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Sporadic and discontinous mountain permafrost occurrence in the Upper Engadine, eastern Swiss Alps

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ABSTRACT: Special aspects of mountain permafrost distribution were investigated in the Upper Engadine, eastern Swiss Alps: discontinuous permafrost occurrence in glacier forefields at high altitude and sporadic permafrost occurrence below the timberline. The thickness of the permafrost bodies inferred through geoelectrical soundings are of similar magnitude. In contrast, the active layer of the permafrost occurrence below the timberline appears to be fairly thin, indicating the impact of the organic horizons in insulating the subsurface and controlling the ground thermal regime. The mean annual ground surface temperatures (MAGST) do not differ substantially, although about 1000 m in altitude lie in between the two investigated sites. Year-round temperature measurements show that a thick snow cover can lead to a MAGST which is higher by several degrees. Thus, seasonal snow cover characteristics are assumed to belong to the key factors for the existence of the sporadic permafrost occurrence below the timberline.

1 INTRODUCTION

Besides the Valaisian and the Bernese Alps, the Upper Engadine is one of the high mountain regions in Switzerland with widespread permafrost occurrence (see Permafrost map of Switzerland, Keller et al. 1998). The study sites in the Upper Engadine, eastern Swiss Alps, are situated in the vicinity of St. Moritz (46°30′N, 9°50′E). The regional climate can be described as continental, with fairly low precipitation and a comparatively high temperature amplitude. Numerous well developed rock glaciers are obvious geomorphological indicators of the discontinous distribution of alpine permafrost. Various aspects of mountain permafrost have been investigated in the past decades with the main focus on rock glacier permafrost. The existing, detailed knowledge of the permafrost within these rock glaciers has been retrieved from borehole investigations (Haeberli et al. 1988, 1998, Vonder Mühll et al. 1998).

Discontinuous permafrost is encountered above 2400 m a.s.l. The investigation of permafrost in glacier forefields at high altitudes in the Upper Engadine was performed during recent years (Kneisel 1999). Below the timberline, sporadic permafrost is assumed to exist only at very shaded sites. One of these special places is situated in the *Bever* Valley, which represents one of the few sites in Switzerland where a permafrost occurrence below the timberline consisting of several permafrost lenses could be confirmed by geoelectrical resistivity measurements, so far (Kneisel et al. 2000).

The focus of the present paper lies on two special aspects of mountain permafrost distribution in the Upper Engadine: discontinuous permafrost occurrence in recently deglaciated glacier forefields at high altitude and sporadic permafrost occurrence below the timberline. Results of near-surface temperature measurements and DC resistivity soundings from the periglacial zone and the permafrost occurrence below the timberline are compared and discussed.

2 SITES AND METHODS

2.1 *Sites description*

In the east-exposed *d'Es-cha* glacier forefield only a small glacier remnant is present today covering an area of 0.15 km^2 (cf. Fig. 1). The glacier forefield extends from 2790 m to 2940 m a.s.l. The sediment grain size at the surface ranges from fine-grained glacio-fluvial sediments to big blocks.

The *Bever* Valley is a trough shaped valley with bottom elevation between 1730 and 1800 m a.s.l. at its lower end (Fig. 2). At present the upper timberline is

Figure 1. *d'Es-cha* glacier forefield.

Figure 2. North-exposed vegetated scree slopes in the *Bever* Valley.

between 2200 m and 2300 m a.s.l. The results of the field measurements presented in this paper were concentrated along a clearing on the north-exposed valley side where only small larch trees are present. The soils are poorly developed and covered by an organic layer of up to 30 cm thickness. Below the organic layer, only a few centimetres of mineral soil exists.

2.2 *Near-surface temperature datalogging*

Miniature dataloggers (*Universal Temperature Logger UTL-1*) were placed at different sites in the forest at the north-exposed vegetated scree slope (embedded at the top of the organic layers) and in the glacier forefield (placed between stones) to register the temperature at the base of the snow cover in the course of several months as well as year-round near-surface temperatures. From the latter data the mean annual ground-surface temperature (MAGST) can be calculated.

