—Plenary Paper—

Research Challenges for Permafrost in Steep and Cold Terrain: An Alpine Perspective

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Abstract

The past few decades have seen a rapid development and progress in research on permafrost in mountain areas with complex and rugged topography such as the European Alps. At the same time, it becomes increasingly clear that climate change impacts have the potential to severely affect future living conditions in areas with steep and cold terrain by influencing the chain of surface processes that link debris production via rock fall to talus/moraine formation, creep deformation of frozen deposits, and material evacuation by debris flows and fluvial transport. Key scientific challenges relate to special aspects induced by complex topography. Corresponding aspects are briefly outlined concerning the relation between the atmosphere and the permafrost in areas with highly variable snow cover and potentially strong lateral energy fluxes, permafrost thermal conditions in mountains with pronounced microclimatic asymmetries, the destabilization of steep to near-vertical rock walls and degrading permafrost, the flow and stability of ice-rich frozen debris with increasing subsurface temperature and melt water availability, interactions between glaciers and permafrost under conditions of rapid if not accelerating change, 4D-evolution of permafrost in rugged mountain topography, and hazards from permafrost slopes in densely populated high-mountain chains.

Keywords: climate change; cold regions; mountains; natural hazards; permafrost; slope stability.

Introduction

The first contributions in the Proceedings of the International Permafrost Conferences about permafrost in mid-latitude, high-altitude mountain regions started to appear in the late 1970s (e.g., Barsch 1978, Fuji & Higuchi 1978, Gorbunov 1978, Haeberli 1978, Harris & Brown 1978). This indicates the essential beginning of systematic research on permafrost in high-mountain areas and led to a first visibility peak at the International Workshop on Mountain Permafrost in Interlaken 1991 with a first set of overview papers (cf. situation reports by Barsch 1992, Guodong & Dramis 1992, Haeberli 1992, Harris & Corte 1992, King et al. 1992, Lautridou et al. 1992). During its rather young history, research on permafrost in steep and cold terrain developed and expanded rapidly. Perhaps the most important impulse was the EU-funded PACE project (Permafrost and Climate in Europe, Harris et al. 2001). The subsequent progress and increase in visibility is impressing: high-mountain permafrost is now described for many regions (for instance, Isaksen et al. 2007, Jin et al. 2000, Marchenko 2007, Trombotto 2000) and is regularly included in international assessments on cryospheric conditions, especially as related to climate change (IPCC 2007, UNEP 2007, cf. also Harris 2008).

Climate change indeed constitutes a major challenge for the science of mountain permafrost as it concerns a phenomenon that depends on atmospheric conditions in a complex way, is not directly accessible through visual observation, often involves logistic problems with difficult access and strikingly lacks observational series over extended time periods. As a consequence, even key questions are still open for detailed investigations. The present contribution focuses on special aspects related to rugged topography and steep terrain. It is primarily built on experience from the European Alps as summarized in recent reviews (Harris et al. 2008, Gruber & Haeberli 2008, Haeberli & Gruber 2008) and briefly outlines a set of high-priority research topics covering process understanding, numerical modeling and the anticipation/assessment of potential climate change impacts. The basic structure of the considered geo-system (Fig. 1) as is characteristic for mountain ranges with transitional to continental climate—where glacier equilibrium lines are far above the 0°C-annual isotherm—is the process chain leading from debris production via rock fall to debris cone or moraine formation, creep deformation of frozen deposits and sediment evacuation to larger valleys by fluvial transportation and debris flows.

In the following discussion, the most important conclusions based on existing knowledge are briefly outlined and major challenges concerning research on mountain permafrost are discussed. We thereby distinguish seven major topics: (1) atmosphere-permafrost coupling in complex topography; (2) permafrost thermal conditions inside mountains; (3) destabilization of permafrost rock walls; (4) flow and stability of ice-rich frozen debris; (5) glacier/permafrost interactions; (6) 4D-evolution of permafrost in mountain topography; and (7) hazards related to rock falls and debris flows from permafrost slopes.

