GLACIER- AND PERMAFROST-RELATED HAZARDS IN HIGH MOUNTAINS: INTEGRATIVE ASSESSMENT IN THE SWISS ALPS BASED ON REMOTE SENSING AND GEO-INFORMATION SYSTEMS

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Abstract

Especially due to their ability to provide information touch-less and with complete spatial coverage air- and satellite-borne remote sensing technologies have a large and still growing importance for analyzing high mountain hazards. Periglacial lakes and their outburst risk can be detected using aerial and satellite imagery as well as related changes be monitored. In a similar way, it is possible to observe glacier fluctuations endangering infrastructure and potentially causing ice avalanches. Early recognition of ice break-offs themselves is difficult by remote sensing, though it contributes to the assessment of hazard disposition. High precision photogrammetry allows for measuring slow creep and slide processes. In such a way, slope instabilities in the periglacial environment and potential starting zones of debris flows can be monitored. A major step towards improving the accuracy and reliability of remote sensing based hazard assessments consists in the fusion of spectral and radiometric data with digital elevation models inside geo-information systems and subsequent application of knowledge-based analysis techniques for such multi-sensor and multi-dimensional data. A downscaling strategy from low resolution imagery and models over large areas towards detailed high resolution analyses of hazard zones detected from previous strategy steps is presently applied in the Swiss Alps.

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 occurring 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 glacierized 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 for 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 periglacial hazards 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 outburst 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 destabilize 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.

Since the European Alps are among the most densely populated high mountain areas in the world, Switzerland is particularly affected by glacial and periglacial hazards but, on the other hand, also has an extensive and well-recognized tradition in investigating such processes. A number of specific monitoring and modelling studies related to single hazardous situations have been performed, mainly based on recent catastrophes or imminent hazard situations (e.g. Kääb, 1996; Margreth and Funk, 1998). Especially recent technologies of remote sensing (RS) and geo-information systems (GIS) have the potential to accomplish the requirements resulting from the above outlined complex system interactions and accelerated trends in environmental change.

In the following we present remote sensing- and GIS-based approaches for high mountain hazard assessment concerning glacier floods, ice falls, glacier fluctuations and slope instabilities. Conclusions and perspectives close the contribution.

Glacier floods

Generally, glacier floods represent the highest and most far-reaching glacial risk, i.e., the risk with the highest potential of disaster and damages (up to 10^2 mill. m^3 volume break-out and up to 10^4 m^3/s runoff). Glacier floods occur in most glacierized mountains of the world (Glacier Lake Outburst Floods, GLOF). In Switzerland they represent a highly relevant hazard potential as a number of specific detailed studies show (e.g. Haeberli, 1983; Kääb and Haeberli, 1996). Glacier floods are triggered by the outburst of water reservoirs in, on, underneath and at the margin of glaciers. Most reservoir types develop slowly and can be identified at the surface, a precondition which favours the application of remote sensing techniques for monitoring glacial and periglacial lakes. Floods from ice-dammed lakes and pro-glacial morainic lakes in particular represent a recurring and severe danger in many glacierized areas. Thus it is that various studies have focused on glacier lakes covering many mountain ranges of the world (e.g., Lliboutry et al., 1977; Yongjian and Jingshi, 1992; Hanisch et al., 1996; Walder and Costa, 1996; Clague and Evans, 1997; Yamada, 1998; Haeberli et al., 1999).

For large-scale detection of glacial and periglacial lakes high-resolution satellite-borne remote sensing offers a large potential, especially in view of cost and time efficient data acquisition. Automatic detection can be achieved by specific algorithms allowing for the separation of the lakes from their environment (Fig. 1). Such algorithms take advantage of different multispectral bands (channels) of a single sensor that measure the reflection of the surface in various ranges of the electromagnetic spectrum. On the basis of Landsat Thematic Mapper (TM) images the ‘Normalized Difference Water Index’ (NDWI) was developed (Huggel, 1998), basically related to the widely used ‘Normalized Difference Vegetation Index’ (NDVI; e.g. Olsson, 1995). The following spectral bands of Landsat TM were used: NDWI=((TM4–TM1)/(TM4+TM1)). The first band (TM1) was chosen due to its characteristic maximum reflection of water. To obtain a maximum difference a further band in the infrared range of the spectrum had to be used since the reflection of water strongly declines towards the infrared. TM4 was preferred because its capability to distinguish water from ice and snow, which is much less the case with the other infrared bands (TM5, TM7).

Thus, a basis for estimating the hazard potential of glacial lakes can be achieved. In a next step, following a downscaling strategy, previously detected potential hazard prones were more precisely analyzed integrating data from sensors with higher resolution such as SPOT-Pan (10 x 10 m ground resolution) or IRS-Pan (5.8 x 5.8 m ground resolution). Special algorithms were applied to fuse remote sensing data from different sensors, for instance multi-spectral (Landsat-TM) with high resolution panchromatic images (SPOT-Pan) (Huggel, 1998; Fig. 2). In fact, multi-sensor datafusion techniques are increasingly under development to overcome ground resolution deficiencies of multi-spectral remote sensing data on one hand and to enhance the information content of high resolution (panchromatic) images on the other hand (Pohl and van Genderen, 1998; Hellwich, 1999). However, for a concluding hazard assessment of glacial lakes traditional field methods (Kääb et al., 1996) often must be included as well and can not be completely replaced by satellite-based techniques. Still, the integration of different types of remote sensing data allows largely for the evaluation of the hazard potential of glacial lakes time- and cost efficiently and especially in remote areas with difficult ground access.

