GEOMORPHOMETRIC MONITORING OF ACTIVE ROCK GLACIERS IN THE AUSTRIAN ALPS

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ABSTRACT

This publication presents the preliminary results of photogrammetric, geodetic and cartographic work carried out on the active Dösen rock glacier (Dösen Valley, Ankogel group, Hohe Tauern range of the Austrian Alps). Furthermore, an overview of former and also recent rock glacier measuring and mapping activities in Austria is given.

Rock glaciers are perennially frozen debris masses which creep down mountain slopes. These creep phenomena of mountain permafrost have been studied intensively all over the world in the past few decades. As a result, long-term monitoring projects of rock glaciers have confirmed that changes of surface velocity and changes of volume, respectively, highly correspond to climatic change on earth.

The outer Hochebenkar rock glacier has the longest continuous record of measurements and thus is the best observed rock glacier in Austria. Nevertheless, this rock glacier occupies a special position because of its quite large annual movements, which are mainly induced by the topographic conditions. The Dösen rock glacier was selected in order to widen the existing geodetic and photogrammetric observation program of active rock glaciers in Austria. As a first step a detailed geomorphometric study map at 1:5,000 scale covering the inner Dösen Valley was evaluated. Further cartographic work comprises a stereo-orthophoto map at 1:30,000 scale, two combined image-line maps at 1:10,000 scale, a detailed map of the Dösen rock glacier at 1:5,000 scale, and a thematic map at 1:5,000 scale indicating the velocity of flow of the Dösen rock glacier. The photogrammetrically determined flow vectors reveal that the mean annual horizontal velocity observed at the snout of the rock glacier has decreased from 22 cm/year (period from 1954 to 1975) to 13 cm/year (period from 1975 to 1993). Similar results were obtained in the Swiss Alps. During the whole observation period the Dösen rock glacier has advanced 6.6 meters in total.
Precise geodetic measurements within an observation network (since 1995), and numerous terrestrial and aerial photographs (since 1994 and 1954, respectively) provide the basis for the first comprehensive geodetic deformation analysis of an active rock glacier in Austria.
The investigations on the Dösen rock glacier were financially supported by the Austrian Science Foundation and by the Carinthian National Park Fund.

KEYWORDS: HIGH-MOUNTAIN PERMAFROST, ROCK GLACIER, AUSTRIAN ALPS, HOHE TAUERN NATIONAL PARK, TOPOGRAPHIC MAPPING, HIGH-MOUNTAIN CARTOGRAPHY, DIGITAL ORTHOPHOTO AND STEREOMATE, COMBINED IMAGE-LINE MAP, GEODETIC DEFORMATION ANALYSIS.

1. INTRODUCTION

The current status on research on permafrost creep and rock glaciers has been summarized in two issues of ***Permafrost and Periglacial Processes*** (HAEBERLI, 1992). For the sake of clarity, however, two definitions for rock glaciers, both taken from BARSCH (1992), are given:

- ***Active rock glaciers*** are lobate or tongue-shaped bodies of perennially frozen debris supersaturated with interstitial ice and ice lenses or even with bodies of massive ice, which move downslope or downvalley by creep as a consequence of the deformation of the ice contained in them and which are, thus, features of cohesive flow.
- ***Active rock glaciers*** are the visible expression of steady-state creep of supersaturated mountain permafrost bodies in unconsolidated materials. They display the whole spectrum of forms created by cohesive flows. (For comparison see Figure 3 and Figure 6.)

Rock glaciers in general are classified in active, inactive and relict (or fossil). Since active rock glaciers are creep phenomena of discontinuous permafrost, the technical term ***rock glacier*** is misleading because rock glaciers are not glaciers - they are periglacial landforms. To emphasize this, some authors even write rock glacier as one word, i.e. ***rockglacier*** (BARSCH, 1992).
In order to understand the genesis and dynamics of rock glaciers in more detail various direct and indirect observation methods have been applied, e.g., in situ observations of outcrops, core drillings, movement measurements, BTS-measurements, seismic soundings, geoelectrical resistivity measurements, impulse radar soundings and measurements of hydrological parameters. Of special interest is the measurement of surface flow velocities. A review of various photogrammetric, geodetic and other measurement techniques, including results of experimental work, has been published by HAEBERLI (1985). Detailed information on photogrammetric and geodetic monitoring of rock glaciers can be found in MESSERLI & ZURBUCHEN (1968), BARSCH & HELL (1975), HAEBERLI & SCHMID (1988), BARSCH & ZICK (1991), and ZICK (1996). As a result of such geometrical surveys information on surface topography, flow line patterns, velocity distributions, principal strain rates and volumetric information can be derived, as well as changes in these parameters with time (HAEBERLI & SCHMID, 1988). The results of long-term monitoring projects of active rock glaciers in the Swiss Alps show that the average surface velocities are in the range of cm/year to around 1 m/year, that velocities have been decreasing during recent decades, and that volume changes can hardly be detected.
The above-mentioned geometrical measurements are not only interesting in order to get a better understanding of the interior of an active rock glacier, but there is also great evidence that climatic conditions, e.g. atmospheric warming of the earth, influence the dynamic behaviour of active rock glaciers (HAEBERLI et al., 1993). As compared to ***glaciers***, rock glaciers do not react very distinctly to short-term climatic changes but reflect more or less long-term trends (GUODONG & DRAMIS, 1992)
LIEB (1996) describes the actual status of knowledge on high-mountain permafrost in the Eastern Austrian Alps. Lieb has set up a multidisciplinary research project on high-

mountain permafrost in 1993 which focuses on the active ***Dösen rock glacier*** (Ankogel group, Hohe Tauern range, see Figure 1). Moreover, he elaborated a complete ***inventory of the rock glaciers*** in the Eastern Austrian Alps (LIEB, 1991 and 1996).
A comprehensive overview of rock glacier mapping and monitoring in Austria is given by KAUFMANN (1996).