Topics (1) to (5) are related to necessary improvements of our process understanding. The spatio-temporal consideration, on the other hand, is more and more urgently needed for realistically assessing consequences and impacts from continued atmospheric warming. The discussion

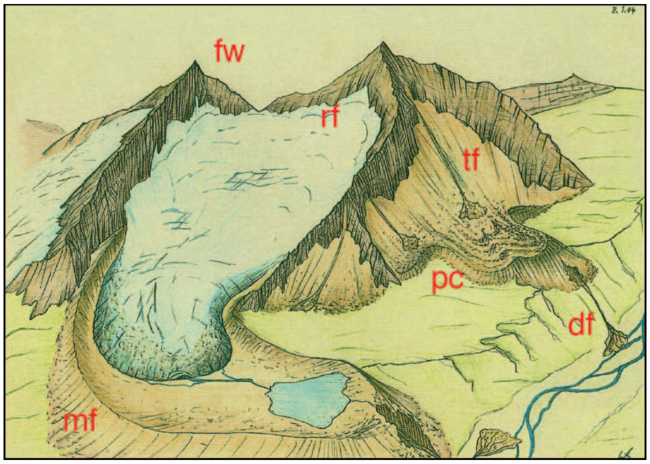

Figure 1. Scheme of the characteristic process chain in cold mountain areas: frost weathering (fw) and debris production, rock fall (rf), talus (tf) or moraine formation (mf), permafrost creep (pc), evacuation by fluvial transport and debris flows (df). Adapted from Haeberli (1996).

therefore also includes two central aspects—topics (6) and (7)—related to the assessment of local, regional and global impacts of climate change and the anticipation of corresponding hazard potentials.

Atmosphere-Permafrost Coupling in Complex Topography

The now 20 years old series of borehole temperatures in the Murtèl rock glacier (Fig. 2) clearly shows the important influence of the winter snow cover on near-surface ground temperatures. This effect of snow on relations between the atmosphere and the permafrost has been investigated using measurements (Keller & Gubler 1993) and snow/permafrost models (e.g., Lütschg et al. 2003). A number of studies also address the cooling influence that coarse blocks exert on ground temperatures when compared with lower porosity or finer-grained surface materials (Hanson & Hoelzle 2004, Hoelzle & Gruber 2008).

The effect of topography on temperatures in steep rock has been investigated with measurements (Gruber et al. 2003) and model experiments (Gruber et al, 2004 a, b, Noetzli et al. 2007, Salzmann et al. 2007). Despite significant progress in understanding these processes of atmosphere-permafrost coupling, the high spatial variability of surface micro-climatology and subsurface properties in mountain terrain makes the generalization of findings to larger areas difficult. One example is the thermal effect of thin and intermittent snow cover in rock faces that has not been quantified to date.

The role of heat advection by moving water or air in sediments or in cleft systems is a further set of processes that is little understood but that bears high relevance for the anticipation of climate change impacts (fast thaw along frozen joint systems and corresponding rock fall) and for the understanding of permafrost dynamics (Gruber & Haeberli

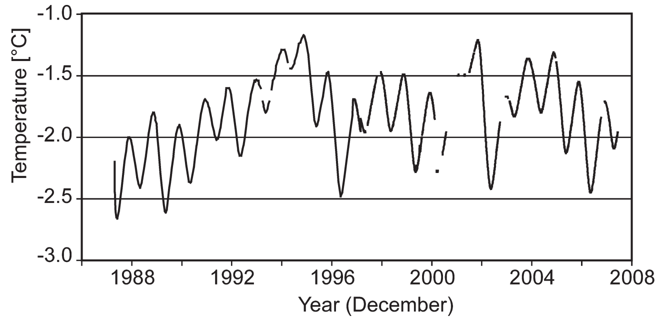

Figure 2. Borehole temperatures in the active Murtèl rock glacier. The winters of 1996, 2002 and 2006 had thin snow cover causing strong ground cooling despite relatively warm air temperatures.

