

Remote sensing of permafrost hazards in mountains

Fjernmåling av faremomenter ved permafrost i høyfjellsområder

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Summary

Present atmospheric warming especially affects terrestrial systems with surface and subsurface ice involved. Norway with its significant areas covered by glaciers and underlain by permafrost is thus particularly vulnerable to climate change. Permafrost (and glacier) hazard assessments may become increasingly difficult because estimates of hazard potentials based on historical data alone will not be sufficient anymore under new environmental conditions.

Empirical knowledge will have to be replaced by improved process understanding (in particular concerning slope stability), spatial modelling of hazard potentials, and intensified monitoring activities, not least by remote sensing. Down-scaling approaches from initial regional-scale assessments of hazard potentials towards high-resolution- and precision observations and simulations at selected sites are needed as a response to the current environmental changes. In this contribution an overview is given of permafrost hazards in mountains and of remote sensing methods for assisting the detection and observation of corresponding hazard source areas.

Sammendrag

Global oppvarming påvirker jordens systemer med is på overflaten og under overflaten. Norge med sine betydelige områder med isbreer og permafrost er derfor spesielt sårbar for klimaendringer. Det blir vanskeligere å vurdere terrengmessige endringer og fare for skred og ras utelukkende fra historiske data under nye miljøforhold. Empirisk kunnskap vil måtte erstattes med økt forståelse av naturprosessene (spesielt skråningsstabilitet), forbedret modellering og intensiverte overvåkningstiltak – ikke minst ved fjernmålingsteknikker. Metoder for nedskalering av farekart i "region-skala" til observasjoner med god

oppløsning og stor presisjon sammen med simuleringer på utvalgte steder er nødvendige for å få tilstrekkelig oversikt under de pågående miljøendringer. Denne artikkelen gir en oversikt over risiko for skred og større terrengendringer i permafrostområder i fjellet og metoder for fjernovervåking som støtte til identifisering og observasjon av risikoområder.

Mountain permafrost hazards

Ground material which is frozen all year round (permafrost) can be the source of various types of natural hazards. Some of these hazards are related to the existence of permafrost alone, others are related to changes in the geotechnical properties of the frozen ground. Basically, permafrost hazards in mountains originate from (1) frozen debris and (2) frozen rock. In rare cases such hazards might directly endanger settlements, for instance, when a rock avalanche is triggered by permafrost warming. More often, however, mountain permafrost hazards affect mountain infrastructure. Construction works, for instance, may be damaged by permafrost-induced debris flows or rockfalls. Installations on creeping permafrost become defective. Construction activities are affected by thaw or instability in frozen material. Buildings and installations influence the ground thermal regime at their base by altering the heat fluxes (e.g. Haeberli, 1992; Instanes, 2005). In some countries, problems related to mountain permafrost have become a significant cost factor for the maintenance or construction of high-mountain infrastructure (Kääb et al., 2005a).

Although the direct reach of permafrost-related hazards in mountains is limited, permafrost hazards may be at the beginning of complex and devastating chain reactions, when, for instance, a permafrost-triggered rock-avalanche falls into a lake or fjord and

