Documentation and visualization of the morphodynamics of Hinteres Langtalkar rock glacier (Hohe Tauern range, Austrian Alps) based on aerial photographs (1954-2006) and geodetic measurements (1999-2007)

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Abstract

Hinteres Langtalkar rock glacier (46°59'N, 12°47'E) is located in a glacially shaped cirque situated in the center of the Schober group of the Hohe Tauern range, Austria. This tongue-shaped creep phenomenon of mountain permafrost is approx. 850 m long, 200 to 350 m wide, and stretches vertically between 2455 m and 2725 m altitude. Over the course of time, the snout of the rock glacier has advanced into the uppermost cirque's lip, which is much steeper than the cirque floor behind, causing disintegration of this part of the rock glacier through active sliding processes (since 1994). Consequently, flow velocities behind the frontal slope have significantly increased because of a lack of counterpressure. Maximum horizontal flow velocities reached 2 to 2.5 m a^{-1}. The prevailing high longitudinal strain rates of up to 20x10-3 a^{-1} (2002-2006) have triggered surface ruptures and crevasse-like openings. In this paper we present quantitative information on the kinematics and surface deformation of the rock glacier based on the photogrammetric evaluation of multi-temporal aerial photographs (10 different epochs between 1954 and 2006) and annual geodetic measurements (1999-2007). Results obtained from recent investigations are highlighted. Based on the available information, covering a time span of 52 years, we analyze the changing kinematic state of Hinteres Langtalkar rock glacier. Special emphasis is put on the more recent situation of the rock glacier, which is characterized by the rapid development of tension cracks and the accelerated disintegration of the permafrost body. The main findings of this paper are as follows: (1) There is most probably a persistent climatically-induced permafrost melt in the order of a few centimeters per year. (2) Specific topographic situations (e.g. increasing slope inclination) may cause acceleration of flow/creep of a rock glacier, with the implication of possible surface ruptures in case of high strain rates and insufficient internal cohesion. (3) Interannual changes of flow/creep velocities are most probably due to the thermal conditions of the permafrost body, more or less true irrespective of (2). Furthermore, the authors propose to augment the present monitoring program by a high-resolution airborne laser scanning (ALS) mission which should be repeated (at least once) at a time interval of several years depending on the height accuracy to be achieved and the prevailing permafrost melt.

KEY WORDS: permafrost, rock glacier, long-term monitoring, geodetic and photogrammetric survey, flow velocity, geomorphometry, Hinteres Langtalkar rock glacier, Hohe Tauern range, Austria.

1. Introduction

Intact rock glaciers are complex landforms of cold mountain areas and are composed of ice/rock mixtures. Their existence is bound to permafrost (temperature at or below 0°C for at least one year). Active rock glaciers creep downslope under the influence of gravity due to internal deformation of the ice. This process can be superimposed by sliding at certain shear horizons. Typically, rock glaciers resemble lava flows showing characteristic sequences of furrows and ridges at the surface, being oriented transversally or longitudinally to the main flow direction, or in an irregular surface texture. Flow/creep velocity is contingent upon various parameters, e.g., thermal condition of permafrost and inclination of the underlying topography, and can range from several centimeters to a few meters per year. The age of various rock glaciers has been estimated at several thousand years. Research on permafrost creep and rock glacier dynamics has been intensified during the last 10 years. The interested reader is referred to Haeberli et al. (2006), Haeberli and Gruber (2008), and Kääb (2005 and 2008).

Climate change (atmospheric warming) is likely to have an impact on the kinematic state of rock glaciers (Kääb et al. 2007). Delaloye et al. (2008) have compared the interannual variations of surface movement of 16 rock glaciers located in the European Alps for the time period 1999-2007. The research team involved concluded that the interannual variations observed are primarily related to external climatic factors, e.g., mean annual air temperature, rather than to the internal characteristics of the rock glacier. However, general process understanding is still lacking.

Rock glaciers are an important system of mass transport in mountain areas. Weathered material (debris, rocks) from mountain slopes and headwalls of cirques can be effectively transported downslope by an active rock glacier. Another comparative study (Roer et al. 2008) investigated recent rapid morphological changes (disintegration) of rock glaciers. The surface morphology of the rock glaciers concerned is characterized by transverse crevasse-like cracks, and landslide-like mass wasting, preferably at the frontal slope. Typically, high horizontal flow velocities prevail. Due to the complexity of the phenomenon and the lack of information on the thermal state and internal structure of the rock glaciers studied, the understanding of the processes involved is still a matter of debate. Destabilization of frontal slopes or even larger parts of rock glaciers (due to permafrost melt, acceleration of flow velocity, or sliding) may cause natural hazards as indicated by Haeberli and Gruber (2008). Debris and rocks, until recently trapped in stable intact rock glacier systems, may get loose and might become part of other geomorphologic processes, such as debris flows or rock falls.

Rock glacier monitoring has a comparatively long history in Austria, commencing in the 1920s. However, photogrammetric and geodetic monitoring of rock glaciers did not start until 1995 at the authors' institute at Graz University of Technology. Currently, three morphologically different rock glaciers of the Hohe Tauern range, Austria, are subject to ongoing (deformation) monitoring within the ALPCHANGE project (see Alpchange 2008) funded by the Austrian Science Fund (FWF). One of the three rock glaciers is Hinteres Langtalkar rock glacier, which is the focus of this paper.

Hinteres Langtalkar rock glacier (46°59'10"N, 12°46'55"E) is situated in a northwest facing cirque of Gössnitz valley, which is part of the Schober group, Hohe Tauern range, Austria. During the last 10 years, this creep phenomenon of mountain permafrost has been the subject of various scientific investigations (geodesy, geology, hydrology, morphology, photogrammetry) conducted by researchers of the University of Graz, Graz University of Technology, Joanneum Research, and the University of Innsbruck. These works were aimed at better understanding mountain permafrost and rock glaciers in general, and the morphogenesis and morphodynamics of the rock glacier in this study area in particular (Lieb 1996, Krainer and Mostler 2001, Kaufmann 2004, Avian et al. 2005, Kellerer-Pirklbauer and Kaufmann 2007, Avian et al. 2008, and Kellerer-Pirklbauer 2008).

Please see Fig. 1 Hinteres Langtalkar rock glacier is approx. 850 m long, 200 to 350 m wide, and stretches vertically between 2455 m and 2725 m altitude. It consists of two main lobes which are attached to each other. Marked depressions exist at the root zones of both units. During the Little Ice Age (LIA), a small glacier had formed covering the upper third of the northern lobe, leaving behind traces of lateral moraines on the rock glacier's surface after melt. The tongue-shaped northern lobe is characterized by strong ongoing morphodynamics. The phototexture of the orthophoto shown in Fig. 1 reveals multiple landslides at the frontal slope and a sequence of several transverse trenches and crevasse-like openings caused by high flow velocities up to 2 m a^{-1} (cp. with the terrestrial view of Fig. 2). The disintegration of the frontal slope started not later than 1994, when the rock glacier had moved into much more steeper terrain. The northern lobe is confined by lateral levees which are dynamically inactive. The smaller southern lobe is a complex system of wrinkled ridges and furrows showing moderate activity (up to max. 10 cm a^{-1}). Surface deformation of the southern lobe is obviously influenced by the larger and faster moving northern lobe.

