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HIGH-MOUNTAIN PERMAFROST IN THE AUSTRIAN ALPS (EUROPE)

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Abstract

Permafrost research in the Austrian Alps (Eastern Alps) is based on a variety of methods, including at large scales, the measurement of the temperature of springs and of the base of winter snow cover, and at small scales, mainly an inventory of some 1450 rock glaciers. Taking all the information available into consideration, the lower limit of discontinuous permafrost is situated near 2500 m in most of the Austrian Alps. These results can be used for modelling the permafrost distribution within a geographical information system. Detailed investigations were carried out in the Doesen Valley (Hohe Tauern range) using additional methods, including several geophysical soundings. In this way, realistic estimates of certain permafrost characteristics and the volume of a large active rock glacier (some $15 \times 10^6 m^3$) were possible. This rock glacier has been chosen as a monitoring site to observe the effects of past and future climatic change.

Introduction

Although mountain permafrost in the Austrian Alps has caused construction problems and damage to buildings at several high-altitude locations, specific investigations of permafrost did not start until 1980. Since then, studies of the distribution and certain characteristics of permafrost have been carried out at a number of sites. Earlier observations, especially surface velocity measurements, had been performed on some rock glaciers since the time between the two world wars without considering them to be permafrost features. In the last few years, the status of knowledge has increased considerably, due to multidisciplinary research projects focussing on small- and large-scale permafrost studies. The following report outlines the main activities and some of the results, with special emphasis on the research methods used, the horizontal and vertical distribution of permafrost in the Austrian Alps as a whole (Figure 1), and a detailed study of a particular location (Figure 2).

Methods of permafrost prospecting

Large-scale Investigations

Almost all the methods for prospecting high mountain permafrost described by King et al. (1992) were used at several sites in the Austrian Alps. Observations of natural outcrops or artificial excavations of permafrost, temperature measurements of springs and soil, measurements of the bottom temperature of the winter snow cover (BTS) and geophysical soundings, such as seismic, geoelectric, electromagnetic and ground penetrating radar surveys have been published (survey and references in Lieb, 1996). The best results for mapping the mere existence of permafrost were obtained by measuring spring temperatures and BTS, both procedures being easily applicable and providing quite accurate interpretation. Thus a high density of information became available at several study sites for which maps of local permafrost distribution could be drawn. An example of a local study with a high quantity of detailed information will be discussed later, including a permafrost map of a small area (Figure 2). From these results, rules of probable permafrost distribution according to elevation, aspect and relief were derived, corresponding well with empirical models of permafrost distribution elaborated by other authors.

Small-scale investigations

In order to get information about the existence of permafrost not only at individual sites, such as cirques or single valleys, but also for mountain ranges and finally for the entire Austrian Alps, other methods had to be used. Firstly, rock glaciers, which are the most important morphological expression of high mountain permafrost (Barsch, 1996), were mapped from aerial photographs covering much of the Austrian Alps (Figure 1). Subsequently, an inventory of all the 1451 rock glaciers identified was elaborated to include for each feature, its horizontal and vertical position (with special regard to the lower limits), activity (intact or relict), and morphometric characteristics (length, width,