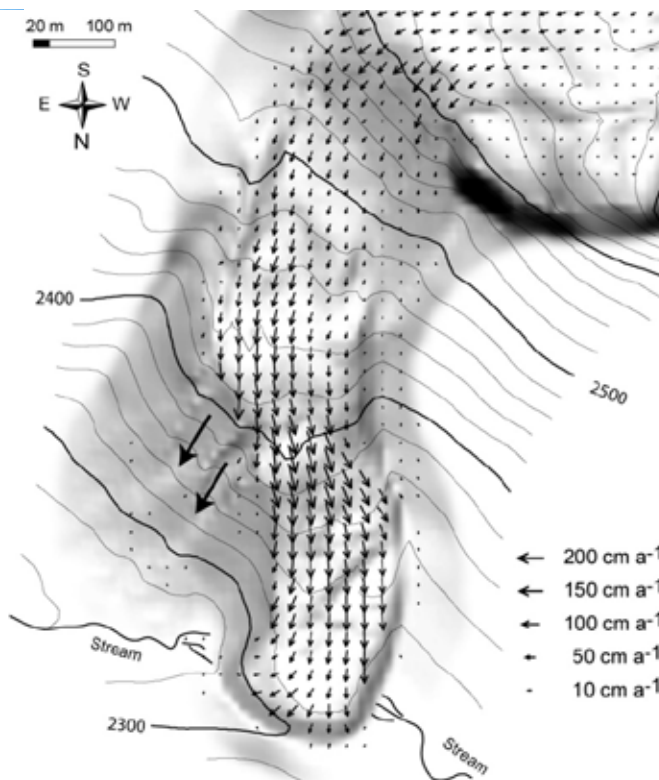


Figure 1. Left: Suvretta rockglacier, Upper Engadine, Swiss Alps. Right: average horizontal surface velocities on the lower part of Suvretta rockglacier, Grisons, measured from aerial photography of 1992 and 1997. The two arrows east of the rockglacier indicate debris flow channels.

causes a tsunami, or when such rock-avalanche causes a much larger ice avalanche with far reach.

Climate change and mountain permafrost hazards

Permafrost as a temperature-driven phenomenon is highly sensitive to changes in ground temperature, especially when ground ice is involved. Questions arise, thus, if and to what extent climate change influences the magnitude and probability of potentially hazardous processes related to mountain permafrost. Marginal or discontinuous permafrost occurrences, such as those found in mainland Norway (Isaksen and Sollid, 2005; Heggem, 2005), are in particular affected by ground temperature warming, because the ground temperatures in such permafrost are often close to the melting point of ice at 0 °C, one of the most important and effective thresholds in nature (Instanes, 2005).

Remote sensing of mountain hazards

Assessment and management of permafrost hazards requires the application of modern integrative earth-

observation techniques for a number of reasons (Kääb et al., 2005b):

- Typically, related hazard source areas are situated in remote high-mountain regions, often difficult to access physically for topographic, political and/or security reasons.
- The remote location of most hazard sources, the potential process interactions and chain reactions, and the far reach of some of the high-mountain hazards require remote sensing sensors capable to cover large areas at once.
- Climate change induces disturbance in permafrost (and glacier) equilibrium and can shift hazard zones beyond historical knowledge. In addition, human settlements and activities increasingly extend towards endangered zones in many regions. As a result, historical data alone are not sufficient any more for hazard assessments and have to be combined with new observation and modelling approaches.
- Due to the rapid change of high-mountain environments, hazard assessments shall be undertaken routinely and regularly, combined with continuous monitoring. Remote sensing is particularly suited for both regular and rapid observation.