2007). Especially lateral transfer of sensible as well as latent heat through ventilation effects in steep, coarse-grained debris or by melt water in heavily fissured, near-vertical rock walls appear to be essential.

Permafrost Thermal Conditions Inside Steep Mountains

Measured borehole temperatures (Harris et al. 2003, Gruber et al. 2004c, Isaksen et al. 2007) and combined time-dependent energy balance and heat diffusion modeling for complex topography (Noetzli et al. 2007) now document the main thermal characteristics of cold mountains. Summits can be frozen to depths of nearly 1000 m, and often have strongly asymmetrical thermal fields with steeply inclined isotherm configurations and predominant lateral heat flow from warmer to colder outer rock walls. The uppermost parts of such ridges and summits are essentially decoupled from geothermal heat and, due to their geometry, enable thermal disturbances to penetrate from two or more sides. Atmospheric warming during the 20th century has caused pronounced thermal anomalies to depths of about 50–70 m below surface. In perennially frozen debris (talus, moraines, rock glaciers) with high ice contents near the lower boundary of local permafrost occurrence, temperatures below the depth of zero annual amplitude have, in places, reached phase equilibrium condition (pressure melting) throughout (zero or near-zero heat flow).

The formation and existence of unfrozen zones within permafrost (taliks) as documented, for instance, in the borehole through Murtèl rock glacier in the Swiss Alps (Vonder Mühll et al. 2003), constitutes a disturbance and heterogeneity for subsurface heat and energy flow. Positive feedback between energy input and hydraulic permeability most likely causes such effects to be widespread in warm permafrost, to increase in importance with continued warming and often to dominate over heat conduction through extended subsurface layers.

The occurrence and intensity of corresponding processes, however, are hardly known and most difficult to predict. Individual observations at high-mountain railway and cable car stations (Fig. 3) point to the importance of the

Figure 3. A roof protects tourists from melt water that only recently began to percolate through the rock mass above the tunnel inside the Jungfraujoch rock crest, 3500 m asl, Swiss Alps.

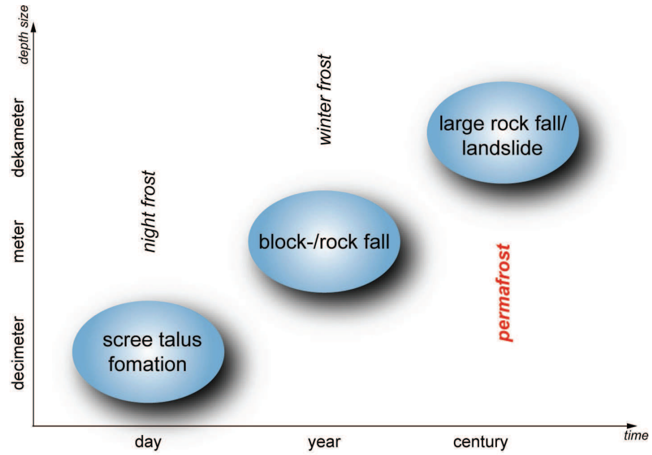

Figure 4. Scales of frost weathering and gravity driven mass wasting in rock walls.

phenomenon (Gruber & Haeberli 2007) and approaches to scientifically investigate these phenomena are now being developed (Hasler et al. 2008). Geophysical tomography (seismic refraction, electrical resistivity, Hauck & Vonder Mühll 2003, Krautblatter et al. 2007, Sass 2003), drilling/borehole temperature monitoring in fissured rock with warm permafrost (cf. Vonder Mühll et al. 2008) and the combination of heat diffusion modeling with other sources of information (Noetzli et al. 2008) for defining the conductive part of changes in the subsurface thermal field appear to be the most viable research avenue.