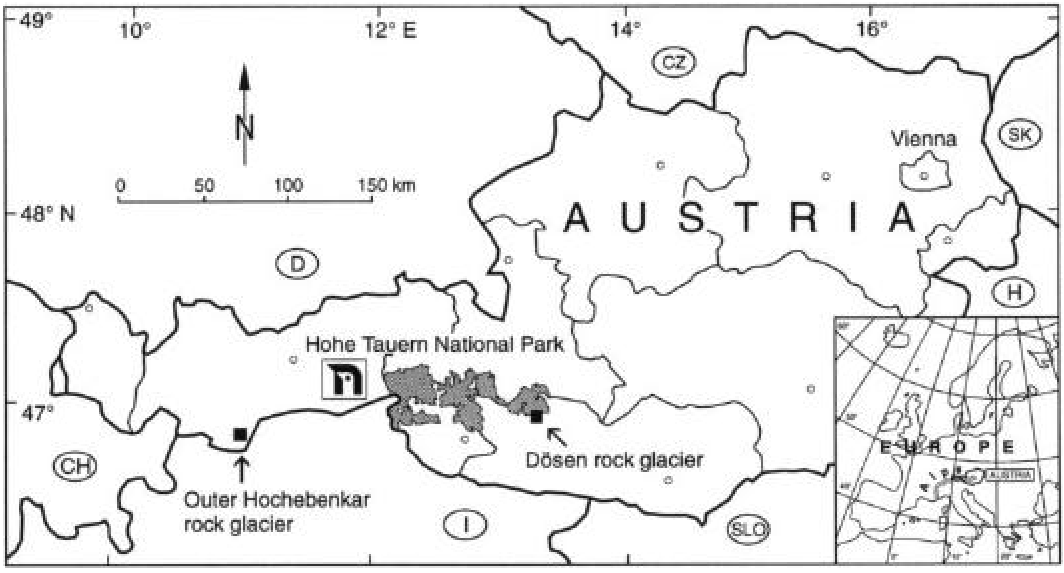

Figure 1: Location map of outer Hochebenkar rock glacier and Dösen rock glacier.

2. OUTER HOCHEBENKAR ROCK GLACIER

The ***outer Hochebenkar rock glacier*** (Ötztal Alps, see Figure 1) has the longest record of continuous measurements, dating back to 1938. In this paper, for reasons of comparison only, some short notes on past and also recent surface velocity measurements will be given. The aerial photograph of Figure 3 shows the cohesive flow pattern of the Hochebenkar rock glaciers very nicely.

In fact, S. Finsterwalder was the first one in Austria who was measuring surface velocities of a rock glacier by means of terrestrial photogrammetry (S. FINSTERWALDER, 1928). For a time period of one year (1923-1924) he got displacements of up to 50 cm for the ***Ölgruben rock glacier*** (Kauner Valley, Ötztal Alps, close to the outer Hochebenkar rock glacier). But this rock glacier was not monitored any longer.

Pillewizer and Vietoris started their own measurements on the outer Hochebenkar rock glacier in 1938 and 1951, respectively. They are thus considered the ***pioneers of rock glacier research*** in Austria. Their respective results were comparable with each other (PILLEWIZER, 1957 and VIETORIS, 1972). The measurements of Pillewizer showed a surprisingly interesting result for the time period 1952 to 1953, i.e., the surface velocities were linearly increasing downward (see Table 1). He estimated the advancement of the rock glacier snout as 4 m/year, which is an exception for rock glaciers in the European Alps. According to HAEBERLI & PATZELT (1982) this is due to the underlying surface which is getting steeper at a certain threshold. Three profile lines had been geodetically remeasured by Vietoris on a regular basis until 1970. From then on Schneider from the University of Innsbruck took over his part. Since 1970 a significant decrease in the annual surface velocity has been observed (Table 1).

profile line/ altitude	period 1952 - 1953	period 1985 - 1990	period 1990 - 1995
1 / 2540 m	357 cm/year	32 cm/year	57 cm/year
2 / 2630 m	180 cm/year	49 cm/year	65 cm/year
3 / 2680 m	75 cm/year	36 cm/year	48 cm/year

Table 1: Mean annual (horizontal) surface velocity at outer Hochebenkar rock glacier given for time periods 1952-1953, 1985-1990 and 1990-1995, respectively. Data derived from photogrammetric (1952-1953) and geodetic measurements.

Kaufmann and Kostka have conducted photogrammetric surveys of the outer Hochebenkar rock glacier using ***terrestrial cameras***, e.g., a phototheodolite Photheo 19/1318, a Rolleiflex 6006 metric and a Hasselblad SWC, in 1986 and 1995. Displacement vectors were determined for a limited number of rock glacier points by comparing the terrestial stereomodel of 1986 with an aerophotogrammetric stereomodel dating from 1977. The mean annual surface velocity of the fastest point has been obtained as 125 cm/year which proves independently of the above-mentioned ground survey that the movements of the tongue in the middle and lower part of the rock glacier have decreased significantly since the fifties. The photographs dating from 1995 will be evaluated at a later stage.

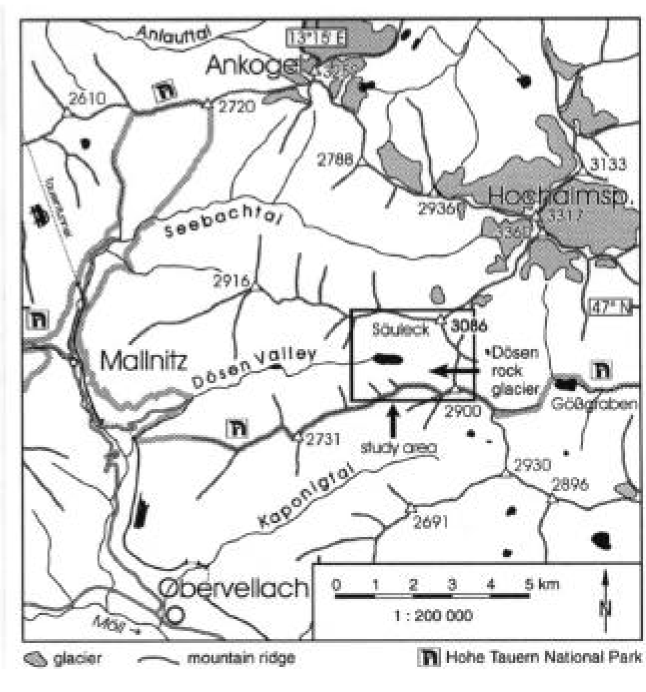

Figure 2: Location of the Dösen rock glacier in the Ankogel-Hochalmspitz group, Hohe Tauern National Park.