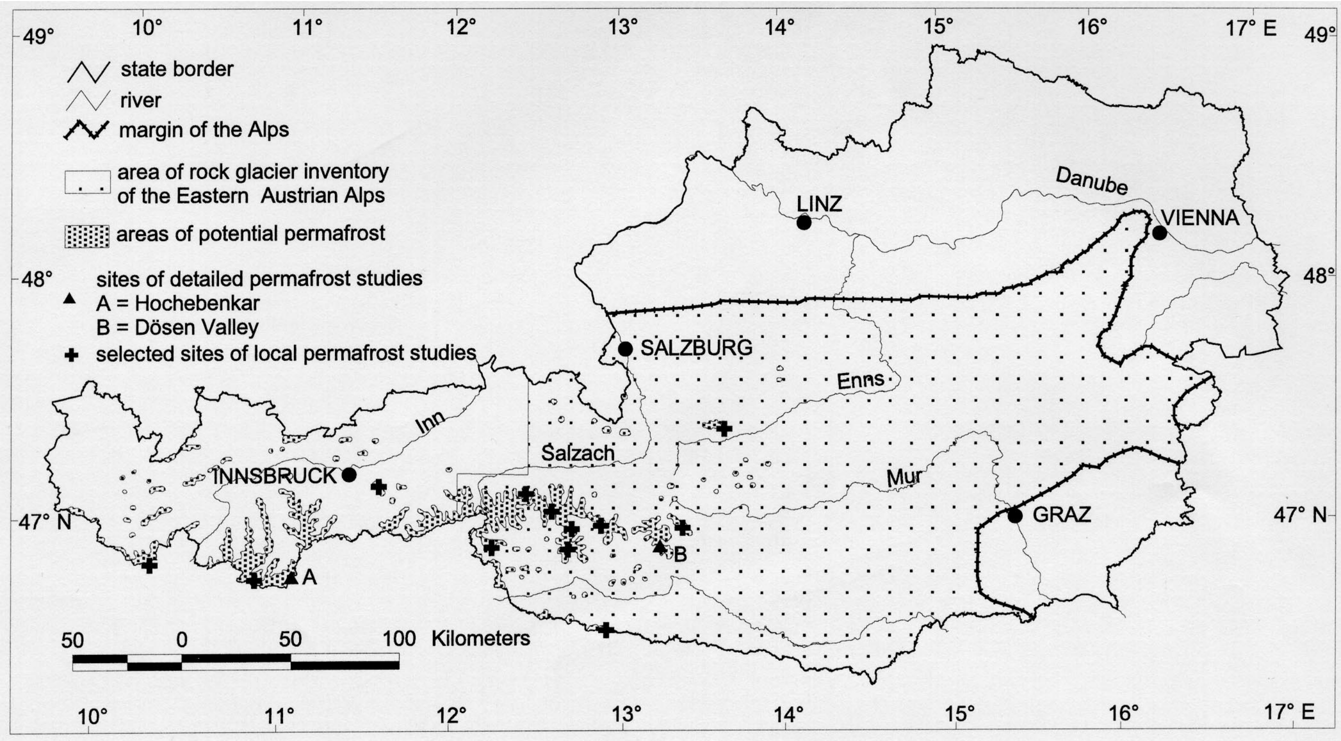

Figure 1. Distribution of potential permafrost and location of permafrost investigation sites in Austria (explanation in the text).

relative height of the catchment area). Unfortunately, the distinction between active and inactive rock glaciers within the activity class "intact" was not always clear due to the quality of the photographs, resulting in a slight inaccuracy in the information derived. Table 1

Table 1. Number and lower limits of rock glaciers in the Eastern Austrian Alps according to activity and exposure

Annotations: The exposure classes comprise the following directions "N" = NW, N, NE; "S" = SE, S, SW; "EW" = E, W; and "all" means the total number of rock glaciers regardless of exposure. The values of the lower limits are means calculated from the numbers given above.

Activity	intact	Relict
N – number	161	487
N – lower limit	2457 m	2026 m
EW – number	71	270
EW – lower limit	2518 m	2089 m
S – number	50	412
S – lower limit	2651 m	2206 m
all – number	282	1169
all – lower limit	2507 m	2104 m

shows some data concerning the lower limits of the rock glaciers which was obtained by statistical analysis of this inventory. Only 19 % of the rock glaciers can be classified as intact, their lower limits representing a minimum extent of present-day permafrost and thus enabling statements on its distribution. Most of the relict rock glaciers (81 %) are of Late Glacial age and are therefore of no further interest in this paper. The differences between the lower limits of the single exposure classes correspond well with findings from other parts of the Alps.

In addition to intact rock glaciers, vegetation and perennial snow - both of which can be easily mapped from aerial photographs - provide indications of the existence of recent permafrost. For the Hohe Tauern range, infrared orthophotographs (scale 1:10,000) were available enabling detailed mapping of surfaces free of vegetation which can, in a first approximation, be considered as areas of potential permafrost occurrence in the Alps (cf. Haeberli, 1975).