Destabilization of Permafrost Rock Walls

It is now quite well understood that frost-induced processes of rock destruction act on scales of time and depth that are often—but not always—connected via heat diffusion (Fig. 4). Seasonal to perennial frost, strong spatial temperature gradients in ridges and the availability of snowmelt water in active layers are likely to promote ice segregation involving depth scales of decimeters to tens of meters. Laboratory investigations (Davies et al. 2001) indicate that critical temperatures for the destabilization of frozen rocks with ice-filled cracks on steep slopes can also be reached at temperatures of -1 or -2°C. With continued warming, permafrost in cold mountains reaches such critical temperatures over more and more extended areas and over increasing depths. As a consequence, the probability of large rock falls from warming permafrost in steep to near-vertical rock walls is increasing. The process of rock destabilization by permafrost thaw is supported by observational evidence and theoretical consideration (Gruber & Haeberli 2007). However, we know little about the dominant processes responsible. Frequent rock fall during the extremely hot and dry summer 2003 in the Alps occurred in July, long before the active layer reached its maximum depth and long before it exceeded maximum thaw depths of previous years based on pure heat conduction modeling (Gruber et al. 2004c). Failure is therefore likely to have taken place under the influence of factors other than pure thaw to excessive depths. This finding points to the role of fast linear thaw along joint systems by heat advection during water transport. The influence of melt water penetrating into partially frozen rock may also be a reason for the strikingly high proportion of detachment zones from partially or at last strongly asymmetrically frozen summits and crests with marginal or even absent permafrost on the warm side. Reanalysis of recent rock falls (cf. Fischer et al. 2006, Noetzli et al. 2003) using energy balance modeling for defining pre-failure thermal conditions in the detachment zones is presently being undertaken in the Swiss Alps. International collaboration and exchange of information is important in order to expand the sample size and to enable reliable statistical analysis.

Flow and Stability of Ice-Rich Frozen Debris

The number of observations concerning flow phenomena in mountain permafrost using high-precision photogrammetry, geodesy and borehole measurements as combined with relative and absolute age dating and numerical modeling is rapidly increasing. The corresponding evidence now provides a quite coherent image of the processes, which govern cumulative long-term deformation of perennially frozen debris (talus, moraines etc.) containing ice in excess of the pore volume available between the rock particles under unfrozen conditions (Haeberli et al. 2006). Corresponding steady-state creep of ice-supersaturated debris over millennia—most probably since the end of the last Ice Age—led to the formation of the widespread and spectacular landforms called (active) rock glaciers. A major part of the straining obviously takes part within discrete shear horizons. The deforming fine-grained material from the upper part of talus cones thereby carries large blocks at its surface, which were deposited at the foot of the same talus cones, ride along the flow trajectory with maximum (surface) speed and, therefore, fall over the rock glacier front (where the creeping fine-grained material is exposed again), are overridden and

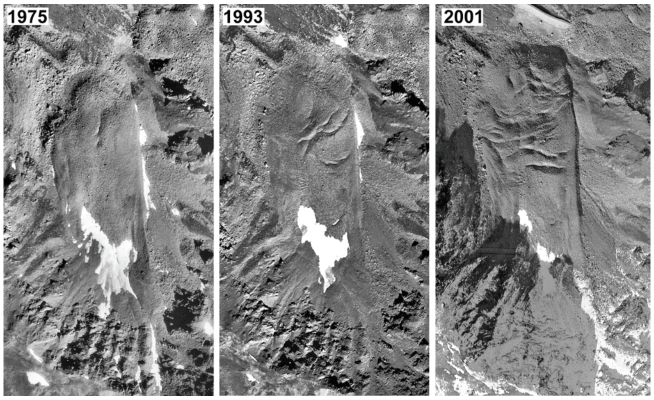

Figure 5. Grueo 1 rock glacier in the Turtmann Valley (Swiss Alps) showing signs of accelerating flow and intense crevasse formation (from Roer 2007).

form a saturated "structured" permafrost layer at depth with damped creep behavior. Seasonal and inter-annual variations of surface velocity can be observed where the permafrost base is not in bedrock but in non-frozen sediments.

