Present and Past Distribution of Mountain Permafrost in the Gaissane Mountains, Northern Norway

Herman Farbrot
Department of Geosciences, University of Oslo and Norwegian Meteorological Institute, Norway
Ketil Isaksen
Norwegian Meteorological Institute, Norway
Bernd Etzelmüller
Department of Geosciences, University of Oslo, Norway

Abstract

The Gaissane Mountains, situated in northern Norway, reach elevations above 1000 m a.s.l. Our study area contains a range of active and relict periglacial features as well as numerous landforms related to the Pleistocene ice sheet. The distribution of permafrost in the mountains has been investigated through basal temperature of snow (BTS) measurements, continuous ground surface temperature (GST) measurements, and electrical resistivity tomography. Solar radiation and the presence or absence of coarse blocks are the two main factors controlling the thermal regime of regularly snow-covered ground. At fairly snow-free sites, the investigations indicate that mountain permafrost is common in the area above 350–450 m a.s.l. On the summits, about 1000 m a.s.l., geomorphic evidence combined with GST measurements suggest that the permafrost probably shows great antiquity, possibly prevailing since the last interglaciation.

Keywords: Gaissane Mountains; palaeopermafrost; permafrost mapping.

Introduction

In southern Norway, the lower regional altitudinal limit of mountain permafrost decreases eastwards with increasing continentality. The investigated sites in southern Norway have in common that the BTS variance to a great extent is explained by elevation, whereas the effect of solar radiation is secondary (Etzelmüller et al. 2003). Although Reusch (1901) a century ago recognized permafrost as a common phenomenon at high altitudes in northern Norway, few quantitative studies on mountain permafrost have been conducted in this area. Rather most investigations have focused on periglacial geomorphology and in particular palsas (Isaksen et al. 2008 and references therein). Gridded mean annual air temperature (MAAT) maps, however, indicate a similar altitudinal gradient for discontinuous permafrost limits also in northern Norway, decreasing from over 1000 m a.s.l. in coastal sites down to below 400 m a.s.l. in interior, more continental areas (Etzelmüller et al. 2008, Isaksen et al. 2008).

The aim of this study is to investigate occurrences of mountain permafrost in the Gaissane Mountains, northern Norway, by using measurements of ground surface temperature (BTS and Miniature Temperature Dataloggers [MTDs]) and electrical resistivity tomography (ERT). The factors controlling the distribution of permafrost are discussed. In addition, the distribution of paleopermafrost is briefly discussed based on geomorphic mapping.

Setting

The Gaissane Mountains are situated southwest of the Varanger Peninsula (70°N, 25°E) in the county of Finnmark, northern Norway (Fig. 1). The mountains reach elevations above 1000 m a.s.l. Western and southwestern parts of Norway are mostly influenced by western, Atlantic air flows bringing unstable weather patterns with high winter temperatures and moist air, whereas eastern parts of northern Norway are frequently dominated by Eurasian high-pressure systems involving stable air with high summer temperatures and low winter temperatures for long periods of time (Johannessen 1970). The official weather station closest to the field area is Banak (5 m a.s.l.), 20 km to the north. There, MAAT

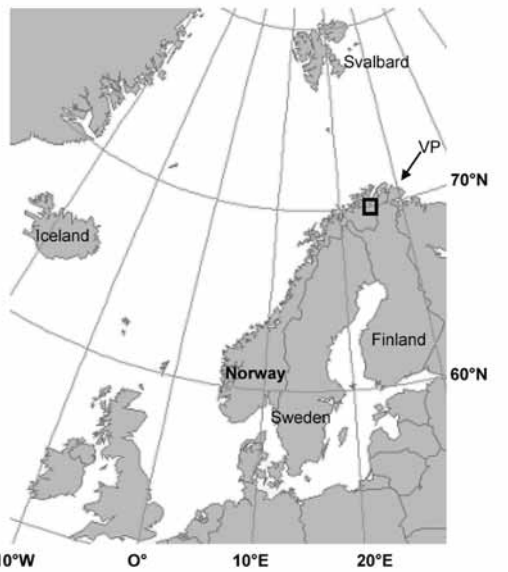

Figure 1. The Gaissane Mountains are situated in northern Norway, southwest of the Varanger Peninsula (VP).

