

Local distribution pattern of discontinuous mountain permafrost. A process study at Flüela Pass, Swiss Alps

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ABSTRACT: The present study focuses on the local pattern of permafrost distribution in an alpine area and its controlling factors. We chose a study site in the Flüela Pass (Grisons, Swiss Alps) that had been investigated in the early 1970s. The snow deposition and melt pattern, mainly affected by avalanche and snow drifting, was documented by an automatic camera with additional compilations from terrestrial and aerial photography. The resulting snow cover data was used to modify a spatial model of potential incoming short-wave radiation. These results were compared to seismic refraction soundings of the actual distribution of ice-rich permafrost. The melt pattern of the snow-cover in spring, the spatio-temporal pattern of snow cover thickness, related ground exposure to radiation and wind, and ground properties, all turned out to be important influences on local permafrost distribution.

1 INTRODUCTION

In recent years, efforts to model mountain permafrost over large areas have markedly increased. A number of GIS-based permafrost distribution models have contributed to substantially improved awareness and knowledge of mountain permafrost distribution (e.g. Keller, 1992; Hoelzle, 1996; Etzelmüller et al., 2001). Incomplete understanding of processes and data quality, however, limit the accuracy of such models at local scales (Lerjen, 2001). The purpose of this study, therefore, was to focus on the local permafrost distribution pattern and on the snow-melt pattern as a possible controlling factor. Snow-melt patterns have already been successfully used for permafrost modelling in sub-arctic terrain (Granberg, 1973; Nicholson & Granberg, 1973) and at larger scales in the Bernese Alps (Imhof, 1996).

In sub-arctic areas, early melt of the snow cover and the related lack of insulation during winter indicates permafrost. On the other hand, in the Bernese Alps the time of melt-out can be correlated with the BTS (basal temperature of snow cover) and, thus, with the permafrost distribution. In this case, late melt-out indicates enhanced protection from incoming radiation (Imhof, 1996).

The latter correlation was assumed to be operating at a smaller scale for a local occurrence of permafrost in the eastern Swiss Alps, within the zone of discontinuous mountain permafrost. Two debris slopes at Flüela Pass (Fig. 1), under study here, were investigated by Haeberli (1975) in the early 1970s. Seismic refraction soundings on two debris fans showed that at that time, a body of ice-rich permafrost was present, with the permafrost table dropping from 1 m depth near the lake to 10 m depth in the lower third of the slope (Fig. 2). In the same study, temperature profiles

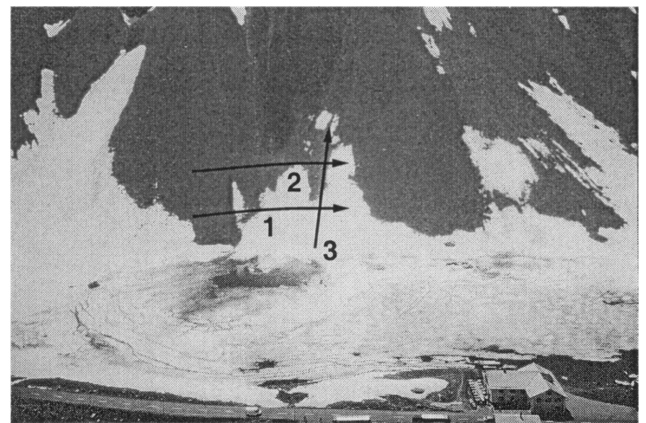


Figure 1. View of the debris slope under study at Flüela Pass, Swiss Alps, in June 1999 from the opposite slope. In the foreground, the restaurant and Schotten Lake are entirely covered by snow and ice. The numbered lines mark the approximate location of the seismic refraction profiles with arrows indicating the profile direction (cf. Fig. 6).

and excavations in the upper part of the debris slope and in the south-eastern foot zone did not show any evidence of permafrost. However, permafrost was predicted for the rock face of the Chlein Schwarzhorn above the debris slope.

The local permafrost occurrences were attributed to avalanche snow remaining at the foot of the slope into the summer. The snow deposits were assumed to influence the energy balance by reflecting direct incoming short-wave radiation and by using available energy for snowmelt (Haeberli, 1975).

Local variability in permafrost distribution and related ice-content within a talus slope was also observed by Delaloye et al. (2000) and Reynard et al. (2001). They attributed local variations to insulation effects by avalanche snow remnants in summer and to geomorphodynamic processes.

