SPATIO-TEMPORAL ANALYSIS OF THE DYNAMIC BEHAVIOUR OF THE HOCHEBENKAR ROCK GLACIERS (OETZTAL ALPS, AUSTRIA) BY MEANS OF DIGITAL PHOTOGRAMMETRIC METHODS

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Abstract

The spatio-temporal variations of the surface of a rock glacier, i.e. the change of elevation and the three-dimensional directional deformation, can be determined using various quantitative measurement methods, i.e., geodetic survey, satellite-based positioning with GPS/GLONASS, photogrammetry, radar interferometry, and also laser scanning. In this paper we introduce a new concept of mapping and monitoring of rock glaciers by means of digital (softcopy) photogrammetry. Digital photogrammetry is based on digital image data and computer processing. Image matching, i.e. digital point transfer, is used as a powerful tool for automatic measurement of homologous, i.e. conjugate, points in the digital data sets. This technique enables a semi-automatic or even automatic triangulation of digital photographs, the automatic computation of digital terrain models, and subsequently, the automatic measurement of a dense field of three-dimensional flow vectors based on multi-year image data, in particular. Various aspects of the proposed processing chain are discussed in detail. The present concept has been implemented in a software package called ADVM (Automatic Displacement Vector Measurement), which is written in Visual C++ for running on a Windows-based personal computer. A case study has been carried out in the Oetztal Alps, Austria, in order to demonstrate the applicability of the concept. Aerial photographs (1953, 1969, 1971, 1977, 1979, 1981, 1990, and 1997) covering two adjacent rock glaciers, i.e. the Outer and the Inner Hochebenkar rock glacier, were acquired from the Austrian Federal Office of Metrology and Surveying. The various steps of the evaluation process, i.e., scanning of the analogue photographs, photogrammetric orientation, orthophoto production, computation of digital terrain models, and the determination of three-dimensional flow vectors, are described. Examples of the results obtained are presented numerically and graphically. For the first time it has been possible to reveal the dynamic behaviour of the Hochebenkar rock glaciers with high spatial resolution and with full coverage of the area of interest. The ease of the proposed method was confirmed, and moreover, the overall accuracy is high and the processing time of the given multi-year data set is promisingly low. The paper concludes with recommendations for further developments and improvements.

1. Introduction

1.1. Motivation

Rock glaciers are creep phenomena of *alpine permafrost* and are supposed to be indicators for the present and former geoecology in high mountain environments (BARSCH 1996, GIARDINO et al. 1987, HAEBERLI 1985). In respect to surface movement (activity), rock glaciers can be grouped into *intact* and *relict (fossil)*. Intact rock glaciers may be either *active* or *inactive*. Detailed knowledge of the dynamic state of rock glaciers concerning space and time is of vital importance in rock glacier research since appropriate information of such kind helps, e.g., to reveal the genesis and also to develop rheological models (WHALLEY and AZIZI 1994) of rock glaciers. Furthermore, this information can be correlated with climatic parameters, e.g. temperature, in order to verify climate models and provide proof of climatic warming.

The International Permafrost Association (IPA) and the International Commission of Snow and Ice (ICSI) have established a *Task Force on Rock Glacier Dynamics and Permafrost Creep*, which is chaired by W. Haeberli of University of Zurich (HAEBERLI and HALLET 1999). During a two-year period (1999-2000), attempts will be made to define the present state of knowledge relevant to numerically modelling the flow and evolution of perennially frozen ice/rock mixtures. In this respect the topic of geometry and kinematics of rock glaciers will also be addressed. It is intended to compile a comprehensive report on the state-of-the-art of measurement techniques, which will also cover photogrammetric methods.

Measurements of surface velocity on rock glaciers have a long tradition (various case studies are shown in HAEBERLI 1985 and BARSCH 1996). Recent publications, e.g., KAEAEB 1996, KAEAEB et al. 1997 and KAEAEB et al. 1998, for the Swiss Alps, and KAUFMANN 1996, 1998a, and 1998b, and KAUFMANN and HEILAND 1998, for the Austrian Alps, also confirm the great possibilities of aerial photogrammetry in mapping and monitoring rock glaciers.

During the last decade *digital photogrammetry* (sometimes called *softcopy photogrammetry*) has evolved as the technology, which is going to take the place of preceding analytical photogrammetry (cp. EBNER and FRITSCH 1991, SCHENK 1997, HEIPKE 1997). Digital photogrammetry has already reached a high degree of maturity.

Thus, the photogrammetric workflow can be speeded up by means of semi-automation or even full automation of specific tasks requiring less production cost and time. Practical investigations state that digital image orientation, i.e. interior, exterior, and absolute orientation, and automatic aerotriangulation, and automatically derived digital terrain models, are highly reliable and the achieved accuracy is in the order of analytical photogrammetry or even better.

Currently, precise image scanners are needed for digitisation of existing analogue photographs, which is to all appearances a weak point of current digital photogrammetry (cp. BALTSAVIAS 1999). However, it is assumed that in a few years from now primary data acquisition can be done directly with enhanced digital cameras that will have a sufficiently high resolution. FRICKER et al. 1999 and HINZ 1999 present recent developments in the sector of digital aerial cameras. In this context one has also to mention the advent of high-resolution satellite imaging, e.g., IKONOS acquires 1-meter image data in panchromatic mode, which is sold on a commercial basis globally.

Concerning rock glacier monitoring we are aiming for a methodology that is quite modular in its concept and open for future developments. The determination of the elements of the exterior orientation of aerial photographs, the digital rectification process, and the generation of digital terrain models (DTMs) will be done with any of the commercially available systems, being either conventional or already digital. In the digital domain it may be a low-cost solution, e.g., DVP from Leica, PHOTOMOD from the RACURS Company, Moscow, IMAGINE OrthoBASE and Stereo Analyst from ERDAS, and OrthoEngine from PCI, or any high-end photogrammetric workstation, e.g., from Zeiss/Intergraph or LH Systems. The concept will offer great flexibility in the workflow since due to the modular structure appropriate solutions should be found according to available resources (software, hardware and financial budget) and the anticipated accuracy of the result. The core of the proposed photogrammetric mapping scheme will be a software package, specifically developed for this rock glacier monitoring task. The input data, i.e., quasi-orthophotos or even true orthophotos, DTMs, photogrammetric orientation elements, will be provided by a database management system/GIS. The software will be written in Visual C++ programming language for running under the Microsoft Windows operating system on a standard personal computer.

1.2. Measurement of rock glacier movement

HAEBERLI 1985 and BARSCH 1996 summarise the various (traditional) observation techniques which provide either *qualitative* information, such as moving, non-moving, slow moving, etc., or *quantitative* information, e.g. numerical values of flow velocity, on the activity of rock glaciers. Since rock glaciers are three-dimensional (3-D) spatial objects, flow velocities should not only be determined at the surface but also inside the rock glacier. The latter can only be accomplished by means of borehole logging which is expensive and therefore limited to a few examples world-wide (cp. HAEBERLI et al. 1999). As a consequence, we only consider *superficial* flow velocities in the following.

An alternative solution to the classical geodetic survey using an electronic theodolite (Total Station) is given by the modern *satellite-based positioning* with GPS/GLONASS. Practical results from Austrian rock glaciers are reported in CHESI et al. 1999 and KAUFMANN and HEILAND 1998. In summer 2000 the latter also conducted further GPS measurements applying the *kinematic method* at the Doesen rock glacier, Austria (see Figure 1). The kinematic method requires an uninterrupted signal from at least 4 satellites. However, this experiment failed due to the large obstructions of the rock glacier from the surrounding mountains, especially those in the south. Loss of lock to satellites and poor geometry of the remaining satellites did not allow determining coordinates of points on the rock glacier at all.

Since in-situ measurements are generally personnel, time and cost intensive, especially when several rock glaciers have to be investigated simultaneously, *remote sensing* methods are an alternative solution. In addition to photogrammetry we have to take into account *radar interferometry* and *laser scanning*. The applicability of interferometric SAR techniques, i.e. InSAR and D-InSAR, in respect to monitoring of movements of ice-rich sediments and rock glaciers based on ERS-1/2 satellite radar image data has been shown by WANG and LI 1999 and ROTT and SIEGEL 1999, respectively. The latter presented the interferometric motion analysis of the Hochebenkar rock glaciers, which are the subject of this paper. Applications of terrestrial and airborne radar interferometry to rock glaciers have not yet been reported in the literature. This is also true for terrestrial and airborne laser scanning. However, in summer 2000 the Institute of Applied Geodesy of the Graz University of Technology (TUG) and the Institute of Digital Image Processing of Joanneum Research Graz have started a joint project aiming to investigate the possibilities of a terrestrial laser scanning device built by the Austrian company RIEGL. The task will be to monitor the front slope of the Hinterer Langtalsee rock glacier, Schober group, Austria (see Figure 1), which has been affected by landslides.

Various solutions have been proposed in order to measure the movement of rock glaciers using multi-date, i.e. multi-year, metric photographs (see KAEAEB 1996 and KAUFMANN 1996). In many cases problems or limitations concerning the direct visual fusion of multi-date photographs were encountered. The reasons for this are, e.g., varying image scales, image rotation, distortion due to relief displacement, temporal and baseline induced de-correlation of image brightness, i.e. grey tone, impossibility of merging mixed sets of black-and-white, colour, or colour-infrared photographs.

It is interesting to note that motion detection and mapping of velocity fields is a well developed area in machine (computer/robot) vision (SONKA et al. 1998), but these concepts have not yet found their application in all earth sciences.

1.3. Test site of the case study

The applied study presented in this paper analyses the dynamic behaviour of two adjacent rock glaciers, i.e. the *Inner (*German *Inneres)* and *Outer (*German *Äußeres) Hochebenkar rock glacier*, located in the Oetztal Alps, Austria (see Figure 1). The geographical setting of both rock glaciers can be deduced from Figures 2 and 3.
The tongue-shaped Outer Hochebenkar rock glacier is well known from various citations in literature, e.g. Barsch 1996. It has a long record of continuous measurements, dating back to 1938. Characteristics of this rock glacier are its comparatively high flow velocity, several crevasse-like features (perpendicular to the flow direction in the middle and upper part, a distinct depression in the rooting zone of the rock glacier, and the landslide topography now developing at the front slope. At the orographic right side of the rock glacier another unit is attached showing a sequence of furrows and ridges. In the vicinity of the Outer Hochebenkar rock glacier three other small rock glaciers can be identified, i.e., two in the SW and another in the NW (see Figure 3).
The Inner Hochebenkar rock glacier shows a comparatively complex sequence of strongly bent furrows and ridges in the lower end, and is composed of two main tongue units. The front slope of the southern tongue is already moving in a steeper area causing rock fall and flattening in certain areas. The particle size of the surface substrate is generally larger at the Outer Hochebenkar compared to that of the Inner Hochebenkar resulting in a courser, i.e. less smooth, phototexture as can be seen in Figure 3.
HAEBERLI and PATZELT 1982 carried out detailed field investigations, e.g., BTS measurements, seismic refraction, and temperature measurements of springs, in the study area covering both rock glaciers. As a result a map showing the permafrost occurrence and a map showing the active layer thickness at 1:10,000 scale were produced.

