**OCCURRENCE OF SURFACE ICE AND GROUND ICE/PERMAFROST IN RECENTLY DEGLACIATED GLACIER FOREFIELDS, ST. MORITZ AREA, EASTERN SWISS ALPS**

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**Abstract**

Numerically simulated permafrost distribution patterns in the St. Moritz area, eastern Swiss Alps, suggest that most of the existing surface ice-bodies are situated in areas of potential permafrost occurrence. Under such conditions, surface ice is predominantly cold or polythermal and perennially frozen ground in recently deglaciated areas may either persist from previous subglacial conditions underneath cold surface ice or form after the disappearance of temperate surface ice.

The results of field investigations (BTS-measurements and electrical DC resistivity soundings) indeed indicate the local occurrence of permafrost/ground ice. Visible surface ice-bodies exist in one of the investigated forefields. The observed resistivity values at this site suggest a polygenetic origin of the ice with a close coexistence of high-resistivity sedimentary ice from snow/firn/ice metamorphosis and low-resistivity congelation ice (interstitial and segregation ice) from freezing processes in the ground.

**Introduction**

Seasonal snow, mountain glaciers and permafrost are known to be highly vulnerable to climatic changes. In contrast to the comprehensive data base existing about length variations and mass balances of numerous Alpine glaciers, systematic investigation of mountain permafrost started only in the past few decades. As a consequence, many basic questions about relationships between surface ice and ground ice in mountain regions remain unanswered. In the present paper, electrical DC resistivity soundings are applied in selected glacier forefields in the St. Moritz area, eastern Swiss Alps, in order to investigate interactions between surface ice and ground ice, and to obtain information about the origin and characteristics of the different ice types.

**Sites and methods**

The study area in the Upper Engadin, district of the Swiss Alps, corresponds to the area covered by the 1 : 25,000 map No. 1257 (St. Moritz). As a consequence of its central alpine position, the amount of precipitation is low (about 900 mm for the station on the valley floor at 1800 m a.s.l.). The maximum elevation difference is 1680 m (Piz Güglia 3380 m a.s.l. and the Inn valley 1700 m a.s.l.). The equilibrium line altitude (ELA) is above 3000 m a.s.l. (Müller et al., 1976) causing, in combination with the local climatic conditions, an alpine moun-
After overlaying the glacier extents, the perennial snow patches and the potential permafrost distribution, several glaciers and glacier forefields were selected for more detailed investigation. In this paper results from the Muragl and the da las Sterlas glacier forefields are presented.

The recently deglaciated forefield of the Muragl cirque glacier was mapped with the BTS-method (bottom temperature of the winter snow cover) introduced by Haeblerli (1973) in order to investigate the probable presence/absence of permafrost or buried "glacier ice" (Haeblerli and Epifani, 1986). If the winter snow cover is sufficiently thick (at least 80 cm), then it insulates the soil from short-term variations in the surface energy balance, because of its very low heat transfer capacity (Goodrich, 1982; Harris and Corte, 1992; Keller and Gubler, 1993). In February and March, the BTS in the Alps 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 (Vonder Mühll and Haeblerli, 1990). Under permafrost conditions, a colder temperature occurs. The following three classes are distinguished: probable permafrost occurrence (BTS < -3 °C), possible permafrost occurrence (-3°C < BTS < -2°C), and no probable permafrost occurrence (BTS > -2 °C).

More than 20 DC resistivity soundings were carried out in both selected glacier forefields. The application of DC resistivity soundings is a reliable method for detecting ground ice/permafrost and has often been used (e.g., Assier et al., 1997; Barsch and King, 1989; Fisch et al., 1977; Haeblerli, 1975; Guglielmin et al., 1997; King, 1982, 1984; King et al., 1987; Ódegard et al., 1996; Vonder Mühll, 1993; Wagner, 1996). The measured data of the presented glacier forefields is based on soundings using the Schlumberger and Hummel configurations. To improve the contact of the steel electrodes to the sometimes bouldery ground, sponges soaked in saltwater were used. In spite of these difficulties during use of DC resistivity soundings in high mountain areas, one major advantage especially in the context of the present study is the possibility of characterizing different types of (ground) ice. In contrast to sedimentary ice which forms from a firnification process and builds up large parts of glaciers, congelation ice (interstitial and segregation ice) which is the predominant form of ice in the ground shows much lower resistivities. Characteristic values for sedimentary ice from temperate firm areas are several MΩm to more than 100 MΩm and for congelation ice are 10 km to a few MΩm (Haeblerli and Vonder Mühll, 1996).