The most surprising recent observation concerns the spectacular inter-annual variations of flow velocity as documented over wide areas in the European Alps in connection with the extremely hot/dry summer of 2003 (Delaloye et al. 2008, Kääb et al. 2006). Many rock glaciers with fronts near the local boundary of permafrost occurrence accelerated their flow speed almost simultaneously in the same year 2003 by a factor of two to five or even more and then more steadily decelerated to average long-term flow rates over the following about three years with less extreme conditions. The processes explaining this striking regional-scale phenomenon still remain to be explained (Roer et al. 2008). Rheological softening of ice/rock-mixtures by permafrost warming at temperatures close to phase equilibrium and at depths close to the expected shear horizons may have been part of the answer (Kääb et al. 2007). Increased melt water infiltration into already "temperate" or at least very warm permafrost may have been another contribution (Ikeda et al. 2007). Higher water pressure causing softening of subpermafrost sediments may also have come into play and enhanced mobility within the shear horizon itself cannot be excluded either. Continued high-resolution flow observations will help clearing the difficult question about corresponding interactions between the processes mentioned. Already now, however, the stability problem connected with warm permafrost in rock glaciers on steep mountain slopes received a new dimension. With the formation of striking crevasse patterns as a result of accelerated flow (Fig. 5, Roer et al. 2005), strong heterogeneities with respect to cohesion, hydraulic permeability and stress distribution developed within the creeping permafrost: possibilities for the triggering of debris flows and even landslides in such cases is no more restricted to the over-steepened frontal parts of rock glaciers alone (cf. Arenson et al. 2002).

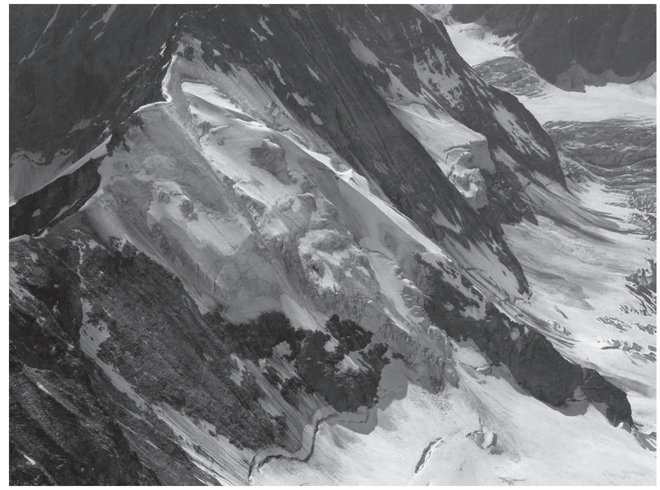

Figure 6. Hanging glaciers and ice faces on the northern side of the ridge extending between the Matterhorn and the Dent d'Herens along the border between Switzerland and Italy. Interactions between polythermal surface ice and subsurface permafrost are complex, especially with conditions of rapid atmospheric warming. Photo by S. Gruber.

Glacier-Permafrost Interactions

Interactions between glaciers and permafrost are widespread in regions with moderately to strongly continental climate, because the equilibrium line on glaciers is situated inside zones and altitudinal belts with discontinuous and continuous permafrost occurrence. Information concerning this important aspect is sparse at present (Haeberli 2005), especially because the scientific communities involved in permafrost and glacier research still communicate far too little. Results from geophysical soundings, miniature temperature data-logging, shallow borehole observations and photogrammetric movement determinations show that subsurface ice in glacier forefields successively exposed since the end of the Little Ice Age is often polygenetic (Kneisel 2003). It is most likely derived from recent ground freezing in cold microclimates of formerly temperate bed parts after glacier retreat, preservation of former subglacial permafrost underneath cold marginal parts of polythermal glaciers, burial of "dead ice" from the glacier itself or a combination of these processes. Ice-containing parts of morainic deposits commonly show signs of lateral flow and vertical displacements (heave, subsidence, cf. Kääb & Kneisel 2006).