If the winter snow cover is sufficiently thick (at least 80 cm) and surface melting is still negligible in mid- to late-winter, the bottom temperature of the winter snow cover (BTS) remains nearly constant and is mainly controlled by the heat transfer from the upper ground layers, which in turn is strongly influenced by the presence or absence of permafrost. Under permafrost conditions, a colder temperature occurs. The following three classes are distinguished: probable permafrost occurrence (BTS < -3°C), possible permafrost occurrence (BTS $= -2$°C to -3°C) and improbable permafrost occurrence (BTS > -2°C) (Haeberli 1973). Since permafrost exists if either the bottom temperature of the snow cover (BTS) is below -3°C and/or the MAGST is perennially below 0°C (van Everdingen 1998) the presence or absence of permafrost can be deduced from the data obtained by the miniature loggers. Additionally the evolution and roughly the thickness of the snow cover can be derived from the appearance of the temperature curve, since short-term temperature fluctuations are either damped under a thick enough snow cover or have even no impact on the temperature at the base of the snow cover.

2.3 *DC resistivity soundings*

Geoelectrical soundings have been standardly applied in different mountain regions to confirm and characterise mountain permafrost for many years. Due to the noticeable resistivity contrast between unfrozen sediments and ground ice or ice-rich frozen sediments this method is suitable for detecting permafrost. The typical sounding curve obtained on alpine permafrost shows a three-layer model with an increase of resistivity at shallow depth representing the active layer and the permafrost underneath, followed by a sharp decrease of resistivities at greater current electrode distances (AB/2) representing the unfrozen ground beneath. Occasionally the resistivity contrast between the active layer, the permafrost layer and the unfrozen underground can be low.

Resistivity values of frozen ground can vary over a wide range depending on the ice content, the temperature and the content of impurities. The dependance of resistivity on temperature is closely related to the amount of unfrozen water. Perennially frozen silt, sand, gravel or frozen debris with varying ice content show a wide range of resistivity values between 5 kΩm to several hundred kΩm (e.g. Hoekstra & McNeill 1973, King et al. 1987, Haeberli & Vonder Mühll 1996).

Due to the geoelectrical principle of equivalence (e.g. Mundry et al. 1985) several calculated models can represent one sounding graph. Thus, it is recommendable to give ranges of resistivity and thickness (Vonder Mühll 1993). For the one-dimensional soundings a *GGA30 Bodenseewerk* instrument was used. In the present interpretations three-layer models were calculated which are assumed to represent the most probable case with respect to the local geomorphological situation. In the selected figures the sounding graphs and the interpreted models (dashed lines) are shown.

3 RESULTS AND DISCUSSION

3.1 *Temperature measurements*

Measured near-surface temperatures from the east-exposed *d'Es-cha* glacier forefield and the *Bever* site are shown in Figures 3 and 4. All mini-loggers (ML) in the *d'Es-cha* forefield (Fig. 3) were obviously covered by a thick enough snow cover as there are no high-frequency temperature variations visible in the

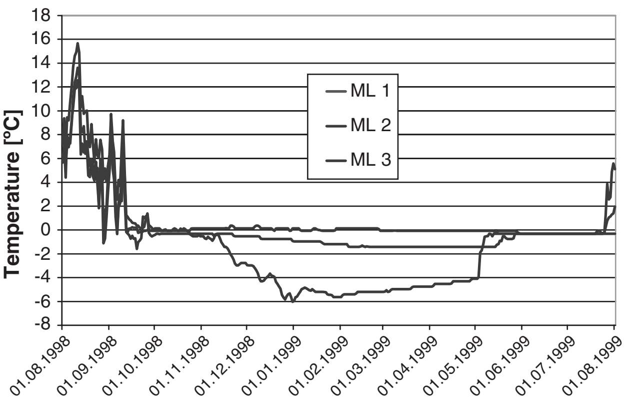

Figure 3. Mean daily near-surface temperatures from three loggers in the *d'Es-cha* glacier forefield.

