10 YEARS OF MONITORING OF THE DOESEN ROCK GLACIER (ANKOGEL GROUP, AUSTRIA) – A REVIEW OF THE RESEARCH ACTIVITIES FOR THE TIME PERIOD 1995-2005

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Abstract: *Doesen rock glacier (46°59' N, 13°17' E, altitude range 2339-2650 m) is located in the Ankogel group of the Hohe Tauern range in Austria. The first permafrost related studies including geomorphological mapping and geophysical investigations were carried out in the early 1990s by the Institute of Geography and Regional Science of the University of Graz. In 1995, the Institute of Remote Sensing and Photogrammetry and the Institute of Navigation and Satellite Geodesy (both Graz University of Technology) commenced geodetic, photogrammetric and cartographic work in order to obtain information on the kinematic state of the rock glacier and to create more accurate maps of the area of interest. Furthermore, satellite-based differential SAR interferometry was applied to obtain additional geomorphometric information. In this paper we want to (1) give a short summary of the work carried out in the last 10 years, based mainly on literature references, and will (2) present an analysis of the photogrammetric and geodetic measurements carried out at Doesen rock glacier using tables, graphs and thematic maps. The geodetic analysis will include 34 object points and additional points of 4 profile lines of the rock glacier. These points were measured every year in August during the last 10 years, with one interruption in 2003.*

INTRODUCTION

Doesen rock glacier (46°59'12" N, 13°17'08" E) is located in the Ankogel group of the Hohe Tauern range, Austria. It is situated at the end of the glacially shaped, W-E oriented inner Doesen valley (cp. Figures 1-3). Rock glaciers are creep phenomena of mountain permafrost and are composed of rocks and interstitial ice. Active rock glaciers creep downslope by force of gravity due to internal deformation of the ice. Sliding may also be possible at certain shear horizons. Due to the above mentioned dynamics, the surfaces of rock glaciers often show characteristic flow features, such as furrows and ridges, reminiscent of lava flows (see also Barsch, 1996).

Doesen rock glacier ranges from 2339 m to 2900 m ASL. The latter value is taken from Doesener Spitz, which is the highest point of the surrounding mountains in the S, SE and E of the rock glacier from where the rock glacier is nourished by weathered material, which is of crystalline type, predominantly granitic gneiss (cp. Figure 2). The frontal slope of the rock glacier is approx. 35-40° steep. The length of the whole permafrost body is about 1000 m, the width varies between 150 and 300 m.

In 1993 Gerhard K. Lieb from the Institute of Geography and Regional Science of the University of Graz started a research initiative on mountain permafrost in Austria with a special geographical focus on the Eastern Austrian Alps. He compiled an inventory of some 1450 rock glaciers of the area of interest by means of geomorphological mapping. For more details see Lieb (1996) and Lieb (1998).

Lieb selected the inner Doesen valley as a study area for closer in-situ investigations on the distribution of mountain permafrost and on rock glaciers. It should be mentioned that Doesen rock glacier is one of the largest active rock glaciers of his inventory. Multi-disciplinary research work funded by the Austrian Science Fund (FWF) comprised not only GIS-based analysis of various field measurements, special geophysical soundings, and cartographic tasks but also geodetic and photogrammetric activities. A detailed description of the results obtained is given in a monograph published by Lieb (see e.g. Lieb, 1996; Schmöller and Fruhwirth, 1996; Kaufmann, 1996).

Lieb estimated the mean thickness of the Doesen rock glacier at 30-40 m based on geophysical soundings. He also calculated the total volume of the rock glacier to be approx. 15×10^6 m^3. The ice volume is estimated at 6×10^6 m^3.

A "rock glacier educational trail" has been installed in the Doesen valley in a follow-on project funded by the Hohe Tauern National Park. People who are interested can walk this trail, which ends near the snout of Doesen rock glacier. A folder gives detailed information on the various aspects of landscape development along the trail, permafrost related subjects, and also rock glaciers (Nutz, 2005).

In this paper we intend (1) to summarize all mapping and geomorphometric projects (initial work and follow-on projects) carried out on Doesen rock glacier and (2) to present some new geodetic and photogrammetric results obtained from recent investigations. The authors concentrated on setting up a long-term (geomorphometric) monitoring program using various observation techniques for obtaining precise and reliable information on the spatio-temporal evaluation of the surface of Doesen rock glacier. All work described in the following pages was carried out under the leadership of the Institute of Remote Sensing and Photogrammetry of the Graz University of Technology (TU Graz) in cooperation with the Institute of Navigation and Satellite Geodesy of TU Graz and the Institute of Digital Image Processing of Joanneum Research, Graz.

Chapter 2 presents the photogrammetric work, while the geodetic surveys are described in chapter 3. The application of radar interferometry and the cartographic work are briefly outlined in chapters 4 and 5, respectively. Chapters 6 to 8 cover the analysis of the photogrammetric and geodetic results with concluding remarks.

PHOTOGRAMMETRIC SURVEYS 1954-1998

Aerial photogrammetry is one of the most powerful techniques for obtaining area-wide three-dimensional (3D) information of high mountain environments. Modern digital photogrammetric techniques and, especially, the digital photogrammetric workstation (DPW) have led to the so-called "democratization" of photogrammetry, which made this technology available to a broader user community. Geographical information systems (GIS) now enable not only indirect but also direct input of data using stereo viewing functionality.

The application of photogrammetry to rock glacier monitoring is very much advanced and well documented in literature (cp. Kääb, 2005; Kaufmann and Ladstädter, 2004).

Aerial photographs of several data takes (1954-1998) covering the study area were acquired from the Austrian Federal Office of Metrology and Surveying, Vienna (see Table 1).

Table 1. Aerial photographs used in the study.

date	photos	image scale	focal length	flying height	type of film
1954+	3	1 : 16,300	210 mm	5930 m	black-and-white
1969++	2	1 : 29,700	153 mm	7040 m	black-and-white
17.9.1975	5	1 : 19,800	153 mm	5520 m	black-and-white
15.8.1983	5	1 : 46,400	153 mm	9580 m	black-and-white
15.8.1993	5	1 : 11,300	215 mm	4930 m	color infrared
1.9.1997*	2	1 : 14,000	152 mm	4640 m	black-and-white
10.9.1998	2	1 : 33,400	153 mm	7600 m	black-and-white

+date of acquisition unknown
++acquisition between 29.9. and 12.10.
*data acquisition by Bildflug Fischer, Graz, Austria