Ice falls

Ice breaking off from steep glaciers causes ice avalanches or, in case of breaking into a lake, dangerous flood waves themselves potentially leading to a lake outburst. Compared to lake outbursts and glacier length variations the possibilities to early recognize ice avalanches by means of remote sensing are limited. Reasons are snow cover and shadows (i.e. low optical contrast), difficult topography and the often small size of the object of interest. Because ice falls generally tend to repetition, comparison of glacier geometry and crevasse evolution with earlier stages can help to detect evolving risks (Fig. 3). Also, the estimation of volumes to potentially break off might be possible in some cases. Monitoring the velocities of frontal ice lamellas and their typical hyperbolic acceleration before break off, however, will succeed only in rare cases (Fig. 4). Whilst space-borne remote sensing is not suitable for early recognition of ice breaking off, satellite-based technology for ice classification (see below section on glacier length variations) and GIS-analyses of digital elevation models allow for assessing the distribution of steep glaciers and related hazard potentials. If once recognized as potentially dangerous selected steep glaciers can be monitored by high resolution imagery as shown above. In such a way, space- and air-borne remote sensing methods and GIS-modelling complement each other towards a downscaling strategy for detecting ice avalanche risks.

Glacier length variations

Glacier retreats or advances are able to endanger infrastructure and – indirectly – also to cause glacier floods and ice falls. Therefore, the scenarios of future glacier fluctuations have to be a basis of every long-term risk analysis in glacierized areas (Haeberli et al., 1989, 1999). Whilst the direct observation of unstable glacier length changes (surges, calving) by remote sensing is often limited due to the low temporal resolution of related imagery, preceding medium- or long-term evolution of glacier geometry often hints to the near-future development of a glacier. Related geometrical information is best acquired by photogrammetric analyses (Kääb, 1996; Kääb and Haeberli, 1996; Kääb and Funk, 1999). Such procedures are presently well established in many glacier hazard studies in the world. However, for small-scale investigations on large areas, for regions with no suitable aerial photography available or for lower accuracy requirements, also satellite-based remote sensing is able to provide valuable information (e.g. Buchroithner et al., 1982; Espizua and Bengochea, 1990).

Using the different spectral properties of ice and snow in the single channels of multi-spectral imagery glacier edges can be extracted automatically (Fig. 5; Paul, 1995). In such a way, glacier distribution over large areas can be mapped, or glacier fluctuations in hazard zones be monitored from repeated imagery. The spatial resolution of typical satellite imagery, however, limits tracking of small glacier fluctuations. Incorrect classification of debris-covered ice represents a further problem in automatic multi-spectral glacier mapping and monitoring. The fusion of satellite imagery with digital elevation models inside a GIS and subsequent application of knowledge-based classification algorithms as presently used for compilation of the Swiss Glacier Inventory 2000, markedly improves the glacier analysis.

Slope instabilities

Glacier retreats and subsequent relief of valley flanks are able to cause periglacial slope instabilities such as rock slides. Such processes are common in many glacierized mountain ranges in the world. Besides their direct impacts on infrastructure and installations, rock slides are able to dam rivers, and to trigger ice avalanches and lake outbursts. Often, the low deformation rates of slope instabilities can only be detected by high resolution air-borne remote sensing (Fig. 6) or interferometric synthetic aperture radar (InSAR; Rott and Siegel, 1999). Space-borne optical remote sensing can be used for detection of potential unstable zones (Mantovani et al., 1996), a valuable prerequisite for the above detailed high resolution studies.

In mountain ranges under permafrost conditions debris is able to form frozen streams – so-called rock glaciers – and creep with rates of decimeters or meters per year. Such permafrost streams transport material in the range of 10^4 m^3 per century, sometimes into debris flow channels or potential starting zones of debris flows (Kääb, 1996; Hoelzle et al., 1998). By special techniques of multitemporal image analysis (Kääb et al., 1997) it is possible to measure creep rates of rock glaciers (and other instabilities) and, thus, to estimate the material transport and related debris flow and rock fall hazards (Fig. 7).

Conclusions and perspectives

Due its capability to record data without being in touch with the object remote sensing is especially suited for applications in high mountain environments where access is often difficult, limited or even inhibited. In particular, analytical and digital photogrammetry provides powerful possibilities for hazard monitoring and assessment, i.e. measuring geometric changes in high mountains such as terrain heave and settlement or terrain displacement. Comparably slow movements can be tracked by air-borne photogrammetric sensors. For faster and even very fast processes terrestrial digital imaging sensors combined with photogrammetric close range techniques can be used.