There are no traces of recent glaciation at the Outer Hochebenkar rock glacier, whereas the Inner Hochebenkar rock glacier was partly covered by the Hochebenferner (see details in HAEBERLI and PATZELT 1982 and PATZELT 1986) reaching a maximum extent around 1850. In 1997 the Hochebenferner covered an area of 15.8 ha. The present size of the Outer Hochebenkar rock glacier is 42 ha, while the Inner Hochebenkar rock glacier covers 57 ha.

Figure 1: Location map.
Figure 2: Topographic map of the study area.
Figure 3: Orthophoto map of the study area.
Image data: © Austrian Federal Office of Metrology and Surveying (BEV), 2000.

1.4. A long record of accurate velocity measurements

B. SCHNEIDER 1999 made an extensive review of all photogrammetric and geodetic measurements that have been carried out on the Outer Hochebenkar rock glaciers. It was also her task to homogenise all existing measurements, especially the geodetic ones. B. Schneider distinguishes between three eras of activities, which refer to the key persons involved in them, i.e., era of *W. Pillewizer* (1938-1955, details in PILLEWIZER 1957), era of *L. Vietoris* (1951-1970, details in VIETORIS 1972), and era of *H. Schneider* (1972-present), the latter being the father of B. Schneider. B. Schneider has continued the measurements from 1997-1999 and she has also improved the geodetic network including the set-up of an additional longitudinal profile and reference points.

Terrestrial photogrammetric surveys of the Outer Hochebenkar rock glacier were carried out by the Institute of Applied Geodesy of TUG in 1986, 1995, and 1999 (KAUFMANN 1996 and 1998a). It is intended to evaluate these data with the new technique described in this paper.

Since the Outer Hochebenkar rock glacier is one of the few rock glaciers on earth with a very long and also continuous record of good and reliable measurements, it is a reasonable assumption to adopt this rock glacier as a test site for new investigations, such as digital photogrammetry, SAR interferometry and other methods.

Quantitative information on the activity of the Inner Hochebenkar rock glacier is scarce. Until now three attempts have been made to determine the flow velocity. The first attempt was by PILLEWIZER 1957. He calculated a mean flow velocity of 1.1 m a^{-1} based on observed motion parallaxes (1953-1955) on 5 points located at the northern rim of the southern tongue of the rock glacier. The second attempt is described in VIETORIS 1972. E. Dorrer used the same photogrammetric measurement technique as applied by Pillewizer. His observation line was positioned in the central part of the rock glacier at an altitude of 2800 m perpendicular to the supposed flow direction (see Figure 2 in VIETORIS 1972). However, he could not obtain evidence for any motion, at least for the period 1959-1966. The third attempt refers to radar interferometry. ROTT and SIEGEL 1999 conclude from their analysis of two 35-day interferograms of summer 1995 that both the right (N) and left (S) sections of the terminus of the Inner Hochebenkar rock glacier are moving. The displacement rate is quantified with several centimetres within the 35 days. By the way, the interferograms of the Outer Hochebenkar allow quantitative analysis of velocity only in the upper part of the rock glacier.

2. Outline of the basic concept

The idea of the automatic measurement of 3-D flow vectors in digital multi-temporal photographs for rock glacier studies has already been formulated in KAUFMANN 1998a. This idea is based on the work of BALTSAVIAS 1996. Baltsavias describes in detail how to perform measurements of 3-D coordinates using orthorectified stereo images and how to implement geometrically constrained matching. Other authors, e.g. SCHENK et al. 1990, have proposed a hierarchical approach to reconstruct surfaces by using iteratively rectified imagery.

2.1. Mapping of flow vectors

Figure 4 provides a graphical description of the principles of the envisaged digital photogrammetric method. Without restricting the general case of multiple photographs we will now consider only two stereopairs of aerial photographs acquired at two different time epochs t1 and t2. The elements of interior and exterior orientation of all photographs are known. If we can track the 3-D location of a particle at the surface, e.g. a larger boulder, over time we can derive its 3-D displacement vector, i.e. flow vector, which describes the movement of the particle P_{t1} to the position P_{t2} of the deformed surface of time t2. Four single digital *quasi-orthophotos*, Schenk denotes them as warped images, can be produced using a *rough*, i.e. a preliminary, DTM. Deviations of this DTM from the true DTMs cause positional errors in the quasi-orthophotos. Automatic digital point transfer using *image pyramids*, which is a hierarchical multi-resolution approach in object space, and *area-based* grey level *matching* techniques detects the homologous, i.e. conjugate, points in the respective quasi-orthophotos. For the sake of simplicity we start with the position $(X´,Y´)_{t1}$ and search for the three other positions where the boulder is supposed to be located. All four points are then back-projected into the respective photographs. The final 3-D position of the boulder for both time epochs is derived by spatial intersection of the respective projection rays. The vector pointing from P_{t1} to P_{t2} defines the 3-D displacement. In fact two different DTMs may be used, one representing the surface at time t1 and the other for t2, respectively. In case the rough DTMs are identical with the true ones, no *disparities*, i.e. image parallaxes, will be detected between quasi-orthophotos belonging to the same epoch, which means that the given orthophotos are already true, i.e. perfect orthophotos. Furthermore, this means that the remaining non-zero disparities between these kinds of orthophotos of different time epochs are due to surface deformation. This is, of course, only valid if the elements of photogrammetric orientation are free of errors and the image scans are perfect.

Figure 4: Computation of 3-D displacement vectors based on digital quasi-orthophotos.

2.2. A small practical example

In order to make the concept described above more transparent, a small data set of the case study of chapter 3 will now be presented. We have selected a small region, 150 m by 150 m in size, which covers a supposed active area of the Inner Hochebenkar rock glacier and its non-moving surroundings. The location of the sample area is shown in Figure 3. The presented example refers to the time interval 1953-1969. A smoothed version of the DTM of 1953 was taken to generate the four quasi-orthophotos (see Figures 5a-5d). A pixel size of 0.25 m was selected for the orthophotos. After the rectification process distinct points in the quasi-orthophoto of Figure 5a were found automatically using the *interest operator* of *Foerstner*. Look for a larger boulder on the rock glacier, e.g. in the lower left corner of the scene. All interest points are shown as white dots. In the following step conjugate points were found by image matching. See the same boulder in the other three quasi-orthophotos of Figures 5b, 5c, and 5d. The final geometric transformation provides the 3-D displacement/flow vectors. Figure 5e shows the horizontal flow component, whereas 5f shows the vertical component of the vectors. See the same boulder to check its movement. Points in the surroundings of the rock glacier, i.e. in the upper third of the scene, do not display significant movement. Of course, all quasi-orthophotos may be fused stereoscopically with one another in order to check the computational results.

2.3. Some comments

Image matching is still an active field of research in photogrammetry and machine vision. It can be stated that there is hardly any image matching algorithm that can serve all applications perfectly. Most algorithms follow a *hierarchical* approach from coarse to fine, which enables quick and stable convergence of image matching to the correct solution (details in SCHENK 1999 and KRAUS 1997). Image matching algorithms can be divided into *area-based* and *feature-based* algorithms, or a combination of both (good overview in BALTSAVIAS 1991). The current version of the software is based on area-based image matching strategies, i.e., using the *cross-correlation method* and the high-precision *least-squares method* (LSM). In both cases the matching entities are grey values. The cross-correlation method is applied in order to derive good approximations for the least-squares matching which has to be good within 1-2 pixels. Positioning with sub-pixel accuracy can also be achieved with the cross-correlation method (SCHENK 1999, KRAUS 1997). The hill-climbing technique is used to efficiently search for the cross-correlation maximum. LSM also has the advantage to provide information on the matching accuracy.

Figure 5a: Quasi-orthophoto (no. 2825) of 1953.
Figure 5b: Quasi-orthophoto (no. 2826) of 1953.
Figure 5c: Quasi-orthophoto (no. 4366) of 1969.

Figure 5c: Quasi-orthophoto (no. 4366) of 1969.
Figure 5e: Horizontal component of the flow vectors 1953-1969, accuracy: ± 4 cm a^{-1}.
Figure 5f: Vertical component of the flow vectors 1953-1969, accuracy: ± 2.5 cm a^{-1}.

Of prime importance is the selection of the appropriate window size of the template image in the matching process. The template size is currently selected heuristically by the experienced operator in order to successfully scope with varying image quality, image texture, and amount of expected image distortion due to incorrect DTMs and speed of rock glacier movement. MENARD and KROPATSCH 1997 and HAHN 1995 provide same solutions to this problem.

High-accuracy measurements require LSM (first introduced by ACKERMANN 1983). Good results, however, can only be expected in areas with prominent features, i.e. grey level gradients. These feature areas can be selected beforehand in order to ensure that the image matching algorithm is performing well. Many so called interest operators have been proposed (see HAHN 1995). We have implemented the well-known *Foerstner operator* (FÖRSTNER and GÜLCH 1987), which can be applied quite successfully in high mountain terrain.

The good prediction (approximation) of the location of the conjugate points is of crucial importance in image matching, especially for LSM. Since we are already working with good approximations of the DTMs the influence of relief displacement is quite diminished. However, if the absolute movement of the rock glacier is very large due to high velocities and long time intervals, the image disparities in the quasi-orthophotos of different time epochs can also be very high. We have implemented a multi-scale approach based on image pyramids with discrete steps of resolution. The aim of this is to iteratively compute a raster-based *disparity map* from coarse to fine, which holds the coordinate differences derived from cross-correlation matching. LSM is done in the finest resolution (cp. also PAAR and POELZLEITNER 1991).

In photogrammetry *epipolar geometry* (co-planarity condition) is taken as a constraint in image matching (SCHENK 1999, KRAUS 1997). This is quite useful since it reduces the 2-D search space into a 1-D search space along the epipolar line. In the current version of our software we have not implemented this geometric constraint explicitly. However, we are using this constraint to check the matched positions when computing the 3-D coordinates of the object point within the stereomodel.

