ON THE RELATION BETWEEN MOUNTAIN PERMAFROST AND SNOWPACK STABILITY

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ABSTRACT: Many recreational avalanche accidents occur in areas where mountain permafrost exists. Consequently, it has been proposed that the presence of sub-zero ground temperatures favours snowpack instability. In the mainly transitional climate of the Swiss Alps, permafrost prevails in shady slopes above about 2500 m a.s.l. To investigate the effect of mountain permafrost on snowpack stability, over 400 snow profiles with stability tests were analysed, taken in both permafrost-free and permafrost terrain. Snowpack characteristics and stability were compared for the profiles from the two areas. Though basal snowpack characteristics were partly different, no indication was found that permafrost terrain causes the development of an unstable snowpack. However, a shallow snow depth favoured below freezing ground temperatures as well as snowpack instability. The occurrence of many avalanche accidents on permafrost terrain rather reflects skiing preference - due to better snow conditions on shady slopes - than a causation, and is therefore merely a coincidence.

KEYWORDS: snowpack stability, stability evaluation, permafrost

1. INTRODUCTION

In the Swiss Alps (46.5°N) mountain permafrost is widespread above about 2500 m a.s.l. on shady slopes and above about 3000 m a.s.l. on south facing slopes. Permafrost is permanently frozen ground (independent of ice content) and can consist of any type of frozen earth material such as bedrock or scree. Mountain permafrost distribution is strongly dependent on the temporal and spatial distribution of the snow cover (Phillips et al., 2000) and avalanche activity has a direct influence on permafrost distribution because snow melt is delayed on avalanche debris cones, thus reducing ground temperature (Lütschg, 2004). Keller and Gubler (1993) compared the snow cover conditions at two sites: on an active rock glacier and on nearby permafrost-free terrain.

Analysis of avalanche accident statistics in the Swiss Alps indicates that 50% of accidents occur above 2400 m (Schweizer and Lütschg, 2001) and that 68% occur between 2000 and 3000 m (Meister, 1987), a large number therefore in potential permafrost terrain. This coincidence might be interpreted as causal. On the other hand, it is surmised that the snowpack may be more stable on permafrost due to the presence of a smaller temperature gradient within the snowpack as ground temperatures are lower. Hence, It is not clear whether or not permafrost has a significant influence on snowpack stability and avalanche formation in high alpine terrain.

The aim of the study is to describe snowpack characteristics in permafrost and permafrost-free areas on comparable types of ground cover and to assess whether the frozen ground (or mountain permafrost distribution) affects snowpack stability in Alpine areas. Over 400 snow profiles with stability tests from the surroundings of Davos, Switzerland that were located at different altitudes in permafrost and permafrost-free terrain were analysed to establish the respective snowpack characteristics, stability, temperature gradients and ground cover characteristics.

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2. METHODS

To verify the number of avalanche accidents in permafrost terrain the SLF Avalanche Data Base was analysed with respect to terrain characteristics (elevation, aspect and slope angle). Only the fatal accidents which occurred between 1981 and 2001 in the Swiss Alps were considered. Avalanches which were triggered on glaciers were excluded from further analysis.

In the course of winters 2001-2002 and 2002-2003, 447 full snow profiles with rutschblock tests were effected on slopes in the surroundings of Davos at altitudes ranging between 1835 and 2965 m a.s.l. (Schweizer et al., 2003). Elevation, slope angle and aspect were measured at the profile site. Snow cover properties were classified according to Colbeck et al. (1990). Layer thickness, grain type, grain size, hand hardness index, and snow temperature were recorded.

