Quantitative Assessment of the Creep Process of Weissenkar Rock Glacier (Central Alps, Austria)

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Abstract

Weissenkar rock glacier (46°57.5' N, 12°45' E) is situated in a glacially shaped cirque in the Schober Mountains of the Eastern Alps, Austria. The rock glacier creeps downslope at a comparatively low velocity of up to 11 cm a^{-1}. The creeping permafrost body has now reached a flat plateau-like area where its motion is retarded due to low inclination resulting in a very pronounced surface topography.

This paper is focused on the documentation of the kinematic state of Weissenkar rock glacier. Geodetic (1997-2001, 2003, 2004) and photogrammetric measurements (1974, 1998, 2002) were carried out in order to obtain quantitative information on surface deformation in general, and creep velocity and surface height change in particular. Results obtained are presented both numerically and graphically. An orthophoto map of the area of interest was compiled to provide a sound basis for cartographic work.

Finally, the kinetics of Weissenkar rock glacier will be discussed in respect to its morphology and its specific topographic situation.

KEYWORDS: Rock glacier monitoring, mapping, geodetic survey, digital photogrammetry, creep velocity, surface deformation, Weissenkar, Schober Mountains, Central Alps, Austria

1. Introduction

The Schober Mountains, a relatively remote mountain group in the Central Alps of Austria, was chosen as a study area by the Institute of Remote Sensing and Photogrammetry, Graz University of Technology, and the Institute of Geography and Regional Science, University of Graz, in order to investigate both glaciological and periglacial phenomena. Ongoing (geomorphometric) research programs of both Institutes are focused on three main sites, i.e., Goessnitzkees (which is a glacier), Hinteres Langtalkar rock glacier, and Weissenkar rock glacier (see Figure 1), which are located right in the center of the Schober Mountains. Geomorphological mapping and monitoring of glacier retreat started as early as the 1980s, whereas more detailed studies did not begin until 1996 for glaciers (Knödl and Troyer 1997) and 1997 for rock glaciers (Kienast and Kaufmann 2004). The emphasis of the ongoing monitoring programs is placed on the detection and documentation of spatio-temporal changes in landforms. Hinteres Langtalkar rock glacier, situated in the north-east of Goessnitzkees, is characterized by high surficial flow velocities (max. values of up to 2.38 m a^{-1}), high strain rates, and disintegration of its permafrost body, especially in the lower part of the rock glacier. Weissenkar rock glacier, situated in the S of Goessnitzkees, is different from a geomorphological point of view (see next chapter). Comparatively low flow/creep velocities of up to max. 11 cm a^{-1} prevail. The long-term monitoring programs at these three sites are intended to (1) better understand mass transport systems, with special regard to rock glacier dynamics and genesis, (2) facilitate comparative analysis of glacial and permafrost areas, and (3) contribute to climate change studies in high-mountain areas. One key issue of rock glacier monitoring is whether it is possible to derive a climate signal from geomorphometric data, together with other collateral data, e.g. temperature. This paper is the first report on the geodetic and photogrammetric work carried out at Weissenkar rock glacier.

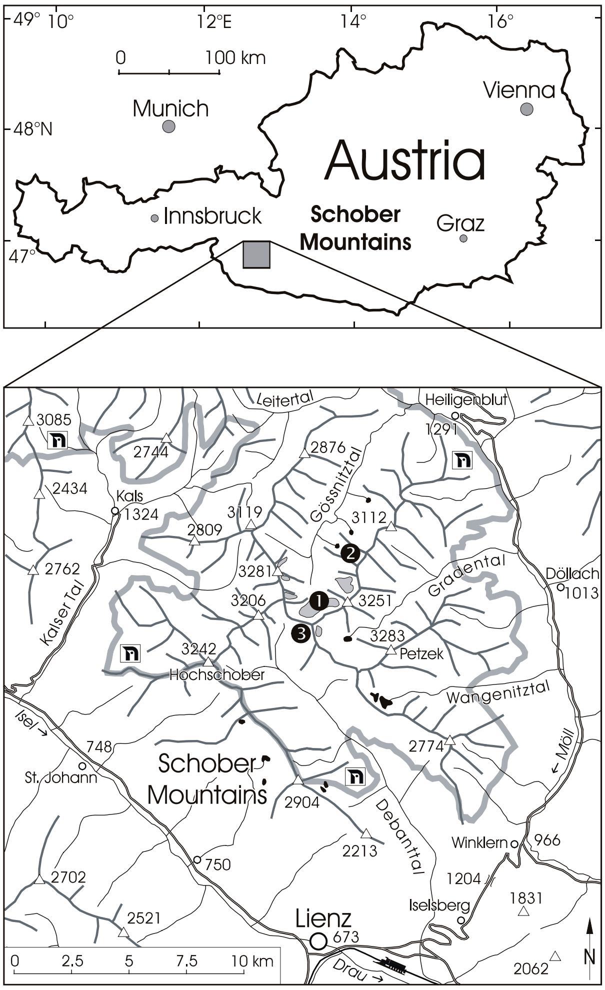


Figure 1: Location of (1) Goessnitzkees, (2) Hinteres Langtalkar rock glacier and (3) Weissenkar rock glacier in the Schober Mountains, Central Alps, Austria. Large parts of the Schober Mountains are within the Hohe Tauern National Park.