Multi-photo matching has already been described in the literature, e.g. BALTSAVIAS 1991. This method can be easily implemented in our approach and it suggests that the matching accuracy is going to be improved. Epipolar constraints may only be considered if one is sure that the selected surface point is stable, i.e. non-moving, throughout the time. The method of Baltsavias may also include a geometrical model of the surface.

Furthermore, a surface flow model derived from rheological considerations can be incorporated in order to facilitate the computation and subsequent interpretation of the results.

HEIPKE 1997 provides a review of recent developments and the state-of-the-art of automatic image orientation, which is not addressed in more detail in this paper since we have assumed the orientations of the photographs to be known.

Of paramount importance is the radiometric and geometric quality of the digitised photographs. In this respect great attention has to be placed on the performance of the scanner used (cp. BALTSAVIAS 1999, GRUBER and LEBERL 2000). Accurate and reliable results in automatic mapping of flow velocity of rock glaciers can only be obtained using a photogrammetric scanner.

The detection of *gross errors*, i.e. *blunder detection*, and the compensation of *systematic errors*, e.g. datum shift and photogrammetric model deformation, are discussed in chapter 3.

Recently, VOLLMER 1999 (Institute of Geography, University of Zurich) has developed one of the first software systems that can automatically derive flow vectors of rock glaciers from digitised multi-temporal aerial photographs. The software system is called **CIAS** (Correlation Image Analysis) and is programmed in IDL (Research Systems Inc., Boulder, USA). The underlying concept is similar to that proposed in this paper. However, the current version of CIAS does not support 3-D measurements. The quality of the derived 2-D flow vectors depend very much on the quality of the respective multi-temporal DTMs used in the rectification process. Orthophotos are produced with the OrthoEngine software from PCI. Image matching is based on cross-correlation with a possibility of a simplified sub-pixel interpolation. 2-D systematic errors are eliminated by means of a conformal coordinate transformation using non-moving reference points. CIAS was successfully tested at the Gruben rock glacier, Switzerland.

3. Case study

LADSTAEDTER 1999 has implemented the basic concept in a software system called **ADVM** (Automatic Displacement Vector Measurement) at the Institute of Applied Geodesy of TUG. The programming language is Visual C++. The software runs under Microsoft Windows 95, 98, 2000 and NT on a standard personal computer and consists of 4 main modules, i.e., (1) INTEREST, (2) PREDICT, (3) PTRANSFER, and (4) INTERSECT. A detailed description of the underlying computer algorithms is not in the scope of this paper. However, some comments are made occasionally during the discussion of the case study.

The first practical test of the software was not carried out on a rock glacier but on a debris-covered cirque glacier (Goessnitzkees, Hohe Tauern National Park, Austria, see Figure 1). Aerial photographs from 1997 and 1998 were taken in order to compute a dense field of 3-D flow vectors and to generate digital terrain models for both years. The results obtained were promising (KAUFMANN and PLOESCH 2000).

A thorough test of the ADVM software and other additional software components, which were needed in the course of evaluation, was accomplished during the present case study, which focuses on the Hochebenkar rock glaciers described in section 1.3. Immediate feedback was very valuable for improving conceptual design and for optimising computer algorithms.

3.1. Aerial photographs

22 multi-temporal panchromatic black-and-white aerial photographs covering the area of interest, shown in Figures 2 and 3, were obtained from the Austrian Federal Office of Metrology and Surveying (Table 1). With this set of photographs we will reconstruct the rock glacier history of the study area in the course of the past 44 years, from 1997 backward. (Remark: This can also be done for the glacier history. In fact, the DTMs obtained for the single stages of the Inner Hochebenkar rock glacier show the changes of the glacier surface of Hochebenferner perfectly). The given data set is quite different concerning image sharpness, image contrast, quality of fiducial marks, image scale and imaging geometry, shadowed areas, and surface cover, e.g. fresh snow, glacier ice, perennial snow, small lakes, etc.

date of acquisition	number of photographs	focal length [mm]	image scale	film format [cm²]
August 31, 1953	6	210.110	1:14,000 – 1:16,900	18 × 18
September 24, 1969	2	151.990	1:27,200 – 1:31,100	23 × 23
August 18, 1971	4	209.480	1:14,400 – 1:17,300	18 × 18
September 7, 1977	2	152.020	1:12,300 – 1:16,200	23 × 23
August 14, 1979	2	152.590	1:22,800 – 1:26,700	23 × 23
September 7, 1981	2	153.240	1:17,200 – 1:21,100	23 × 23
October 10, 1990	2	152.800	1:32,300 – 1:36,300	23 × 23
September 11, 1997	2	152.700	1:34,600 – 1:38,500	23 × 23

Table 1: Aerial photographs covering the Hochebenkar rock glaciers.

3.2. Photogrammetric scanning of aerial photographs

In a first step all photographs were digitised using the high-precision photogrammetric scanner *UltraScan5000* from Vexcel Imaging Austria Gmbh. A *geometric resolution* of 2540 dpi was selected for all image scales, resulting in a pixel size of 10 µm. Approximately 450 (325) MB of storage capacity, on CD-ROM or hard disk, is needed for the given image formats using 8 bit/pixel. Data is stored in uncompressed TIFF. The high geometric and radiometric quality of the UltraScan5000 is demonstrated in GRUBER and LEBERL 2000. Nevertheless, the geometric accuracy of the scanner was checked before scanning all photographs using two independent test procedures, i.e., scanning of a calibrated grid plate with small crosses which are placed at a distance of 2 mm, and scanning of a selected photograph of the given data set twice, i.e., in two orthogonal directions. Since the analysis of the acquired test data is comparable to deformation analysis, it was straight forward to use ADVM software without any major adoption. More than 10,000 points were matched in each data set. The results of the geometric accuracy test show that the planimetric accuracy is better than $m_p = \pm 3$ µm for any point in the test data.

It must be stressed here once again that above all, the geometric accuracy of the image scans is of great importance for correct and reliable results derived through digital photogrammetric methods.

In the analysis of the temporal change of the debris-covered cirque glacier mentioned above, we were working on digitised data, which was acquired using the photogrammetric scanner RM-1 from Wehrli. Detailed analysis of the left-over parallaxes in the stereomodels revealed that the scanner had introduced systematic errors, which were due to cyclic geometric scanning errors in scan direction. Furthermore, the radiometric quality of the scans was not good, which resulted in a reduced range of digital numbers. The latter caused a weaker performance of LSM. In the meantime the successor RM-2 is on the market which overcomes all previously mentioned geometric and radiometric problems.

3.3. Exterior orientation of aerial photographs

Photogrammetric orientation of all aerial photographs has been carried out using independent stereomodels on the analytical plotter DSR-1 from Kern. Control points were provided by the Austrian Federal Office of Metrology and Surveying and the Tyrolean Federal Government. The absolute orientation of the stereomodels of 1997 and 1977 was actually performed with the given control points within the Austrian Gauß-Krüger coordinate system, however, the orientation of the other stereomodels is based on natural points, i.e. non-moving boulders in the surroundings of the rock glaciers, which were identified both in the two reference models and in the other stereomodels. This work could also have been done on a digital photogrammetric workstation (DPW). Unfortunately, we had no access to such a workstation at this stage of the project.

In general, the exterior orientation of a set of overlapping aerial photographs can be determined in many ways (KRAUS 1993). The simplest method is the procedure of *spatial resection*, which needs at least three full control points for each photograph. This method has been used by VOLLMER 1999 (cp. section 2.3).

Interior orientation should be done preferably using an affine transformation, if the elements of exterior orientation are to be transferred from an analytical plotter to a digital workstation.

In summary, it can be said that the visual selection of an appropriate number of identical control points in the given multi-temporal stereomodels was a difficult task.

3.4. Photogrammetric mapping using the analytical plotter

Two detailed geomorphometric maps at 1:5,000 scale covering the study area were produced using the DSR-1 for the 1997 and 1953 stage. These maps serve as a cartographic basis for the project and as a means of comparison. It is interesting to mention that the complete maps could only be produced with the help of the other stereomodels because plenty of shadowed areas, steep mountain slopes and areas with low contrast caused problems in 3-D mapping.
High-resolution DTMs of 1997 and 1953 with a grid spacing of 2.5 m were derived using the Intergraph software ”MGE Terrain Modeler” (actually, a TIN was first computed and afterwards gridded). Figure 2 shows a plot of the re-interpolated contour lines derived from the raster-based DTM of 1997.

Following the procedure of KAUFMANN 1998b some 10 three-dimensional flow vectors have been determined for each of the two rock glaciers for four different time intervals in order to get an idea of the performance of the method applied to this data set and to derive first quantitative numbers of surficial flow velocity.

3.5. Computation of quasi-orthophotos

From that time on an Intergraph DPW (ImageStation ZII) was available. For each of the two rock glaciers a rectangular work space has been defined which includes the rock glacier itself and a sufficiently large area around it (see Figure 3). The latter is supposed to be stable, i.e. non-moving. These terrain units outside the rock glaciers are needed to check the geometric datum of the multi-temporal stereomodels and to compensate for systematic effects.

In total 12 different stereomodels were set up on the DPW. This was a comparatively easy task since only the interior orientation of the digital photographs must be performed and because the elements of the exterior orientation were available from the analytical plotter. Using the stereoscopic viewing system of the Intergraph DPW all stereomodels were checked for y-parallaxes. The 3-D vector data of the geomorphometric maps 1997 and 1953 were also superimposed on the stereoscopic models. 8 out of the 12 stereomodels were finally selected for further analysis with ADVM, representing 8 different rock glacier stages.

The software ”BaseRectifier” from Intergraph was used to produce the required quasi-orthophotos, which serve as input data for ADVM. From a theoretical and also practical point of view an orthophoto pixel size of 0.25 m is appropriate. This number relates to the image scales, which are generally acquired by governmental mapping agencies at the proposed scanning resolution of 10 µm. If the image scale is smaller, e.g. as is the case for 1981-1997, the pixel size of the quasi-orthophotos should be 0.5 m. In any case, sampling, i.e. scanning, and re-sampling, i.e. orthorectification, must be done accordingly.

Table 2 lists the selected pixel size for each of the quasi-orthophotos and the DTM used for rectification.

year	1953	1969	1971	1977	1979	1981	1990	1997
pixel size [cm]	25/50	25	25	25	25	25/50	50	50
year of DTM	1953	1953	1997	1997	1953	1953	1953	1997

Table 2: Parameters of quasi-orthophotos.

