (TLS) is designed to study local test sites with high spatial and temporal resolution. Successful examples of monitoring rock glaciers and other mass movements, such as landslides, are given by Bauer et al. (2003), Avian et al. (2009), Abellán et al. (2014), Ravanel et al. (2014) and Travelletti et al. (2014). Area-wide mapping of rock glacier surface change, providing complete information on whole mountain regions or even mountain belts, is still a challenge in respect to both data acquisition and data evaluation. A synoptic view can only be provided by proper remote sensing techniques as outlined previously.

3 Towards process understanding

Rock glaciers are commonly formed over long time spans. The computation of three-dimensional surface velocity fields (as described above) allows the quantification of creep rates. The detected creep rates form the basis for the calculation of streamlines which allow a first estimation of the age of a rock glacier assuming constant formation rates. Combining this rock glacier dating approach with other relative (e.g. Schmidt hammer) or absolute (e.g. cosmogenic nuclides) dating methods, gives a clearer picture of initial formation, changes in movement rates over time and total age of individual rock glaciers (e.g. Haeberli et al. 2003; Kellerer-Pirklbauer et al. 2008). Dating results generally indicate that rock glaciers have formed over a time span of several hundreds to thousands of years. Furthermore, datings clearly demonstrate that rock glaciers are commonly not simply debris-covered glaciers remaining from the more glacier-friendly Little Ice Age period.

Rock glaciers form initially from perennially frozen debris material either originating from talus slopes or from other sources of debris (e.g. till). In an early phase a simple protalus rampart might evolve in particular at the foot of a talus slope. Compressional stresses act within the rock glacier body when the rock glacier moves into cirque overdeepenings or plain surfaces forming transverse ridges and furrows. Contrary, extensional forces act when the rock glacier leaves the cirque or plain surface and moves further down a (steep) slope. Only recently, the morphology of furrows and ridges was explained by gravity-driven buckle folding (Frehner et al. 2014). Buckle folding is the mechanical response to compression of a layered viscous material with substantial mechanical differences between the layers. However, other theories of ridge formation have also been proposed such as differential movement due to ridge growth through bulging under compressive flow (Kääb & Weber 2004).

The temporal change in surface flow velocity of rock glaciers is primarily related to climate as indicated by recent studies. Correlations between changes in rock glacier movement and air temperature support the theory that the temporal change of the surface flow velocity is primarily related to climatic conditions (Kääb et al. 2007; Delaloye et al. 2008; Kellerer-Pirklbauer & Kaufmann 2012). Air temperature and other climate elements such as snow affect ground temperatures in a complex way. An increase in the ground temperature of an active rock glacier leads to warming and partial thawing of the permafrost body. Temperatures slightly below 0°C change the rheological properties of the warming rock glacier ice causing higher internal deformation (Roer et al. 2008). Laboratory experiments have shown that frozen rock joints reach minimal stability just below 0°C (Davies et al. 2001). In addition an increasing availability of liquid water due to thawing within the rock glacier might increase rock glacier movement rates (Ikeda et al. 2008). Potentially, basal sliding could also take place along a water-saturated, fine-grained till layer below the rock glacier body (Hausmann et al. 2007). Further permafrost thawing would cause an increase in internal friction due to an increasing degree of clast contact leading eventually to rock glacier stabilization.

4 The role of cartography in rock glacier monitoring

Since rock glaciers are phenomena of cold mountainous regions, it seems natural that primarily methods and ideas of mountain (glacier) cartography have been adopted for visualization of rock glacier related topics. In this respect the cartographic visualization of (white) glaciers and their changes, i.e., in extent, surface elevation and flow velocity, is the basis for most of the rock glacier related visualizations (Häberling 1998; Hurni et al. 2000; Buckley et al. 2004). Mountain cartography itself has a relatively long tradition of more than 100 years (at least in Europe) and has gained strong impetus in the last decades because of mountain tourism (hiking, skiing, etc.), environmental issues (glacier recession), and also technological progress (new electronic media for visualization).

Specific cartographic representations of rock glacier related topics may slightly differ from those of (white) glaciers because of the obvious difference in their phenology and the amount of potential surface change (Kääb 1998; Kääb et al. 2003). We must keep in mind that rock glaciers, in contrast to (white) glaciers, are mostly unknown to non-professionals and will therefore not be recognized as such in the field. Moreover, rock glacier change is not in fact visible in-situ at all (apart from some cases of very fast ones; cf. Schoeneich et al. 2014). Rock glacier related cartography thus means making the invisible visible.

Rock glacier related visualization comprises (1) the cartographic representation of the landform itself in a map or map-like depiction and (2) the depiction of the landform's spatio-temporal change. Rock glaciers (all four different types) are visually perceived by their flow-like surface structure. Thus, the various cartographic means, i.e., contour lines, shaded relief, orthophoto, and possibly also hachures, must represent the landform in such a way that it is clearly identifiable. 3D perception of the landform can be achieved, for example, through stereo orthophoto maps, as shown in Kaufmann & Heiland (1998, see also Fig. 2), or by lenticular foil systems. Only a few examples of dedicated rock glacier maps are known. Printed maps of this kind are scarce (Kaufmann 2004).