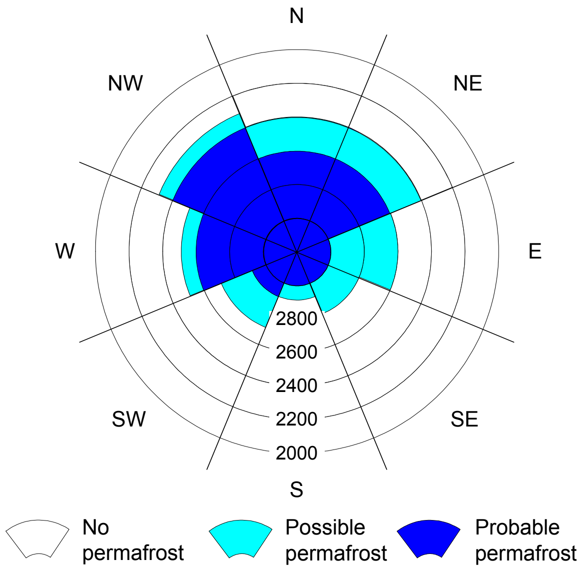

Figure 1: Permafrost distribution in the Alps on slopes steeper than 11° (based on the rules of thumb developed by Haeberli, 1975).

Each snow profile was attributed to a permafrost or non-permafrost category. As it was not possible to verify the presence of permafrost directly, permafrost distribution was determined according to the rules of thumb developed by Haeberli (1975), whereby two classes of permafrost are distinguished (Possible permafrost and Probable permafrost) as well as permafrost-free terrain (Fig. 1). The determining factors used for the classification are elevation, aspect and general surface morphology. The term Potential permafrost terrain is used in this paper to group the two classes Possible and Probable permafrost.

In order to exclude bias due to stability variations caused by aspect, the analysis was restricted to the profiles taken on generally shady slopes oriented N, NE and NW. This reduced the number of profiles for analysis to 254 at elevations between 1980 and 2940 m a.s.l. 84 profiles were located in permafrost-free terrain, 80 in Possible permafrost terrain, and 90 in Probable permafrost terrain.

For analysis, the ram profile of each snow profile was assigned a profile type (1-10) according to the classification proposed by Schweizer and Lütschg (2001). Profile types 1-5 indicate snowpacks which have a weak, poorly consolidated base, whereas profiles types 6-10 represent snowpacks with well consolidated bottom layers. Each profile was classified in respect to stability into Very Poor (1), Poor (2), Fair (3), Good (4), and Very Good (5) following the classification scheme proposed by Schweizer and Wiesinger (2001).

To compare snowpack conditions in permafrost and non-permafrost terrain, the following variables were analysed for profiles in both types of terrain: profile type, snow depth, ram hardness (averaged over the total snow depth), snowpack stability, ground surface temperature; temperature gradient in the lowermost 50 cm of the snowpack, maximum grain size, dominant grain type and hand hardness index in both the bottom 50 cm and the lowermost layer of the snowpack as well as type of ground cover (three classes: blocks, scree, grass).

Comparison of permafrost and non-permafrost data sets was effected using the non-parametric Mann-Whitney *U*-Test, which allows to determine whether the two samples are different.

Table 1: Characteristics of fatal avalanche accidents (Swiss Alps, 1981-2001) in regard to permafrost distribution assigned by rules of thumb (Fig. 1, Haeberli, 1975).

Terrain	N	Median elevation (m a.s.l.)	Most frequent aspect	Median slope angle (°)
Non-permafrost	160	2200	N	39
Possible permafrost	38	2550	N	39
Probable permafrost	56	2745	NW	39.5
Glacier	37	3160	N	42.5

A level of significance $p = 0.05$ was chosen to decide whether the observed differences were statistically significant. Comparing categorical variables such as grain type or profile type, the distributions were compared by cross-tabulating the data and calculating the Pearson χ^2 statistic.

3. RESULTS AND DISCUSSION

3.1 Avalanche accidents

Between 1981 and 2001 a total of 291 fatal avalanche accidents occurred in the Swiss Alps. The altitude of the avalanche fracture lines ranged between 1230 and 4070 m a.s.l. 50 % of the avalanches started above 2435 m (median), i.e. near the lower limit of mountain permafrost. If glaciers were excluded from the analysis, 37% of the accidents occurred in Potential permafrost terrain (i.e. Possible and Probable permafrost sites combined), independent of aspect and slope angle (Table 1). Accidents most frequently occurred in the aspects N, NW and NE (62% of all accidents). Median slope angle of avalanche accident sites in both permafrost and permafrost-free terrain was about 39°.

