# Photogrammetry for Early Recognition of High Mountain Hazards: New Techniques and Applications

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# Photogrammetry for Early Recognition of High Mountain Hazards: New Techniques and Applications

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**Abstract.** Steady mass shift as well as catastrophic mass-movement events are the natural expression of the dynamics of high-mountain mass-transport systems, causing a variety of natural hazards. Computer-aided aerial photogrammetry, especially a newly developed technique for determining surface velocity fields in 3D, offers a wide range of possibilities to map disasters and hazard potentials, to monitor medium- and long-term development of dangerous situations and to provide area-wide boundary conditions for 2D- and 3D-modelling of kinetic and dynamic processes. Three pilot studies in the Swiss Alps illustrate the potential of high-precision and multi-temporal image analysis for early recognition of glacial and periglacial hazards: (1) The increasing risk of lake-outbursts and related debris-flows (up to several $10^5 m^3$) was detected by a 25-year monitoring series of glacier geometry, ice flow, permafrost creep and changes of glacier-lakes. (2) Analyzing permafrost creep above a potential starting zone of debris flows allowed for assessing mass transport and accumulation rates in this zone. (3) The kinetic processes and the extent of a rock slide ($\sim 10^6 - 10^7 m^3$), induced by a marked retreat of a glacier tongue and the related stress-relief at the valley flanks could be determined.

## 1 Introduction

Steady mass shift as well as catastrophic mass-movement events are the natural expression of the dynamic equilibria of high-mountain mass-transport systems. These equilibria are markedly influenced by ice occurrences which make high mountains especially sensitive to climate impacts. A variety of glacial and periglacial natural hazards are the consequence affecting many human activities in high mountain regions (Haeberli et al., 1989; Haeberli, 1992): (1) Glacier floods represent the highest and most far reaching glacial risk occuring in most glacierized mountain areas of the world. The related water outbursts from intra-, supra- and sub-glacial water reservoirs as well as from ice-marginal lakes. Characteristically, such reservoirs often develop slowly and can be monitored remotely (Haeberli, 1983; Huggel, 1998). (2) Ice avalanches occur in most glazierized and steep mountain ranges, but due to their smaller run-out distances they endanger only densely populated mountain areas, e.g. the Alps (Haeberli et al., 1989). (3) Glacier length variations themselves are able to directly affect human infrastructure, but represent a more important risk when causing other glacial and periglacial hazards (cf. topic 6). (4) Creeping and thawing frozen debris, often found as permafrost, is a significant factor of the disposition of periglacial debris flows and related slope instabilities (Zimmermann and Haeberli, 1992). (5) Not only instabilities of debris slopes but also instabilities of rock slopes can be connected to glacial and permafrost processes. Glacier retreats, for instance, affect the stability of valley flanks, or varying ice content affects the rock hydrology (Haeberli et al., 1997). (6) However, very important glacial and peri-glacial risks consist in combinations of the above and other hazard types: The development of glacier lakes, for instance, is often connected to fluctuations of glaciers which dam such lakes. Lake out-burst in turn can be triggered by ice avalanches. Glacier retreats or advances over terrain ridges often enhance the risk of ice breaking off. Ice avalanches are able to trigger snow avalanches of extraordinary high volume. Retreating glaciers destabilise steep valley flanks and uncover large debris reservoirs amplifying the potential of debris flows and rock instabilities. Such system interactions clearly show the urgent need of integral hazard assessments accounting for a variety of relevant processes in high mountains.

Owing to their contactless and often area-wide object coverage, remote sensing techniques represent especially suitable tools for integral hazard mapping and monitoring in high mountains which are typically difficult to access. The present contribution will focus on photogrammetric techniques and their application for early recognition of high mountain hazards. After briefly describing the used photogrammetric techniques, the potential as well as the limitations of these tech-

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niques for hazard recognition is shown by means of three case studies. Conclusions and perspectives terminate the contribution.