The cartographic visualization of rock glacier surface change is diverse, and it mostly relates to similar visualizations known in glaciology (Wiesmann et al. 2009) and in applied earth sciences where mass movements, for example landslides, are of interest (Kenner et al. 2014; Ravanel et al. 2014; Travelletti et al. 2014). In general, visualizations of surface deformation intend either (1) to make quantitative information (i.e., flow direction and velocity, surface elevation change, strain parameters, etc.) quickly perceivable for immediate interpretation in order to understand the area-wide deformation pattern and its spatio-temporal change or (2) to simply animate surface depictions (such as shaded reliefs or orthophotos, representing distinct epochs) for obtaining more qualitative information about the inherent surface deformation.

Surface deformation of rock glaciers is preferably visualized by means of horizontal displacement vectors (irregularly distributed point data or regular grid data) and isolines (isotachs) both of horizontal flow velocity and surface elevation change. For reasons of comparison quantitative data from time series analysis is often normalized, e.g., to annual values. Color is often used as an additional or even redundant information channel (choropleth maps), see, e.g., Kääb & Vollmer (2000), Kääb (2005), Kaufmann et al. (2006a, b), Kaufmann & Ladstädter (2010).

Special thematic maps have been generated to visualize multi-year flow, streamlines, principal strain components, etc. Isopleths can only be derived in good quality from remote sensing data because it provides dense and evenly distributed data for interpolation. The corresponding choropleth maps can be combined with point data information, e.g. displacement vectors.

Computer animations (using animated GIFs) of multitemporal orthophotos or shaded reliefs are an ideal means to visualize surficial morphological processes and also surface movement. Images of the various epochs form the key frames of the animation. Time-lapse photography of rock glaciers offers great potential for making the slow movement of a rock glacier visible (e.g. Kaufmann 2014a). Furthermore, computer-generated 3D fly-through animations over areas with rock glaciers help readers visualize and perceive such landforms (e.g. Kaufmann 2014b). Interactive 3D visualizations of rock glacier change are not known to the authors (cp. with Bruengger et al. 2013).

5 Rock glacier monitoring in the Hohe Tauern Range: Examples

5.1 Overview

The Hohe Tauern Range is an extensive mountain range in the central part of the Eastern Alps covering approx. 6,000 km² in Austria and – to a very minor extent – Italy. The Hohe Tauern Range is partly glaciated, widely influenced by permafrost and reaches a maximum elevation of 3,798 m a.s.l. at the Grossglockner (the highest mountain in Austria). This study focuses on four rock glaciers in the Hohe Tauern Range. One is located in the Ankogel Mountains sub-unit (Dösen rock glacier/DOE) and three are situated in the Schober Mountains sub-unit (Hinteres Langtalkar rock glacier/HLK, Weissenkar rock glacier/WEI, Leibnitzkopf rock glacier/LEI). On a more regional scale we quantified rock glacier movement rates for a 125 km² large area in the central part of the Schober Mountains/CSM (see Fig. 1).

5.2 Dösen rock glacier (DOE)

Dösen rock glacier (L: 950 m, W: 300 m) is located in the Inner Dösen Valley (see Fig. 1, 2). Multi-disciplinary research at this rock glacier is diverse and started in the early 1990s (Lieb 1998; Kaufmann 1998; Kellerer-Pirklbauer & Kaufmann 2012; Kellerer-Pirklbauer et al. 2014). Long-term monitoring of surface flow velocity is based on geodetic, photogrammetric and radar interferometric techniques (Kenyi & Kaufmann 2003; Kaufmann et al. 2006a). For example, the horizontal movement of the geodetically measured points is shown in Figure 3. The red lines show the horizontal movement of the observation points over time. The movement shown is exaggerated by a factor of 15. Point 15 (central location) is the fastest one and has moved in total 7.44 m down-valley during the last 19 years, which results in a mean flow velocity of 39.2 cm/a. The maximum annual horizontal flow velocity of 52.2 cm/a was observed for the time period 2013–2014.