DTMs of 1997 and 1953 were smoothed and introduced into the rectification process as preliminary DTMs. At this point we can already state that it would have been better to rectify all photographs 1969-1997 with the DTM of 1997, as later confirmed in the example of 1971-1977. The reason lies in the fact that in comparison to 1953, the DTM of 1997 is a far better approximation of the topographic situation of 1969-1990. However, the example of the

Outer Hochebenkar rock glacier is an exceptional case, which is due to the rapid mass movement (landslide) of the front slope. For the Inner Hochebenkar rock glacier it makes no difference which DTM is selected.

3.6. Computation of 3-D flow vectors

The following time intervals were evaluated with ADVM: 1953-1997, 1953-1969, 1969-1979, 1971-1977, 1979-1981, 1981-1990, 1990-1997, and, additionally 1981-1997 for the Inner Hochebenkar rock glacier since a thin layer of fresh snow, which covers the terrain of 1990, hampered successful image matching in the area of interest.
The processing of data caused no major problems except for the time interval 1953-1997 at the Outer Hochebenkar rock glacier. Because of the great amount of horizontal movement, i.e. more than 50 m, the PREDICT module could not obtain correct estimates for the position of conjugate points, especially in the lower part of the rock glacier. A simple linear 2-D rock glacier flow model has been set up to solve this problem. We could also have taken any of the results of other time intervals appropriately scaled to the expected horizontal movement in respect to the elapsed time.
The INTERSECT module computes the 3-D coordinates. Erroneous data is eliminated by a specific threshold of the y-parallax. This module can actually handle an unlimited number of photos. Stereotriplets covering the area of interest would have been optimal. All data is stored in tables (spreadsheets) for further processing. 3-D flow vectors are calculated by merging appropriate tables. The final result is output as an ASCII table, which provides all data and information, e.g., sequence number, point number, point flag, 3-D coordinates of both time epochs, time interval, 3-D coordinate differences, 3-D movement, 2-D movement, annual values of coordinate differences and absolute movements, slope and azimuth of vector, accuracies, etc.

3.7. Blunder detection, systematic errors and quality check

An issue in automatic digital photogrammetry is the detection of *gross errors*, i.e. blunders (cp. KRAUS 1997). This is also true in our case because image matching may give incorrect results due to various reasons, e.g., wrong approximations, changing surface cover, changing surface texture, dark shadows, hidden surfaces, etc. In this section we will only consider blunder detection of the computed 3-D displacement vectors. For the sake of simplicity we assume that the 3-D displacement vectors are free of systematic errors (see next paragraph) and that the data set is already classified into two classes, i.e., points on the rock glacier and non-moving points in the surroundings. Blunders in the non-moving areas can be eliminated easily by means of simple statistical tests. To detect errors in the vector field on the rock glacier it is necessary to establish assumptions about the movement, e.g. smoothness, direction of motion, and maximum velocity. In this respect, the theory of motion analysis developed by machine vision can be applied efficiently. A path coherence function (SONKA et al. 1998) can be set up which may also be based on time-series of velocity fields and on an appropriate rock glacier flow model.
RISER 1998 has developed a software package written in Visual C++ at the Institute of Applied Geodesy which analyses the geometrical properties of the flow of rock glaciers based on 3-D displacement vectors. Within this software, error detection and filtering of input data is based on a least-squares linear prediction model, well-known from geostatistics. From our experience we can conclude that an automatic blunder/error detection algorithm does not provide a really satisfying result. In all practical cases an experienced operator, familiar with high-mountain geomorphology and rock glacier dynamics, had to support the error detection process interactively. This was facilitated by providing additional information, e.g., orthophotos, contour lines, and interpolated isotachs, as a backdrop to the displayed vector fields. In order to deal with different types of terrain units ADVM can handle up to 256 different classes, e.g. we have introduced three new classes for the smaller rock glaciers next to the Outer Hochebenkar rock glacier, which, by the way, did not show any significant movement at all.
In general, editing work was greatest at the borderlines of snow patches, at the borderlines of larger cast shadows, and on rather steep slopes, and, in particular at the front slope of the Outer Hochebenkar rock glacier and at the borderline and inside of the Hochebenferner located at the rooting zone of the Inner Hochebenkar rock glacier.

KRAUS 1993 and 1997 describes in detail the error theory of the various photogrammetric orientation procedures. Interior, relative and absolute orientation can only be executed with a certain accuracy, and the derived orientation elements therefore display certain errors. Unfortunately, these errors cause *systematic errors* in the object space. Of major importance is model deformation *in height* and *datum shift* of the stereomodel. Model deformations arise not only from errors of the interior and relative orientation, but also from other systematic sources of error, in particular from lens distortion, which was, e.g., not available for the 1953 aerial photographs, and image scanning (cp. section 3.2). Since in our approach we have transferred the numerical values of the exterior orientation from the analytical plotter to the DPW, model deformations are probable due to imperfect reproduction of inner orientation and inherent image scan errors. Systematic datum shift is due to measurement errors of control points in absolute orientation, i.e. the coordinate systems of the individual stereomodels do not exactly correspond with each other and may have different offsets, scales, and rotations. However, these systematic errors are, with two exceptions, mainly linear (for more details see KRAUS 1993) and therefore can be removed to a high degree by a *spatial similarity transformation* between stereomodels of two different time epochs. As already mentioned in section 2.3 VOLLMER 1999 has applied a 2-D similarity transformation to cope with systematic errors.
In the current version of ADVM such a 3-D similarity transformation has not yet been implemented. Instead of such a rigorous solution we compensate only for translation, which was found to be sufficient. The mean values of

coordinate differences of the non-moving points are tested against the root mean square error (r.m.s.e.) in all three coordinate directions. In cases where this is of significance the observed systematic effect is compensated for.
From the case study we have learned that the *z*-coordinate is much more affected by systematic errors than for example, by planimetry. The r.m.s.e. in *z*-direction is also significantly larger than the other two horizontal components, i.e. more than 1 m in some cases.
We also compared the digitally derived DTMs of 1953 and 1997 with the respective DTMs obtained from the analytical plotter and found out that they also show a systematic height shift. It is known that photogrammetric operators introduce systematic height errors in the compilation process, e.g. during terrain contouring or profiling.

Quality control comprises not only accuracy but also *reliability*. Reliability means that the 3-D flow vectors are free from gross errors. However, this can only be guaranteed if an experienced operator thoroughly checks all vectors visually as performed in the case study.

3.8. Horizontal flow velocity

From the time intervals listed in section 3.6 we only show graphically one representative interval for each of the two rock glaciers (Figures 6-9). For reasons of comparison see also KAEAEB 1998, KAEAEB et al. 1998 and KAUFMANN 1998. In the following the main findings concerning the horizontal movement of both rock glaciers are presented.

Outer Hochebenkar rock glacier

Displacement vectors at the front slope of the rock glacier tongue could not be mapped sufficiently well with the available aerial photographs. Nevertheless, it is possible to trace the evolution of the sliding process of the front slope using multi-temporal stereograms and orthophotos, both prepared at 1:7,500 scale, for visual inspection. Figures 6 and 7 reveal the spatial distribution of the velocity field very nicely. The area affected by the landslide is excluded from further analysis. For more information on this portion of the Hochebenkar rock glacier see SCHNEIDER 1999. In general, flow velocity increases continuously from the rooting zone towards the upper edge of the front slope. The maximum horizontal flow velocity within cross-sectional profiles is observed close to the stromstrich (cp. PILLEWIZER 1957). In the 90’s the maxima shifted to the orographic right side as can already be seen in Figure 7 (cp. also SCHNEIDER 1999). Horizontal flow velocities slow down significantly beneath the upper edge of the landslide area. However, in these areas extraordinarily high downward movements are observed (see next section).

Horizontal flow velocities were highest in the time interval 1953-1969 with a maximum of 1.8 m a^{-1} at the lower end of the steady state creeping zone of the rock glacier (cp. also PILLEWIZER 1957). For 1969-1979 the same value amounts to 1.1 m a^{-1}, which reflects a significant decrease of flow velocity especially in the lower elevations of the rock glacier. The situation of 1971-1977 shown in Figures 6 and 7 is of course more or less a copy of the situation of 1969-1979. It should be mentioned in passing that such overlapping time intervals are a useful means for quality control. A slight decrease in flow velocity was observed until 1990. The plot of isotachs of 1990-1997 shows a marked increase of flow velocity with a maximum of up to 1.1 m a^{-1} and generally higher velocities in the lower and middle part of the rock glacier as compared to the 80’s.

Furthermore, the vector plot of Figure 6 reveals that the longitudinal ridge (upper edge of the rock glacier) at the orographic left side is inactive. This is also true for a small region at the right side located between 2650 and 2660 m.
The attached unit at the upper right side of the rock glacier is characterised by flow velocities of up to 30 cm a^{-1} in the central part, which is composed of a sequence of furrows and ridges. Concerning this part of the rock glacier the situation of 1971-1997 is more or less representative for all other stages.

Inner Hochebenkar

The dynamic behaviour of the Inner Hochebenkar rock glacier is most interesting as can be deduced from Figures 8 and 9. Both figures reveal two active regions separated from each other by an inactive zone (cp. ROTT and SIEGEL 1999). The active region in the S consists of two distinctly moving units which can be identified by their respective flow pattern. These two units virtually merge to form the southern tongue of the rock glacier. The delimitation of both units is quite sharp against the non-moving upper parts.
A maximum of 55 cm a^{-1} is reached for the time period of 1953-1969 in the northern region. All the younger stages present lower flow velocities, e.g. 30 cm a^{-1} for 1969-1979. Since the Inner Hochebenkar rock glacier was covered by a thin layer of fresh snow in 1990, the acquired aerial photographs could not be used for motion analysis. Thus, an increase in flow velocity as observed at the Outer Hochebenkar rock glacier for the 90’s cannot be confirmed.
Figure 8 also reveals that a debris slope in the E of the rock glacier is moving.

Figure 6: Flow vector field at Outer Hochebenkar rock glacier for the time period 1971-1977.
Figure 7: Mean annual horizontal flow velocity at Outer Hochebenkar rock glacier for the time period 1971-1977.
Figure 8: Flow vector field at the Inner Hochebenkar rock glacier for the time period 1953-1997.

Figure 9: Mean annual horizontal flow velocity at Inner Hochebenkar rock glacier for the time period 1953-1997.