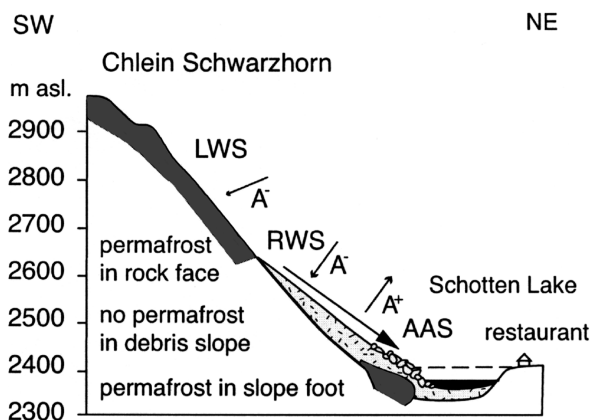


Figure 2. Permafrost and topo-climate at Flüela Pass (after Haeberli, 1975). LWS: lack of winter snow cover due to avalanche denudation. RWS: reduction of winter snow cover due to avalanches. AAS: accumulation of avalanche snow. A⁺: high albedo due to prolonged snow cover. A⁻: low albedo due to the lack of snow cover. Above the lake: tendency to temperature inversions.

In this paper, we describe in more detail how the snow-melt pattern and the related pattern of potential direct incoming radiation correlate with, or influence, respectively, the permafrost distribution. Furthermore, we test whether a GIS-based approach taking into account the snow-melt pattern can provide more realistic results for permafrost distribution (cf. Hoelzle et al., 2001).

In the study area, patchy permafrost was found only in the foot zone of a debris slope consisting of two fans of more or less uniform exposure and slope. Factors governing mountain permafrost distribution at large scales (e.g. mean annual air temperature as approximated by elevation, and incoming short-wave radiation as approximated by aspect and slope) must be overlain by local factors in order to explain the localized occurrences found here. Existing models based on the large-scale factors generally fail at this locality. They predict a vertical gradient from no permafrost to permafrost with increasing elevation, but are not able to model a local inversion (Lerjen, 2001; cf. Haeberli, 1975). Large scale models which include slope-foot situations (i.e. avalanche deposition zones), are potentially better able to reflect the permafrost distribution at the study site (Keller, 1992).

2 STUDY SITE

The study site, an area of approximately 0.1 km², is located on Flüela Pass, Grisons, Swiss Alps, between 2380 and 2500 m a.s.l. In its lower part, it consists of two active debris fans reaching from the rock faces of the Chlein Schwarzhorn to Schotten Lake. The fans

have a northeast exposure and a slope gradient of approximately 30 degrees. In their lower parts, the fans consist predominantly of coarse blocky amphibolite material, whereas in the furrow between the fans and in the upper part of the fans, the material is finer, partly organic, and partly paragneiss (Haeberli, 1975). The mean annual air temperature is approximately -2°C.

3 METHODS

In order to compute the pattern of incoming solar radiation reaching the ground, the snow-melt pattern between the date of the first snow-free area until the date of maximum melt-out was documented for 1999 using an automatic camera. The camera was installed on the slope opposite the investigation area and pictures were taken daily. 25 selected images were ortho-rectified using a high-resolution digital elevation model, geo-referenced with an accuracy of approximately 1 m, and then integrated in a GIS. (For details on the method see Lerjen, 2001; cf. also Krummenacher et al., 1998; Kääb & Vollmer, 2000). The pattern of potential direct incoming short-wave radiation was computed daily using the algorithm of Funk & Hoelzle (1992). This model was modified so that all snow-covered ground cells absorbed zero radiation. This procedure, following Imhof (1996), assumes that no short-wave radiation reaches the ground underneath the snow cover. Direct radiation and energy balance measurements were not available for this study. The necessary snow cover map was computed from the ortho-images compiled as described above. The pattern of the incoming short-wave radiation for days without image availability was computed by linear interpolation. The entire procedure ultimately led to a modified spatial pattern for potential incoming short-wave radiation.