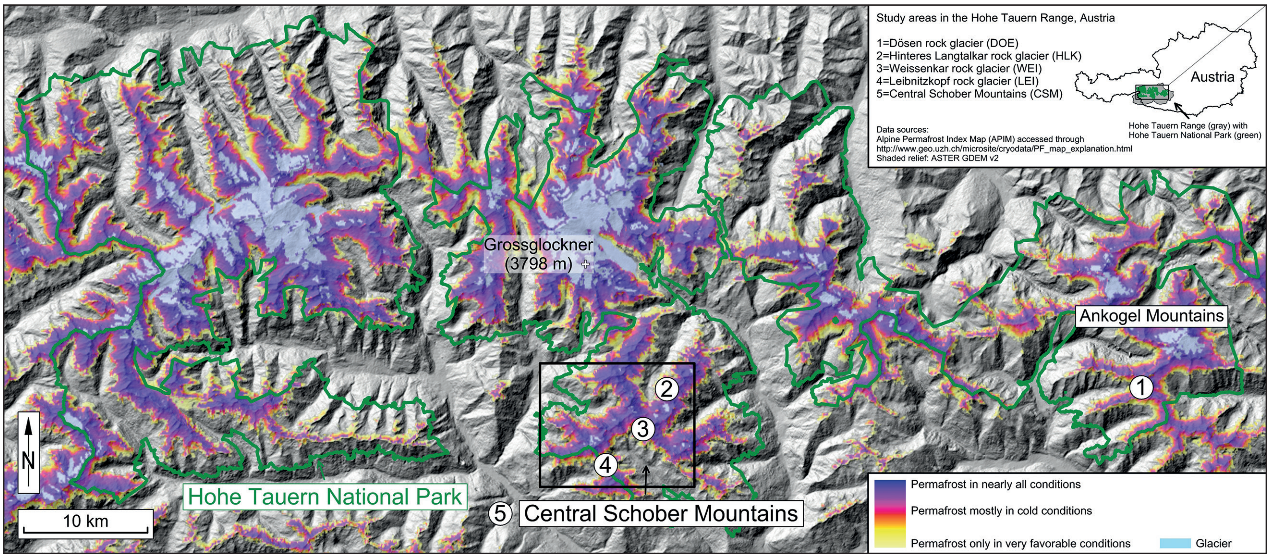

Fig. 1: Location of the study areas in the Hohe Tauern Range, Austria. The main map depicts the distribution of glaciers and modelled permafrost (Boeckli et al. 2012).

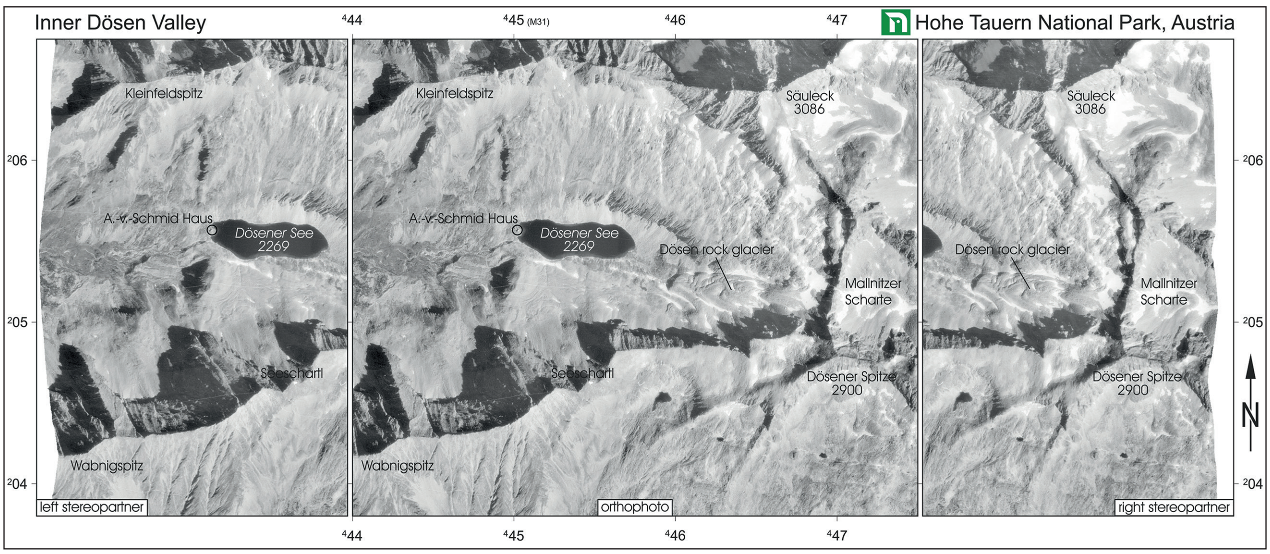

Fig. 2: Stereo-orthophoto map of Dösen valley. Map modified after Kaufmann & Heiland (1998).