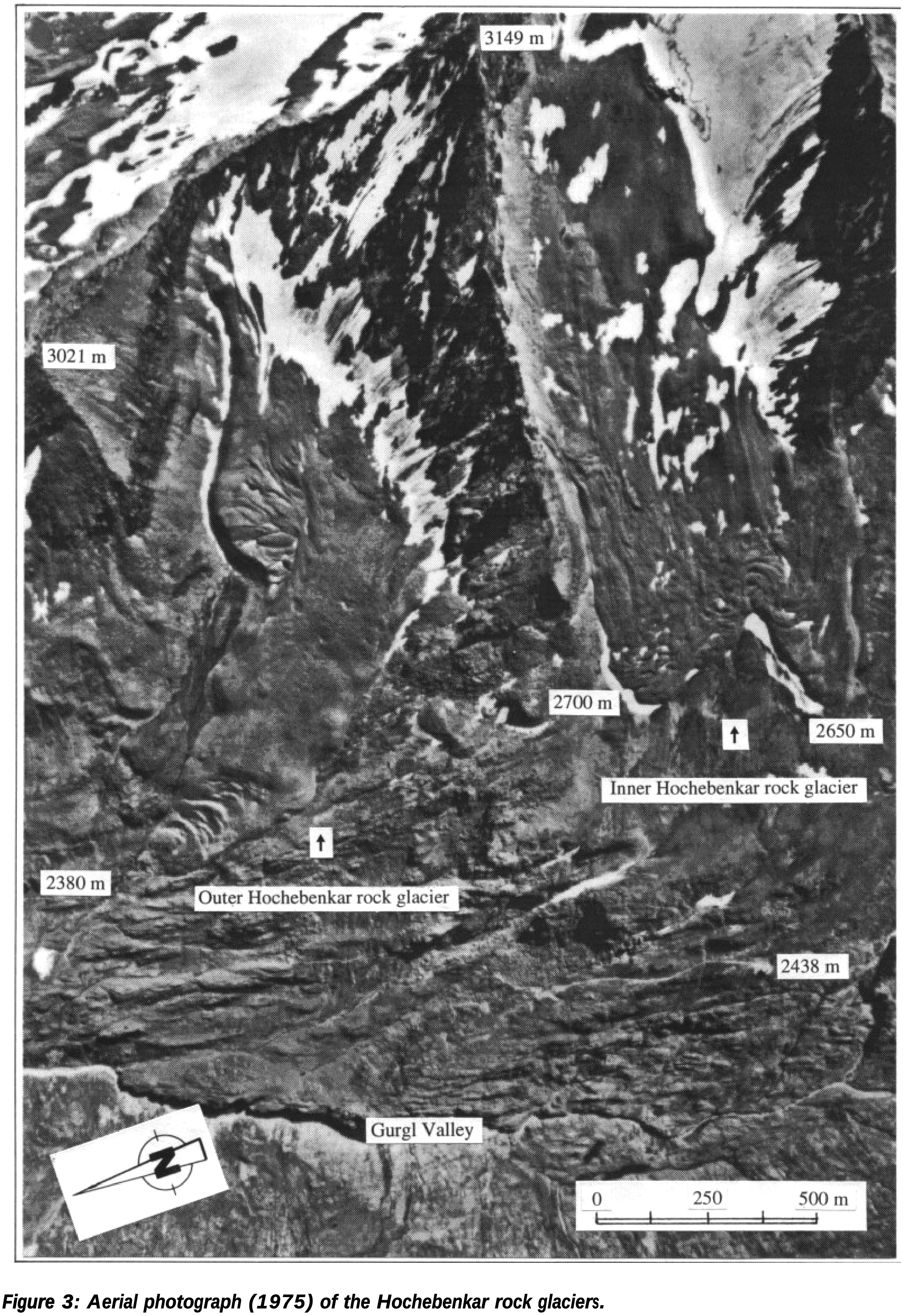

Figure 3: Aerial photograph (1975) of the Hochebenkar rock glaciers.

3. DÖSEN ROCK GLACIER

The inner Dösen Valley near Mallnitz, Carinthia, was selected by Lieb as a main ***study area*** (Figure 2) within the previously mentioned research project on permafrost in the Austrian Alps. According to LIEB (1996), from 1993 to 1995 geomorphological mapping, measurements of ground and spring temperatures, BTS-measurements, refraction seismic and electromagnetic transects, and georadar soundings were carried out in order to delineate permafrost areas in the study area and to give a realistic estimation of the permafrost thickness (30-40 m) and the volume of the Dösen rock glacier ($15.10^6 m^3$). The rock glacier is located in a cirque between Dösen Lake (2269 m) and Mallnitzer Scharte (2674 m), and it is 900 m long and 150-250 m wide.

The research project on permafrost was extended by a ***Dösen rock glacier monitoring program*** in 1995, which has been stimulated mainly by similar projects already conducted in the Swiss Alps. The key task is to periodically measure and obtain geometrical parameters, e.g., flow velocities and topographic information, describing the dynamics of the rock glacier. The concept of this long-term monitoring program is to get sufficient and accurate geomorphometric information about the Dösen rock glacier in order to help geomorphologists to study this landform in more detail and to provide input data for climatic models.