Permafrost occurrence in Austria - an overview

Based on the information currently available, discontinuous permafrost can be expected at altitudes above 2400 m in the marginal parts of the Austrian Alps (especially the Northern Limestone Alps) and above 2500 m in the central section (Central Alps, e.g., Hohe Tauern range). In the innermost parts of the Tyrolean Alps, with a relatively continental climate, the lower limit of

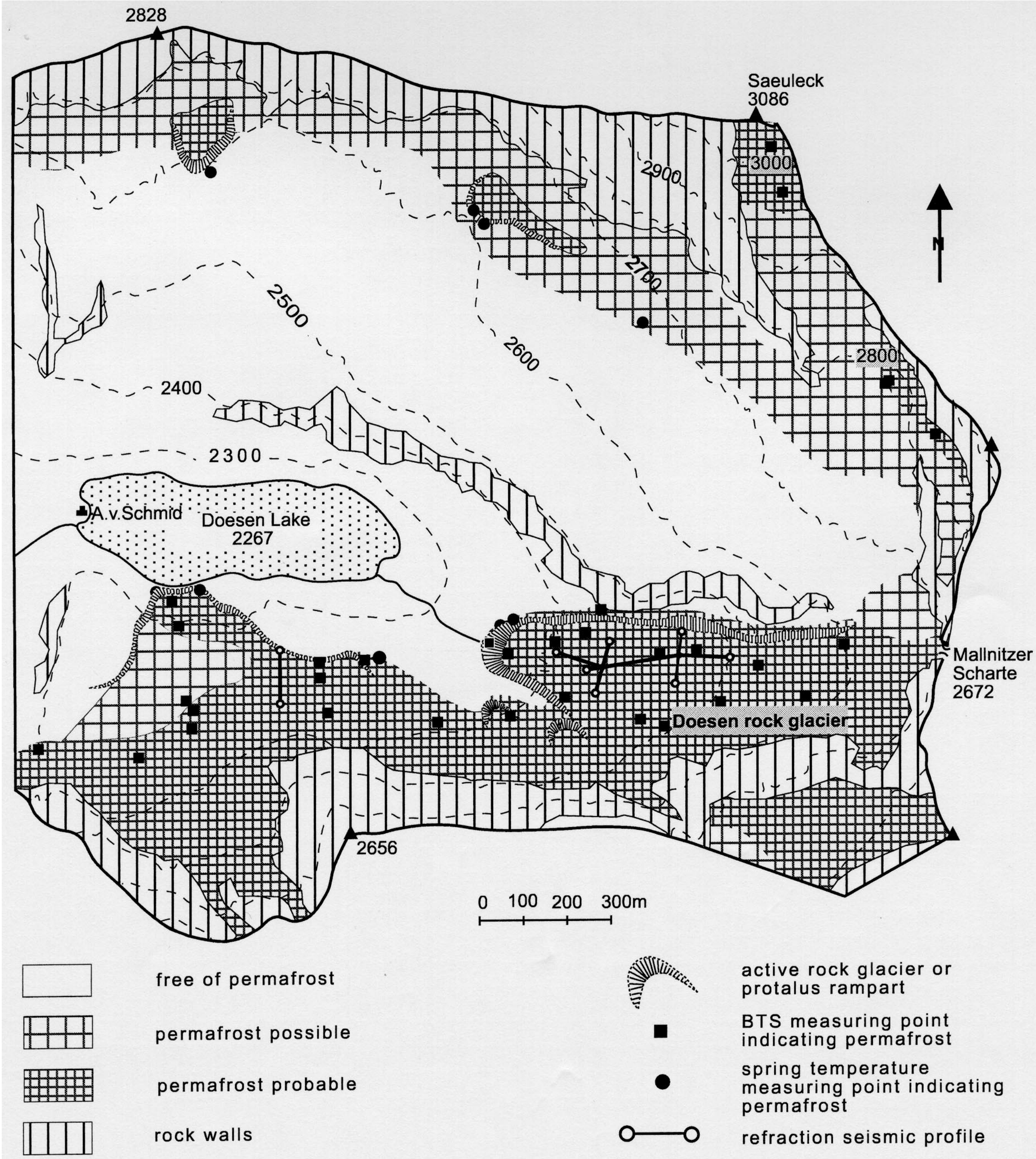

Figure 2. Map of permafrost distribution in the inner Doesen Valley.