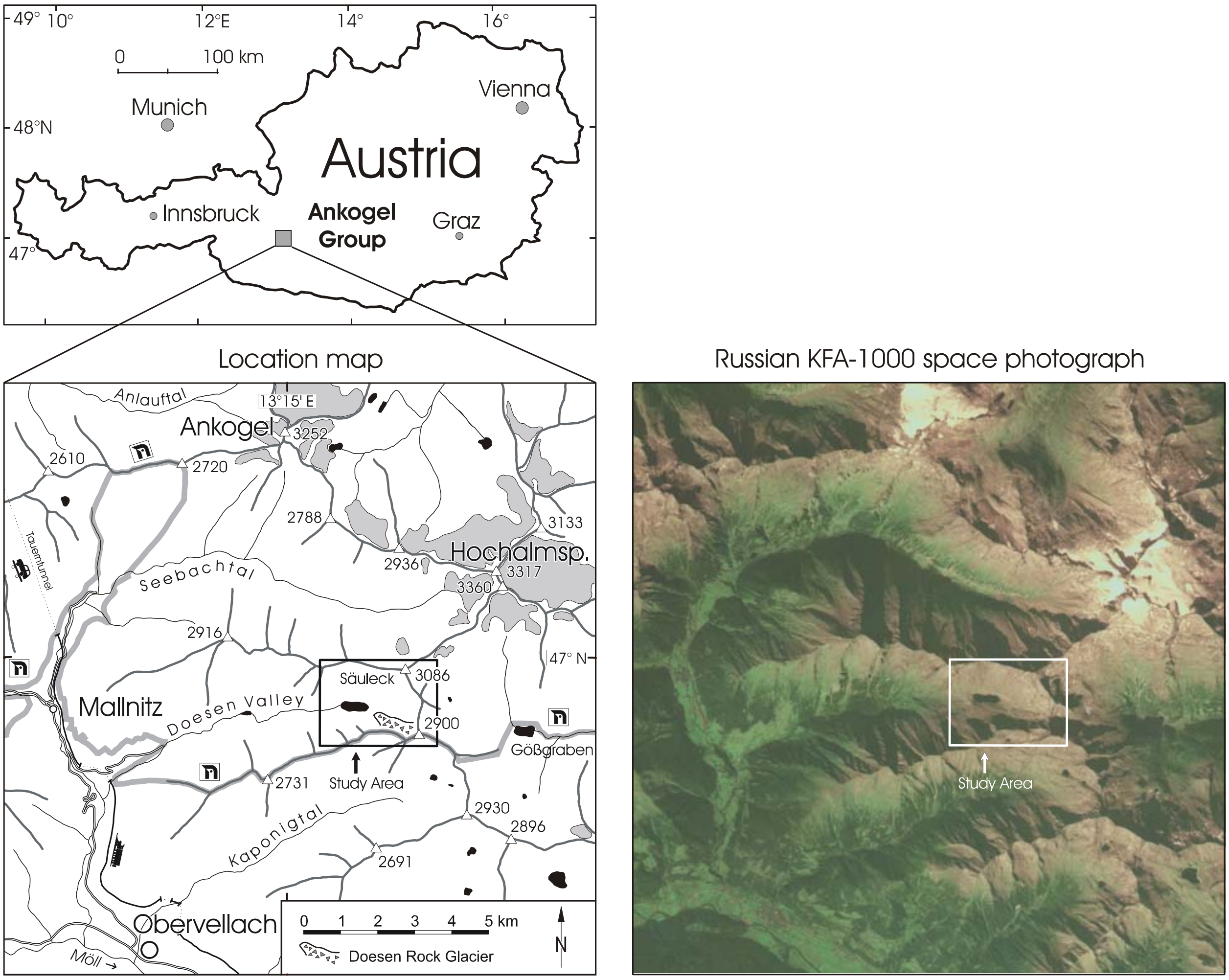


Figure 1. Location of Doesen rock glacier in the Ankogel group, Hohe Tauern range, Austria. Large parts of the Ankogel group are within the Hohe Tauern National Park (). The Russian KFA-1000 space photograph (spectrozonal film emulsion) on the right hand side shows the same area indicating relief and landcover. The photograph (no. 21528, original scale 1:410,000) was taken from the MIR space station on 25 September 1991 during the Austrian-Russian AUSTROMIR project. The photograph shown is not an exact orthoimage. The study area is indicated by a box. A close-up of this area is shown in Figure 2. (The KFA-1000 photograph was provided by R. Kalliany, Graz.)

The photogrammetric evaluation of the aerial photographs 1954-1993 is described in Kaufmann (1996, 1997, and 1998). The task was to derive high resolution digital terrain models (DTMs) with a grid spacing of 2.5 m for a selected area partly covering the Doesen rock glacier (see Figure 2, white box) for 1954, 1975, 1993, and 1997, and for the whole study area (as shown in Figure 2) using the aerial photographs of 1975. 3D feature collection was performed using an analytical stereoplotter DSR-1 of Kern. At this stage of photogrammetric work, photographs were scanned in parts – disk space was still a limiting factor at that time – using a VX3000 scanner of Vexcel Imaging Austria, and orthophotos were produced using the in-house developed software GAMSAD (Kaufmann, 1984).

In order to derive a dense field of 3D deformation vectors some 600 distinct corner points of rocks/boulders on the rock glacier surface were traced in the multi-temporal stereomodels of 1954-1997 and measured with care. High quality measurements were achieved (cp. Figure 4), although work was quite troublesome and tedious, since the more convenient technique of simultaneous multi-temporal point transfer (cp. Kääb, 1996) was not available at that time. The identification of multi-temporal homologous points was facilitated by prediction based on previous measurements.

From the experience gained in previous work, a much more efficient solution for measuring 3D displacement vectors based on digital photogrammetric techniques was proposed by Kaufmann (1996). The idea was to apply high accuracy image matching algorithms, e.g. least squares matching, to multi-temporal "pseudo-orthophotos", which are pre-rectified aerial photographs. This concept has several advantages as described in Kaufmann and Ladstädter (2004).