2. Geographical Setting

The Schober Mountains are characterized by a rather continental climate, due to their central location within the Eastern Alps, and also provide suitable topographical and geological conditions for the formation of rock glaciers. This abundance of rock glaciers (n=126, 67 of them containing recent permafrost, cf. Lieb, 1996) was the main reason for choosing this mountain range as a study area for the above mentioned (chapter 1) research projects on rock glaciers and permafrost.

Weissenkar rock glacier is situated in a west-exposed cirque nourished from active scree slopes beyond a steep, glacially shaped peak formed of crystalline rocks (Western Klammerkopf, 3126 m). The rock glacier mass creeps from the cirque (in which the existence of a Little Ice Age glacier is probable) to a quite flat plateau-like area composed of roches moutonees. These are remnants of transfluent ice transport from NE to SW across Goessnitzscharte (2732 m) during the periods of maximum ice extent in the Pleistocene. The lower limit of the rock glacier has an elevation of 2615 m, which is slightly above the mean value of this exposure in the Schober Mountains. Its dimensions (length some 500 m, maximum width 300 m) make it one of the larger rock glaciers of the Central Alps.

The rock glacier is characterized by a pronounced surface topography (see Figure 2):

- The furrows and ridges (cf. chapter 5) are very well developed with relative height differences of a few meters over the entire lower half of the rock glacier. The surface relief indicates a reduction in creep velocities

Figure 2: Panoramic view of Weissenkar rock glacier. Photographs taken in August 2004. The viewing direction is from the geodetic reference point F1 in a southerly direction.

and compressive flow because of the low inclination of the flat terrain which the snout has reached.

- The rock glacier is divided into at least two internal rock glacier subsystems with clearly visible margins forming a surface topography similar to a stairway with slopes up to 10 m high (best visible in Figure 4). An older western lobe (see below) is obviously overridden by a younger lobe covering the central part of the rock glacier. There is also another outstanding snout orientated to the South (southern lobe).

First investigations on the geomorphology and internal structure of Weissenkar rock glacier were carried out by Buchenauer, 1990, 57-59, using standard methodology such as measurement of spring temperatures and refrac-