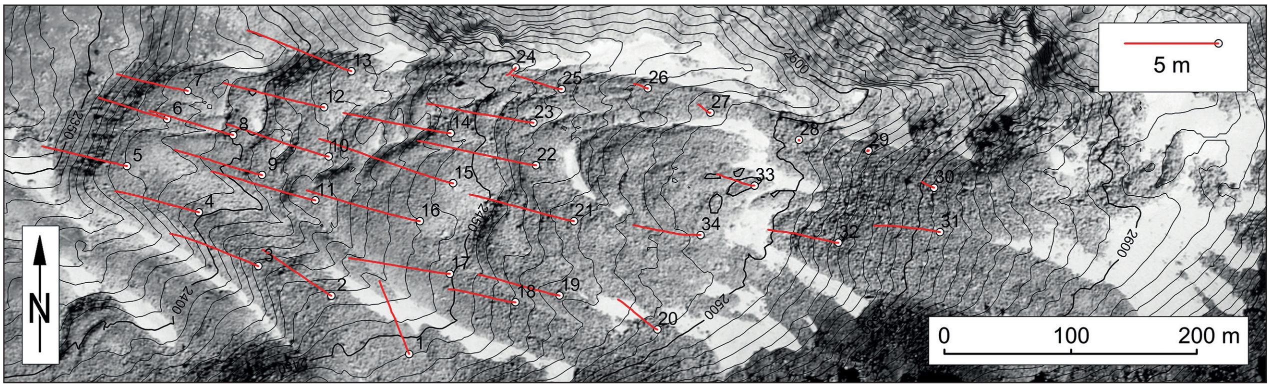

Fig. 3: Multi-annual movement (1995–2014) of the 34 observation points at Dösen rock glacier.

5.3 Hinteres Langtalkar rock glacier (HLK)

Hinteres Langtalkar rock glacier (L: 700 m, W: 200–350 m) is located in a west facing cirque (see Fig. 1, 4, and 9). It is composed of a main tongue in the north and a smaller side lobe in the south. The surface topography of the main tongue is peculiar. The lower end of the rock glacier is affected by active landsliding, whereas several transversal tension cracks in the upper part give evidence of high longitudinal strain. The frontal slope of the rock glacier is monitored on a regular basis by means of terrestrial laser scanning (BAUER et al. 2003; AVIAN et al. 2008, 2009). Long-term geodetic and photogrammetric measurements document the rock glacier's kinematics and pronounced topographic changes (KAUFMANN & LADSTÄDTER 2002; 2010; KELLERER-PIRKLBAUER et al. 2014). Figure 4 visualizes the horizontal movement of the geodetic observation points for the time period 2013–2014. The movement shown is exaggerated by a factor of 25. Point 25 shows the greatest horizontal displacement, 5.92 m, of all points observed. DEM differencing reveals marked surface height change (see Fig. 5). The DEMs used were derived photogrammetrically from aerial photographs (1954) and ALS (2012). Volume loss of the rock glacier is approx. 394,350 m^3. Mean surface elevation change amounts to -1.65 m, which is equivalent to a mean surface lowering of -2.8 cm/a. Figure 6 provides a detailed visualization of the surface kinematics of the rock glacier's highly active lower part. The precision of the respective measurements is ±7 cm/a (1σ). The maximum flow velocity is 3.37 m/a.