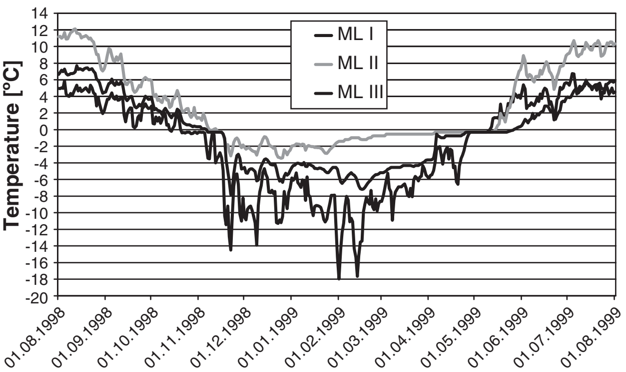

Figure 4. Mean daily near-surface temperatures from three loggers at the *Bever* site.

graph during the winter months. The values decrease gradually until the final more or less constant high winter temperature is reached. Thus, the bottom temperatures of the snow cover can be analysed according to the three distinguished BTS-classes. ML 1 and ML 3 show bottom temperatures around 0°C (ML 1) and −1.5°C (ML 3), respectively, and do not point to permafrost conditions underneath. ML 2 recorded temperatures around −5°C during the high winter months which lie within the BTS class <−3°C indicating that this site is underlain by permafrost.

Compared with the results of the *d'Es-cha* glacier forefield, the near-surface temperature measurements at the *Bever* site (Fig. 4) show considerable differences. In early winter frequent temperature variations are visible in the graphs indicating that the logger sites were covered only by a comparatively thin snow cover. Since February 1999 ML II was covered by a thick snow cover preventing that the temperature at the base of the snow cover was influenced by short-term variations of the surface energy balance. From mid of February to beginning of April the bottom temperature is more or less constant around −0.5°C.

Considering the whole year, the temperature fluctuations are most pronounced for ML I, while ML II and

Table 1. Mean annual ground-surface temperatures in the *d'Es-cha* glacier forefield and at the *Bever* site (measurement period 1.08.98–1.08.99).

Location	Logger	Elevation (m) a.s.l.	Mean temperature (°C)
d'Es-cha	ML 1	2840	+0.7
d'Es-cha	ML 2	2840	−1.6
D'Es-cha	ML 3	2920	+0.3
Bever	ML I	1800	−2.1
Bever	ML II	1840	+2.7
Bever	ML III	1820	−0.3

ML III show minor variations. The graph of ML I shows distinct peaks and valleys in the temperature curve throughout the whole winter (Fig. 4).

This graph can therefore not be interpreted with regard to the typical BTS-classes, and no interpretation concerning permafrost presence/absence can be deduced. The graph of ML III shows minor variations in the temperatures during winter, but still the snow cover was obviously not thick enough, that undisturbed BTS could develop.

The logger ML I, which was embedded at the top of the organic layers at a small larch at the *Bever* site, was either covered by only a thin snow cover or was located under a funnel through the snow as there are marked temperature variations visible in the curve throughout the winter. The latter assumption seems to be more likely since several funnels could be observed during a BTS measurement campaign in March 1998. These funnels occur around tree trunks and where large boulders stick out above the snow cover. The results of BTS-measurements which were repeated during three years indicate the local presence of permafrost at the *Bever* site. However, as visible in the results of the near-surface temperature measurements, results from BTS-measurements have to be regarded carefully. The use of the mini-loggers enable to figure out whether the BTS-measurements have been performed in the right period with constant temperatures at the base of the snow cover.

Additionally, the year-round temperature data allow to compute the mean annual ground-surface temperature. The MAGST for both investigated sites are summarized in Table 1. The MAGST obtained in the *d'Es-cha* glacier forefield above 2800 m a.s.l. ranged from +0.7°C (for ML 1) to −1.6°C (for ML 2). For the location of ML 2 not only the BTS but also the MAGST (−1.6°C) point to a local permafrost occurrence and permafrost favourable conditions for the measurement period. For ML 1 and ML 3 the MAGST are above 0°C, however, concerning the MAGST the thermal offset has to be taken into account (see discussion further below).