Three tests were performed to evaluate the reliability of the approach:

1. Ten postcards and terrestrial images taken in former years, and five aerial photographs of former years were ortho-rectified and geo-referenced to evaluate whether the melt pattern observed for 1999 was similar to those from previous years.
2. Using the above-mentioned five aerial photographs with known acquisition dates, it was determined whether the progression of melt in 1999 was advanced or delayed compared to previous years. (The winter of 1998/1999 had extraordinary snow-falls with up to 1 m more than the 25-yr average).
3. Eight miniature temperature loggers (Krummenacher et al., 1998) were placed under the snow cover in July 1999 to examine the degree of correspondence between visual melt-out of the snow cover and rise of surface temperatures above 0°C.

In August 1999, seismic soundings were performed. We attempted to reconstruct the local setting used by Haeberli (1975) in order to allow direct comparison of the data-sets. Instead of using explosives (Haeberli), the initial impulse was given by a sledgehammer on a metal plate. Sounding results were interpreted using the same methods as Haeberli (1975): break-point and plus-minus methods (Hagedorn, 1959).

4 RESULTS

The compilation of the automatic camera imagery for 1999, and its comparison to postcards and to terrestrial and aerial imagery, showed that snow remains longest in the furrow between the two slopes (Figs. 1, 3 and 4).

Snow cover disappeared up to 100 days earlier on the upper part of the debris slope and on the convex centres of the fans, than in the furrows. The snow accumulations in the slope-foot zone result mainly from avalanches. The other zones of late snow melt to the left and right of the slope under study (Fig. 1) can be attributed to enhanced snow accumulation by snow drifting. The study area is subject to strong winds due to its topographic location.

The spatial snow-melt pattern observed in 1999 appears to be representative of other years (Fig. 4). The heavy snowfalls in winter 1998/1999 had neither a large influence on the spatial pattern nor on the date of local snow melt-out. The date of complete snow melt for an individual point was about 6 days later in 1999 compared to the average of the other five years. It appears that the heavy snowfalls only resulted in larger snow-drifts in the areas NW and SE of the pass.

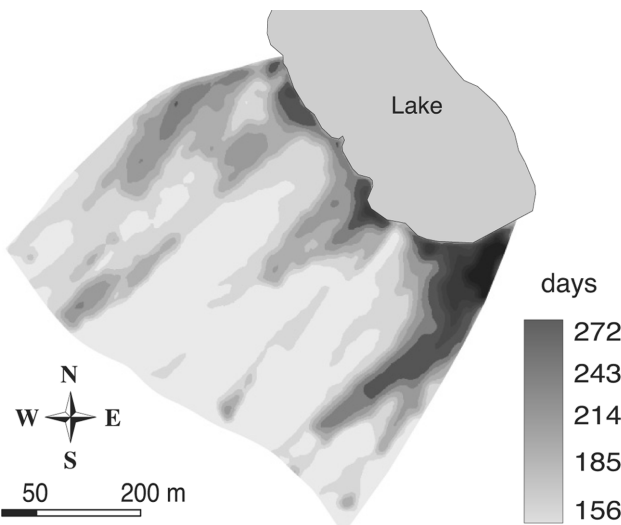


Figure 3. Pattern of snow melt-out in the study area observed for 1999. The melt-out happened between 5 June (day 156) and 30 September (day 273), the day of first snowfall in autumn.

Results from the temperature logging show good agreement with the observed snow disappearance. For the eight test locations with miniature loggers the date of visible snow disappearance differed by no more than two days from the date when the observed ground surface temperature rose above 0°C.

The distribution of computed potential direct radiation reaching the ground surface is shown in Figure 5. The major influence of the snow melt pattern included in the model can clearly be seen.

The measured unfrozen layer thickness differs from that found by Haeberli (1975) by up to 5 m: the unfrozen layer observed in our study is significantly thinner and shows a uniform, but much weaker gradient (i.e. getting thicker upwards the slope) compared to that