The spatio-temporal evolution of the flow field of Hinteres Langtalkar rock glacier has already been revealed by aerial photographs (1969-1999) and geodetic surveys (1999-2004). See Kaufmann and Ladstädter (2002, 2003, and 2004), Kienast and Kaufmann (2004), and Avian et al. (2005). In this paper we intend to augment the research by looking at additional time periods that have not yet been covered. Photogrammetric and geodetic measurements will be considered.

Chapter 2 describes the application of digital photogrammetry in deriving motion fields and mass balances of Hinteres Langtalkar rock glacier.

New results will be presented based on aerial photographs dating from 1954, 2002, and 2006. Chapter 3 outlines the geodetic monitoring scheme and gives results for the time period 2004-2007. In Chapter 4, all datasets will be compared and conclusions will be drawn on kinematics and permafrost/ice melt. Finally, Chapter 5 presents general conclusions and an outlook on future research.

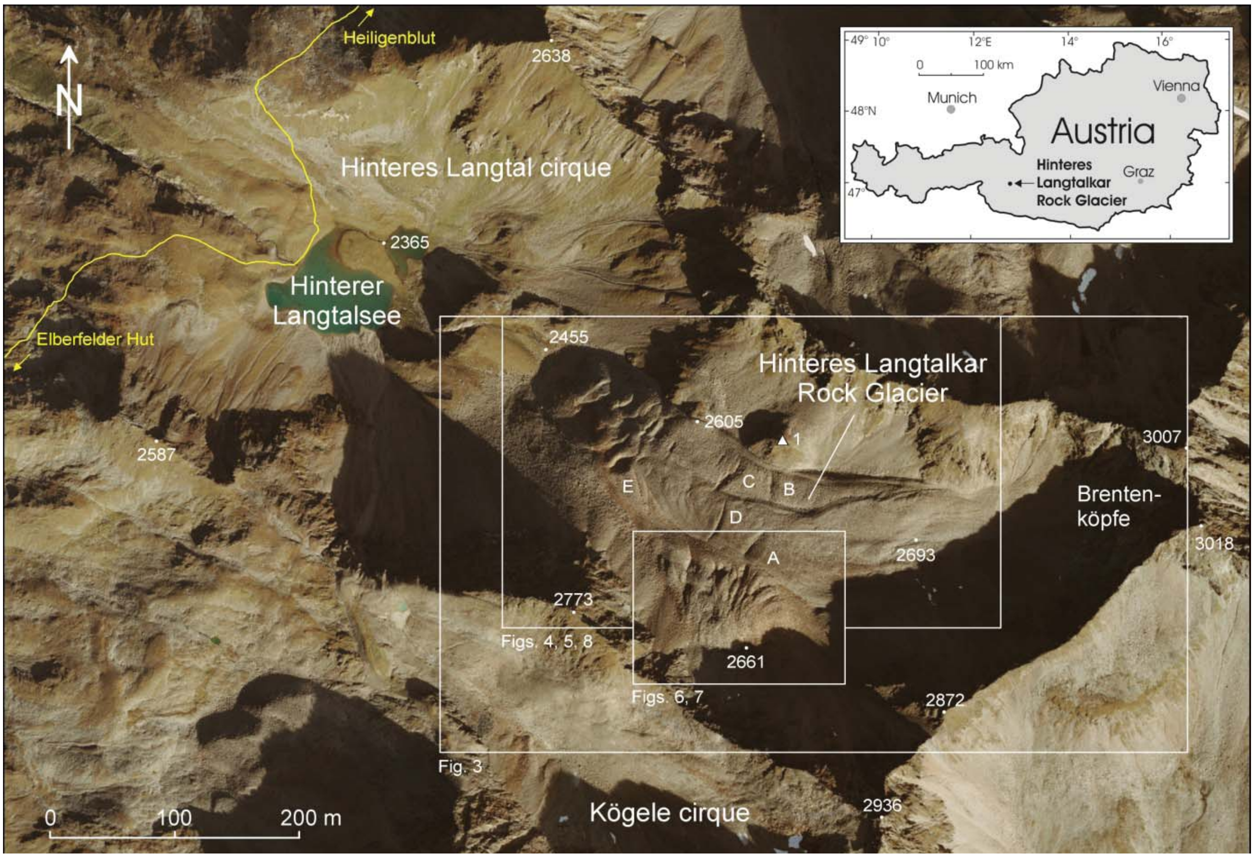


Figure 1: Orthophoto of 21 September 2006 showing the Hinteres Langtalkar (cirque) with Hinteres Langtalkar rock glacier. (Remark: "kar" is the German word for cirque.) The long shadows visible are due to acquisition early in the morning. White rectangles indicate areas of interest. The study area can be reached conveniently on a hiking trail. The aerial photograph was taken by the Austrian Federal Office of Metrology and Surveying, Vienna (BEV).

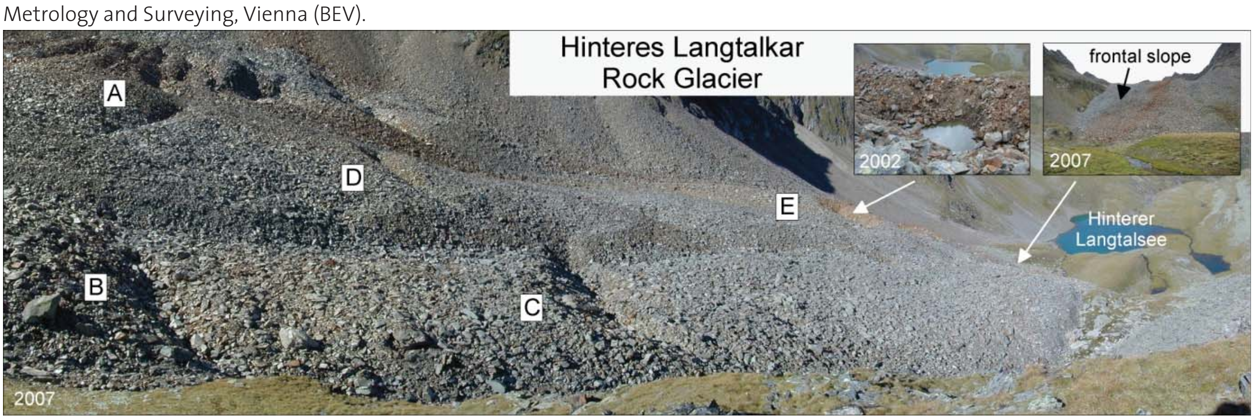


Figure 2: Terrestrial panoramic view of the central part of Hinteres Langtalkar rock glacier of 24 August 2007. Photo taken from geodetic reference point no. 1 (shown in Fig. 1) in southwesterly direction. The two inset photographs show (left) a temporal pond of August 2002 (also observed in August 2004) in a crevasse-like landform of the uppermost part of the sliding zone and (right) the rock glacier's frontal slope which is severely affected by landsliding.