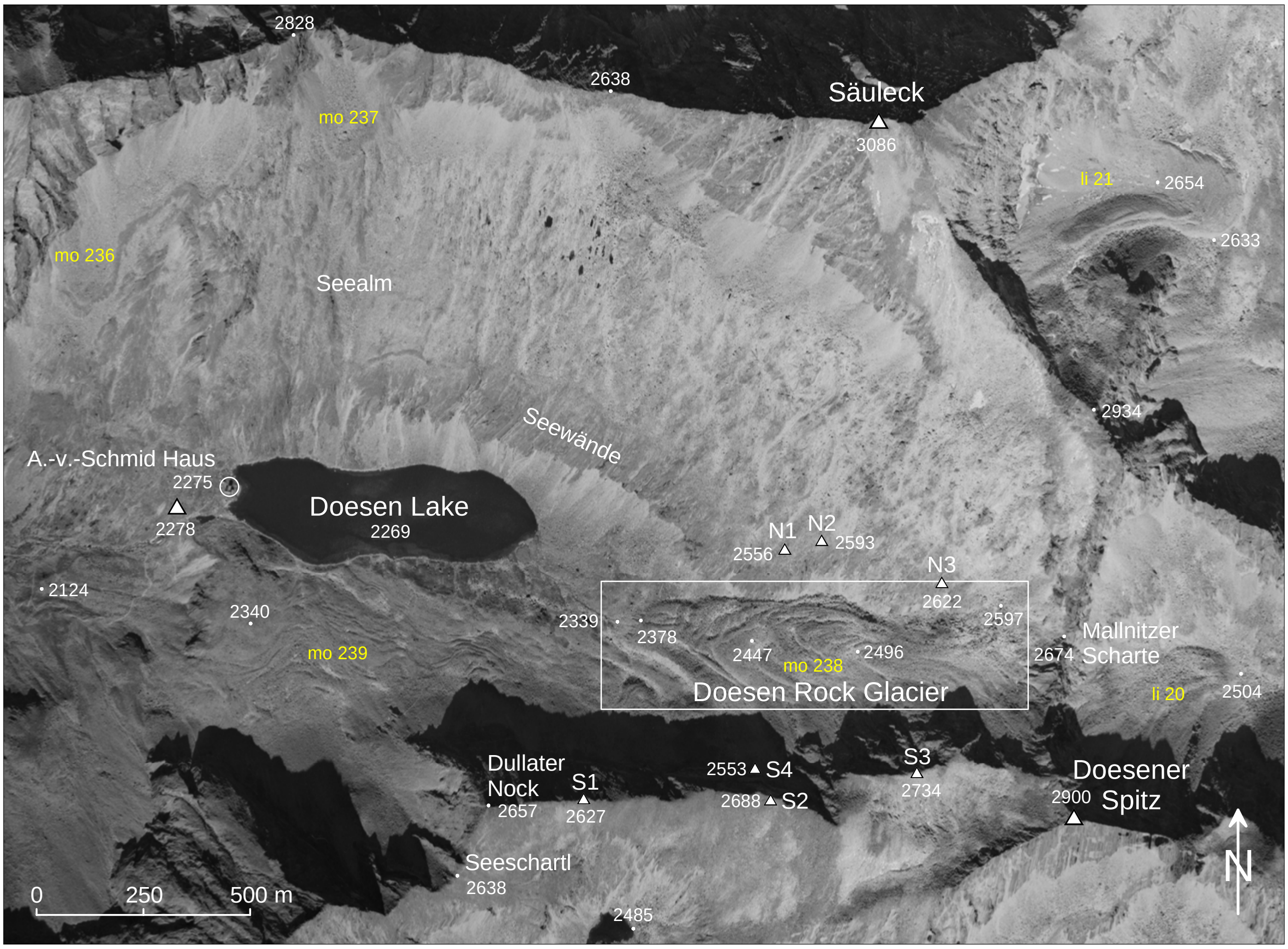


Figure 2. Orthophoto of 10 October 1998 showing the inner Doesen Valley with the impressive Doesen rock glacier. There are some five more rock glaciers within the study area shown. All rock glaciers are indicated by index numbers mo and li (in yellow) according to the rock glacier inventory of Lieb (Lieb, 1996). These rock glaciers have been classified by Lieb as intact, except mo 236, which is regarded as a relict rock glacier. The white box refers to the area shown in Figures 4-10. The area shown in this figure belongs to the inner (= most protected) zone of the Hohe Tauern National Park and can be reached by a foot path maintained by the Austrian Alpine Club (OeAV) within 2.5 hours from a parking lot in the Doesen valley. Visitors can stay overnight at the A.-v.-Schmid Haus, which provides full board. A hike up to the highest summit of this area, Säuleck, is a rewarding experience, since it is more than 3000 m high and the panoramic view it offers is beautiful.

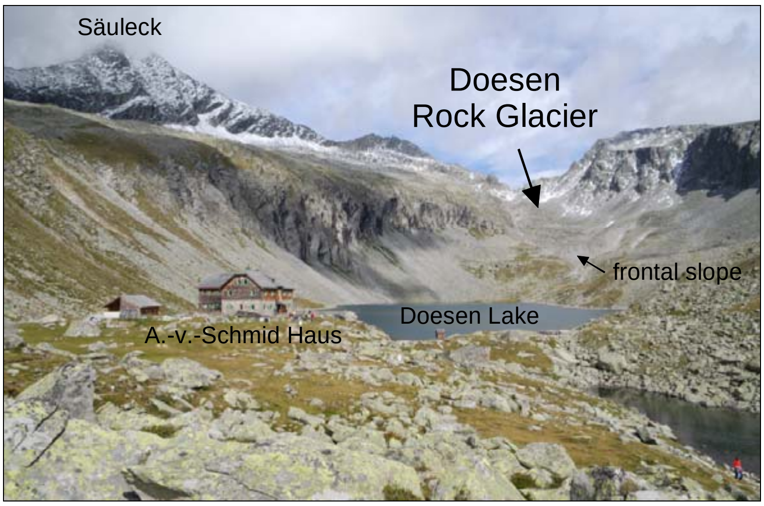


Figure 3. Terrestrial view of Doesen rock glacier of 17 August 2005.

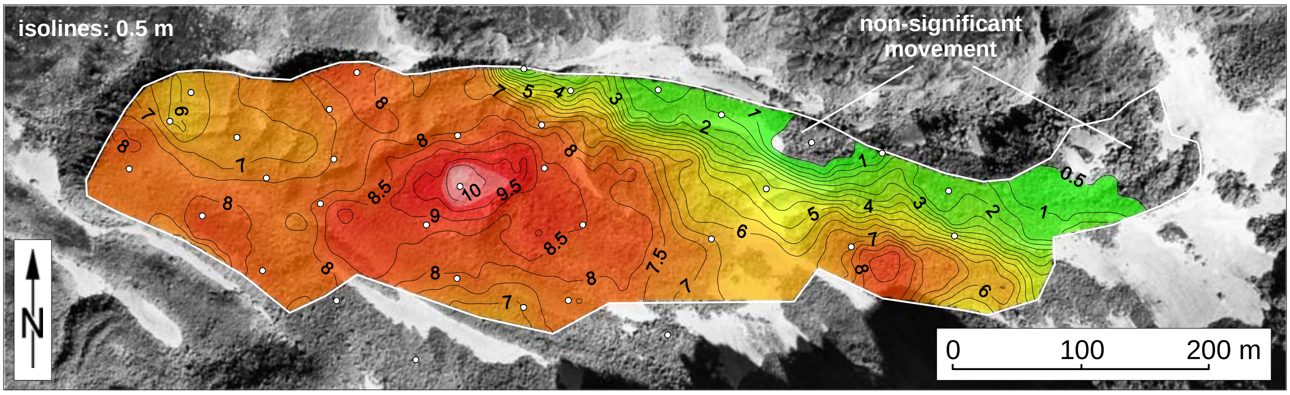


Figure 4. Total horizontal movement (m) of Doesen rock glacier for the time period 1954-1997. Data collected by photogrammetric means and manual mapping. An area of interest (= white polygon) for valid measurements had to be defined due to snow cover and shadowing in the multi-temporal stereomodels. The positions of the 34 geodetic observation points are marked with white dots. Orthophoto of 1 September 1997.

A first prototype of a software package based on the above mentioned concept, later called ADVM (Automatic Displacement Vector Measurement), was implemented by Ladstädter. In his diploma thesis (Ladstädter, 1999) he also performed practical tests with aerial photographs of the Doesen project. However, the results obtained were disappointing from a practical point of view, since the 3D displacement vectors measured revealed not only the real 3D deformation of the rock glacier but also the systematic cyclic scanning errors of the RM-1 photogrammetric scanner of Wehrli & Associates Inc., which was used for scanning the film material. As a consequence, ADVM was used to study the scanning errors in more detail.

The ADVM software was further developed and enhanced by special features, e.g. multi-photo constrained matching. For more details see Kaufmann and Ladstädter (2004). Currently ADVM works not only with pseudo-orthophotos but also with the original photographs. ADVM has already been successfully applied in several rock glacier monitoring projects in Austria (see Kaufmann and Ladstädter, 2003; Kaufmann et al., 2005b) and other projects on deformation measurement.

For this paper we have decided to compute high resolution 3D displacement vectors of Doesen rock glacier using ADVM for the time period 1993-1997. The photographs were scanned with 10 μm pixel size using the UltraScan 5000 scanner of Vexcel Imaging Austria. As a result, 3D displacement vectors were obtained for the time period 1993-1997. Figure 5 shows the horizontal component of the flow/creep vectors. The spatial distribution of the mean annual horizontal flow velocity is depicted in Figure 6.