3.1. STUDY MAPS AND DIGITAL TERRAIN MODEL

Precise and up-to-date topographic information is a prerequisite for most geoscientific projects. For this project a detailed ***geomorphometric study map*** at 1:5,000 scale covering the inner Dösen Valley was evaluated. Photogrammetric mapping of the study area (10,325 km^2) was carried out on a Kern DSR-1 analytical stereoplotter using multi-year aerial photographs provided by the Austrian Federal Office of Metrology and Surveying (see also Table 2). Most of the terrain could be mapped from panchromatic B/W photographs dating from 1975, except for hidden areas and regions with dark shadows where stereomodels of other years had to be used. This study map is available as a multi-layered AutoCAD drawing file (LADSTÄDTER, 1996).

Based on these three-dimensional relief data, i.e., contour lines, drainage lines, ridge lines, break lines and spot heights, a high-quality ***digital terrain model (DTM)*** was generated using the software package GTM (Graz Terrain Model). The grid spacing was selected with 2.5 m, whereas the resolution in elevation is 0.1 m. Especially for high-mountain permafrost research a sufficiently accurate DTM is needed for a multitude of computerized tasks, e.g., production of orthophotos and stereo-orthophotos, axonometric and perspective visualizations, morphometric terrain analysis, computation of potential solar radiation (FUNK & HOELZLE, 1992) and evaluation of permafrost models and climatic scenarios (KELLER, 1992). An axonometric plot of the DTM is shown in Figure 4.

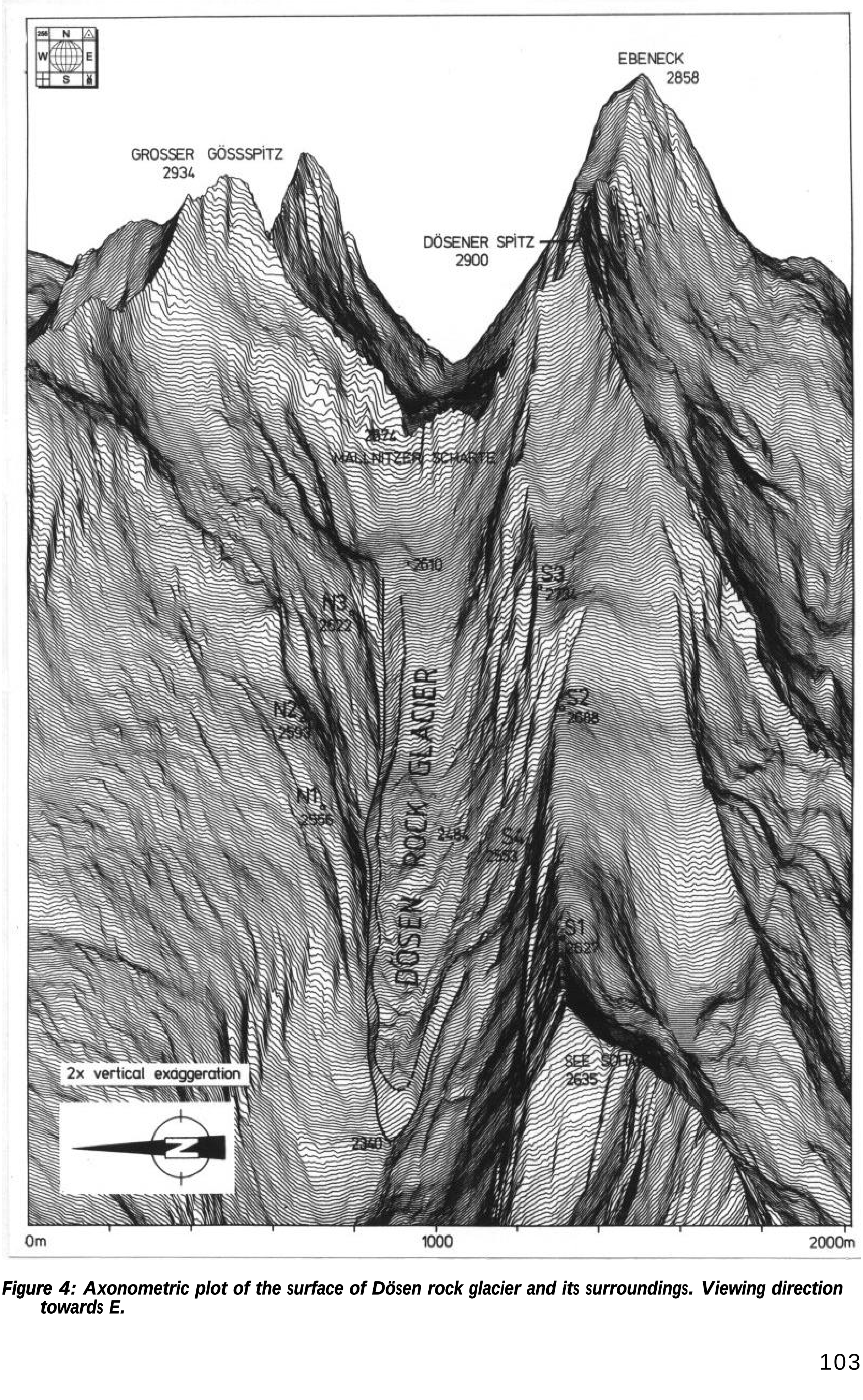

Figure 4:* *Axonometric plot of the surface of Dösen rock glacier and its surroundings. Viewing direction towards E.

