Available online at www.sciencedirect.com

ScienceDirect

Cold Regions Science and Technology 47 (2007) 43 – 49

cold regions science and technology

www.elsevier.com/locate/coldregions

Effect of mountain permafrost on snowpack stability

Marcia Phillips, Jürg Schweizer *

Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland

Abstract

Statistics on recreational avalanche accidents suggest that a substantial part of all accidents occur in areas where mountain permafrost exists. Accordingly, 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. In order 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, i.e., at different elevations. Samples were collected in January, February and March, when the snowpack was cold. Locations on glaciers were excluded from the analysis. To compare profiles from the two areas they were rated into five classes of stability. Also, the temperature at the base of the snowpack, the temperature gradient and the maximum grain size in the lowermost 50 cm were compared. No significant difference in snowpack stability between permafrost and permafrost-free profile locations could be found. Basal snow temperatures were statistically significantly lower for the permafrost locations. Snowpack depth had a significant effect on the ground surface temperature. With the slightly lower basal temperatures, temperature gradients were accordingly slightly lower as well. The effect on the maximal grain size, supposedly an index for the past temperature gradient, and on snowpack stability was minor. Overall, 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. Snow depth was significantly positively related to snowpack stability. In conclusion, the presence 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: Snow avalanche; Snowpack stability; Stability evaluation; Mountain permafrost

1. Introduction

In the Swiss Alps 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 (Haeberli, 1975). Permafrost is permanently frozen ground (independent of ice content) and can consist of any type of frozen earth material such as bedrock, scree or moraine. 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 (Luetschg et al., 2004).

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.

It is not clear whether or not permafrost has a significant influence on snowpack stability and avalanche

---

* Corresponding author. Tel.: +41 81 4170111; fax: +41 81 4170110.
E-mail addresses: phillips@slf.ch (M. Phillips), schweizer@slf.ch (J. Schweizer).

0165-232X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2006.08.010

formation in high alpine terrain. However, 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. Keller and Gubler (1993) investigated the snowpack on a rock glacier (a permafrost feature consisting of creeping rocks and ice) and in adjacent permafrost-free terrain and observed that snow on the permafrost site contained larger amounts of rounded grains. Keller (1994) nevertheless also observed that a thin autumn snow cover often persists in permafrost areas, leading to the formation of a weak basal layer due to a high temperature gradient. The constitution of the snowpack on alpine permafrost has mainly been investigated on rock glaciers or on block scree slopes, i.e., on very coarse blocky terrain, where air circulation within the snowpack appears to have an important role (e.g., Bernhard et al., 1998; Delaloye et al., 2003; Hoelzle et al., 1999; Lütschg, 2005).

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 regions—where the climatic conditions are similar in permafrost and non-permafrost areas, as is not the case, for example, in Arctic or sub-Arctic 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.

2. Methods

To verify the number of avalanche accidents in permafrost terrain the SLF Avalanche Database was used (Harvey, 2002) and the fatal avalanche accidents which occurred between 1981 and 2001 in the Swiss Alps were analysed with respect to terrain characteristics (elevation, aspect and slope angle). Avalanches which were triggered on glaciers were excluded from further analysis. Unclear cases were verified in the SLF Winter Reports.

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. The data were obtained in the context of a field campaign to verify snowpack stability and avalanche danger (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. Hand hardness for individual layers was indexed from 1 to 6 for Fist (F), Four-Finger (4F), One-Finger (1F), Pencil (P), Knife (K) and Ice (I), respectively. Rutschblock tests were performed as described in Schweizer (2002).

The two winters had distinct snow conditions. In winter 2001–2002, the profiles were collected on 10 days between 21 January 2002 and 21 March 2003. During this period the snow depth was about 75% of the long-term average at Weissfluhjoch study plot above Davos. In winter 2002–2003, the snow depth was about 130% of the long-term average during the data collection period (9 days between 14 January 2003 and 20 February 2003). The forecasted level of avalanche danger ranged from Low (1) to High (4) on the days of data collection. Accordingly, the data cover a variety of snowpack conditions and no bias is expected in this respect.