3.2 Snowpack analyses

The Potential permafrost and permafrost-free samples are compared in Table 2, where the key statistics are shown. The profiles were assigned to the two categories based on elevation and aspect (Fig. 1). Only profiles in the aspects NW, N, NE were considered.

The test statistics computed for each variable individually might not be independent due

Table 2. Median values for each parameter analysed in non-permafrost and potential permafrost terrain (data from winters 2001-2002 and 2002-2003). Modal values are shown for categorical variables marked with an asterisk (*). The three most frequent categories are given for profile type and grain type. The level of significance p based on the U-Test indicates whether the two samples are significantly different.

Variable	Non-permafrost N = 82-84 (median or *mode)	Potential permafrost N = 164-170 (median or *mode)	Level of significance p
Elevation (m)	2275	2520	<0.001
*Aspect	N	N	0.03
Slope angle (°)	34	35	0.015
*Profile type	1, 6, 4	6, 7, 8	<0.001
Stability	Fair (3)	Fair (3)	0.36
*Ground cover	Grass	Scree	<0.001
Snow depth (cm)	120	138	0.002
Average ram hardness (N)	39	89	<0.001
*Grain type in bottom layer of snowpack	5, 4, 9	5, 4, 9	0.15
Max. grain size in bottom layer (mm)	3	3	0.64
Hand hardness index in bottom layer	2	3	<0.001
Max. grain size in lowest 50 cm of snowpack (mm)	4	4	0.59
*Grain type where max. grain size in lowest 50 cm	5, 9, 4	5, 4, 9	0.047
Mean hand hardness index in lowest 50 cm	2	3	<0.001
Ground temperature (°C)	-0.4	-1.6	<0.001
Snow temperature at 50 cm (°C)	-2.8	-3.5	0.003
Temperature gradient in lowest 50 cm (°C/m)	4.1	3.2	0.004

to possible correlations between variables. Since the classification into non-permafrost and Potential permafrost was based on elevation (and aspect) it was expected that some of the variables that show a significant difference at the 95% confidence level will simply reflect the effect of elevation. In fact, snow depth and elevation were highly correlated, as were snow depth and ram hardness, mean hardness in the bottom 50 cm and snow depth. All these variables showed a significant difference between the non-permafrost and the Potential permafrost locations. Also, ground surface temperature which was highly correlated with elevation (and to a lesser degree with snow depth) was a statistically significant variable.

At permafrost-free sites 67% of the profiles were weak-based (types 1, 6 and 4 predominated; 1 and 4 are weak-based) and at sites with potential permafrost 59% of the profiles were strong-based (types 6, 7 and 8 predominated, all strong-based). Profile type was strongly correlated with snow depth, which explains these differences as median snow depth was larger at the permafrost sites.

Maximum grain size in the bottom layer of the snowpack and in the lowermost 50 cm was the same in both types of terrain, as were the grain types. In both samples depth hoar (5), faceted crystals (4) and mixed forms (rounded facets: 4c) were most frequently found. As ground temperature was colder in permafrost terrain, the temperature gradient in the lower 50 cm was also smaller which would imply that conditions were less conducive to kinetic growth and hence to the formation of facets and depth hoar (Fig. 2). This was not observed. However, grain types in the bottom layer rather reflect early winter conditions, as snow tends to arrive earlier at high altitudes and depth hoar can form when there is a thin snow cover with a strong temperature gradient.

The median snow stability level was the same for both types of terrain (Fair: 3) with very similar stability distributions (Fig. 3), despite the fact that parameters such as profile type, ram hardness, hand hardness, ground temperature and temperature gradient were different. This is because the variables considered do not have a direct dominating influence on stability. The strongest (significantly positive) correlation with stability was found for snow depth. However, the crucial factors influencing stability are of course weak layer formation, survival before burial and consolidation. These can easily be similar for sites on permafrost and non-permafrost terrain.