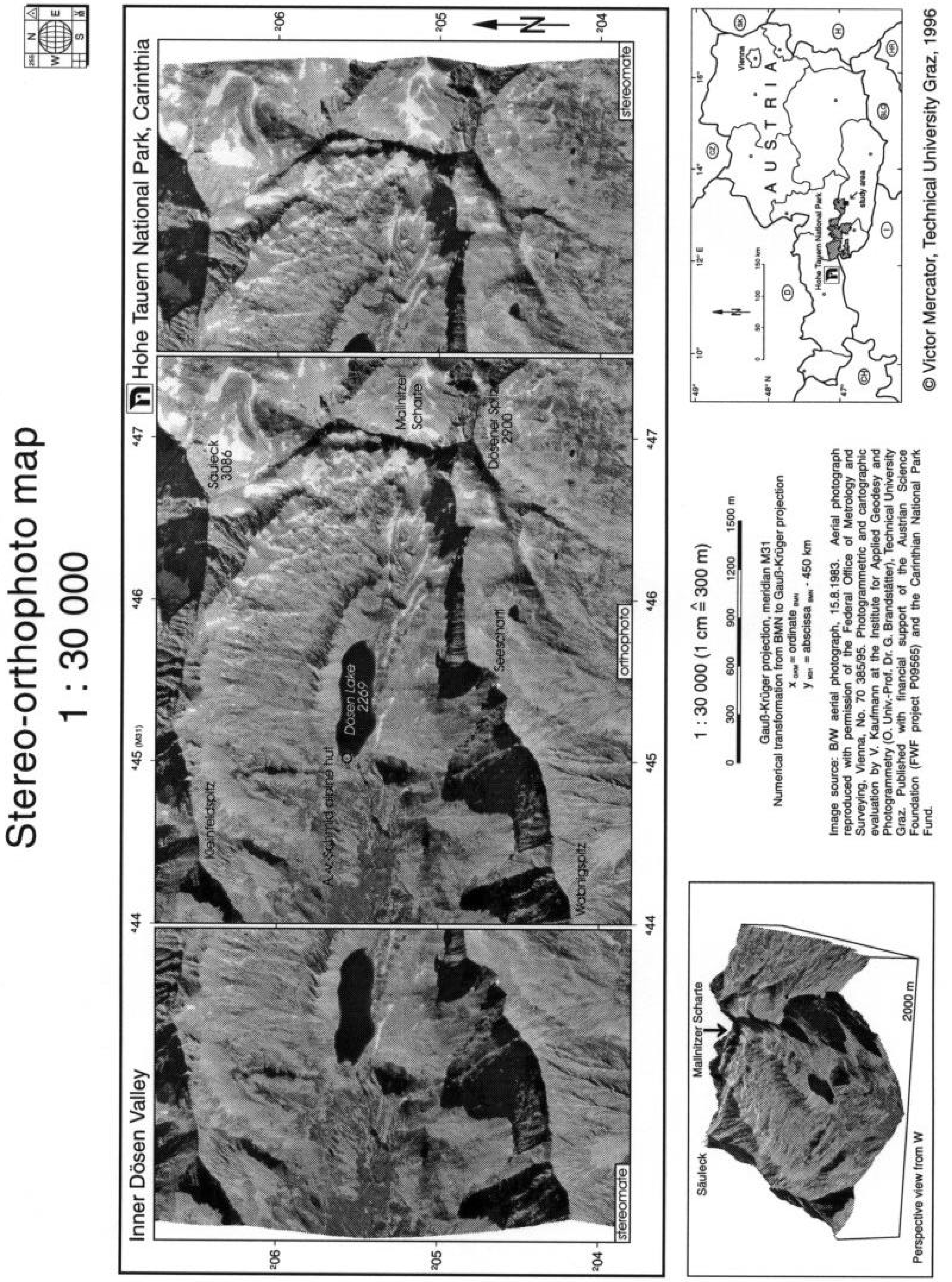

Figure 5: Stereo-orthophoto map showing the study area of inner Dösen Valley. Image source: Aerial photograph dating from 1983. Size of reproduction: 80%.