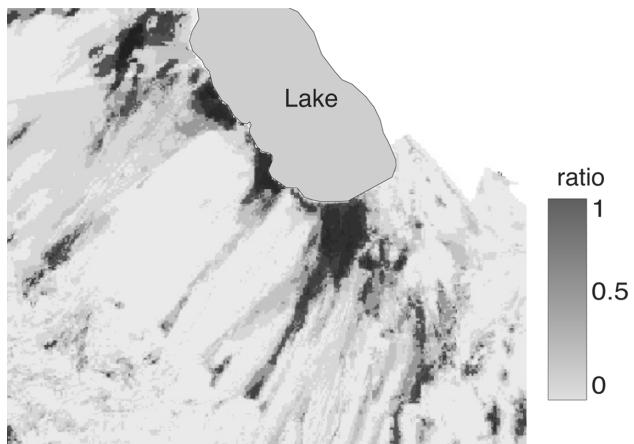


Figure 4. Pattern of melt-out in the investigation area based on samples between 1910 and 1997. Shown is the ratio between the images showing snow cover and all images depicting an individual point. This normalisation is necessary to account for different terrain coverage of the images. 1 (=100%) means snow cover on all images covering the pixel, 0 (=0%) means no snow cover on any image covering the pixel.

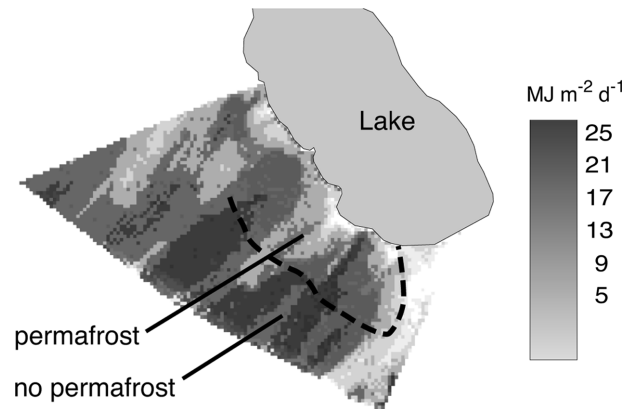


Figure 5. Modelled pattern of potential incoming short-wave radiation reaching the ground surface in 1999 and the estimated permafrost distribution resulting from measurements in 1975 and 1999 (dashed line). The radiation pattern was modelled including the snow-melt pattern.

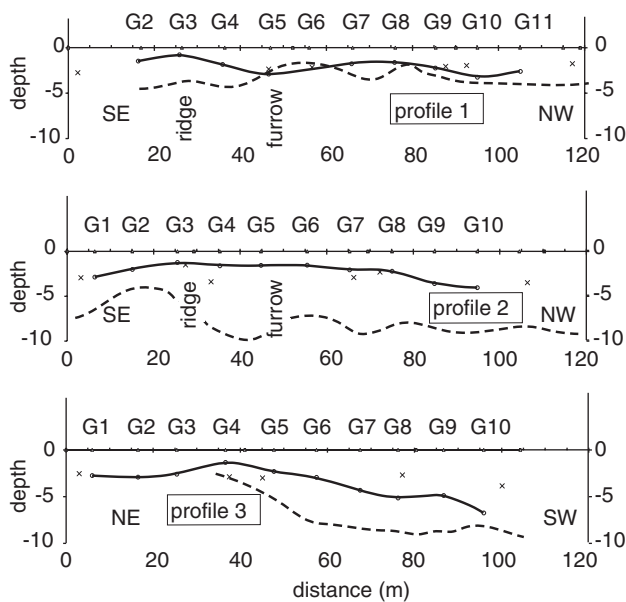


Figure 6. Unfrozen layer depth derived from seismic profiles. The location and direction of the profiles is given in Figure 1. Dashed line: results from Haeberli (1975). Bold line with circles: plus-minus method, 1999. Crosses: break-point method, 1999. G: geophone positions.

recorded by Haeberli (1975) (Fig. 6). The unfrozen layer thickness increased from 1 m in the foot zone to 10 m in the upper part of the permafrost patch according to Haeberli (1975). We found an increase of only 5 m. However, the lack of knowledge about annual and seasonal variations in thaw layer conditions and the different impulse-generation techniques employed, make comparisons difficult. Further investigations on this topic are necessary. Geophysical surveys in the upper part of the slope and to the northeast of the study site were not repeated. We assume that these zones are still permafrost-free.

5 DISCUSSION

The comparison of the pattern of potential incoming short-wave radiation and the observed permafrost distribution suggests that at the scale of the entire slope, permafrost inversion (i.e. permafrost at the foot, but not in the upper part) is controlled by long-lasting avalanche snow deposits. At a more detailed local scale, however, permafrost can be present or absent at places that become snow-free very early and therefore are exposed to similar incoming short-wave radiation. For the study site, the date of complete snow-melt does not appear to be a strong indicator of permafrost presence. For instance, areas melting out very early such as the ridge in Figure 7 (arrow) showed permafrost. On the other hand, for the area to the northeast of the study site, where melting-out happened very late, no evidence for permafrost was found (Haeberli, 1975).



