# Deriving proxy variables for frequency and magnitude of rock fall induced by permafrost thaw using Monte-Carlo simulation of surface and sub-surface heat transfer.

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Permafrost degradation has been hypothesized and demonstrated to influence rock-wall stability. Both thaw and warming of permafrost (entering the range of -1.5 to 0 °C) as well as the build-up of hydrostatic pressure following thaw are possible mechanisms that link warming to the reduction in strength of ice-bonded rock joints (Haeberli et al. 1997, Davies et al. 2001, Gruber et al. 2004a).

Quantitative information on the spatial distribution of this additional, warming-related stability factor is desirable to support the assessment of natural hazards in mountain areas. This contribution proposes variables that describe this effect and explores a way to account for the large uncertainty inherent in their modelling.

The most important variable to delineate zones of possible rock fall induced by permafrost degradation is the occurrence of permafrost underneath a surface. The degradation of a permafrost body will take place along its boundary. This can be at the permafrost table, the permafrost base and also result from lateral heat fluxes in complex topography. The depth of the degrading boundary of the permafrost body corresponds to the magnitude of a rock fall induced by thaw. The additional heat flow at the boundary corresponds to the frequency or likelihood of an event taking place as a consequence of warming as it is proportional to the volume of material that can be warmed or the volume of ice melted (Fig. 1).

For any given warming scenario, the resulting frequencies and magnitudes change over time. Especially for regional-scale modeling sub-surface thermo-physical properties and water/ice contents are unknown and can thus vary in a wide range and influence the subsurface temperature field accordingly. Additionally, the surface temperature boundary condition simulated by energy-balance models has a high uncertainty in complex topography. Uncertainties of driving temperature scenarios further add to this for future projections. The uncertainties of these effects can be propagated using Monte-Carlo techniques.

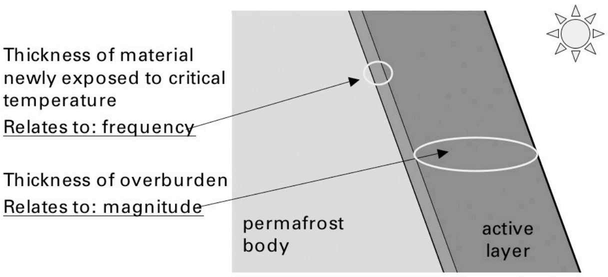

Figure 1. Schematic of proxies for the frequency and magnitude of instabilities induced by permafrost degradation.

In this investigation we explore the calculation and interpretation of the proposed proxies together with uncertainty propagation techniques. Rock temperatures for south- and north-facing locations and diverse elevations were simulated with the model TEBAL (Gruber et al. 2004b) based on hourly meteorological data. The uncertainty of four key parameters was propagated. Volumetric heat capacity, thermal conductivity and water content of the rock as well as an assumed error of the simulated surface temperature were sampled along assumed probability density functions during Monte-Carlo simulations with 150-500 realizations per point. These parameters were sampled from normal distributions truncated at $3\sigma$. No stratification and no change in total water content was assumed for the sub-surface. A standard random sampling scheme was employed without dedicated improvements such as latin hypercube sampling. Temperature profiles were initialized with the mean surface temperature of 1990-1993 and then spun with 1993 data to achieve a realistic temperature profile. During the simulation, the years 1993-2002 were taken as the baseline run that the simulated temperatures from the extreme year 2003 were compared to.

From the modelled transient temperature fields three quantities were extracted: 1) probability of permafrost occurrence based on the percentage of realizations with permafrost in the baseline run; 2) active layer depth based on the depth of 0 °C in maximum temperature of baseline; and 3) excess heat content of the permafrost body defined as the additional heat content (including latent heat) at a specific date compared with the maximum during the baseline run. From these results, the active layer depth not exceeded with a certain probability (Fig. 2) can be derived from its cumulative frequency (either for the baseline or 2003). The excess heat content of the permafrost body (proxy for frequency of likelihood of destabilization) was calculated for several dates during 2003 and expressed in mm water equivalent that could have been melted in order to arrive at numbers that can readily be put into context.

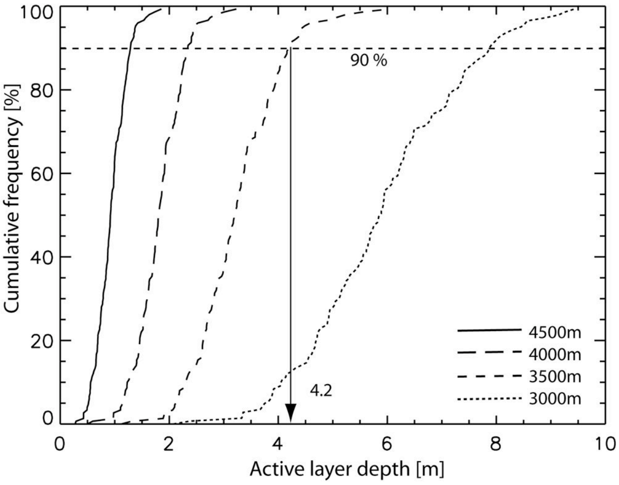

Figure 2. Cumulative probability distribution of the active layer depth (magnitude proxy) for several elevations, north-facing during the baseline run 1993-2002.

The findings of earlier modelling (Gruber et al. 2004a) were reproduced: The timing of observed rockfall and modelled destabilization conditions does not match. While much rock fall in 2003 took place at low altitudes and early in the year simulations results suggest destabilization in late summer or autumn for those locations. This points towards important challenges for future research about the processes that connect warming and permafrost degradation with the destabilization of rock slopes. Ice segregation due to the migration of unfrozen water along thermal gradients (Murton et al. 2001) is a process that may be underestimated in this context. Since it is driven by temperature gradients it may act earlier in the year that maximum temperatures or heat contents.

In contrast to the experiment presented here, permafrost bodies in mountain environments are complex and heterogeneous 3-dimensional objects. For the future, not only active-layer thickening but also long-term changes in the geothermal field need to be taken into account in the context of temperature-related stability changes (Fig. 3).

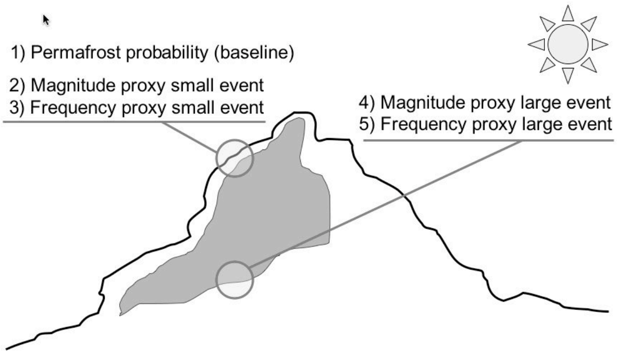

Figure 3. Schematic of possible future destabilization proxies.

The propagation of uncertainty in such models will be a key future step because it gives importance and visibility to the unknown instead of presenting accuracy in selected example cases. Findings based on simulations results can thus be interpreted and trusted better. However, such a development should not lead to the illusion of “certainty of uncertainty”. Especially the determination of the probability distribution of input parameters will continue to be challenging and require careful interpretation of results.

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