4. CONCLUSIONS

Snow profile data from an Alpine region in Switzerland obtained in the context of an extensive field campaign in 2002 and 2003 was analyzed with respect to differences between permafrost-free and Potential permafrost sites. As expected, the main difference was that ground surface temperature was lower, and correspondingly the

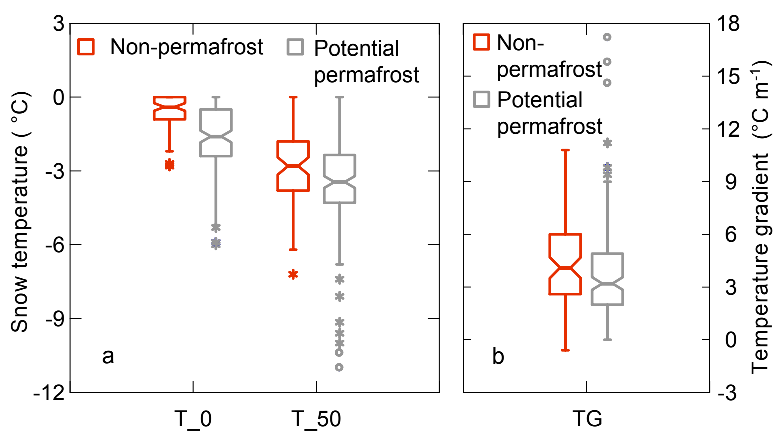

Figure 2: Comparing thermal conditions for non-permafrost (*N* = 82) and Potential permafrost sites (*N* = 164). (a) Ground surface temperature (T_0) and snow temperature at 50 cm (T_50), and (b) the temperature gradient in the lower 50 cm (TG) were all significantly different. For each variable non-permafrost data are on the left and Potential permafrost on the right given. Boxes span the interquartile range from 1st to 3rd quartile with a horizontal line showing the median. Notches at the median indicate the confidence interval ($p < 0.05$). Whiskers show the range of observed values that fall within 1.5 times the interquartile range above and below the interquartile range. Asterisks show outliers, open dots show far outside values.

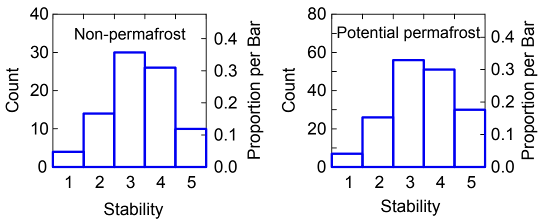

Figure 3: Comparing stability distributions for non-permafrost and Potential permafrost sites (N = 254). Median stability was Fair (3) for both samples.

temperature gradient in the lowermost 50 cm of the snowpack was reduced at the permafrost sites. However, in both samples kinetic growth grain types dominated in the lower parts of the snowpack. The permafrost snowpack was slightly harder and better consolidated in the lower parts. Most of the other statistically significant differences stemmed from the correlation of the variables with elevation which is the key parameter to assess permafrost distribution. Despite the differences in snowpack characteristics at the base of the snowpack, the overall snowpack stability was not significantly different in permafrost terrain when compared to that in permafrost-free terrain.

It was confirmed that a substantial part (37%) of the fatal avalanche accidents in the Swiss Alps occurred in potential permafrost terrain, primarily on shady slopes above 2500 m a.s.l. However, this portion is similar to the portion of potential permafrost terrain that exists according to the rules of thumb (Haeberli, 1975) in the same elevation range as the accidents occur. This and our analysis suggest that the parallel occurrence of avalanche triggering and permafrost terrain is not causal but coincidental. The relation is most likely due to skiing preferences, as shady slopes above 2500 m a.s.l. often have good skiing conditions and are therefore sought out by recreationists.

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