Figure 7. The snow pattern of 22 June 1999 showing the large influence of snow drifting on the snow cover, as is the case for the ridge marked with an arrow.

This weak correlation between the time of melt-out and permafrost existence is underlined by the fact that some zones which melt out very early show significantly lower unfrozen layer thicknesses (0.5 m under the ridge) than areas melting out up to two months later (up to 3 m under the area in the lee of the ridge).

At the study site, especially early or late melt-out dates relate to certain characteristic situations:

1. Early melt-out occurs where the snow cover is thin due to loss by avalanches or by persistent wind exposure. For the latter, snow insulation effects are low throughout the winter, and the exposure to the wind favours ground cooling by latent and sensible heat fluxes, and by outgoing long-wave radiation. In contrast, for the avalanche-denudation zones, the snow cover provides insulation until loss by the first avalanche event, and the zones are usually less exposed to wind cooling. Thus, although both situations melt out early, their energy fluxes and budgets are very different.
2. Late melt-out of the snow cover occurs in situations with deep snow accumulation from drifting or avalanche deposition. While the avalanche activity starts at some point during the course of the winter, snow drifting and deposition represent nearly continuous processes that start with the first snowfall. In the latter locations, energy exchange with the atmosphere stops comparatively early.

In addition to the effects of snow on the local permafrost pattern, a clear correlation was found between permafrost existence and surface properties. Zones with and without permafrost differ in grain-size and sorting. In the zone with abundant permafrost at the slope foot, coarse blocky materials dominate. Finer sands and partly organic material are found in the upper part of the slope and in the north-eastern

slope foot (Fig. 2). This distribution of grain sizes can be partially explained by sorting due to gravity.

It is possible, therefore, that the observed permafrost distribution to be mainly influenced by either the composition of the ground, or the resulting energy fluxes at the ground-atmosphere boundary. In previous studies the kind of surface and material was found to be crucial to winter heat loss from the ground: blocky material cools significantly faster than fine sands and organic materials (Harris & Pedersen, 1998; Mittaz et al., 2000). Cooling in cavernous blocky material can be accelerated by fluxes of cold air (Wakonigg, 1996; Bernhard et al., 1998; Delaloye et al., 2001).

6 CONCLUSIONS

For the study site at Flüela Pass, Swiss Alps, we propose the following hypotheses about influences on local permafrost distribution:

1. At wind-exposed situations, strong ground cooling during the entire winter out-weighs the related early snow melt and subsequent ground heating.
2. Terrain with late snow melt also shows high snow thickness in early winter. The ground is not able to cool, and heats up quickly after snow melt. The latter hypothesis applies to snow drift accumulation sites, but not to avalanche deposits sites.
3. Avalanche deposits sites accumulate deep snow in mid- or late-winter, so that the ground is able to cool in early winter, and is protected from heating in spring due to the late-lying avalanche remnants.
4. Avalanche source zones and tracks show normal snow thicknesses in early winter, but snow melts early in spring, both favouring higher ground temperatures.
5. The above-mentioned influences can interact with each other leading to a complex spatio-temporal evolution of energy fluxes.
6. The development of active layer thickness and permafrost distribution on the debris slopes clearly is linked to grain sizes and ground cover.

Permafrost conditions were not only dependent on the time of melt-out. Instead, the entire snow cover history seems crucial for the permafrost existence (cf. Zhang et al., 2001). For the study site it can clearly be disproved that the snow melt pattern alone is a good indicator of permafrost distribution at a local scale. For larger scales and areas with smaller impacts from wind and avalanches a better correlation between snow melt pattern and permafrost distribution can be found (Imhof, 1996).

Surface roughness and other properties may have a decisive influence on permafrost distribution at local

scales, potentially even over-riding the effects of snow cover.

Finally, despite the clear atmospheric warming that has occurred since Haeberli's study in the 1970s no significant difference was found between the present and the 1970s permafrost distribution in the Flüela slope. Repeated investigations and higher measurement accuracy would be necessary to better detect such potential permafrost changes.

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