3.9. Change of surface elevation

The change of surface elevation was only computed for the time period 1953-1997. DTMs for both years covering both rock glaciers were derived by means of classical photogrammetric mapping (see section 3.4) and also digital photogrammetry. The DTMs obtained were compared with each other. In all combinations systematic height errors were encountered. DTMs obtained by ADVM software are of good quality except the fact that small geomorphological features, e.g. small-scale ridges and furrows, could not be mapped because of insufficient point density. However, this is of minor importance for the anticipated task of computing surface height change on a regional scale.
Figure 10 shows the change of surface height elevation of the Outer Hochebenkar rock glacier, which occurred between 1953 and 1997. This figure also gives an idea about the mass movement in the front slope since 1953 (cp. also the respective analysis of SCHNEIDER 1999). With both DTMs of the Outer Hochebenkar rock glacier a mass balance calculation was carried out in a similar way to procedures already applied in glacier studies (KAUFMANN and PLOESCH 2000). Numerical results indicate that this rock glacier has not undergone significant volumetric changes as far as photogrammetric accuracy is concerned.

The northern unit of the southern active region at the Inner Hochebenkar rock glacier shows a marked lowering of approx. 8 m in the course of the 44 years.

Figure 10: Change of surface elevation at Outer Hochebenkar rock glacier for the time period 1953-1997.

4. Discussion and Outlook

In this paper we have introduced a new concept for mapping and monitoring of rock glaciers based on digital photogrammetry. The present concept is modular and flexible. Standard photogrammetric tasks needed in the implementation of the concept can be accomplished with any of the commercially available digital photogrammetric systems, and only the monitoring task, i.e. the computation of 3-D flow vectors, requires the special software ADVM. The new concept was successfully tested in a case study. The spatio-temporal variations of the surface of both the Outer and Inner Hochebenkar rock glacier were determined with high accuracy and reliability using multi-year aerial photographs dating from 1953-1997.

Digital photogrammetry will be an integral part of Geographic Information Systems (GIS). Thus, photogrammetry is no longer restricted to specialists and therefore accessible to a broader user community, e.g. geographers and other earth scientists.

The rapid development of ever better high-resolution digital cameras suggests that the classical film-based aerial camera may become obsolete in the near future.

Concerning ADVM software we would like to make the system more operational. This requires the implementation of a user-friendly graphical interface for man-machine communication, and furthermore all project relevant data must be managed by a database management system, e.g. we propose Microsoft ACCESS.

5. Acknowledgments

V. Kaufmann is grateful to L. Vietoris and the late W. Pillewizer († 2.2.1999), who despite their advanced ages were still greatly interested in current rock glacier studies in Austria and provided information about the Outer Hochebenkar rock glacier to the author. Special thanks are due to B. and H. Schneider for handing over basic information on the Hochebenkar rock glaciers. The support of G. Patzelt of the Institute for High Mountain Research, University of Innsbruck, during three field work campaigns is very much appreciated. The authors gratefully acknowledge the support of VEXCEL Imaging Austria.

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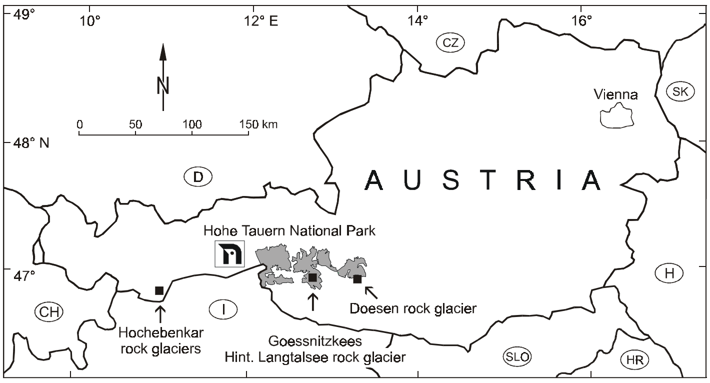

Figure 1: Location map.

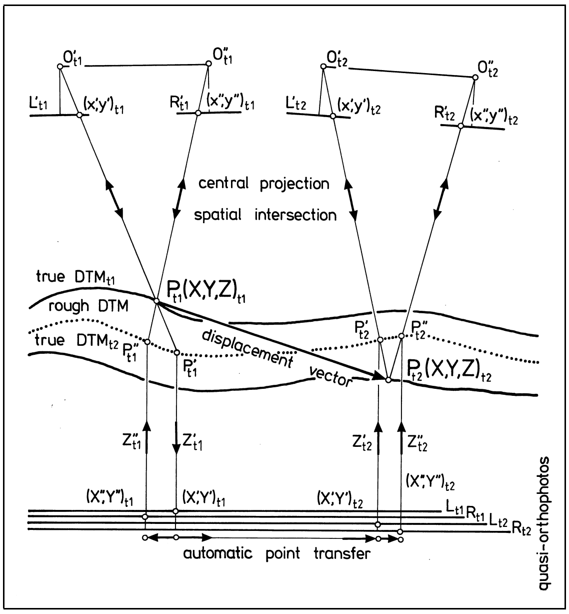

Figure 4: Computation of 3-D displacement vectors based on digital quasi-orthophotos.

Hochebenkar rock glaciers

Oetztal Alps, Austria

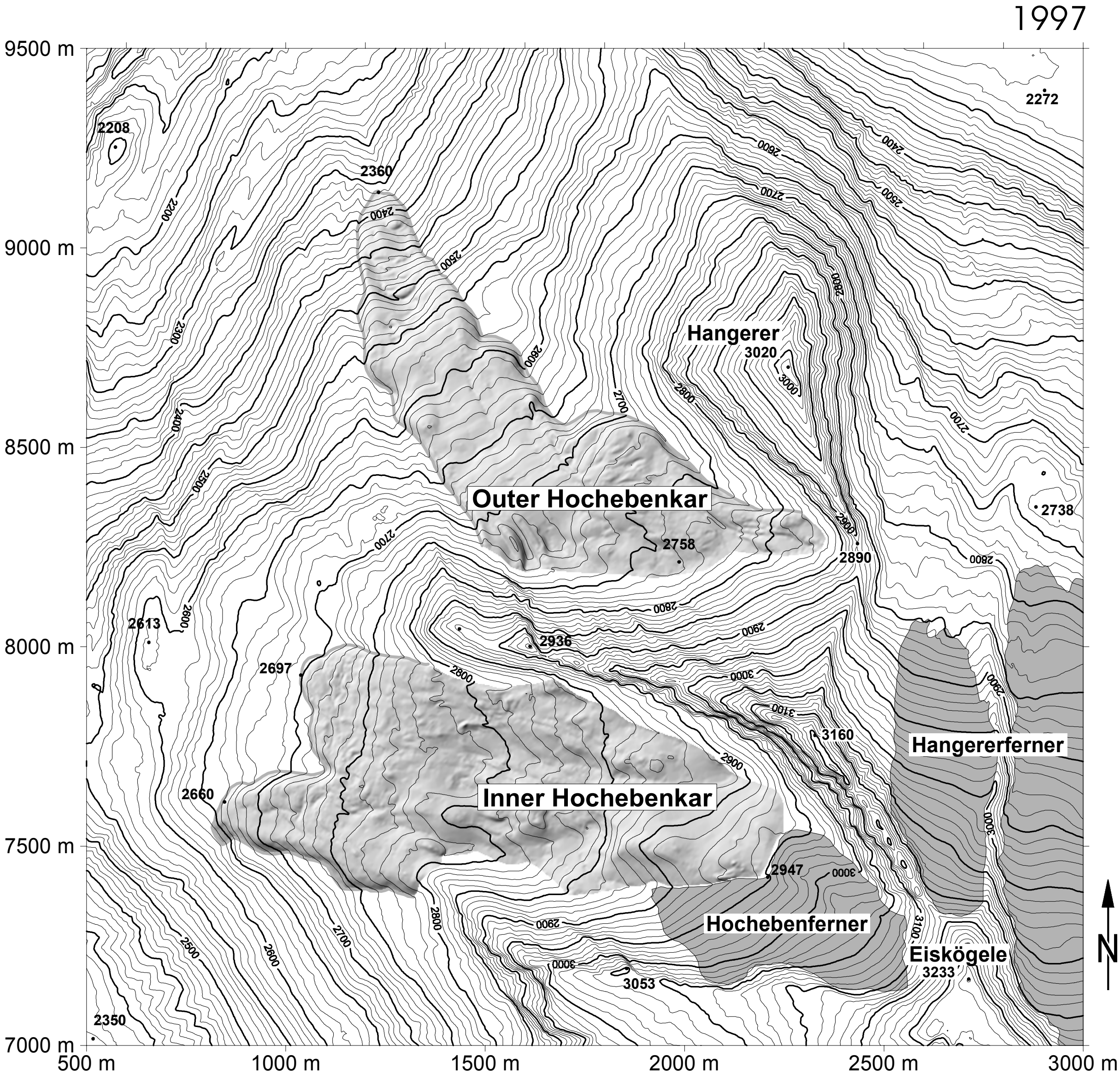

Figure 2: Topographic map of the study area.