Figure 5. Horizontal displacement vectors derived from large-scale aerial photographs 1993 and 1997 using image matching techniques (ADVM software). 7631 vectors were computed. The accuracy achieved in vector length is ±3-5 cm a^{-1}.

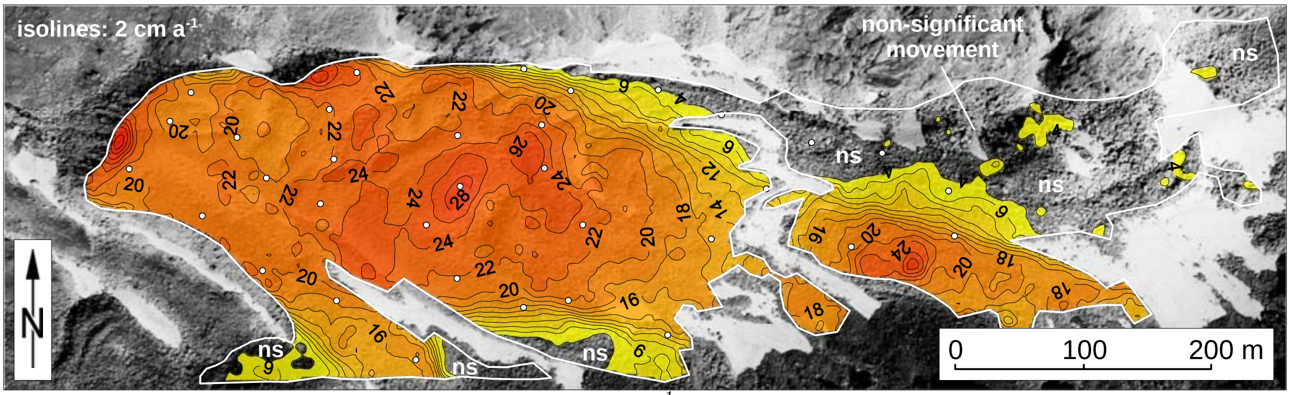


Figure 6. Mean annual horizontal flow/creep velocity (cm a^{-1}) of Doesen rock glacier for the time period 1993-1997. Original measurements shown in Figure 5. The positions of the 34 points are marked with white dots. Orthophoto of 15 August 1993.

In an earlier stage of the Doesen monitoring project, terrestrial photogrammetry was considered as an alternative method to the comparatively expensive aerial surveys. Terrestrial surveys were carried out using a semi-metric Rolleiflex 6006 rèseau camera (Benzinger, 1996; Kaufmann, 1996; Woschitz, 1997). Woschitz, e.g., deployed white spherical targets (PVC, ∅ 13.9 cm) on selected observation points of the rock glacier. These points serve as photogrammetric control points since their location is known with high accuracy from geodetic survey. In 2003, the terrestrial photogrammetric survey of 1997 was repeated using the same Rolleiflex and, additionally, a digital Nikon D100 camera. This time no targets were deployed on the rock glacier surface. The digital photogrammetric evaluation of the photographs (1997, 2003) was not successful for various reasons. Following the pioneering work of W. Pillewizer at the Outer Hochebenkar rock glacier, however, terrestrial photogrammetry was for the first time successfully applied to the monitoring of the same rock glacier by Ladstädter and Kaufmann (2005).

Rollei and Hasselblad now offer digital backs for their professional 6×6 SLR cameras. It is planned in the near future to acquire image data at Doesen rock glacier using a digital 22 Megapixel Hasselblad H2D, this time, however, from a small single-engine airplane.

GEODETIC SURVEYS 1995-2005

In 1995 a geodetic network was set up in order to measure the annual displacement vectors of selected points of the rock glacier surface (Heiland and Tilg, 1996; Urbanz and Zölss, 1996). The design of the network had to support a long-term monitoring program over several decades. Since we are talking about deformation measurements, great emphasis was put on the selection, stabilization and measurement of the 7 stable reference points in the north (N1, N2, and N3) and south (S1-S4) of the rock glacier. Actually, there is another point S5 in the close vicinity of S4, which serves as an additional excentral point for S4. All points were fixed with brass bolts driven into solid rock. S4 is situated on a small, heavily fractured protrusion approx. 100 m above the middle part of the rock glacier in the north face of the southern mountain ridge. Access to this point is very troublesome because of unstable ground (scree slope). S4 is the lowermost point from which the whole Doesen rock glacier can be overlooked and where a geodetic tripod can be set up securely. Coordinates of all reference point were determined in the Austrian Gauss-Krueger coordinate system (see Table 2).

The stability of all reference points has never been checked by a complete re-measurement of the whole geodetic network since 1995/1996 because of time and money constraints. However, the stability of S4 was checked each year depending on the availability of measurements. The first significant movement of S4 (1.9 cm in northerly direction) was detected in 2002 (cp. also Table 2). The geodetic measurements of 2005 were supported by a GPS campaign (Nunner, 2005; Rieser, 2005).

Two sets of observation points in respect to point stabilization exist on the rock glacier. 34 points were fixed in the same way as the reference points. A geodetic reflector can be placed directly on the bolt by means of an adapter, which makes the measurements more precise. 75 points were engraved in the rock by means of chisel and hammer. These point locations were taken from the geophysical soundings and form two transversal profiles (3000, 4000) and two longitudinal profiles (1000, 2000). Two points (5001, 5002) are located elsewhere. The location of all 109 points is shown in Figures 7 and 8.

Table 2. Coordinate list of the 7 reference points and the additional excentral point S5 located in the vicinity of Doesen rock glacier. The coordinates were determined using a total station and GPS. The coordinates are given in the Austrian

Gauss-Krueger coordinate system M31. Coordinates of the respective reflector centers of all points are given in Nunner (2005).

point	year	x (m)	y (m)	h (m)
N1	1996	-3670.222	5205425.853	2556.009
N2	1996	-3583.591	5205446.041	2592.562
N3	1996	-3302.202	5205347.463	2621.604
S1	1996	-4141.076	5204841.458	2626.657
S2	1996	-3703.336	5204838.816	2687.837
S3	1996	-3360.567	5204902.637	2733.668
S4	1996	-3740.072	5204912.868	2553.206
S4[+]	2002	-3740.072	5204912.887	2553.206
S4[+]	2005	-3740.070	5204912.899	2553.195
S5	1996	-3728.526	5204900.347	2558.963
S5[++]	2005	-3728.531	5204900.360	2558.957

[+]In 2002 and 2005 a significant movement of point S4 was detected.
[++]New coordinates were derived in 2005.

All points were measured each year in August for the past 10 years, with one interruption in 2003. (Kienast and Kaufmann, 2004; Stangl, 2004). Because of constraints immanent in annual field campaigns, i.e., time, money, weather conditions, and number of co-workers (volunteers, students), the measurement scheme had to be very flexible. The shortest measurement time can be achieved if all 109 points are measured once (or twice) from point S4 using polar point determination. A better solution is a double survey from S4 and both N1 and N3. Detailed information on the technical parameters of each year's survey can be found in the technical reports available at the authors' institute.

In 1999 several measurement campaigns were carried out in order to study the seasonal changes of flow/creep velocity of Doesen rock glacier. The results obtained, however, were not significant (Worsche, 2000).

The applicability of GPS for measuring point locations on the rock glacier was tested during a field campaign in 1996 (Patka, 1997). The outcome of this study was that not all of the (34) points could be measured successfully because of obstruction of the GPS signals by the surrounding mountains, especially by the mountain ridge in the S of the rock glacier.