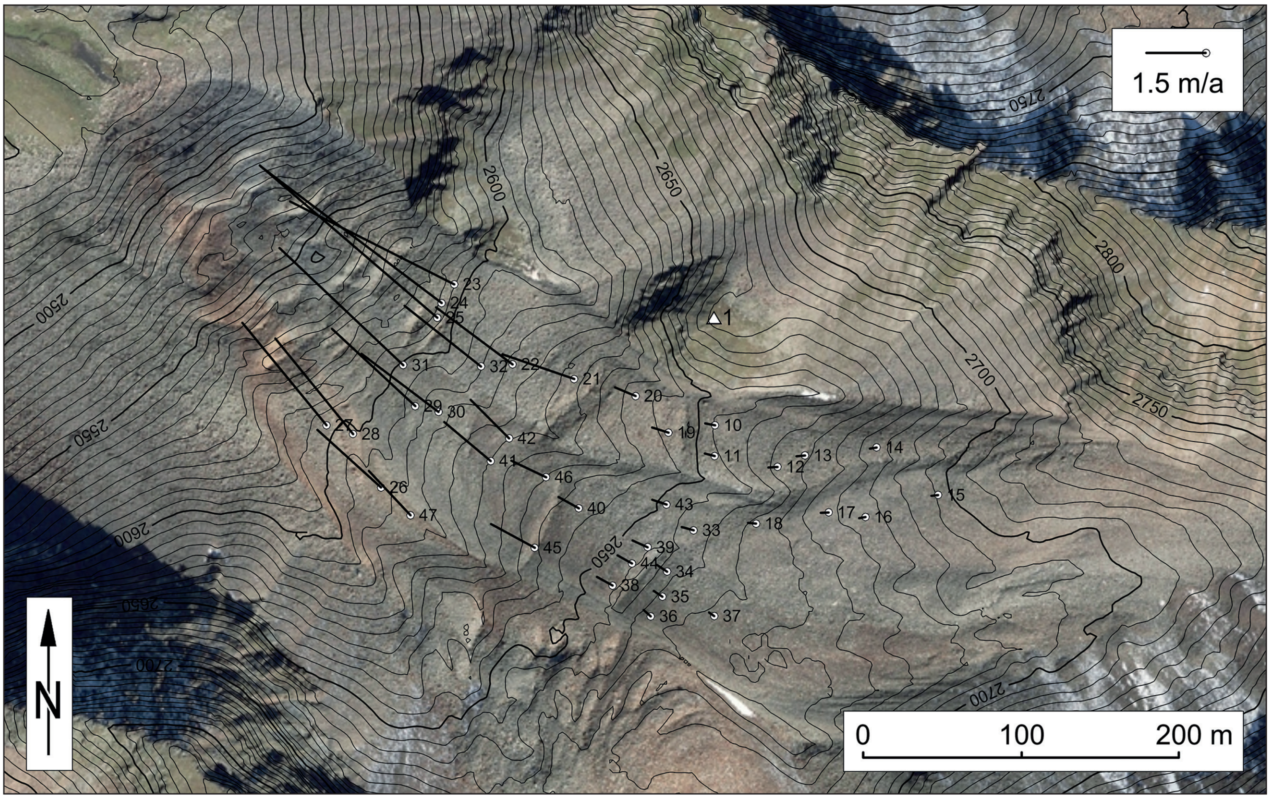

Fig. 4: Annual horizontal movement 2013–2014 of Hinteres Langtalkar rock glacier.

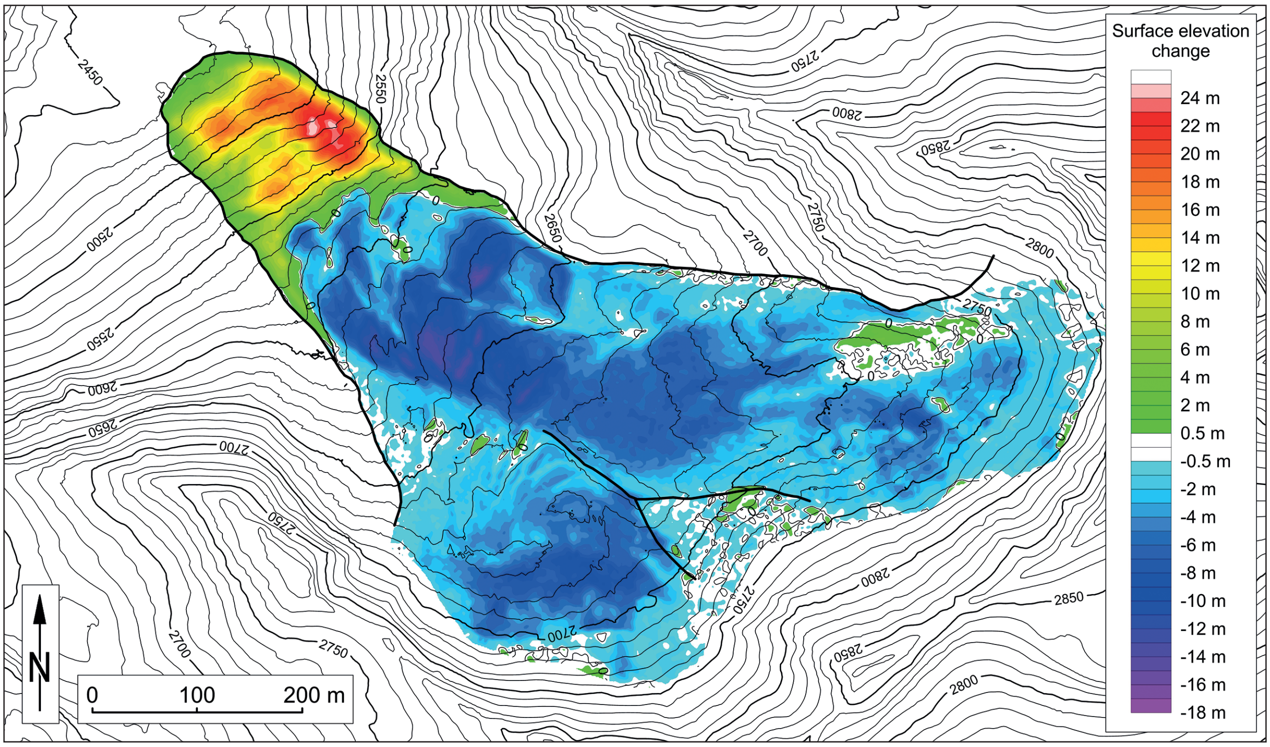

Fig. 5: Surface elevation change at Hinteres Langtalkar rock glacier during the period 1954–2012.

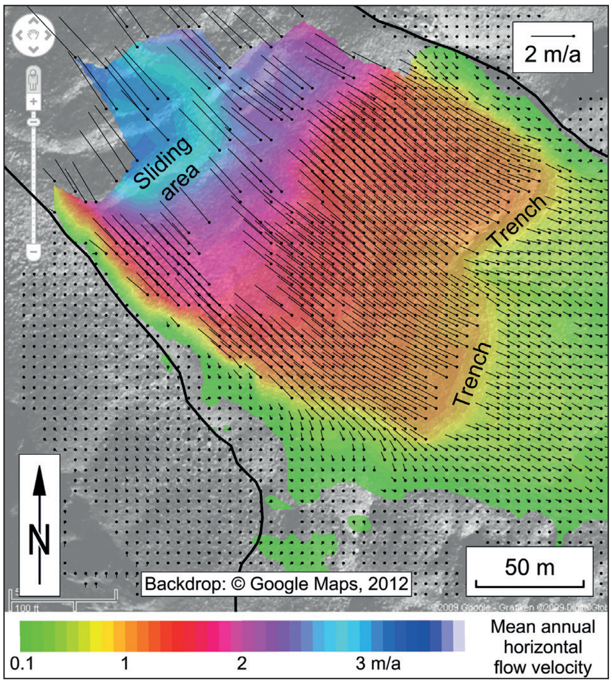

Fig. 6: Mean annual horizontal movement of the very active lower part of Hinteres Langtalkar rock glacier derived from image data of Google Maps (epoch 2002) and Microsoft Bing Maps (epoch 2006).