Most important questions concern the evolution of permafrost in recently deglaciated moraines under the influence of changing surface conditions and continued atmospheric warming at lower altitudes and the thermal structure and stability of high-altitude hanging glaciers in steep, perennially frozen rock walls at higher elevations (cf. Gruber & Haeberli 2007). The stability of often polythermal hanging glaciers with temperate and permeable firn behind and above cold and rather impermeable cliffs (Fig. 6) and their thermal and hydraulic interaction with the permafrost inside the underlying rock walls (Lüthi & Funk 1997) may indeed constitute a key factor concerning large ice/rock avalanches with extremely far runout (Haeberli et al. 2004, Huggel et al. 2005). At a different level of process understanding, another common phenomenon deserves much more attention: basal regelation layers of glaciers are nothing else than epigenetic permafrost in fine grained sediments—often with large amounts of excess ice and ice lenses—attached to the base and deforming under peak stresses and at maximum strain rates of the corresponding glaciers. Improved knowledge about the rheology of the involved creep phenomena would provide essential insights with respect to non-isotropic flow characteristics of ice sheets, glaciers and rock glaciers.

Spatial Patterns and 4D-Evolution of Permafrost in Mountain Topography

Spatial distribution patterns of permafrost in complex high-mountain topography can be estimated by distributed modeling of the surface energy balance and sub-surface heat transfer. However, this implies knowledge of surface and sub-surface characteristics, proper initialization techniques, as well as methods for snow redistribution by wind and avalanches (Gruber 2007). Full energy balance models (e.g., Lehning et al. 2002) can make use of high (hourly or more frequent) time resolution, and thus resolve effects like the diurnal variability of convective cloud formation that often can have an essential influence on spatial ground temperature distribution.

A variety of models from empirical-statistical to more process-oriented approaches have so far been used with considerable success (Etzelmüller et al. 2001, Gruber & Hoelzle 2001). The Swiss Federal authorities have now produced a 1:50,000 map of permafrost distribution for the entire Swiss Alps. The model used for producing this map is more empirical-statistical but includes a discrimination between steep rock faces with little snow and less inclined slopes with thick winter snow (Gruber et al. 2006). First experiments with coupling regional climate models and GIS-based impact models indicate that warming trends are stronger in north-facing (shadow) than on sunny south-exposed slopes, because the relative influence of sensible heat effects in comparison to solar radiation is stronger (Salzmann et al. 2007). First successful attempts have also been made to couple surface energy balance with heat diffusion at depth for high mountains (Noetzli et al. 2007).

The main steps to follow this successful development consist in expanding such spatial modeling to all cold mountains on earth based, for instance, on SRTM or ASTER digital elevation and global climate data or model scenarios. Another important progress would be to further improve and validate modeling also on less inclined slopes covered by thicker and more irregular snow cover including cases with high ice contents using transient modeling. A possible result could be the coupling of thermal and geomorphic spatial models such as the modeling of creep phenomena as demonstrated in first encouraging attempts by Frauenfelder (2005). There is, undoubtedly, a long way to go for even partially reaching such research goals. However, already relatively rough approaches and early accomplishments could help with making it clear to scientists as well as policymakers and the public that permafrost belongs to the primary characteristics of cold mountain areas, that it relates to many other phenomena like snow, glaciers, erosion or slope stability, and that atmospheric warming causes growing disequilibria already now but even much more so in the foreseeable future.