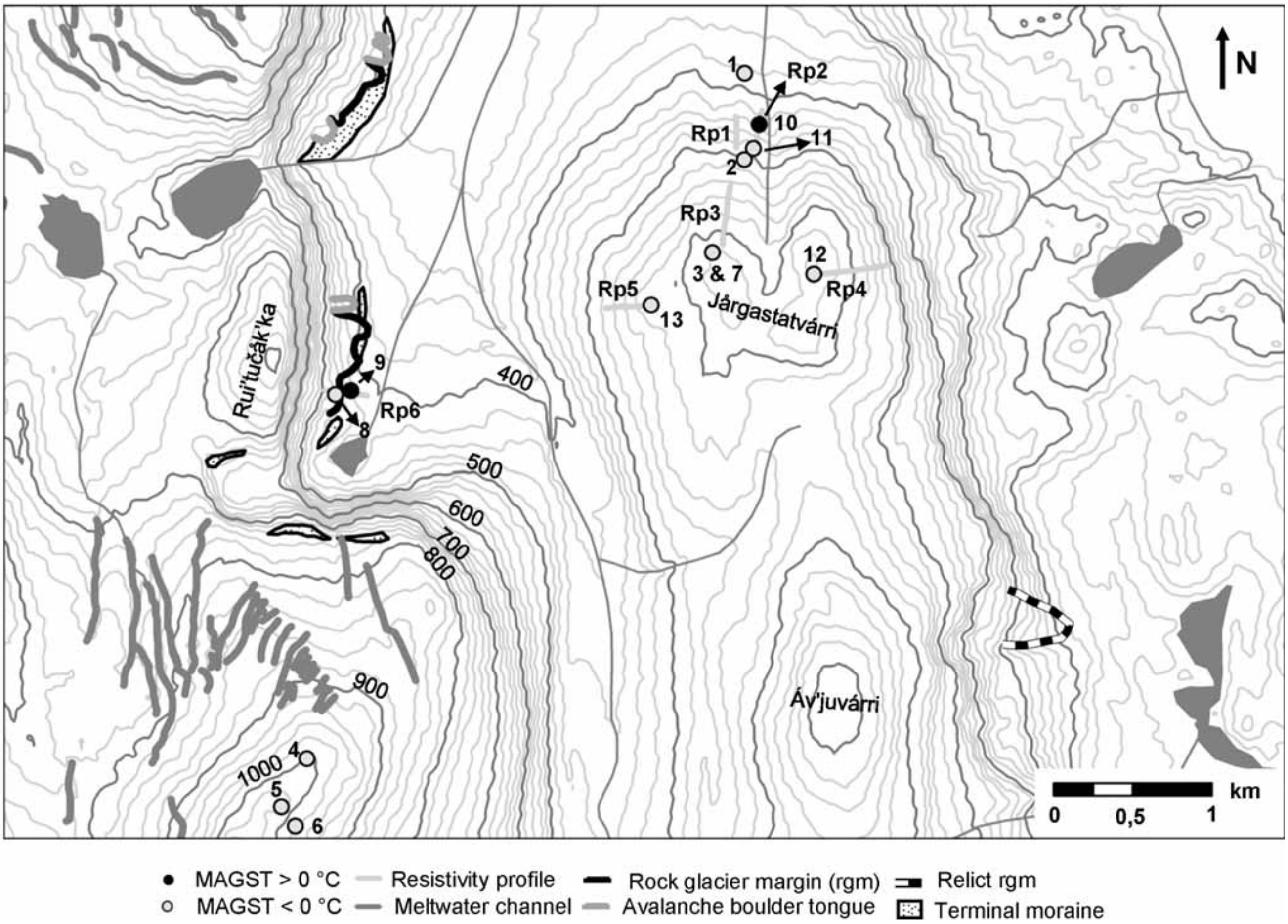

Figure 2. Map of the field area in Gaissane Mountains containing the positions of the ERT profiles (Rp1-6), MTDs and some geomorphic features. Letters refer to the MTDs in Table 1. The westernmost rock glaciers partly cover morainic ridges of presumable Preboreal age (Kellerer-Pirklbauer 2008).

(1961–1990) is 0.6°C and mean annual precipitation 345 mm. The winds are strong during winter, and above the forest line (250–300 m a.s.l.) extensive snow cover is commonly restricted to depressions.