Compared to results of other north- and west-exposed glacier forefields at high altitude in the

Upper Engadine, the computed MAGST (for ML 1 and ML 3) of the east-exposed *d'Es-cha* glacier forefield are slightly warmer (Kneisel 1999).

The MAGST obtained at the *Bever* site about 1000 m lower in altitude than the *d'Es-cha* glacier forefield ranged from +2.7°C (for ML II) to −2.1°C (for ML I) with ML III slightly below 0°C (−0.3°C). These results imply permafrost and permafrost favourable conditions throughout the measurement period for the sites of ML I and ML III. But permafrost can not be excluded at the site of ML II since geoelectrical resistivity measurements point to a local permafrost lense in this area (Kneisel et al. 2000).

Furthermore, concerning the MAGST, the thermal offset has to be taken into account as well as the fact, that the year 1998 worldwide mark one of the warmest years since 1860 (WMO 1999). Hence, the near-surface temperatures and the calculated MAGST which often point to permafrost occurrences were possibly recorded in an extraordinary warm period. Thermal offset is defined as the difference between the mean annual temperature at the permafrost table and the mean annual ground surface temperature. Temperature differences with more than 2°C are reported from different sites in Canada and Alaska (e.g. Burn & Smith 1988, Burn 1998, Zhang et al. 1997).

Burn and Smith (1988) have suggested that permafrost may be in equilibrium, or even aggrading, in environments where the mean annual ground surface temperature is above 0°C. Thus, permafrost can not be excluded at the sites where the mean annual ground surface temperature is around or even above 0°C.

Comparing the temperature curves in Figures 3 and 4 the importance of the insulating effect of the seasonal snow cover as well as interactions of topography, exposure, wind, microrelief and vegetation for the ground thermal regime can be deduced (cf. Goodrich 1982, Zhang et al. 1997, Harris & Pedersen 1998). In the glacier forefield the late-lying snow prevents the warming of the ground. At the *Bever* site a thin snow cover in combination with funnels through the snow can lead to a cooling of the ground surface and the permafrost in winter. Furthermore, the northern exposure is one of the important factors which limits the amount of incoming solar radiation. The ground thermal regime and thus the permafrost occurrence below the timberline can be assumed to be a result of the interaction of climatic conditions and topography as well as surface and subsurface factors (organic layers, blocky surface material) (Kneisel et al. 2000).

3.2 *DC resistivity soundings*

The resistivity sounding profile *d'Es-cha* (Fig. 5) was measured at the site of ML 3 in the *d'Es-cha* glacier forefield using the asymmetrical Hummel configuration. The graph shows only a slight increase of the resistivity values. The three-layer model suggest a first layer of 2–3 m and a comparatively thin second layer with a resistivity of 30 kΩm for the best model interpretation. The obtained specific resistivity values, between 18 kΩm and 55 kΩm, lie in the range of perennial frozen ground and suggest a shallow permafrost occurrence at this site. The third layer with better conductivity represents the unfrozen ground underneath. Ranges for equivalent models which are assumed to represent the most probable cases with respect to the local geomorphological situation are given in Table 2.

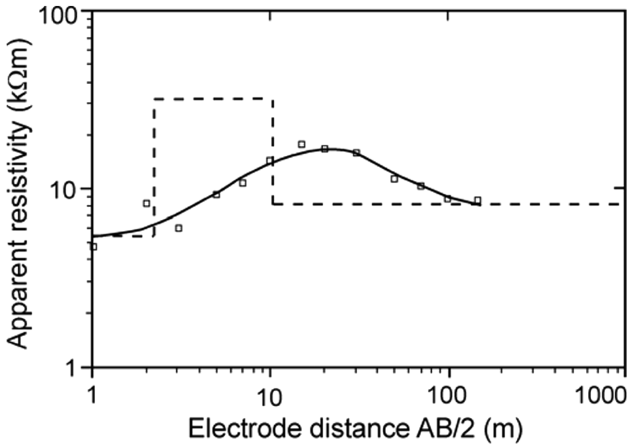

Figure 5. DC resistivity sounding profile from the *d'Es-cha* glacier forefield at 2920 m a.s.l.