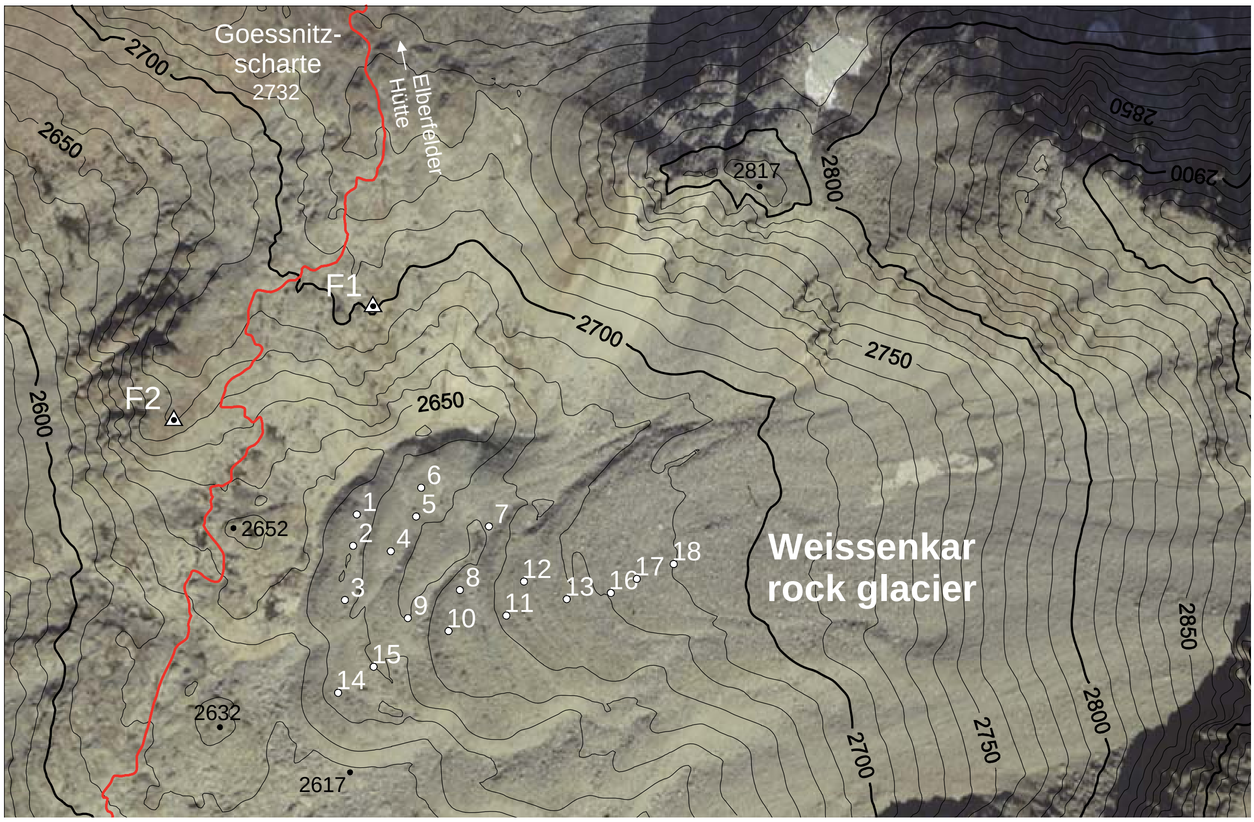


Figure 3: Orthophoto map showing Weissenkar rock glacier. F1 and F2 are geodetic reference points. Points 1-18 are object points fixed by brass bolts on large boulders of the rock glacier surface. The color photograph was taken on 18 September 2002 by the Austrian Federal Office of Metrology and Surveying. Photograph © Amt der Tiroler Landesregierung, 2004. Contour lines derived by (manual) photogrammetric mapping.

Point	x (m)	y (m)	h (m)
F1	-44406.449	5202402.789	2704.820
F2	-44538.079	5202327.568	2681.493
F2ex	-44538.222	5202327.670	2681.490

Table 1: Coordinate list of the three stable reference points located in the vicinity of Weissenkar rock glacier. The coordinates are given in the Austrian Gauss-Krueger coordinate system M31.

tion seismics, all of them indicating the existence of permafrost. Of special interest is the estimation of the active layer thickness, which in 1985 showed significant differences between the western lobe (6.7 m) and the southern lobe as well as the central part (2.9 and 2.6 m, respectively). From this it was concluded that the western lobe moves much slower than the southern one or might even be inactive. The fact that the marginal western slope had a lower gradient and showed some vegetation patches supported this assumption. Soil temperatures at the surface and within the active layer have been monitored (Krobath, 1999) since 1999, but have not yet been evaluated.

3. Geodetic Surveys 1997-2004

As indicated previously, a geodetic monitoring program was started at Weissenkar rock glacier in 1997. Two stable reference points, F1 and F2, were selected on bedrock northwest of the rock glacier. These points can be reached easily from the nearby hiking trail (see Figure 3). 15 object points (points 1-15, see Figure 3) were marked on large boulders on the surface of the rock glacier. All point locations were engraved in the rock by means of chisel and hammer and, additionally, marked with a red color spot. Geodetic measurements were carried out as described in Wack (1997), and preliminary coordinates of all points were computed in the Austrian Gauss-Krueger coordinate system. All of the 1997 points plus 4 additional points - F2ex, which is an auxiliary point located very close to F2, and three new object points, 16-18 - were fixed with brass bolts driven into solid rock in 1998. This enabled the reflector to be placed directly on the bolt by means of an adapter. A total station (electronic theodolite) is used for the geodetic measurements, which are carried out from both positions, F1 and F2. GPS measurements were carried out in 1998 (Constantini and Heugenhauser 1999) for better absolute positioning of the reference points. The geodetic measurements have been repeated every year since 1997, with one interruption in 2002. Due to the circumstances of the 1997 campaign as already described, the accuracy of the point coordinates of the first survey is inferior to that achieved on the subsequent campaigns. The 1997 data will thus not be considered in this paper. Point accuracies are in the order of ± 0.5-1 cm in planimetry and height. The coordinates of F1, F2 and F2ex are listed in Table 1 for documentary purposes. The annual measurements provide the basis for computing three-dimensional (3D) point displacement vectors. The horizontal and vertical move-

Point No.	1998-1999	1999-2000	2000-2001	2001-2003	2003-2004	1998-2004	1974-1998	1998-2002
1	2.4	2.5	3.0	3.6	4.8	3.3	1.6	2.1
2	3.3	3.1	3.4	4.9	6.5	4.3	1.7	3.8
3	2.9	3.4	4.0	5.2	6.1	4.5	2.1	3.0
4	3.3	3.3	4.3	5.2	6.3	4.6	2.1	4.0
5	4.2	3.9	5.7	5.5	6.8	5.2	1.7	4.6
6	3.6	3.0	4.5	4.9	6.1	4.8	2.6	4.1
7	3.9	3.9	5.4	5.9	7.5	5.4	3.1	4.3
8	4.5	5.1	5.8	6.6	9.7	6.4	2.9	5.6
9	5.8	3.8	6.2	8.0	10.9	7.1	3.2	6.2
10	4.4	4.9	5.5	7.3	9.2	6.4	3.0	6.8
11	6.1	5.7	7.5	8.4	11.2	7.9	4.2	7.1
12	5.6	4.9	6.7	7.7	9.4	7.0	4.2	5.1
13	4.8	3.5	6.3	6.4	6.7	5.7	4.1	6.1
14	3.7	4.0	6.3	7.2	9.8	6.4	2.9	4.2
15	3.1	3.2	5.1	6.5	7.4	5.3	2.9	4.0
16	7.9	5.9	8.6	7.8	10.0	7.9	4.6	8.3
17	9.9	10.5	10.0	11.6	10.0	10.5	5.3	9.5
18	7.8	8.7	8.5	9.0	8.4	8.5	5.1	7.7
average	**4.9**	**4.6**	**5.9**	**6.8**	**8.2**	**6.2**	**3.2**	**5.3**

Table 2: Mean annual horizontal movement (cm a^{-1}). Values of the last two columns derived from aerial photogrammetry.

ments given are scaled to annual values (see Tables 2 and 3). Figure 4 shows a cumulative vector plot of the moving surface points of the rock glacier.