The field area contains a range of active and relict periglacial features including rock glaciers, solifluction lobes, ploughing boulders, and patterned ground, as well as numerous landforms related to the Scandinavian ice sheet. The field area is situated well inside the glacial limit of the Younger Dryas ice; however, the summits were nunataks at that time (Marthinussen 1960).

Methods and Results

MTDs

13 UTL-1 MTDs were used during the period 2003–2006, 12 measuring ground surface temperatures and one measuring air temperature (Fig. 2, Table 1). The thermistors have a temperature range of −29° to +39°C, and the accuracy of the sensors are ±0.27°C (Hoelzle et al. 1999). The MTD data is probably not representative for long-term ground surface temperature conditions, since the observational period was characterized by considerably higher air temperatures than normal (1961–1990). By correlating the daily ground surface means with daily air temperature means from the weather station at Banak, a simple linear regression model was established. Using MAAT from Banak as independent variable, mean annual ground surface temperatures (MAGSTs) for the normal period 1961–1990 were estimated for the MTD sites. For these estimates to be reliable, we only used data from more or less snow-free sites, as indicated by the existence of high-frequency temperature fluctuations during winter (MTDs 1, 3-5, 8-13). The assumption is, thus, that these areas also remained snow free during the normal period 1961–1990 (cf., Farbrot et al. 2007). In general, a R^2 of > 0.70 (for all records: $p << 0.001$) was achieved in these analyses. Fitting a linear trend line through the estimated MAGST from the MTD sites indicate that the MAGST 0°C-isotherm of fairly snow-free sites is found at ~350 m a.s.l.

One year of air temperature measurements at an elevation of 614 m a.s.l. (MTD 7) combined with corresponding measurements from Banak weather station (5 m a.s.l.) reveal a mean altitudinal lapse rate of ~ -0.005°C m^{-1}. This fits well with investigations by Laaksonen (1976) indicating a similar mean vertical temperature gradient for Fennoscandia and in particular other investigations from northern Norway indicating comparable lapse rates (Isaksen et al., in prep.).

Table 1. Measured and estimated ground surface and air temperatures at the MTD sites in the Gaissane Mountains. MTD 10–13 were operating less than a year, but have been used for estimation of MAGST. MGST = Mean ground surface temperature, FDD = freezing degree days, TDD = Thawing degree days, MAAT = Mean annual air temperature, MAGST = Mean annual ground surface temperature, N = number of values in the statistical analyses, R^2 = Goodness-of-fit of a straight line fitted by least squares to the points.

	1	2	3	4	5	6	7 (Air)	8	9	10	11	12	13
Elevation (m a.s.l.)	389	508	614	1002	1034	982	614	471	428	433	487	643	593
MGST 03-04 (°C)	-	0.5	-1.1	-2.7	-2.8	-0.5	-	-	-	-	-	-	-
FDD 03-04	-	748	1379	1620	1692	783	-	-	-	-	-	-	-
TDD 03-04	-	942	977	634	683	597	-	-	-	-	-	-	-
MGST 04-05 (°C)	-	0.8	-0.9	-2.2	-2.4	-2.1	-0.9 (air)	0.3	1.3	-	-	-	-
FDD 04-05	-	679	1327	1501	1600	1211	1381	917	830	-	-	-	-
TDD 04-05	-	957	988	705	729	429	1048	1010	1291	-	-	-	-
MGST 05-06 (°C)	-	0.5	-0.8	-2.4	-2.4	-1.4	-	0.1	1.4	-	-	-	-
FDD 05-06	-	789	1254	1456	1439	1075	-	998	841	-	-	-	-
TDD 05-06	-	965	976	594	549	577	-	1051	1334	-	-	-	-
Est. MAGST (°C)	-0.4	-	-2.2	-3.5	-3.6	-	-	-0.8	0.2	0.4	-1.1	-1.6	-1.7
N	313	1039	1039	1039	1039	1039	398	725	725	336	336	333	335
R^2	0.853	-	0.887	0.812	0.788	-	0.895	0.804	0.884	0.705	0.887	0.913	0.892
Est. MAAT (°C)	-1.3	-1.9	-2.5	-4.1	-4.5	-4.3	-2.5	-1.8	-1.7	-1.5	-1.7	-2.6	-2.3
Est. surface offset (°C)	0.9	-	0.3	0.6	1.0	-	-	0.9	1.9	1.9	0.5	1.0	0.6

Hence, the measured mean lapse rate is assumed fairly representative for the 1961–1990 period, and, thus, MAATs for this period can be estimated for the MTD sites (Table 1), thereby enabling estimates of the surface offset (i.e., MAGST–MAAT). Surface offsets are mainly less than 1°C at dry sites without pronounced snow cover (Table 1). This fits with investigations from southern and northern Norway (Isaksen et al. 2007, 2008) and Iceland (Farbrot et al. 2007). From this approach, permafrost should be common at locations with thin or no snow cover above the elevation of the –1°C-isotherm. Using the assumed mean altitudinal lapse rate of $-0.005°C\ m^{-1}$, the –1°C-isotherm is found at ~330 m a.s.l. in the field area.