2 Evaluation of Aerial Photographs 1954-2006 OF

Multi-temporal aerial photographs are an excellent source for documentation of landscape change. Appropriate photogrammetric techniques provide area-wide information about surface movement and height change (a concise survey of all remote sensing techniques applicable to permaforst problems and hazards is given in Kääb 2008). Digital photogrammetry is currently the most powerful tool in this context (cp. Haeberli et al. 2006).

In this study we want to (1) derive dense fields of three-dimensional (3D) displacement vectors of superficial rock glacier points, and (2) obtain area-wide information on surface height change based on aerial photographs. The latter implies the extraction of digital terrain models (DTMs). Aerial photographs of 10 different epochs were at our disposal (see Tab. 1 and Fig. 3). The photogrammetric evaluation of the image data of the time period 1969-1999 has already been described elsewhere (see above). The recently applied digital photogrammetric workflow is briefly described in the following.

The frame size of the 1954 photographs is 18cm x 18cm. The transparencies were scanned with a resolution of 10µm using a photogrammetric scanner of Vexcel Imaging Austria. At the time of the 1954 overflight, the terrain was covered by a thin veneer of fresh snow, and this dataset was therefore excluded from photogrammetric evaluation in the beginning of the project. The image data of 2002 and 2006 was already provided in digital format (resolution of 15µm). The stereomodels of 1954, 2002, and 2006 were photogrammetrically oriented by means of aerotriangulation using control points of the 1998 stage. The work was accomplished using a digital photogrammetric workstation of Intergraph. High-resolution DTMs were derived by interactive mapping (2002 and 2006) and automatic image matching (1954). Intergraph's software tools were used applying photogrammetric standard procedures. Surface height change from one epoch to the other was calculated by subtracting the respective DTMs.

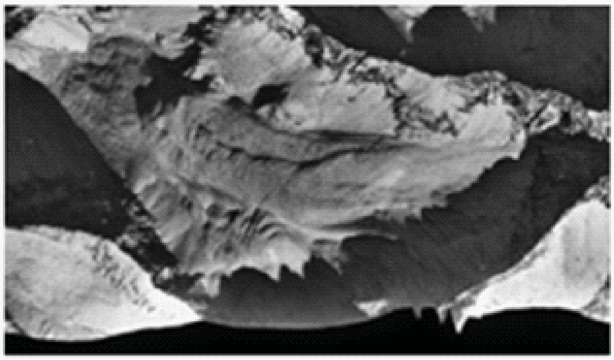
The in-house developed software ADVM (Automatic Displacement Vector Measurement, see Kaufmann and Ladstädter 2002) was applied obtaining 3D displacement vectors for the time periods 1998-2002 and 2002-2006. The aerial photographs of 1954 were not considered because of the snow cover, which was supposed to hamper successful image matching, e.g., with the 1969 data. In this paper we present isotachs derived from the displacement vectors 1998-2002 (Fig. 4) and 2002-2006 (Fig. 5). A close-up view of the southern lobe of Hinteres Langtalkar rock glacier for the time period 1998-2002 reveals a wealth of information concerning horizontal movement (see Figs. 6 and 7).

The accuracy of the automatic image-based velocity measurement was estimated from point data of stable non-moving areas of the rock glacier's neighborhood. The values obtained, shown in Figs. 4 and 5, were checked against velocity data derived from the geodetic measurements (see next chapter). The latter were assumed to be error-free, at least for this analysis. An RMS of ±3.6 cm a-1 was calculated for 1998-2002 and a value of ±2.9 cm a-1 for 2002-2006. These values are in good agreement with the photogrammetrically estimated ones and demonstrate the high potential of the digital-photogrammetric method.

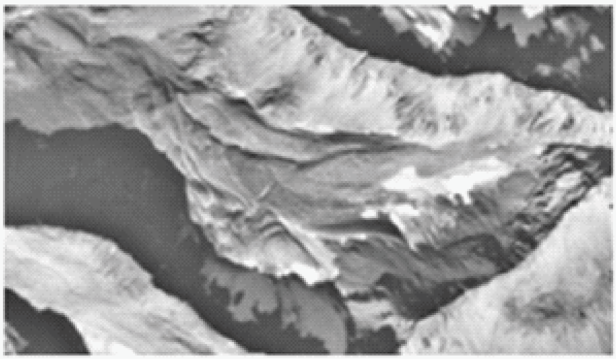
DTMs were extracted for the years 1954, 1974, 1998, 2002, and 2006. Quality control was carried out twofold: (1) qualitatively, through stereoscopic superimposition of features, such as contour lines, breaklines and points of a reference epoch onto the stereomodel of a second epoch, and/or (2) quantitatively, by analyzing the vertical height differences of larger stable areas in the proximity of the rock glacier. The differences observed were always in the expected range of uncertainty, following basic photogrammetric reasoning.

date	image scale	focal length	mean flying height	type of film
24.09.1954	01:15.8	210 mm	3320 m	black-and-white
09.10.1969	01:29.1	153 mm	4440 m	black-and-white
05.09.1974	01:10.0	210 mm	2100 m	black-and-white
09.10.1981	01:31.1	153 mm	4760 m	black-and-white
04.09.1991	01:34.4	153 mm	5260 m	black-and-white
24.09.1997	01:32.6	153 mm	4970 m	color infrared
26.8.1998+	01:10.5	152 mm	1600 m	black-and-white
12.09.1999	01:33.9	153 mm	5180 m	black-and-white
18.9.2002++	01:13.6	305 mm	4159 m	color
21.09.2006	01:15.6	304 mm	4730 m	color

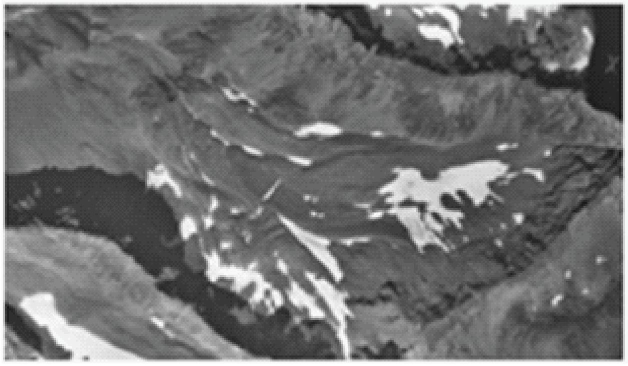
Table 1: Aerial photographs used in the study.
Aerial photographs acquired by the Austrian Federal Office of Metrology and Surveying, Vienna.
+data acquisition by Bildflug Fischer, Graz, Austria
++data provided by the regional government of Tirol, Austria