4. Aerial Surveys 1974, 1998, 2002

Aerial photographs of several data takes (1954-2002) covering the study area were acquired from the Austrian

Point No.	1998-1999	1999-2000	2000-2001	2001-2003	2003-2004	1998-2004	1974-1998
1	0.4	1.3	0.7	0.2	-0.1	0.5	-2.1
2	-0.1	1.1	0.3	-0.1	-0.3	0.2	-1.3
3	-0.4	1.3	0.4	-0.1	0.7	0.3	-1.2
4	-1.9	0.9	-1.3	-1.3	-1.7	-1.1	-1.3
5	-2.2	-0.3	-1.0	-2.0	-4.3	-2.0	-2.0
6	-2.3	0.0	-2.0	-1.8	-2.3	-1.7	-2.5
7	-1.7	0.3	-1.3	-1.2	-1.6	-1.1	-2.7
8	-1.5	-0.1	-0.7	-1.5	-2.3	-1.3	-1.6
9	-2.3	-0.6	-2.1	-2.8	-3.4	-2.3	-1.4
10	-2.4	-0.9	-1.5	-3.5	-3.7	-2.6	-2.2
11	-6.9	-6.2	-5.5	-10.7	-8.4	-8.1	-3.5
12	-2.1	-1.2	-2.9	-3.8	-5.1	-3.2	-2.5
13	-3.5	-1.9	-2.4	-3.6	-5.4	-3.4	-2.8
14	-1.0	-0.7	-0.7	-2.5	-3.1	-1.8	-0.5
15	-1.9	0.1	-1.1	-1.9	-1.9	-1.4	-2.8
16	-9.1	-6.7	-4.6	-7.4	-6.6	-7.0	-4.5
17	-6.3	-6.1	-4.6	-9.6	-6.6	-7.2	-4.9
18	-7.9	-8.4	-6.1	-11.6	-7.9	-8.9	-5.0

Table 3: Mean annual vertical movement (cm a^{-1}). Values of the last column derived from aerial photogrammetry.

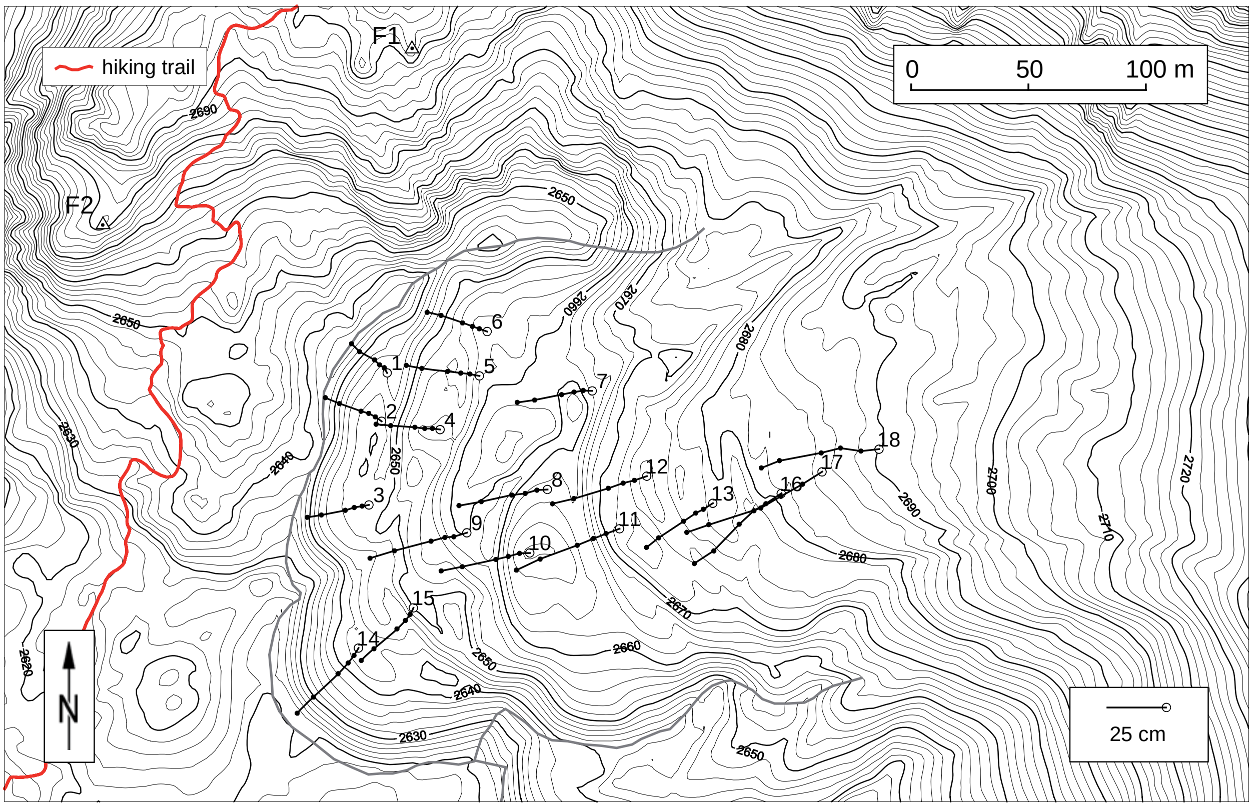
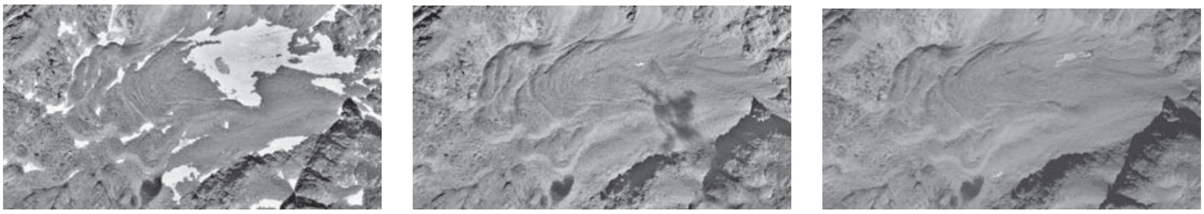