The annual measurements provide the basis for computing point displacements. The movements are scaled to annual values for reasons of comparison (see Tables 3 and 4). Figure 7 shows a cumulative vector plot of the horizontal movement of the 34 points marked with brass bolts. The mean annual movement of the 75 profile points is shown in Figure 8.

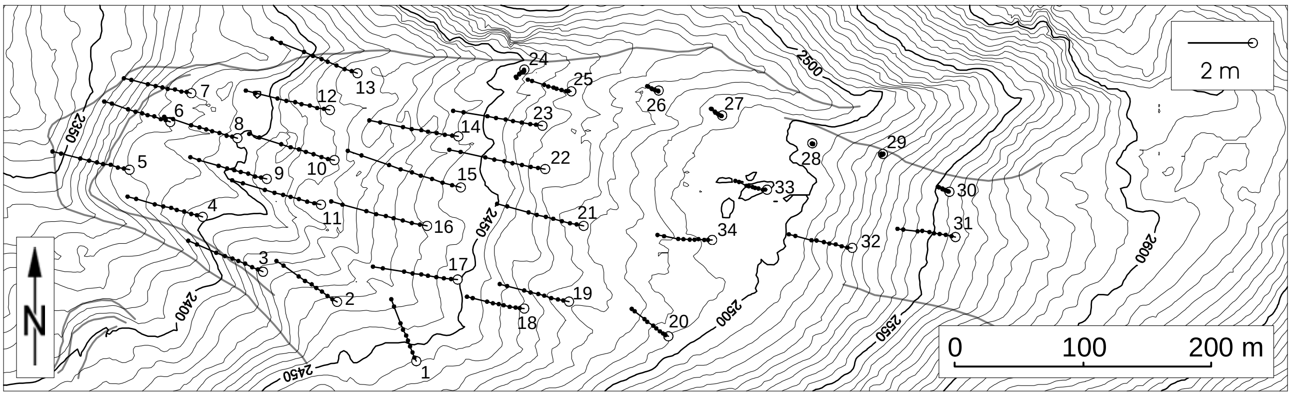


Figure 7. Total horizontal movement of the 34 points marked with brass bolts on the Doesen rock glacier for the time period 1995-2005. The black dots of the horizontal flow/creep trajectory represent the position of the object points at the time of measurement. Note that the depicted displacements are exaggerated by a factor of 25. Maximum movement of 3.70 m was measured at point 15. Contour lines derived from (manual) photogrammetric mapping.

Table 3. Mean annual horizontal movement (cm a^{-1}).

point no.	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2004	2004-2005	1993-1997+
1	12.8	17.0	20.1	19.4	16.4	20.5	21.5	28.0	24.0	17.3
2	17.4	17.7	22.4	20.6	18.2	23.3	24.4	28.9	26.4	18.2
3	17.8	19.1	24.3	22.6	20.1	24.6	28.7	32.8	29.6	21.0
4	19.0	17.9	23.4	23.4	18.7	24.7	27.5	30.2	27.5	20.5
5	18.4	18.8	24.0	23.6	20.0	24.9	28.2	31.0	27.5	21.2
6	15.4	15.3	22.4	21.2	17.8	21.3	24.4	26.7	24.6	18.7
7	15.5	16.2	21.4	22.5	17.3	21.4	24.9	26.5	23.8	19.2
8	17.5	17.4	23.9	23.0	19.5	21.9	26.7	29.7	28.4	19.4
9	18.9	18.8	23.3	23.6	20.7	23.1	27.7	31.8	28.2	20.1
10	21.2	20.7	26.1	24.8	23.0	26.7	30.7	35.7	33.2	22.4
11	21.9	22.2	27.1	26.6	24.2	27.7	31.2	35.8	34.4	22.9
12	19.5	20.9	24.2	26.0	20.7	27.7	28.6	35.5	30.5	21.7
13	19.8	22.4	27.8	29.2	21.1	28.4	30.6	38.9	30.4	24.2
14	19.9	22.6	26.0	27.1	21.5	30.0	27.9	36.3	34.3	23.2
15	28.5	30.4	34.9	36.1	29.4	36.6	38.1	45.6	44.6	28.9
16	23.2	25.5	29.1	29.2	25.3	30.6	32.0	38.6	36.2	25.0
17	21.2	22.2	23.7	26.3	21.4	27.0	27.1	33.5	31.0	21.8
18	14.7	12.6	18.5	19.3	15.9	18.3	18.9	23.1	18.2	15.3
19	18.8	16.7	21.3	22.9	19.5	24.4	20.9	27.4	23.6	19.8
20	10.1	9.0	11.9	14.3	12.6	22.1	12.2	19.7	11.5	11.4
21	22.9	20.8	26.2	27.8	23.7	28.8	26.8	34.6	32.1	23.0
22	23.1	22.8	28.0	29.6	26.2	31.4	29.1	39.4	35.6	25.4
23	20.7	17.9	27.0	27.5	23.6	30.2	27.4	37.7	32.4	23.1
24	1.5	4.4	1.8	5.1	1.6	8.7	2.0	6.4	4.1	6.5
25	9.5	7.0	14.6	16.0	10.0	16.8	13.7	19.8	13.5	13.4
26	1.9	1.9	5.5	5.4	2.7	7.6	2.6	5.9	3.2	3.9
27	2.6	0.7	4.1	6.1	4.6	6.5	4.4	6.1	2.4	4.0
28	2.8	3.1	1.3	1.1	0.9	2.8	0.9	0.7	0.7	0.7
29	1.0	2.6	1.9	2.0	1.5	3.4	0.4	2.0	1.8	2.7
30	2.7	2.5	3.4	4.5	3.1	8.5	2.0	6.2	3.9	4.1
31	13.0	18.1	19.2	17.5	14.9	22.5	14.5	22.6	17.9	17.5
32	15.4	18.2	19.6	19.6	17.9	23.3	15.9	26.0	20.4	19.2
33	6.3	6.7	14.5	10.7	8.2	12.2	6.8	13.2	11.8	10.0
34	13.4	11.5	18.3	12.2	14.9	19.8	16.1	22.5	20.6	15.6

+Values of the last column are derived from digital photogrammetry (see chapter 2 and cp. Figure 6).
Mean accuracy of geodetically derived values: ±2 cm a^{-1}.
Mean accuracy of photogrammetrically derived values: 3-5 cm a^{-1}.