discontinuous permafrost may rise to 2600 m or slightly higher. The occurrence of continuous permafrost may be expected on the highest mountains (e.g., Großglockner, 3797 m), but has not been proven to date. Sporadic and island permafrost is known for some places down to about 1000 m or even slightly below. The values given above are averages for all exposure classes; the differences between individual exposures for the Central Alps, which are best documented, are shown in Table 2. These data were derived from the extrapolation of results of large-scale and small-scale investigations (which agree quite well with each other). They were used for modelling the permafrost distribution within the geographical information system Arc/Info, which in two study areas has proven to be a suitable tool for predicting permafrost, a finding that agrees with similar research carried out in the nearby Swiss Alps (Keller 1992). They also allow a small-scale map of potential permafrost distribution in Austria to be drawn (a very generalized version of this map is shown in Figure 1). Thus the total area of potential permafrost in Austria can be estimated to be in the order of 2000 km^2, representing about 2 % of the total area of Austria. In comparison, Keller (1997) has calculated 4-6 % for Switzerland.

Table 2. Empirical values of probable lower limits of discontinuous permafrost in the Central Alps of Austria

Annotation: The differentiation between slope and footslope position was based on Haeberli (1975) and Keller (1992).

Exposure	Permafrost on slopes	Permafrost on footslopes
W	2700 m	2510 m
NW	2580 m	2470 m
N	2500 m	2410 m
NE	2600 m	2500 m
E	2720 m	2520 m
SE	2850 m	2630 m
S	2900 m	2690 m
SW	2850 m	2630 m

Special studies in the Doesen valley (Hohe Tauern range)

Basic Information

In the Austrian Alps, two permafrost study sites are under detailed investigation using a number of different methods: the cirque Hochebenkar (Oetztal Alps, Tyrol, Haeberli and Patzelt, 1983) and the inner Doesen Valley (Hohe Tauern, Carinthia, 46°59'N, 13°17'E) (Figure 1). The latter will be presented below.

The glacially shaped, W-E oriented inner Doesen Valley covers an area of about 3 km^2 and stretches from 2200 m to 3086 m above sea level. It consists of crystalline rocks (predominantly granitic gneiss) and is characterized by a diversified glacial and periglacial morphology containing various talus features, most of them formed by permafrost processes. The centre of the study area is occupied by the active "Doesen rock glacier" (length 900 m, area 0.4 km^2) which has been a subject of intensive research activities since 1994. The climatic conditions are in good concurrence with the central alpine position with a mean annual air temperature of -2°C at 2550 m and an annual precipitation of some 2000 mm at the same altitude, thus enabling areas with and without permafrost to be studied. The site is situated above the timberline (2000-2100 m); small patches of alpine meadows occur up to 2500 m, but most of the area is free of compact vegetation cover.

Permafrost Distribution

The widespread existence of permafrost within the study site is indicated by active rock glaciers (especially the one already mentioned) and protalus ramparts as well as by several perennial snowfields and the lack of vegetation; in a few cases ice could furthermore be observed in small outcrops. For delineation of the extent of permafrost, the BTS was measured at 67 points (at some of them in two different years) and a network of 27 springs was examined. The temperature of these springs was measured at least once every summer from 1993, providing they were accessible, proving that spring temperatures in the permafrost area are constantly below 1°C from one year to another. Based on these data, it was possible to generate a map of permafrost distribution (Figure 2) and to locate geophysical soundings at permafrost sites.