## 2 Techniques

To measure 2D-objects (e.g. lakes) and their changes photogrammetric standard techniques are available which will not be discussed here (3D point determination, orthoprojection). A common format to geometrically describe the terrain surface (often called 2.5D) is a digital terrain model (DTM) consisting of elevation information of the terrain surface. By analytical photogrammetry DTMs can be collected from stereo-photography, allowing for high elevation accuracy and operator interaction, but hardly for fast, dense and (semi-) automatic data acquisition (Kääb, 1996). On the other hand, automatic digital DTM generation by digital photogrammetric stations produces less time consuming and more dense height information from multiple photos, resulting in somewhat lower reliability and special difficulties in rough terrain (shadows, terrain distortion, etc.) (Grün and Baltsavias, 1987; Baltsavias et al., 1996). Changes in surface elevation (1D-variation) are usually calculated as differences between multitemporal DTMs.

Whereas photogrammetric standard techniques can be used for the above tasks, special approaches are needed for determining surface displacements (2D-movements). Two different methods have been used for the following case studies: (1) Simultaneously comparing two photos taken from different places (stereo-base) and at different times (temporal base), horizontal displacements on the surface can be measured. This procedure can be performed using a computer-based photogrammetric compilation system, a so-called analytical stereo-plotter (Kääb et al., 1997; Knizhnikov et al., 1998; Kääb and Funk, 2000). (2) For a digital approach two (or more) high-precision digital orthoimages of the observed object are generated for every time of photography. For any location selected manually or automatically in one orthophoto the corresponding point in the other orthophoto is measured by block matching techniques (area-based digital correlation). Thus, the horizontal terrain displacements directly result (Kaufmann, 1998; Ladstädter, 1999; Vollmer, 2000). All the mentioned techniques can be applied to terrestrial photography, but aero-photogrammetry typically facilitates the data acquisition.

The case studies presented here are based on aerial photos taken by the Swiss Federal Office of Cadastral Surveys and the Swiss Federal Office of Topography. Whereas the study on the Schafberg rock glacier (Sect. 3.2) is based on aerial photographs commonly used for map revision (scale $\sim 1:23,000$), special deep-flown photography with scales of $\sim 1:6000-1:14000$ was used for the other studies. Due to the high optical contrast on the investigated rock glaciers and slopes all photogrammetric measurements could be performed at regular grid points, except a few measurements on debris-free ice of Gruben glacier (Sect. 3.1) (Kääb, 1996). Therefore, nearly no interpolations were used to obtain the depicted results. As derived from geodetical control measurements and independent photogrammetric measurements (Kääb, 1996) an accuracy of up to 0.02% of flying height above ground can be expected for elevation measurements, and an accuracy of up to 30 $\mu m$ times the image scale for the displacement measurements. Such, both the thickness changes and displacements have an error between $\sim \pm 0.2m$ (for scale $1:6000$) and $\pm 0.8m$ (for scale $1:23,000$). These values have to be divided by the time interval between the photo flights in order to obtain the accuracy of the presented velocities.

## 3 Case studies

### 3.1 Glacier lake outbursts

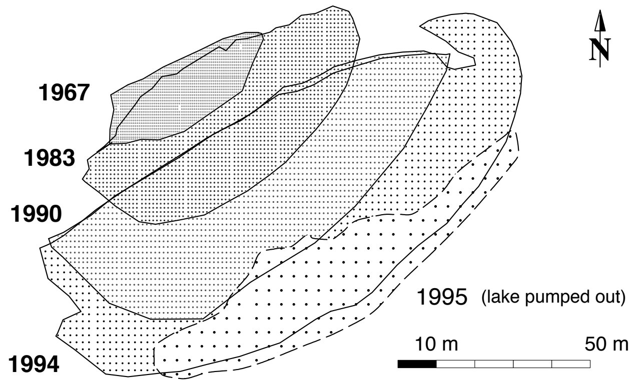


**Fig. 1.** Gruben area: Planimetric representation of the margin of a lake in selected years of the time period 1967-1995. The lake increasingly melted the surrounding permafrost and dead glacier ice.