Table 4. Mean annual vertical movement (cm a^{-1}).

point no.	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2004	2004-2005
1	-8.4	-8.7	-17.2	-8.2	-6.2	-7.4	-7.7	-10.2	-7.6
2	-9.8	-9.8	-17.1	-8.5	-7.1	-6.4	-8.4	-10.6	-8.4
3	-9.0	-7.9	-14.7	-6.3	-4.5	-4.5	-6.8	-7.6	-5.0
4	-7.5	-9.0	-14.8	-4.9	-3.8	-4.0	-5.8	-5.5	-4.3
5	-9.5	-10.3	-15.6	-5.8	-6.0	-6.2	-7.7	-8.4	-5.4
6	-9.0	-12.1	-13.2	-6.0	-5.2	-4.9	-6.8	-7.2	-6.0
7	-8.5	-10.2	-12.3	-4.6	-4.2	-4.1	-6.0	-5.9	-4.9
8	-7.0	-9.2	-10.9	-4.1	-3.3	-2.0	-5.4	-4.5	-3.2
9	-7.1	-8.3	-12.3	-3.7	-3.0	-1.9	-3.4	-4.1	-3.3
10	-12.0	-8.3	-16.0	-7.0	-4.4	-5.2	-7.2	-8.3	-7.0
11	-9.0	-8.4	-14.2	-6.3	-5.4	-4.0	-6.4	-7.5	-5.5
12	-9.6	-9.8	-15.1	-7.1	-4.5	-5.4	-8.6	-7.8	-6.9
13	-9.4	-10.1	-15.3	-8.3	-6.3	-6.3	-9.7	-10.8	-7.6
14	-12.0	-14.5	-19.8	-12.7	-8.9	-10.8	-13.2	-15.9	-14.5
15	-10.7	-11.4	-17.7	-9.5	-6.7	-8.5	-10.0	-11.9	-12.1
16	-10.2	-11.1	-16.8	-8.5	-7.0	-7.3	-8.4	-10.2	-9.5
17	-11.3	-11.7	-18.5	-10.5	-8.2	-8.3	-10.0	-12.2	-11.0
18	-10.1	-9.7	-18.4	-10.0	-8.8	-8.1	-10.0	-12.2	-9.1
19	-10.2	-10.4	-17.5	-8.5	-7.2	-6.7	-9.1	-11.2	-9.7
20	-8.0	-9.1	-14.9	-9.8	-14.1	-10.0	-9.0	-13.5	-6.2
21	-12.3	-13.6	-18.6	-12.0	-8.4	-8.7	-11.4	-13.2	-12.8
22	-12.1	-13.7	-20.2	-11.1	-8.7	-9.5	-12.6	-15.1	-14.2
23	-10.2	-12.7	-16.1	-10.0	-7.6	-8.0	-11.5	-15.2	-14.6
24	-6.1	-7.0	-11.3	-2.8	-1.8	-2.6	-3.5	-4.5	-2.1
25	-10.1	-10.3	-16.1	-9.1	-6.1	-8.7	-10.6	-12.6	-11.0
26	-7.5	-7.2	-12.7	-2.8	-1.9	-1.0	-3.2	-5.1	-2.5
27	-7.2	-5.9	-13.2	-3.7	-6.0	-2.5	-5.8	-10.3	-2.9
28	-7.7	-4.4	-11.6	0.2	-1.0	1.4	-1.7	-0.4	0.2
29	-9.8	-2.6	-12.0	-1.1	-0.7	-0.9	-1.2	-0.8	-0.5
30	-9.7	-6.8	-15.1	-3.6	-2.7	-2.7	-6.0	-5.3	-4.2
31	-14.8	-14.0	-25.2	-14.9	-14.6	-14.7	-16.9	-16.7	-11.2
32	-17.2	-16.1	-26.1	-15.4	-15.7	-15.8	-15.9	-24.1	-17.0
33	-6.7	-6.0	-10.3	-2.2	-3.4	-0.4	-3.0	-5.3	-0.5
34	-8.9	-10.9	-15.2	-7.0	-7.3	-4.8	-8.6	-7.5	-6.2

Mean accuracy of vertical movements: ±2-3 cm a^{-1}.

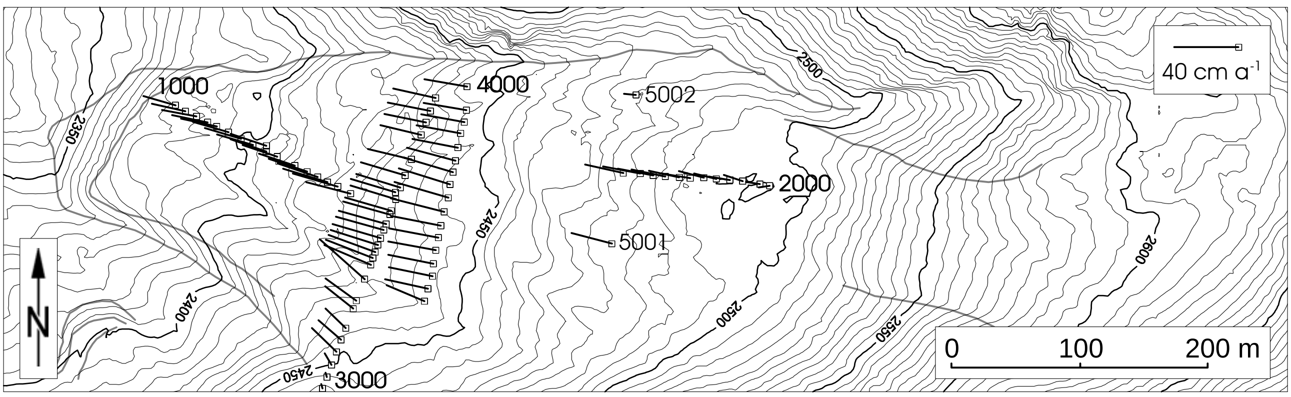
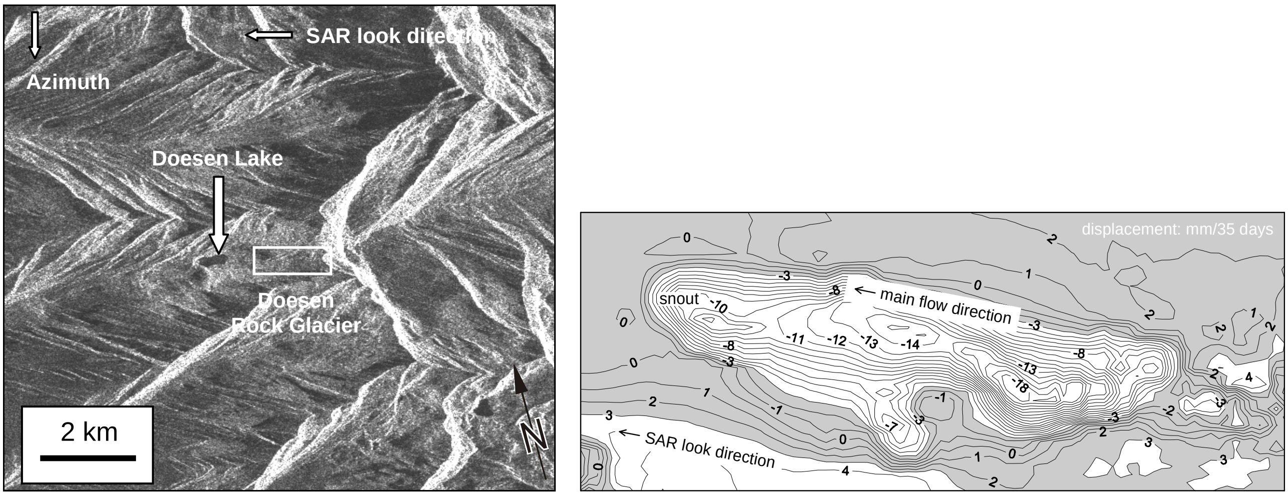


Figure 8. Mean annual horizontal movement of the 75 profile points of the Doesen rock glacier for the time period 1995-2005. Note that the depicted displacements are exaggerated by a factor of 125.