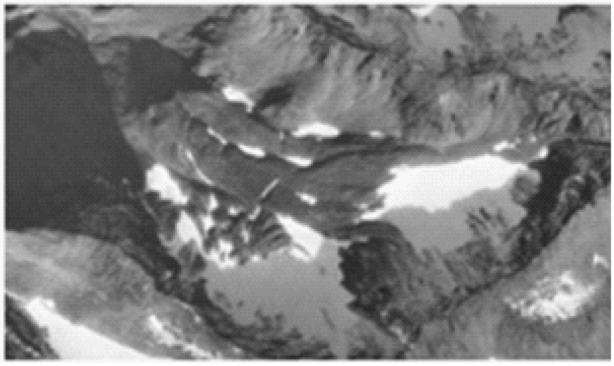
1954



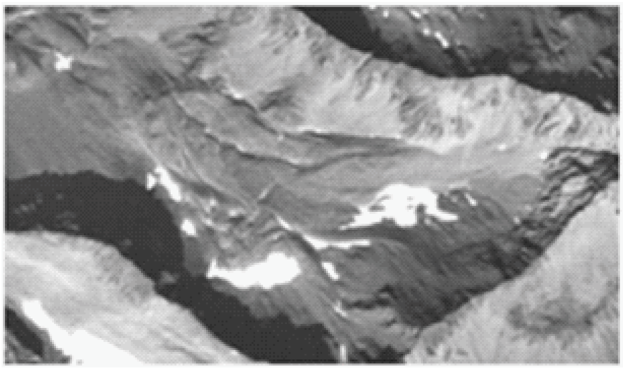
1969



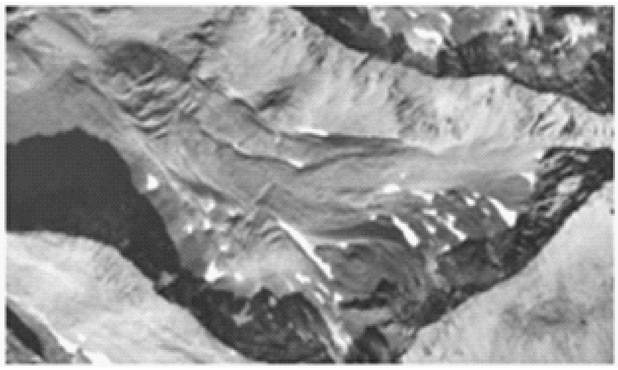
1974



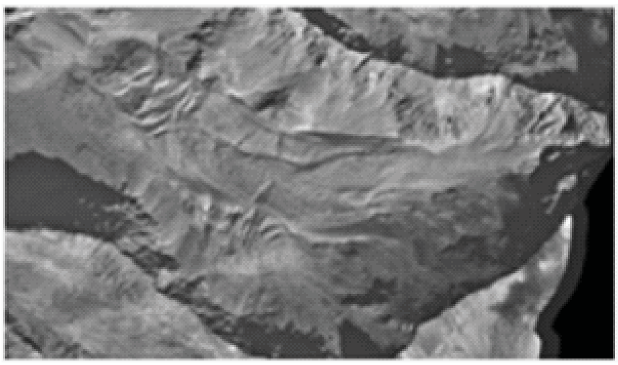
1981



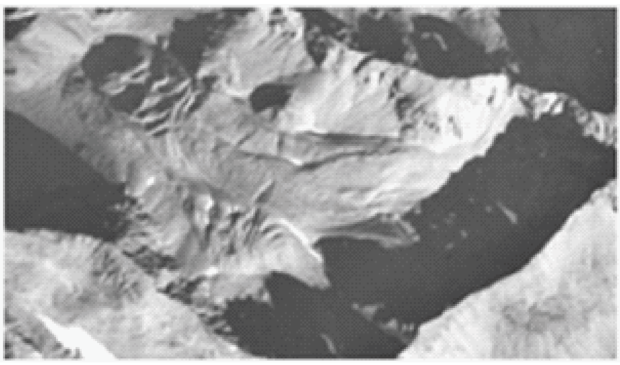
1991



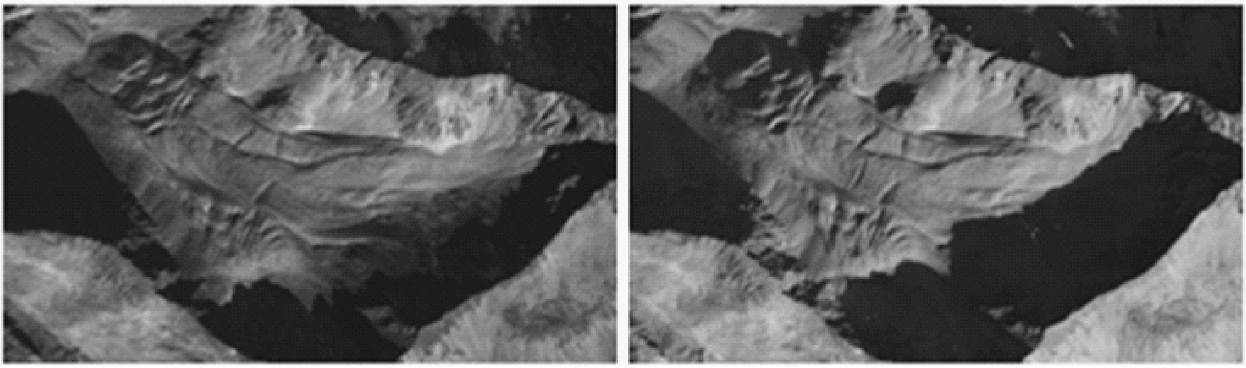
1997



1998



1999



2002 2006

Figure 3: Aerial photographs used in the study (cp. Table 1).