In 1968 and 1970 glacier lake outbursts from the Gruben area (Valais, Switzerland) caused large floods and debris flows of up to $400,000m^3$ volume and $15m^3s^{-1}$ run-off leading to heavy damages in the village Saas Balen (Lichtenhahn, 1979). Since then a variety of investigations and a photogrammetric monitoring program started in order to early recognize further lake outbursts (Kääb and Haeberli, 1996; Kääb et al., 1996; Haeberli et al., 1999). A lake (no.5) on the Gruben rock glacier (i.e. creeping mountain permafrost) was thereby detected to increasingly enlarge by thermal water convection processes melting surrounding ice occurrences (Fig.1) (Kääb et al., 1996). Such process of lake evolution is called thermokarst. By photogrammetrically monitoring surface displacements (Fig.2) and elevation changes of the rock glacier (Fig.3) the sub-surface extent of dead-ice remains inside the permafrost body could be assessed allowing for an estimation of the potential future growth and outburst of the thermokarst lake. High subsidence rates (Fig.3), high creep velocities and the variations in creep directions (Fig.2) marked an especially high ice content (i.e. dead ice) in the rock glacier body (Kääb et al., 1997). The thermokarst lake had a volume of about

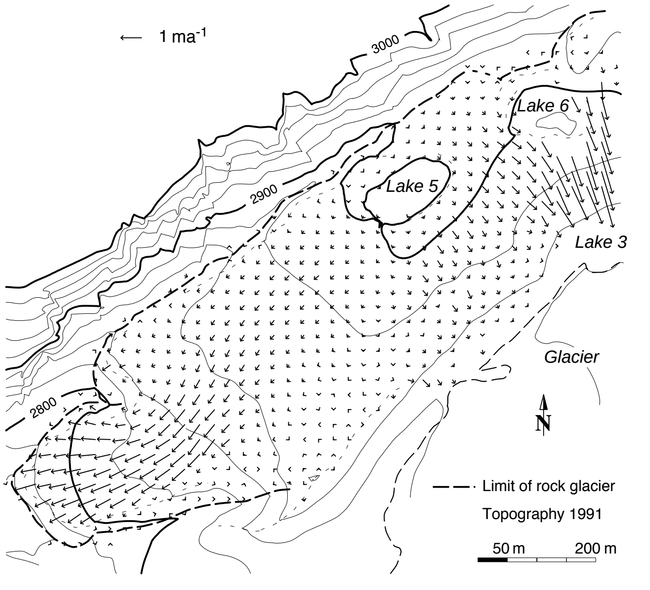


**Fig. 2.** Gruben area: Surface displacements on creeping mountain permafrost (a so-called rock glacier) during 1970-1995, indicating different creep regimes of the rock glacier.

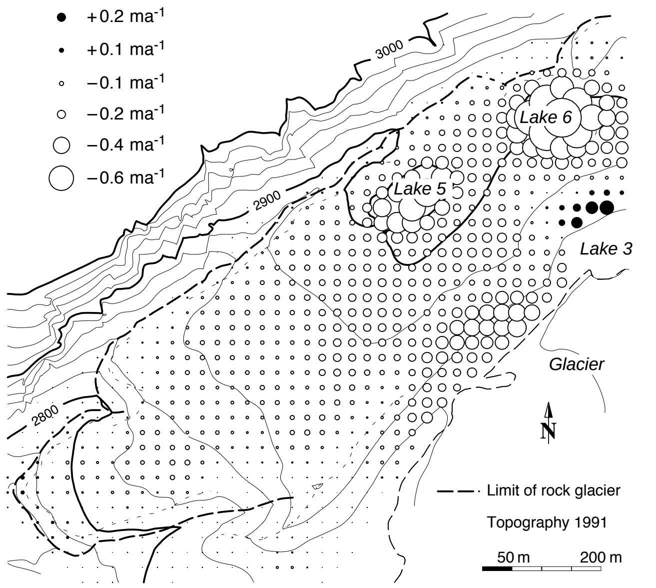


**Fig. 3.** Gruben area: Changes in surface elevation on the rock glacier during 1970-1995, indicating different subsidence rates, and, together with the velocity field (Fig.2), allowing to estimate dead-ice occurrences influencing the development of the thermokarst lake.

$50,000 m^3$ in 1994, and was expected to possibly burst out around the year 2000 having a volume of about $100,000 m^3$. Due to that risk the lake was pumped out and subsequently drained by an open ditch (Kääb et al., 1996; Haeberli et al., 1999).