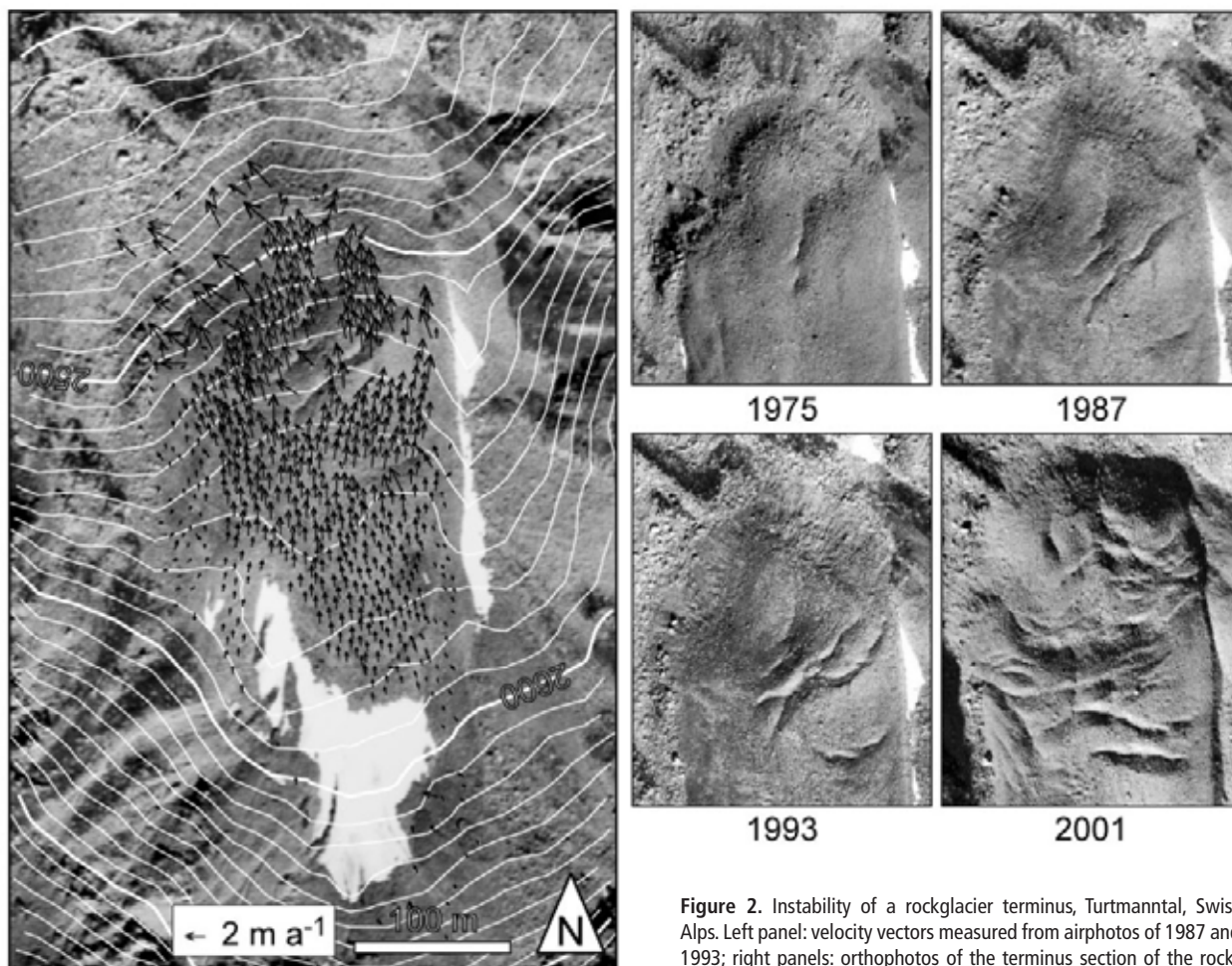


Figure 2. Instability of a rockglacier terminus, Turtmanntal, Swiss Alps. Left panel: velocity vectors measured from airphotos of 1987 and 1993; right panels: orthophotos of the terminus section of the rockglacier. Images of 1975, 1987, and 1993 are courtesy of swisstopo; the 2001 image is a linear array CCD (pushbroom) image taken by the HRSC-A camera, courtesy of Department of Geography, University of Bonn. The rockglacier instability led to enhanced rockfall and required construction of a protection dam (not depicted) (see also Roer et al., 2005).

- Where direct access to the hazard sources is hindered, and/or large areas have to be covered, remote sensing techniques represent often the most cost-efficient solution for mapping and monitoring.

Recent developments in ground-based, airborne and spaceborne remote sensing open up new possibilities for the assessment of permafrost related hazards (Kääb et al., 2005b). Remote sensing will therefore substantially gain importance for such works in the near future.

Frozen debris

a) Hazards from frozen debris slopes

Creeping mountain permafrost, often forming so-called rockglaciers, may be the source of a number of natural hazards:

- Rockglaciers represent an efficient long-term debris transport system. They are able to displace debris volumes in the order of 10^3 to 10^4 m³ per millennium into steep flanks or channels, where they contribute to the formation of potential debris flow starting volumes (Hoelzle et al., 1998) (Fig. 1).
- Rockglacier advance leads to frequent rock falls along the steep rock glacier front. This process represents a hazard endangering e.g. hiking paths or other infrastructure, under special topographic conditions, however, also larger areas.
- Rock glacier sections might become unstable. Such rockglacier slides enhance the rock fall activity or debris flow formation (Kaufmann and Ladstädter, 2003; Kääb et al., 2005b; Roer et al., 2005) (Fig. 2).