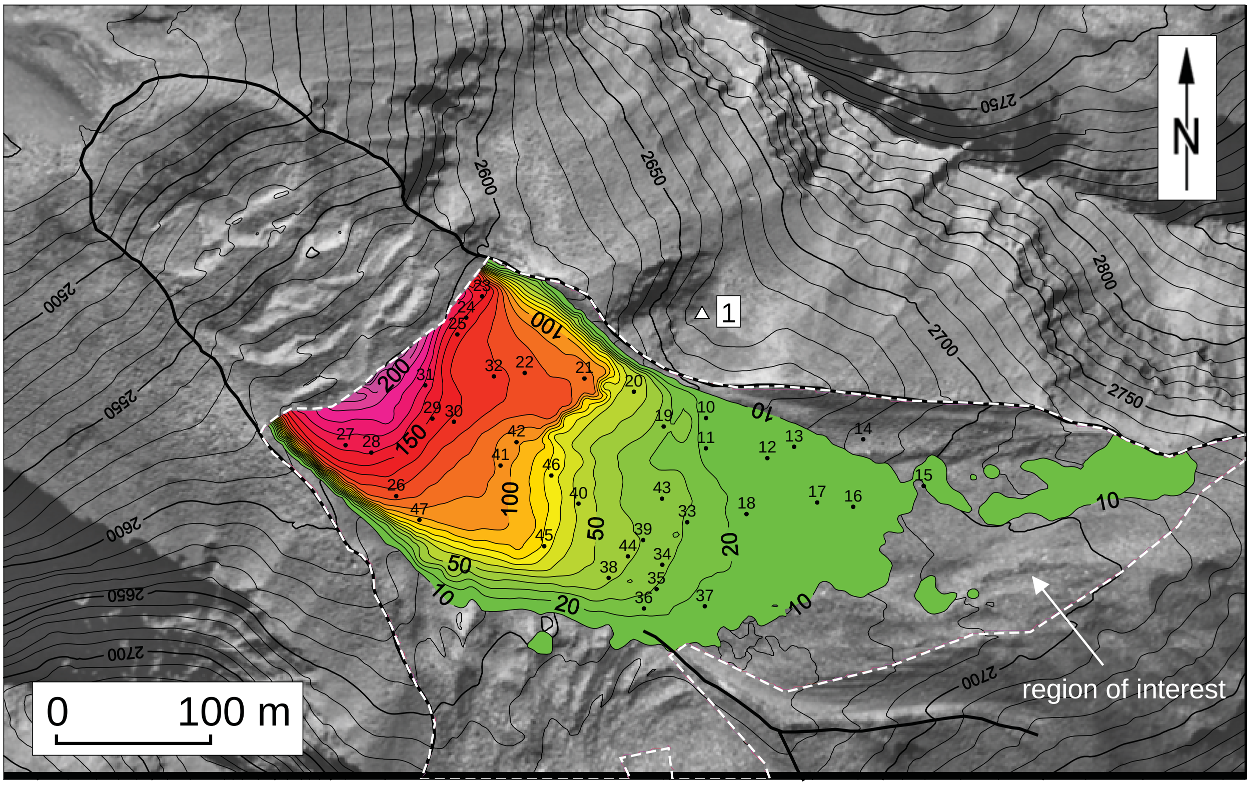


Figure 4: Mean annual horizontal flow/creep velocity (cm a-1) of Hinteres Langtalkar rock glacier for the time period 1998-2002. The result shown has been derived by means of automatic feature tracking (21,000 points matched, accuracy: ±1.3 cm a-1). For reasons of comparison, the 38 geodetic observation points are shown as black dots. Orthophoto from 26 August 1998.

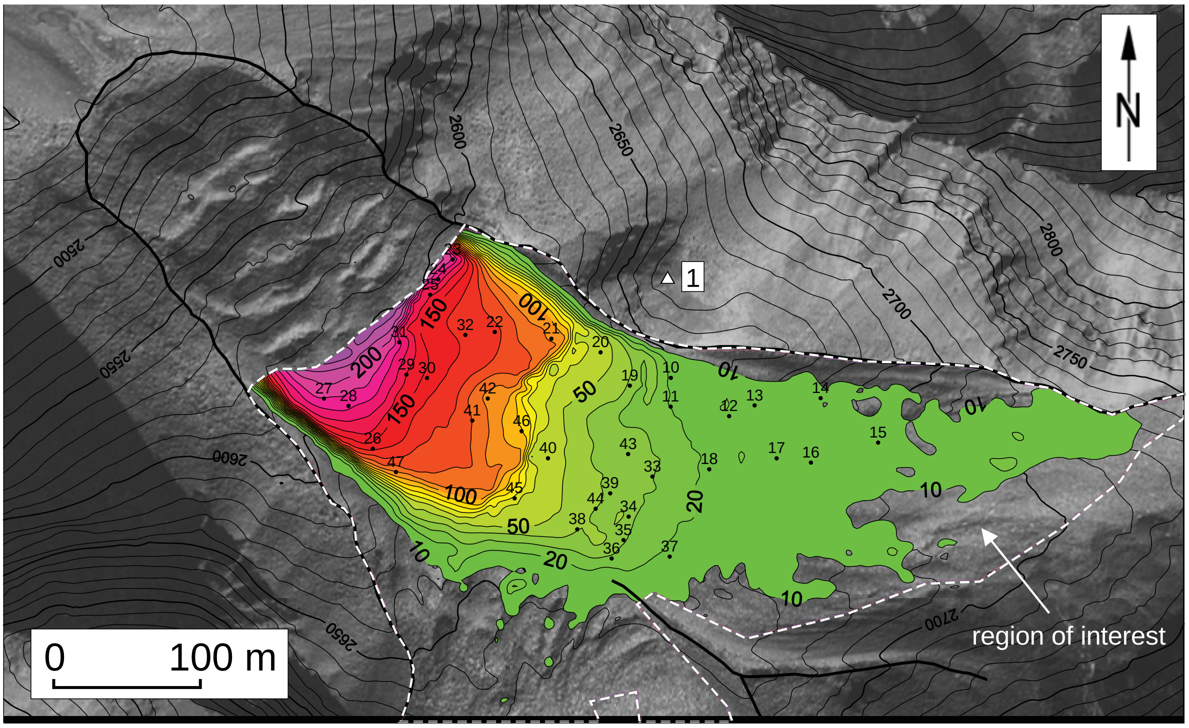


Figure 5: Mean annual horizontal flow/creep velocity (cm a-1) of Hinteres Langtalkar rock glacier for the time period 2002-2006. The result shown has been derived by means of automatic feature tracking (22,600 points matched, accuracy: ±2.0 cm a^{-1}). For reasons of comparison, the 38 geodetic observation points are shown as black dots. Orthophoto from 18 September 2002.