Hochebenkar rock glaciers

Oetztal Alps, Austria

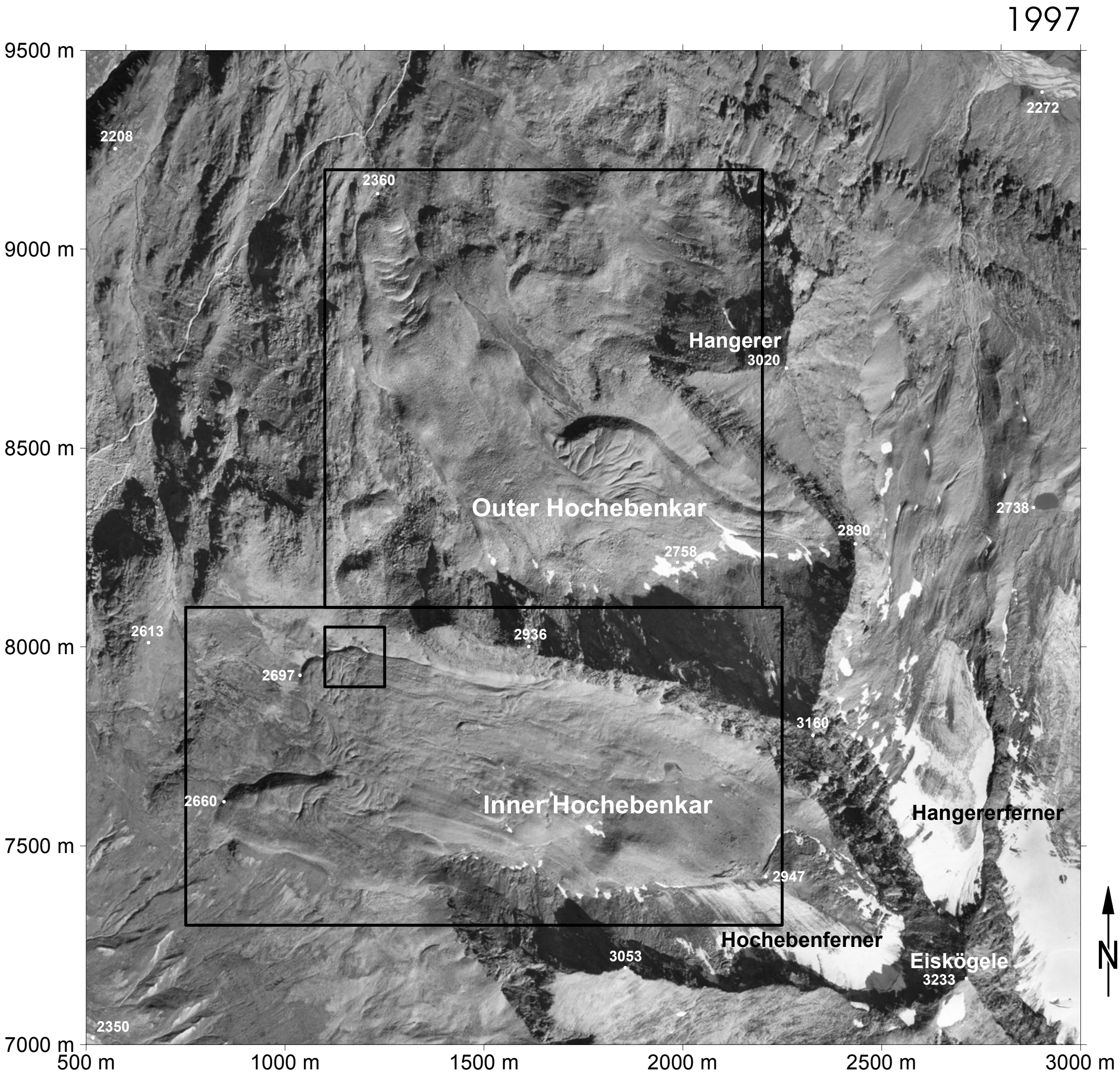

Figure 3: Orthophoto map of the study area.
Image data: © Austrian Federal Office of Metrology and Surveying (BEV), 2000.

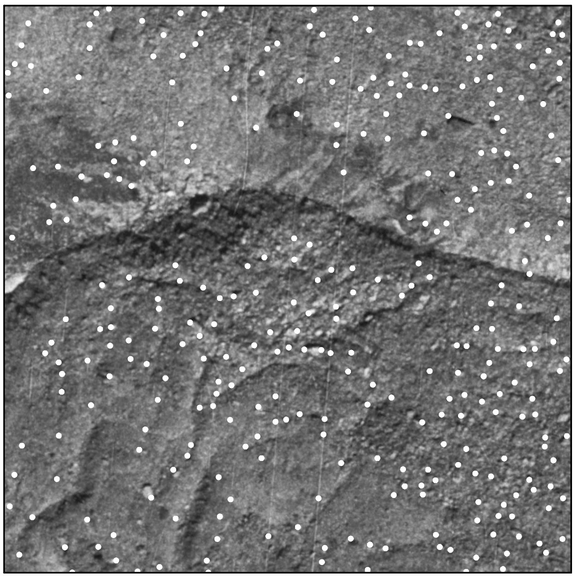

Figure 5a: Quasi-orthophoto (no. 2825) of 1953.

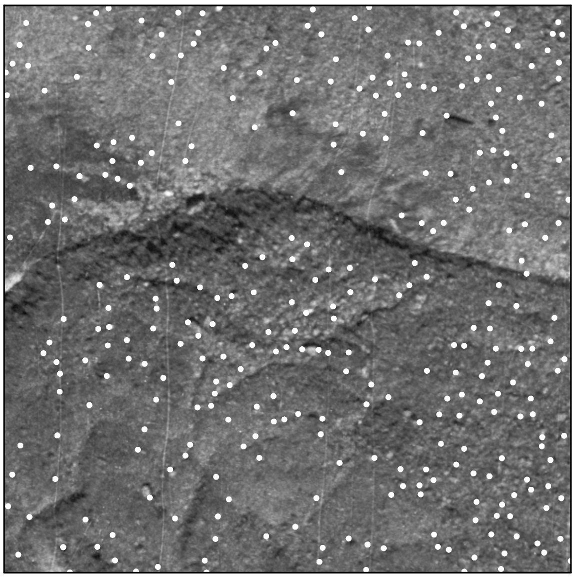

Figure 5b: Quasi-orthophoto (no. 2826) of 1953.

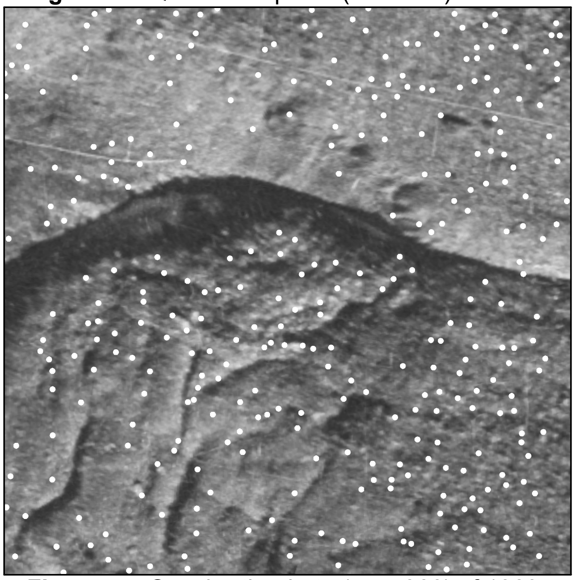

Figure 5c: Quasi-orthophoto (no. 4366) of 1969.

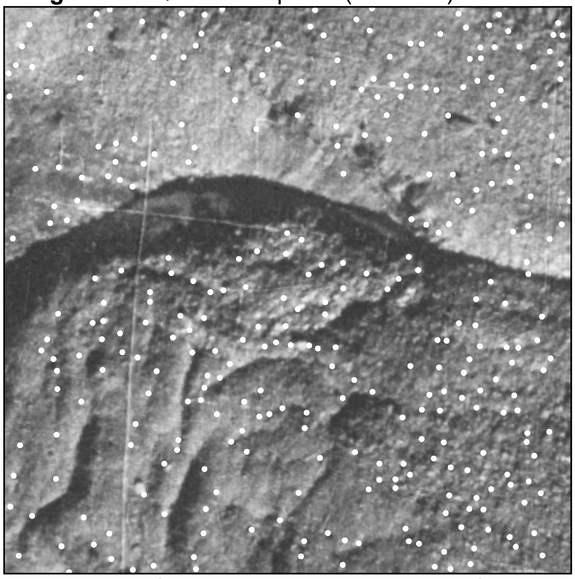

Figure 5d: Quasi-orthophoto (no. 4367) of 1969.

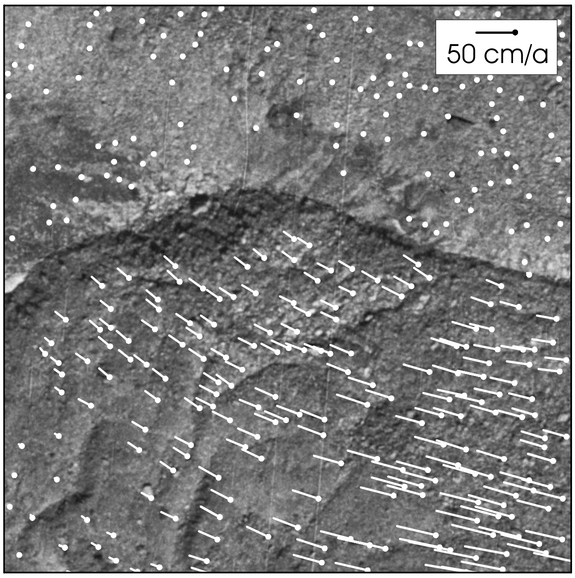

Figure 5e: Horizontal component of the flow vectors 1953-1969, accuracy: ± 4 cm a^{-1}.

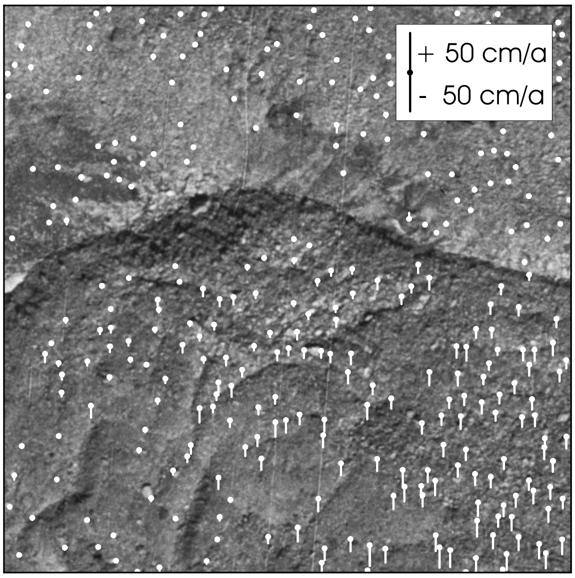

Figure 5f: Vertical component of the flow vectors 1953-1969, accuracy: ± 2.5 cm a^{-1}.