Ground warming as recently observed in some mountain ranges is able to increase the above-cited hazards. Increasing creep rates are, for instance, currently

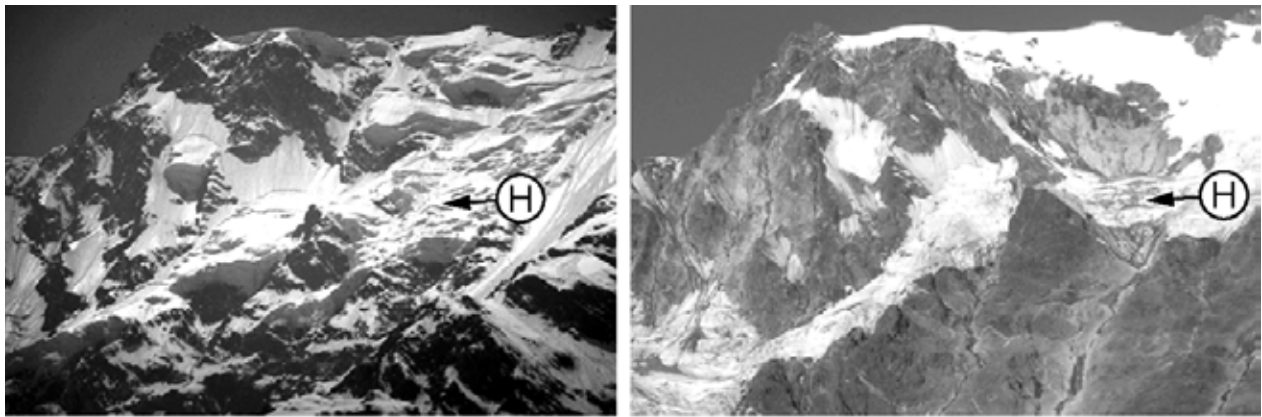


Figure 3. Upper part of the Mont Rosa east face, Italian Alps, in the mid-1980s (left, photo W. Haeberli) and on 6 August 2003 (right, photo A. Kääb). Some steep glaciers have totally disappeared; some have significantly lost mass. In the recently de-glaciated zones drastic mechanical, thermal, hydraulic and hydrological changes affect the frozen and unfrozen rock and debris deposits, and cause increased rock fall activity. Zones of increased rock-fall activity are to the right of the right image, above and below a steep hanging glacier (H).

observed for a number of rockglaciers in the European Alps (Kääb et al., 2006).

Ice-rich permafrost influences the hydrology and the geotechnical properties of debris slopes. Ground water concentration above the permafrost table is able to trigger active layer detachments or debris flows. Thawing permafrost in debris slopes might lead to complex hydrological interactions including water storage in unfrozen caverns, and enhanced melt water release. Ground ice cements debris slopes. In the case of thaw, slope stability is decreased. On the other hand, ice-cemented debris prevents retrogressive erosion caused by debris flows (Zimmermann and Haeberli, 1992).

In cold mountain regions, ground thermal conditions in moraines are often a crucial factor in the damming of moraine lakes. Permafrost or near-permafrost conditions support the long-term preservation of dead ice bodies, which leave cavities when they melt (Richardson and Reynolds, 2000). For another class of lakes – thermokarst lakes – permafrost represents the fundamental condition of their formation through positive feedback mechanisms of water convection and ground ice melt.

In these cold mountain regions, glaciers and permafrost often coexist in close spatio-temporal proximity. For instance, permafrost may be able to penetrate into recently deglaciated glacier forefields, to alter the thermal, hydrological and dynamic conditions of thick glacial deposits, and to influence related hazards. Such effects are of increasing interest in the light of the current drastic worldwide glacier retreat.

b) Remote sensing of frozen debris slopes

A number of remote sensing methods are able to assist the observation of frozen debris slopes (Kääb et al., 2005b):

- Monitoring of ground displacements is possible from repeat terrestrial photographs, air-photos or high resolution satellite images using image matching techniques (Figs 1 and 2). This method is particularly interesting where, like in Norway, old air-photos exist and can be compared to more recent ones. The accuracy of the method is in the cm-dm range.
- Ground-based or spaceborne radar interferometry is able to measure ground deformation with mm-accuracy for suitable terrain and imaging conditions.
- Thaw settlement or frost heave, or other processes which result in a change in terrain geometry can be quantified by subtracting repeat high-precision digital terrain models (DTM). Such DTMs can be obtained from terrestrial or aerial photogrammetry, terrestrial and airborne laserscanning, or airborne radar interferometry.
- Furthermore, repeat visual inspection of repeat remotely sensed data or other change detection techniques can be quite useful in order to identify changes on the terrain surface, which might hint to hazards (e.g. formation of ground cracks, small land slides and debris flows, changes in vegetation, etc.).
- Where permafrost-glacier interactions play a role in a hazard potential, monitoring of glacier changes can be advisable using mapping and change detection techniques based on repeat air-photos or satellite imagery (Kääb, 2005).