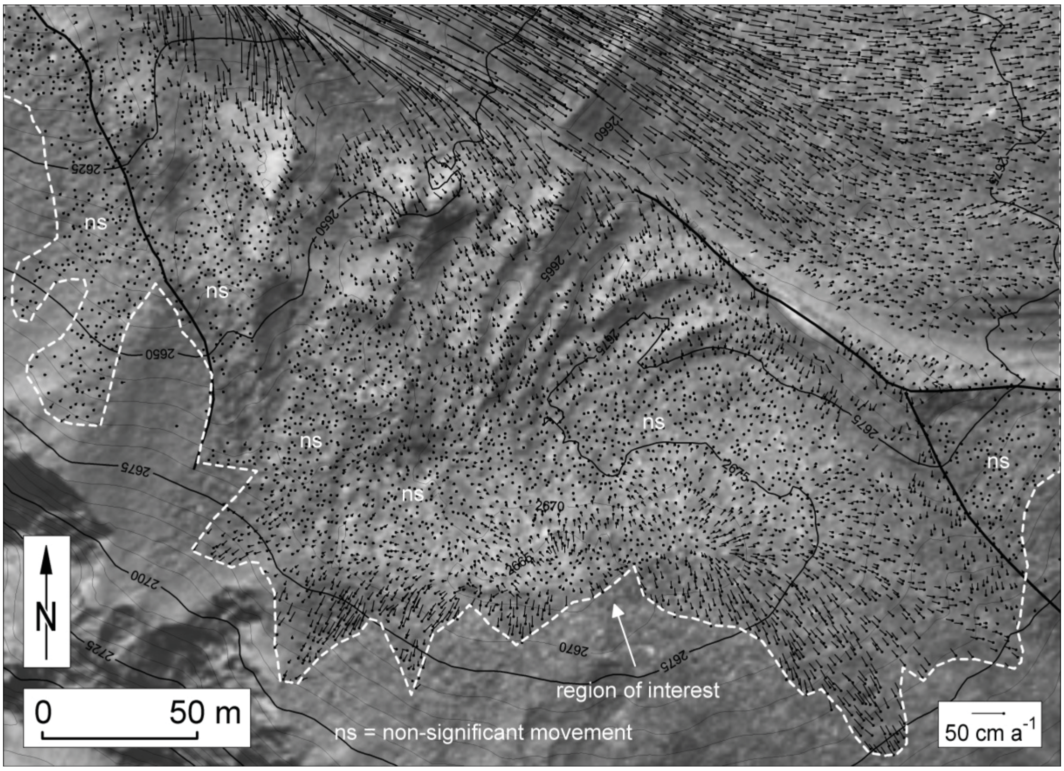


Figure 6: Horizontal displacement vectors derived from large-scale aerial photographs from 1998 and 2002 using image matching techniques (ADVM software). 6849 vectors were computed. The accuracy achieved in vector length is ±1.3 cm a^{-1}. Orthophoto from 1998 showing the southern lobe of Hinteres Langtalkar rock glacier.

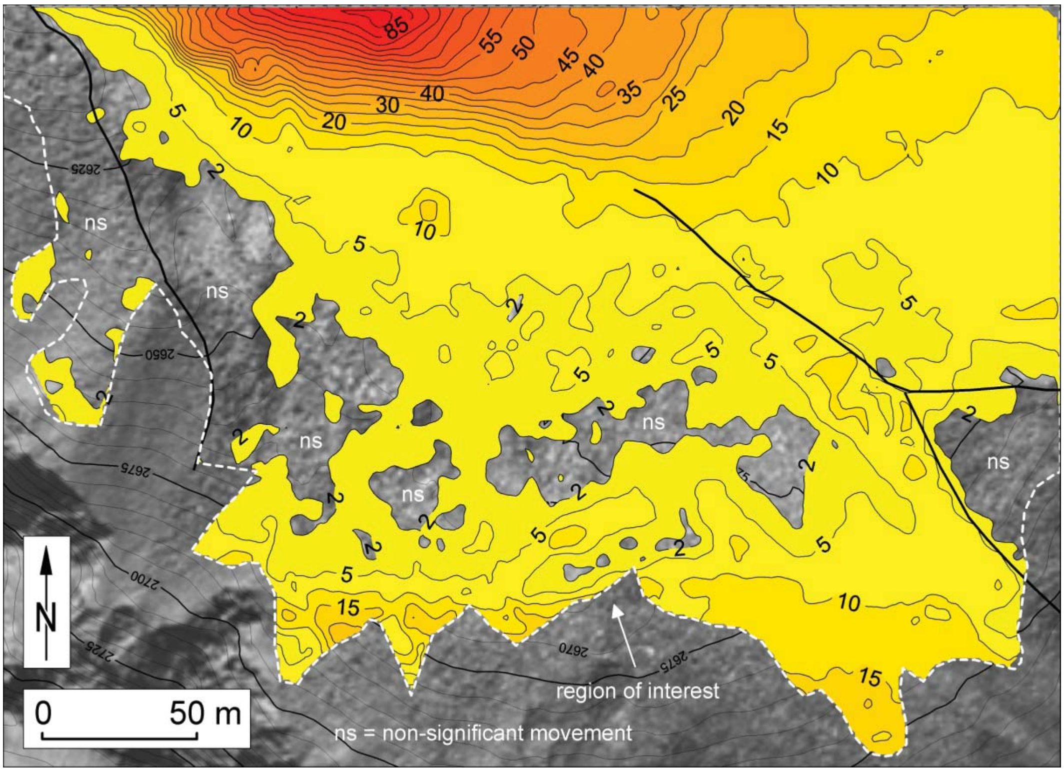


Figure 7: Mean annual horizontal flow/creep velocity (cm a-1) of Hinteres Langtalkar rock glacier for the time period 1998-2002. The result shown has been derived from measurements shown in Figure 6. Orthophoto from 1998. Compare with Figure 6.

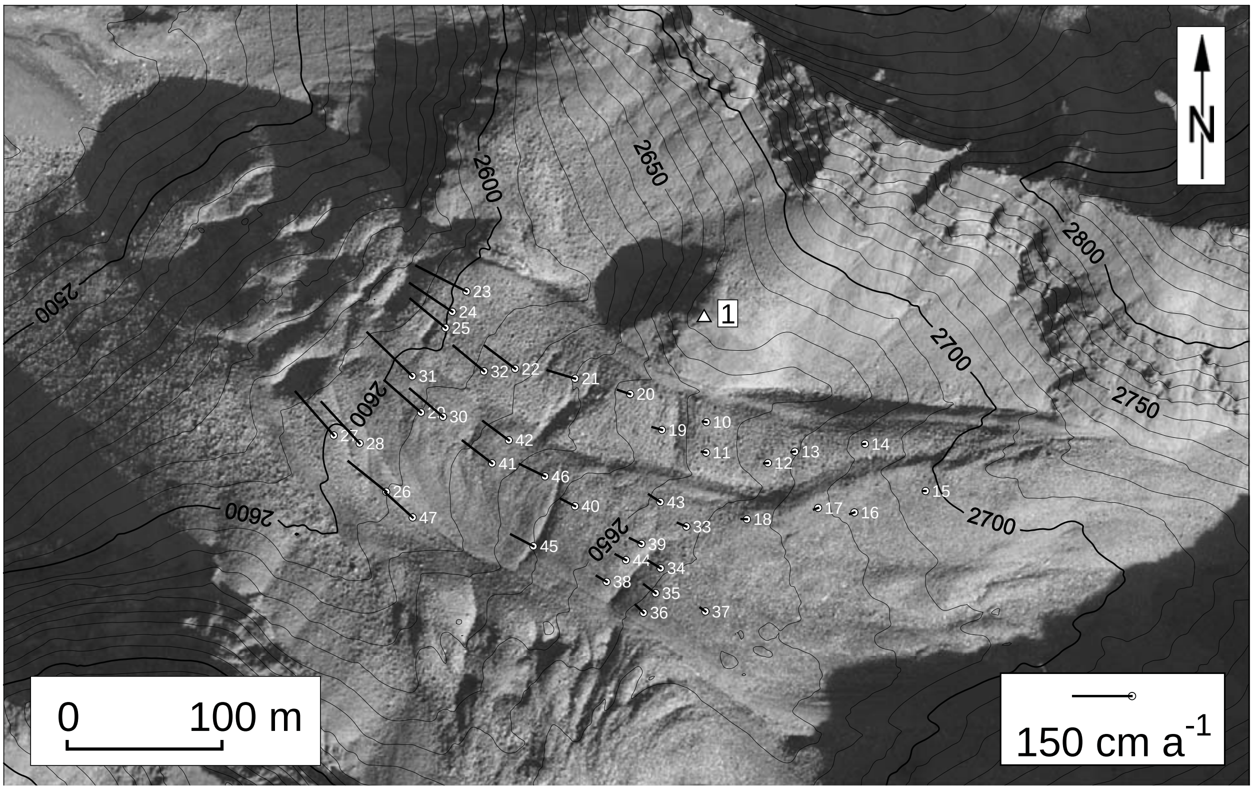


Figure 8: Horizontal movement of the 38 observation points of the Hinteres Langtalkar rock glacier for the time period 2006-2007. The position of the total station used is at reference point no. 1 marked with a triangle. Orthophoto of 21 September 2006.