SPACE-BORNE DIFFERENTIAL SAR INTERFEROMETRY

Differential SAR interferometry (D-InSAR) from space is another powerful remote sensing technique for detecting and measuring earth surface deformations in the range of cm or even mm. Due to the principle of SAR mapping geometry, D-InSAR is only sensitive to surface displacements in the radar line-of-sight. Literature references on the basics of SAR interferometry can be found in the citations of this section. Successful applications of D-InSAR using ERS-1/2 and J-ERS data on the measurement of rock glacier surface deformation have been reported in Nagler et al. (2002) and Kenyi and Kaufmann (2003a, 2003b) for two rock glaciers in Austria, i.e., Hochebenkar rock glacier and Doesen rock glacier, and in Kääb (2005) and Strozzi et al. (2004) for several rock glaciers in the Swiss Alps.

For the Doesen rock glacier an ERS-1 orbit pair of 35 days temporal baseline and very small perpendicular baseline (7 m) in August 1992 showed sufficient coherence for computing surface deformation (see Figure 9). The maximum deformation was about –18 mm/35 days in the steeper upper part of the rock glacier, while the deformation at the snout of the rock glacier was –10 mm/35 days. The overall mean deformation rate was about –6 mm/35 days. The computation of surface flow velocities has to be restricted to some assumptions, e.g., surface parallel flow and flow direction parallel to the radar line-of-sight.



a) b)

Figure 9. (a) ERS-1 SAR amplitude image of the study area showing Doesen rock glacier and its surroundings. (b) Close-up of the area marked with a box in (a) in isolines of 1 mm displacement for a 35 day orbit pair (23.8.1992, 27.9.1992) with non-significant movements indicated in gray. The two figures are shown in SAR ground range representation.

The Hohe Tauern National Park funded a follow-on project in order to investigate the potential and also the limitations of satellite-based D-InSAR for detecting and measuring flow velocities of glaciers and rock glaciers. An internal report about this project is available (Kaufmann et al., 2005). The most important factors for the successful application of D-InSAR to the monitoring of glaciers and rock glaciers using ERS-1/2 data are:

- scene coherence,
- data availability,
- main flow direction of (rock) glacier,
- aspect of (rock) glacier,
- size of (rock) glacier,
- accuracy of DTM,
- accuracy of orbit parameters, and
- strength of algorithms, e.g. phase unwrapping.

The practical investigations carried out during the above-mentioned project provided the basis for developing a simplified scheme for selecting appropriate ERS-1/2 orbit pairs for the detection of surface deformation of glaciers and rock glaciers in an alpine environment.

Table 5. Constraints for the successful monitoring (= detection of surface deformation) of glaciers and rock glaciers using ERS-1/2 SAR data in a European alpine environment.

feature	optimal time interval between data takes (days)	optimal season for data takes	main flow direction	aspect	orbit
fast moving glaciers (> 6.6 m a^{-1})	1	winter months (no wet snow and no snow drift by wind)	EW	west slope	descending
			(WE)	east slope	
			WE	east slope	ascending
			(EW)	west slope	
rock glaciers and slowly moving glaciers+	35 (70, 105)	summer months (no old/perennial snow and no fresh snow cover)	EW	west slope	descending
			WE	east slope	ascending

Annotation: The perpendicular baseline must be very small.
The DTM should be as accurate as possible.
The size of the (rock) glacier must be larger than 10-20 hectares.
+The probability for good scene coherence after 35, 70 or even 105 days is very low for slowly moving glaciers.

CARTOGRAPHIC WORK

Five maps have been published within the framework of the Doesen rock glacier project, i.e.:

- an orthophoto map 1:10,000 of the study area which is a combined image-line map showing the orthophoto of 1975 (for comparison see also Figure 2),
- a hill-shaded map 1:10,000 which has the same layout as the above-mentioned orthophoto map,
- a stereo orthophoto map 1:30,000 for stereo viewing of the study area using a lens stereoscope,
- a stereo orthophoto map and line map 1:5,000 of the Doesen rock glacier area, and
- a thematic map 1:5,000 showing photogrammetrically derived flow vectors for three time periods, 1954-1975, 1975-1993, and 1995-1996.

Details on the production of the above mentioned maps can be found in Kaufmann (1996) and Kaufmann and Heiland (1998). The first publication also includes the maps described as prints.

ANALYSIS OF PHOTOGRAMMETRIC MEASUREMENTS

The evaluation of the manually derived photogrammetric data, i.e., displacement vector fields and DTMs, has already been published in Kaufmann (1998). A mean surface height change of –2.6 cm a^{-1} for the time period 1975-1993 was derived from relative volumetric change. Strains and flow trajectories were computed and analyzed by Riser (1998).

The digitally derived mean annual horizontal flow velocities shown in Figure 6 are in good accordance with the results obtained from manual mapping. All (manual and digital) photogrammetric measurements reveal that the displacement vector fields are smooth and that highest flow velocities are reached in the center of the rock glacier near point 15 (cp. Figures 4 and 6). Areas of rather low flow/creep velocity or complete inactivity were always identified in the northerly parts of the upper half of the rock glacier (cp. Figures 4 and 6). The decision whether a certain part of the rock glacier is classified as active or inactive depends, of course, on the significance level of the computed movement.

ANALYSIS OF GEODETIC MEASUREMENTS

Precise geodetic measurements covering a time span of 10 years (1995-2005) are now available for detailed analysis. The measured displacement vector fields are smooth, since both horizontal and vertical flow velocity and flow directions change only gradually. The 109 observation points have been found to be quite stable, "riding" on the rock glacier surface. Only occasionally were profile points reported to have toppled downslope (cp. point 3008 of profile 3000 in Figure 8).

We measured a linear increase in flow velocity from 6.7 (uppermost part) to 25.0 cm a^{-1} (lowermost part) within profile 2000 shown in Figure 8, whereas profile 1000 shows a decrease in flow velocity from 29.8 (uppermost point) to 21.9 cm a^{-1} (lowermost point).

The maximum flow velocity for the given observation period was measured at point 15 in 2002/2004 and amounts to 45.6 cm a^{-1}. Table 6 summarizes the mean annual flow/creep velocities of various groups of points for the sake of comparison.

Table 6. Mean annual horizontal movement (cm a^{-1}) of selected points of the Doesen rock glacier.

	selected points							
time period	1-34	10-17, 21-23	15	profile 1000	profile 2000	profile 3000	profile 4000	all 109 points
1995-1996	14.9	22.0	28.5	18.4	14.9	18.8	21.5	17.4
1996-1997	15.3	22.6	30.4	13.7	12.6	20.8	22.4	17.2
1997-1998	19.4	27.3	34.9	26.4	18.3	24.2	29.2	23.1
1998-1999	19.6	28.2	36.1	23.5	17.5	24.4	30.8	22.9
1999-2000	16.4	23.6	29.4	20.8	13.1	18.6	21.0	17.9
2000-2001	21.4	29.6	36.6	22.3	19.0	30.9	33.2	25.4
2001-2002	20.4	30.0	38.1	27.1	15.3	26.5	31.0	24.0
2002-2004	25.9	37.4	45.6	30.7	20.6	31.7	37.0	29.1
2004-2005	22.6	34.1	44.6	28.6	16.8	30.8	36.6	27.0
1995-1997	15.10	22.30	29.45	16.05	13.75	19.80	21.95	17.30
2002-2005	24.80	36.30	45.27	30.00	19.33	31.40	36.87	28.40
relative change	64.2 %	62.8 %	53.7 %	86.9 %	40.6 %	58.6 %	68.0 %	64.2 %
mean acceleration	0.97 cm a^{-2}	1.40 cm a^{-2}	1.58 cm a^{-2}	1.40 cm a^{-2}	0.56 cm a^{-2}	1.16 cm a^{-2}	1.49 cm a^{-2}	1.11 cm a^{-2}

Annotation:	Relative change/ acceleration is computed between the averaged means of 1995-1997 and 2002-2005. Point 15 is the fastest moving point of the 34 points. The points of the column (10-17, 21-23) represent the 11 fastest points of the 34 points. longitudinal profiles: 1000 (17 points), 2000 (12 points) transversal profiles: 3000 (27 points), 4000 (16 points) The location of the points is shown in Figures 7 and 8.