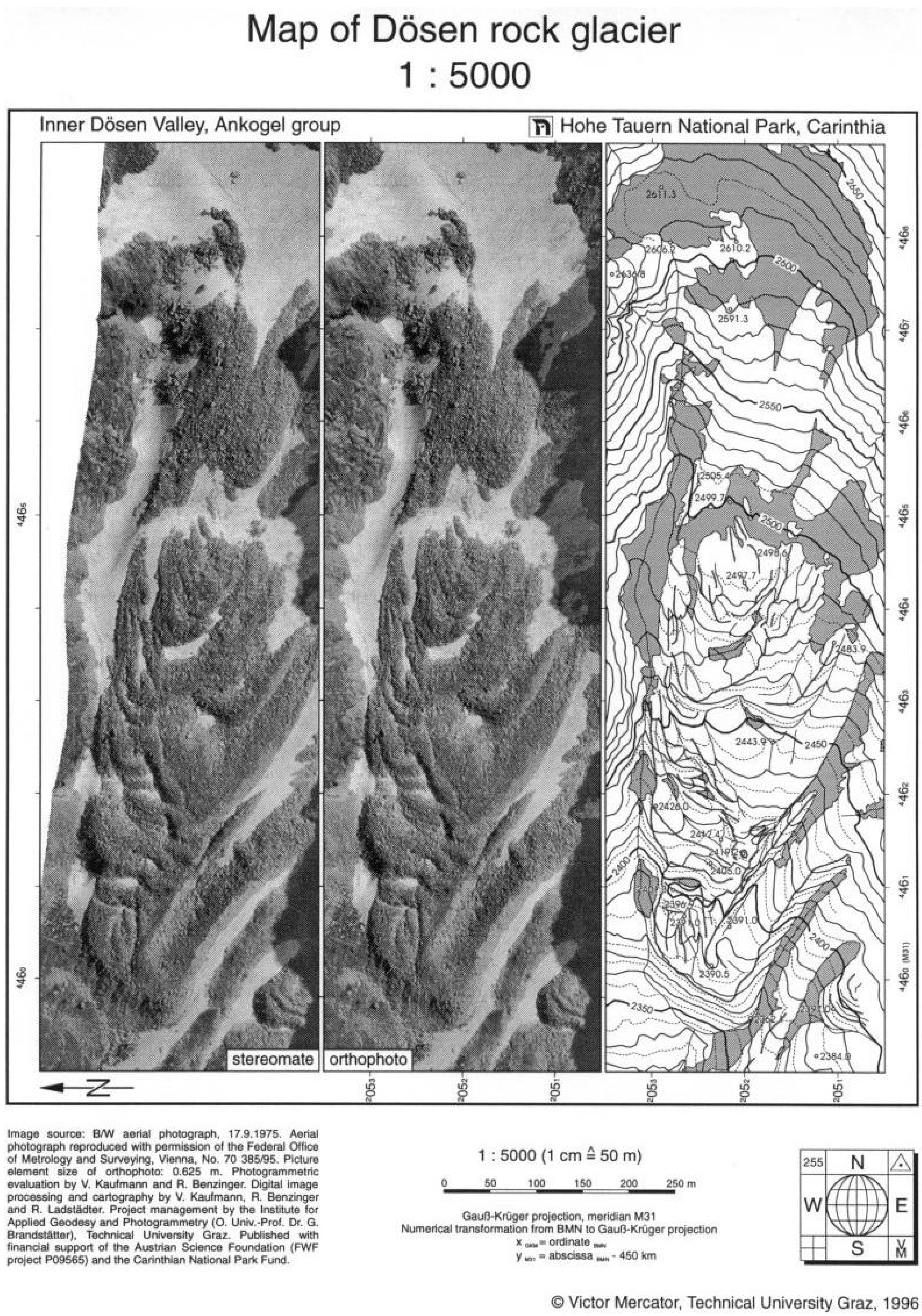

Figure 6: Map of Dösen rock glacier. Image source: Aerial photographs dating from 1975. Size of reproduction: 80%.

A general overview of the study area is given in a B/W ***stereo-orthophoto map*** at 1:30,000 scale (Figure 5), whereas Figure 6 shows a map of the tongue-shaped Dösen rock glacier at 1:5,000 scale. Two ***combined image-line maps***, i.e., an ***orthophoto map*** and a ***relief map***, both at 1:10,000 scale have been produced and published in KAUFMANN (1996). In latter publication further details on map compilation and map design are outlined.

year	date	scale	film type
1954	—	1:13,600 - 1:18,500	B/W
1969	29.9. - 12.10.	1:26,000 - 1:32,000	B/W
1975	17.9.	1:16,100 - 1:22,800	B/W
1983	15.8.	1:33,100 - 1:35,200	CIR
1993	15.8.	1: 8,700 - 1:13,500	CIR

Table 2: Aerial photographs used in the monitoring program of Dösen rock glacier.

3.2. MEASUREMENT OF SURFACE FLOW VELOCITY

One of the main tasks of the monitoring program is to determine the ***surface flow velocity*** of the Dösen rock glacier for the past, present and future. The obtained displacement vectors should be the input for a mathematical deformation analysis as worked out by HAEBERLI & SCHMID (1988) for rock glaciers, and HELLMEIER & WENDT (1982) for crustal movements, respectively. In general, the ***mass balance*** of rock glaciers is difficult to deal with, since volume changes are very small and digital terrain models with the necessary high accuracy do not exist (HAEBERLI 1985, pp. 84-86, BARSCH & HELL 1975, and HAEBERLI & SCHMID 1988). For monitoring of the Dösen rock glacier two different approaches are employed: The ***photogrammetric approach*** is based on the evaluation of aerial or terrestrial photographs, both of metric or semi-metric type, whereas the ***geodetic approach*** includes the classical measurement of a ***network*** and also the modern technology of the ***Global Positioning System (GPS)***.

3.2.1. PHOTOGRAMMETRIC APPROACH

The photogrammetric methods for the mapping and monitoring of glaciers explained by KONECNY (1964) are also valid for rock glaciers. As already indicated in KRUMMENACHER & BUDMIGER (1992), ***digital photogrammetric methods*** are going to be used in the mapping and monitoring of rock glaciers. ***Digital point transfer*** (FÖSTNER, 1995) is a powerful tool for automatic measurement of homologeous points in digitized photographs. This technology will enable a semi-automatic or even automatic triangulation of digital photos, the automatic computation of digital terrain models (BALTSAVIAS et al., 1996, for glaciers) in general, and the measuring of a dense field of displacement vectors for computing flow velocities in particular (KNIZHNIKOV et al., 1996, for glaciers). In this project some ideas have already been put into practice (see BENZINGER, 1996). A proposed algorithm for measuring displacement vectors in digital multi-temporal photos using digital photogrammetry is outlined in Figure 7. The basic ideas of this procedure have been described by BALTSAVIAS (1996).