Space-borne optical sensors have the potential of monitoring larger areas and are well suited for first hazard assessments. Many of those sensors record data in different bands of the electromagnetic spectrum which is important for the discrimination of hazard-relevant objects (e.g. water, vegetation, debris, etc.). Recently, a few high to very high resolution optical sensors have been launched successfully. Apart from the ASTER sensor (onboard the Terra satellite) currently in application for global glacier monitoring (GLIMS), particularly the IKONOS sensor opens new perspectives in commercial space-borne remote sensing (1 m ground resolution and close to real-time data supply).

Optical remote sensing provides excellent surface information, but has no access to depth information which has to be obtained from geophysical approaches or in combination with physical or numerical models. Furthermore, the application of optical remote sensing is limited in unfavorable meteorological conditions (cloud cover, etc.). Space- and air-borne Synthetic Aperture Radar (SAR) as well as new and upcoming remote sensing techniques such as stereo-scanning or laser-scanning have the capabilities to overcome present restrictions.

Terrain data including digital elevation models (DEM) is generally one of the key elements in linking remote sensing data to Geographic Information Systems (GIS). The combination of remote sensing technologies and GIS is increasingly able to fulfill the requirements of complex interactions in high mountain environments. In Switzerland, a downscaling strategy both of interconnected observational and modelling approaches is developed to integratively assess hazard potentials related to glaciers and permafrost: Mountain lakes and glaciers as well as their changes in time are automatically extracted for large areas from satellite imagery using multi-spectral algorithms and their hazard potential estimated. Potentially dangerous situations are monitored by high-precision techniques of digital photogrammetry providing DEMs, mass changes and surface velocities of ice and slope instabilities. Such hazard assessment is cross-linked to GIS-modelling of different scales: Glacier fluctuations, permafrost distribution and maximum run-out distances for ice avalanches and debris-flows are simulated with GIS-techniques using e.g. RS-derived DEM. Vice-versa, the modelling results help identifying hazard potentials for further precise RS-based monitoring.

Whilst the site accessibility and wealth of reference data predestine the European Alps for such method development and testing, adaptation and application in remote regions which are much more affected by glacier and permafrost hazards (e.g. parts of the Andes and Himalayas) is urgently needed and not possible without the collaboration with local experts.

Acknowledgements

The presented projects have been enabled by the Swiss National Science Foundation within the research programs and projects NFP31, NF21-54073.98 and NF21-59045.99. The photogrammetric

analyses are based on aerial photography taken by the Swiss Federal Office of Cadastral Surveys (R. Hübscher, H. Gautschi and D. Lüscher).

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Figure 1: High mountain lakes in the Simplon area, Valais, Swiss Alps. The water areas (marked as ellipses) have been extracted automatically from multi-spectral satellite imagery using the normalized differences method. Remaining classification problems in shadowy zones can be solved by terrain correction based on a digital elevation model.

Figure 2: The lake ‘Lago delle Locce’ in the Monte Rosa area as depicted on a SPOT-PAN image (arrow and ellipse to the bottom). The damming moraine dam (upper arrow) and a lake outburst breach (upper ellipse) can be distinguished by the high reflexions.