Each snow profile was attributed to a permafrost or non-permafrost category. As it was not possible to verify the presence of permafrost directly, in a first step permafrost distribution was determined according to the rules of thumb developed empirically by Haeberli (1975) for slopes steeper than 11°, whereby two classes of permafrost are distinguished (possible permafrost and probable permafrost) as well as permafrost-free terrain (Table 1). The determining factors used for the classification are elevation, aspect and general surface morphology. The rules of thumb were largely determined by geophysical measurements, ground temperature data and visual observations. The model has been confirmed by numerous measurements effected since 1975 (Keller et al., 1998). The term potential permafrost terrain is used in this paper to group the two classes possible and probable permafrost.

Table 1
Permafrost distribution in the Swiss Alps according to the rules of thumb developed empirically by Haeberli (1975) for slopes steeper than 11°

Aspect	Elevation below which there is probably no permafrost (m)	Elevations at which permafrost is possible (m)	Elevation above which permafrost is probable (m)
N	2400	2400–2600	2600
NE	2400	2400–2600	2600
E	2600	2600–3000	3000
SE	2800	2800–3000	3000
S	2900	2900–3000	3000
SW	2700	2700–2900	2900
W	2500	2500–2600	2600
NW	2300	2300–2400	2400

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. Most of the profiles effected in other aspects were also at altitudes too low to be in potential permafrost terrain.

In a second step of the analysis, to increase the contrast between the two categories permafrost-free and potential permafrost, conditions to fall into the permafrost category were amended and only sites with ground surface temperature colder than −2 °C were considered as being in potential permafrost. Generally, permafrost can be assumed to be present when ground temperatures are below −2 °C to −3 °C in February and March with a snow depth of around 100 cm (Hoelzle, 1992). 80 profiles which were already classified as being in permafrost-free terrain and which had ground temperatures above −2 °C were used for the non-permafrost sample. 70 profiles from the categories probable permafrost (37), possible permafrost (29) and permafrost-free (4) had temperatures colder than −2 °C and were classified as being potential permafrost. The remaining profiles (from the initial categories possible and probable permafrost with temperatures warmer than −2 °C) were ignored in order to possibly increase distinct differences between the two data sets.

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 parameters were analysed for profiles in both types of terrain: profile type, snow depth, average ram hardness (over the whole depth), snowpack stability, temperature at the base of the snowpack (also called 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 or not there is a difference between the two samples. 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 (Spiegel and Stephens, 1999).

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. The median elevation was 2435 m, i.e., 50% of the avalanches started above this altitude (i.e., near the lower limit of mountain permafrost). 160 occurred in non-permafrost terrain, 38 in possible, 56 in probable permafrost and 37 on glaciers. If glaciers are 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. Accidents most frequently occurred in the aspects N, NW and NE (62% of all accidents). This dominance of the shady aspects was observed for both accidents in non-permafrost terrain (61%) and accidents in potential permafrost terrain (62%). Median slope angle of avalanche accident sites in both permafrost and permafrost-free terrain was 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 (Table 1). Only profiles in the aspects NW, N, NE were considered.

The test statistics computed for each variable individually might not be independent due 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 (Fig. 1).

Despite the fact that N is the most frequently occurring aspect for both non-permafrost and potential permafrost locations, there is a significant difference between the two categories ($p=0.03$) because the second most frequently occurring aspect for non-permafrost is NE, whereas it is NW for potential permafrost sites. The difference is due to the lower elevation limit of permafrost (Table 1) on northwesterly slopes so that the potential permafrost sample included relatively more profiles from northwesterly slopes than from northerly and northeasterly slopes. Similarly to snow depth, ground cover is an altitude dependent variable so grass dominates in the lower, permafrost-free sites whereas scree is the predominant ground cover in the permafrost areas.