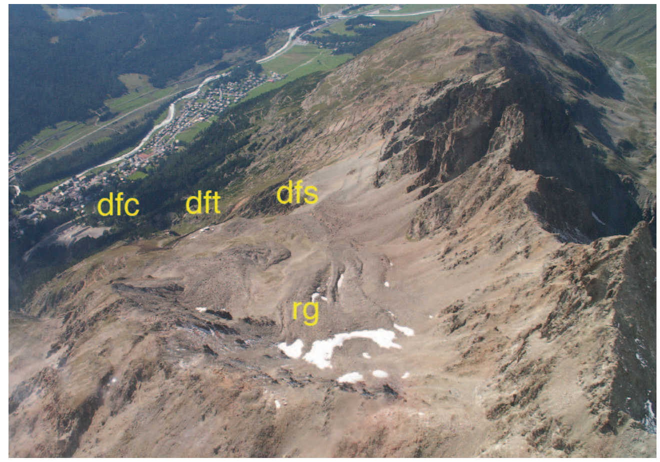

Figure 7. Creeping permafrost (rock glaciers rg) and debris flow starting zone (dfs), trajectory (dft) and cone (dfc) above Potresina (Swiss Alps). Note recently constructed avalanche and debris flow retention dam on cone. Photo by C. Rothenbühler.

Hazards Related to Rock Falls and Debris Flows from Permafrost Slopes

Debris flows from rock glaciers and moraines in permafrost areas (Fig. 7) can be among the largest debris flow events in mountain areas and cause devastating damage to settlements and infrastructure in valley bottoms.

Large-scale rock falls from steep to near-vertical rock faces seem to take place at increasing frequency and can propagate to areas far below timberline. They can dangerously erode or mobilize thick snow packs, glaciers, or water bodies, thereby undergo process changes, transform into high-speed flows or trigger flood waves which can reach extremely far runout distances and cause severe damage to human lives and economy. In the Swiss Alps, for instance, the 500,000 m^3 debris flow at Guttannen in 2005—probably the largest during decades back in time—started from a large moraine accumulation where (rather marginal) permafrost may have helped to transfer the water runoff from extreme precipitation to cross the flat cirque floor and to reach the steep outer moraine slopes. In the valley bottom, the large deposited debris volume dammed the Aare river which itself had peak flood discharge and soon started to overflow the debris dam and to cut a new bed on the other side of the principal road. As a logical consequence, the large river reached and damaged the village before heavy machines could cut an opening through the road and force the river back into its abandoned bed.

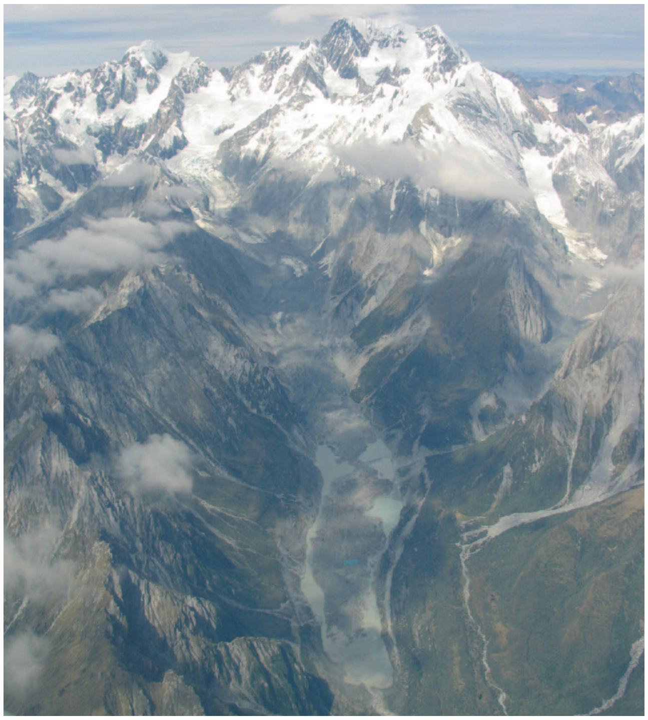

Figure 8. Disintegrating glacier tongue and formation of a large lake in the New Zealand Alps. Such lakes constitute an increasing hazard potential with respect to flood-waves triggered by rock falls from deglaciated slopes and/or slopes with warming and degrading permafrost. Photo by M. Hoelzle.