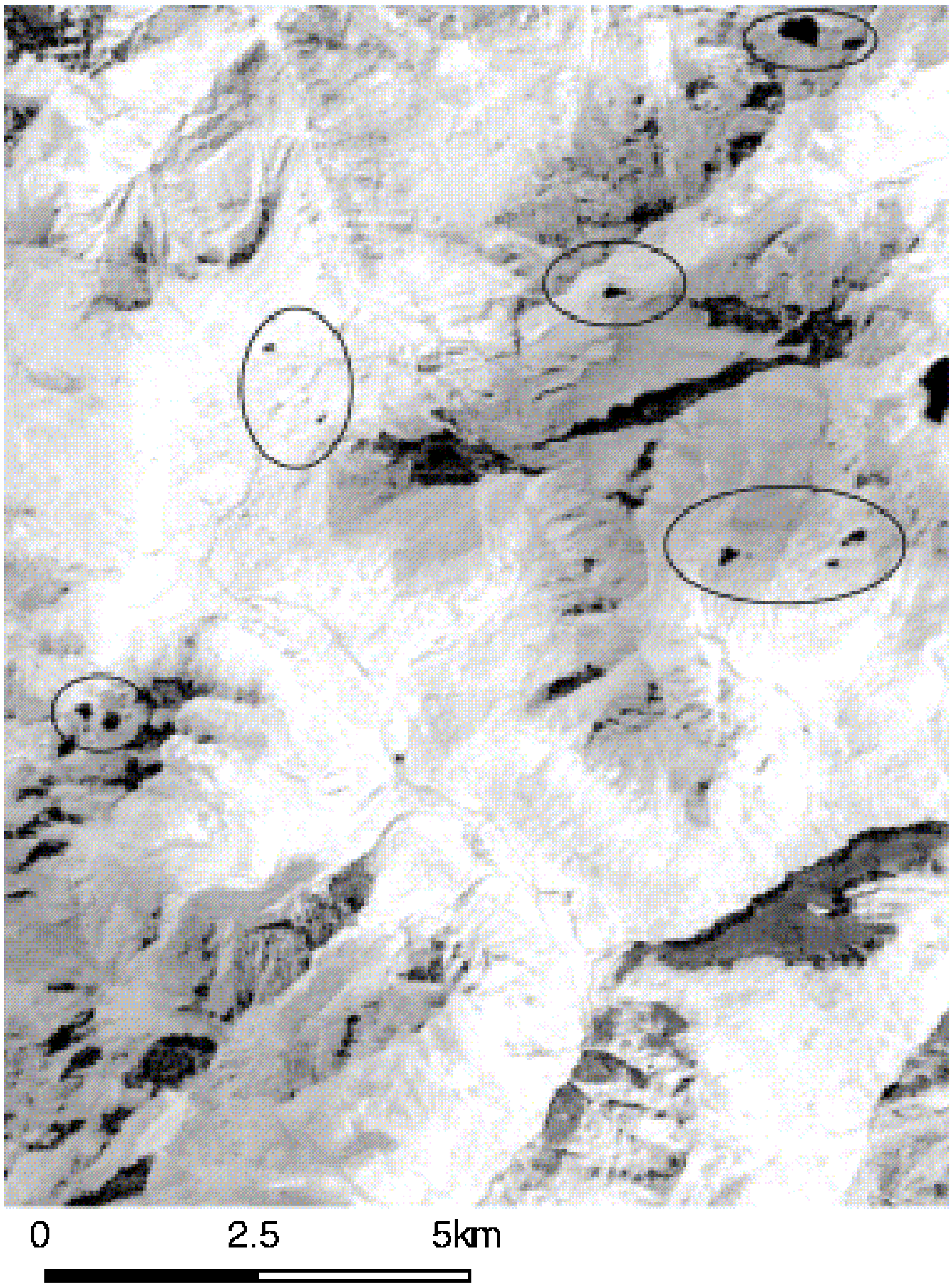
Figure 3: Longitudinal profiles on a steep glacier at Eiger, Bernese Alps, Switzerland. The ‘calving’ front was markedly removed after an ice fall in August 1990 (shortly after acquisition of the August 1990 profile) but was again approaching a critical geometry in 1994. The dashed line approximates the glacier bed.

Figure 4: Surface velocities on a steep glacier at Eiger (cf. Fig erved velocities lie in the normal range and indicate no critical acceleration.

Figure 5: Automatic extraction of glacier edges from Landsat TM imagery (Ötztal, Austria). Division of channel 4 (upper left) by channel 5 (upper middle) gives a ratio-image (upper right). Threshholding (lower left) and noise reduction (lower middle) provide the glacier outlines, here superimposed on the original image (lower right).

Figure 6: Changes in elevation and displacements 1976-1995 on a rockslide at the Aletsch glacier, Valais, Swiss Alps. The measured displacements amount up to 20 cm per year. In the upper part surface lowering prevails, in the lower part surface uplift, both pointing to a vertical rotation of the mass. The rock slide is due to massive glacier retreat and subsequent relief of the adjacent valley flanks.