A second, ice-marginal lake (no.3), which was the source of the 1968- and 1970- floods, was levelled by a pipe in the 1970s to prevent rising water level and subsequent outburst by uplift (swimming up) of the ice dam. While this measure was successful, the ice dam increasingly lowered in the 1980s and 1990s by glacier retreat and approached its swim equilibrium. This fact could be clearly seen from repeated photogrammetric DTMs indicating the shrinkage of the ice dam (Fig.4) and from photogrammetric ice velocity measurements indicating decreasing ice supply (Fig.5). In 1996, the water level of the ice-marginal lake was, therefore, lowered by an open ditch and the lake mostly filled up by the excavated debris (Kääb et al., 1996; Haeberli et al., 1999).

### 3.2 Debris flows starting from creeping permafrost

Periglacial debris flows in high mountains originate to a significant degree from zones with known or assumed permafrost involved (Zimmermann and Haeberli, 1992; Zimmermann et al., 1997). Slope destabilization and changing hydrology by thawing ice content may play a major role in view of short and medium terms. Debris supply by creeping permafrost into potential starting zones or steep channels, both enlarging risk and volume of debris flows, affects the debris flow disposition mainly in long terms. The potential debris supply by a typical rock glacier ranges in the order of up to $10^2 m^3$ per year ($a^{-1}$).

At Schafberg/Pontresina (Grisons, Swiss Alps) rock glaciers are photogrammetrically monitored in order to estimate the order of magnitude of debris supply into a potential debris flow starting-zone (Kääb, 1996). The low surface velocities of a few $cma^{-1}$ (Fig.6) indicate debris supply of only some $m^3a^{-1}$ distributed over a crosssectional area of approx. $1000m^2$ (Hoelzle et al., 1998). Thus, permafrost creep has only a long-term effect on the debris flow disposition at Schafberg, whereas the major problem consists in the permafrost temperatures being close to the melting point as observed in two boreholes (Hoelzle et al., 1998). On the other hand, the example of Suvretta rock glacier (Grisons, Swiss Alps) clearly shows the effect of creep on debris reservoirs.

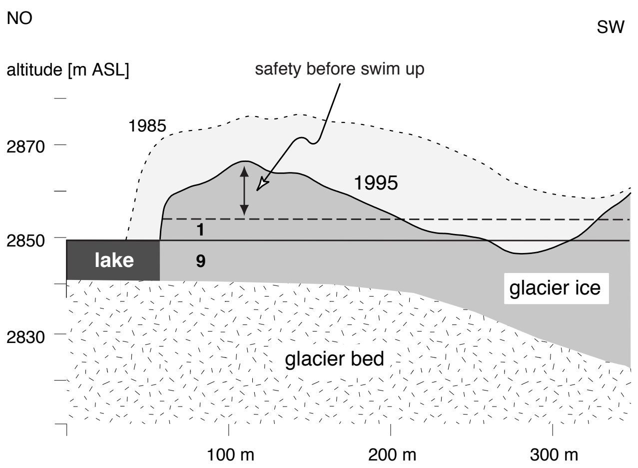


**Fig. 4.** Gruben area: Cross section of the glacier dammed lake in 1985 and 1995 showing a strong melting of the ice dam. According to the iceberg-model the damming ice is able to swim up (and cause a lake outburst) when the ratio between ice thickness above lake level and the one below it reaches 1:9. The ice thickness above this swimming-equilibrium can be considered as according safety.