Table 2
Median values for each parameter analysed in non-permafrost and potential permafrost terrain (data from winters 2001–2002 and 2002–2003)

Parameter	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, 4a, 4c	5, 4a, 4c	0.15
Maximum grain size in bottom layer (mm)	3	3	0.64
Hand hardness index in bottom layer	2	3	<0.001
Maximum grain size in lowest 50 cm of snowpack (mm)	4	4	0.59
*Grain type where maximum grain size in lowest 50 cm	5, 4c, 4a	5, 4a, 4c	0.047
Mean hand hardness index in lowest 50 cm	2	3	<0.001
Ground surface 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

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.

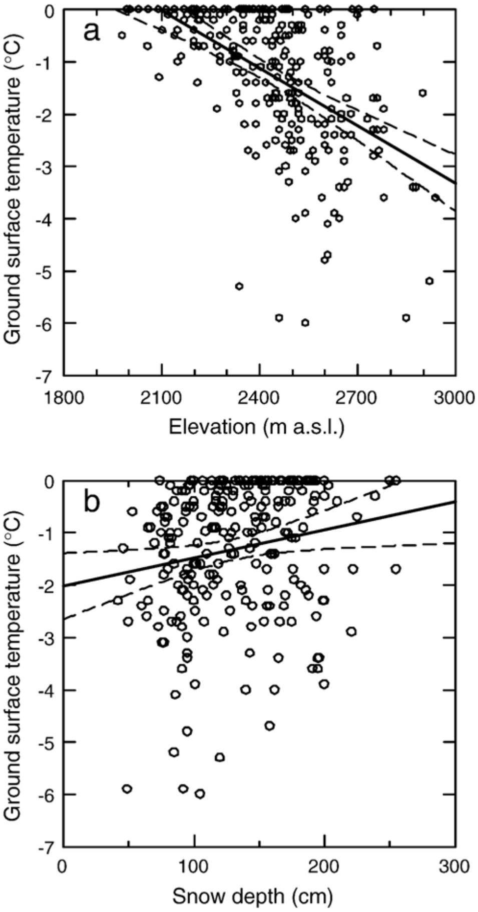

Fig. 1. Ground surface temperature (at the bottom of the snowpack) in relation to (a) elevation and (b) snow depth (N=246). Linear regression lines are shown (solid) with 95% confidence intervals (dashed). Both regressions were statistically significant. Surface ground temperature decreased with increasing elevation (−0.37 °C/100 m, $p<0.001$) and increased with increasing snow depth (0.54 °C/m, $p=0.004$).

There is a slight but nevertheless statistically significant difference in slope angle that is incidental due to sampling preferences. Although snowpack stability is correlated with slope angle this small difference will not affect stability in our distribution sample (about 15° modification in slope angle correspond to 1 level of stability).

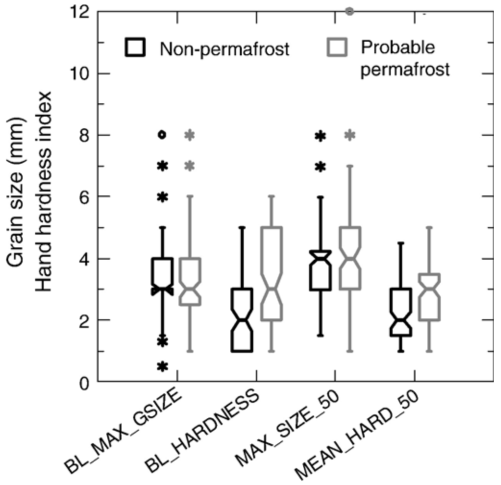

Fig. 2. Grain size and hand hardness index in the bottom layer (BL) and the lowermost 50 cm of the snowpack. Grain size was similar, hand hardness index was different, with lower hardness at the non-permafrost sites. For each variable, non-permafrost data are on the left and probable permafrost is given on the right. Boxes span the interquartile range from first to third 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.