5.4 Weissenkar rock glacier (WEI)

Weissenkar rock glacier (L: 500 m, W: 250 m) is located in a west-facing cirque. WEI is creeping rather slowly downslope (see Fig. 1, 7, and 9) presumably due to a lower ice content as indicated by geophysical measurements (Kellerer-Pirklbauer et al. 2014). Longitudinal compression has generated a pronounced surface pattern of furrows and ridges. Results of the most recent geodetic measurements (2012–2013) are presented in Figure 7. The movement shown is exaggerated by a factor of 500. Point 14 shows the largest horizontal displacement, 12.7 cm, of all points observed.

5.5 Leibnitzkopf rock glacier (LEI)

Leibnitzkopf rock glacier (L: 370 m, W: 230 m) is also located in the Schober Mountains, but in contrast to HLK and WEI, outside of the Hohe Tauern National Park (Fig. 1, 9). Buchenauer (1990) classified this rock glacier in the 1980s as intact but inactive. Change detection analysis using data (2002, 2006) of virtual globes suggested, however, that this rock glacier is quite active (Kaufmann 2010). The results obtained were later confirmed by more precise photogrammetric and geodetic measurements. Figure 8 shows the kinematics of this rock glacier for the time period 2009–2012 derived from orthophotos. The accuracy of the isotachs is ±10 cm/a (1σ). Maximum flow velocities of slightly over 4 m/a were measured geodetically for the observation period 2013–2014 at points 14 and 15.

5.6 Central Schober Mountains (CSM)

On the regional scale, we intended to detect all fast moving rock glaciers in a 125 km² test area in the central part of the Schober Mountains (see Fig. 1) using