Frozen rock walls

a) Hazards from frozen rock walls

A second class of permafrost hazards concerns frozen rock walls. Permafrost in rock faces leads to ice-filled discontinuities, and influences the rock hydrology and the hydrostatic pressure. Steep temperature gradients

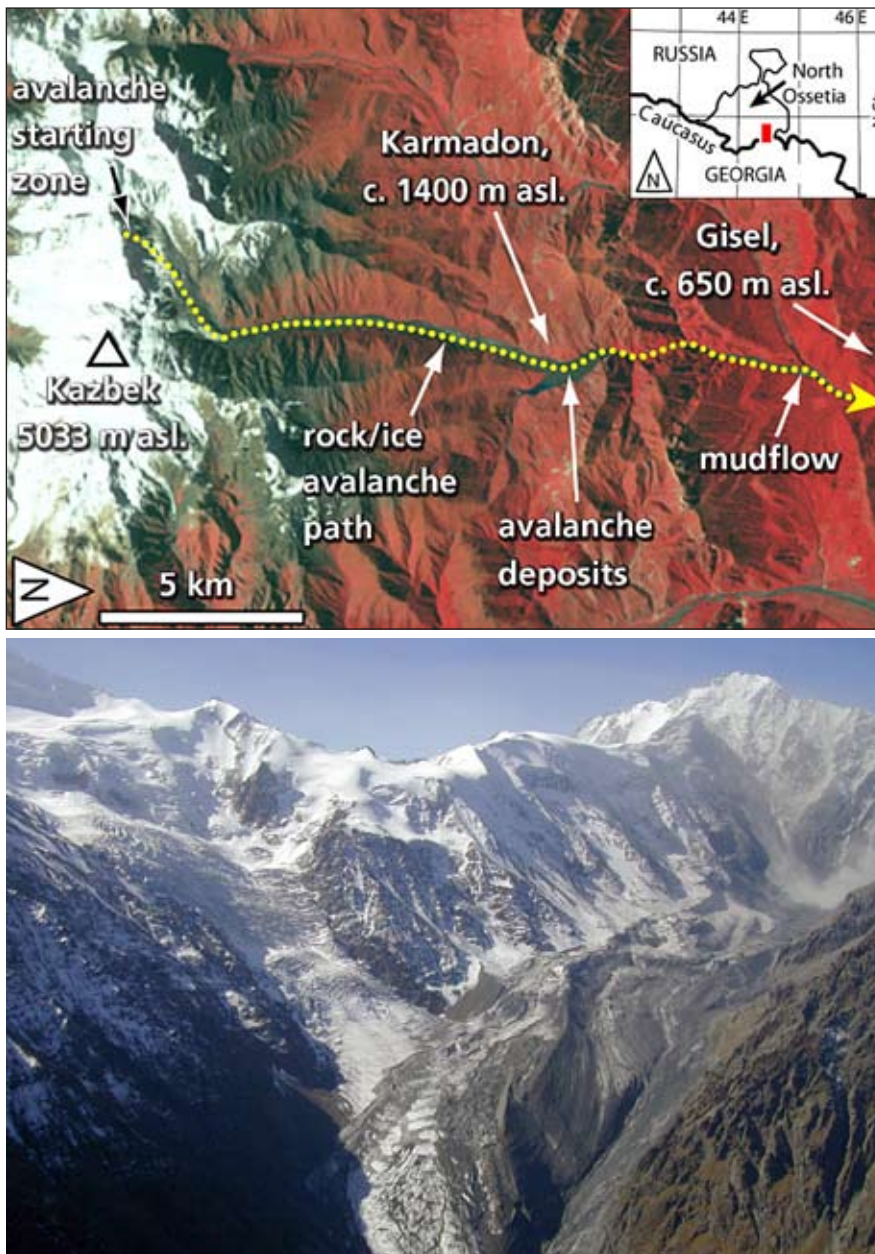


Figure 4. Upper panel: Overview of the 20 September 2002 rock-ice avalanche at Kolka/Karmadon, Russian Caucasus. Lower panel: avalanche starting zone (see upper panel) shortly after the event (photo: I. Galuschkin).