BTS

Basal temperature of snow (BTS) measurements involve measuring temperatures at the bottom of the snow cover when the temperatures have stabilized before onset of melting. Under a thick, dry snow cover (>0.8–1.0 m) the ground surface temperature is mainly controlled by heat conduction from the subsurface, thereby reflecting the thermal regime of the ground. Permafrost is considered probable if BTS values <–3°C, possible if values are between –2° and –3 °C and improbable if values > –2°C (Haeberli 1973).

Table 2. Parametric (Pearsons r) correlation matrix for BTS as dependent variable and selected topographic attributes and presence and absence of coarse blocks at the ground surface expressed as a dummy variable. PR = Potential radiation, N = 163.

	Elevation	PR	Coarse blocks	Snow depth	Wetness index
BTS	-0.065	0.445*	-0.604*	0.289*	0.092

* Correlation is significant at the 0.01 level (2-tailed)

In March 2004, February 2005, and February 2006, a total of 334 BTS measurements were obtained. The measuring points' topographical characteristics such as elevation, slope, and aspect were estimated from a DEM with 25 m grid spacing (© Statens Kartverk). Further, the annual potential solar radiation (PR) was estimated based on the SRAD topographic model (Wilson & Gallant 2000). A potential topographic wetness index—defined as the quotient of the specific upstream area and the surface slope—was estimated based on Beven & Kirkby (1979). In addition, the surficial material type (presence or absence of coarse blocks) was recorded at each measuring