From Table 6, we can see that there is a general increase in flow/creep velocity during the observation period, with one exception in 1999/2000. The 34 stabilized points with the highest measurement accuracy, which are quite representative of the whole kinematics of the rock glacier, reveal a significant 64% increase in overall flow velocity for the observation period, which is equivalent to a mean acceleration of 0.97 cm a^{-2}.

The vertical components of the displacement vectors were decomposed based on the "kinematic boundary condition at the surface" as described by Kääb (2005) and the corresponding graphs were plotted. From these graphs, we see that in most of the cases e.g. the slope of particle movement does not coincide with the surface slope. The fact that particle displacement depends on (1) basal slope and speed, (2) mass balance, and (3) straining makes the interpretation, e.g. of Figure 10, in terms of mass balance (= gain or loss of ice) very difficult or even impossible. As stated in Kääb (2005), borehole measurements are necessary for sorting out the contributing factors. However, a rough estimate of –2 to –2.5 cm a^{-1} for general surface lowering (= permafrost melt) was calculated considering prevailing strain rates and also especially looking at non-moving or slowly moving surface points. From Figure 10 we can deduce that we have emergence velocities above the 2440 m contour line and mainly submergence velocities below that altitude. This is in good accordance with the results obtained by Riser (1998).

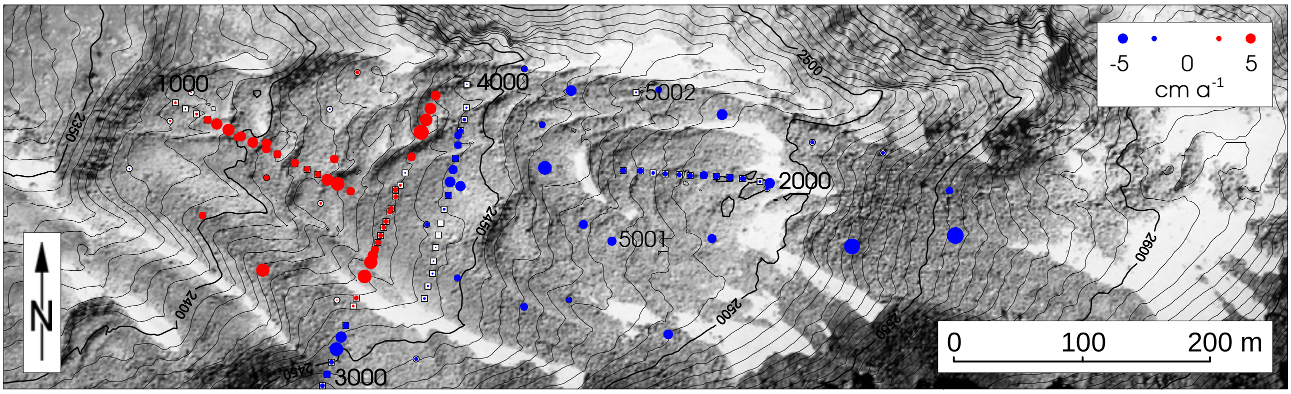


Figure 10. Mean annual vertical particle displacement of the 109 points of the Doesen rock glacier for the time period 1996-2005. Orthophoto of 15 August 1993. Blue dots = submergence, red dots = emergence.

SYNTHESIS AND CONCLUSIONS

The measurements and results presented in this paper very nicely reveal the surface kinematics of the Doesen rock glacier. 3D displacement vectors generally display a very smooth flow field. Highest flow velocities were measured in the surroundings of point 15. In this area a surface point has moved approx. 13.3 m in horizontal direction during the last 51 years (1954-2005), which is equivalent to a mean surface speed of approx. 26 cm a^{-1}. Comparatively low flow velocities were observed at the orographic right margin. The area around point 28 seems to be very much inactive.

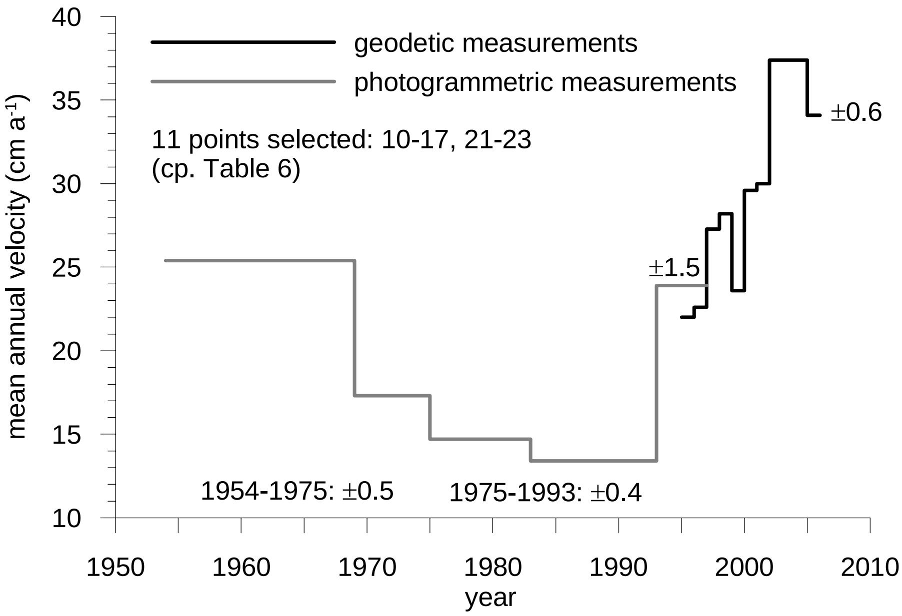
Combining the results obtained from the photogrammetric and geodetic measurements, the change of mean surface flow/creep velocity in time can be reconstructed with good confidence (see Figure 11). From this graph we can see that the flow velocities for the time period 1954-1975 were more or less equal to those measured for the 1990s. After a period of reduced activity in the 1980s, higher velocities have been measured since 2000.

The question of permafrost melt is difficult to answer. Complementary data describing the internal deformation of the permafrost body is still lacking. Further studies could benefit greatly from appropriate borehole measurements. However, such measurements are very unlikely since Doesen rock glacier is part of the Hohe Tauern National Park. Nevertheless, an estimate of –2 to –2.5 cm a^{-1} of surface lowering (= net permafrost melt) may be used as a working hypothesis.

A photogrammetric flight using the UltraCam$_D$ of Vexcel Imaging Austria is scheduled for the year 2006. Furthermore, it is planned to thoroughly check the stability of the geodetic network as soon as possible using GPS and classical geodetic measurements.

Differential SAR interferometry is a very interesting and promising technique for detecting and measuring surface deformation in mountainous areas. As far as rock glacier monitoring is concerned, application based on ERS-1/2 data must be restricted to the detection of the state of activity, i.e. active or inactive. A rough estimation of surface flow velocity is possible. However, forthcoming satellite and airborne SAR systems will open up new opportunities.

Figure 11. Change of mean annual surface flow/creep velocity (cm a^{-1}) at Doesen rock glacier.



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