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 is 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 (Fig. 2), as were the grain types. In both samples depth hoar (5), faceted crystals (4a) 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. 3). 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. 4), 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 variable showing the strongest correlation with stability was snow depth. Snow depth was significantly positively related to snowpack stability. However, weak layer formation, survival and consolidation are of course the crucial factors influencing stability.

If ground temperature at the base of the snowpack (≤ −2 °C) was added to the permafrost-determining factors elevation and aspect, a few small changes in relations between the different parameters investigated in both

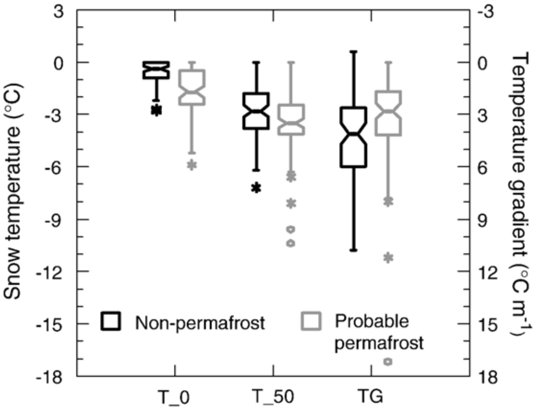

Fig. 3. Comparing thermal conditions for non-permafrost ($N=82$) and probable permafrost sites ($N=87$). Ground surface temperature (T_0), snow temperature at 50 cm (T_50) and thereof calculated temperature gradient (TG) were all significantly different (same figure type as shown in Fig. 2).

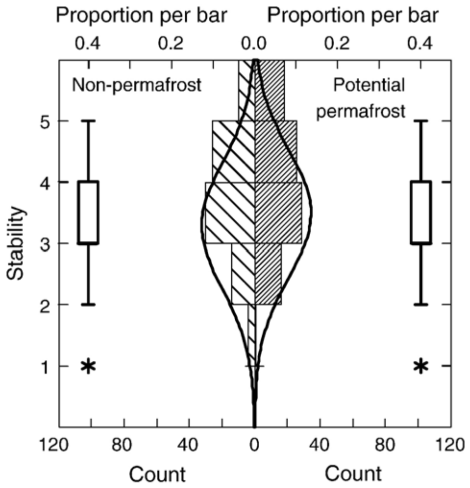

Fig. 4. Comparing stability distributions for non-permafrost and potential permafrost sites ($N=254$). Median stability was fair (3) for both samples.

types of terrain appeared, but essentially the patterns described above hold. The potential permafrost and non-permafrost samples determined according to elevation (see Table 1), the aspects N, NW and NE and ground temperatures above or below −2 °C are compared in Table 3, where the key statistics are shown.

Using ground temperatures below −2 °C as an additional permafrost indicator has the effect of making snow depths on both types of terrain more similar (colder ground temperature is statistically significantly related to lower snow depth, see Fig. 1). There is no longer a significant difference in aspect as N is now clearly predominant for both types of terrain. Profile types are still similar but there is now also a weak-based profile type (2) on permafrost sites. This is probably also linked to the fact that snow depths were generally lower.

Table 3
Comparison with restricted conditions for potential permafrost occurrence: permafrost is determined according to elevation and aspect (N, NW, NE) (based on Table 1), and in addition ground temperature (≤−2 °C)