Complex thermal (permafrost, steep glaciers), hydraulic and geological conditions in the rock face to the upper right of the photo are believed to have been involved in the formation of rock-ice avalanches which finally triggered the rupture and shearing off of the entire tongue of Kolka glacier (right and lower middle of the photo).

at the surface zones cause the transport and refreezing of free water and subsequent growth of ice lenses. The resulting increase in pressure is able to destabilize the rock locally (Haerberli et al., 1997; Wegmann et al., 1998).

With a rise in temperature, frozen rock joints reach minimal stability at temperatures between -1.5°C and 0°C , i.e. even before thaw (Davies et al., 2001). In parallel, the hydrostatic pressure within the rock wall might change. As a consequence, enhanced rockfall activity and rock avalanches are expected in particular for the lower boundary of permafrost distribution (Noetzli et al., 2003).

Complex thermo-mechanical conditions are found for partially glacier-covered alpine rock faces (Fischer et al., 2006). Through advection of temperate firn, the base of steep glaciers might be temperate or compa-

rably warm. At the same time, enhanced heat flux at the front of such glaciers leads to cold frontal sections stabilizing the glacier front. Though little understood, it is clear that changes in the surface temperatures can cause highly complicated feedback mechanisms and chain reactions both for rock and glacier stability. In that context, the retreat of steep glaciers and the connected uncovering of rock might have even more drastic and rapid consequences than a rise in mean annual air temperature itself. Beside the thermally-governed impacts, retreat of steep glaciers leads to mechanic changes in the underlying and surrounding rock wall (de-buttressing).

Indeed, increasing rockfall activity, as currently observed in the European Alps, and a number of recent large rock avalanche disasters might have been influenced by thermo-mechanical changes in the source

rock-faces (Fig. 3). Under the most recent events is the 20 September 2002 rock-ice avalanche at Kolka/Karmadon, Russian Caucasus, where a combined rock-ice avalanche of approximately 10 million m³ triggered the disastrous shear-off of an entire glacier tongue (over 100 million m³). The resulting avalanche and mudflow killed more than 120 people (Haeberli et al., 2005) (Fig. 4).

b) Remote sensing of frozen rock walls

In principle, similar remote sensing methods can be applied to frozen rock walls as useful for debris slopes. However, the difficult topographic conditions of rock walls severely limit the application of most remote sensing methods. Often, parts or entire rock faces are hidden in the images due to adjacent topography or depicted with strong distortion due to the steep surface slope. The most promising remote sensing techniques for monitoring rock faces include thus

- aerial photogrammetry for mapping and quantifying surface changes,
- terrestrial imaging, for instance using automatic cameras,
- terrestrial non-contact laser-ranging or laserscanning for deriving (repeat) high-resolution DTMs of rock faces,
- ground-based radar interferometry.

The three latter techniques can be installed as automatic sensor stations with direct data transfer through telecommunication. The techniques can thus also be used in early warning systems.

Challenges and perspectives

Present atmospheric warming especially affects terrestrial systems with surface and subsurface ice involved. Norway with its significant areas covered by glaciers and underlain by permafrost is thus highly vulnerable to climate change. Permafrost (and glacier) hazard assessments may become increasingly difficult because estimates of hazard potentials based on empirical data from the past (e.g. historical documents, statistics, geomorphological evidence) will not be directly applicable under new environmental conditions. Empirical knowledge will have to be replaced in parts by improved process understanding (in particular concerning slope stability), spatial modelling of hazard potentials, and intensified monitoring activities, not least using remote sensing methods.

Downscaling approaches from initial regional-scale assessments of hazard potentials towards high-resolution and -precision observations and simulations at selected sites are needed as a response to the current environmental changes. High-magnitude low-fre-

quency events such as huge rock or combined rock-ice avalanches and their relation to changes in permafrost conditions represent a special challenge in risk assessment. In that view, particular scientific efforts are necessary for understanding the complex spatio-temporal, thermo-mechanical processes in glacierized and frozen rock walls, and large debris bodies under permafrost conditions. The impacts of environmental change on hazard potential need to be continually monitored and a rapid transfer of this information is critical for the successful mitigation of hazards in highly sensitive mountain environments.

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