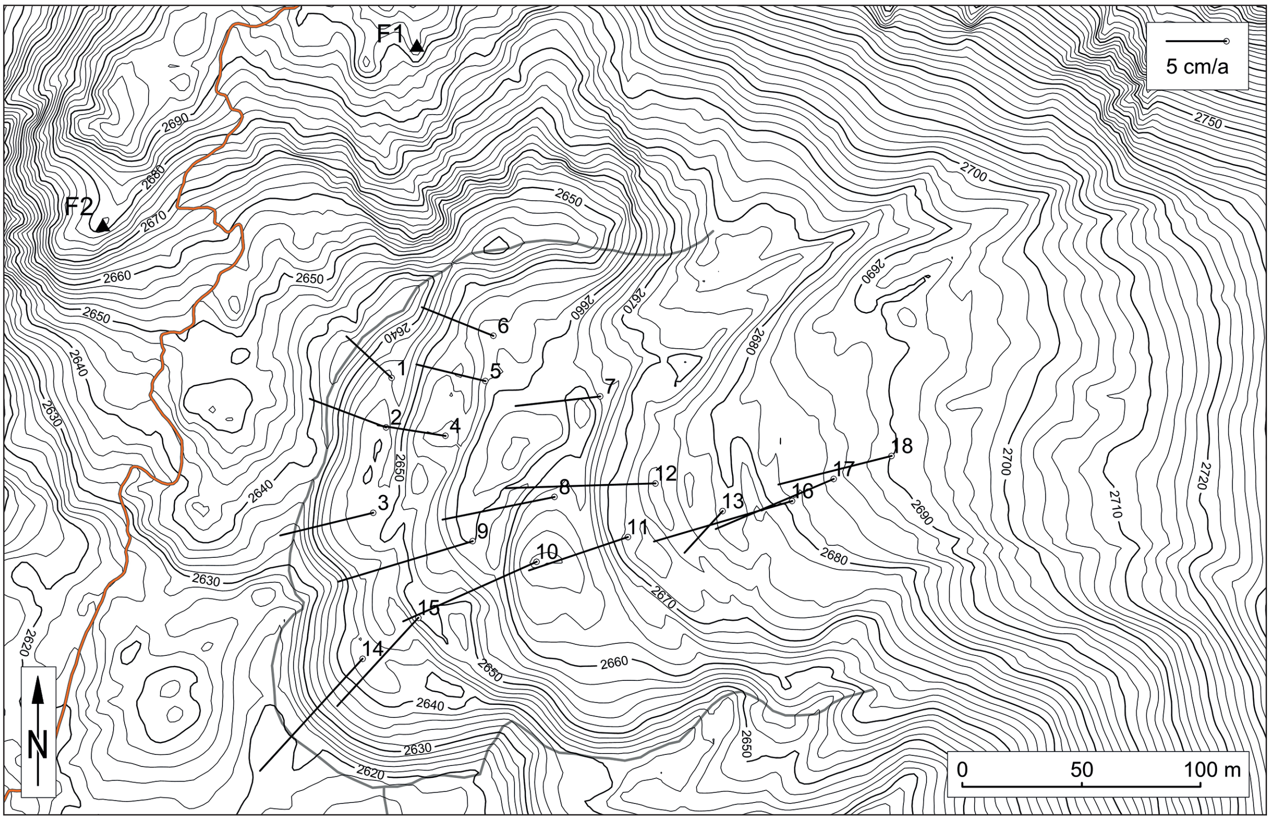

Fig. 7: Annual horizontal movement 2012–2013 of Weissenkar rock glacier.

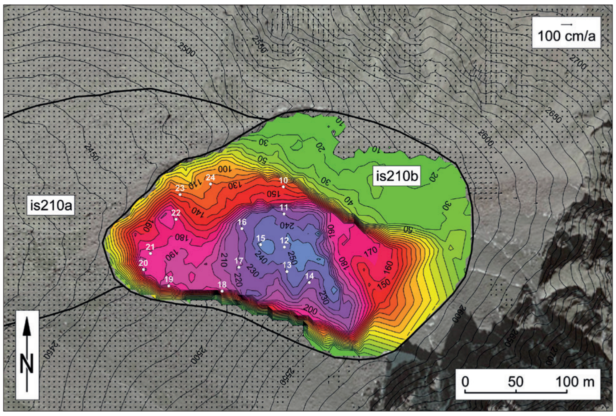

Fig. 8: Mean annual horizontal flow velocity (cm/a) at Leibnitzkopf rock glacier for the time period 2009–2012.

publicly available (governmental) orthophotos. A total of 99 rock glaciers were inventoried in the test area by KELLERER-PIRKLBAUER et al. (2012). They classified 64 rock glaciers as intact and 35 as relict. Orthophotos of three different epochs, i.e., 2002, 2009 and 2012, were made available. For computational reasons the resolution of the original high-resolution orthophotos was reduced to obtain a common ground sampling distance (GSD) of 50 cm. Change detection was carried out for the time periods 2002–2009 (see Fig. 9) and 2009–2012. The significance level of the velocities computed depends primarily on the geometric quality of the orthophotos involved and the associated time spans. Good estimations (3σ) are ~20 cm/a for 2002–2009 and ~30 cm/a for 2009–2012.

The following conclusions can be drawn: (1) About 12 intact rock glaciers display a maximum horizontal flow velocity of more than 50 cm/a. (2) Flow velocities have significantly increased within the observation period. Maximum flow velocities of up to 4.4 m/a were detected at Hinteres Langtalkar rock glacier. (3) The accuracy of the orthophotos available for high mountain areas of Austria is limited due to insufficient quality/accuracy of the DEMs involved. (4) The latter could be easily improved by using ALS-derived DEMs or contemporaneous DEMs obtained from the aerial photographs of the orthophoto project.

6 Rock glacier monitoring in the Hohe Tauern Range: A synopsis

The mean surface velocities of the four rock glaciers differ substantially. However, despite the substantial differences in absolute movement rates, flow complexity or morphology, the acceleration or deceleration over time is rather synchronous. Results of correlation analyses between the mean movement rates of the four rock glaciers indicate strong and statistically significant positive correlations for the rock glaciers with longer time series (DOE, HLK, WEI; r=0.80–0.97), and strong but partly insignificant correlations for the rock