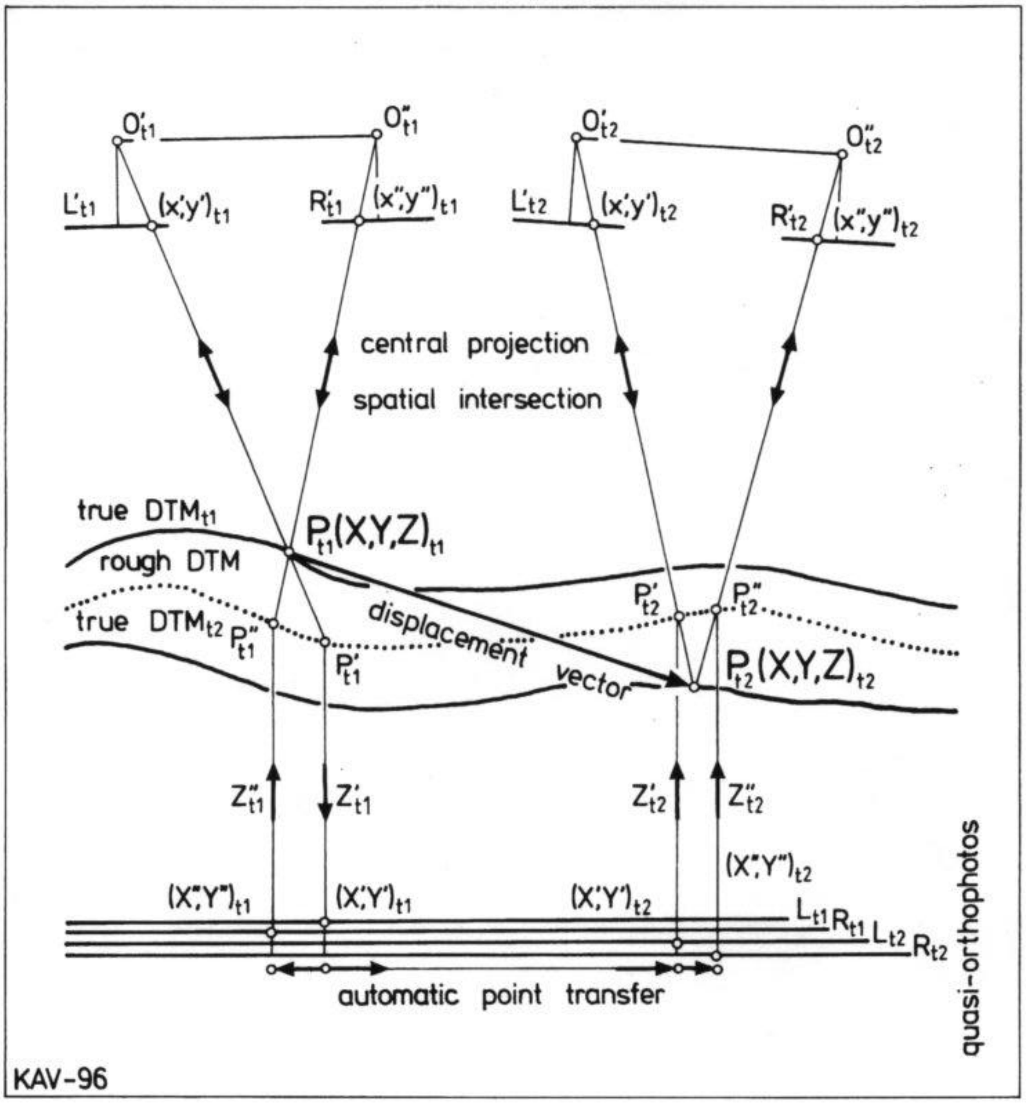

Figure 7: Computation of displacement vectors by means of digital photogrammetry.

With the help of old, multi-year aerial photographs (Table 2) it was possible to analyze the movements of the Dösen rock glacier, at least for some time periods.

The stereomodel dating from 1993 was selected as a reference model for the absolute orientation of the other stereomodels given in Table 2 using homologeous control points. The aerotriangulation for the 1993 photographs had already been performed by the Federal Office of Metrology and Surveying. In a time-consuming work nearly

600 distinct edges of boulders (see Figure 8, photogrammetric points, 1993), evenly distributed over the whole rock glacier, were identified and measured using the DSR-1 analytical stereoplotter. In a first phase approximately 150 points were selected and remeasured in the four older stereomodels. Due to the small scales of the photographs and sometimes due to very bad image quality even the identification of bigger boulders was quite troublesome and tedious. Three-dimensional displacement vectors and mean annual flow velocities were computed. As an example, the horizontal movement of individual boulders over a time range of 39 years (1954 - 1975 - 1993) is shown in Figure 8. The final analysis is given in the results. Because of budgetary reasons there was no aerial survey of the Dösen rock glacier. Whereas, for example, in Switzerland large-scale aerial photographs are taken on a regular basis over several rock glaciers.
To overcome this drawback great emphasis is put on ***terrestrial photogrammetry*** within the monitoring program. In 1994 and 1995 terrestrial-photogrammetric surveys had been conducted using the Rolleiflex 6006 metric réseau camera. Within the framework of a feasibility study (BENZINGER, 1996) these photographs were evaluated by means of digital photogrammetry on a Silicon Graphics Computer using software developed at the Institute for Computer Graphics, Technical University Graz. Following the results of this study, e.g., the Rolleiflex was equipped with a new interchangeable objective with a longer focal length (150 mm), and moreover, it was found that targets had to be used for control points and object points in order to reduce the pointing error. Since the annual movements of the Dösen rock glacier are in the order of a few decimeters, the time period between two surveys should be at least two or three years in order to get significant results. In summer 1996 the first operational terrestrial-photogrammetric survey will take place.

3.2.2. GEODETIC APPROACH

Independently of the photogrammetric approach a ***geodetic network*** has been installed at the Dösen rock glacier (KAUFMANN, 1996, and HEILAND & TILG, 1996) in 1995. The network consists of 7 ***reference points*** (Figure 4, points S1-S4 south of the rock glacier and points N1-N3 north of the rock glacier) which have been permanently fixed in the bedrock by brass bolts. These points are supposed to be stable. Furthermore, 34 ***object points*** were selected on the rock glacier (Figure 8, points with target, 1995). These points were stabilized preferably on large boulders in the same way as the reference points, the bolts allowing targets and retro-reflectors to be mounted. Additionally, two transversal and two longitudinal profile lines (see Figure 8) consisting of painted points on smaller boulders complete the points to be monitored on the rock glacier. These profile lines were used in the geophysical surveys in 1995. In summer 1996 all geodetic measurements (distances and directions) will be repeated. A rigid deformation analysis will provide the first results on actual flow velocities on the Dösen rock glacier.