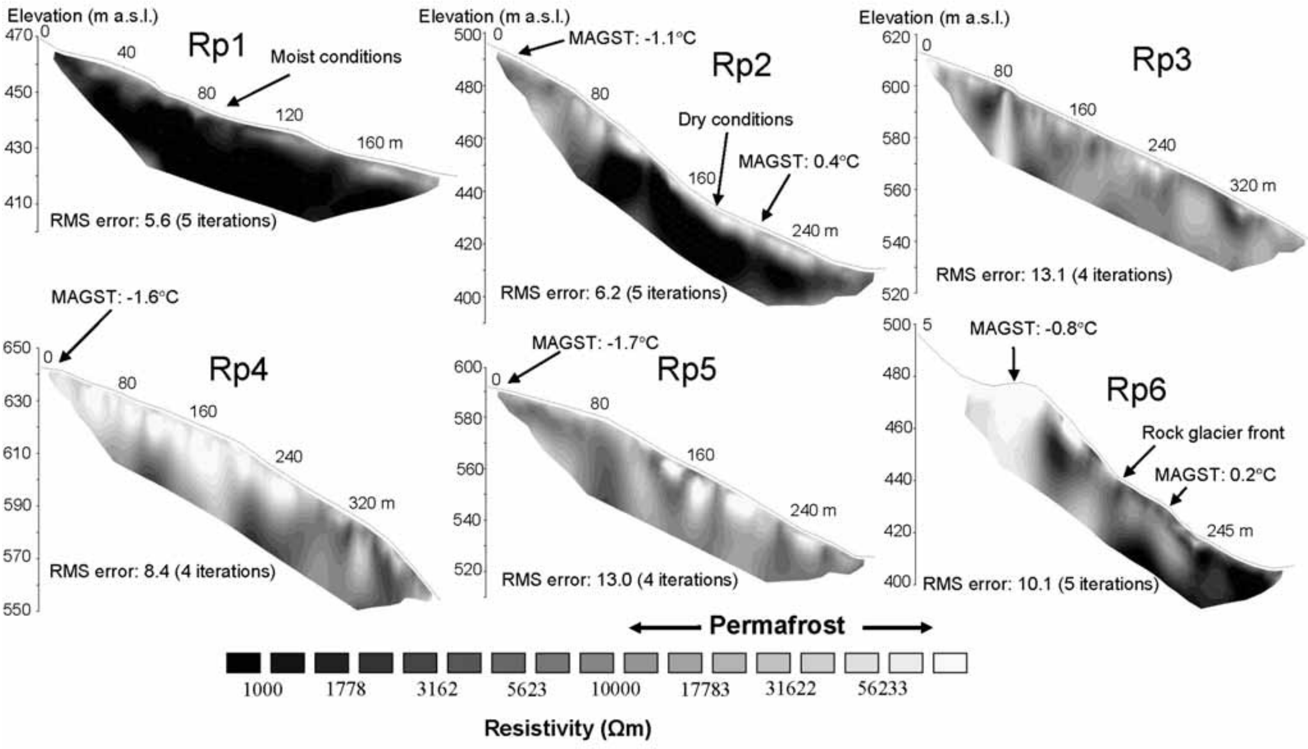

Figure 3. ERT profiles obtained in the Gaissane Mountains (for location, see Fig. 2). There is an overall increase in resistivity with elevation. The profiles indicate permafrost at elevations >450 m a.s.l., which corresponds well with estimated MAGSTs along the profiles.

site. Mean values were computed within diameters ≤10 m with consistent topographical and ground surface characteristics to try to overcome the problem of micro-scale variability and spatially clustered data (cf., Brenning et al. 2005), and these means (N=163) were used in the further analyses. From the correlation analysis, it is evident that PR and the presence or absence of coarse blocks, expressed as a dummy variable (1 means coarse material is present; 0 means coarse material is absent), are the major factors controlling BTS (Table 2). Mean BTS value for sites with coarse blocks is ~2.2°C lower than for sites without. However, the coarse-grained sites reveal less PR than the fine-grained sites. This effect is excluded by subtracting the assumed effect of lower PR on BTS values from the linear regression, thereby indicating that the effect of coarse blocks lowers the mean BTS value with 1.6°C. A linear regression model with the presence or absence of coarse blocks and PR as independent variables, explains 65% of the BTS variability. No significant correlation was found between BTS and elevation (at the 0.01 level [2-tailed]). Correlation between BTS and snow depth is significant but weak.

Electrical resistivity tomography

Electrical resistivity tomography (ERT) measurements are conducted by inserting an electrical current into the ground via two current electrodes. The resulting electrical potential between two other electrodes is measured, and from these measurements the true resistivity of the ground can be estimated. The existence of ice in the ground increases the resistivity markedly since the resistivity of ice is several orders of magnitude higher than water. Thus, resistivity measurements are highly valuable for detecting and characterizing ice-bearing permafrost (e.g,. Hauck & Vonder Mühll 2003). Six two-dimensional ERT profiles have been obtained in the field area (Fig. 3). Resistivity profile 1 (Rp1) is the lowermost profile (~400 m a.s.l.) across presumably permafrost free ground as indicated by BTS measurements. Hence, this profile presumably represents bedrock resistivities, thereby indicating that resistivity values >10 000 Ωm can serve as a conservative estimate for permafrost. This assumption corresponds well with the MTD measurements (Fig. 3). Generally, there is an overall increase in resistivity with elevation, and the profiles indicate permafrost above ~450 m a.s.l. Furthermore, Rp 6, a longitudinal profile along a rock glacier, indicates ice rich subsurface conditions within the rock glacier, although the possibility of air-filled cavities causing the high-resistive zone can not be excluded from the ERT measurements solely (cf., Hauck et al. 2004).

Discussion

BTS variability

The BTS measurements indicate that solar radiation and the presence or absence of coarse blocks are the two main factors controlling the thermal regime at snow covered sites (Table 2). The influence of PR is greater than what is found in southern Norway where ground thermal regime is highly correlated with elevation and to a lesser extent PR (Isaksen et al. 2002, Heggem et al. 2005). This difference seems plausible as the solar height is lower in northern Norway.

The occurrence of openwork blocky debris in the field area is clearly a cooling factor for ground surface temperatures. Similar results have been found in a range of studies (e.g., Harris & Pedersen 1998), and recently in southeastern Norway (Juliussen & Humlum 2007). This is presumably due to air circulation within the voids, which was indicated by several observations of air ventilation funnels through the snow cover in wintertime.