Figure 7: Surface velocities 1992-1997 on a permafrost stream in the Suvretta valley, Engadine, Swiss Alps, measured by digital photogrammetry. The permafrost creep transports loose material by 2m per year into two debris flow starting zones (arrow). The related refill of the debris reservoir enhances the debris flow hazard.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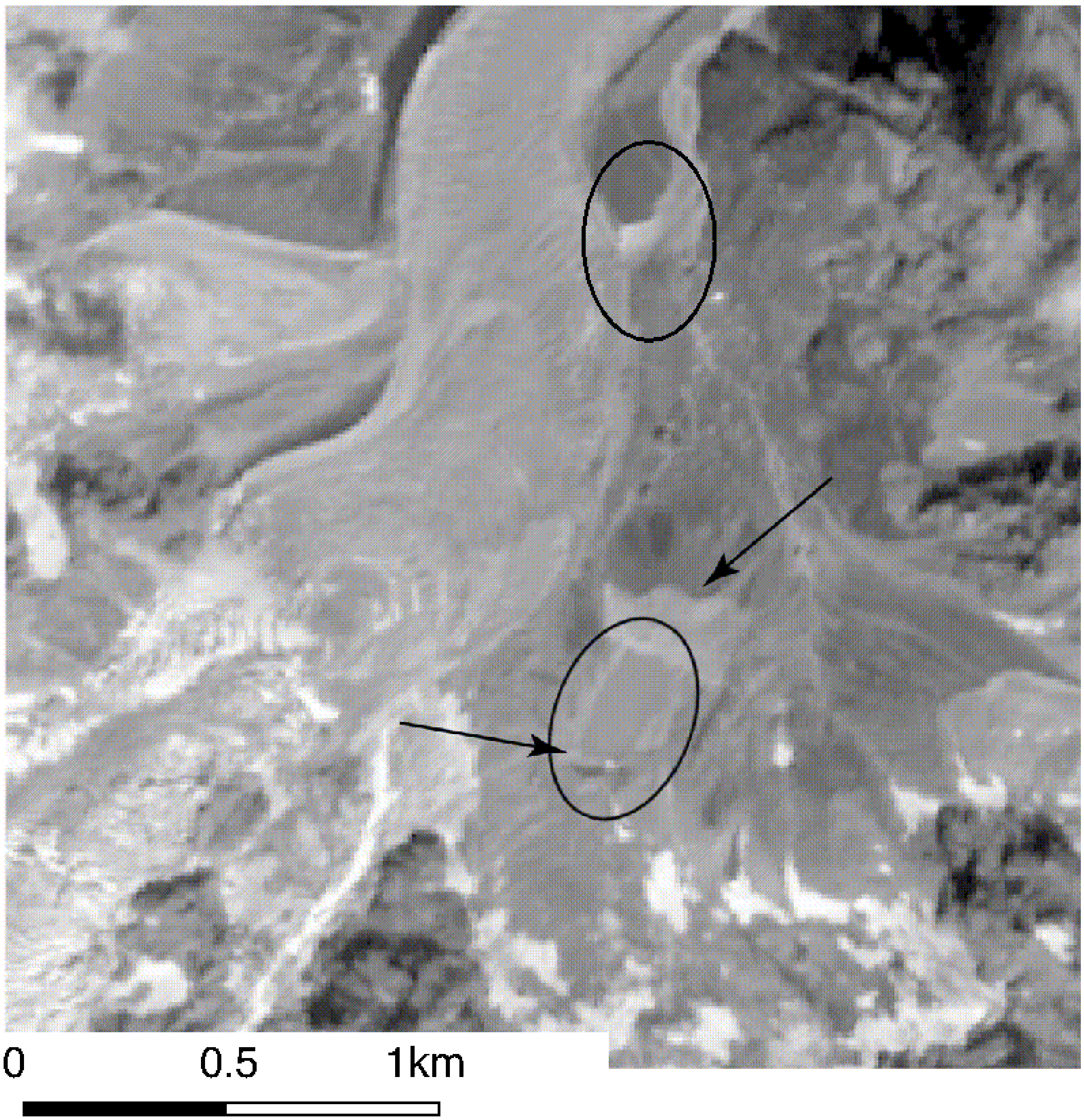
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