Similarly to photogrammetry, surveying is increasingly relying on new technologies and methods which have evolved in the last two decades. In the framework of the monitoring program the applicability of GPS (HOFMANN-WELLENHOF et al., 1992) will

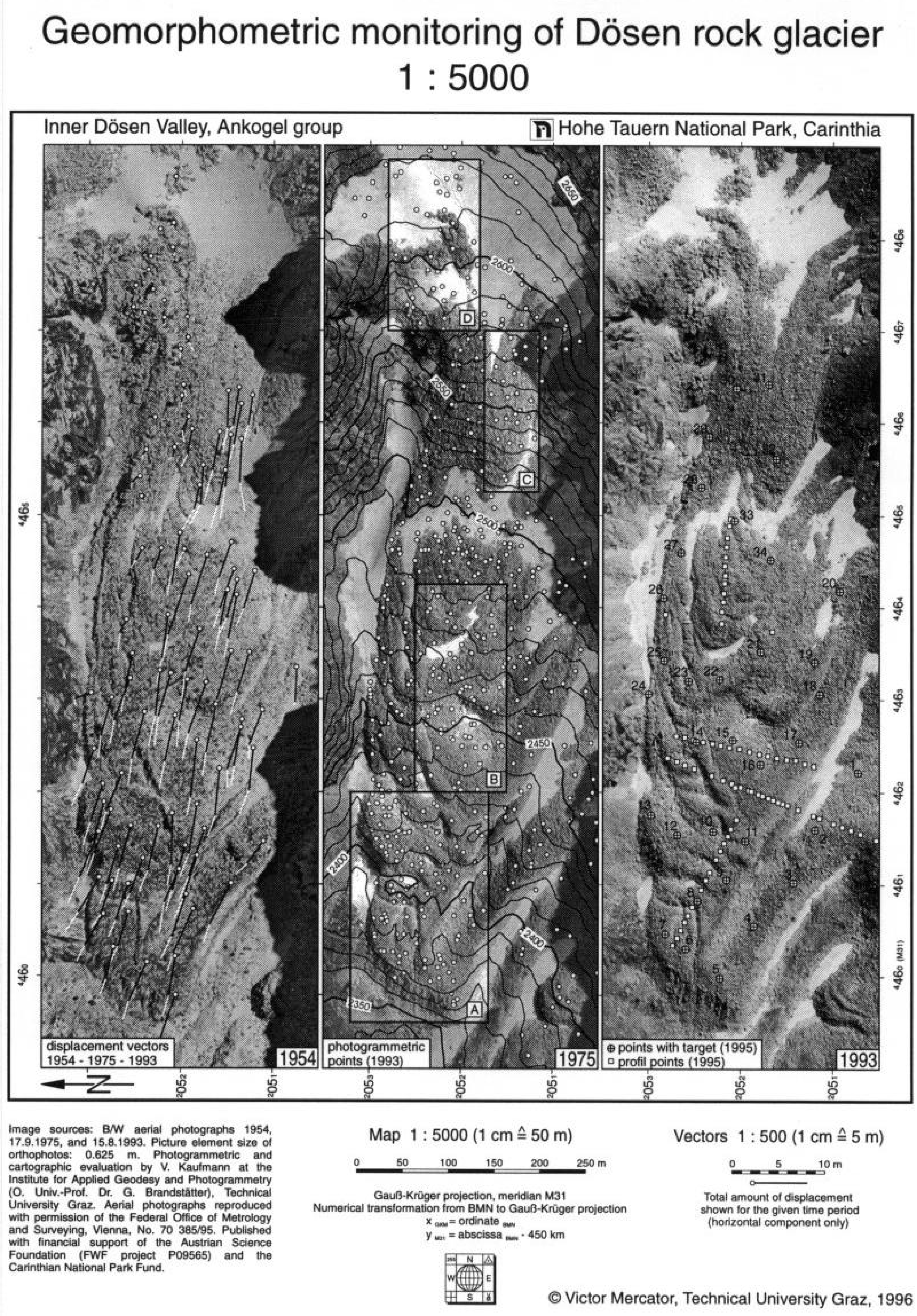

Figure 8: Geomorphometric monitoring of Dösen rock glacier. Size of reproduction: 80%.

be investigated. The reference points and also some other trigonometric points in the surrounding of the study area will be monitored by means of ***static methods***, and the object points using the time-saving ***reoccupation*** and ***rapid static*** methods. The field experiment is scheduled for summer 1996.

4. RESULTS AND DISCUSSION

region	1954-1969	1969-1975	1975-1983	1983-1993	1954-1975	1975-1993	1954-1993	mean slope
				cm/year				
A	24	20	12	15	22	13	18	13 °
B	31	16	16	17	25	16	21	15 °
C	24	17	15	16	21	15	17	26 °
D*	—	—	—	—	—	—	—	17 °

* in region D no significant horizontal movement of boulders has been observed.

Table 3: Mean annual horizontal surface velocity (cm/year) of Dösen rock glacier. Accuracy ≤ ±1 cm/year.

In this paper the results of the evaluation of aerial photographs is presented. Table 3 lists the mean annual horizontal surface flow velocities which refer to four specific areas on the Dösen rock glacier as can be seen in Figure 8. In this table only the horizontal component of the velocity vector is given due to the low accuracy in height measurements in some cases. Based on various graphical plots of the displacement vectors (compare Figure 8) and on statistical data derived thereof, the following conclusions can be drawn:

- The upper edge of the front slope of the Dösen rock glacier has advanced ***6.6 m ± 0.2 m*** from 1954 to 1993. This corresponds to a mean annual horizontal flow velocity of ***17 cm/year*** over the whole observation period.
- The flow velocities had their maximum in the time period from 1954 to 1969, whereas the minimum was observed between 1975 and 1983. The amount of decrease since 1954 is between 30-40 %, which is a reliable estimation.
- For the last two decades a steady-state creep with average (horizontal) flow velocities between ***12 to 17 cm/year*** is assumed.
- Boulders of the upper orographic right side of the rock glacier (region D) do not show any significant movements.
- The movement of the outer orographic right side of the rock glacier (between 2450 m - 2600 m, up to 25 m left of the northern margin) is far less than on the other areas.

- Both areas can be classified as a rather inactive zone of the Dösen rock glacier. The dynamically active zone of the Dösen rock glacier gets its rock and scree supply from the steep slopes in the S and SE of the rock glacier.

At this stage of the project a more detailed analysis of the dynamics of the Dösen rock glacier cannot be made because time series of precise photogrammetric or geodetic measurements are yet not available. The planned long-term monitoring program is the best basis for a reliable deformation analysis of the Dösen rock glacier.

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