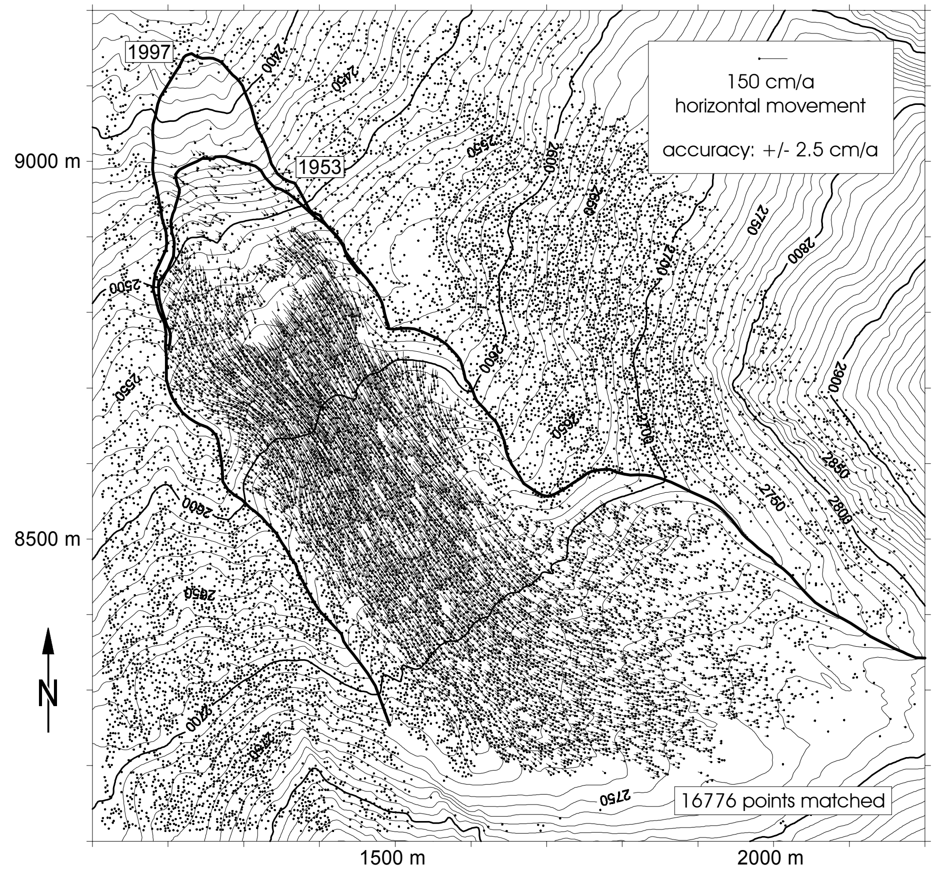

Figure 6: Flow vector field at Outer Hochebenkar rock glacier for the time period 1971-1977.

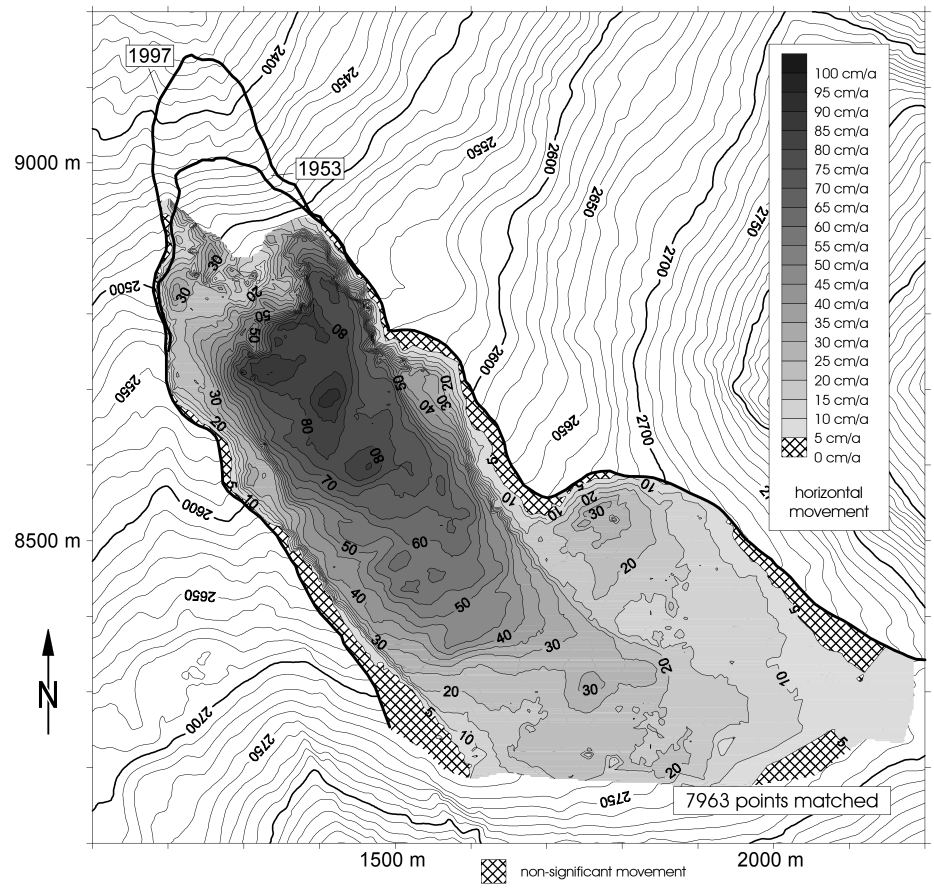

Figure 7: Mean annual horizontal flow velocity at Outer Hochebenkar rock glacier for the time period 1971-1977.

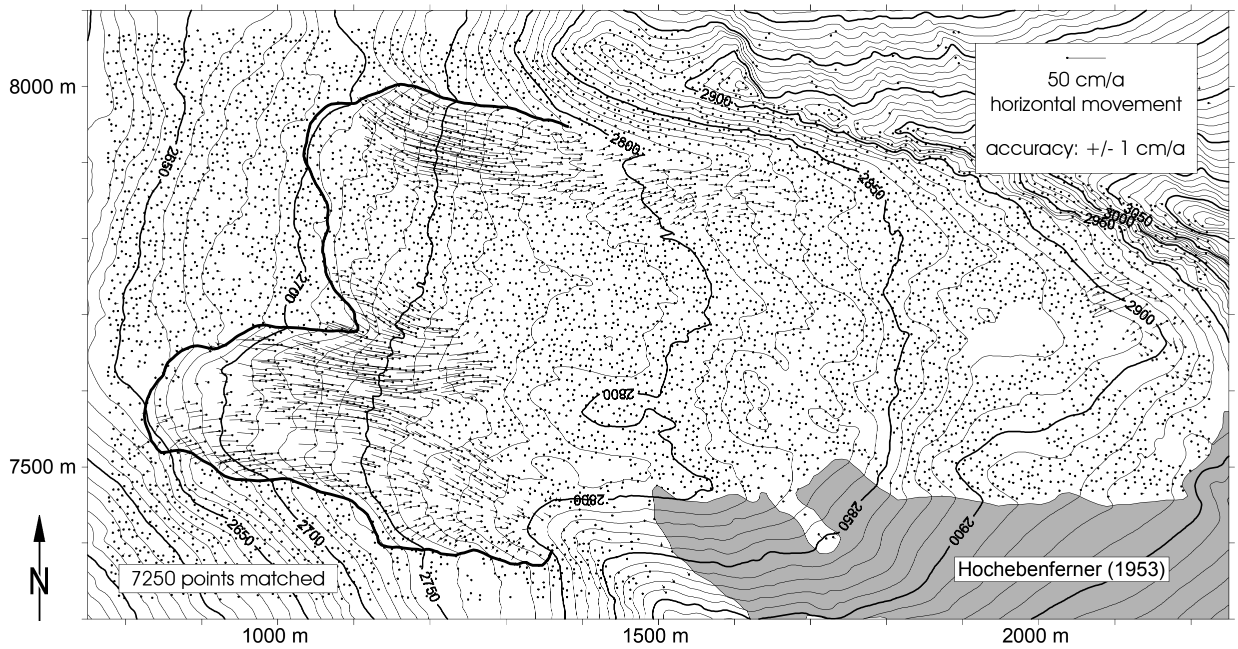

Figure 8: Flow vector field at the Inner Hochebenkar rock glacier for the time period 1953-1997.

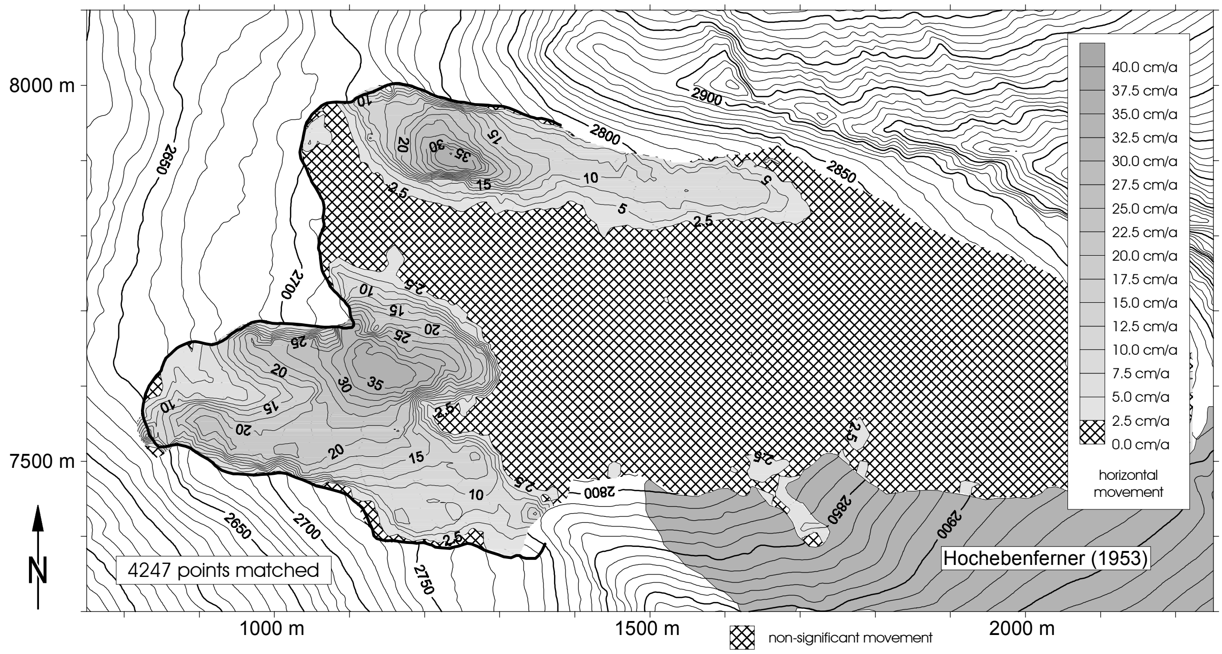

Figure 9: Mean annual horizontal flow velocity at Inner Hochebenkar rock glacier for the time period 1953-1997.