Figure 4: Horizontal movement of Weissenkar rock glacier for the time period 1998-2004. The black dots of the horizontal flow/creep trajectory represent the positions of the object points at the time of measurements. Note that the depicted displacements are exaggerated by a factor of 100. Contour lines derived from (manual) photogrammetric mapping.



date	photos	image scale	focal length	flying height	type of film
5.9.1974	*3*	*1:10,000*	*210 mm*	*4700 m*	*B & W*
*26.8.1998**	*2*	*1:10,500*	*152 mm*	*4050 m*	*B & W*
18.9.2002	*2*	*1:14,000*	*305 mm*	*6800 m*	*color pos.*

* data acquisition by Bildflug Fischer (Graz, Austria)

Table 4: Aerial photographs used in the study.

Federal Office of Metrology and Surveying, Vienna. Large-scale photographs only were selected for further digital photogrammetric processing in order to accomplish the specific task of the present paper (see Tabel 4).

The main task of the photogrammetric work was to derive a dense field of 3D displacement vectors for the time intervals 1974-1998 and 1998-2002 using our in-house developed software package ADVM (Automatic Displacement Vector Measurement). For details (concept, algorithms and practical examples) on ADVM software see Kaufmann and Ladstädter (2004). In a first step all photographs were scanned with 10 µm pixel size using the UltraScan 5000 scanner of Vexcel Imaging Austria. Photogrammetric orientation was carried out on a digital photogrammetric workstation (ISSK) of Z/I Imaging resulting in a total of 4 stereomodels. A high-resolution digital terrain model (DTM) of 2002 was obtained through manual photogrammetric feature collection. This DTM was used to compute orthophotos (for 2002) and pseudo-orthophotos (for 1974 and 1998) from all photographs with a ground sampling distance (GSD) of 12.5 cm and 25 cm, respectively. These orthophotos, the DTM and other collateral data were the input data for subsequent multi-photo constrained image matching using ADVM software. As a result, 3D displacement vectors were obtained for the time intervals 1974-1998 and 1998-2002. Figure 5 shows the horizontal component of the flow/creep vectors obtained for 1974-1998. The spatial distribution of the mean annual horizontal flow velocity for both time intervals is shown in Figures 6 and 7 using iso-lines. Statistical data is provided within the figures shown. Furthermore, high-resolution DTMs for all three epochs were computed, and stereo orthophotos were prepared at 1:5,000 scale for visual interpretation.