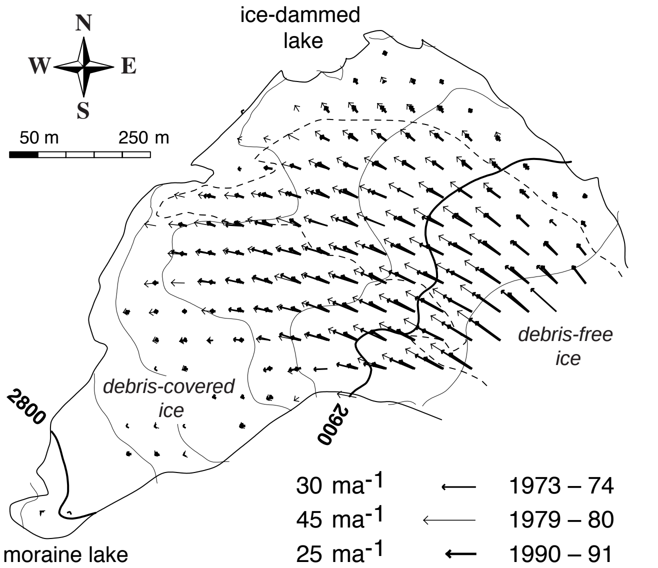


**Fig. 5.** Gruben area: Annual velocity fields of the glacier tongue of 1973/74, 1979/80 and 1991/92. The ice velocity (and, thus, the ice supply towards the ice-dammed lake) dropped drastically during this time enhancing the melt down of the ice dam.

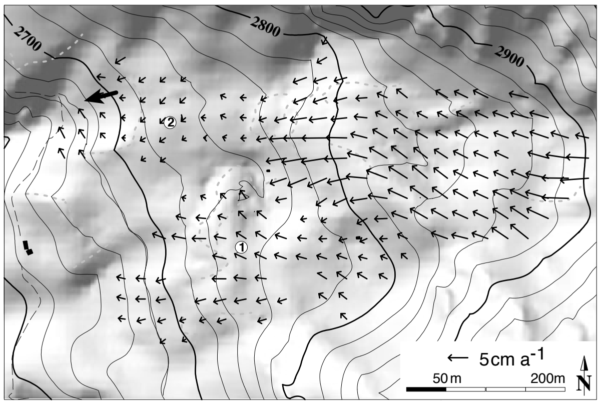


**Fig. 6.** Schafberg/Pontresina: Horizontal surface displacements 1971-1991 on the rock glacier system indicating only low debris supply into the potential debris flow starting zone to the North-West (bold arrow). Numbers 1 and 2 mark permafrost boreholes.

Just above two starting zones of debris flows the horizontal surface velocities reach up to $1.50ma^{-1}$ (Fig.7). The corresponding debris supply of several $10^2m^3a^{-1}$ can be photogrammetrically observed in surface uplift sticking out of the general subsidence in this part of the rock glacier (Fig.8). However, at this time debris flows from Suvretta rock glacier seem not to endanger settlements or infrastructure.

### 3.3 Periglacial rock slides

Since the end of the Little Ice Age (approx. 1850) the tongue of Aletsch glacier, the largest Alpine glacier (Valais, Swiss Alps), retreated by ca. $2km$. In the same time, the ice at the tongue lost up to $300m$ thickness as determined by terrestrial and, since the 1950s, by photogrammetric measure-

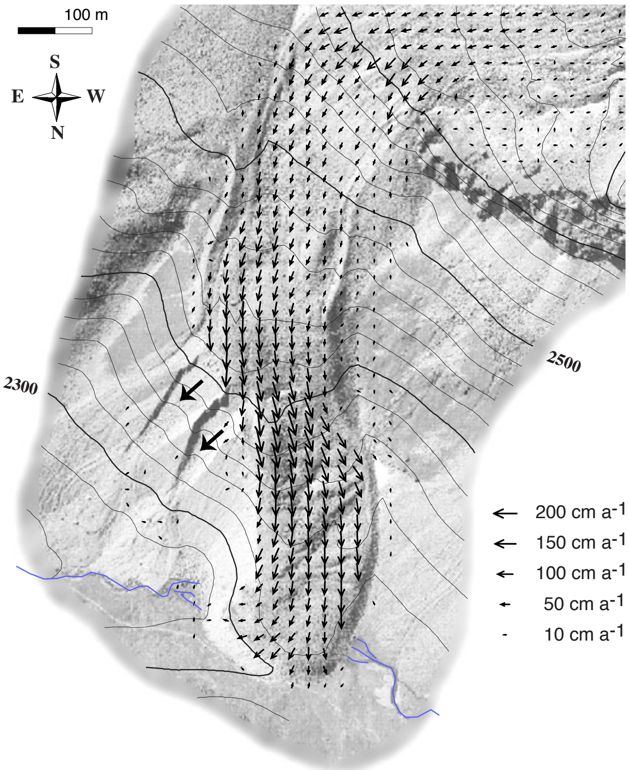


**Fig. 7.** Suvretta rock glacier: Horizontal surface displacements 1992-1997. High velocities in the middle part provide debris supply into the starting zone of two debris flows to the East (bold arrows).