In the Caucasus, a combined ice/rock avalanche from the perennially frozen north wall of Dzimarai Khkok near Kazbek volcano eroded a medium size debris-covered glacier almost entirely. The mobilized mass squeezed out large amounts of probably subglacial water, turned into a high-speed two-phase mass flow and traveled over a runout distance of about 33 kilometers. Rivers from tributary valleys were dammed by the deposits to form lakes drowning parts of a local village and constituting a flood wave threat to people even in settlements situated far downstream (Haeberli et al. 2004, Huggel et al. 2005). Despite large uncertainties involved with the present understanding about the exact triggering and flow mechanisms of such events, hazard potentials from similar future phenomena must be anticipated and assessed at the best possible level of experience and knowledge.

GIS-based models to estimate flow paths and runout distances of ice/rock avalanches and debris flows in rugged high-mountain topography exist and can be applied already now (Huggel et al. 2003, Noetzli et al. 2006). Perhaps the most urgent need concerns the possibility of large ice/rock falls into existing lakes or lakes that newly form as a consequence of glacier retreat and downwasting (Haeberli & Hohmann 2008, Fig. 8). Debuttressing of formerly glacierized valley walls in combination with permafrost warming could thereby be an especially critical condition. In fact, primary factors influencing the stability of steep permafrost slopes are:

- slope inclination and topographically unsupported parts;
- geological structure (layer dipping, crack density and orientation);
- permafrost conditions (temperature, ice content, hydraulic permeability); and
- topographic evolution (erosion, glacier vanishing, earlier events).

Among these factors, permafrost and glacier conditions are changing most rapidly. Together with slope inclination, they can be spatially modeled in order to find most critical factor combinations. In a second step, possible flow trajectories of avalanches from such sites and their potential interactions and process chains involving snow, glaciers and/or water bodies could be modeled in order to detect places of highest risk. Such preliminary analyses over large areas would help to direct more detailed geological investigations and to establish focused monitoring or adequate protection measures. Integrative hazard assessment is far more than an academic idea: the potential for very large catastrophes is neither negligible nor undetectable. It rises at an accelerating rate with continued deep warming of high mountain permafrost, rapid glacier vanishing and drastic changing of alpine landscapes and habitats.

Further Issues and Perspectives

Besides the concrete challenges mentioned with respect to the described specific topics, three important challenges can be envisaged for future research on mountain permafrost: (a) holistic understanding; (b) increasingly quantitative methods; and (c) applied research. Holistic understanding is the broad understanding of all permafrost and its role in mountain landscapes. Our understanding at present is largely focused on special cases such as rock glaciers or steep bedrock but in fact, most permafrost has characteristics that lie in between these two cases and that are poorly constrained. Also, the transient interaction between permafrost and glaciers or the long-term influence of permafrost on the evolution of mountain topography remains largely unknown. Quantitative methods are necessary in order to understand and disentangle processes of increasing complexity. This requires not only infrastructure (such as data and models), but also novel concepts for the validation of models and for the analysis of uncertainty and scale issues that are among the most prominent characteristics of quantitative research in mountain areas. Applied research, for example in collaboration with public authorities or operators of high-elevation infrastructure, helps to transfer knowledge and evidence between researchers and people who work in permafrost environments on a daily basis, and, it is important in order to remain focused on research areas of direct importance to society.

Acknowledgments

Our special thanks go to all friends and colleagues who share with us the fascination and learning process related to mountain permafrost research. Their scientific progress, open discussions and feedbacks formed the basis of this review. An anonymous reviewer provided constructive comments.

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