Altogether 26 % of the area was classified as "probable permafrost", and 17 % as "possible permafrost", the latter indicating areas with uncertain information. The remarkably high percentage of permafrost-free areas can be explained by the considerable extent of south-facing slopes. Nevertheless the pattern of permafrost is quite typical of high mountain areas with discontinuous permafrost in the Austrian Alps. Under the bouldery surfaces at the foot of the north-facing slopes, including Doesen rock glacier, permafrost extends down to approximately 2270 m (snout of Doesen rock glacier at 2350 m), while on southern aspects, permafrost occurs only in footslope positions above 2600 m and in "normal" slopes only above 2950 m. The information regarding rock walls is very scarce, so they have not been classified in Figure 2. Some ground temperature measurements in fissures, however, suggest that north faces should be classified as "probable permafrost" while south faces should be classed as "free of

Table 3. Seismic velocities according to a 3-layer-model in the permafrost of Doesen rock glacier (after Schmoeller and Fruhwirth, 1996)

mean depth	Layer	mean velocity
2 m	Dry boulders, active layer	350-400 m/s
4.6 m	intermediate layer with melt-water and ice, fine grained substrate	1800-2000 m/s
no lower limitation	permafrost and bedrock	3600-3900 m/s

permafrost" at lower elevations and "possible permafrost" at higher elevations.

STRUCTURE AND VOLUME OF PERMAFROST

Research on this topic makes use of geophysical soundings: seismic, electromagnetic and ground-penetrating radar measurements have been performed so far. The main object of these soundings was to examine the permafrost of Doesen rock glacier in order to provide basic information for deformation analysis (Kaufmann, 1998). Refraction seismics provided an insight into the internal structure of the permafrost which can be described by a three-layer-model (Table 3). The interpretation of the second layer, which occurs only in some sections of the profiles, was quite difficult. The preliminary explanation is that it represents an intermediate layer with an upper water-saturated part and a lower part of ice-rich substrate, with temperatures near the freezing-point. Another problem was that the permafrost thickness could not be proved by refraction seismics because of the low velocity contrast between the rock glacier permafrost and the basement, as has often been observed in other alpine areas (e.g., Haeberli et al., 1988). This is probably due to severe tectonic fracturing and deep weathering of the underlying bedrock. By modelling the traveltime curves, however, a minimum permafrost thickness of about 30-40 m was estimated.

These findings agree well with electromagnetic measurements which also allow different layers to be recognized. The permafrost thickness calculated from the results of this method also turned out to be some 30 m, with thicknesses of up to 60 m indicated in some places. Since the ground-penetrating radar survey did not contradict these findings, a mean thickness of the rock glacier of 30-40 m is likely. The total volume of the rock glacier can therefore be calculated as some 15 x 106 m^3. Subtracting the active layer and assuming that the ice content is about 50 % (which seems to be realistic in accordance with other alpine rock glaciers, cf. Haeberli, 1985), the ice volume can be estimated at about 6 x 106 m3. Finally, it is worth mentioning that the results of the electromagnetic soundings as well as the temperature of the main spring at the rock glacier snout indicate the existence of sub-permafrost groundwater flow which will be investigated in the near future.

Conclusions

It has been shown that knowledge about the basic patterns of probable permafrost distribution in Austria is satisfactory, although there are big areas which have not yet been studied in detail. The empirical data discussed could serve as a basis for GIS-based preparation of an exact map of potential permafrost distribution covering the entire Austrian Alps. Further emphasis should be placed on extending the rock glacier inventory to the western parts of the country. The main tasks, however, seem to be first, the acquisition of additional data on the internal structure of permafrost - also aside from rock glaciers and especially in bedrock - and, second, the monitoring of changes in permafrost environments. For the first purpose, a borehole measurement site should be installed. At present, however, this seems to be beyond financial possibilities, because the hazardous aspect of permafrost is much less important in the more moderate high mountain relief of the Austrian Alps than, e.g., in Switzerland. Monitoring activities have already been started by establishing a geodetic and geophysical measurement network on Doesen rock glacier (and partly also on Hochebenkar rock glacier) which has proven to be a suitable study site for the future. Thus a lot of work remains to be done to make permafrost in Austria as well-known as it is in those countries which have a long tradition of permafrost research.

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