**Recent size reduction of surface ice**

The warm decade 1981-1990 (cf. IPCC, 1990) caused a very striking area loss of the small cirque glaciers and glaciérts in the investigated region. The smallest glaciérts below 100,000 m² have either disappeared entirely or show a very distinct retreat. There are few exceptions with a smaller area loss due to the particular altitude, size and topography of the glacier accumulation areas. Even some of the cirque glaciers have disappeared entirely (Kneisel et al. 1997, cf. excerpt of the St. Moritz investigation area in Figure 1: Vadret da las Sterlas - area in 1973: 54000 m², no. 1; Fuorcla Clüx - area in 1973: 135000 m², no. 2).

The glaciérized area within the investigated region was reduced by about 68% (from 1973 to 1988) as compared to the glacier area present in 1973. Since 1993 no further recession is recognizable. The ELA of the remaining cirque glaciers appears to be at altitudes and in topographic conditions where a relative equilibrium with the current climatic conditions exists.

**Spatial relationship between perennial snow patches, surface ice and permafrost**

The perennial snow patches as mapped from the 1988 IR-images were compared to the simulated potential permafrost distribution and the 1973 glacier extents. In the St. Moritz investigation area 69% (simulation with PERMAKART) and 74% (simulation with PERMAMAP) respectively of the perennial snow patches are lying in the probable permafrost area. These results confirm the usefulness of perennial snow patches as indicators of mountain permafrost (Furrer and Fitze, 1970; Haeblerli, 1975), at least for the local distribution pattern, despite varying origins of snow patches. These include avalanche deposits, wind accumulation and the remains of decaying glaciers. Representing only about 8% of the entire sample, the snow patches which originated from vanishing glaciers seem to be of less significance in the St. Moritz area. Together with the results from the permafrost simulation, the mapped occurrence of snow patches was used as a criterion for selecting glaciers and forefields with a view to conducting borehole temperature measurements and geophysical soundings.

Overlaying of the mapped glacier extents with the simulated potential permafrost distribution and the perennial snow patches shows that most of the mountain glaciers in the St. Moritz investigation area are situated in the potential permafrost area (Figure 1). This could mean that the glaciers probably contain cold ice in the impermeable ablation area surrounded by permafrost and, hence, that subglacial permafrost may be expected at the margins. Furthermore it is possible that permafrost conditions could exist in areas not covered and insulated by glaciers and that permafrost evolution might take place after the retreat of the glaciers.
For verification of the first assumption, ice-temperatures were measured in three hand drilled boreholes on the Muragl cirque glacier. The results of the borehole temperature measurements (-0.86°C, -0.98°C and -1.29°C at 6 m depth) indicate that the Muragl cirque glacier consists of slightly cold ice (Kneisel et al., 1997). Potential therefore exists for subglacial permafrost conditions to occur beneath thin ice margins.

**Permafrost and ground ice investigations**

**BTS-MEASUREMENTS IN THE MURAGL GLACIER FOREFIELD**

Permafrost presence in the higher parts of the glacier forefield between 2850 m a.s.l. and 2910 m a.s.l. is probable. Ground ice at this site may have originated as a former subglacial permafrost occurrence during the retreat of the partially cold Muragl glacier at an especially cold site, but remains of buried surface ice may also persist today at the margins. The area below 2850 m a.s.l. with uncertain information (permafrost possible) was covered by the former Muragl glacier which can be assumed to have been polythermal with a temperate accumulation (firn) area and a slightly cold ablation (ice) area (Haebler, 1976; Hooke et al., 1983). Such a scheme of a probably polythermal former Muragl glacier partly insulating the 1850 forefield and, therefore, prohibiting permafrost formation in the corresponding areas agrees with BTS-measurements conducted in 1985 within the 1850 forefield of the Muragl glacier (Haebler, 1992). At the margins of its 1850 extent, the glacier was probably frozen to its bed and the permafrost could at least persist until today from...
previous subglacial conditions underneath the cold surface ice. The latter assumption of a marginal permafrost occurrence is confirmed by DC resistivity soundings carried out at these sites (see profile MU-AB_3 in Figure 2).

DC Resistivity Soundings in the Glacier Forefields

Interpretation of the data is made difficult by the fact that it is based on horizontal layers, conditions which are not always found, especially in high mountain permafrost areas. In addition, as a consequence of the equivalence principle, different theoretical models can show similar curves fitting the data. According to Vonder Mühll (1993) it is therefore recommended to present ranges for the apparent resistivity values and the thickness of the layers. In this first interpretation, however, only the model which is supposed to be the best fit with respect to the geomorphological situation is given. Figures 2 and 3 show the sounding graphs and the interpreted models (dashed lines). Crosses represent values which are not considered for the interpretation.