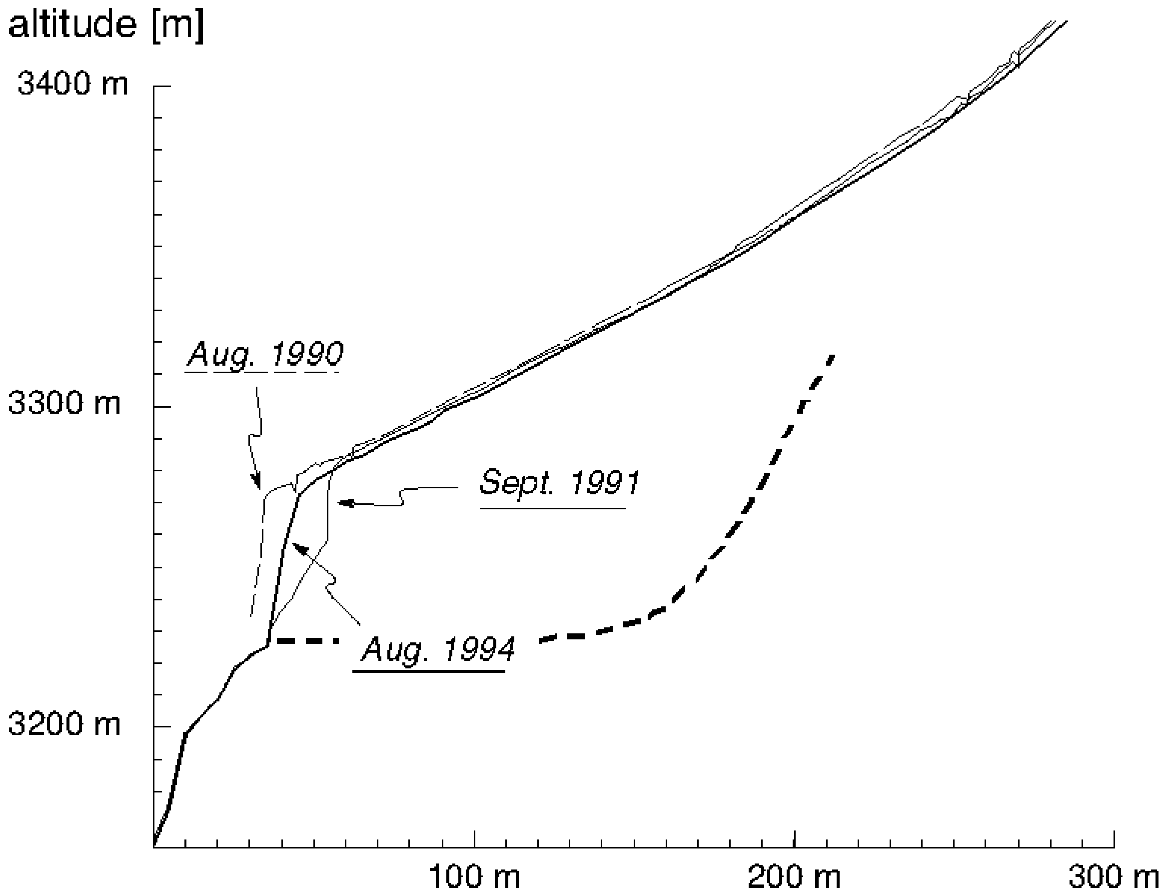
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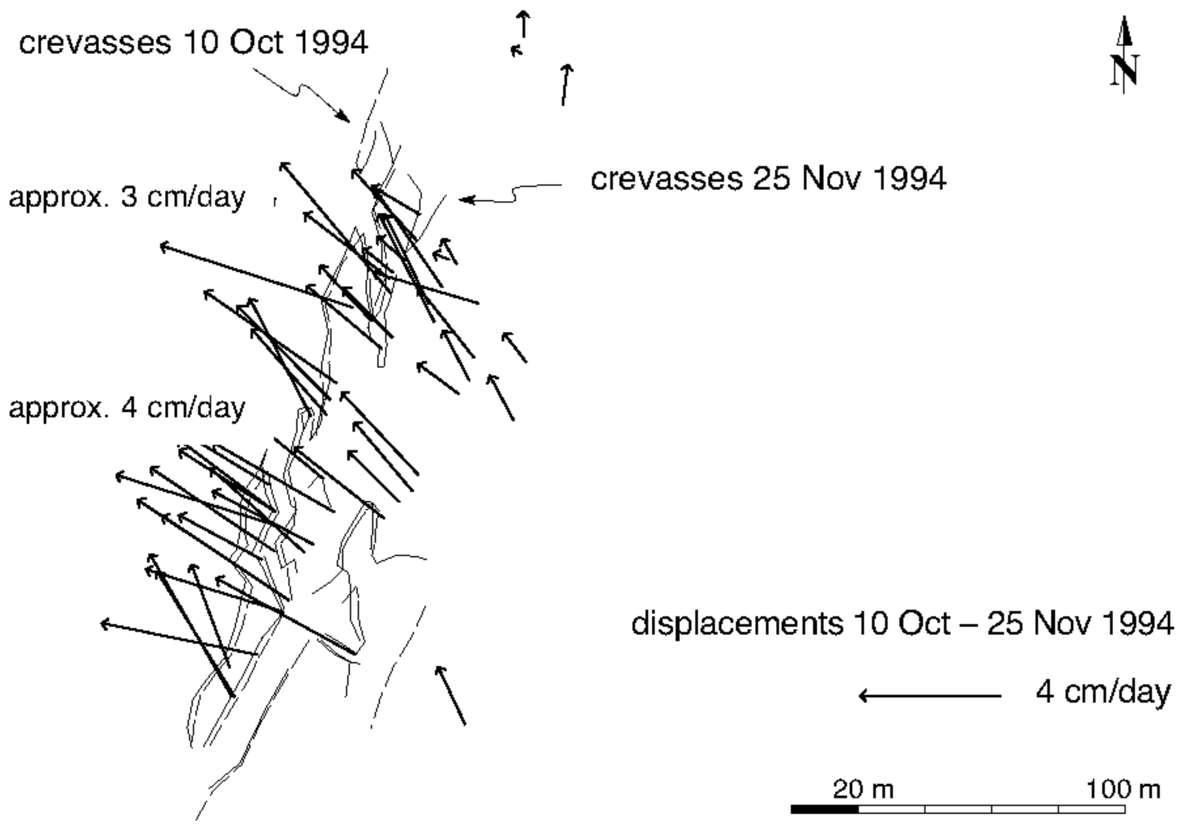
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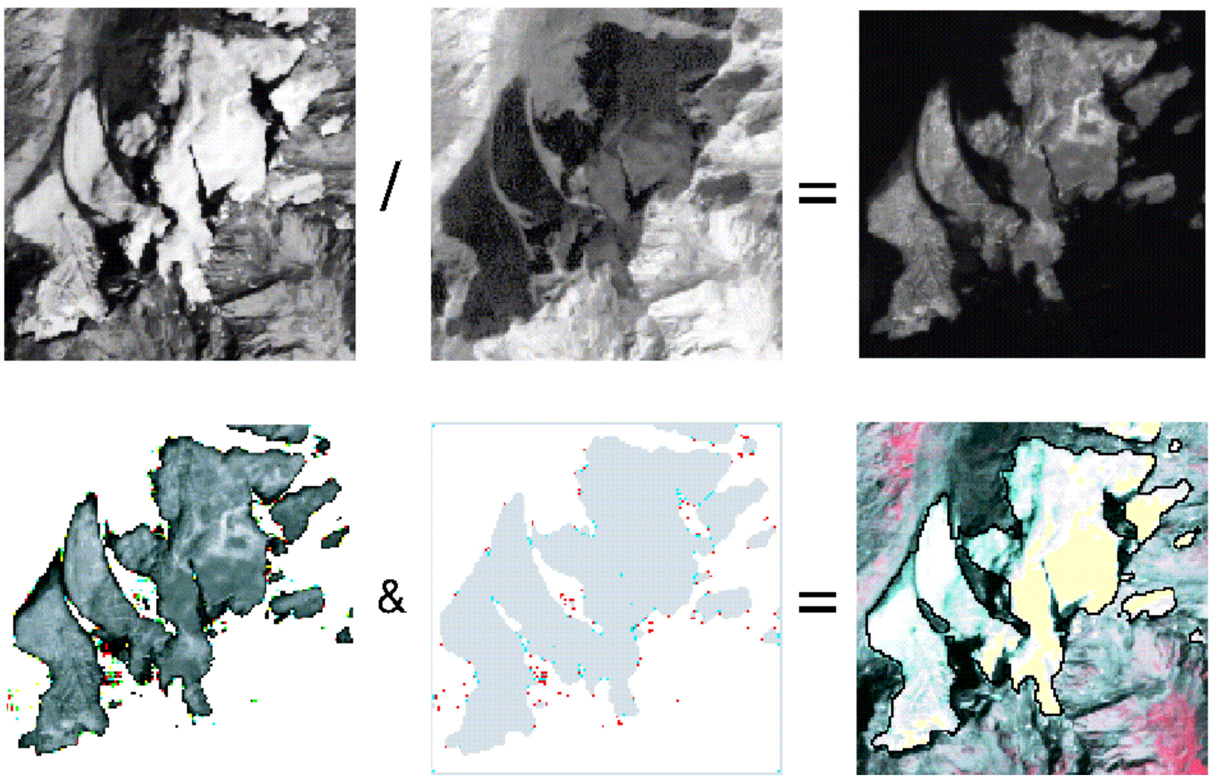