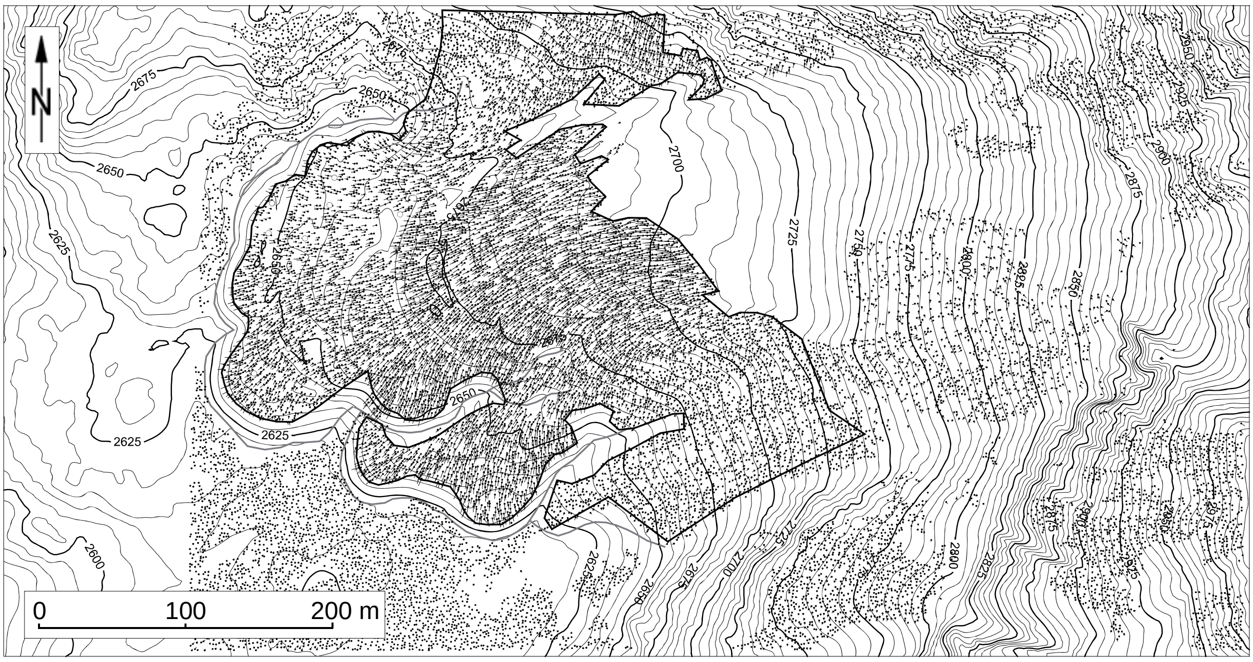


Figure 5: Horizontal displacement vectors derived from aerial photographs 1974 and 1998.

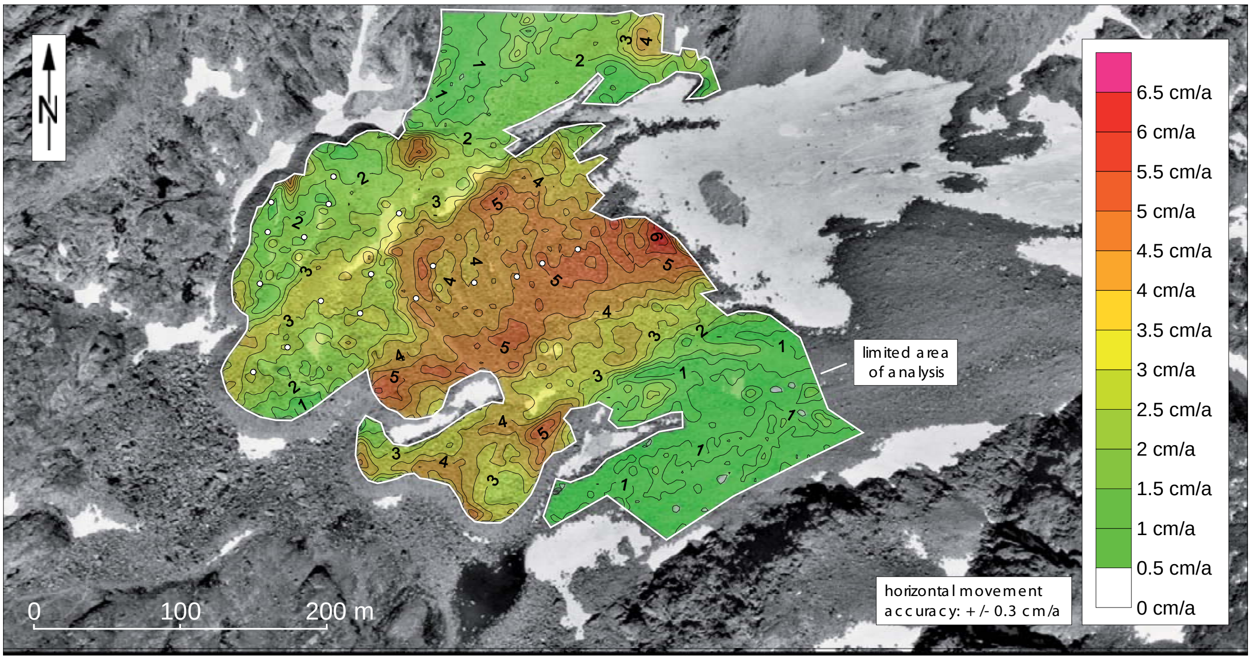


Figure 6: Mean annual horizontal flow/creep velocity for the time interval 1974-1998.