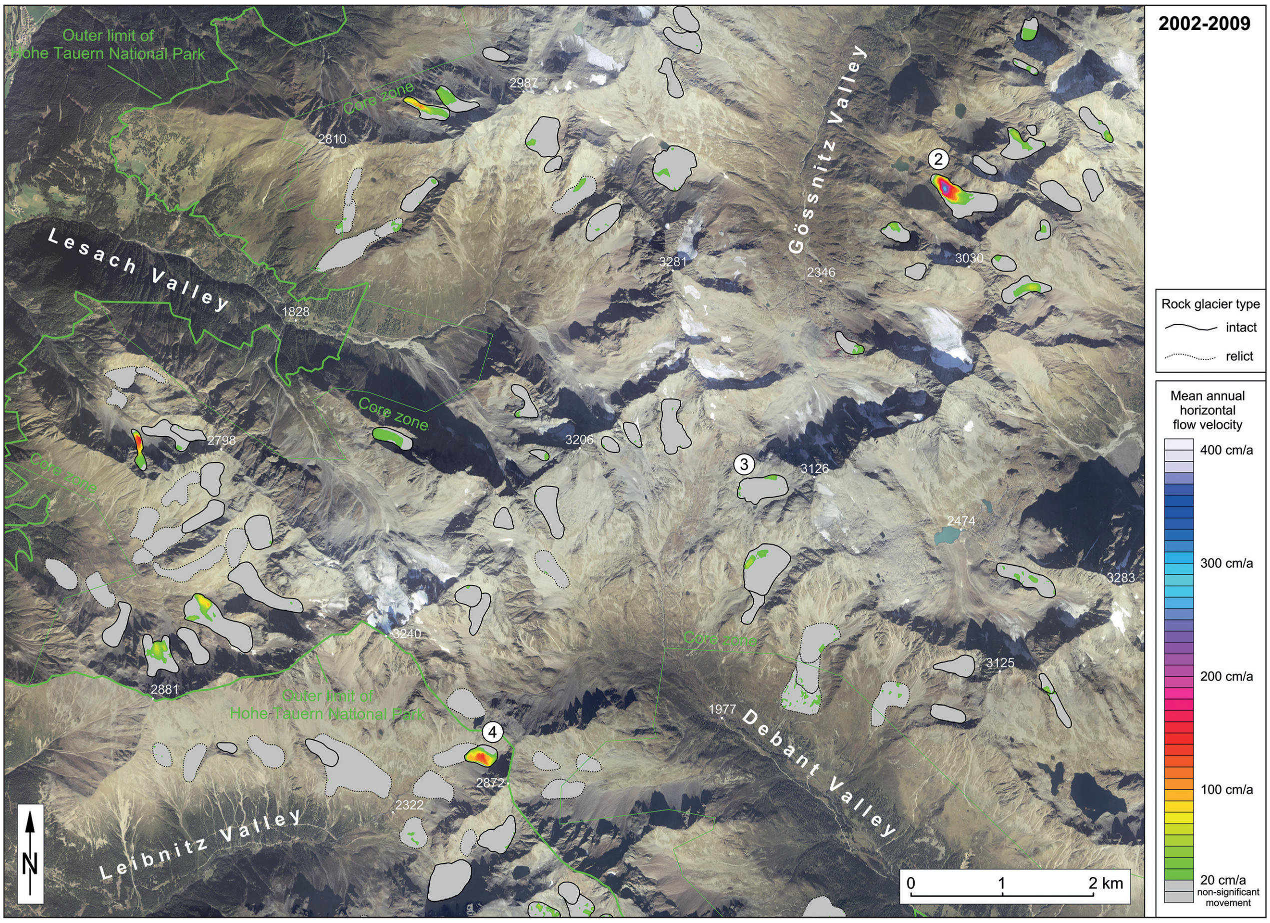

Fig. 9: Mean flow velocity of active rock glaciers (movement >20cm/a) of the Central Schober Mountains for the time period 2002–2009. Indicated rock glaciers with numbers are: 2=HLK, 3=WEI, 4=LEI.

glacier with a shorter time series (LEI; r=0.63–0.99). A synchronous movement pattern of rock glaciers in the European Alps has already been observed earlier based on data from France, Switzerland, Italy and Austria (Delaloye et al. 2008). This clearly indicates that climatic conditions are the main driver for changes in rock glacier velocity.

Changes in the movement rates might cause substantial changes in the geomorphology and acting processes of rock glaciers. Schoeneich et al. (2014) pointed out that changes in rock glacier dynamics range from moderate velocity variations to strong acceleration or even total collapse. In some cases downslope areas might be exposed to higher risks, including risks to people and infrastructure. The rock glaciers considered in our study in most cases pose no direct threat to infrastructure but may be a potential risk for hikers, e.g. where the trail crosses an unstable rock glacier or where rock falls in the nourishment area of a rock glacier threaten hikers below (e.g. at DOE).

7 Conclusion and Outlook

This study gives an overview of different approaches for quantifying geomorphic changes and cartographic presentations of rock glaciers and their changes. We presented results of local-scale studies from four rock glaciers and results with a regional focus (test area 125 km²). All rock glaciers studied are located in a high mountain area in central Austria. All rock glaciers – irrespective of local or regional scale studies – show an increase in movement rates during recent years.

We discussed the advantages and disadvantages of the different terrestrial, airborne and spaceborne methods currently in use, outlining the roles of total stations, GNSS-based positioning, digital photogrammetry, laser scanning, and differential SAR interferometry for rock glacier monitoring. It was pointed out for instance that dense and area-wide information on rock glacier surface deformation can only be provided by image-based techniques or laser scanning. A high temporal resolution in movement data (despite lacking area-wide information) on the other hand can best be achieved by GNSS techniques. Ideally, several fixed GNSS receivers should continuously monitor rock glacier movement, an approach that is a subject of current research.

We conclude that appropriate cartographic visualization is indispensable for good rock glacier research. The various methods of depicting rock glacier surface change in particular were discussed. Computer animations using multi-temporal orthophotos or shaded reliefs were identified as powerful means to make the invisible visible.

Finally, we showed by a simple statistical analysis that the rock glaciers monitored changed their horizontal movement rates synchronously in recent years. Warmer years caused rock glacier acceleration whereas cooler years caused deceleration. This highlights the fact that rock glaciers can be regarded as essential climate indicators in high-relief terrain influenced by permafrost.

8 Acknowledgments

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9 References

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