Parameter	Non-permafrost (and ground temperature > −2 °C) *N*=80 (median or *mode)	Potential permafrost (ground temperature ≤ −2 °C) *N*=70 (median or *mode)	Level of significance *p*
Elevation (m)	2265	2575	<0.001
*Aspect	N	N	0.183
Slope angle (°)	33.5	36	0.003
*Profile type	1, 6, 4	7, 8, 2	<0.001
Stability	3	3	0.656
*Ground cover	Grass	Scree	<0.001
Snow depth (cm)	120	113	0.584
Average ram hardness (N)	39	96	<0.001
*Grain type in bottom layer of snowpack	5, 4a, 4c	5, 4a, 7	0.024
Maximum grain size in bottom layer (mm)	3	3	0.858
Hand hardness index in bottom layer	2	3	0.001
Maximum grain size in lowest 50 cm of snowpack (mm)	4	4	0.487
*Grain type where maximum grain size in lowest 50 cm	5, 4a, 4c	5, 4a, 7	0.046
Mean hand hardness index in lowest 50 cm	2	3	0.003
Ground surface temperature (°C)	−0.25	−2.7	<0.001
Snow temperature at 50 cm (°C)	−2.8	−4.1	<0.001
Temperature gradient in lowest 50 cm (°C/m)	4.2	2.6	<0.001

See key to Table 2.

Overall, the two different ways of classifying profiles into permafrost-free and permafrost terrain revealed the same results. This indicates that the above findings are not caused by peculiarities of the choice of permafrost classification, as we do not know for certain whether permafrost really exists at the locations classified as permafrost terrain (for obvious reasons, no direct or indirect permafrost verification techniques such as borehole drilling or geoelectric soundings can be carried out at each snow profile site). However, in particular the second classification also considering ground temperature should reduce misclassification and prevent incorrect conclusions. Even narrowing of the conditions for permafrost occurrence further (ground surface temp ≤−3 °C, only 24 cases remaining) confirmed the above results.

4. Conclusions

Snow profile data from an Alpine region in Switzerland obtained in the context of an extensive field campaign in 2002 and 2003 were analyzed with respect to differences between permafrost-free and potential permafrost sites. As expected, due to method of classification used, the ground surface temperature was lower, and correspondingly the 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. The 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 ($p=0.50$) to the portion of potential permafrost terrain (41%) 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. Although data on skiing activity according to aspect are lacking, we presume that the relation is most probably 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.

Our analysis focused on sites with similar ground cover, similar roughness, and similar climatic characteristics (precipitation). The characteristics of the snow cover in steep, blocky permafrost terrain such as rock glaciers where air circulation has an important role, in particular in early winter, is probably different and still needs to be further investigated with respect to snowpack stability.

Acknowledgements

We are grateful to all colleagues at SLF who effected snow profiles during the field campaigns in 2002 and 2003 and to E. Hegglin and C. Pfammatter for help with data entry. R. Meister and J. Rhyner are warmly thanked for reading the manuscript and making constructive suggestions. We thank the editor Kelly Elder and the reviewers for helpful comments.

References

Bernhard, L., Sutter, F., Haeberli, W., Keller, F., 1998. Processes of snow/permafrost-interactions at a high-mountain site, Murtèl/Corvatsch, eastern Swiss Alps. In: Lewkowicz, A.G., Allard, M. (Eds.), 7th International Conference on Permafrost, Yellowknife, Northwest Territories, Canada, 23–27 June 1998. Université Laval, Centre d'études nordiques, Sainte-Foy, Québec, Canada, pp. 35–41.

Colbeck, S.C., Akitaya, E., Armstrong, R., Gubler, H., Lafeuille, J., Lied, K., McClung, D., Morris, E., 1990. The International Classification of Seasonal Snow on the Ground. International Commission on Snow and Ice (ICSI). International Association of Scientific Hydrology, Wallingford, Oxon, U.K. 23 pp.

Delaloye, R., Reynard, E., Lambiel, C., Marescot, L., Monnet, R., 2003. Thermal anomaly in a cold scree slope (Creux du Van, Switzerland). In: Phillips, M., Springman, S., Arenson, L. (Eds.), International Conference on Permafrost, 8th, Zurich, Switzerland, 21–25 July 2003. Balkema, Lisse, The Netherlands, pp. 175–180.

Haeberli, W., 1975. Untersuchungen zur Verbreitung von Permafrost zwischen Flüelapass und Piz Grialetsch (Graubünden). Mitteilung der Versuchsanstalt für Wasserbau. Hydrologie und Glaziologie, vol. 17. ETH, Zurich, Switzerland, p. 221.