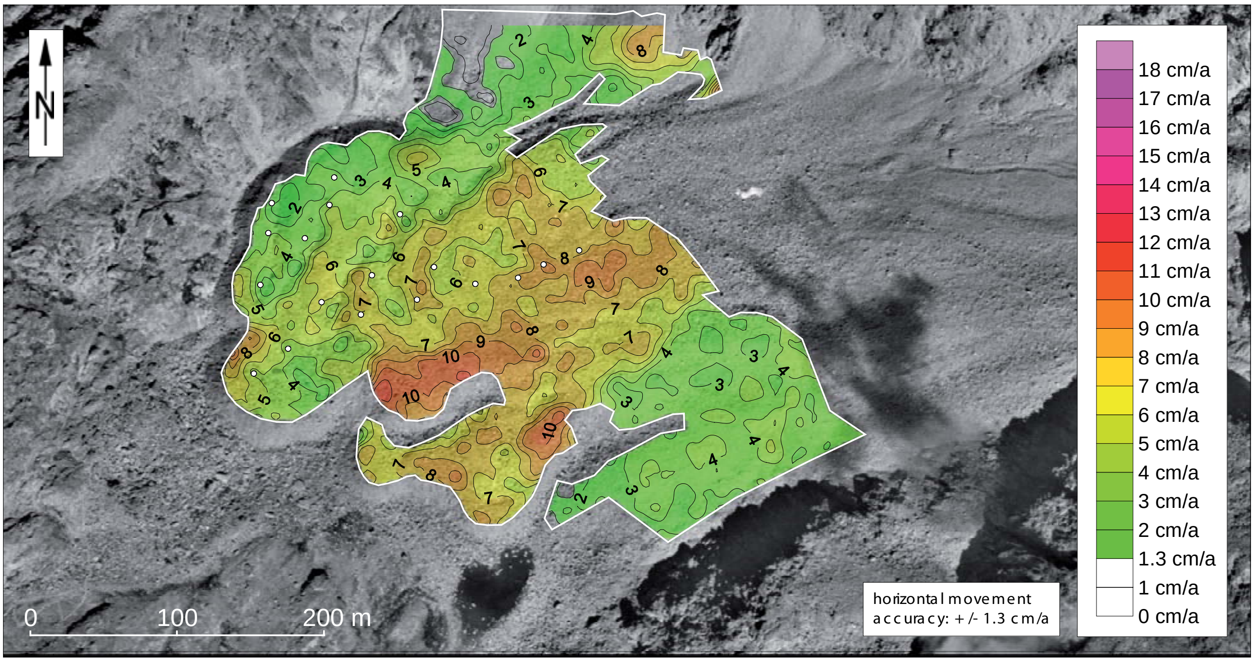


Figure 7: Mean annual horizontal flow/creep velocity for the time interval 1998-2002. Please notice that the color scales of Figures 6 and 7 are different.

5. Analysis of geodetic measurements

Precise geodetic measurements covering a time period of 6 years (1998-2004) are now available for detailed analysis. The minimum flow velocity for the given observation period amounts to 3.3 cm a^{-1}, the maximum 10.5 cm a^{-1}, and the mean value 6.2 cm a^{-1}. From Table 2 we can deduce Table 5, which provides information about the change of flow velocity. The numbers given are derived from the averaged mean values of flow velocity for the individual observation periods (= last row of Table 2).

From Table 5 we can conclude that the mean annual flow velocity (= average over 18 measurements) of Weissenkar rock glacier has increased significantly starting from 1999-2000. The 2003-2004 flow velocity is about 176 % of the value measured 4 years earlier. The highest flow velocities

from – to	change of mean value	relative change	significance level
1998/1999 – 1999/2000	-0.3 cm a^{-1}	-4 %	non-significant
1999/2000 – 2000/2001	+1.3 cm a^{-1}	+28 %	significant
2000/2001 – 2001/2003	+0.9 cm a^{-1}	+14 %	significant
2001/2003 – 2003/2004	+1.4 cm a^{-1}	+21 %	significant
1998/1999 – 2003/2004	+3.3 cm a^{-1}	+68 %	significant

Table 5: Change of mean annual flow/creep velocity.

were measured each year at point locations 11-13 and 16-18 of the upper-most, younger rock glacier lobe. This region of the rock glacier shows a prominent sequence of at least 7 transversal ridges. Flow velocities decrease towards the lower end of the rock glacier. This is especially true for the northern points and confirms compressive flow, which has already been assumed by morphological observations (chapter 2). Looking at the vertical displacements of the geodetically measured points we see, for example, that points 1, 2 and 3 remain more or less at the same height throughout the observation period. Numerical calculations even show a small uplift. In contrast, the points of the previously mentioned upper lobe show higher rates of vertical change than one would expect from surface parallel flow. This implies that marked surface lowering in the order of 2-7 cm a^{-1} is taking place. This may be attributed to permafrost degradation and/or extensive flow. Longitudinal strain rates are in the order of -0.3 x 10^{-3} a^{-1} (points 1-6) and 0.2 x 10^{-3} a^{-1} (middle part, points 8, 10-12).

6. Analysis of Photogrammetric measurements

Figures 5-7 and other thematic maps not shown in this paper clearly reveal the overall kinematics of Weissenkar rock glacier. For reasons of comparison, the mean annual horizontal flow velocity at the 18 object points was interpolated from the photogrammetrically determined displacements, see Table 2, last two columns. Based on averaged values, a significant increase in flow velocity of about 68 % can also be deduced from the photogrammetric data. The change amounts to +2.1 cm a^{-1}. An area-based analysis of the results shown in Figures 6 and 7 shows an increase of 93 % (+2.6 cm a^{-1}). Surface height change was computed twice, i.e., by subtracting multi-temporal DTMs and by subtracting the contribution of assumed surface parallel flow from the z-component of the displacement vector. Very similar results were obtained for both methods (see Figure 8). Significant findings about surface height change can only be given for the time period 1974-1998. Due to limited height measurement accuracy and the short time interval of the 1998-2002 data set, it is only possible to make some general remarks concerning sur-