Table 2. Ranges of specific resistivity and thickness for the three-layer models.

	Layer 1		Layer 2		Layer 3
Sounding	ρ (kΩm)	thick. (m)	ρ (kΩm)	thick. (m)	ρ (kΩm)
D'Es-cha	4–6.5	1.3–3.3	18–55	5–15	6.5–9.5
Bever	8–15	0.5–2	30–90	6–18	2–5

This shape of geoelectrical sounding graphs is considered to be typical of permafrost in glacier forefields. Similar curves have also been measured in other investigated forefields (Kneisel 1998). With the special conditions in glacier forefields, permafrost occurrences can be assumed to be shallow, "warm" and thus, rich in unfrozen water, what can explain the comparatively low apparent resistivity values (Kneisel 1999).

The sounding from the north-exposed clearing at the *Bever* site (measured with the symmetrical Schlumberger configuration) is displayed in Figure 6. The shape of the sounding graph is typical of permafrost: increasing resistivities at greater depth and a distinct decline of the resistivities with larger current

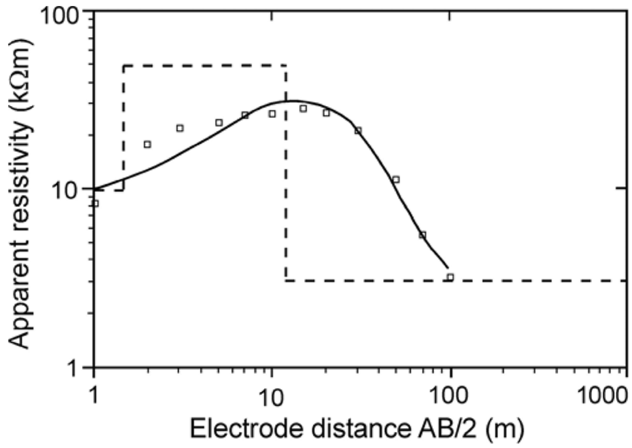

Figure 6. DC resistivity sounding profile from the *Bever* site at 1840 m a.s.l.

electrode distances AB/2. The apparent resistivities obtained for the second layer were about 30 kΩm, leading to specific resistivities between 30–90 kΩm (cf. results of equivalent models shown in Table 2).

Surprisingly, the active layer seems to be fairly thin. Compared to the permafrost in the glacier forefield, at this low altitude site a much thicker active layer should be expected. This could be a model artefact due to the comparatively thick organic horizons. These hold the moisture and therefore provide a good conductor, so that the current is quickly transmitted into the next horizon what can lead to an underestimation of the thickness of the top layer in the model interpretation (Kneisel et al. 2000).

4 CONCLUSIONS

Comparison of results of investigations from adjacent discontinuous and sporadic mountain permafrost occurrences in the eastern Swiss Alps shows that:

- the thickness of the permafrost bodies inferred through geoelectrical soundings are of similar magnitude. However, the active layer of the permafrost occurrence below the timberline appears to be fairly thin compared to the active layer of the discontinous permafrost occurrence in the periglacial zone. Hereby, the organic horizons are considered to play an important role in insulating the subsurface and controlling the ground thermal regime.
- the MAGST do not differ substantially, although about 1000 m in altitude lie in between the two investigated sites.
- the year-round temperature data provide evidence that a thick snow cover can raise the MAGST by several degrees. Thus, seasonal snow cover (accumulation, thickness, duration) is assumed to be one of the key factors for the existence of the sporadic permafrost occurrence below the timberline.
- a thin snow cover and/or the direct access of cold air to the ground through funnels in the snow with the resulting cooling of the ground are favourable conditions for the survival of the permafrost at this site. Further research, which is currently in progress, will enable a more detailed interpretation of the ground thermal regime.

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