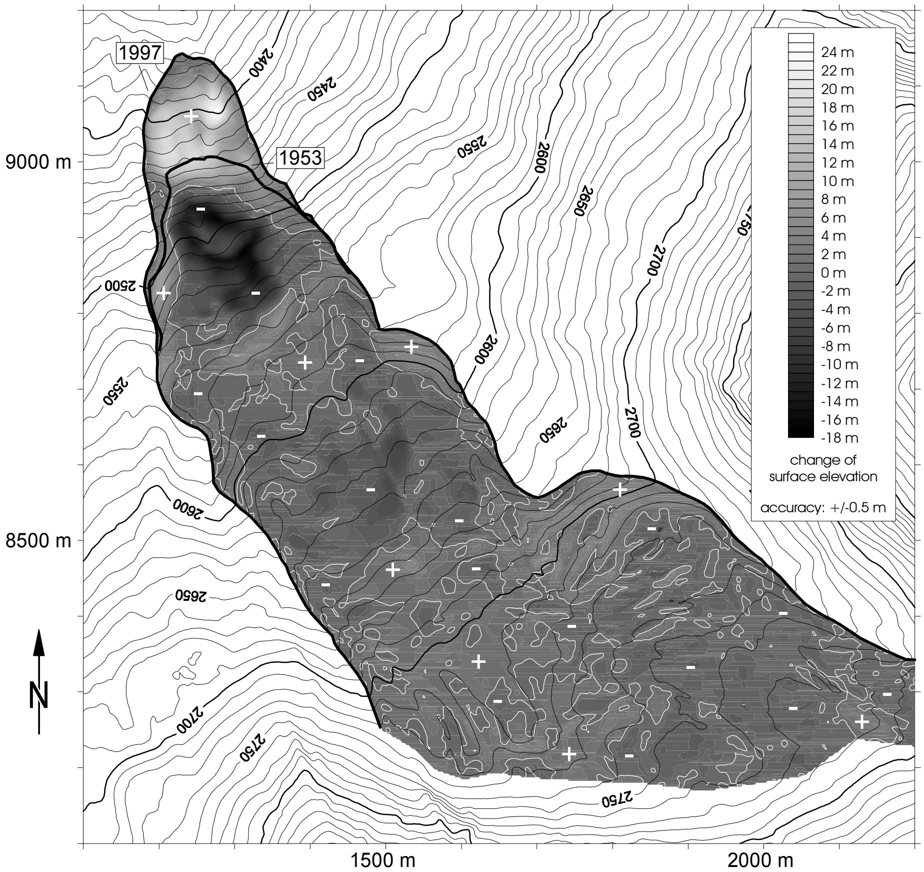

Figure 10: Change of surface elevation at Outer Hochebenkar rock glacier for the time period 1953-1997.

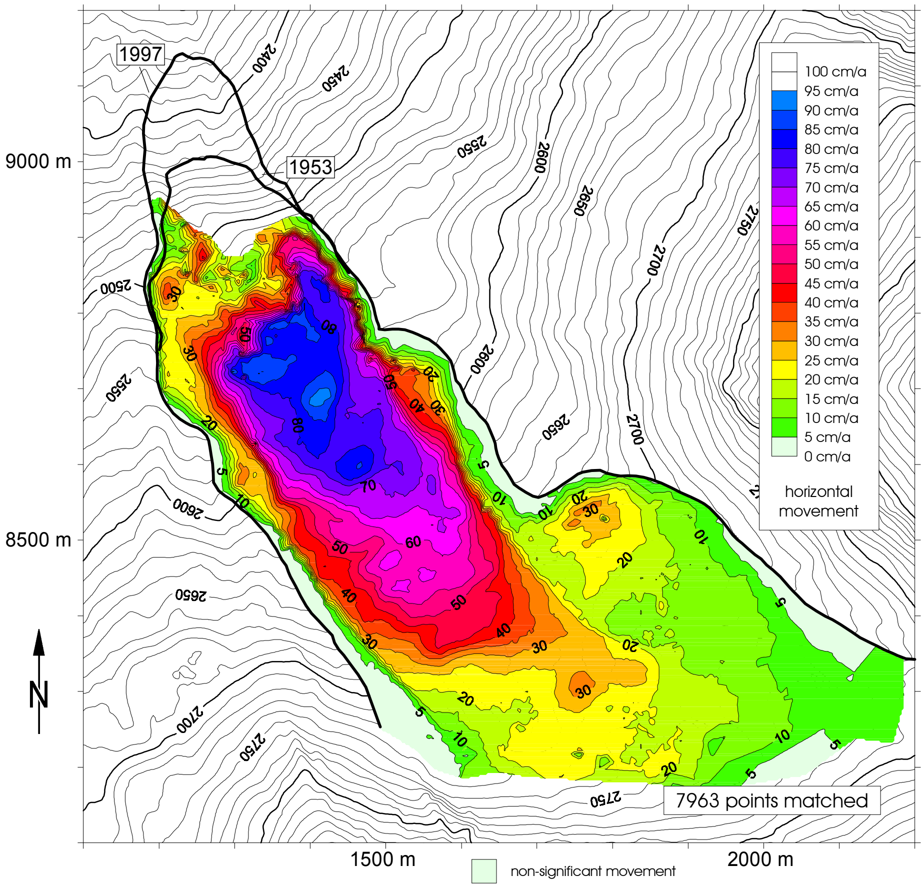

Figure 7: Mean annual horizontal flow velocity at Outer Hochebenkar rock glacier for the time period 1971-1977.

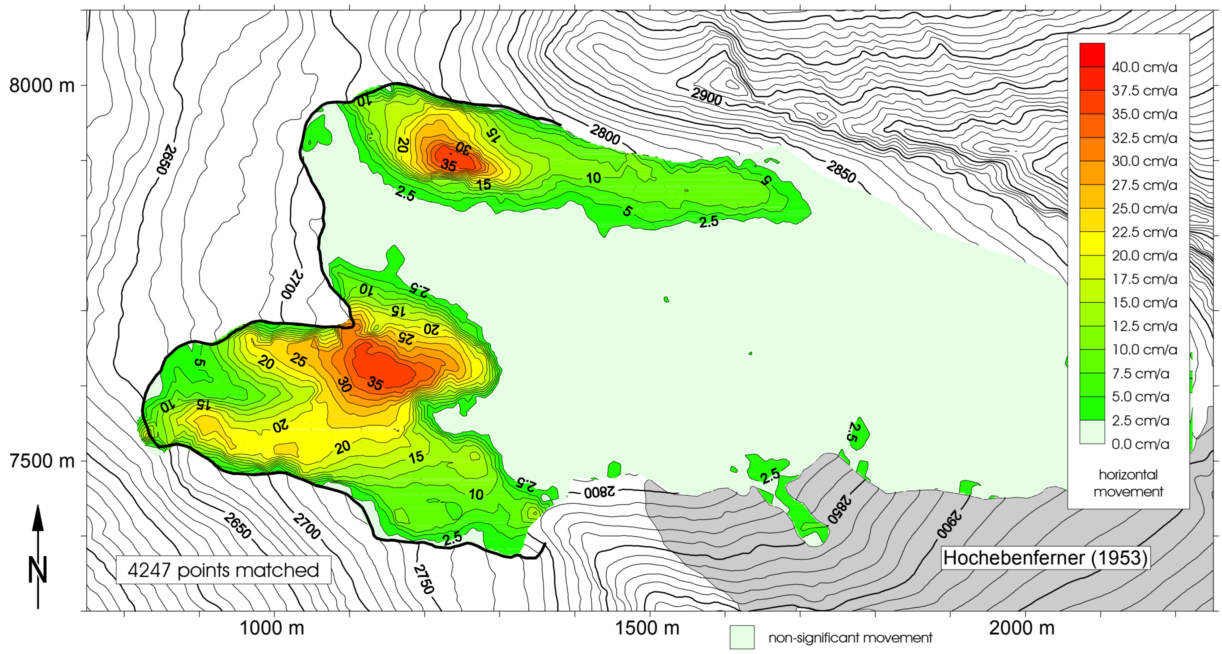

Figure 9: Mean annual horizontal flow velocity at Inner Hochebenkar rock glacier for the time period 1953-1997.

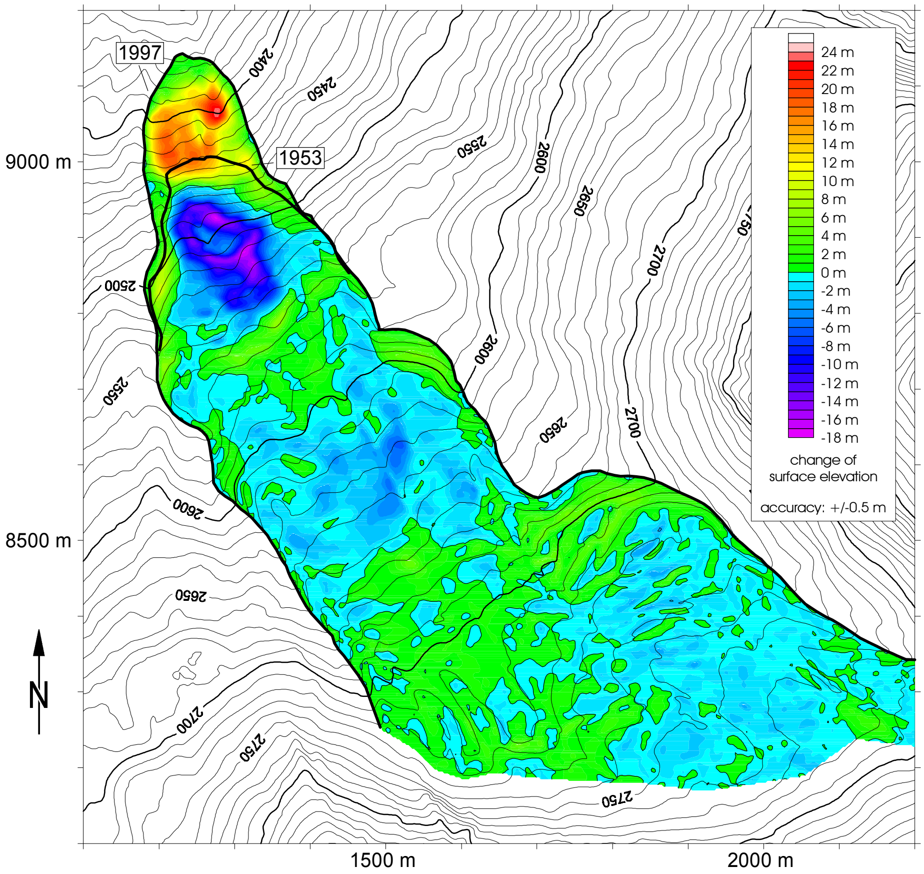

Figure 10: Change of surface elevation at Outer Hochebenkar rock glacier for the time period 1953-1997.