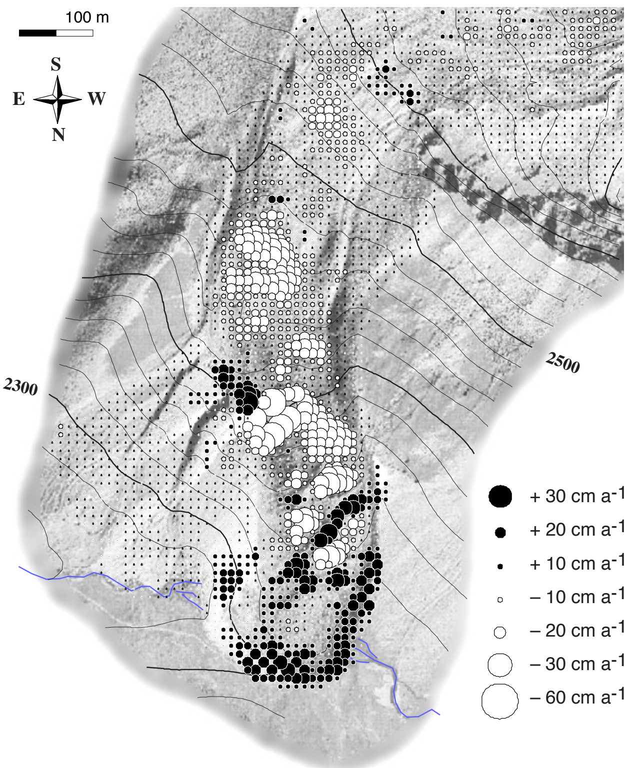


**Fig. 8.** Suvretta rock glacier: Changes in surface elevation 1992-1997 indicate the refilling of debris reservoirs emptied by debris flows to the East.

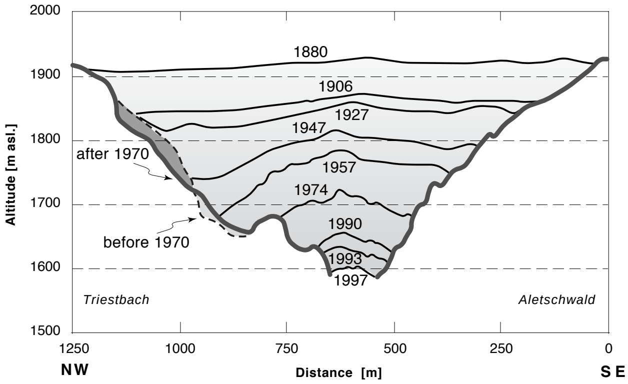


**Fig. 9.** Aletsch glacier: Cross sections of the glacier tongue in selected years between 1880 and 1997. The glacier retreat caused a rock slide to the Nort-West during the late 1960s and early 1970s. (After HADES, 1999).

ments (Fig.9).

This marked retreat caused relief and destabilization of the according valley flanks which, together with a steep rock cleavage parallel to the glacier, resulted in a small rock slide at the end of the 1960s and beginning 1970s (Fig.9) (VAW, 1982) and an ongoing larger one of about $10^{6} - 10^{7} m^{3}$ volume. Photogrammetric analyses showed horizontal surface displacements of up to $2m$ between 1976 and 1995, and elevation changes of the same order of magnitude occurring as surface lowering in the upper part and surface heave at the lower part (Fig 10). The combination of the horizontal velocity field with the vertical one (i.e. 3D vectors on the surface) indicates a vertical longitudinal rotation as typical for rock slides. Due to the low changing rates photogrammetrical monitoring is not suitable for higher temporal resolution. A geodetical surveying network was therefore started in 1997 to obtain more detailed deformation measurements. While the rock mass changed hardly between 1997 and 1998, increasing velocities of $10 cm a^{-1}$ and more could be observed between autumn 1998 and spring 1999. Sudden destabilization of large rock masses of the rock slide could potentially endanger a hiking path passing the slide area or even dam up the river sourcing from the Aletsch glacier tongue.