Harvey, S., 2002. Avalanche incidents in Switzerland in relation to the predicted danger degree. In: J.R. Stevens (Editor), Proceedings ISSW 2002. International Snow Science Workshop, Penticton BC, Canada, 29 September–4 October 2002. International Snow Science Workshop Canada Inc., BC Ministry of Transportation, Snow Avalanche Programs, Victoria BC, Canada, pp. 443–448.

Hoelzle, M., 1992. Permafrost occurrence from BTS measurements and climatic parameters in the Eastern Swiss Alps. Permafrost and Periglacial Processes 3, 143–147.

Hoelzle, M., Wegmann, M., Krummenacher, B., 1999. Miniature temperature dataloggers for mapping and monitoring of permafrost in high mountain areas: first experience from the Swiss Alps. Permafrost and Periglacial Processes 10, 113–124.

Keller, F., 1994. Interaktion zwischen Schnee und Permafrost: eine Grundlagenstudie im Oberengadin. Mitteilung der Versuchsanstalt für Wasserbau. Hydrologie und Glaziologie, vol. 127. ETH, Zurich, Switzerland, p. 145.

Keller, F., Gubler, H., 1993. Interaction between snow cover and high mountain permafrost: Murtèl/Corvatsch, Swiss Alps. International Conference on Permafrost, 6th, Beijing, China, 5–9 July 1993. Proceedings, vol. 1. South China University of Technology Press, Guangzhou, China, pp. 332–337.

Keller, F., Frauenfelder, R., Gardaz, J.M., Hoelzle, M., Kneisel, C., Lugon, R., Phillips, M., Reynard, E., Wenker, L., 1998. Permafrost map of Switzerland. In: Lewkowicz, A.G., Allard, M. (Eds.), International Conference on Permafrost, 7th, Yellowknife, Northwest Territories, 23–27 June 1998. Université Laval, Centre d'études nordiques, Sainte-Foy, Québec, Canada, pp. 557–562.

Luetschg, M., Stoeckli, V., Lehning, M., Haeberli, W., Ammann, W., 2004. Temperatures in two boreholes at Flüela Pass, Eastern Swiss Alps: the effect of snow redistribution on permafrost distribution patterns in high mountain areas. Permafrost and Periglacial Processes 15 (3), 283–297.

Lütschg, M., 2005. A model and field analysis of the interaction between snow cover and alpine permafrost. Schriftenreihe Physische Geographie, Glaziologie und Geomorphodynamik, vol. 47. Institute of Geography, University of Zurich, p. 204.

Meister, R., 1987. Lawinenniedergänge mit Todesopfern in der Schweiz. In: Jaccard, C. (Ed.), Schnee und Lawinen in den Schweizer Alpen—Winter 1985/86. Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland, pp. 195–206.

Phillips, M., Bartelt, P., Christen, M., 2000. Influences of avalanche-defence snow-supporting structures on ground temperature in Alpine permafrost terrain. Annals of Glaciology 31, 422–426.

Schweizer, J., 2002. The Rutschblock test—procedure and application in Switzerland. The Avalanche Review, 20 (5) 1, 14–15.

Schweizer, J., Lütschg, M., 2001. Characteristics of human-triggered avalanches. Cold Regions Science and Technology 33 (2–3), 147–162.

Schweizer, J., Wiesinger, T., 2001. Snow profile interpretation for stability evaluation. Cold Regions Science and Technology 33 (2–3), 189–188.

Schweizer, J., Kronholm, K., Wiesinger, T., 2003. Verification of regional snowpack stability and avalanche danger. Cold Regions Science and Technology 37 (3), 277–288.

Spiegel, M.R., Stephens, L.J., 1999. Schaum's outline of theory and problems of statistics. Schaum's Outline Series. McGraw-Hill, New York, p. 538.