The lack of significant correlation between BTS and elevation probably reflects that the BTS points are mainly scattered between 300 and 600 m a.s.l., and a greater elevation span would have increased the correlation (cf., Brenning et al. 2005), as obtained for the MTDs. The mentioned elevation range obviously shows large snow cover, soil moisture and vegetation cover variations, covering the elevation signal in the statistical analysis (cf., Isaksen et al. 2002).

Present permafrost distribution

No borehole temperature measurements are available within the field area, so identification of mountain permafrost relies on indirect methods. Below the forest line of about 250–300 m a.s.l., winter snow cover is fairly extensively developed, so permafrost is presumably absent there due to the insulating effect of snow (cf., Johansson et al. 2006). The lowermost presumably active rock glaciers in the area have their margins at ~430 m a.s.l., and both BTS and ERT measurements indicate that these features contain permafrost at present.

The consistency of the independent indirect methods (Table 3) leads to the conclusion that mountain permafrost is common above 350–450 m a.s.l. As all BTS measurements rely on point measurements with a stable snow cover of a least 80 cm, this should imply that these points represent warmer ground conditions compared to areas with limited snow cover, due to the isolating effect of snow (cf., Jeckel 1988). Developed snow covers are limited in the field area due to low precipitation and strong winds. Thus, the aerial extent of permafrost is presumably greater than indicated by BTS measurements (cf., Sollid et al. 2003). The permafrost distribution pattern indicated fits generally well with Johansson et al. (2006), stating that permafrost is common in the tundra zone above the forest line in the Torneträsk region, northern Sweden. The pattern also agrees with investigations by King & Seppälä (1987) in north-western Finland which indicate a lower limit of discontinuous permafrost of 300–500 m a.s.l. based on geoelectrical soundings.

Past permafrost conditions

Several relict periglacial landforms in the field area point to a cooler environment in the past than at present. Such landforms include a rock glacier, terminating in the birch forest, with its fronts at 180 m a.s.l., presumably relict tundra polygons, ploughing boulders found in the birch forest, and extensive areas of vegetated patterned ground. The low-elevation rock glacier witnesses a past lower limit of permafrost at least 200 m below the present.

The past lower limit of mountain permafrost in the field area were obviously variable during the Holocene climate fluctuations

Table 3. Elevation of different environmental parameters and permafrost limits indicated by different indirect approaches. See text for details.

Environmental parameter/ permafrost limit	Elevation (m a.s.l.)
Tree line	250-300
Blockfield limit	~800
BTS	?
Estimated MAGST	350
ERT measurements	~450
-1°C isotherm	330
Active rock glacier	430

(cf., Kukkonen & Šafanda 2001). However, on the summits of about 1000 m a.s.l., a different picture emerges. The blockfields of the summit areas show no signs of Holocene modification. The lateral meltwater channels eroded into the blockfields together with the terminal moraines found on top (cf., Marthinussen 1960) indicate a pre-Late Glacial Maximum age of the blockfield and subsequent survival underneath cold-based, non-erosive ice. This interpretation is supported by investigations of blockfields on the Varanger Peninsula (Fjellanger et al. 2006). According to Heikkilä & Seppä (2003) maximum annual air temperatures in Fennoscandia were approximately 1.5–2.0°C higher during the mid-Holocene thermal optimum (HTO) than the reconstructed mean temperature of the last 200 years. Assuming a roughly equal coupling between air and ground surface temperatures, sub-zero MAGST probably still occurred in the summit areas of about 1000 m a.s.l. during HTO. This is based on the assumption that the summits have prevailed bare-blown, with limited influence of changes in the Holocene wind and precipitation patterns. Thus, although warm periods have occurred during the Holocene, affecting thermal regime and the permafrost thickness, permafrost conditions have presumably prevailed in the summit areas. This is supported by numerical modelling of permafrost in bedrock in northern Fennoscandia during the Holocene by Kukkonen & Šafanda (2001). Hence, assuming cold-based ice in the summit areas at least during the last glaciation, permafrost at these elevations probably is of considerable age, potentially spanning the Weichselian.

Conclusions

Based on these investigations the following conclusions concerning mountain permafrost in the Gaissane Mountains seem supported:

- At present permafrost is common above 350–450 m a.s.l.
- Coarse, openwork blocks tend to reduce ground surface temperatures significantly.
- The permafrost in the summit areas at about 1000 m a.s.l. is of considerable age, possibly prevailing since the last interglaciation.

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