## 4 Conclusions and perspectives

Analytical and digital techniques of photogrammetry are highly suitable for monitoring geometric changes in high mountains such as terrain heave and settlement or terrain displacements. The possibility to contactless obtain area-wide information of objects with high geometrical accuracy predestines this method for early recognition of high mountain hazards. Compared to the expenditure needed to achieve such results by terrestrial techniques, photogrammetry is clearly cost-efficient. Nevertheless, some limitations exist especially for high mountain areas: snow cover diminishes the surface contrast needed for stereo-photogrammetry; steep terrain leads to high distortions and information reduction in the image; displacement measurements require corresponding targets at all times of photography which is sometimes problematic due to terrain destruction. Photogrammetry has the potential to determine surface information, whereas it has no access to depth information which has to be obtained from geophysical approaches or in combination with physical or numerical models. Photogrammetric monitoring allows for early recognition of hazards, but will only in rare cases be appropriate for concrete forecasting of an event. Air-borne photogrammetric sensors are able to track only comparable slow movements.

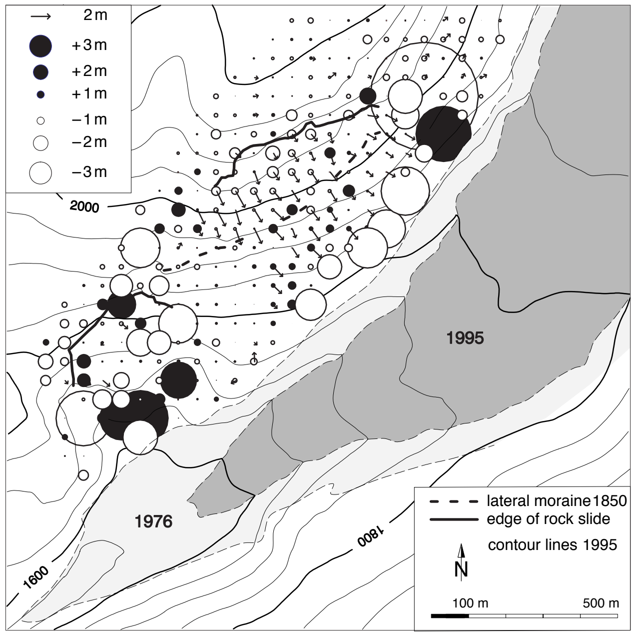


**Fig. 10.** Aletsch glacier: Horizontal and vertical displacements 1976-1995 of a large rock slide near the glacier tongue. Surface subsidence in the upper part and uplift in the lower part indicate, together with the horizontal displacements, a vertical rotation. The rock slide shown in Fig.9 is situated to the South-West of the figure. Large elevation changes at the ice margin are due to glacier retreat and moraine erosion.

Digital imaging sensors combined with photogrammetric close range techniques, however, can be used to monitor even very fast processes. New upcoming remote sensing techniques such as laserscanning or space- and air-borne synthetic aperture radar have the potential to partially overcome the restrictions of photogrammetry. However, the most promising approach will be a combination of these techniques integrating their specific advantages. The potential of digital (photogrammetric) techniques for accelerating and simplifying data acquisition will allow for applications covering larger areas and facilitate integral hazard assessments.

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## References

Baltsavias, E. P., Li, H., Stefanidis, A. and Sinning, M., Automatic DSMs by digital photogrammetry, *Surveying World*, *4(2)*, 18–21, 1996.

Grün, A., and Baltsavias, E., High precision image matching for digital terrain model generation, *Photogrammetria*, *42*, 97–112, 1987.

HADES (Hydrological Atlas of Switzerland), *Map 3.7*, Wabern-Bern, 1999.

Haeberli, W., Frequency and characteristics of glacier floods in the Swiss Alps, *Annals of Glaciology*, *4*, 85–90, 1983.

Haeberli, W., Construction, Environmental Problems and Natural Hazards in Periglacial Mountain Belts, *Permafrost and Periglacial Processes*, *3*, 111–124, 1992.