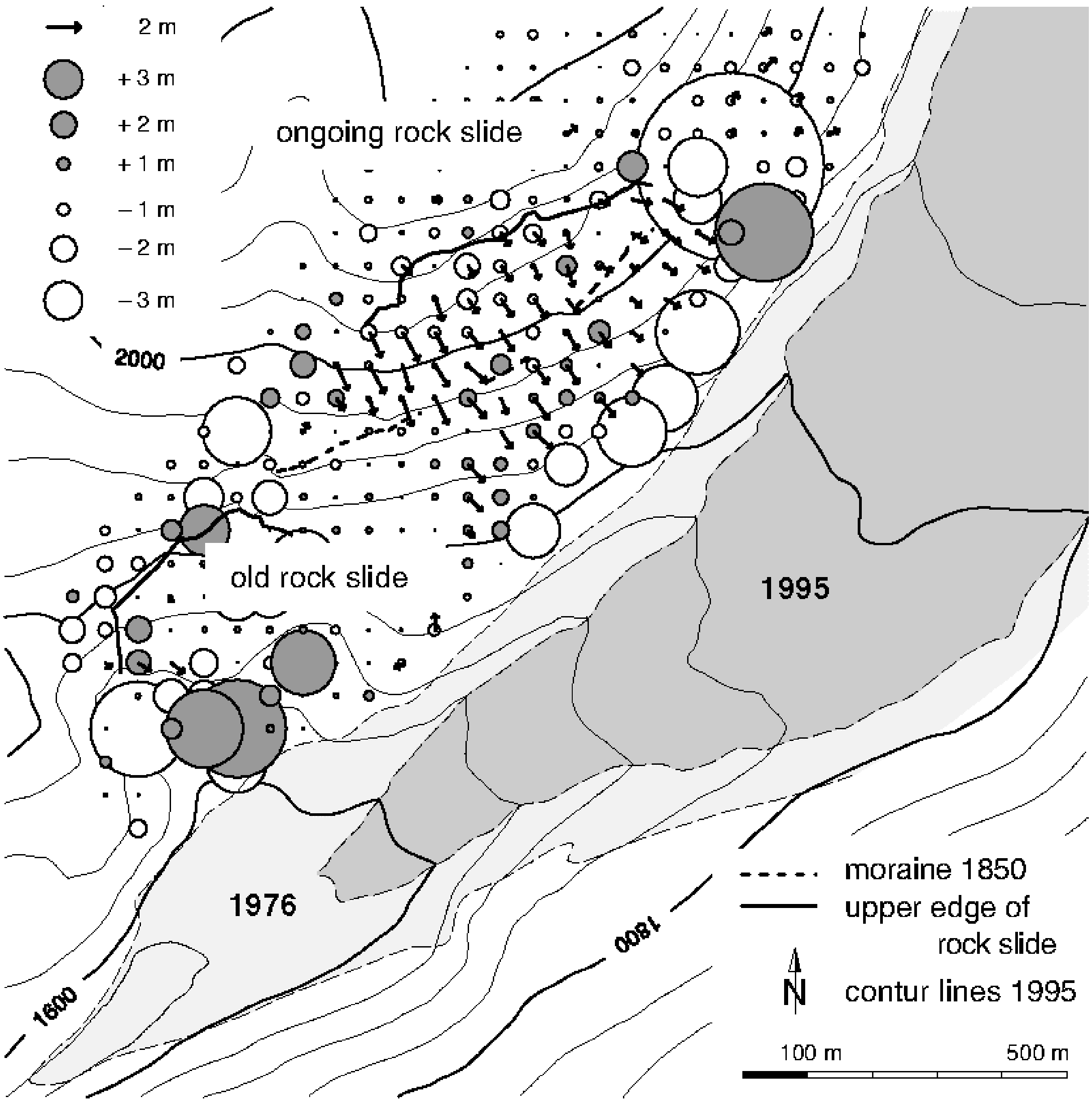

2 m
+3 m
+2 m
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ongoing rock slide
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N
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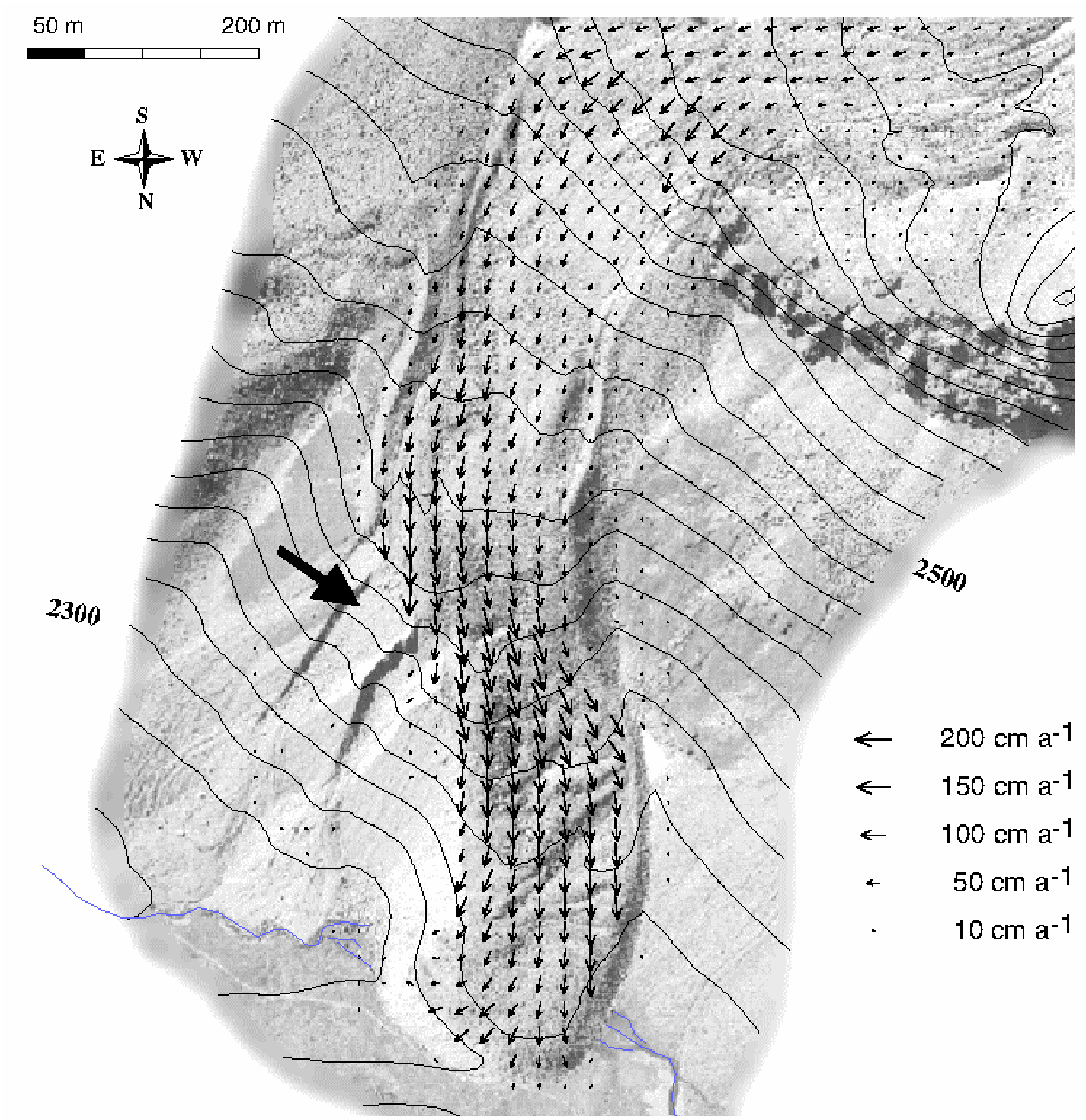
500 m



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