3. Geodetic measurements 1999-2008

In 1998, a geodetic network was set up in order to measure the annual movement of selected points of the rock glacier surface (cf. Kienast and Kaufmann 2004). Currently, the network consists of 17 stable reference points which were fixed with brass bolts driven into solid rock. 38 observation points were selected on the rock glacier and fixed in the same way as the reference points (see Fig. 8). Annual measurements of the observation points started in 1999, and have been repeated up to the present. The measurements are carried out every year in the week following August 15. From the database of multi-year coordinates we can compute 3D displacement vectors, strain rates, horizontal and vertical flow/creep velocities, and thickness change. The latter, though, is based on specific assumptions. Fig. 8 shows the mean annual horizontal movement of the 38 observation points for the most recent time period, 2006-2007. The position of the total station is always at reference point no. 1 marked with a triangle. Table 2 summarizes the interannual changes of flow velocity for two areas (lower and upper region) of the rock glacier.

point group (lower points): 23-25, 27, 28, 31 (see Figure 8)	
time period	flow velocity ($m\ a^{-1}$)
1969-1991+	0.824
1991-1997+	1.427
1999-2000	1.400
2000-2001	1.559
2001-2002	1.473
2002-2003	1.716
2003-2004	2.217
2004-2005	1.961
2005-2006	1.512
2006-2007	1.399
+derived photogrammetrically (cp. Kaufmann & Ladstädter 2002)	

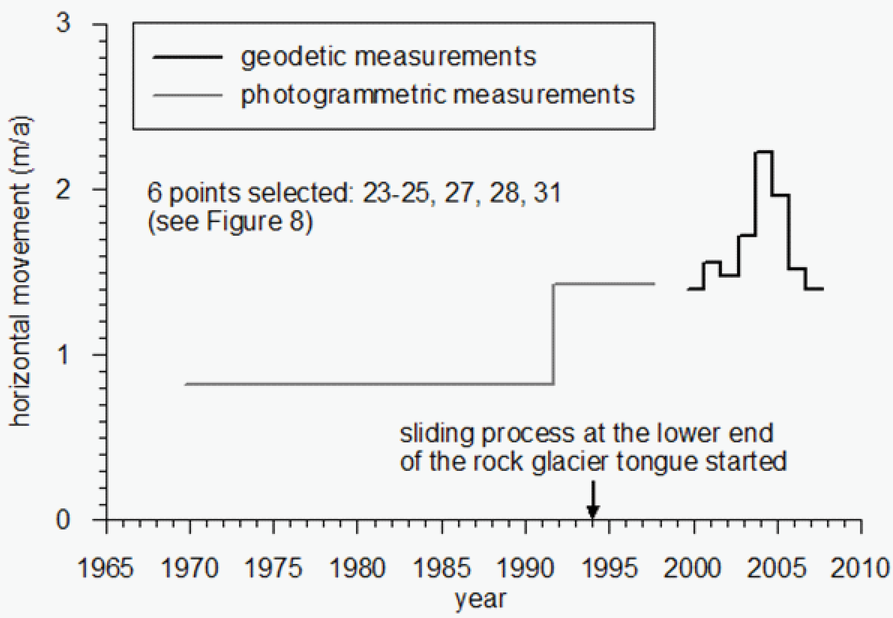
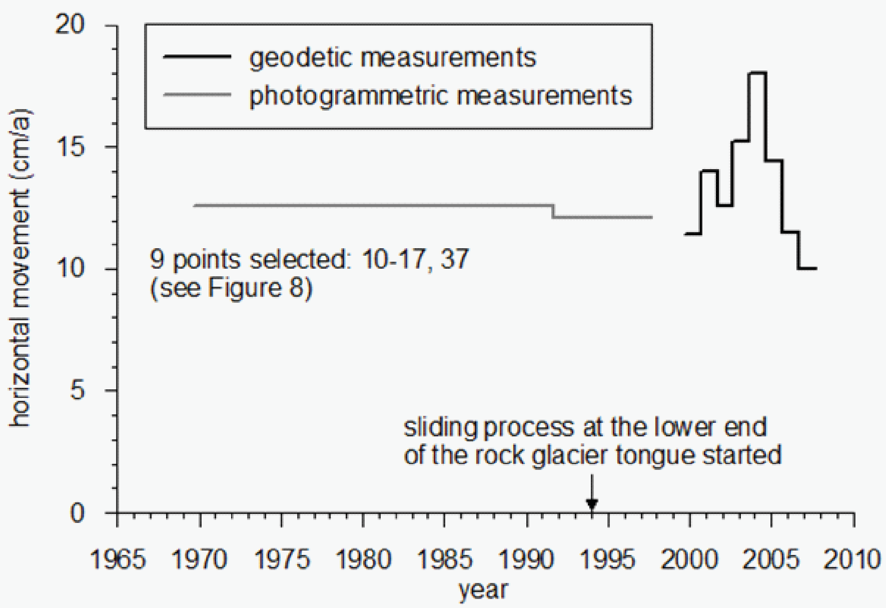


Table 2a: Mean annual horizontal movement ($m\ a^{-1}$) of selected points of the Hinteres Langtalkar rock glacier.

point group (upper points): 10-17, 33 (see Figure 8)

time period	flow velocity (cm a⁻¹)
1969-1991+	12.6
1991-1997+	12.1
1999-2000	11.4
2000-2001	14.0
2001-2002	12.6
2002-2003	15.2
2003-2004	18.0
2004-2005	14.4
2005-2006	11.5
2006-2007	10.0



+derived photogrammetrically (cp. Kaufmann & Ladstädter 2002)

Table 2b: Mean annual horizontal movement (m a-1) of selected points of the Hinteres Langtalkar rock glacier.

4. Discussion

The analysis of the kinematics of Hinteres Langtalkar rock glacier is primarily based on geometric information obtained from photogrammetric and geodetic measurements, sustained by field observations and visualizations (computer animations).

Can we measure the rate of surface lowering due to ice melt of the permafrost body?