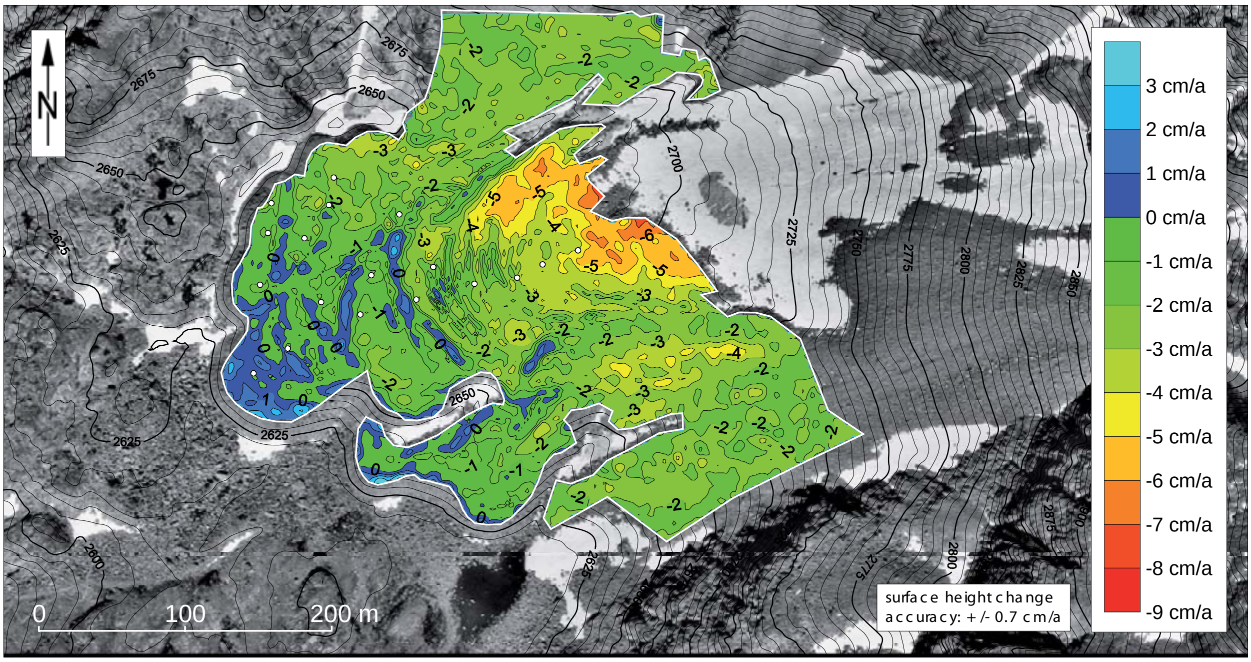


Figure 8: Mean annual surface height change (cm a^{-1}) for the time interval 1974-1998. Surface height change has been derived from 3D displacement vectors and surface slope data assuming surface parallel flow of particles.

face height change. The overall average of surface height change as shown in Figure 8 was calculated at -2 cm a^{-1}. The maximum thickness of the 1974 perennial snow field covering the northern part of the rock glacier was 8.4 m. The comparison of the 1998 and 2002 DTMs reveals a clear depression with a relative height difference of -1.4 m. This feature developed at the place of the former snow field. The upper-most lobe of Weissenkar rock glacier generally displays the highest rates of surface lowering.

7. Comparative Analysis and Conclusions

A direct comparison of the photogrammetric and geodetic measurements is not possible, since the observation periods do not coincide. In order to validate the digital photogrammetric results obtained for the time period 1998-2002, however, displacement vectors for the same time period were estimated from the geodetic data. Averaging of the geodetically measured horizontal flow/creep velocities at the 18 object points produced a value of 5.5 cm a^{-1}, which is in very good agreement with the photogrammetrically derived value of 5.3 cm a^{-1}. A comparison of the interpolated 1974-1998 horizontal flow velocities at the 18 object points with the respective geodetic values, e.g., of the time period 1998-2004, shows a significant increase in flow velocity of about 93 %. Since the photogrammetrically determined flow velocities of 1974-1998 are also smaller than the respective values of the first two years of geodetic measurements, it can be concluded that the flow velocity of Weissenkar rock glacier has increased significantly throughout all time periods for which measurements are available, i.e., from 3.2 cm a^{-1} (1974-1998) to 8.2 cm a^{-1} (2003-2004) based on averaged mean annual flow velocities observed at the 18 object points. The results of geodetic and photogrammetric measurements shown in this paper thus correspond very well with the morphological and periglacial observations outlined in chapter 2. The horizontal creep velocities of the western lobe of the rock glacier are smaller (well pronounced in the period 1974-1998, see Figure 6) than in the central and southern part. The overall pattern of horizontal flow velocities as well as the vertical changes shown in Figure 8 corroborate the assumption of compressive flow.

Marked surface lowering was observed within the limits of the upper-most, younger lobe and especially at the location of a former perennial snow field. Overall surface lowering suggests permafrost degradation of -2 cm a^{-1} for the time period 1974-1998. Recent geodetic measurements (1998-2004) confirm the continuation of permafrost degradation. This statement is rather speculative, however, and is currently a matter of general discussion (see Kääb and Weber 2004). The recent increase in surface velocity also remains to be explained.

8. Acknowledgments

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