Haeberli, W., Alean, J.-C., Müller, P., and Funk, M., Assessing risks from glacier hazards in high mountain regions: some experiences in the Swiss Alps, *Annals of Glaciology*, *13*, 96–102, 1989.

Haeberli, W., Wegmann, M., and Vonder Mühll, D., Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps, *Eclogae Geologicae Helvetica*, *90*, 407–414, 1997.

Haeberli, W., Kääb, A., Hoelzle, M., Bösch, H., Funk, M., Vonder Mühll, D. und Keller, F., *Eisschwund und Naturkatastrophen im Hochgebirge*, Schlussbericht NFP31, vdf Hochschulverlag an der ETH Zürich, Zürich, 1999.

Hoelzle, M., Wagner, S., Kääb, A., and Vonder Mühll, D., Surface movement and internal deformation of ice-rock mixtures within rock glaciers in the Upper Engadin, Switzerland, *Proc. of 7th International Conference on Permafrost, Yellowknife, Canada*, 465–472, 1998.

Huggel, C., *Periglaziale Seen im Luft- und Satellitenbild*, Diploma thesis, University of Zurich, 1998.

Kääb, A., *Photogrammetrische Analyse zur Früherkennung gletscher- und permafrostbedinger Naturgefahren im Hochgebirge*, Mitteilungen der VAW / ETH Zürich, *145*, Zürich, 1996.

Kääb, A., and Funk, M., Modelling mass balance using photogrammetric and geophysical data. A pilot study at Gries glacier, Swiss Alps, *Journal of Glaciology*, *45*, in press, 2000.

Kääb, A., and Haeberli, W., Früherkennung und Analyse glazialer Naturgefahren im Gebiet Gruben, Wallis, Schweizer Alpen, *Tagungspublikation Interpraevent 1996*, *4*, 113–122, 1996.

Kääb, A., Haeberli, W., and Teysseire, P., Entwicklung und Sanierung eines Thermokarstsees am Gruben-Blockgletscher (Wallis), *Berichte und Forschungen, Department of Geography, University of Freiburg / CH*, *8*, 145–153, 1996.

Kääb, A., Haeberli, W., and Gudmundsson, G.H., Analyzing the creep of mountain permafrost using high precision aerial photogrammetry: 25 years of monitoring Gruben rock glacier, *Permafrost and Periglacial Processes*, *8*, 409–426, 1997.

Kaufmann, V., Deformation analysis of the Doesen rock glacier (Austria), *Proc. of 7th International Conference on Permafrost, Yellowknife, Canada*, 551–556, 1998.

Knizhnikov, Y.F., Gelman, R.N., Osipova, G.B., and Tsvetkov, D.G., Aerophotogrammetric study of ice movement in surging glaciers, *Zeitschrift für Gletscherkunde*, *34*, 69–84, 1998.

Ladstädter, R., *Automatisierte Messung von Geländemodellen und Fliessvektoren aus digitalen, multitemporalen Orthophotos: ein neuer Ansatz für das Blockgletscher-Monitoring*, Diploma thesis, Technical University of Graz, 1999.

Lichtenhahn, C., Die Verbauung des Fellbachs in der Gemeinde Saas Balen (Wallis), *Mitteilungen der VAW / ETH Zürich*, *41*, 169–176, 1979.

VAW (Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich), *Die Gletscher der Schweizer Alpen 1973/74 und 1974/75*, *95/96*, Glaziologische Kommission der SANW , Zürich, 1982.

Vollmer, M., *Kriechender alpiner Permafrost: Digitale photogrammetrische Bewegungsmessung*, Diploma thesis, University of Zurich, 2000.

Zimmermann, M., and Haeberli, W., Climatic change and debris flow activity in high mountain areas: a case study in the Swiss Alps, *Catena Suppl.*, *22*, 59–72, 1992.

Zimmermann, M., Mani, P., and Gamma, P., *Murganggefahr und Klimaänderungen: ein GIS-basierter Ansatz*, Schlussbericht NFP31, vdf Hochschulverlag an der ETH Zürich, Zürich, 1997.