The profile MU-AB_1 in Figure 2a was measured at the site where the BTS measurements indicate a probable permafrost occurrence. The two layered model is not typical for a sounding in alpine permafrost because the active layer is missing. However, the first layer with a thickness of 3-4 m shows resistivities of 50 kΩm which are typical for congelation ice (“permafrost ice”), although surface ice was partly visible under the snow cover. The assumption of a former remnant of “glacier ice” at that site is therefore unlikely, supported by the fact that measurements on the cirque glacier have shown resistivity values of 1 MΩm.

The profile MU-BC_2 in Figure 2b was carried out on a visible surface ice body close to the profile MU-AB_1. The three layered model consists of a high resistivity layer with values of more than 20 MΩm beneath a thin layer of better conductivity. The profile MU-AB_3 in Figure 2c was measured at the margins of the 1850 extent of the Muragl cirque glacier. The second layer with resistivity values about 150 KΩm beneath the active layer suggests a low resistivity permafrost near 0°C, which can be possibly interpreted as marginal and/or melting permafrost, originating as a former subglacial permafrost occurrence underneath cold surface ice or newly formed after the disappearance of temperate surface ice.

Figures 3a to 3c show the results from the Val Champagna (da las Sterlas glacier forefield). In this cirque, the former small glacier has totally disappeared; only perennial snow patches are left today. The profile CH-AC_1 was carried out in September 1996 just below a perennial snow patch. As a result of the late-lying snow, the active layer at this site is quite thin - only about 1 m. The high resistivity layer is interpreted to have a thickness of about 20 m. The profile CH-AC_2 in Figure 3b is located on the north-facing lateral moraine, while the profile CH-AB-3 is from the central part of the cirque. The moraine is interpreted to be ice-cored with a depth of the high resistivity layer (400 kΩm) of about 20 m and an active layer thickness of 2-3 m. Profile CH-AB_3 in Figure 3c shows a three layered model with a second layer of only about 30 kΩm and an active layer thickness of 3-4 m. Similar curves have been measured also in other glacier forefields and can be interpreted either as remains of a subglacial permafrost occurrence which is possibly melting, or as permafrost which
developed after the retreat of the insulating glacier. The low values of resistivity could be an indication of a permafrost occurrence which consists of a high amount of frozen material of different grain size rather than a very ice-rich layer.

Discussion and conclusions

Small cirque glaciers and glacierets at high altitudes occur in the potential permafrost area. The existence of cold or polythermal ice at altitudes of 3000 m a.s.l. and below must be seen in context with the local permafrost distribution. The results of the BTS-measurements in the Muragl glacier forefield indicate the presence of ground ice. The origin of this ice up to now remains difficult to interpret, because various ice-forming processes can be involved with the evolution of small mountain glaciers, cirque glaciers, frozen (push)moraines, rock glaciers and alpine permafrost. Remnants of former surface ice in a permafrost environment cannot easily be recognized and defined on the basis of simple visual field inspection (Haeberli and Vonder Mühll, 1996). It is therefore recommended that the genetic/petrographic classification of ice types (after Shumskii, 1964) should be used to differentiate between congelation ice and sedimentary ice. A nearby coexistence of sedimentary ice from glacierets and small cirque glaciers and congelation ice from ground freezing in the potential permafrost environment can be assumed. Thus, several geophysical methods as well as geomorphological studies should be applied in order to detect and correctly interpret ground ice/permafrost in recently deglaciated forefields. DC resistivity soundings, often used for detection of (rock glacier) permafrost, facilitate the characterization of different types of ice because of the marked resistivity difference between congelation and sedimentary ice (King, 1984; Vonder Mühll, 1993).

According to the interpreted DC resistivity soundings in the Muragl glacier forefield, it can be supposed that

the observed small ice-bodies are of polygenetic origin. In the da las Sterlas glacier forefield, only perennial snow patches are left today. The results of the DC resistivity soundings indicate the presence of permafrost, probably in contact with perennial snow patches. Interpretation of the data is made difficult by the fact that permafrost in Alpine glacier forefields is probably warm, shallow and rich in unfrozen water. The surest information is obtained from combined geophysical soundings and surface temperature logging. Corresponding research programmes are underway in the Alps (Engadin) and in Northern Sweden (Tarfala). The present results indicate that it would be advisable to drill and instrument boreholes in glacier forefields with permafrost occurrence with a view to temperature monitoring and investigation of possible permafrost evolution in recently deglaciated forefields.

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Figure 3. DC Resistivity Profiles CH-AC_1, CH-AC_2 and CH-AB_3 located in the da las Sterlas glacier forefield.
References