Surface lowering due to permafrost degradation is rather difficult to determine from a technical point of view, since its geometric effect is generally in the order of a few cm a^{-1}, if at all. Theoretical issues were already discussed in Kääb (2005) and Kääb and Weber (2004). Since a rheological model was not available for Hinteres Langtalkar rock glacier, we simply calculated the volumetric change between two selected photogrammetric epochs for a catchment area large enough to cover the whole rock glacier mass transport system. The mean annual net mass balance is a good indicator for the mean annual ice melt. The values calculated are in the range between -1.2 and -5.0 cm a^{-1}. The same value for the time period 1954-2006 amounts to -2.7 cm a^{-1} (= 24.3 mm a^{-1} water equivalent), which is significant from a statistical point of view. However, this result is to a certain (small) extent biased by a true glaciological component caused by the melting of residual (buried) ice from LIA times in the two depression zones and adjacent talus/scree slopes. The areal extent of the latter process, which is still ongoing, can be nicely traced in the multitemporal stereopairs and in the difference DTMs (cp. also Kellerer-Pirklbauer & Kaufmann 2007). Overall surface lowering of nearby Weissenkar rock glacier suggests permafrost degradation of -2.0 cm a^{-1} for the time period 1974-1998. A value of -2.0 to -2.7 cm a^{-1} was estimated for Dösen rock glacier. A. Kääb (cp. Haeberli et al. 2006) reports several cm per year for Murtèl rock glacier, Switzerland.

Modern airborne laser scanning (ALS) can provide surface height information with an anticipated accuracy of a few centimeters. Mass balance calculations have to be carried out for the whole catchment area. An appropriate time interval of several years is needed between consecutive surveys in order to obtain significant results. From a theoretical point of view, large-scale aerial photographs can also achieve the anticipated result, but require longer observation periods.

Panta rhei?

The time-series of 10 orthophotos (shown in Fig. 3) covering a time-span of 54 years reveals very clearly the spatio-temporal evolution of Hinteres Langtalkar rock glacier. Based on the visible changes of phototexture, we can identify three characteristic zones: (1) lower end of the rock glacier tongue (= snout) which is affected by massive landsliding, (2) main, central part of the northern lobe which also displays signs of surface disintegration including crevasse-like structures (asymmetric V-shaped trenches, most probably associated with sliding), and (3) the root zones characterized by changes in snow/ice cover with time. The kinematics of the rock glacier is best shown in a rapid fading of the multi-temporal orthophotos (see the animated GIFs of Kaufman 2008). The optical flow (motion parallaxes) observed provides a qualitative clue for surface motion and also local surface deformation. For example, the fast moving northern lobe is deforming the contact zone with the rather inactive southern lobe (cp. Figs. 6 and 7). Of course, all visual observations can be sustained by precise measurements as shown in this paper.

A first transverse trench (indicated with A in Fig. 1) already existed in 1954. Between 1954 and 1991, a steady-state creep of the rock glacier tongue could be assumed at first glance, however, extension cracks have already started to develop (B in 1974, C in 1981). The 1991 surface opening below C and close to the frontal slope (see Fig. 3) can be understood as a distinct sign of incipient destabilization of the frontal slope. Looking at the photographs of 1954, we can clearly recognize (residual) landslide material at the footslope of the frontal slope. It was most probably detached from the rock glacier snout in an earlier event. In fact, this process of mass movement into the oversteepened slope (approx. 36°) is well-documented in the surface height changes derived from the DTMs of 1954 and 1974 and by stereoscopic vision superimposing the contour lines of 1954 onto the stereomodel of 1969. We measured max. surface height change of +11.7 m at the frontal slope (sliding zone) and surface lowering with maximum values of -6.9 m in the zone below trench A. According to M. Krobath (as reported in Avian et al. 2005), the massive landslide, which was recognized for the first time in the aerial photographs of 1997, occurred in 1994. The aerial photographs of the 1990s show at least 3 to 4 major and several minor shear planes in this zone. Large surface changes are still ongoing. It is estimated that some 260,000 m^3 of material (ice/rock mixture) have slid into the steeper terrain beneath the rock glacier's former frontal end of 1954.

The 1994 event also had a significant impact on the flow/creep velocities of the rock glacier. For the time period 1969-1991, max. mean annual horizontal velocities of up to 0.9 m a^{-1} were measured (cp. Fig. 12 of Kaufmann and Ladstädter 2002) at the snout. The landslide event of 1994 triggered a significant increase in flow/creep velocity of the rock glacier below the opening zones of C and D (cp. Figs. 4 and 5), which is still ongoing. For the time period 2002-2006, max. mean annual horizontal flow velocities of up to 2.3 m a^{-1} were measured photogrammetrically at the upper edge of the disintegrated frontal slope (cp. Fig. 4).

Image-based measurements of displacement vectors for the time periods 1998-2002 and 2002-2006 were, unexpectedly, quite successful for the rapidly changing sliding zone and produced maximum values of 3.3 m a^{-1} and 3.6 m a^{-1}, respectively. For the sake of clarity, however, these relatively inhomogeneous results are not shown in Figs. 4 and 5.

The influence of the accelerated movement of the lower part on the kinematics of the upper parts of the rock glacier is rather small.

Another prominent surface opening had developed most probably in early summer of 2004 (D, Fig. 1). This V-shaped transverse trench was first recognized during the fieldwork in August 2004. The geodetic observation point no. 45 had slid into the 6 m deep trench. The two slopes in the trench were unstable and a massive ice outcrop was observed close to the surface.

From a kinematic point of view, the rock glacier can be divided into three units: (1) sliding zone at the frontal slope (max. horizontal movement of 3.6 m a^{-1}, max. vertical movement of -1.8 m a^{-1}, area-wide positive long-term surface height change with max. values of 23 m within the time period 1954-2006), (2) zone with rapid movement and surface disintegration within the limits of the upper edge (scarp) of the landslide area and the transverse rupture zones of C and D (flow/creep velocities presently in the range of 1.0-2.2 m a^{-1}, marked surface lowering with max. values of -12.7 m for the period 1954-2006), and (3) zone above the rupture zones C and D (creep rates less than 0.5 m a^{-1}, root zones with depressions, glacial interference).

Horizontal strain rates of about 20-23x10^{-3} a^{-1} were measured photogrammetrically at C and D for the time period 2002-2006.

Annual geodetic measurements provide another source of information. The graphs depicted in Tab. 2 clearly show that the flow/creep velocity is subject to synchronous interannual change, independent of the speed (slow, fast) of the points. Maximum velocities were measured for the time period 2003-2004. This accelerated movement can be attributed to the hot summer of 2003. The interested reader is referred to Buck and Kaufmann (2008) and Delaloye et al. (2008) for further comparative analysis of the interannual variations observed with data from other rock glaciers in Austria and in Europe, and with respective meteorological data, for example air temperature.

5. Conclusions and outlook

In this paper we have presented basic information on the kinematics of Hinteres Langtalkar rock glacier, such as flow velocity, surface height change, strain rates, and mass balances, for the time period 1954-2006. The authors agree that combined photogrammetric and geodetic monitoring efforts need to be continued. Furthermore, interdisciplinary work is urgently needed to better address morphodynamics and the processes involved. As far as monitoring is concerned, a repeated high-resolution airborne laser scanning (ALS) survey is highly recommended in order to better understand the impact of ongoing atmospheric warming (global change) on high mountain permafrost degradation.

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